Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2021.26959

219 (2021) 392–398
April

Selection of appropriate nature-based solution for stormwater through multi-criteria performance indices

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Received 13 August 2020; Accepted 4 December 2020

ABSTRACT

Selection of stormwater management technique was often done using rule of thumb without understanding the capacity and behavior of each low impact development (LID) technique. In this study, multi-criteria performance of each LID technique was evaluated to identify the most appropriate technology for a specific objective. Selection criteria for appropriate LID technology were derived based on different indicators such as pollutant reduction, hydraulic performance, construction, operation, and maintenance cost and other benefits of LID technologies gathered from 680 research articles. According to experts from different countries, LID technologies were mostly used for their hydraulic performance. However, few other countries also used LID technologies due to its pollutant removal capabilities. Depending on a specific objective, an LID technology may be more applicable than the other.

Keywords: Low impact development; Multi-criteria performance index; Nature-based solution for stormwater; Stormwater management

1. Introduction

Land use and land-use changes drastically altered the hydrological pattern, flow regimes, and has imposed too much stress on our ecosystem [1]. Land use and land-use changes do not just focus on urbanization but the transformation of many terrestrial biospheres for different functions suitable to the human population [2]. The amount of urban, mixed settlements, and populated areas continuously increasing while the wildlands and natural landscapes continuously decreased. Alongside the changes in land uses, climate change was observed through rising temperatures and the occurrence of high-intensity rainfall affecting densely populated cities. Besides, increased impervious surfaces combined with altered natural hydrology have intensified the production of non-point source or diffuse pollution. Increased impervious surfaces and engineered waterways alter natural suspended solids (TSS) transport processes [3]. Several studies have found that the increase in TSS and heavy metals wash off in urban areas was attributed to several rainfall characteristics including longer rainfall duration, greater rainfall intensity, and greater antecedent dry days (ADD) [4].

Through the years, many terms have been different terms have been associated with urban stormwater management including sustainable urban drainage systems (SUDS), water sensitive urban design (WSUD), low impact development (LID) technologies, green infrastructures and best management practices (BMP) have been developed [5]. Most of the developed countries have identified problems

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brought about by non-point source pollution or diffuse pollution that is why legislated priorities have increased together with a dedicated budget [6]. These mimic the predevelopment hydrology of an area by using decentralized technologies that infiltrate, filter, store, evaporate, and detain runoff close to its source [7,8]. The concept of BMPs includes source control wherein a treatment system is used to intercept stormwater pollutants before entering the combined sewer systems and eventually discharging these to nearby surface water bodies [9]. Thus, increasing urban water quality issues and its impact on the receiving water bodies has resulted in an increase in the use of stormwater BMPs compared to conventional drainage approaches [10,11].

Many studies have already been conducted to assess and fully understand the performance of different LID technologies. However, most of these studies used generalized observations in selecting the most appropriate LID technology without fully understanding the mechanisms affecting the whole performance of the systems from catchment to the facility itself. Up to the present, these LID technologies have been treated as a black box due to fluctuating flow and environmental conditions affecting its operation and treatment performance [12]. As such, this study developed selection and performance criteria in identifying the most appropriate and effective LID technology considering pollutant removal and hydraulic performance from different studies.

2. Materials and methods

2.1. Data collection and analysis

A total of 76, 245, 81, 123, and 155 published research works about rain gardens, bioretention, infiltration basin, constructed wetlands, and infiltration trenches were collected to be used in identifying the most appropriate LID technology for a specific target performance. Fig. 1 shows the distribution of published articles about LID technologies per country. Data showed that the USA published most articles comprising 48% of all the published articles about LID technologies followed by China, France, South Korea, and Australia. Among these countries, the USA, France, South Korea, and Australia have developed their LID design manuals. The annual distribution of publication about LID technologies is demonstrated in Fig. 2. From 2007, research globally about LID technologies have exponentially increased since this year up to 2019, almost 76% of the research article found was published. This finding implied that awareness and application of LID technologies have started even before 2007 when these research articles have been published. Increasing concern about the harmful effects of NPS pollution is the main driving factor for the increase in research interest about LID technologies. Factors including pollutant removal performance, hydraulic performance, construction, operation, and maintenance cost and other benefits of LID technologies were used to evaluate the performance of each LID type.

2.2. Calculation of weight and assessment scores

Weight of each criteria was calculated from a total of 14 experts' opinion. Table 1 summarizes the focus of each country in implementing, installing stormwater LID. Using a scoring scheme of 7 having the highest priority and 1 being the lowest priority, experts from different countries identified peak flow control and volume reduction as the main focus of most countries followed by pollutant reduction and other ecological benefits in installing LID technologies. Values were normalized by dividing the score of each criterion with the largest score. The assessment scores were evaluated using the weighted sum model indicated in Eq. (1).

$$A_i 0^{\text{WSM-score}} = \sum_{j=1}^{n} \left(w_j a_{ij} \right) \tag{1}$$

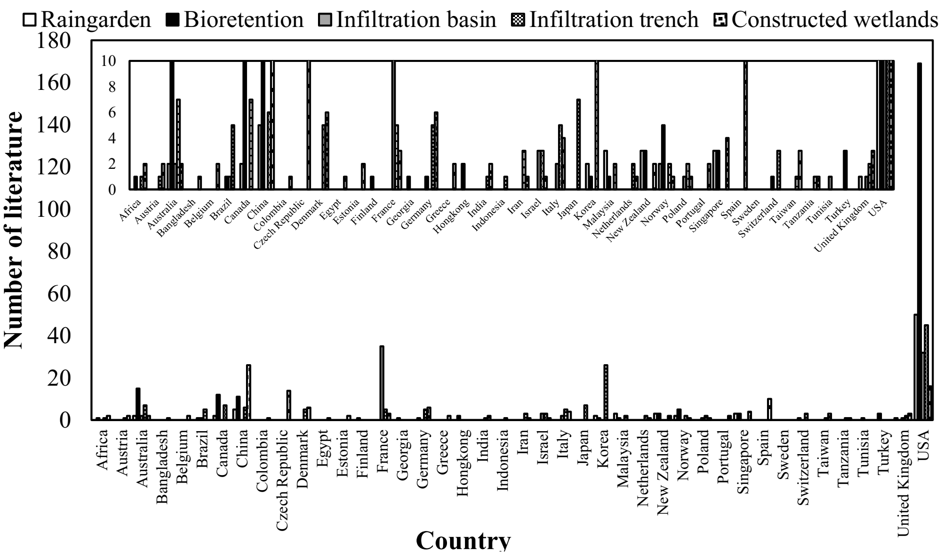

Fig. 1. Distribution of published research article about LID technologies per country.

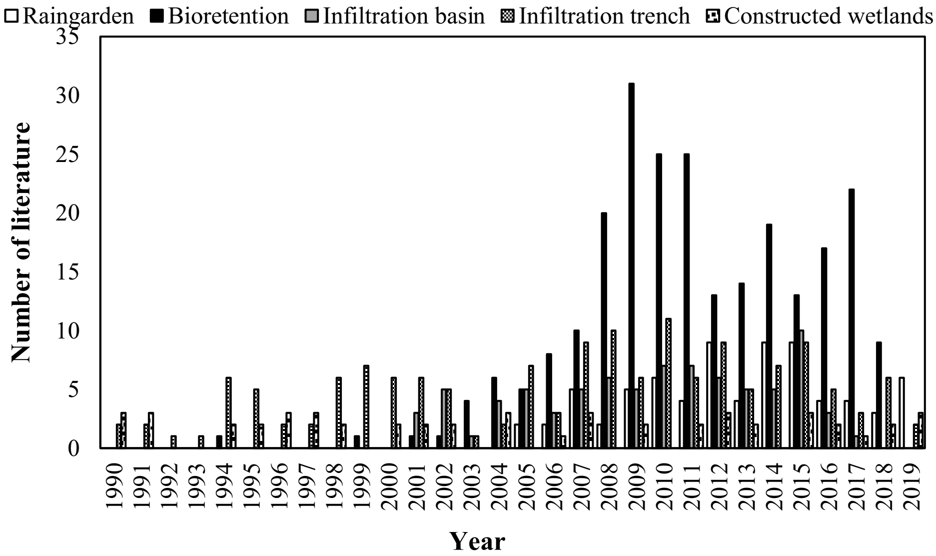

Fig. 2. Distribution of published research article about LID technologies per year.

Table 1
Summary of the importance of each criterion per country

Criteria	Country								Average	Normalized value
	Brazil	China	France	Germany	Japan	USA	Korea	Vietnam		
Pollutant reduction (nutrients)	2	4	1	1	4	5	1	1	2.79	0.60
Pollutant reduction (organics)	1	2	1	3	2	4	2	1	2.43	0.52
Pollutant reduction (suspended solids and heavy metals)	3	3	3	4	2	6	5	3	3.43	0.74
Flood control (peak flow reduction)	7	6	4	5	5	3	7	2	4.64	1.00
Flood control (volume reduction)	6	6	4	5	4	3	6	2	4.21	0.91
Rainwater harvesting	5	5	2	2	3	2	4	5	3.07	0.66
Urban heat island effect mitigation	4	1	2	4	1	1	3	4	2.07	0.45

where $A_i^{\text{WSM-score}}$ is the assessment score, w_j represents the weight of the criteria and a_{ij} is the normalized considering a specific criterion.

3. Results and discussion

3.1. Pollutant reduction performance

Pollutant reduction is one of the most important indicators of the performance of a specific LID technology [13]. To assess the pollutant reduction performances of different LID technologies, the performances of different types of LID technologies were collected from different studies. Since there is a possibility of overestimating or underestimating the pollutant removal performance of a specific LID technology and to eliminate extreme values or outliers, 75th percentile of the data collected and listed in Table 2 was used in calculating the assessment score. Apparently, the data collected were not normally distributed which either has negative or positive skewness implying that the overestimation and underestimation might affect the result considerably. Considering TSS, organics, nutrient, and heavy metal, this study recommended bioretention and rain gardens as the most appropriate LID technology followed by infiltration trenches and basins, and constructed wetlands. The difference in the performance of these technologies was affected by the filter media, catchment area characteristics, and environmental conditions. Bioretention, rain gardens, and infiltration trenches have infiltration and filtration capabilities enhancing its pollutant removal performance. Specifically, while constructed wetlands efficiency has been known for decades, its efficiency in treating stormwater runoff has not been widely studied compared to its wastewater, surface water, and landfill application. The efficiency of any LID technology developed based on this study may still vary since its pollutant removal performance is affected by many environmental factors and design.

3.2. Hydraulic performance

Most of the countries including the United Kingdom, China, Japan, and Germany prioritize volume reduction and peak flow reduction in selecting appropriate stormwater

Table 2
Statistical summary of pollutant removal of different LID technologies from different studies

LID technology	*n*	Statistical parameter	Removal efficiency									
			TSS	BOD	COD	TN	TP	TCr	TNi	TZn	TCd	TPb
Bioretention and rain gardens	22	Minimum	53	50	60	–244	–111	60	67	37	27	35
		Maximum	100	99	99	100	100	100	99	100	99	100
		90th percentile	98	98	99	98	98	99	99	99	99	100
		80th percentile	97	97	98	93	92	99	98	99	98	99
		75th percentile	96	97	98	74	84	99	98	99	98	99
		Mean	86	86	83	28	33	84	90	86	80	86
		Median	90	96	96	54	68	96	97	96	96	97
		Skewness	–1.27	–2.06	–0.61	–2.30	–1.06	–0.40	–1.64	–1.77	–1.70	–1.87
Constructed wetlands	15	Minimum	78	42	15	48	36	8	28	54	45	43
		Maximum	86	93	94	87	98	48	47	65	46	58
		90th percentile	85	90	93	74	96	44	45	64	46	57
		80th percentile	84	87	88	67	90	40	43	63	46	55
		75th percentile	83	85	85	66	83	38	42	62	46	54
		Mean	81	72	73	62	64	28	38	60	46	51
		Median	80	79	75	61	67	28	38	60	46	51
		Skewness	1.28	–0.72	–1.75	1.03	0.26					
Infiltration trenches and basins	17	Minimum	36	60	75	52	66	57	89	69	55	6
		Maximum	99	93	93	95	94	57	89	89	94	91
		90th percentile	95	93	93	94	91	57	89	89	94	90
		80th percentile	92	92	93	93	88	57	89	89	94	90
		75th percentile	91	92	93	91	86	57	89	89	94	90
		Mean	78	83	85	78	80	57	89	82	81	71
		Median	86	89	85	84	82	57	89	85	88	90
		Skewness	–1.18	–1.32	–0.10	–0.82	–0.28			–0.79	–1.48	–1.90

LID since flooding has been a problem in these developed countries. Similar to pollutant reduction performances of LID technologies, fluctuating values from related literature might cause overestimation or underestimation of the hydraulic performance of the different LID technologies since most of the data sets were either negatively or positively skewed. Due to the lack of studies about the hydraulic performance of constructed wetlands only four data were used for this study. Table 3 reveals that considering the hydraulic performance, bioretention, and ran gardens were found to have the highest peak flow reduction and volume reduction followed by constructed wetlands and infiltration trenches and infiltration basins.

3.3. Construction, operation, and maintenance cost and other benefits of LID technologies

Summarized in Table 4 are the construction cost, operational requirements, maintenance cost, and other environmental benefits score of the LID technologies. Apparently, infiltration trenches and infiltration basins were found to have the lowest construction cost and maintenance cost followed by bioretention and rain gardens and constructed wetlands. Higher maintenance costs in bioretention and constructed wetlands were due to the need for plant irrigation and harvesting and sometimes even replanting. Apparently, constructed wetlands were identified as the most applicable LID considering ecological benefits and potential use for rainwater harvesting followed by bioretention, and infiltration trench and infiltration basin.

3.4. Summary of assessment score for each LID technology

Considering the different criteria, it was found that globally, bioretention is the most suitable type of LID to be applied followed by infiltration trenches and infiltration basins, and constructed wetlands demonstrated in Table 5. Depending on the focus of a country where these LID technologies may be applied, the weight for each criterion and indicator may vary. The findings in this assessment may be used in selecting appropriate LID technology for a specific purpose. For an area, that needs an LID technology with good TSS and heavy metal removal, and hydraulic performance bioretention and rain garden is the most applicable. For an area, that requires low-cost and less maintenance LID technology, infiltration trench, and infiltration basins may be recommended. For an area, that requires rainwater harvesting and enhanced ecological functions, constructed wetlands should be recommended.

Table 3
Statistical summary of hydraulic performance of different LID technologies from different studies

LID technology	n	Statistical parameter	Hydraulic performance		
			Peak flow reduction	Flow reduction	Volume reduction
Bioretention and rain gardens	23	Minimum	58	53	14
		Maximum	100	96	99
		90th percentile	98	96	97
		80th percentile	97	96	91
		75th percentile	96	96	86
		Mean	85	86	62
		Median	91	94	69
		Skewness	–0.663	–1.877	–0.350
Constructed wetlands	4	Minimum	38	22	43
		Maximum	97	54	51
		90th percentile	87	52	50
		80th percentile	78	50	49
		75th percentile	73	49	49
		Mean	63	40	47
		Median	58	44	47
		Skewness	1.002	–1.072	
Infiltration trenches and basins	13	Minimum	19	28	10
		Maximum	90	91	70
		90th percentile	76	69	61
		80th percentile	61	63	52
		75th percentile	60	62	48
		Mean	55	51	39
		Median	55	50	37
		Skewness	–0.034	0.672	0.356

Table 4
Summary of construction cost, maintenance cost, operational requirement, and other benefits score of different LID technologies [13]

Structural BMPs	Construction cost, Euro/m^3	Operational requirement	Maintenance cost, Euro/m^3	Rainwater harvesting score	Ecological benefits (urban heat Island mitigation) score
Infiltration trench and basin	30–70	Regular inspection, dredging Requires infill replacement every 5–10 y	1.5–5	2.5	1
Constructed wetlands	20–230	Annual maintenance for first 5 y Pruning, harvesting, and replanting for wetland plants Regular inspection or infill replacement	1.2–20 Maintenance costs can be reduced by 50% after 3 y	5	5
Bioretention	70–140	Regular pruning, weeding, adding plants, and soil irrigation when rainless	3.5–9.8	3	4

Table 5
Summary of assessment score and ranking for each LID technology

Criterion	LID technology		
	Bioretention and rain gardens	Constructed wetlands	Infiltration trenches and basins
TSS	1.00	0.86	0.95
BOD	1.00	0.88	0.95
COD	1.00	0.87	0.95
TN	0.81	0.73	1.00
TP	0.98	0.97	1.00
TCr	1.00	0.38	0.58
TNi	1.00	0.43	0.91
TZn	1.00	0.63	0.90
TCd	1.00	0.47	0.96
TPb	1.00	0.55	0.91
Peak flow reduction	1.00	0.76	0.63
Flow reduction	1.00	0.51	0.65
Volume reduction	1.00	0.57	0.56
Rainwater harvesting	0.50	1.00	0.60
Ecological benefits (Urban heat Island mitigation)	0.20	1.00	0.80
Construction cost	1.00	0.33	0.67
Operational requirement	1.00	0.33	0.67
Maintenance cost	1.00	0.33	0.67
Weighted total	11.20	7.72	9.95
Ranking	1	3	2

4. Conclusion and recommendation

Selection criteria for appropriate LID technology were derived based on different indicators such as pollutant reduction, hydraulic performance, construction, operation, and maintenance cost and other benefits of LID technologies gathered from 680 research articles. Based on the experts' survey conducted, it was found that in most of the countries, peak flow control and volume reduction were the focus for installing LID technologies. Depending on the purpose of the application, a specific LID technology may be more suitable than the other. For an area, that needs an LID technology with good TSS and heavy metal removal, and hydraulic performance bioretention and rain garden is the most applicable. For an area, that requires low-cost and less maintenance LID technology, infiltration trench, and infiltration basins may be recommended. For an area, that requires rainwater harvesting and enhanced ecological functions, constructed wetlands should be recommended. This study may be useful in selecting an appropriate LID technology in the future.

Acknowledgments

This work was supported by the research grant of Kongju National University in 2019.

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