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Role of Resilience in Sustainable Urban Stormwater Management

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Abstract

Typically, best management practices (BMPs) are implemented to help sustainable stormwater management in urban areas. Over recent decades the selection of urban stormwater management measures for a site has been a challenge among urban planners where the criterion based on flood volume no longer suffices for selecting urban drainage solutions. Therefore there is a need to consider a set of holistic criteria beyond runoff and inundation objectives by which it would be possible to evaluate sustainability of urban drainage projects. Frequent urban flooding events have justified the use of 'resilience' concept and pertaining criteria. This paper proposes a methodology to verify the sustainability of BMPs projects alongside their resilience. The multi criteria decision making (MCDM) technique has been applied for BMPs ranking based on proposed criteria. The methodology has been applied to urban drainage system of a municipal district of Tehran (Iran). Results indicate the effects of manager's preferences on selecting BMPs. The proposed methodology provides an effective tool for urban managers to adopt more resilient-sustainable decisions in urban areas.

Keywords: *sustainability, resilience, urban drainage, stormwater, best management practices*

1 Introduction

Urban stormwater has adverse impacts on the performance of urban infrastructures and the life of residents (Karamouz et al. [16]) causing extreme damages and disorder in the serviceability of urban infrastructures as well as transportation. Initially, Stormwater was conveyed through concrete pipe or channel into urban downstream. This approach has resulted in urban areas flooding and water quality degradation which come into conflict with sustainable development objectives. Therefore, there is a need to adopt decisions which satisfy sustainable development criteria with respect to technical, social, environmental and economic aspects.

Currently, strategies applied for mitigating the impact of urbanization comprise the use of BMPs for urban stormwater runoff quality and quantity control (Jia et al. [15]). BMPs comprise of structural or non-structural measures such as green roofs, infiltration trenches, pervious pavements, rain barrels, bio retentions, detention ponds, etc. (Butler and Davies [7]; Chang and Liou [8]). Many investigators have applied BMPs in their case studies to mitigate stormwater adverse impacts (Åstebøl et al. [3]; Villarreal et al. [26]; Chang and Liou [8]; Stovin [24]; Pyke et al. [20]; Jia et al. [15]). The most applied objectives considered have been the volume and the peak flow rate reductions as well as pollutant loads(Ackerman and Stein [1]; Pyke et al. [20]; Ahiablame et al. [2]; Jia et al. [15]).

However, BMP selection and placement on site or watershed are still challenging for urban managers and planners; Therefore, some research have been conducted to facilitate BMP selection. Martin et al. [19] performed an institutional analysis in France using Multi Criteria Analysis (MCA) approach to rank BMPs. Young and Younos.[28] developed an Analytical Hierarchy Process (AHP) based algorithm to rank BMPs on a given site and introduced a tool (VT BMP DSS) for selecting BMPs. Although these investigations are adequate for decision making at preliminary stormwater planning stages where stakeholders' preferences in a subjective manner are important, it seems that use of qualitative decision making alone cannot be enough in terms of efficient urban drainage systems. The reasons may be attributed to implementation problems and dependency of adopted criteria on local situations. To handle these problems, a comprehensive MCDM tool, "Definite Software" (Janssen et al.[14]), has been used in this research with an ability to use both qualitative and quantitative criteria to prioritize BMPs scenarios.

Furthermore, in spite of remarkable developments in urban drainage facilities, frequent urban flood events occur throughout the world where urban drainage systems cannot cope with rainfalls greater than the urban drainage system design rainfall implying no absolute protection against uncertainties such as extreme rainfalls or even land use developments are warranted. It has therefore been the main goal of this research to introduce the concept of "resilience" for stormwater management systems.

2 Methodology

2.1) Sustainable Development

The concept of sustainability has brought fundamental changes in terms of development and environment since the 1980s (Lele [17]). Sustainability involves considering the consequences of present actions from a long-term perspective, the goal being to achieve a satisfactory quality of life both in the present and in the future (Gasparatos et al. [10]). Recently, there is a growing interest in shift towards sustainable urban water management. Water management in new residential developments is tasked with the requirement to achieve acceptable levels of service, not overburden existing infrastructure, have minimal impacts on the natural environment and to be, at the same time, socially and economically acceptable (Makropoulos et al. [18]) and all these components in the system must be also in balance to achieve sustainability (Sandoval-Solis et al. [23]). As a consequence, a sustainable urban drainage system as a part of sustainable urban water system should be conformed to above-mentioned directives.

2.2) Sustainability indicators

As mentioned earlier in section 2.1, Sustainable development must satisfy environmental, economic and social criteria (Bruce [6]). Therefore, in practical terms a number of criteria and associated indicators are selected. As shown in Table 1, four sub-criterion including system performance (resilience index), stormwater quality, aesthetic benefit, and construction and maintenance cost imply the main sustainability criteria. They are divided into six indicators by which BMPs sustainability are evaluated. Flood volume and recovery time are indicative of system performance. The amount of total suspended solids (TSS) at site outfall is considered as an indicator for stormwater quality. The ability of BMP to beautify the city is an indicator for aesthetic benefit sub-criterion and refers to social aspect of stormwater management decision making. Finally, both Construction and Maintenance (C&M) costs are taken into account to quantify economic aspect of stormwater management. It is noted that technical, environmental and economic criteria are quantitative and social criteria is qualitative.

2.2.1) Recovery index

The concept of resilience was initiated by Holling [12] in ecological management which was defined as the ability of a system to absorb disturbances and recover from their impacts. In the context of water resources management, Hashimoto et al. [11] define resilience as the speed of recovery from an unsatisfactory condition. It denotes resilience can be described as how quickly a system recovers from failure, once failure has occurred. It can be inferred from above definitions that quantifying resilience requires to determination of the amount of disturbance absorption and the time of recovery. DeBruijn [9] presented a solution to measure the amount of disturbance absorption. Based on her study, when a system is disturbed by a perturbation, system reacts to it. The magnitude of disturbance that can be absorbed depend to this reaction. Larger reaction results in smaller absorption and vice versa. Inspired by De Bruin [9]'s Definition, this study considers total flood volume above all the nodes of urban drainage network as an indicator to describe system reaction to the disturbance. Based on Hashimoto et al. [11], the time in which the flood water above the nodes returns to drainage channels is considered as recovery time. In other words, recovery time is the time of flooding between the beginning of the flood at least in one node of urban drainage system and finishing of the flood at all urban drainage system nodes. Both the flood volume and recovery time are indicators to explain resilience index. Although, resilience index depends on physical, social, environmental and economic factors, this study deals with physical/technical characteristics of resilience alone. In this study, rainfall is further considered as perturbation to disturb urban drainage system.

2.2.1.1) Stormwater management model

In this investigation, EPA Storm Water Management Model (SWMM) model (Rossman [21]) has been used to quantify technical and environmental categories indicators. SWMM is a comprehensive mathematical model used for simulation of urban runoff quantity and quality in storm and combined sewer systems and natural waterways. It incorporates dynamic rainfall-runoff computations for both single-event and continuous simulations of runoff quantity (Huber and Dickinson [13]). Precipitation is applied to defined subcatchments, infiltration excess is determined using Horton's or Green and Ampt's models, the time of concentration is computed based on kinematic wave theory, and runoff is generated using the nonlinear reservoir algorithm. Surface runoff is computed in SWMM considering land use type and topography and accounting for antecedent moisture conditions, infiltration losses in pervious areas, surface detention, overland flow, channel/pipe flow and constituents carried by runoff into inlets. Important input parameters include catchment slope, pervious and impervious depression storages, channel and conduit layouts, geometries and properties, the Manning roughness coefficients for both overland and channel flows, and rainfall intensity. Flows are routed using the dynamic wave solution of the Saint-Venant equations through pipes, channels, and other drainage system elements. Runoff quality is simulated using one of several options, including accumulation/wash-off, rating curve, or constant concentration. In this study, dynamic flow routing is applied to run SWMM model for various BMP scenarios which solves full one-dimensional Saint Venant flow equations. These equations are as follows:

$$S_f = S_0 - \frac{\partial y}{\partial x} - \frac{v}{g}\left(\frac{\partial v}{\partial x}\right) - \frac{1}{g}\left(\frac{\partial v}{\partial t}\right) \quad (1)$$

$$v\left(\frac{\partial y}{\partial x}\right) + y\left(\frac{\partial v}{\partial x}\right) + \frac{\partial y}{\partial t} = 0 \quad (2)$$

where y,v,x,t,g,S_f,S_0 are flow depth, flow velocity, distance, time, gravity acceleration, friction slope and bed slope respectively. Recovery time, flood volume are calculated for various BMP scenarios using SWMM model.

2.2.2) Environmental Criteria

Nowadays, the quality of receiving water from urban stormwaters is one of the urban authority's growing concerns. Therefore, it is important to incorporate stormwater quality assessment into decision making regarding urban drainage projects in order to improve urban stormwater quality. Over recent decades, there is an increasing trend to use BMPs among urban planners. For example, a survey of urban stormwater managers from Australia, New Zealand, and the United States revealed a widespread trend of increasing use of nonstructural measures among leading stormwater management agencies, with at least 76% of 41 types of nonstructural measures being found to be increasing in use (Taylor and Fletcher [25]). In this context, TSS are the most suggested indicators by environmental organizations such as EPA. Because TSS are themselves a cause of water and stream quality degradation but can also transport significant amounts of attached contaminants (Balascio and Lucas [4]). This study considers the amount of TSS at the urban drainage system outfall as stormwater quality criteria. EPA SWMM is used to simulate TSS. To set up BMP scenarios using SWMM, pollutant buildup and washoff processes should be defined in advance. To compute TSS buildup, an exponential function is used as follows:

$$B = C_1(1 - e^{-C_2 t}) \quad (3)$$

in which B is pollutant buildup, C_1 is maximum buildup possible (mass per unit of area or curb length) and C_2 is buildup rate constant ($1/days$). In this study, C_1 and C_2 are considered 1.48 and 0.5 respectively.

Event mean concentration method is considered to compute pollutant washoff as follows:

$$W = C'_1 . Q^{C'_2} \quad (4)$$

in which C'_1 is washoff coefficient, Q is runoff rate ($\frac{m^3}{s}$) and C'_2 is wash of exponent. It should be note that EMC is a special case of rating curve washoff method where exponent is 1 and C'_1 is washoff pollutant concentration in mass per litter.

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Table 1 Criteria considered for this study

Criterion	Sub-Criterion	Indicator	Unit
Technical	System Performance (Resilience Index)	Flood Volume	Minute
		Recovery Time	Cubic meter
Environmental	Stormwater quality	Total Suspended Solids	Kilogram
Social	Aesthetic Benefit	Ability of BMP to Beautify the City	H/M/L*
Economic	Construction and Maintenance Cost	BMP Construction Cost	$
		BMP Maintenance cost	$/year

*H/M/L: High/Medium/Low

2.2.3) Economic Criteria

One of the parameters which is highly impressive in projects planning and implementation is C&M costs. Therefore, accurate C&M cost estimation should be accomplished before projects implementation. In this Research, BMP C&M costs have been estimated based on (Young [27]) and (Brown and Schueler [5]). Table 2 reports some methods for estimating BMPs C&M costs.

In order to accurately reflect the present day cost associated with C&M cost, it is necessary to adjust these studies to account for the change in monetary value as a function of time. This adjustment is accomplished by employing the following equation:

$$PDC = P(1 + i)^n \quad (5)$$

in which PDC is Present Day Cost, P is the BMP C&M cost ($) originally reported in the study, i is discount rate and n is difference between present year and the year that project would be constructed.

2.2.4) Social Criteria

BMPs constructions in urban areas usually provide green landscapes and pleasing views. For this reason, the ability of BMP to beautify the city from the resident's viewpoints is considered as an indicator to show aesthetic benefit of BMPs. This criterion is a qualitative and it cannot be easily quantified using certain equations. The method used to quantify aesthetic benefit is based on Saaty [22] which used relative importance of alternatives. Table 3 explain how to quantify social indicator by Saaty [22].

2.3) Multi Criteria Decision Making

Multi criteria decision making (MCDM) analysis have been employed to prioritize BMPs based on defined criteria. DEFINITE software (Janssen et al. [14]) has been deployed to apply MCDM analysis. DEFINITE is a comprehensive toolkit of methods that can be used for a wide variety of problems. The program contains a number of methods for supporting problem definition, as well as graphical tools to support representation. DEFINITE includes five different multi-attribute methods, as well as cost-benefit and cost-effectiveness analysis tools. Related procedures, such as weight assessment, standardization, discounting, and a large variety of methods for sensitivity analysis, are also available. Analytical hierarchical process (AHP) is then applied in order to quantify qualitative indicators.

3 Case study

Proposed methodology is applied for part of the 22nd municipal district of Tehran (Iran). The study area bounded by latitudes 35°44' and 35°45' N and longitudes 51°15 and 51°16, is approximately 85 hectares. The main land cover is residential and small part of this area includes green spaces. Figure 1 shows 22nd municipal district map and selected study area as well as its land use.

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Table 2 BMP C&M Cost based on Young (2006) and Brown and Schueler (1999)

BMP scenarios	Construction Cost	Maintenance Cost
Detention Pond	$12.4\ V^{0.76*}$	3-5% construction Cost
Bio Retention	$7.3\ WQCV^{0.99**}$	5-7 % construction cost
Filter Strips	1.3 $ per square foot	350 $per acre
Pervious Pavement	2-7 $ per square foot	5% construction cost
Rain barrel	20-100 $	(here)2% construction cost
Trench	$2.5\ WQCV$	5-20% construction cost
Green Roof	8-15 $ per square foot	3 worker's wage for 1000 sq. feet

* V is the volume of detention pond
** WQCV is water quality capture Volume

Table 3 Scale of relative importance (Adapted from Saaty 1980)

The intensity of importance	Definition
1	The alternatives being compared contribute equally to the defined objective
3	One alternative is favored slightly over the other in terms of achieving the defined objective
5	One alternative is favored strongly over the other in terms of achieving the defined objective
7	One alternative is favored very strongly over the other in terms of achieving the defined objective
9	The evidence favoring one alternative over the other is absolute in terms of achieving the defined objective
2, 4, 6, 8	Intermediate values available to express user-defined comparisons

The choice of selected study area is due to its vicinity to Kan River and Azadi sport complex (Fig. 2). In addition, urban drainage system implemented on study area, convey stormwater through concrete open channels network to Kan River (Fig. 3). Because of existing high impervious area, striking runoffs are introduced when extreme rainfalls occur. This would cause large amounts of runoff as well as urban flooding.

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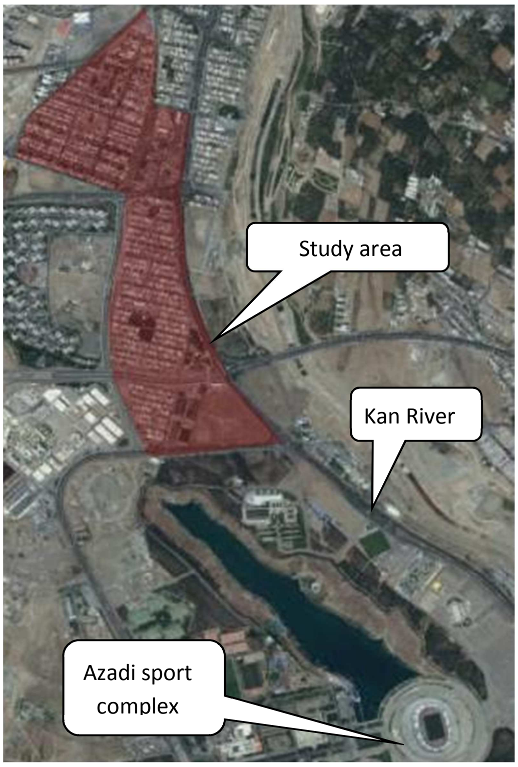

Fig. 2 The vicinity of study area to the important regions

Therefore, the aim of this research is selection of the most efficient BMP scenarios to add to existing urban drainage system which would satisfy sustainable criteria. For this reason, each scenario has been designed throughout the area based on space constraints. These scenarios consist of seven BMPs (Detention Pond, Pervious Pavement, Infiltration Trench, Rain Barrel, Bio Retention, Filter Strips and Green Roof) as well as Channels Enlargement. It should be noted that scenario ranking is accomplished for 50 year return period rainfall IDF at the Mehrabad meteorological station which has the least distance to study area. In addition, discount rate has been considered 10% as a World Bank suggestion for developing countries.

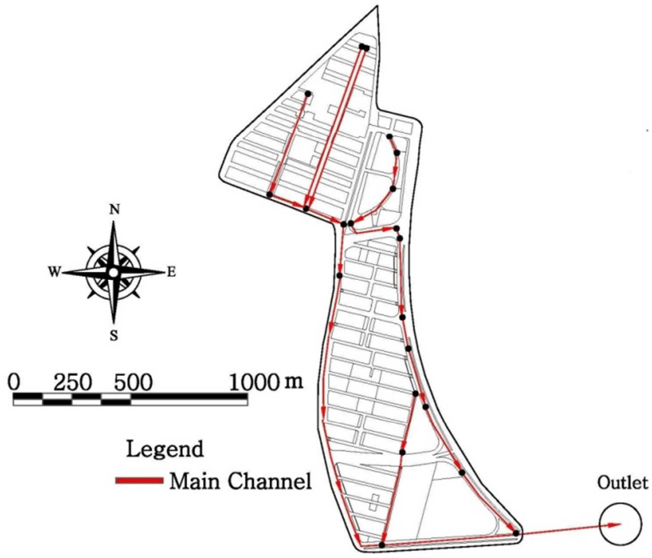

Fig. 3 The layout of main urban drainage channels

4 BMP ranking

In this study, BMPs prioritization is accomplished through manager's and urban planner's preferences. Decision scenarios are then adopted to consider these preferences which would eventually consider manager's goals priorities affecting decision making. These scenarios are divided into four categories as follows:

1) *Technical and economic criteria preference (TE)*

2) *Technical and environmental criteria preference (TEn)*

3)*Technical, environmental and economic criteria preference (TEnE)*

4) *Technical, environmental, Social and economic criteria preference (TESE)*

4.1) TE scenario

In this scenario, it is assumed that manager prefers considering technical and economic goals to select BMPs for a site. In this context, two goals priorities are considered to rank BMPs. Firstly, technical and economic criteria have the same priority (T1E1) and secondly technical criteria have an excellence relative to economic ones (T1E2). Table 4 has listed BMPs ranks based on these two preferences. As shown in Table 4, scenarios ranks have expectedly changed when change in the goals priorities occur. For example, detention pond has rank 1 in sub- scenario T1E1, whilst its rank descends to third under T1E2. It can be inferred that

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since the cost of detention pond is relatively low and its ability to control flood volume is high, its ranking is 1 in scenario T1E1. This ranking descends to 3 in scenario T1E2 in which economic criteria have less importance. It implies there are two choices which have better performance but more expensive than detention pond. These two choices are channel enlargement and pervious pavement. Another example is green roof which has last position in T1E1, however, its position ascend to 4 under T1E2. This is due to its high C&M costs.

Table 4 BMPs rank based on T1E1 and T1E2 sub-scenarios

Urban drainage scenarios	Preference scenario	
	T1E1	T1E2
Detention pond	1	3
Bio retention	6	6
Filter strips	4	7
Pervious pavement	3	2
Rain barrel	5	8
Infiltration trench	8	5
Green roof	9	4
Channel enlargement	2	1
Existing system	7	9

4.2) Scenario TEn

Scenario TEn assumes technical and environmental objectives are important in decision making. Three states are considered in this scenario including 1) technical and environmental criteria have the same priority (T1En1), 2) technical criteria have priority 1 and environmental criteria have priority 2 and 3) environmental goals are more important than technical ones (T2En1). Results are listed in Table 5. As shown in Table 5, current condition is the last choice in all three scenarios and BMPs or other urban drainage scenarios should then be added to existing system to satisfy technical-environmental criteria. Pervious pavement has position 1 in T1En and T1En2 scenarios and 2 in T2En1. It implies pervious pavement is a suitable BMP to meet technical-environmental indicators where C&M cost and social benefits is insignificant from the urban planner's viewpoints. Green roof is also another appropriate option to meet TEn scenarios objectives especially when environmental aspects of urban drainage management is dominant. It can clearly be seen that channel enlargement option is unsuitable to improve stormwater quality.

Table 5 BMPs rank based on T1En1, T1En2 and T2En1 sub-scenarios

Urban drainage scenarios	Preference scenario		
	T1En1	T1En2	T2En1
Detention pond	3	3	5
Bio retention	6	6	4
Filter strips	7	7	6
Pervious pavement	1	1	2
Rain barrel	8	8	8
Infiltration trench	5	5	3
Green roof	2	4	1
Channel enlargement	4	2	7
Existing system	9	9	9

4.3) Scenario TEnE

This scenario considers economic aspects of urban drainage management as well as TEn scenario. Criteria prioritizing are divided into three states including 1) technical, environmental and economic criteria have the same priority (T1En1E1), 2) technical and environmental criteria are more important than economic criteria and 3) technical and economic aspects have an excellence relative to environmental ones (T1En2E1). It can clearly be seen that detention pond returns to upper ranks when economic aspects are considered. Detention pond has rank 1 when C&M costs are significant for managers. Pervious pavement is the next option which can be used to meat TEnE scenario objectives (Table 6).

Table 6 BMPs rank based on T1En1E1, T1En1E2 and T1En2E1 sub-scenarios

Urban drainage scenarios	Preference scenario		
	T1En1E1	T1En1E2	T1En2E1
Detention pond	1	2	1
Bio retention	4	5	5
Filter strips	6	7	4
Pervious pavement	2	1	3
Rain barrel	8	8	6
Infiltration trench	5	6	7
Green roof	7	3	9
Channel enlargement	3	4	2
Existing system	9	9	8

4.4) Scenario TEnSE

In this scenario, all sustainable criteria are considered to evaluate sustainability of urban drainage measures. Three sub-criteria are also considered to show manager's preferences to prioritize criteria to select urban plans such as BMPs. Similar to previous scenarios; there is a need to prioritize introduced criteria. This prioritization consists of 1) four sustainable criteria have equal ranking, 2) technical, environmental and social criteria are more important than economic ones and 3) technical-economic criteria have relative importance to socio-environmental criteria. As listed in Table 7, detention pond is the best option to satisfy sustainable criteria. Bio retention has ranks 2 and 3 in T1EnS1E1 and T1En1S1E2 where social criteria have just been added to criteria. Channel enlargement has been placed in position 7 where aesthetic benefit has priority 1. Green roof is an appropriate option to satisfy social criteria due to creating green space and pleasing views. It can be seen that some options such as detention pond, bio retention, filter strips and green roof are more probable to be selected when the sustainable development objectives are being considered with the same priority. However, selecting an option highly depends on the weights assigned to the criteria.

Table 7 BMPs rank based on T1En1S1E1, T1En1S1E2 and T1En2S2E1 sub-scenarios

Urban drainage scenarios	Preference scenario		
	T1En1S1E1	T1En1S1E2	T1En2S2 E1
Detention pond	1	1	1
Bio retention	2	3	4
Filter strips	3	6	5
Pervious pavement	5	4	3
Rain barrel	8	8	6
Infiltration trench	6	5	7
Green roof	4	2	8
Channel enlargement	7	7	2
Existing system	9	9	9

In order to have an overview of BMP ranks with respect to various criteria, the numbers of times which BMPs have taken different ranks are listed in Table 8. It can be seen that detention pond is placed in the first position for six times. The next option is pervious pavement which has had rank 1 for 3 times.

5 Discussion and Conclusion

Due to urbanization, stormwaters in urban areas have increased so that conventional systems can no longer perform well in conveying urban runoff. This has in turn resulted in water quality degradation, increasing runoff volume as well as flooding throughout urban drainage system; therefore, an integrated view is required to properly manage stormwaters. Integrated stormwater management can efficiently contribute to achieve sustainable development through finding alternatives which satisfy different criteria in various aspects. This has taken a leap by introduction of Best Management Practices (BMPs) or Sustainable Urban Drainage Systems (SUDS) whilst urban flood occurrences are still experienced. Further introduction of resilient strategies and associated appropriate decision criteria adopted thereby have shown an effective approach to further assessing viable sustainable scenarios/solutions. In this study, six indicators were considered to evaluate sustainability of urban drainage options. Technical aspects of resilience were considered as system response to 50 years return period rainfall and the speed of recovery to normal situation to support evaluation of urban drainage options performance. Furthermore, MCDM tools can contribute effectively in supporting decisions based on integration and sustainability.

Since decision making is a subjective process and depends on manager's goal and tendencies, therefore, manager's preferences should be taken into account in decision making process. In the context of urban drainage management, some of the BMPs projects are aimed at dealing with technical goals and other may also follow social, environmental or economic goals. Hence, manager's preferences may change BMPs selection priority.

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Notations

y = Flow depth

v = Flow velocity

x = Distance

t = Time

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g = Gravity acceleration

$S_{f=}$ Friction slope

$S_{0=}$ Bed slope

$B =$ Pollutant buildup

C_1 = Maximum buildup possible

C_2 = Buildup rate constant

C'_1 = washoff coefficient

Q = Runoff rate

C'_2 = washoff exponent

PDC= Present day cost

P= The BMP C&M cost

i = Discount rate

n = Difference between present year and the year that project would be constructed

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