Integrating flood hazard into site selection of detention basins using spatial multi-criteria decision making

Article *in* Journal of Environmental Planning and Management · October 2015

DOI: 10.1080/09640568.2015.1077104

Ebrahim Ahmadisharaf
Danish Hydraulic Institute (DHI)

Massoud Tajrishy
Sharif University of Technology

Nasrin Alamdari
Virginia Polytechnic Institute and State University

Journal of Environmental Planning and Management

ISSN: 0964-0568 (Print) 1360-0559 (Online) Journal homepage: http://www.tandfonline.com/loi/cjep20

Integrating flood hazard into site selection of detention basins using spatial multi-criteria decision-making

Ebrahim Ahmadisharaf, Masoud Tajrishy & Nasrin Alamdari

To cite this article: Ebrahim Ahmadisharaf, Masoud Tajrishy & Nasrin Alamdari (2016) Integrating flood hazard into site selection of detention basins using spatial multi-criteria decision-making, Journal of Environmental Planning and Management, 59:8, 1397-1417, DOI: 10.1080/09640568.2015.1077104

To link to this article: http://dx.doi.org/10.1080/09640568.2015.1077104

Published online: 15 Oct 2015.

Journal of Environmental Planning and Management, 2016
Vol. 59, No. 8, 1397–1417, http://dx.doi.org/10.1080/09640568.2015.1077104

Integrating flood hazard into site selection of detention basins using spatial multi-criteria decision-making

Ebrahim Ahmadisharaf [a]*, Masoud Tajrishy [b] and Nasrin Alamdari [c]

[a] *Civil and Environmental Engineering Department, Tennessee Technological University, Cookeville, TN, USA;* [b] *Civil Engineering Department, Sharif University of Technology, Tehran, Iran;* [c] *Biological Systems Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA*

(*Received 25 October 2014; final version received 23 July 2015*)

This study presents an innovative approach for the integration of flood hazard into the site selection of detention basins. The site selection process is conducted by taking into account multiple criteria and disciplines. Hydraulic modeling results derived from stormwater management model are employed by Technique for the Order of Prioritization by Similarity to Ideal Solution (TOPSIS) to determine flood hazard score. The score generated by TOPSIS is used in a spatial multi-criteria decision-making site selection framework. Applying the framework, a suitability map is generated in which primary locations for detention basin placement are determined. The method is demonstrated through the case study of Darakeh River Catchment, which is located in northern Tehran, Iran. The presented framework can be easily utilized for site selection of other stormwater management techniques, such as low impact development and best management practices, due to its versatility.

Keywords: detention basin; site selection; SWMM; spatial multi-criteria decision-making; flood hazard

1. Introduction

Floods are some of the most damaging events among natural disasters. More than half of worldwide flood damage occurs in Asia (Tingsanchali 2012). In spite of extensive research on river flooding, urban flooding has not been considered extensively important and is yet to be studied (Chen, Hill, and Urbano 2009). In particular, among developing countries such as Iran, urban flood planning and management is often carried out by using traditional approaches, such as channelization (discharging the rainwater into the channel network), without consideration of novel techniques (source control approaches) such as low-impact development (LID) and best management practices (BMPs). It is, therefore, necessary to study the capabilities of novel stormwater measures such as detention basins for urban flood control in developing countries.

Recent developments have brought a wide variety of novel techniques such as LID and BMPs into stormwater management (Young *et al.* 2009). Effectiveness of these measures depends on their geographic location and unplanned application may worsen an existing situation (McCuen 1974; Emerson, Welty, and Traver 2005; Gilroy and McCuen 2009; Fang *et al.* 2010). As these techniques influence several disciplines, the site selection problem is multi-objective and needs a strong synergy between various

*Corresponding author. Email: eahmadish42@students.tntech.edu

stakeholders from different areas (Yeh and Labadie 1997). A flexible tool capable of integrating multiple objectives is thus required. Multi-criteria decision-making (MCDM) methods are useful tools and can provide a systematic framework to deal with such complex multi-disciplinary problems (Fattahi and Fayyaz 2010).

There is extensive literature on MCDM applications in environmental and water resource disciplines. Hajkowicz and Collins (2007) reviewed 61 MCDM methods which were employed in such contexts. Several MCDM techniques were employed in a wide variety of water resource problems, namely: Willett and Sharda (1991) for the selection of flood control projects; Ahmadisharaf, Kalyanapu, and Chung (2015) for spatial assessment of flood management alternatives; Abrishamchi *et al.* (2005) for urban water supply; Zarghami (2006) for irrigation planning; Zarghami (2010) for integrated urban water management (IUWM); Young *et al.* (2009, 2010), Young, Dymond, and Kibler (2011) for urban stormwater BMP selection; Giri and Nejadhashemi (2014) for agricultural BMP selection; Dang, Babel, and Luong (2011) for evaluation of the most important flood risk parameters; Fernandez and Lutz (2010) for flood hazard mapping; Afshar *et al.* (2011) for evaluation of water resource management alternatives; and Kim and Chung (2013) for assessing the vulnerability to climate change. However, there exist few applications of MCDM tools for selection and siting of LID/BMPs.

Martin, Ruperd, and Legret (2007) carried out the first application of MCDM for LID/BMP selection where Elimination and Choice that Translates Reality (ELECTRE) (Roy 1978) was employed for the analysis of decision criteria for BMP selection. Young *et al.* (2009) introduced analytical hierarchy process (AHP) (Saaty 1980) for selection of suitable BMPs. Young *et al.* (2010), Young, Dymond, and Kibler, 2011) later coupled Geographic Information System (GIS) with this methodology and applied it to a real world problem of BMP selection. Ahammed, Hewa, and Argue (2012) used AHP for evaluation of different water sensitive urban design and LID technologies. Jia *et al.* (2013) developed a software program, BMPSELEC, based on a multi-criteria selection index system for LID/BMP planning and selection. Jato-Espino *et al.* (2014) applied AHP for the selection of different types of urban pervious pavements. Moving forward with the MCDM-based studies, some efforts have been made to develop models for selection and siting of LID/BMPs. Cheng, Zhen, and Shoemaker (2009) developed a BMP decision support system, BMPDSS, which is a decision-making tool for BMP placement based on hydrologic, hydraulic and water quality modeling results. The system for urban stormwater treatment and analysis integration, which was developed by the US Environmental Protection Agency (Shoemaker *et al.* 2009; Lee *et al.* 2012), is another tool for modeling, siting and optimization of a set of LID/BMPs. But research on the application of the hydrologic models and MCDM methods together remains unclear (Chung and Lee 2009). Additionally, it is noted through the literature review that hydraulic modeling results have not yet been directly used in MCDM-aided site selection problems. Chung *et al.* (2011) illustrated the benefits of integrating continuous runoff simulation results and MCDM techniques for evaluation of urban watershed management alternatives. Nevertheless, there has been no effort for the integration of hydraulic modeling results into site selection of BMPs, including detention basins. The conventional methodology for BMP site selection entails two major steps: (1) assessment of the current drainage network by using a hydrologic–hydraulic modeling tool and (2) placement of BMPs in the areas of concern by consideration of project limitations and case study restrictions. However, the hydraulic modeling results are not directly applied in the site selection framework. The subjective decision pertaining to the locations for BMP placement may potentially yield uncertain solutions for the site-selection problem.

Thus, a less subjective automated procedure needs to be established in order to incorporate hydraulic modeling results into the site selection of BMPs.

The main objective of this study is to integrate hydraulic modeling results into the site selection of detention basins by using a spatial MCDM (SMCDM)-based framework. Hydraulic modeling results are used as a criterion called "flood hazard" in the site-selection framework. Considering the scope of the study focusing on flood control, detention basins are selected among the existing LID/BMPs due to their efficiency in runoff control, as shown in previous studies (Young *et al.* 2010; Young, Dymond, and Kibler 2011) and literature suggestions (e.g., Young 2006; Jia *et al.* 2013). In particular, as a high return period is analyzed, detention basins are chosen which are effective in large magnitude runoffs. Other techniques, such as LIDs, are more efficient in small rainfall events (Schneider and McCuen 2006; Gilroy and McCuen 2009; Zahmatkesh *et al.* 2014).

The presented site selection framework consists of three modules and generates a raster map showing the suitability of each grid cell for detention basin placement. A highly urbanized catchment, Darakeh, located in the city of Tehran, Iran is used to illustrate the presented framework. The framework can be easily utilized for site selection of other stormwater management techniques, such as LID and BMPs, due to its versatility.

2. Methodology

The methodology used by the SMCDM-based framework is presented in this section. The framework entails three modules: (1) hydrologic−hydraulic modeling; (2) flood hazard determination; and (3) site selection of detention basins. Primary required data to apply the framework are intensity-duration-frequency (IDF) curves, as well as GIS datasets of landuse, soil infiltration, terrain and stream cross sections. The framework for site selection of detention basins is visualized in Figure 1. Each module is clarified in the next sections.

2.1. Hydrologic−hydraulic modeling

Hydrologic and hydraulic modeling is carried out by applying USEPA's stormwater management model (SWMM) version 5.1.002. SWMM is a distributed dynamic simulation model that can handle single-event or continuous simulation of both water quantity and quality (Gironás *et al.* 2010; Rossman 2010). Rainfall-runoff transformation and flow routing are the hydrologic and hydraulic processes, respectively. The Soil Conservation Service method (US Department of Agriculture (USDA) National Resources Conservation Service (NRCS) 2004) is selected for rainfall-runoff modeling due to its simplicity and low data requirement. Full dynamic wave is chosen as the flow routing technique due to its high accuracy and ability to simulate non-uniform unsteady flow conditions. The technique solves one-dimensional (1D) full Saint Venant flow equations. More details about hydrologic−hydraulic modeling by SWMM can be found in Rossman (2010).

2.2. Flood hazard determination

This section describes the methodology used to determine flood hazard. The innovative approach to integrate flood hazard into the site selection of detention basins is also presented in this section. The output results of the first module (hydrologic−hydraulic

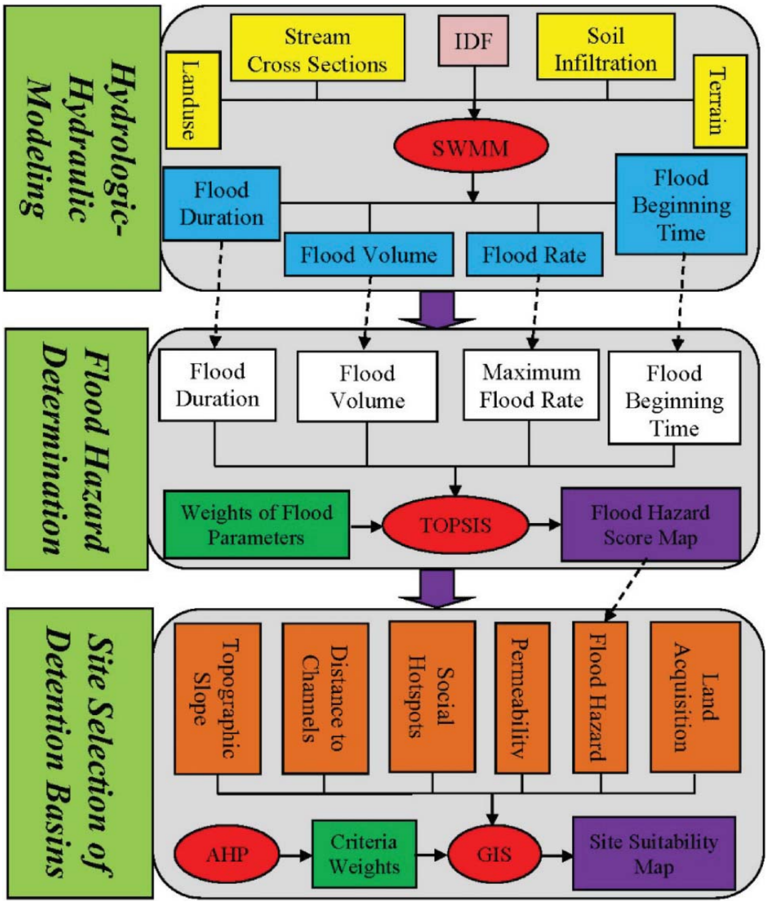

Figure 1. Schematic of site selection framework.

modeling) are employed as input into this module. Flood hazard is defined as a linear function of four indicators: flood beginning time, duration, volume and maximum rate. The values of the four parameters are combined using a distance-based MCDM approach, Technique for the Order of Prioritization by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon 1981). TOPSIS can be easily programmed as it has a simple computational procedure (Kim, Park and Yoon 1997). It is utilized here as it can directly use the original values of evaluation criteria and does not need subjective judgments by the decision-maker (DM) to post-process hydraulic modeling results. Furthermore, using TOPSIS enables the DM to avoid the situation that two alternatives under evaluation have the same value and cannot be appropriately ranked (Hsieh, Chin, and Wu 2006). TOPSIS is also preferred here to another popular distance-based approach, Compromise Programming (Zeleny 1973), which only accounts for the distance to utopia (positive ideal solution) but not the distance to nadir (negative ideal solution), whereas TOPSIS takes into account both ideal solutions (Hwang and Yoon 1981). In TOPSIS, the best alternative is the option with closest distance to utopia and farthest from nadir. For these reasons, TOPSIS is employed for flood hazard determination by post-processing hydraulic modeling results generated by SWMM.

TOPSIS is applied in the current study in the following steps:

(1) Construction of the evaluation matrix: an evaluation matrix is constructed which consists of m flooded junctions and n (which is four here) flood hazard indicators. The values are taken from SWMM modeling results (generated in the first module). Let F denote the evaluation matrix and f_{ij} denote the pixels of F. Subscripts i and j refer to the flooded junction and flood hazard indicator, respectively.
(2) Standardization of the pixels of the evaluation matrix: the values of the four flood hazard indicators, including flood beginning time, duration, volume and maximum rate, are standardized at flooded junctions. The following equation is applied to standardize the pixels of evaluation matrix:

$$r_{ij} = \frac{f_{ij}}{\sum_{\mathrm{i}=1}^{m} f_{ij}} \tag{1}$$

in which r_{ij} is the pixel of standardized evaluation matrix.
(3) Determination of the weighted standardized values of the evaluation matrix: the standardized values of each flood hazard indicator (determined in the previous step) are multiplied to the associated weight at each flooded junction. The following equation is applied to standardize the pixels of evaluation matrix:

$$v_{ij} = w_j f_{ij} \tag{2}$$

where v_{ij} is the pixel of weighted standardized evaluation matrix and w_j is the weight of flood hazard indicator j.
(4) Determination of the utopia and nadir for each flood hazard indicator: values of utopia and nadir are determined for each of the four flood hazard indicators in the flooded junctions. Utopia is the value of the flood hazard indicator at the junction with the least crucial flooding status. In other words, it is the junction with the latest flood beginning time, shortest flood duration, minimum flood volume and minimum flood rate, among all flooded junctions. On the other hand, nadir is the junction that has the earliest flood beginning time, longest flood duration, maximum flood volume and maximum flood rate, among all flooded junctions.
(5) Computation of the distance to utopia and nadir: Euclidean distance of each flood hazard indicator at each flooded junction to the corresponding utopia and nadir is computed in this step. The following equations are used to calculate the distance to utopia and nadir:

$$d_{iu} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{uj})} \tag{3}$$

$$d_{in} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{nj})} \tag{4}$$

in which v_{uj} and v_{nj} are the utopia and nadir for flood hazard indicator j, and d_{iu} and d_{in} are the distance to utopia and nadir for flooded junction i, respectively.

(6) Computation of the relative distance to nadir: relative distance to nadir is computed for each flooded junction based on the following equation:

$$c_i = \frac{d_{iu}}{d_{in} + d_{iu}} \tag{5}$$

where c_i is the relative distance to nadir for flooded junction i. The greater this relative distance, the closer to the nadir. In other words, a higher relative distance refers to a more crucial flood hazard status. Relative distance values are then normalized and the standardized values are called the final flood hazard score. The normalization is performed to have the summation of the scores equal to unity.

$$s_i = \frac{c_i}{\sum_{i=1}^{m} c_i} \tag{6}$$

in which s_i is the flood hazard score for flooded junction i.

Applying the above mentioned procedure, a flood hazard score is assigned to each of the flooded junctions. The flood hazard scores are then assigned to the contributing drainage areas (CDAs) of the junction. CDAs with a higher flood hazard score are more suitable for the construction of a detention basin. In other words, a detention basin is preferred to be placed upstream of the junctions with a higher flood hazard. The common areas between the CDAs of two junctions are assigned the flood hazard score of the junction located upstream. A GIS raster layer is the final product in which the grid cells indicate the flood hazard score. Thus, flood hazard can be integrated into the other decision criteria for site selection of detention basins. TOPSIS calculations are performed in a simple spreadsheet in Microsoft Excel.

2.3. Site selection of detention basins

Site selection of detention basins is conducted by using a SMCDM-based framework, in which AHP determines the weight of decision criteria and GIS performs the geospatial analysis. In contrast to many MCDM methods, AHP has a unique approach for weight determination and can also check the inconsistencies of DM judgments. While AHP could be alternatively used for the flood hazard determination, it is to be noted that conducting a similar process with AHP requires building a large PCM (with rows and columns equal to the number of junctions in the channel network) and thus performing many pairwise comparisons. Moreover, because AHP cannot use original values of the criteria (it uses a $1-9$ qualitative scale), carrying out pairwise comparisons needs DM judgments and thereby adds subjective uncertainty to the process. AHP consists of three steps for weight determination: (1) construction of criteria pairwise comparison matrix (PCM); (2) extraction of criteria weights; and (3) consistency assessment of the DM judgments reflected in the criteria PCM. AHP calculations are performed in a spreadsheet within a Microsoft Excel environment and GIS analyzes are performed within ESRI's ArcGIS™ environment.[1]

Site selection of LID/BMPs is commonly carried out based on hydrologic, environmental and economic concerns. Here, permeability, topographic slope, flood hazard, land acquisition, distance to channels and social hotspots are selected as decision criteria. For each criterion, multiple classes are defined and the score for each class is determined by construction of a PCM. The following notes about the decision criteria should be clarified:

- Selection of criteria depends on the study area characteristics. For instance, social hotspots may vary with the case study.
- As the infiltration process in the detention basin is allowed, the permeability is an important factor. Here, curve number (CN) is considered as a permeability indicator, as it represents infiltration of both landuse and soil (USDA NRCS 2004).
- Both surface and underground detention basins are proposed, but surface options are preferred due to the lower required costs of implementation. Thus, in land acquisition criterion, the first priority is given to open spaces and parks that are well suited to surface options, and the second priority is given to the areas owned by the government and municipality that are appropriate for underground options. Residential areas and health centers are the least favorable landuse areas, which cannot be occupied due to the restrictions by the cities on urban encroachment.

The final step is GIS application to generate a spatial suitability map for detention basin placement. A model is developed within ArcGIS™ Model Builder for geoprocessing operations. The criteria raster layers are overlaid using the model and following Equation (7):

$$V_i = \sum_{j=1}^{n} w_j v_{ij} \tag{7}$$

in which, V_i is the aggregated score of grid cell i, w_j is the weight of criterion j, v_{ij} is the score of grid cell i with respect to criterion j and n is the number of criteria. The output of this model is a suitability map in which the grid cells show the suitability for detention basin placement. This map is the final product of the framework presented here for site selection of detention basins.

3. Case study

A highly urbanized case study in the city of Tehran, Iran, is selected to illustrate the applicability of the SMCDM framework. The drainage network of the study region has several complexities due to the rapid, heterogeneous and disorganized development (Mahab Ghodss Consulting Engineers (hereafter called "MGCE") and Pöyry 2011). In recent years, the increase in impervious surfaces as a result of rapid urbanization and landuse modification has intensified the risk of flooding and caused frequent overflows of the drainage network. In this study, the Darakeh Catchment located in northern Tehran is chosen as the study site to illustrate the applicability of the SMCDM-based framework. The catchment is vulnerable to flooding due to the presence of a high population, as well as several buildings and assets. It has an area of 43.7 km^2, including 17 km^2 of urban area and 26.7 km^2 rural area. The drainage network of the study site has a total length of 33 km. Sedimentation is obvious in a large portion of the network which blocks up to 50% of the capacity in some portions (MGCE and Pöyry 2011). A combination of natural and manmade channels is employed for flood control without using any novel stormwater management approach (e.g., LID/BMPs). Figure 2 presents the location map for the case study.

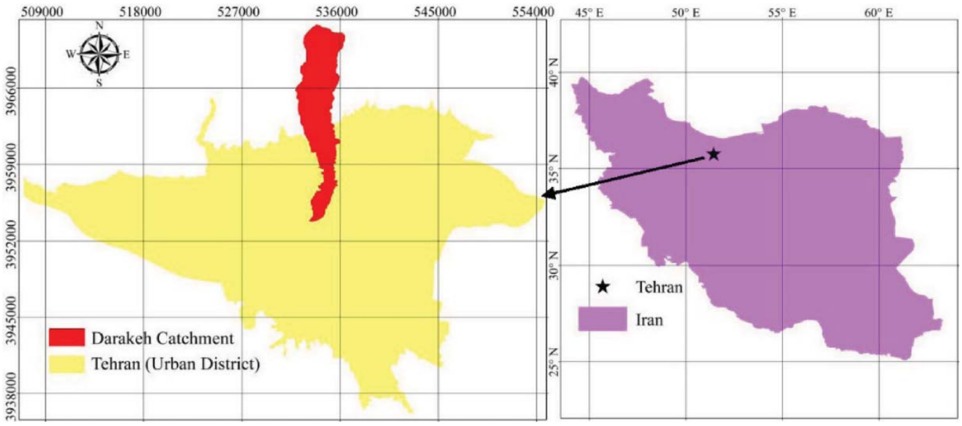

Figure 2. Location map of the study area.

Heavy traffic is evident in the study region during the daytime, so the five major highways are considered social hotspots. Distance to highways is selected as the indicator of social hotspot criterion. It is to be noted that while distance to highways is considered as the only indicator of social hotspots in the present study, other indicators, such as distance to health centers, can be potentially used to further describe this criterion. The hierarchical structure of the decision criteria for site selection of the detention basins in the study area is depicted in Figure 3. Goal, criteria and indicators are organized in three levels. The first level refers to the goal, or the site selection of detention basins. The second level presents the six decision criteria. The third level shows the indicators of the decision criteria.

4. Framework demonstration

In this section, the presented SMCDM-based framework is demonstrated through a case study of the Darakeh Catchment. As discussed earlier, the framework consists of three modules of hydrologic–hydraulic modeling, flood hazard determination and site selection of detention basins.

4.1. Hydrologic–hydraulic modeling of the study area

The first step in applying the presented methodology is performing a hydrologic–hydraulic modeling. A hyetograph is created for 100-yr, six-hr design rainfall event using Tehran

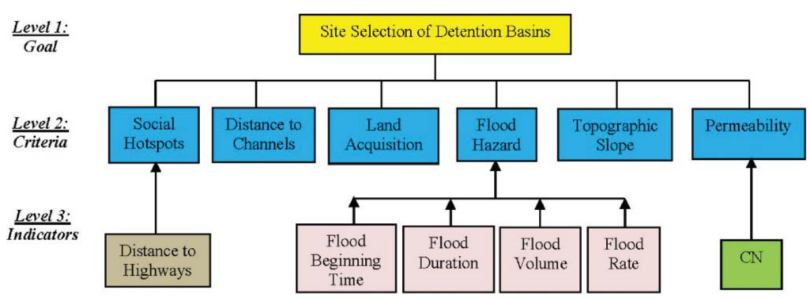

Figure 3. Hierarchy for site selection of detention basins.

IDF equations developed by MGCE and Pöyry (2011). The IDF equations are a function of return period and invert elevation. The created storm hyetograph is used as the input for the rainfall-runoff transformation process. Based on MGCE and Pöyry (2011), Darakeh Catchment delineates into eight subcatchments, five urban and three rural. A rain gage is set for each subcatchment in SWMM, based on the subcatchment mean invert elevation. CN values of the subcatchments and Manning's roughness coefficients of the channels are directly extracted from MGCE and Pöyry (2011). The values are not calibrated against field-observed flow data due to the lack of such information. Nevertheless, local reports on surcharge of channels and specific discharges from the neighbor catchments were used to verify the CN values.

Taking the abovementioned information, a SWMM model is built to simulate rainfall-runoff transformation and flow routing processes in the study area. The flow routing time step is set to 1 second with a maximum of 20 trials per time step. An adjustment factor of 25% is used as a variable time step to satisfy the Courant condition within the channels and to avoid numerical instabilities. A head convergence tolerance of 0.1 mm is also used. Ponding is not allowed due to the lack of data on ponded area at the junctions. Furthermore, allowing ponding results in several numerical oscillations in the flow hydrographs of the channel junctions. Hence, to avoid these types of numerical problems, the ponding is ignored here.

Running the SWMM model, the simulation summary shows mass continuity errors of −0.002% and −0.005% for surface runoff and flow routing, respectively, which implies the validity of analyzed results. No flow instability is seen in the channels. Table 1 summarizes the SWMM modeling results of a 100-yr storm, including flood parameters in flooded junctions. Figure 4 depicts the flood status in the study area. High flooding occurs upstream of the drainage network, especially junctions D6 and D7. Moving further downstream, junctions D8 and D9 have minor flooding, but junctions D10 and D11 have more flooding due to the overland flow from two subcatchments. The junctions downstream of D11 are not flooded aside from WDC2, which has remarkable flooding and is located close to the catchment outlet.

It is important to remember that due to the lack of historical flood data, modeling results are not calibrated with the observed values. The modeling results, therefore, cannot be taken as final definitive predicted values. However, this does not affect the illustration of the site selection framework as the paper focus does not lie in the representation of calibrated hydrologic−hydraulic modeling results for the case study. Rather, the modeling process is conducted as a part of the framework to illustrate the general site selection procedure.

Table 1. Flood parameters in flooded junctions.

Junction	Flood beginning time (min)	Flood duration (min)	Flood volume (m^3)	Maximum flood rate (cms)
D6	190.6	40.2	94,070	80.0
D7	195.3	43.8	40,017	24.2
D8	200.2	17.4	250	1.7
D9	214.9	25.8	60	0.1
D10	200.8	39.6	13,100	10.9
D11	200.6	47.4	15,745	9.3
WDC2	203.1	116.4	278,491	65.5

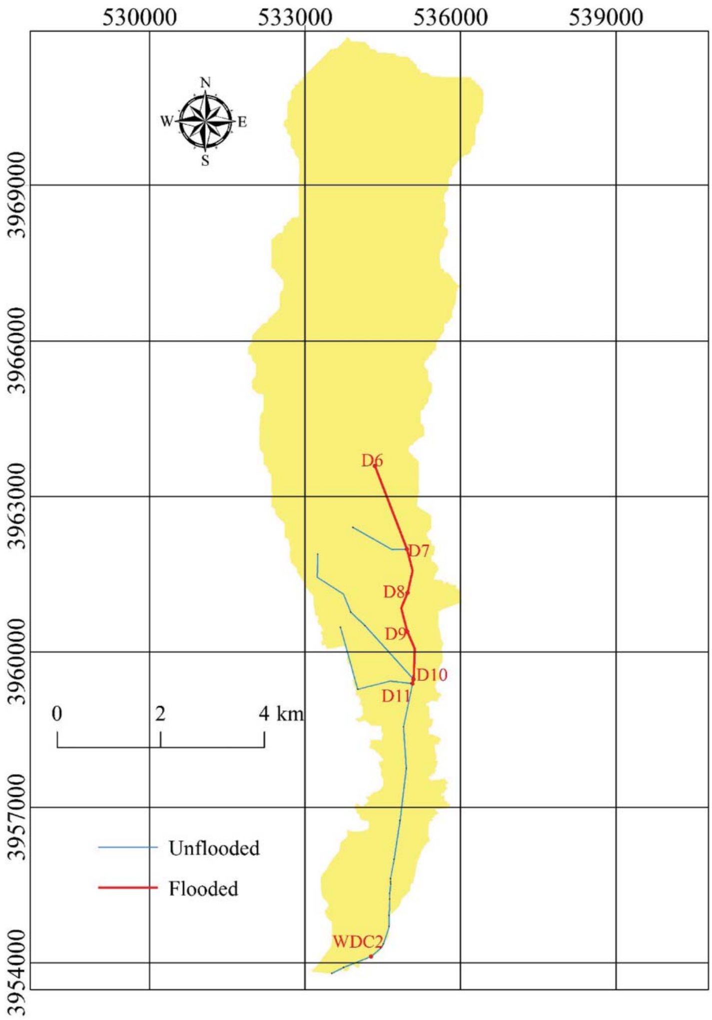

Figure 4. 100-yr flood status in the case study.

4.2. *Flood hazard determination for the study area*

Taking the hydrologic–hydraulic results and the presented algorithm for flood hazard determination, a flood hazard score is determined at drainage network junctions, applying TOPSIS and following the outlined methodology. An equal importance of 0.25 is assigned to each of the four flood hazard indicators. Flood hazard scores at flooded junctions are presented in Table 2. The most crucial flood hazard status belongs to the upstream junctions (D6 and D7) and a downstream junction (WDC2) in accordance with the SWMM modeling results discussed earlier. Midstream areas are mostly unflooded, but minor overflow much less than junctions D6, D7 and WDC2 is evident.

The next step is to assign junction flood hazard scores to the corresponding CDAs. CDAs of junction D6, D7 and WDC2 are assigned the highest scores. The upstream areas of the catchment, which are common areas between CDAs of all the flooded junctions,

Table 2. Scores of network junctions in terms of flood hazard criterion.

Junction	D6	D7	D8	D9	D10	D11	WDC2
Score	0.253	0.115	0.011	0.020	0.067	0.080	0.453

are assigned the score of D6 (upstream of the other flooded junctions). Finally, downstream areas of junction WDC2 (from WDC2 to catchment outlet) are given a score of zero as there is no flooding downstream of this junction. The spatial variability of flood hazard scores is presented in Figure 5.

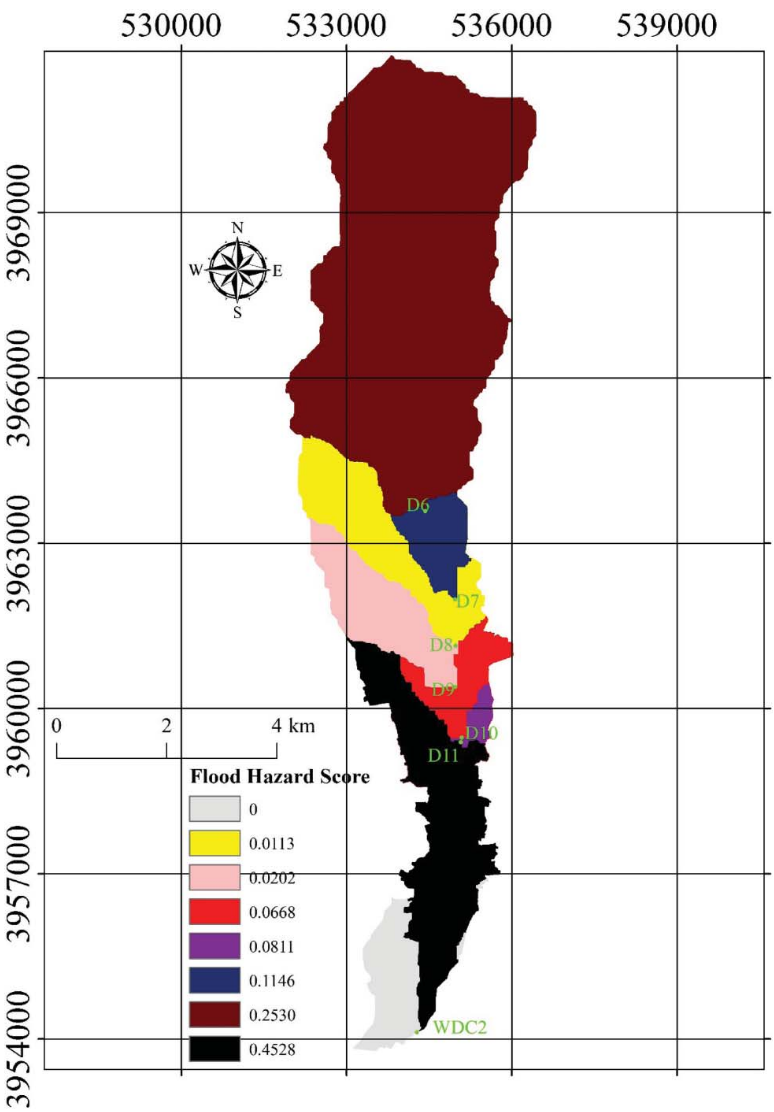

Figure 5. Spatial variability of flood hazard score in the Darakeh River.

4.3. Site selection of detention basins for the study area

In this section, the presented SMCDM-based site selection framework is applied to the case study of Darakeh River. The rasters of the two criteria distance to channels and social hotspots (with the indicator of distance to highways) are produced using the Euclidean Distance function of ArcGIS^{TM}. First, each criterion is classified into multiple non-overlapping classes. An AHP PCM, which consists of the classes as rows and columns, is then constructed for each criterion to derive the score of the classes in each criterion. Table 3 shows the scores of the criteria (or the indicators) classes. It is to be noted that the flood hazard criterion is not listed in this table as the scores were previously determined by TOPSIS in module 2 (hydrologic–hydraulic modeling). The GIS rasters of the criteria are then reclassified to the scores presented in Table 3 using the ArcGIS^{TM} Reclassify function.

The next step is building the AHP PCM of the decision criteria to determine the weights. A 6 $\times$ 6 matrix is built, as shown in Table 4. The judgments are conducted based on the authors' preferences and also by taking into account the opinions of a limited number of experts from the private sector. Preferences of the stakeholders from government and municipalities are not reflected in the judgment. The inconsistency ratio of the criteria PCM is computed as 0.04, which is less than 0.10 (maximum allowable value of the inconsistency

Table 3. Scores of the criteria classes for the study area.

Criterion	Indicator	Class	Score	Inconsistency ratio
Topographic slope	–	0%–5%	0.566	0.06
		5%–10%	0.267	
		10%–15%	0.127	
		>15%	0.040	
Distance to channels	–	0–100 m	0.513	0.05
		100–250 m	0.261	
		250–500 m	0.129	
		500–1000 m	0.063	
		>1000 m	0.033	
Social hotspots	Distance to highways	>5000 m	0.583	0.06
		2500–5000 m	0.290	
		1000–2500 m	0.085	
		0–1000 m	0.042	
Permeability	CN	65–70	0.513	0.05
		70–75	0.261	
		75–80	0.129	
		80–85	0.063	
		85–90	0.033	
Land acquisition	Landuse	Open spaces/parks	0.654	0.09
		Urban facilities	0.249	
		Mountainous	0.048	
		Residential/health centers	0.048	

Table 4. AHP PCM of site selection criteria.

Criterion	Topographic slope	Distance to channels	Social hotspot	Permeability	Flood hazard	Land acquisition
Topographic slope	1	1/3	1/7	1/3	1/9	1/9
Distance to channels	3	1	1/5	1	1/7	1/7
Social hotspot	7	5	1	5	1/3	1/3
Permeability	3	1	1/5	1	1/7	1/7
Flood hazard	9	7	3	7	1	1
Land acquisition	9	7	3	7	1	1

ratio suggested by Saaty (1980)) and verifies the consistencies of the judgments. Extracted criteria weights are presented in Table 5. The highest weight belongs to the land acquisition criterion due to the Tehran municipality restrictions on urban encroachment, and the flood hazard criterion due to the main objective of the current study which is flood control. The second priority is given to social hotspots due to the importance of traffic flow in the city and its role in daily transportation. Distance to channels and permeability are given the next priority and topographic slope is assigned the lowest importance.

The final step is the application of the ArcGIS™ Model Builder, discussed earlier in the methodology section, to generate the suitability map for detention basin placement. Running the model for the study site of Darakeh River, a suitability map is produced, where the grid cells show the suitability of detention basin placement. To give a better understanding of the final results, aggregated scores are qualitatively classified into three different groups regarding the detention basin placement. They are presented in Table 6 and are stated as: unsuitable (class 1), moderately suitable (class 2) and highly suitable (class 3). The areas of class 3 (highly suitable) are obviously desired for the construction of a detention basin.

The final suitability map for detention basin placement in the Darakeh River is presented in Figure 6 based on the abovementioned qualitative classification. Based on the figure, 47.2%, 51.1% and 1.6% of the catchment areas are occupied with classes 1–3, respectively. Areas of class 3, which are the most suitable for detention basin placement, are mostly located in the midstream areas (upstream of junction WDC2) for two main reasons: First, SWMM modeling results show that junction WDC2 has remarkable flooding issues and the upstream sections are assigned the highest score for the flood hazard criterion. Due to the high importance of this criterion, these locations are given a considerable score. Second, open spaces and parks are located in the midstream sections, which attain a high value from the land acquisition criterion (also of high importance). There are also upstream areas (upstream of junction D6)

Table 5. Site selection criteria weights.

Land acquisition	Flood hazard	Permeability	Social hotspot	Distance to channels	Topographic slope	Criterion
0.348	0.348	0.050	0.176	0.050	0.026	Weight

Table 6. Qualitative classification of aggregated score for detention basin placement.

Class	1	2	3
Aggregated score	0–0.20	0.2–0.40	0.40–1
Qualitative description	Unsuitable	Moderately suitable	Highly suitable

with high suitability due to the high flood hazard criterion score and the existence of open spaces upstream of junction D6. Other areas upstream of junction D6, which are mostly mountainous with steep topographic slopes, do not fall within the highly suitable class (class 3).

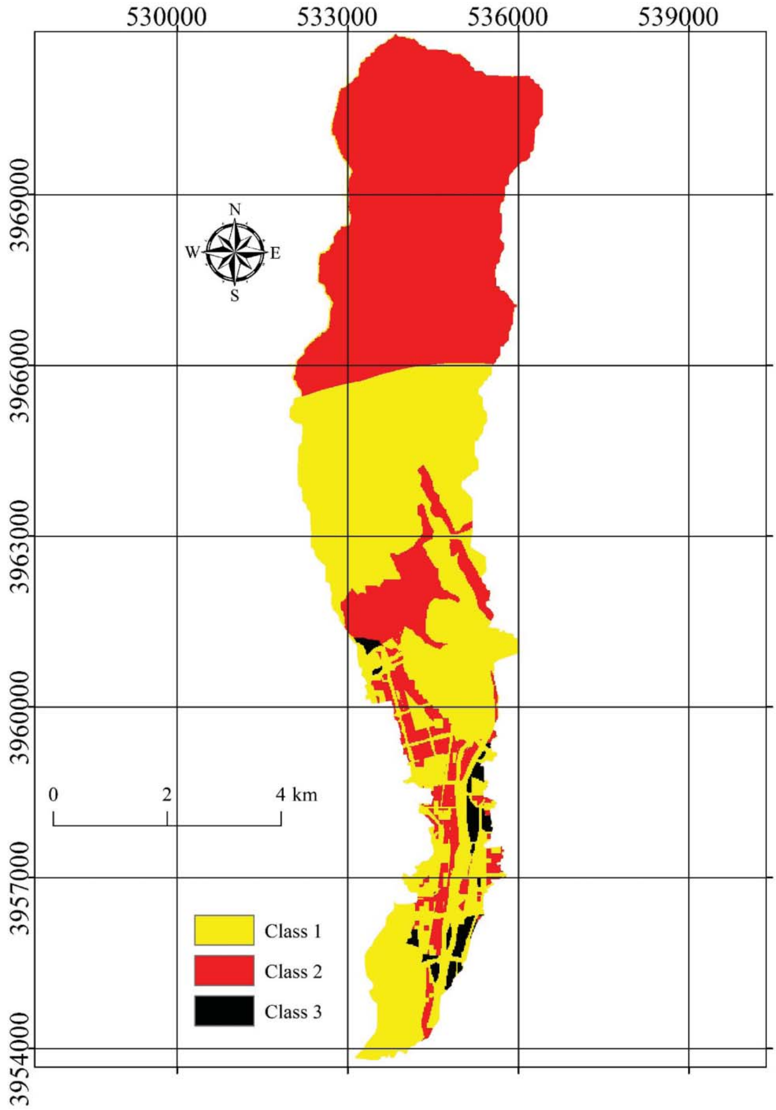

Figure 6. Suitability map for detention basin placement in the Darakeh River.

To select the final location for detention basin placement, class 3 regions should be scrutinized. Taking the average score of these regions, the values are found to be very close and are therefore difficult to prioritize. In this situation, an additional criterion (with discrimination capacity) can be considered. However, this is not conducted here and instead the sensitivity of the preliminary suitable regions with respect to the criteria weights is analyzed in order to evaluate the robustness of these regions. The most robust region is selected as the best location for detention basin placement. The next section describes the sensitivity analysis for the present study.

5. Sensitivity analysis

A sensitivity analysis is performed to assess the robustness of preliminary selected regions with respect to the criteria weights. Six additional weight sets are defined in tandem with the preliminary weight set. The weight set scenarios are defined by the variation of the weights of the three most important decision criteria: flood hazard, land acquisition and social hotspots. Six other weight sets are defined, along with the preliminary assigned weights, producing a total of seven weight sets. The seven weight set scenarios are: (1) preliminary assigned weights (Table 7); (2) 10% increase in flood hazard criterion weight; (3) 10% decrease in flood hazard criterion weight; (4) 10% increase in land acquisition criterion weight; (5) 10% decrease in land acquisition criterion weight; (6) 10% increase in social hotspots criterion weight; and (7) 10% decrease in social hotspots criterion weight. Table 7 shows the criteria weights in different weight set scenarios. For each scenario, a suitablity map is generated in ArcGIS™ and the map is classified into three groups using the classification in Table 6. Final suggested areas are those that are in suitability class 3 (highly suitable) in all seven weight set scenarios. Moreover, regions with an area of less than 4 ha (10 acre) are eliminated according to the recommendations by USEPA (2000). Figure 7 visualizes the final suggested locations for detention basin placement. Three locations are selected, based on the map, as final regions for detention basin placement. These locations have areas of 4.7, 25.8 and 5.7 ha, respectively. Selected location 1 is in an open space area, but the two others are located in parks. Discriminating these three locations depends on the project goals and limitations. Location 2 has a remarkably higher area compared to the other choices and will be more desirable in a condition that a larger detention basin is needed. Location 1 will also be desirable when open spaces are preferred to parks. Again, the hydrologic and hydraulic modeling results are not calibrated, and it is to be highlighted that the suggested areas for detention basin placement should not be taken as ultimate choices and should be used cautiously.

Table 7. Criteria weights in different sensitivity analysis scenarios.

Criterion weight set	Topographic slope	Distance to channels	Social hotspot	Permeability	Flood hazard	Land acquisition
1	0.026	0.050	0.176	0.050	0.348	0.348
2	0.019	0.044	0.169	0.044	0.383	0.341
3	0.033	0.057	0.183	0.057	0.314	0.355
4	0.019	0.044	0.169	0.044	0.341	0.383
5	0.033	0.057	0.183	0.057	0.355	0.314
6	0.023	0.047	0.194	0.047	0.345	0.345
7	0.030	0.054	0.159	0.054	0.352	0.352

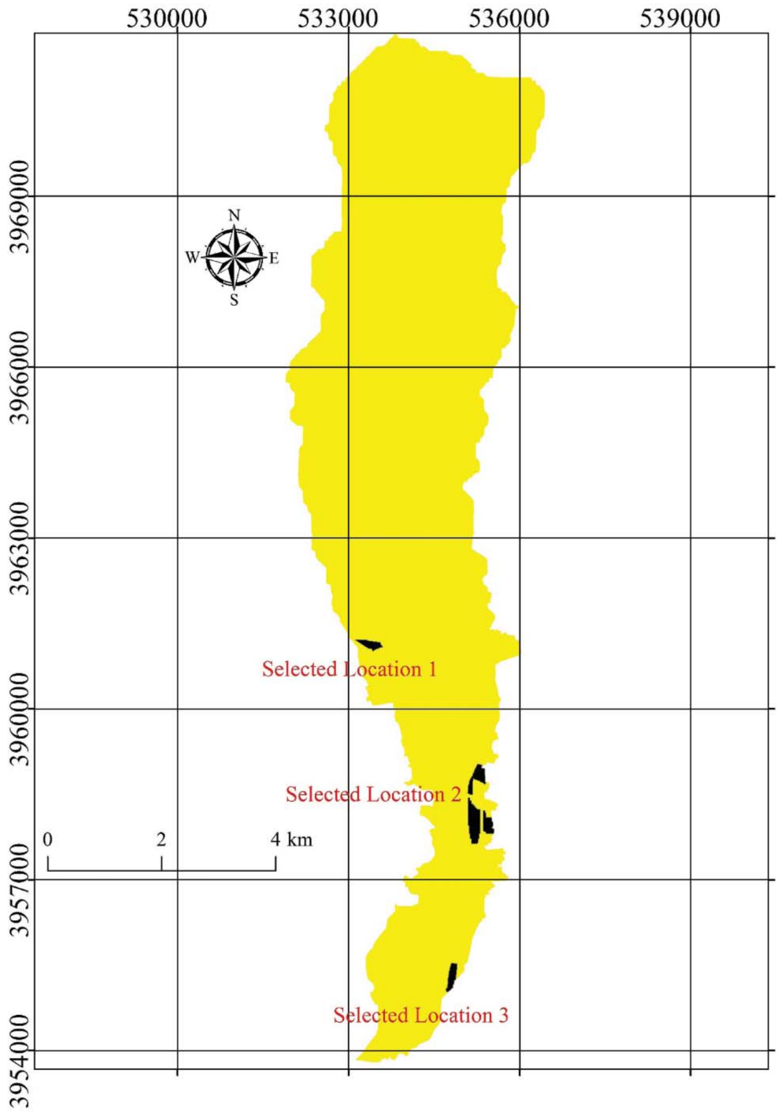

Figure 7. Final suggested locations for detention basin placement in the Darakeh River.

6. Summary and conclusions

In this study, an innovative methodology for site selection of detention basins was presented. The approach integrates flood hazard into site selection of detention basins using a SMCDM-based framework. It entails three modules: hydrologic–hydraulic modeling, flood hazard determination and site selection of detention basins. In the first module, USEPA's SWMM was used for hydrologic–hydraulic modeling. The hydraulic modeling results, including flood beginning time, duration, volume and rate, were used as flood hazard indicators. In the second module, TOPSIS was applied to combine the four indicators and to determine the flood hazard scores. Flood hazard was then employed as a decision criterion in the third module. Six criteria were considered for site selection, including permeability, topographic slope, flood hazard, land acquisition, distance to channels and social hotspots. The final product of the framework is a raster map, in which the grid cells indicate the suitability of the locations for detention basin placement. An illustrative example in a highly urbanized catchment, in this case the Darakeh area located in the city of Tehran, Iran, was also provided. Sensitivity of primary candidates for detention basin placement was analyzed to evaluate the robustness of selected areas.

The framework for site selection of detention basins can be used for other types of stormwater management techniques such as LID/BMPs due to its versatility. Nevertheless, it has some limitations which are discussed in this section.

First, due to the importance of criteria weights in MCDM, stakeholders are commonly engaged in the weighting process (Munda 2006; Lai, Lundie, and Ashbolt 2008). Nevertheless, the weights were determined here based on the authors' preferences and also by accounting for the opinions of a limited number of experts from the private sector, as this was not the main scope of this paper and was only a step to illustrate the general procedure of the innovative SMCDM-based site selection framework. Consequently, the results of this study cannot be taken as the final absolute suitability map for detention basin placement and need to be coupled with a more sophisticated process of public engagement and stakeholders' participation before it can be utilized in practice. Weighting should be carried out with the participation of stakeholders from government and municipalities to validate the results of this study. This can be performed by using some interviews, questionnaires, and workshops.

Second, a distance-based MCDM method, TOPSIS, was used in this study for flood hazard determination. Other MCDM methods, including but not limited to, outranking techniques (e.g., ELECTRE), can be potentially used in the future to verify current findings. Similarly, for the criteria weight determination, a pairwise comparison MCDM technique, AHP, was used. Another pairwise comparison method, analytical network process can be employed in the situation that the criteria are not independent. Additionally, other methods such as Entropy can be employed for criteria weighting.

Third, the robustness of the selected areas for detention basin placement was assessed through a simple sensitivity analysis. However, this approach analyzed the subjective uncertainty; it cannot express the probabilistic and imprecise forms of uncertainty (Bender and Simonovic 2000). A potential solution is coupling the fuzzy sets (Zadeh 1965) into the decision-making framework (Ascough *et al.* 2008). In this context, the studies of Anagnostopoulos and Vavatsikos (2012) for site selection of natural systems for wastewater treatment, and Chen, Khan and Paydar (2010a) for the evaluation of irrigated cropland suitability, is noteworthy. Alternatively, recent advanced sensitivity analysis methodologies such as that proposed by Chen, Yu and Khan (2010b, 2013), can be utilized. Apart from the evaluation criteria weights, uncertainty of the decision criteria values was not analyzed in our study. For example, the impact of the design storm uncertainty, which might be due to statistical analysis of rainfall datasets or future climate change, on the suitability of the areas for detention basin placement would be an interesting research topic for future studies. In particular, in the absence of observed data, which was the case in our study site, this type of study will be valuable. A possible solution is using probabilistic methods such as Monte Carlo simulation instead of the conventional deterministic approaches. A recent study by Jato-Espino *et al.* (2014), in which Monte Carlo methods were employed to stochastically model the criteria variability in selection of urban pervious pavements, is notable. Nevertheless, there is still rare application in the context of LID/BMP selection or siting.

Fourth, even though the paper focused on flood control, the site selection process was performed with an integrated perspective of urban stormwater management by accounting for various selection criteria. It is, therefore, more holistic in comparison with the recent detention basin site selection by MGCE and Pöyry (2011) in the Tehran Stormwater Master Plan, that was only based on the hydraulic capacity of the drainage network. Nonetheless, more efforts still need to be made to meet the key requirements of sustainable stormwater management (Lai, Lundie, and Ashbolt 2008; Barbosa, Fernandes, and David 2012). For instance, water quality improvement capabilities of detention basins were not taken into consideration in this study. Adding such criteria to the current decision-making framework will enhance the sustainability of the suitability map.

Finally, flood hazard was determined as a linear function of four flood parameters generated by SWMM, which has some limitations. First, other flood parameters can be considered for flood hazard determination, such as rate of rise and warning time. Second, SWMM is not a raster-based model and cannot determine flood inundation extent. A more advanced flood model tool should be employed to determine flood hazard. Future elaborations are recommended to investigate the effect of flood modeling and flood hazard determination on the final suitability map.

Acknowledgements

The authors are grateful to Dr Alfred Kalyanapu at Tennessee Technological University for providing MCDM and GIS resources. We would also like to acknowledge support provided by the Center for the Management, Utilization and Protection of Water Resources at Tennessee Technological University. Special thanks to Steven A. Stratz for assistance in improving the English language structure of the article.

Disclosure statement

No potential conflict of interest was reported by the authors.

Note

1. It is to be noted that in order to perform all the computations of the third module in ArcGIS™ environment, AHP calculations can also be performed by implementing a Python script in ArcGIS™ environment.

ORCID

Ebrahim Ahmadisharaf http://orcid.org/0000-0002-9452-7975
Nasrin Alamdari http://orcid.org/0000-0001-6595-6669

References

Abrishamchi, A., A. Ebrahimian, M. Tajrishi, and M.A. Marino. 2005. "Case Study: Application of Multicriteria Decision Making to Urban Water Supply." *Journal of Water Resources Planning and Management* 131 (4): 326–335.

Afshar, A., M.A. Marino, M. Saadatpour, and A. Afshar. 2011. "Fuzzy TOPSIS Multi-Criteria Decision Analysis Applied to Karun Reservoirs System." *Water Resources Management* 25 (2): 545–563.

Ahammed, F., G.A. Hewa, and J.R. Argue. 2012. "Applying Multi-Criteria Decision Analysis to Select WSUD and LID Technologies." *Water Science and Technology: Water Supply* 12 (6): 844–853.

Ahmadisharaf, A., A.J. Kalyanapu, and E.S. Chung. 2015. "Evaluating the Effects of Inundation Duration and Velocity on Selection of Flood Management Alternatives Using Multi-Criteria Decision Making." *Water Resources Management* 29 (8): 2543−2561.

Anagnostopoulos, K., and A. Vavatsikos. 2012. "Site Suitability Analysis for Natural Systems for Wastewater Treatment with Spatial Fuzzy Analytic Hierarchy Process." *Journal of Water Resources Planning and Management* 138 (2): 125−134.

Ascough, J.C., H.R. Maier, J.K. Ravalico, and M.W. Strudley. 2008. "Future Research Challenges for Incorporation of Uncertainty in Environmental and Ecological Decision-Making." *Ecological Modelling* 219 (3): 383−399.

Barbosa, A.E., J.N. Fernandes, and L.M. David. 2012. "Key Issues for Sustainable Urban Stormwater Management." *Water Research* 46 (20): 6787−6798.

Bender, M.J., and S.P. Simonovic. 2000. "A Fuzzy Compromise Approach to Water Resource Systems Planning Under Uncertainty." *Fuzzy Sets and Systems* 115 (1): 35−44.

Chen, J., A.A. Hill, and L.D. Urbano. 2009. "A GIS-Based Model for Urban Flood Inundation." *Journal of Hydrology* 373 (1): 184−192.

Chen, Y., S. Khan, and Z. Paydar. 2010a. "To Retire or Expand? A Fuzzy GIS−Based Spatial Multi−Criteria Evaluation Framework for Irrigated Agriculture." *Irrigation and Drainage* 59 (2): 174−188.

Chen, Y., J. Yu, and S. Khan. 2010b. "Spatial Sensitivity Analysis of Multi-Criteria Weights in GIS-Based Land Suitability Evaluation." *Environmental Modelling and Software* 25 (12): 1582−1591.

Chen, Y., J. Yu, and S. Khan. 2013. "The Spatial Framework for Weight Sensitivity Analysis in AHP-Based Multi-Criteria Decision Making." *Environmental Modelling and Software* 48: 129−140.

Cheng, M.S., J.X. Zhen, and L. Shoemaker. 2009. "BMP Decision Support System for Evaluating Stormwater Management Alternatives." *Frontiers of Environmental Science and Engineering in China* 3 (4): 453−463.

Chung, E.S., W.P. Hong, K.S. Lee, and S.J. Burian. 2011. "Integrated Use of a Continuous Simulation Model and Multi-Attribute Decision-Making for Ranking Urban Watershed Management Alternatives." *Water Resources Management* 25 (2): 641−659.

Chung, E.S., and K.S. Lee. 2009. "Prioritization of Water Management for Sustainability Using Hydrologic Simulation Model and Multicriteria Decision Making Techniques." *Journal of Environmental Management* 90 (3): 1502−1511.

Dang, N.M., M.S. Babel, and H.T. Luong. 2011. "Evaluation of Flood Risk Parameters in the Day River Flood Diversion Area, Red River Delta, Vietnam." *Natural Hazards* 56 (1): 169−194.

Emerson, C.H., C. Welty, and R.G. Traver. 2005. "Watershed-Scale Evaluation of a System of Storm Water Detention Basins." *Journal of Hydrologic Engineering* 10 (3): 237−242.

Fang, Z., A. Zimmer, P.B. Bedient, H. Robinson, J. Christian, and B.E. Vieux. 2010. "Using a Distributed Hydrologic Model to Evaluate the Location of Urban Development and Flood Control Storage." *Journal of Water Resources Planning and Management* 136 (5): 597−601.

Fattahi, P., and S. Fayyaz. 2010. "A Compromise Programming Model to Integrated Urban Water Management." *Water Resources Management* 24 (6): 1211−1227.

Fernandez, D.S., and M.A. Lutz. 2010. "Urban Flood Hazard Zoning in Tucuman Province, Argentina, Using GIS and Multicriteria Decision Analysis." *Engineering Geology* 111 (1): 90−98.

Gilroy, K.L., and R.H. McCuen. 2009. "Spatio-Temporal Effects of Low Impact Development Practices." *Journal of Hydrology* 367 (3): 228−236.

Giri, S., and A.P. Nejadhashemi. 2014. "Application of Analytical Hierarchy Process for Effective Selection of Agricultural Best Management Practices." *Journal of Environmental Management* 132: 165−177.

Gironás, J., L.A. Roesner, L.A. Rossman, and J. Davis. 2010. A New Applications Manual for the Storm Water Management Model (SWMM). *Environmental Modelling and Software,* 25 (6): 813−814.

Hajkowicz, S., and K. Collins. 2007. "A Review of Multiple Criteria Analysis for Water Resources Planning and Management." *Water Resources Management* 21 (9): 1553−1566.

Hsieh, L.F., J.B. Chin, and M.C. Wu. 2006. "Performance Evaluation for University Electronic Libraries in Taiwan." *The Electronic Library* 24 (2): 212−224.

Hwang, C.L., and K.P. Yoon. 1981. *Multiple Attribute Decision Making: Methods and Applications*. New York: Springer-Verlag.

Jato-Espino, D., J. Rodriguez-Hernandez, V.C. Andrés-Valeri, and F. Ballester-Muñoz. 2014. "A Fuzzy Stochastic Multi-Criteria Model for the Selection of Urban Pervious Pavements." *Expert Systems with Applications* 41 (15): 6807−6817.

Jia, H., H. Yao, Y. Tang, L.Y. Shaw, J.X. Zhen, and Y. Lu. 2013. "Development of a Multi-Criteria Index Ranking System for Urban Runoff Best Management Practices (BMPs) Selection." *Environmental Monitoring and Assessment* 185 (9): 7915−7933.

Kim, Y., and E.S. Chung. 2013. "Assessing Climate Change Vulnerability with Group Multi-Criteria Decision Making Approaches." *Climatic Change* 121 (2): 301−315.

Kim, G., C.S. Park, and K.P. Yoon. 1997. "Identifying Investment Opportunities for Advanced Manufacturing Systems with Comparative-Integrated Performance Measurement." *International Journal of Production Economics* 50 (1): 23−33.

Lai, E., S. Lundie, and N.J. Ashbolt. 2008. "Review of Multi-Criteria Decision Aid for Integrated Sustainability Assessment of Urban Water Systems." *Urban Water* 5 (4): 315−327.

Lee, J.G., A. Selvakumar, K. Alvi, J. Riverson, J.X. Zhen, L. Shoemaker, and F.H. Lai. 2012. "A Watershed-Scale Design Optimization Model for Stormwater Best Management Practices." *Environmental Modelling and Software* 37: 6−18.

Martin, C., Y. Ruperd, and M. Legret. 2007. "Urban Stormwater Drainage Management: The Development of a Multicriteria Decision Aid Approach for Best Management Practices." *European Journal of Operational Research* 181 (1): 338−349.

McCuen, R.H. 1974. "A Regional Approach to Urban Storm Water Detention." *Geophysical Research Letters* 1 (7): 321−322.

MGCE, and Pöyry. 2011. *Tehran Stormwater Management Master Plan*. Tehran. (in Persian).

Munda, G. 2006. "Social Multi-Criteria Evaluation for Urban Sustainability Policies." *Land Use Policy* 23 (1): 86−94.

Rossman, L.A. 2010. *Storm Water Management Model User's Manual, Version 5.0*. Cincinatti: National Risk Management Research Laboratory, Office of Research and Development, USEPA.

Roy, B. 1978. "ELECTRE III: Un algorithme de classements fondé sur une représentation floue des préférences en présence de criteres multiples." *Cahiers du CERO* 20 (1): 3−24.

Saaty, T.L. 1980. *The Analytical Hierarchical Process: Planning, Priority Settings, Resource Allocation*. New York: McGraw-Hill.

Schneider, L.E., and R.H. McCuen. 2006. "Assessing the Hydrologic Performance of Best Management Practices." *Journal of Hydrologic Engineering* 11 (3): 278−281.

Shoemaker, L., J. Riverson, K. Alvi, J.X. Zhen, S. Paul, and T. Rafi. 2009. *SUSTAIN: A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality*. Cincinnati: National Risk Management Research Laboratory, Office of Research and Development, USEPA.

Tingsanchali, T. 2012. "Urban Flood Disaster Management." *Procedia Engineering* 32: 25−37.

USDA NRCS. 2004. "Estimation of Direct Runoff from Storm Rainfall." In *National Engineering Handbook−Part 630 Hydrology*, 10.1−10.22, Washington, DC. Accessed 10 April 2012. http://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/NEHhydrology/ch10.pdf

USEPA. 2000. "National Menu of Stormwater Best Management Practices: Dry Detention Ponds." Accessed 1 May 2012. http://water.epa.gov/polwaste/npdes/swbmp/Dry-Detention-Ponds.cfm

Willett, K., and R. Sharda. 1991. "Using the Analytic Hierarchy Process in Water Resources Planning: Selection of Flood Control Projects." *Socio-Economic Planning Sciences* 25 (2): 103−112.

Yeh, C.H., and J.W. Labadie. 1997. "Multiobjective Watershed-Level Planning of Storm Water Detention Systems." *Journal of Water Resources Planning and Management* 123 (6): 336−343.

Young, K.D. 2006. "Application of the Analytic Hierarchy Process Optimization Algorithm in Best Management Practice Selection." M.Sc. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Young, K.D., D.F. Kibler, B.L. Benham, and G.V. Loganathan. 2009. "Application of the Analytical Hierarchical Process for Improved Selection of Storm-Water BMPs." *Journal of Water Resources Planning and Management* 135 (4): 264−275.

Young, K.D., T. Younos, R.L. Dymond, D.F. Kibler, and D.H. Lee. 2010. "Application of the Analytic Hierarchy Process for Selecting and Modeling Stormwater Best Management Practices." *Journal of Contemporary Water Research and Education* 146 (1): 50−63.

Young, K.D., R.L. Dymond, and D.F. Kibler. 2011. "Development of an Improved Approach for Selecting Stormwater Best Management Practices." *Journal of Water Resources Planning and Management* 137 (3): 268−275.

Zadeh, L. 1965. "Fuzzy Sets." *Information and Control* 8 (3): 338−353.

Zahmatkesh, Z., S.J. Burian, M. Karamouz, H. Tavakol-Davani, and E. Goharian. 2014. "Low-Impact Development Practices to Mitigate Climate Change Effects on Urban Stormwater Runoff: Case Study of New York City." *Journal of Irrigation and Drainage Engineering* 141 (1): 04014043 1−13.

Zarghami, M. 2006. "Integrated Water Resources Management in Polrud Irrigation System." *Water Resources Management* 20 (2): 215−225.

Zarghami, M. 2010. "Urban Water Management Using Fuzzy-Probabilistic Multi-Objective Programming with Dynamic Efficiency." *Water Resources Management* 24 (15): 4491−4504.

Zeleny, M. 1973. "Compromise Programming." In *Multiple Criteria Decision Making*, edited by J. L. Cochrane, and M. Zeleny, 262−301. Columbia: University of South Carolina Press.