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Cost Efficiency of Green Infrastructure in Flash Flood Management: An Economic Model for Local Authorities

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ABSTRACT

The gradual increase in the urbanization process over the years has increased the impervious surfaces while reducing green spaces, thereby contributing to the frequent occurrence of flash floods. The higher prevalence of flash foods has impacted the local authorities in spending huge amounts of costing for the purpose of repairing and cleaning the damaged public infrastructures. Therefore, numerous studies have proven the positive association between the availability of green infrastructures, namely green roofs, bioswales, and permeable pavements and their roles in minimizing stormwater runoff and flood risks in city area. However, there are limited studies which evaluate the economic worth of implementing these green infrastructures in preventing flash floods. Hence, it is vital to evaluate the potential long-term cost reductions from implementation of green infrastructure in flash flood mitigation to local authorities. Henceforth, this study aims to develop an economic model of the green infrastructure's efficiency of green roof, permeable pavement, and bioswale in managing stormwater runoff. This study is conducted within the jurisdiction of Dewan Bandaraya Kuala Lumpur. It integrated data from systematic analysis from literature reviews and cost-benefit analysis based on interviews with local authorities to estimate the savings achieved through green infrastructure in flash flood management for local authorities. The findings show that the estimated cost savings by implementing green roof, permeable pavement and bioswale are approximately RM6,848, RM7,500 and RM6,875 per km² respectively. However, it is recommended to implement all three green infrastructures to maximize the overall effectiveness in reducing stormwater runoff and to achieve optimal cost savings from economic and environmental perspectives. This study is significant in promoting sustainable practices in infrastructure management and achieving the nation's Sustainable Development agenda.

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1. Introduction

Urbanization has its positive perks in contributing towards the local economy but on the other hand, it has some negative impacts towards the environment as well. According to Samsuri et al. (2018), one of the negative effects of urbanization is flash flood due to the high density of buildings and an abundance of impervious surface. Besides, the absence of adequate green areas in urban area contributes to higher surface stormwater runoff which leads to sudden rise in water levels (Gaitan et al., 2016; Webber et al., 2020). Conventional drainage systems, commonly referred to as grey infrastructure used to manage stormwater runoff and mitigate flood risks (Keeley et al., 2013). However, Abera et al. (2021) stated that the use of grey infrastructure is less effective than green infrastructure in facilitating stormwater absorption, evaporation, and temporary storage especially in developed area.

Various research supports that green infrastructure plays a role in flood mitigation while providing various benefits in stormwater control (Demuzere et al., 2014; EC, 2012; Versini et al., 2018). Therefore, the combination of grey and green infrastructure is categorized as a hybrid innovation which offers comprehensive solution to urban stormwater challenges and enhances urban drainage systems (Fletcher et al., 2015; Foster et al, 2011). Green roofs, permeable pavements, and bioswales are among the effective green infrastructure that promote infiltration and managing stormwater runoff specifically in urban areas. Numerous countries, including Australia, Singapore, Japan, the United States and including Malaysia have adopted innovative approaches by integrating grey infrastructure green infrastructure within their planning guidelines to manage flood problems (Azis & Zulkifli, 2021; Gustafsson & Platen, 2018). Although these green infrastructures is proven to be effective and reliable, the cost-savings that could be gained in terms of its economic benefits remains undiscovered for green roofs, permeable pavements, and bioswales. Therefore, this study aims to examine the cost-savings from implementing green infrastructure, specifically green roofs, permeable pavements, and bioswales by developing an economic performance model of each attribute of green roof, permeable pavement, and bioswale in stormwater runoff reduction for Local Authorities.

1.1 Green Infrastructure Efficiency in Managing Stormwater Runoff

The widespread presence of impervious surfaces in urban area has been preventing rainwaters from travelling into the ground which causes high amount of surface ponding in developed areas (McFarland et al., 2019). However, the implementation of green infrastructure by using environmental methods such as vegetation and soil is becoming a widely adopted solution as alternative approach to manage stormwater runoff while offering a sustainable complement to grey infrastructure. The application of green infrastructure can enhance the absorption and filtration of stormwater into the soil, allowing it to flow back at nearest rivers (Green et al., 2021; O'Donnell et al., 2020, Vijayaraghavan et al., 2016;). This objective of this study is to identify the literature review of green infrastructures including bioswale, green roofs and permeable pavements, which has demonstrated significant potential in mitigating flash flood risks and minimizing stormwater runoff.

1.1.1 Green Roof

Green roofs are commonly referred as rooftop gardens which are defined as roofs system consist of plants with growth mediums (Le Trung et al., 2018; Vijayaraghavan, 2016). The implementation of green roofs in urban areas has shown great potential by being an effective solution to reduce stormwater runoff especially during heavy rains (Raji et al., 2015; US EPA, 2015). The integration of green roofs has demonstrated the capacity to minimize stormwater runoff approximately 23% to 92% depending on specific attributes, such as soil layer thickness, plant species, and roof steepness.

In terms of soil thickness, studies show that effectiveness increases with increasing thickness, but the relationship is not linear. Previous studies indicate that a green roof with a soil thickness of 50 mm can reduce stormwater runoff by 26% and 30% to 50% while at 75 mm the reduction range between 23.2% and 64% (Cascone, 2019; Gong et al., 2019; Hathaway et al., 2008; Liu et al., 2020; Wilkinson & Feitosa, 2016). At 80 mm, the efficiency from 34% to 72.5% in reducing stormwater runoff (Chai et al., 2017; Stovin, 2010). A thickness of 100 mm shows 27% to 87%, efficiency in managing stormwater runoff (Gong et al., 2019; Mentens et al., 2006; Razzaghmanesh & Beecham, 2018; Wilkinson & Feitosa, 2016; Zhang et al., 2021). Further studies shows that 114 mm of soil thickness may achieve 77.7% efficiency, while 300 mm records 85 to 92% (Razzaghmanesh & Beecham, 2018; Volder & Dvorak, 2014). However, at 400 mm and 800 mm, runoff reduction decreases to 33 to 40%, suggesting that excessive soil thickness does not necessarily enhance performance (Wilkinson & Feitosa, 2016).

In terms of plant species, findings show that Sedum is commonly used, with efficiency ranging from 66% to 89% (Rowe et al., 2003; Soulis et al., 2017; Whittinghill et al., 2015). In addition, Origanum is able to reduce stormwater runoff by 71 to 79%, while mosses demonstrate a more moderate efficacy of 46 to 60% (Anderson et al., 2017; Soulis et al., 2017). A study by Whittinghill et al. (2015) further reported that vegetation in general provides an effectiveness range of 35 to 88% in reducing stormwater runoff. Shetty et al. (2022) reported that green roofs with native vegetation achieved a 64% reduction in stormwater runoff. Meanwhile, roof steepness also has a significant effect. A green roof with 2 degree slope can reduce stormwater runoff by approximately 28 to 87% (VanWoert et al., 2005; Wen et al., 2019). According to Wen et al. (2019), a roof slope of 6.5 degree achieves around 66% effeciency, while at 12 degree the efficiency decreases to 26%. However, at a 25 degree slope, runoff reduction increases again to 75% (Getter et al., 2007). Therefore, these three green roof attributes are important for minimimizing the stormwater runoff in urban areas (Cascone, 2019; Hu et al., 2019; Shultz et al., 2019; Wen et al., 2019; Wilkinson & Feitosa, 2016). The summary of efficiency of each green roof attributes through literature review are briefly mentioned in Table 1.

Table 1 The efficiency of each green roof attributes

Green Roof Attributes		Efficiency (%)	Authors
Soil layer thickness	50mm	26	Wilkinson & Feitosa (2016)
		30 – 50	Gong et al. (2019) Liu et al. (2020)
	75mm	23.2	Cascone (2019) Shultz et al. (2019)
		64	Hathaway et al. (2008)
	80mm	34	Stovin (2010)
		72.5	Chai et al. (2017)
	100mm	27	Wilkinson & Feitosa (2016)
		27 – 81	Mentens et al. (2006)
		66 – 81	Razzaghmanesh & Beecham (2018)
		40 – 60	Gong et al. (2019)
		81 – 87	Zhang et al. (2021)
	102mm	51.4	Gregoire & Clausen (2011)
	114mm	77.7	Volder & Dvorak (2014)
	125mm	32.9	Cascone (2019) Shultz et al. (2019)
	150mm	45 – 60	DeNardo et al. (2005); Mentens et al. (2006);
	155mm	65 – 85	Mentens et al. (2006)
	170mm	65.7	Speak et al. (2013)
	200mm	29	Wilkinson & Feitosa (2016)
	300mm	85 – 92	Razzaghmanesh & Beecham (2018)
	400mm	33	Wilkinson & Feitosa (2016)
	800mm	40	
	1600mm	64	
Plant species	Sedum	66	Rowe et al. (2003)
		70	Soulis et al. (2017)
		77	
		89	Whittinghill et al. (2015)
		54	Shetty et al. (2022)
	Origanum	71	Soulis et al. (2017)
		79	
	Vegetation	35 – 88	Whittinghill et al. (2015)
	Mosses	46 – 60	Anderson et al. (2017)
	Native vegetation	64	Shetty et al (2022)
Roof steepness	2 degree	28	Wen et al. (2019)
		85	Getter et al. (2007)
		87	VanWoert et al. (2005)
	6.5 degree	66	
	12 degree	26	Wen et al. (2019)
	25 degree	75	Getter et al. (2007)

1.1.2 Permeable Pavement

Permeable pavements are considered as sustainable drainage infrastructure because this type of pavement not only supports structural loads, but it is allowing stormwater to infiltrate and be stored temporarily without causing damage to structure performance (Ball & Rankin, 2010). The main function of permeable pavements is to collect, filter, and treat stormwater runoff to increase groundwater recharge and improved hydrological infiltration (Imran et al., 2013; Marchioni & Becciu, 2015). Generally, permeable pavements are installed in urban areas especially in less congested areas, pedestrian paths, and parking areas to mitigate stormwater runoff and support sustainable drainage (Koiv-Vainik et al., 2022). The implementation of permeable pavements is capable in reducing stormwater runoff volumes by up to 95% and by around 90% under light rain, when compared to conventional asphalt surfaces (Shafique et al., 2018).

Previous studies on surface types show that porous pavements have efficiencies ranging from 26% to 93% in controlling rainwater runoff (Collins, 2007; Dreelin, et al., 2006; Imran et al., 2013; Liu, Vralts & Engel, 2015; Sambito et al., 2021). Concrete blocks have recorded efficiencies of 71.4% to 89.3%, while plastic grids and grass can achieve up to 93% in reducing runoff (Collins, 2007; Dreelin, Fowler & Carroll, 2006; Imran et al., 2013; Park et al., 2014). Concrete grid systems have been reported to be 37% to 66% efficient, whereas interlocking concrete shows efficiency rates of 30% to 77% (Pfannerstill et al., 2016; Shafique et al., 2018; Smith, 1984; Zhang et al., 2020). In addition, interstitial permeable systems demonstrate an efficiency of approximately 81.37% in rainwater infiltration (Park et al., 2014).

In terms of aggregate material, permeable pavements constructed with travertine (limestone) reduce stormwater runoff by about 68.66%, while a sand–travertine mixture can achieve up to 94% efficiency (Li et al., 2024; Rahimi et al., 2019;). The thickness of the aggregate layer also influences performance wheres a thickness of 15 cm achieves only 52.94%, whereas 30 cm can reach 94.12% efficiency (Zhu et al., 2019).

Moreover, permeable joint materials also contribute significantly to stormwater runoff reduction. The use of pea gravel provides efficiencies of 71.5% to 84.4%, while silty clay achieves 89% to 92% (Collins, 2007; Drake et al., 2012; Fassman & Blackbourn, 2010;). Sandy clay shows an efficiency of 60% to 77%, whereas silty sand records the highest value at 100% in stormwater runoff control (Collins et al., 2008; Kwiatkowski et al., 2007). Table 2 shows the summary of efficiency of each permeable pavement attributes in managing stormwater runoff.

Table 2 The efficiency of each permeable pavement attributes

Permeable Pavement Attributes		**Efficiency (%)**	**Authors**
Types of surfaces	Porous pavement	79.7	Collins (2007)
		26 – 61	Sambito et al. (2021)
		93	Dreelin, Fowler & Carroll (2006)
		86	Imran et al. (2013)
		61	Liu, Vralts and Engel (2015)
		60 – 74	Pfannerstill et al. (2016)
	Concrete blocks	88.5	Collins (2007)
		71.4 –89.3	Park et al. (2014)
	Plastic and grass grid	93	Imran et al. (2013) Dreelin, Fowler & Carroll (2006)
	Concrete grid system	65	Smith (1984)
		37 – 66	Pfannerstill et al. (2016)
	Interlocking concrete	30 – 65	Shafique et al. (2018)
		37 – 38.7	Zhang et al. (2020)
		77	Pfannerstill et al. (2016)
	Intersitial permeable	81.37	Park et al. (2014)
Type of aggregate material	Travertine (limestone)	68.66	Rahimi et al. (2019)
	Sand dan travertine	94	Li et al. (2024)
Thickness of aggregate material for water storage	15 cm	52.94	Zhu et al. (2019)
	20 cm	70.59	
	25 cm	82.35	
	30 cm	94.12	
Permeable joint material	Pea gravel	71.5 – 84.4	Collins (2007)
	Silty clay	92	Drake et al. (2012)
		89	Fassman & Blackbourn (2010)
	Sandy clay	60 – 77	Collins et al. (2008)
	Silty sand	100	Kwiatkowski et al. (2007)

1.1.3 Bioswales

Bioswales have been widely recognized as the best management method for stormwater management (Cilliers & Chillers, 2016). Bioswales serve as engineered stormwater by using vegetation and organic elements to maximize the infiltration of stormwater runoff into the soil or nearby drainage systems (Brankovic & Protic, 2018). The implementing bioswales in urban areas offer various benefits including filtering stormwater, minimizing stormwater runoff, facilitating transpiration to manage soil moisture levels, and enhancing groundwater storage capacity (Bartens et al., 2008; Brankovic and Protic, 2018; Scharenbroch et al., 2016). Based on research carried out by Purvis et al. (2019), bioswales performed successfully for almost 37 out of 39 recorded rainfall events and achieving a stormwater runoff reduction rate of 85% during storms in North Carolina.

Bioswales show varying levels of effectiveness depending on the plant species, soil type, and component thickness. Findings from past studies indicate that bioswales with turf grass can reduce stormwater runoff by 80 to 90% (Bloorchian et al., 2016; Osouli et al., 2017). Prairie grass has been shown to achieve 40 – 92% efficiency in reducing runoff (Osouli et al., 2017). Another study by Xiao and McPherson (2011) reported that Platanus x acerifolia 'Bloodgood' trees also demonstrate 89% efficiency in managing stormwater runoff. Moreover, bioswales can still achieve 83% efficiency in runoff reduction even without vegetation (Bloorchian et al., 2016).

In terms of soil type, sandy clay achieves 58 to 81% efficiency, while silt loam reaches 36 to 86% in managing runoff (Bloorchian et al., 2016; Hunt et al., 2010; Osouli et al., 2017; Poresky et al., 2011). Silty clay soil shows relatively higher efficiency at 84% (Bloorchian et al., 2016). Limited studies have examined the effect of component thickness. Bioswales with layers 30 cm of component thickness recorded 23% to 24% efficiency in reducing stormwater runoff (Kuok et al., 2024). Meanwhile, bioswales with layers of 50 cm to 60 cm have recorded efficiencies of up to 97% (Jiang et al., 2020). Table 3 provides a summary of the efficiency of each bioswale attribute in reducing the surface rainwater runoff in urban areas derived from literature review.

Table 3 Summary of the efficiency of each bioswale attributes

Bioswales Attributes		**Efficiency (%)**	**Authors**
Plant species	Turd grass	90	Osouli et al. (2017)
		80	Bloorchian et al. (2016)
	Prairie grass	40 – 92	Osouli et al. (2017)
		73	Bloorchian et al. (2016)
	Platanus x acerifolia 'bloodgood'	89	Xiao & McPherson (2011)
	Without vegetation	83	Bloorchian et al. (2016)
Type of soil	Sandy clay	58	Osouli et al. (2017); Hunt et al. (2010)
		81	Bloorchian et al. (2016); Hunt et al. (2010); Poresky et al (2011)
	Silt loam	36	Osouli et al. (2017)
		86	Bloorchian et al. (2016); Hunt et al. (2010); Poresky et al (2011)
	Silty clay	84	Bloorchian et al. (2016); Hunt et al. (2010); Poresky et al (2011)
Component thickness	30cm	23 – 24	Kuok et al. (2024)
	50cm	86 – 97	Jiang et al. (2020)
	60cm		

2. Methodology

A combination of qualitative and quantitative analyses was applied in this study by using various data sources and analysis tools. The combination of methods for data acquisition and analysis was adopted to enhance the comprehensiveness and robustness of the study's findings.

2.1 Description of Study Area

This study focuses on urban areas that are frequently affected by flash floods in Kuala Lumpur. This is due to Kuala Lumpur's high urban density and often experiences occurrence of flash floods which almost every month throughout the year (Yusoff & Thomas, 2021). Following the flash flood disaster in 2024, DBKL has identified 14 flood-prone areas around Kuala Lumpur. Therefore, the data collection for this study will focus on areas under the administration of the Kuala Lumpur City Hall (DBKL). The total area of these flood-prone zones is approximately 67.1 square kilometers, as illustrated in Figure 1.

Figure 1 Flood-prone area in Kuala Lumpur via Google Earth

2.2 Data Collection

This study involves two stages of data collection, consisting of literature reviews and interview surveys. During the initial phase of data gathering, literature review is conducted to collect data regarding the efficiency of green roof, permeable pavements and bioswales attributes in mitigating stormwater runoff. Literatures such as journals, articles and conferences papers are identified and reviewed based on its relevance and quality to obtain information. Then, the data gathered is analyzed using systematic review which will be used in the next stage of this study.

The following process of data collection is to identify the costs that was spent in the recovering and repairing process of damaged infrastructures due to the flash floods. Data was collected by using the interview method with the Local Authorities. According to Fox (2009), the interview method is a fundamental qualitative research method which involves verbal communication between the researcher and the participant. Interviews were conducted with DBKL to obtain average cost data incurred by DBKL for public infrastructure damage and the cleaning of public areas affected by flash floods around Kuala Lumpur. The data collected from DBKL used to estimate the cost-saving from the implementing of green roofs, permeable pavements and bioswale in reducing stormwater runoff using a benefit transfer approach.

2.3 Data Analysis

Based on the findings from the literature reviews, data on the efficiency percentages of green roofs, permeable pavements, and bioswales in reducing stormwater runoff were obtained and analyzed using a systematic approach. A systematic review is defined as a structured approach to identifying, evaluating, and synthesizing all relevant empirical studies on a specific research question which is widely employed in social science research (Clark, 2016). The main purpose of using systematic review is to present an impartial and detailed overview of the most reliable findings in existing literature (Petticrew & Roberts, 2006).

Next, the data obtained from interview with DBKL during the second stage of data collection will be analyzed using costing analysis to achieve cost savings by implementing green infrastructures in urban areas. Cost analysis is defined as the method for forecasting and evaluating expenses from different options for achieving study objectives. The goal is not to provide exact cost but to identify which alternative offer greater or lesser cost efficiency (Balut & Gulledge, 2001). The results of this analysis will be combined with literature review findings, specifically through the Benefit Transfer Approach (BTA), by applying cost analysis and benefit percentage from the implementation of green roofs, permeable pavements and bioswales.

BTA defines as an approach of applying economic values or models derived from previous area studies to estimate benefits from similar areas. It is often used when conducting a new site with specific data, when there are constraints in collecting data such as expensive or time-consuming (Johnston et al., 2015; Navrud & Ready, 2007). DEFRA (2007) outlines in its manual that the benefit transfer approach performs using systematic reviews, which compile and examine findings from multiple previous studies for differences in their outcomes.

The BTA approach requires multiple data inputs such as the percentage efficiency in stormwater runoff reduction achieved by implementing green infrastructure based on empirical results from past studies and the costs incurred by Local Authorities for asset damage post-flood to estimate the cost savings. The monetary savings are identified by multiplying the estimated percentage of efficiency with the total expenditure by Local Authorities after flash floods.

The performance model estimates the cost saving benefit according to attributes of each green infrastructure. This study uses data on the effectiveness of green infrastructure attributes namely green roof, permeable pavement and bioswale in reducing stormwater runoff, alongside the cost data incurred by Local Authorities for public infrastructure damage and cleaning post-flash flood to construct the performance model.

3. Results and Discussions

3.1 Effectiveness of Green Infrastructure Attributes in Stormwater Reduction

The development of a performance model in this study based on previous literature findings to identify the performance of each attribute of green roof, permeable pavement, and bioswale in reducing urban rainwater runoff. Therefore, the findings show the highest efficiency of green roof attributes in stormwater runoff reduction is recorded at 85% for soil layer thickness, 89% for plant species and 87% for roof steepness. Meanwhile, among permeable pavements attribute, namely types of surfaces, type of aggregate material, the thickness of aggregate material for water storage and permeable joint material contributes the highest percentage at 93%, 94%, 94%, and 100% respectively. As for the bioswales attributes, plant species, type of soil and thickness of the component are contributing to the reduction of stormwater runoff at 90%, 86% and 86% respectively. Based on the identified attributes shown in Table 4, the highest efficiency of green roof, permeable pavements and bioswale, are 87%, 95%, and 86% respectively in reducing stormwater runoff in urban area. Permeable pavement has the highest average contribution in reducing stormwater runoff.

The standardization performance contributes significantly to the development of the performance model to ensure the model able to deliver more reliable outcomes. The highest efficiency obtained from literature review will be used for the standardization calculation. The findings indicate the green roof attributes, namely soil layer thickness, plant species and roof steepness offer to 33%, 34% and 33% respectively in managing rainwater runoff. Meanwhile, permeable pavement attributes contributed to reducing stormwater runoff at 24% for types of surfaces, 25% for type of aggregate material, 25% thickness of aggregate material for water storage, and 6% for permeable joint material. The bioswale attributes, namely types of plant species, type of soil and thickness of the component, manage to reduce stormwater runoff by 34%, 33%, and 33% respectively. Table 5 and Figure 2 below shows the overall performance and standardization performance of each attribute of green roof, permeable pavement and bioswale in reducing stormwater runoff in urban areas.

The attributes that influence the identified green infrastructures have their designated characteristics and features that enhance the function of these green infrastructures in providing optimum ability in mitigating stormwater runoffs in the urban areas. Diving deep into the efficiencies, the permeable pavement has shown highest capability among the others as an innovative infrastructure that should be integrated into urban areas for better management of stormwater runoffs. Apart from that, these identified attributes will not only increase the quality of the said green infrastructure but also increase confidence in implementers and public as the proven attributes are focused and considered in the implementation phase. The green roof and bioswale has more emphasis on the type of vegetation present on the infrastructure which determines the capacity in mitigation of floods while the permeable pavement is highly influenced by its permeable joint material. These specific attributes should be given extra attention as the percentage is relatively then others while not neglecting the other attributes as well .

Table 4 Summary of the highest efficiency attribute for each green infrastructure attributes

Attribute of each green infrastructure		Highest efficiency (%)	
Green roof	Soil layer thickness	300 mm	85
	Plant species	Sedum	89
	Roof steepness	2 degrees	87
		Average efficiency	**87**
Permeable pavement	Types of surfaces	Porous pavement	93
	Type of aggregate material	Sand and Travertine	94
	Thickness of aggregate material for water storage	30 cm	94
	Permeable joint material	Silty sand	100
		Average efficiency	**95**
Bioswale	Plant species	Turf grass	90
	Type of soil	Silt loam	86
	Thickness of component	60 – 50 cm	86
		Average efficiency	**86**

Table 5 Overall performance and standardization green infrastructure efficiency

Attributes of Green Infrastructures		Efficiency (%)	Standardization performance (%)
Green roof	Soil layer thickness	85	33
	Plant species	89	34
	Roof steepness	87	33
Permeable pavement	Types of surfaces	93	24
	Type of aggregate material	94	25
	Thickness of aggregate material for water storage	94	25
	Permeable joint material	100	26
Bioswales	Plant species	90	34
	Type of soil	86	33
	Thickness of the component	86	33

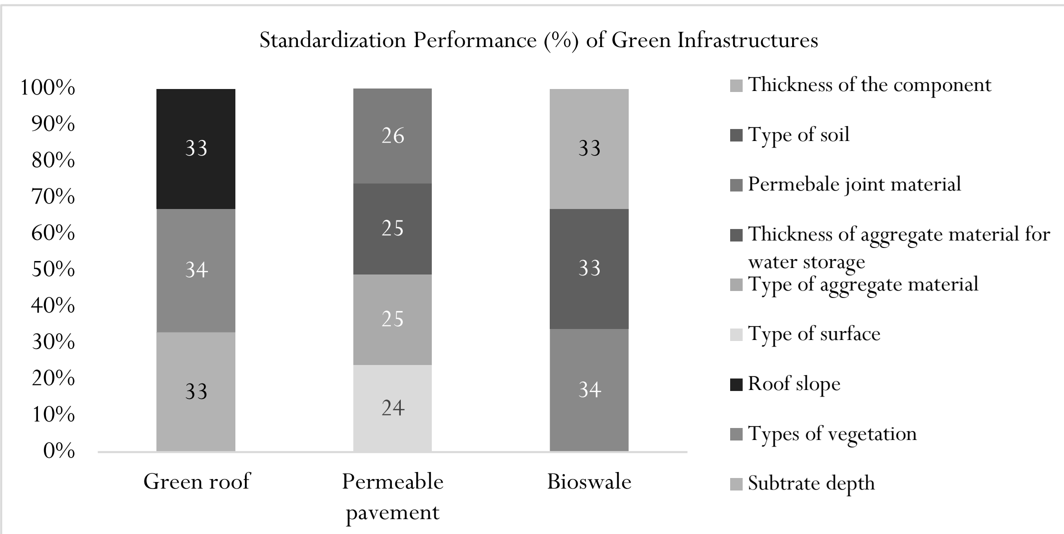

Figure 2 Standardization performance of each green infrastructure attribute

3.2 Expenditure by Local Authorities on Infrastructure Repair and Clean-Up Operations after Flash Flood Events

Asset destruction due to flash floods has the most significant impact on all parties affected. In the case of public infrastructure damage in municipal areas, it is fall under the obligation of the local authorities to bear all economic burdens and damage to public infrastructure and assets due to floods (Azis & Zulkifli, 2021; Mansor et al., 2023; Ramli et al., 2023). The types of public infrastructures that have high tendency on getting damaged due to frequent occurrence of flash flood are roads, bridges, drainage systems, and electricity supply. The Department of Statistics Malaysia (DOSM, 2023) report confirms that, the infrastructure damage category experienced the most severe damage from flash floods events in 2022 compared to other categories. The extensive destruction impacted transportation and public safety, while also imposing high repair expenses and prolonged restoration timelines.

Based on findings from the interview survey, the overall cost incurred by flash flood consists of two main categories, namely infrastructure and cleaning. The total damage cost incurred by DBKL is recorded at RM 528,200. Infrastructure cost represents the highest portion of total cost, comprising 91% (RM 481,700). These costs cover the restoration of damaged roads, pothole repairs, clearing of clogged and collapsed drains, and insufficient drain capacity. In contrast, cleaning activities constituted only 9% (RM 46,500) of the overall cost, which includes expenses for cleaning and excavation work in the main drainage system. Table 6 below provides an overall cost incurred by DBKL post-flash flood. The high amount of expenditure by the local authority to recover the damage portrays the criticality of the flash flood phenomenon in urban areas and the necessity to implement green infrastructures for mitigation of stormwater runoff. In accordance with that, the study will incorporate the findings of green infrastructure and its attributes effectiveness data together with costing data to develop a model that quantifies cost saving of implementing green infrastructures for the local authority.

Table 6 Cost incurred by DBKL for affected assets and services post flood

Categories of affected assets and services		Cost (RM)	Percentage (%)
Infrastructure	Damaged road, potholes, clogged drain, collapsed drain, insufficient outlets, insufficient drain capacity	481,700.00	91
Cleaning service	Clean and excavation work in the main drain	46,500.00	9
Total cost		**528,200.00**	**100**

3.3 Model Development of Economic Performance of Green Infrastructure in Stormwater Reduction

This study developed an economic model of green infrastructure to manage flash floods in areas under the jurisdiction of Local Authorities. This model identifies efficiency and evaluates the financial benefit obtained from green infrastructure according to each attribute of green roof, permeable pavement and bioswale in reducing stormwater runoff. This model evaluates the cost saving gained for Local Authorities in post-flash flood through the integration of green infrastructure under its authority.

The calculation formula below illustrates the monetary benefits achieved through the implementation of green infrastructure based on each attribute of green roof, permeable pavement and bioswale in reducing stormwater runoff.

a) Economic performance of attributes of green roof;
Green roof monetary benefits = [Average percentage of green roof efficiency (%) X Repair Cost by PBT (RM)] + [Addition of all green roof attributes (%) X Repair cost by PBT (RM)]

b) Economic performance of attributes of permeable pavement;
Permeable pavement monetary benefits = [Average percentage of permeable pavement efficiency (%) X Repair Cost by PBT (RM)] + [Addition of all permeable pavement attributes (%) X Repair cost by PBT (RM)]

c) Economic performance of attributes of bioswale;
Bioswale monetary benefits = [Average percentage of bioswale efficiency (%) X Repair Cost by PBT (RM)] + [Addition of all bioswale attributes (%) X Repair cost by PBT (RM)]

The development of economic performance model calculates cost saving based on the efficiency of each green infrastructure attribute based on findings from literature reviews and cost incurred by DBKL for public infrastructure damage and cleaning post-flash flood. It is estimated that DBKL bears post-flash flood costs amounting to RM 528,200. To develop this performance model, the flood cost is multiplied by the total flood-prone area, which is 67.10 square kilometer (km²), as shown in Figure 1. This results in an estimated total flash flood cost of RM 7,871.38 per km², as specific in Table 7 below.

Findings indicate that the implementation of the green roof attribute provides cost saving of RM 2,564 per km² for substrate depth, RM 2,684 per km² for types of vegetation and RM 2,624 per km² for roof slope. Plant species stand out as the most cost-effective among the three main green roof attributes. The overall average effectiveness of green roof attribute shows a cost saving of RM 6,848 per km².

Meanwhile, for the implementation of the permeable pavements attribute, the cost saving recorded at RM 1,921 per km² for types of surfaces, RM 1,942 per km² for type of aggregate material, RM 1,944 per km² for thickness of aggregate material for water storage, and RM 2,065 per km² for permeable joint material. Permeable joint material shows the highest in cost saving among other permeable pavement attributes. The overall average performance of permeable pavement contributes cost savings at RM 7,500 per km².

Finally, the implementation of bioswale attributes, including types of vegetation, type of soils, and thickness of the component showed cost saving of RM 2,704 per km², RM 2,584 per km² and RM 2,584 per km², respectively. The findings of the study show that among the three bioswale attributes, types of vegetation of bioswale contributes the highest cost saving compared to other attributes. On average, the implementation of the bioswale attribute indicates potential to provide cost saving of RM 6,875 per km². Table 8 shows the overall cost saving based on performance of each green infrastructure attribute in managing stormwater runoff in urban areas.

Therefore, to maximize cost savings, it is recommended to Local Authorities prioritize the implementation of permeable pavement for stormwater runoff management as findings show this green infrastructure provides the highest cost saving compared to green roods and bioswales. This finding aligns with existing study by Antunes et al. (2018), which indicates that life-cycle assessments of permeable pavement offer up to 30% in cost reductions compared to conventional systems. However, the combination of all three green infrastructure types, namely green roofs, permeable pavement, and bioswale are highly recommended, as it offers the maximum cost saving in mitigating flash floods in urban areas at RM 21,226 per km².

Table 7 The total flash flood cost per square kilometer (km²)

Categories of affected assets and services	Total cost (RM/km²)
Total cost flash flood (RM)	528,200.00
Total flood-prone area (km²)	67.10
Total flash flood cost (RM/km²)	**7,871.83**

Table 8 Overall cost saving based on performance of attributes each of green infrastructure

Types of Green Infrastructure	Performance (%)	Cost Saving (RM/km²)
Green roof		
Overall performance	**87**	**6,848**
a) Soil layer thickness	33	2,564
b) Plant species	34	2,684
c) Roof steepness	33	2,624
Permeable pavement		
Overall performance	**95**	**7,500**
a) Types of surfaces	24	1,921
b) Type of aggregate material	25	1,942
c) Thickness of aggregate material for water storage	25	1,944
d) Permeable joint material	26	2,065
Bioswale		
Overall performance	**87**	**6,875**
a) Types of vegetation	34	2,704
b) Type of soil	33	2,584
c) Thickness of the component	33	2,584
Total overall performance of green roof, permeable pavement and bioswale		**21,226**

4. Conclusion

In summary, the adoption of green infrastructures, namely green roof, permeable pavements and bioswale provides Local Authorities with cost saving benefits in managing flash floods in urban areas. This implementation has demonstrated positive results for both environmental impact and cost efficiency in terms of flash flood management. Therefore, the implementation of green infrastructure is efficient and capable of managing stormwater runoff in urban areas. Hence, among the three green infrastructures studied, permeable pavement shows the highest cost saving benefit compared to green roof and bioswale. However, in terms of economics standpoint, the implementation of all three green infrastructures is recommended for Local Authorities because it provides significant cost-saving benefits involving post flood maintenance and cleanliness while enhancing flood resilience while reducing long-term financial burdens. Thus, the findings of this study are very crucial for fostering new innovative eco-development initiative and implement effective solutions in flash flood management among Local Authorities. This effort will indirectly contribute to the realization of the national Development agenda. Future studies should explore the implementation costs and long-term economic benefits of green infrastructure for local authorities. This will help justify investment decisions and support cost–benefit evaluations for urban planning.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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