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Comprehensive Assessment of Water Sensitive Urban Design Practices based on Multi-criteria Decision Analysis via a Case Study of the University of Melbourne, Australia

Hanxiang Xiong [1,2], Yafei Sun [2] and Xingwei Ren [1,*]

[1] Faculty of Engineering, China University of Geosciences, Wuhan 430074, China; hanxiangx@student.unimelb.edu.au

[2] Department of Infrastructure Engineering, The University of Melbourne, Parkville VIC 3010, Australia; yafeis@student.unimelb.edu.au

* Correspondence: xingweiren@cug.edu.cn

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Abstract: Water sensitive urban design (WSUD), as a typical green stormwater infrastructure (GSI), contains various facilities to decrease the urbanization impacts and enhance the values of amenity, ecosystem, and livability in Australia. Although WSUD has developed over 30 years, existing studies for WSUD performances have sometimes ignored its economic and social benefits, and there is still a lack of an integrated framework to optimize the GSI combinations based on various criteria in a site. This paper aims to utilize "score-rank-select" strategy to comprehensively assess WSUD combination scenarios from functional, economic, social, and environmental aspects, by taking the University of Melbourne (Parkville campus) as a case study. In detail, multi-criteria decision analysis (MCDA) was used for weight determination and scenario comparison. The results showed that scenario 4 with 52% green WSUD facilities had the highest assessment score (0.771) among the five scenarios, while the final score (0.758) of scenario 5 was lower than scenario 4 although its green facility proportion reached 69%. The trade-off relation between the proportion of grey and green WSUD facilities was further demonstrated. Additionally, this paper strongly recommends that the MCDA-based comprehensive assessment framework described here can be generally promoted for the water sector to solve the decision-making problems. The use of such a framework can further promote sustainable development by helping water managers to make informed and inclusive decisions involving a variety of factors.

Keywords: urbanization; WSUD; stormwater; MCDA; comprehensive assessment; green stormwater infrastructure; sustainability

1. Introduction

Urbanization in recent years has dramatically increased the amount of impervious surfaces [1] and affected local environmental conditions such as landscape or stream morphology [2], species richness [3,4], air temperature [5], climate change [6], and particularly a region's hydrology [7–11]. When heavy storms hit, a large volume of stormwater with pollutants containing sediment, nutrients, litter, oxygen-demanding waste, and heavy metals runs off the impervious areas, giving rise to flooding risk and water quality concerns [12–14], as well as a series of social problems [15]. Despite the fact that the conventional stormwater management approaches including gutters, pipes, and channels can control flooding by conveying runoff directly into receiving points [16–18], they have been considered unsuitable for urban sustainability development [16,19,20] because of limited storage [21], lack of contamination treatment [16], amenity value impact [22] and ecological degradation [23], and backwater risks and overflow [24].

For these reasons, city planners have been adopting a green stormwater infrastructure (GSI) philosophy (e.g., water sensitive urban design (WSUD), low-impact development (LID), sustainable urban drainage systems (SuDS), low-impact urban design and development (LIUDD), and Sponge City) rather than "rapid-draining"-based traditional approaches in stormwater management over recent decades [25,26]. These new approaches are driven by a more sustainable outcome including impervious surfaces reduction, on-site runoff retaining, infiltration and evapotranspiration promotion, and hydrologic conditions predevelopment [27,28]. The concept of WSUD was firstly coined in 1994 and widely cited and implemented from 2000 in Australia [25]. It is an integrated urban stormwater management approach, comprising water storage, water treatment, and sustainable techniques in the urban water cycle, aiming to decrease the impacts of urban expansion and enhance the values of amenity, ecosystem, livability, and society in urban planning [25,29,30]. This type of design involved several facilities such as bioretention areas, ponds and lakes, buffer strips, stormwater tanks, wetlands, and green roofs [31,32]. These facilities are often designed to accelerate economic, social, and environmental development while dealing with a series of stormwater functional problems [33,34]. These facilities can simply be classified into grey and green components. The grey parts mainly rely on the strategies of drainage, reuse, retention, and detention functions (e.g., stormwater tanks and ponds) [35], and the green facilities mainly include the vegetated areas and natural controls such as bioretention areas, swales, and wetlands [36].

The existing studies for WSUD mainly focus on the functional benefits such as water quantity reduction and water quality improvement (e.g., [37–39]) and environmental benefits (e.g., carbon emission elimination in the studies of [40,41]). A limited number of studies have comprehensively assessed the stormwater management options to optimize the WSUD combinations [42]. In fact, the various benefits provided by WSUD facilities such as economic and social benefits (e.g., water retaining function, livability, and O&M costs) are also essential for the WSUD implementation [20,42–44]. Additionally, there is still a lack of a comprehensive and integrated assessment framework to optimize the stormwater facility combinations based on various criteria [45–48]. Zhou [49] also illustrated the importance of designing sustainable drainage system integrating several aspects such as technical, social, environmental, economic, and legal systems. In fact, the assessment and selection of WSUD facility combinations for a catchment is always challenging for decision-makers, which requires an innovative assessment and selection framework with multi-criteria decision analysis (MCDA) tools encompassing several criteria are required [45,48,50].

Developed more than forty years ago [51], MCDA has become an effective technical tool to solve decision problems based on the "compromise principle" with several conflicting points in the evaluation process [52–54]. The common MCDA methods widely used in decision-making cases include analytic hierarchy process (AHP), case-based reasoning (CBR), data envelopment analysis (DEA), multi-attribute utility theory (MAUT), fuzzy set theory, Elimination and Choice Expressing the Reality (ELECTRE), goal programming, PROMETHEE, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and simple additive weighting [55]. Some previous studies only used either AHP or TOPSIS to determine weights for selected indicators or provide rankings of alternatives [42,56]. Conversely, this paper proposes to combine AHP and MAUT methods as a more integrated MCDA framework to score, rank, and select the optimum WSUD facility combinations. AHP and other qualitative methods served as indicator weighting tools, while MAUT and some quantitative methods further assessed the alternatives. Additionally, MUSIC (Model for Urban Stormwater Improvement Conceptualization), as a unique GSI assessment software, was used to develop WSUD combination models in this study.

For these reasons above, this study focuses on comprehensively assessing and optimizing WSUD facility combinations based on AHP and MAUT through a case study of Melbourne University's Parkville Campus, taking functional, economic, social, and environmental aspects into account. Also, the assessment framework based on MCDA described in this paper is strongly recommended to be promoted for the water sector to solve the decision-making problems. In the following section, we briefly introduce the study area and the assessment framework and method. The results, discussions, recommendations, and limitations are shown in Section 3.

2. Materials and Methods

2.1. Study Area

The study area (The University of Melbourne: Parkville campus, approximately 580,000 m^2) is located at the northern edge of the Elizabeth Street catchment of the City of Melbourne council (Figure 1), which has been significantly affected by flooding in the past. In history, the City of Melbourne and Victoria State Emergency Service recorded many significant flooding issues in this catchment [57,58]. Also, the study area has obvious characteristics of lowland and highly urbanized areas with a variety of land uses [57], meaning the flooding risks will further increase as the urban development process. Compared to other regions of Australia, the University of Melbourne is a representative of highly developed and urbanized area. Therefore, there is a need for WSUD implementation to decrease the urbanization impacts, while the variety of land uses provides sufficient spaces for WSUD construction in the study area. Current stormwater management in the study area is mainly based on traditional drainage pipe systems. It was considered unsuitable for urban sustainable stormwater development, though several WSUD projects have been included in the new campus buildings [59] (Table 1). It has been found that the existing stormwater tanks are grey-based WSUD facilities, and the green-based WSUD facilities such as bioretention areas and swales are very few. For these reasons, it is far from achieving the sustainable stormwater management goals (Table 2) at the University of Melbourne, and it is necessary to design an optimal WSUD combination for the university to solve the problem of stormwater management and urbanization impacts.

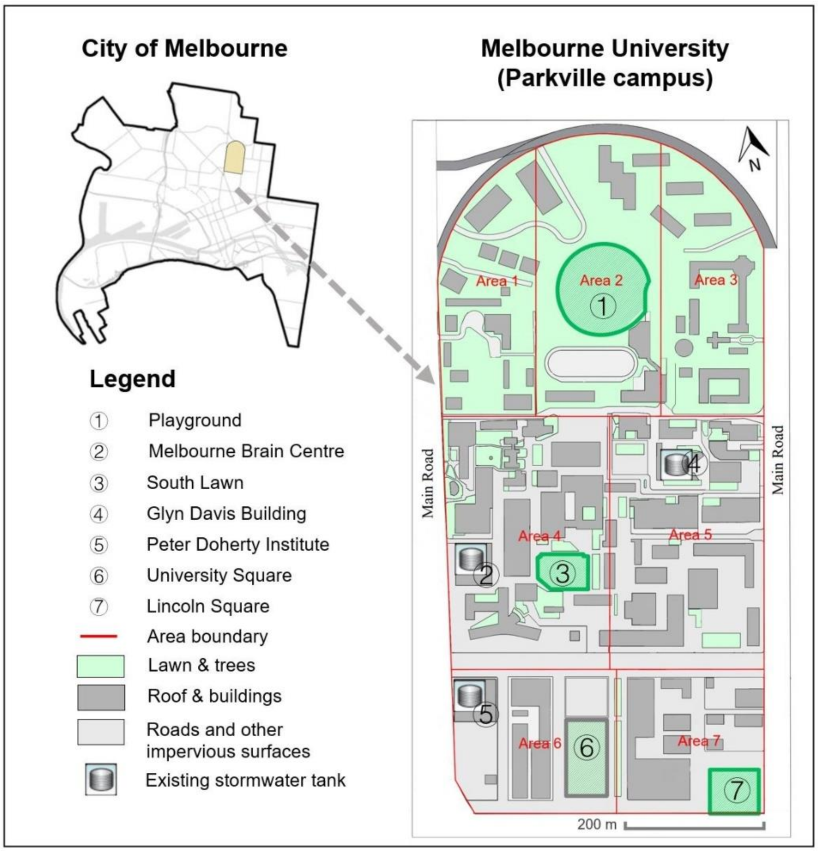

Figure 1. The study area (Parkville campus of Melbourne University).

Table 1. The existing water sensitive urban design (WSUD) projects in the University of Melbourne.

Project No.	Building Name	WSUD Facility	Green or Grey
1	Peter Doherty Institute	100 kL stormwater tanks	Grey-based
2	Melbourne Brain Centre	50 kL stormwater tanks	Grey-based
3	Glyn Davis Building	750 kL stormwater tanks	Grey-based

Table 2. Sustainable stormwater management goals in the study areas.

No.	Sustainable Stormwater Goals	Reference
1	Reduce the risks and damage caused by flooding.	[57,60–63]
2	Mimic the natural water cycle by retaining more rainwater in the upper catchment and reducing surface runoff.	[57,60,62]
3	Improve the health of existing vegetation, urban forest, and ecosystem by water quality improvement.	[57,60,61,63,64]
4	Increase the provision of open space in the catchment with canopy cover to support a healthy population.	[57,60,64]
5	Increase water recreations and livability in the strategic planning processes.	[60,61,63,64]
6	Achieve net-zero emission for climate change adaptation in the water sector.	[61,65]
7	Increase the water reuse and harvesting from stormwater.	[57,60,61,63,64]

To make better use of WSUD facility combinations in the design, the study area is divided into seven sub-areas by site characteristics. The land use of study area can be simply classified as roof and buildings, road and other impervious areas, lawn and trees, and a few landmarks (e.g., South Lawn, playground, University Square, and Lincoln Square) (See Figure 1). The impervious rates of different land use are summarized in Table 3 and the area size and characteristics of the seven sub-areas are shown in Table 4. It is noted that the land use of University Square is assumed as "urban mix area" because the impervious rate is approximately 50%. The rest of the landmarks are regarded as "lawn and trees" surface type. The rainfall and evapotranspiration data are both from 1 January 2019 to 31 December 2019 in a daily time step and shown in Figure 2. Flemington station (rainfall data) [66] and Melbourne Airport station (evapotranspiration data) [67], as the closest stations to the University of Melbourne, were selected as the data source. The concentration of pollutants of total suspended solid (TSS), total nitrogen (TN), and total phosphorus (TP) were stochastically generated by MUSIC following Gaussian Distribution. Table 5 shows the parameters of these pollutants classified by different surface types.

Table 3. The impervious rates of different land use in the study area.

Land Use	Roof and Building	Road	Lawn and Trees	Playground	South Lawn	University Square	Lincoln Square
Impervious rate (%)	100	100	5	0	0	50	1

Table 4. The characteristics of 7 sub-areas.

Area Number	Proximate Area Size (m^2)	Roofs and Buildings (m^2)	Roads and Other Impervious Surfaces (m^2)	Lawn and Trees (m^2)	Landmarks
1	68,000	13,800	6600	47,600	No landmark
2	108,000	15,000	5300	54,200	Playground (33,500 m^2)
3	60,000	10,900	2100	47,000	No landmark
4	117,000	60,300	11,000	39,800	South Lawn (5900 m^2)
5	112,000	76,200	10,400	25,400	No landmark
6	60,000	28,400	9400	200	University Square (22,000 m^2)
7	52,000	30,000	13,900	400	Half Lincoln Square (7700 m^2)
Total	577,000	234,600	58,700	214,600	Landmarks (69,100 m^2)

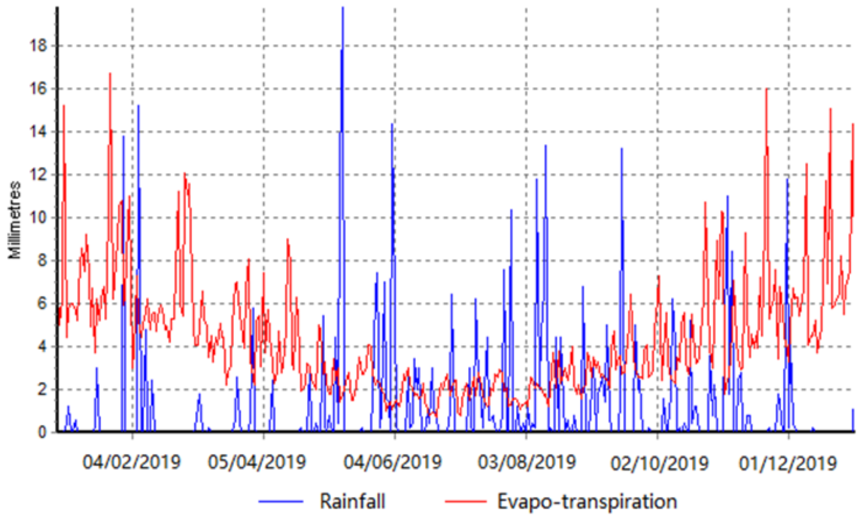

Figure 2. Meteorological data (rainfall and evapotranspiration) from Flemington station and Melbourne Airport station.

2.2. Five Scenarios Design

Based on different characteristics and land uses of seven sub-areas, the schematic diagram of five designed scenarios comprising WSUD facilities for the University of Melbourne are shown in Figure 3. In this figure, the dashed arrows indicate the assumed flow paths, and the solid arrow refers to the flow outlet to the municipal pipes. Four WSUD facilities including bioretention areas, pond, rainwater tank, and swale were selected for design, and the size of different WSUD facilities used are summarized in Table 6. The descriptions, functions, parameters, and specifications of different WSUD facilities for designs are provided in Appendix A.

Figure 3. Five designed scenarios.

To explore how the changes of proportion of grey and green WSUD facilities affect the final assessment scores in the study area, five scenarios were generated to be further evaluated. The five scenarios comprised different proportions of grey and green WSUD facilities (Figure 4). From scenario 1 to scenario 5, the proportion of green-based WSUD facilities was gradually increasing. It is noted that the scenario 1 to 4 contained the existing 225 m^2 stormwater tanks, while scenario 5 assumed that the 750 kiloliters (150 m^2) stormwater tank installed in the Glyn Davis Building did not exist. The descriptions of 5 scenarios are presented as follow.

Table 5. Gaussian Distribution parameters of pollutants total suspended solid (TSS), total phosphorus (TP), and total nitrogen (TN).

Surface Type	Pollutant	Surface Flow		Base Flow	
		Mean (log mg/L)	SD (log mg/L)	Mean (log mg/L)	SD (log mg/L)
Roof and buildings	TSS	1.30	0.32	n/a	n/a
	TP	−0.89	0.25	n/a	n/a
	TN	0.30	0.19	n/a	n/a
Road and other impervious surface	TSS	2.43	0.32	n/a	n/a
	TP	−0.30	0.25	n/a	n/a
	TN	0.34	0.19	n/a	n/a
Lawn and trees	TSS	1.90	0.20	0.90	0.13
	TP	−1.10	0.22	−1.50	0.13
	TN	−0.075	0.24	−0.14	0.13
Urban mixed area (University Square)	TSS	2.20	0.32	1.10	0.17
	TP	−0.45	0.25	−0.82	0.19
	TN	0.42	0.19	0.32	0.12

Note: "n/a" refers to the base flow does not occur from the surface.

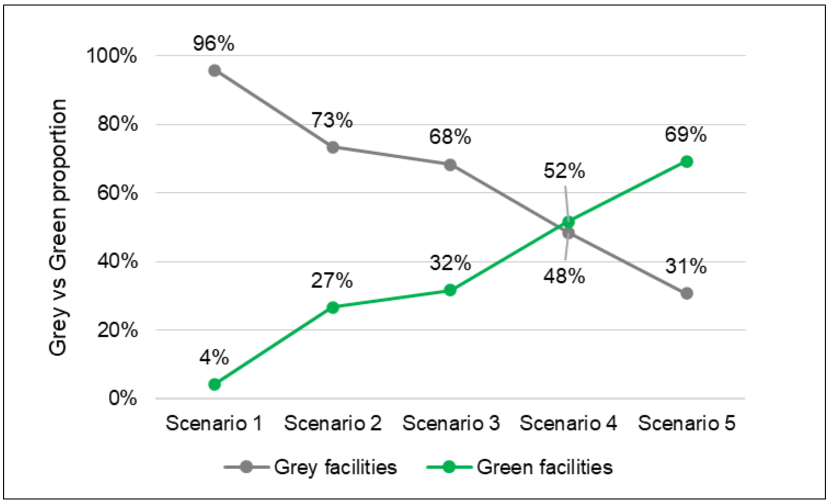

Figure 4. Different proportion of grey and green WSUD facilities in different scenarios.

Scenario 1: "Grey-based" design. This scenario mainly relied on the large size of stormwater tanks and ponds for water harvesting and retention. Its total areas of grey-based facilities reached 675 m^2 while the green-based areas were only 30 m^2.

Scenario 2 and Scenario 3: "Grey-green" design. The two scenarios comprised all the four WSUD technologies with different sizes. Scenario 2 had a higher proportion of bioretention areas and stormwater tanks, and scenario 3 comprised more swales.

Scenario 4: "Equal grey-green" design. This scenario had more plant-support facilities including bioretention areas and swales (a total of 320 m^2), while its size of grey-based facilities (a total of 300 m^2) was much smaller than first three scenarios. The proportions of grey and green facilities were equal. However, the existing 225 m^2 stormwater tanks in this scenario made it difficult to further increase the proportion of green-based facilities.

Scenario 5: "Green-based" design. It designed more bioretention areas and swales (a total of 450 m^2) than scenario 4 and assumed that the 750 kiloliters (150 m^2) stormwater tank installed in the Glyn Davis Building did not exist.

Table 6. Areas of different WSUD facilities designed five scenarios.

WSUD Facility	Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Stormwater tank (50 kL)	Quantity	3	6	7	2	2
	Location	Area 1, 3, 4	Area 1, 2, 3, 4, 6, 7	Area 1, 2, 3, 4, 5, 7	Area 4, 7	Area 4, 7
Stormwater tank (100 kL)	Quantity	6	3	1	1	2
	Location	Area 2, 4, 5, 6, 7	Area 4, 5, 6	Area 6	Area 6	Area 5, 6
Stormwater tank (750 kL)	Quantity	1	1	1	1	-
	Location	Area 5	Area 5	Area 5	Area 5	-
Total area (m^2)		525	450	375	250	150
Bioretention areas (20 m^2)	Quantity	-	5	3	6	-
	Location	-	Area 1, 2, 3, 5, 7	Area 1, 3, 7	Area 1, 2, 3, 5, 6, 7	-
Bioretention areas (30 m^2)	Quantity	1	-	2	-	5
	Location	Area 4	-	Area 4, 5	-	Area 1, 2, 3, 5, 7
Bioretention areas (50 m^2)	Quantity	-	1	-	1	2
	Location	-	Area 4	-	Area 4	Area 4, 6
Total area (m^2)		30	150	120	170	250
Pond (50 m^2)	Quantity	1	-	-	1	1
	Location	Area 6	-	-	Area 6	Area 6
Pond (100 m^2)	Quantity	1	1	1	-	-
	Location	Area 2	Area 6	Area 6	-	-
Total areas (m^2)		150	100	100	50	50
Swale (50 m^2)	Quantity	-	1	-	1	-
	Location	-	Area 2	-	Area 4	-
Swale (100 m^2)	Quantity	-	-	1	1	2
	Location	-	-	Area 2	Area 2	Area 2, 4
Total area (m^2)		0	50	100	150	200
Total land use (m^2)		705	750	695	620	650

Note: The conversion of stormwater tanks' volume and area is provided in Appendix A. Grey shade refers to grey WSUD facilities and green shade refers to green WSUD facilities. This table includes existing stormwater tanks referred in Section 2.1.

2.3. Criteria, Sub-criteria, and Indicator

2.3.1. Criteria and Indicator Selection

According to general stormwater goals (See Table 2), GSI cases [68–71], and functional specifications of selected WSUD (See Appendix A), 10 sub-criteria and several indicators from functional, economic, social, and environmental variables were determined and shown in Figure 5. The rationale for each sub-criterion and indicator is as follows.

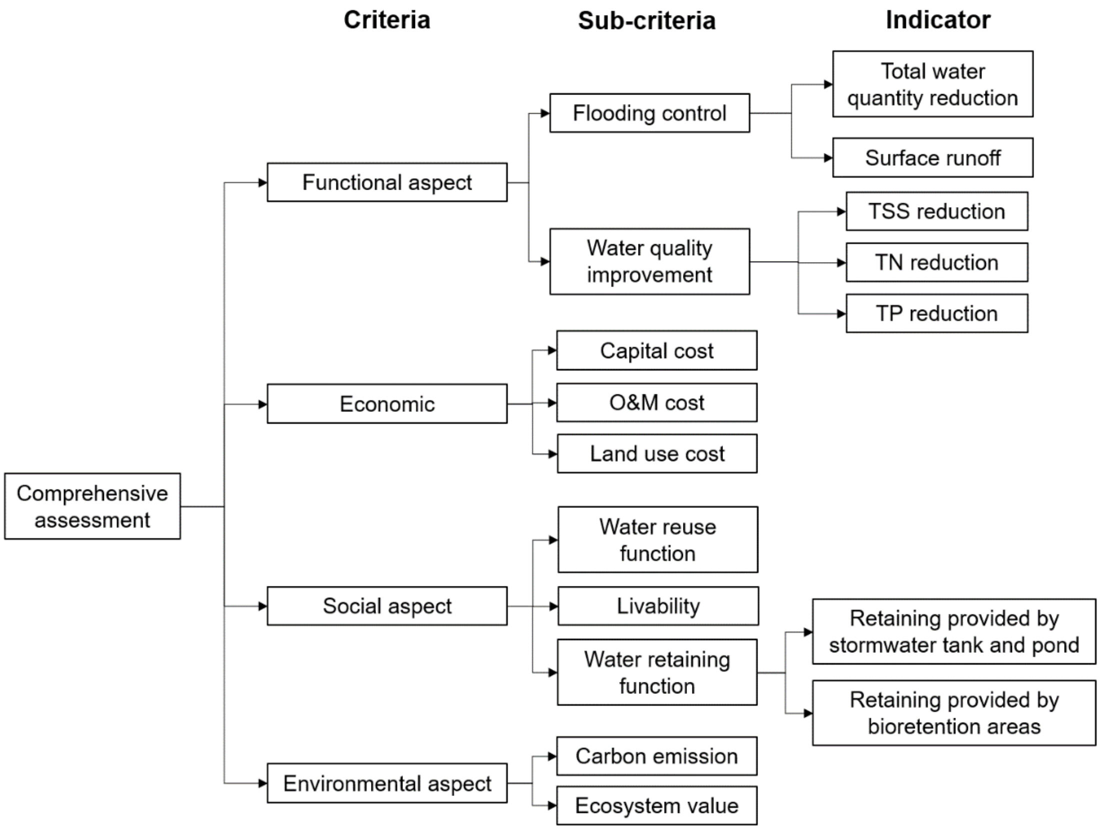

Figure 5. The selected criteria, sub-criteria, and indicators for comprehensive assessment.

Functional aspect. The functions of WSUD mainly comprised flooding control and water quality improvement [38,39,72,73]. For stormwater flooding control, total water quantity reduction and surface runoff, as important factors affecting runoff control efficiency, were selected as two indicators based on related cases [36,42]. WSUD facilities can promote evapotranspiration to reduce the total water quantity and temporarily retain water to reduce surface runoff [13,74]. For water quality improvement, the major pollutants included total suspended solid (TSS), total nitrogen (TN), and total phosphorus (TP) [75]. The WSUD's performance of TSS, TN, and TP treatment has been demonstrated by Parker [76], Hatt et al. [38] and Passeport et al. [72]. Hence, TSS, TN, and TP were selected as three indicators of water quality improvement.

Economic aspect. Compared to traditional approaches, the application of WSUD facilities or general GSI can reduce the capital costs and operation and maintenance (O&M) costs spent on stormwater treatment [77,78]. Additionally, land use cost is also a consideration in WSUD's economic performance because the land used for WSUD could have been used for other purposes [29,47]. The more land WSUD facilities occupied, the greater the land cost incurred, while the conventional pipe systems are generally buried under the ground. Thus, capital cost, O&M cost, and land use cost were selected as economic sub-criteria.

Social aspect. Livability, water reuse functions, and water retaining functions were selected as three social sub-criteria because they are not only important factors for people who live around the study area, but also are identified as significant goals and targets in stormwater management (see Table 2). The functions of water reuse and water retaining provided by WSUD have been broadly demonstrated in the guidelines [32]. Livability comprises recreational values, people's wellbeing, and aesthetic values, which are closely related to people themselves [44]. Further, Leonard et al. [44], Moores and Batstone [79], and Bowen et al. [80] reported that WSUD or other GSI can effectively improve the human-related values. Because of the different performance of water retaining functions for grey and green facilities [30,81], the two types of facilities were assessed respectively under the sub-criteria of water retaining function.

Environmental aspect. Many cases reported that carbon emission is an essential environmental indicator in stormwater infrastructure development [40,82] and it was demonstrated that WSUD can provide less carbon emission than conventional approaches [40,41]. Also, this indicator is consistent with the target of "net-zero emission" and "climate change adaptation" in the water sector (See Table 2). Meanwhile, ecosystem value is another environmental benefit that the selected WSUD facilities can provide [83], which is helpful to improve the water's health and biodiversity of the study area.

2.3.2. Weight Determination

The AHP method, developed by Saaty, is mainly used to determine the weights of sub-criteria and indicators [55]. The term consistency index (CI) is used to ensure the accuracy of AHP method. If CI result is less than 0.1, the weights determined by AHP method are considered reliable and the further assessment can be conducted [84]. The initial pair-wise comparison matrix of AHP is determined by seven procedures and shown in Figure 6. The designed questionnaire template is provided in Appendix B and the questionnaire results are enclosed in the Supplementary Materials. Also, the procedure of questionnaire assessment is to select effective questionnaires. In detail, the results provided by the experts who are not very relevant to this study and the results whose CI values are less than 0.1 will not be accepted. Taking the subjectivity of these experts into account, the procedure of peer review allows more experts to assess the rationality of these values to ensure the accuracy of the assessment. In this research, four experts from China University of Geoscience filled out the questionnaires and three of them were accepted by questionnaire assessment. Two experts from the University of Melbourne participated in the peer review.

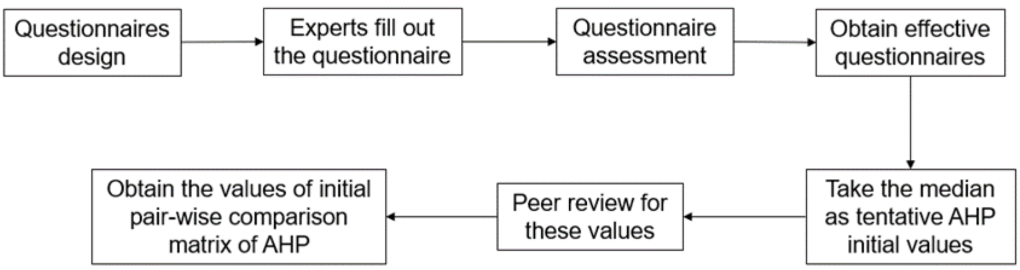

Figure 6. The procedures of initial pair-wise comparison matrix of analytic hierarchy process (AHP) determination.

Weight determination procedures based on AHP method are shown in Figure 7 and the detailed calculation results are provided in Appendix C. The weights of indicators under a sub-criterion were qualitatively determined from literature (water retaining function) or equal weighting systems (flooding control and water quality improvement).

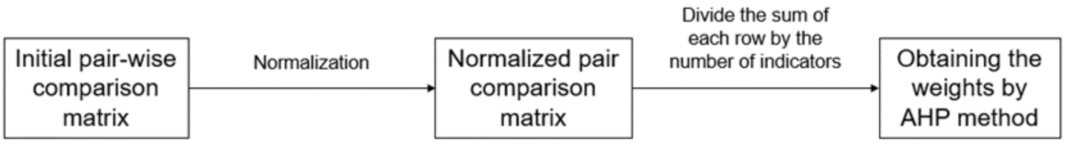

Figure 7. The procedures of weight determination by AHP method.

2.3.3. Indicator and Sub-criteria Calculation

As Table 7 shows, each sub-criteria and indicator were respectively assessed qualitatively or quantitatively. The functional benefits including flooding control and water quality improvement were evaluated by MUSIC. The rainfall-runoff model in MUSIC is based on the research of Chiew and McMahon [85]. In this model, the rainfall can go into impervious store, pervious store, and ground water. The outflow can be divided into surface runoff, baseflow, and deep loss. In this paper, the models of scenarios disregarded deep loss and only considered surface runoff and baseflow.

Table 7. The assessment methods for individual sub-criteria.

Sub-criteria	Assessment Method
Flooding control	MUSIC
Water quality improvement	MUSIC
Capital cost	Cost analysis
O&M cost	Cost analysis
Land use cost	Size estimation
Water reuse function	Size estimation
Livability	Hedonic pricing method and size estimation
Water retaining function	Size estimation
Carbon emission	Carbon footprint
Ecosystem value	Qualitative analysis

Table 8 summarizes the important parameters and coefficients for sub-criteria calculation. The data sources of initial capital cost and annual O&M cost of each WSUD facility were extracted from Melbourne Water [86] and Jayasuriya and Khastagir [87]. The indicators' values of capital cost and O&M cost can be easily obtained by simple cost calculations. The land use cost, water reuse, and water retaining function were estimated by the size of corresponding WSUD facilities in different scenarios. It is noted that the water retaining functions of grey-based facility (tank and pond) and green-based facility (bioretention area and swale) were calculated separately because of different performance features. As a human-related indicator, the livability of each scenario was assessed by using hedonic pricing method. It utilizes the home price fluctuation to estimate the values related to people's willingness to pay. Ira [88] provided the proportion of house price increase around each WSUD facility. The carbon footprint was used to calculate the carbon emissions. The emissions contribute to global warming, which can be defined as the total amount of greenhouse gases (GHG) released directly or indirectly into the atmosphere by human activities [89]. The raw data of the carbon footprint of different WSUD facilities were provided by Moore and Hunt's research [40] based on a 30-year life cycle. The ecosystem value was assessed by qualitative analysis. It was assigned an identical score with the water quality indicator because of the close relationships between the two sub-criteria.

As some sub-criteria comprised several indicators (see Figure 5), weighted sum model (WSM) (Equation (1)) was utilized to calculate the values of flooding control, water quality improvement, and water retaining function.

$$A_i = \sum_{j=1}^{n} w_i a_{ij}, \text{ for } i = 1, 2, 3, \ldots, m. \quad (1)$$

where: A_i is the score of sub-criteria in scenario i, $w_i a_{ij}$ is the performance of alternative A_i when it is evaluated in terms of indicator j, n is the number of indicators under one sub-criterion, and a_{ij} is the linear normalized results for indicator j, which is given by Equation (2)

$$a_{ij} = \frac{B_{ij}}{\sum_{j=1}^{N} B_{ij}} \tag{2}$$

where: B_{ij} is the initial value of indicator j in scenario i, and N refers to the number of WSUD scenarios.

Table 8. The important parameters and coefficients for sub-criteria calculation.

	Stormwater Tank	Pond	Bioretention Area	Swale
Unit cost (AU$/unit)	1000 *	150	1000	25
O&M cost (AU$/unit/year)	0.5 *	10	5	3
Net carbon footprint (kg CO_{2-e}/m^2)	80	8.1	2.5	3.5
House price increase (AU$/$m^2$)	0	0.0646	0.0484	0.0484

Note: * refers to when the unit of WSUD facility is kL.

The indicator values comprised benefit value and non-benefit value, and the non-benefit values should be transferred into benefit forms by Equation (3).

$$b_{ij} = B_{\min(ij)} - B_{ij} + B_{\min(ij)} \tag{3}$$

where: b_{ij} is the benefit form value after transformation, $B_{\max(ij)}$ is the maximum value of indicator j in scenario i, and $B_{\min(ij)}$ is the minimum values of indicator j in scenario i.

2.4. Comprehensive Assessment

After determining the values of sub-criteria, the MAUT method, as an extension of Multi-Attribute Value Theory (MAVT) [51], was adopted to obtain the comprehensive results. It is the closest to the public acceptance MCDA method [55]. It assumes that the preferences of decision-makers can be presented as an analytical utility function and effectively combined the risk preferences and uncertainty in decision-making [90]. Generally, MAUT's functions are divided into three main types: additive, multiplicative, and reference point [91]. In this paper, the additive method was selected for comprehensive assessment and calculation follows Equation (4).

$$U(v) = \sum_{i=1}^{n} a(i)u(i) \tag{4}$$

where: $U(v)$ is the overall utility of an option, $a(i)$ is the magnitude of the option on the i^{th} attribute, $u(i)$ is the importance of the option on the i^{th} attribute, and n is the number of attributes.

One step of MAUT is determining the benefit and non-benefit indicators for the following normalization. In this paper, the beneficial indicators and non-beneficial indicators are normalized by Equations (5) and (6), respectively.

$$A_{n1} = \frac{X_{ij}}{Max(X_j)} \text{ for beneficial values} \tag{5}$$

$$A_{n2} = \frac{Min(X_j)}{X_{ij}} \text{ for non} - \text{beneficial values} \tag{6}$$

where A_{n1} is the normalized value of indicator j in scenario i for beneficial values, A_{n2} is the normalized value of indicator j in scenario i for non-beneficial values, X_{ij} is the values of indicator j in scenario i,

$Max(X_j)$ is the maximum value of indicator j in all the scenarios, and $Min(X_j)$ is the minimum value of indicator j in all the scenarios.

Because MAUT procedures comprised normalizing the evaluating matrix, the normalized results can be used to respectively obtain the scores of functional, economic, social, and environmental aspects of different scenarios. Based on AHP, MAUT, and several qualitative and quantitative methods, the comprehensive assessment framework used is summarized in Figure 8. This framework is made of four main phases: preparation, design, assessment, and recommendation.

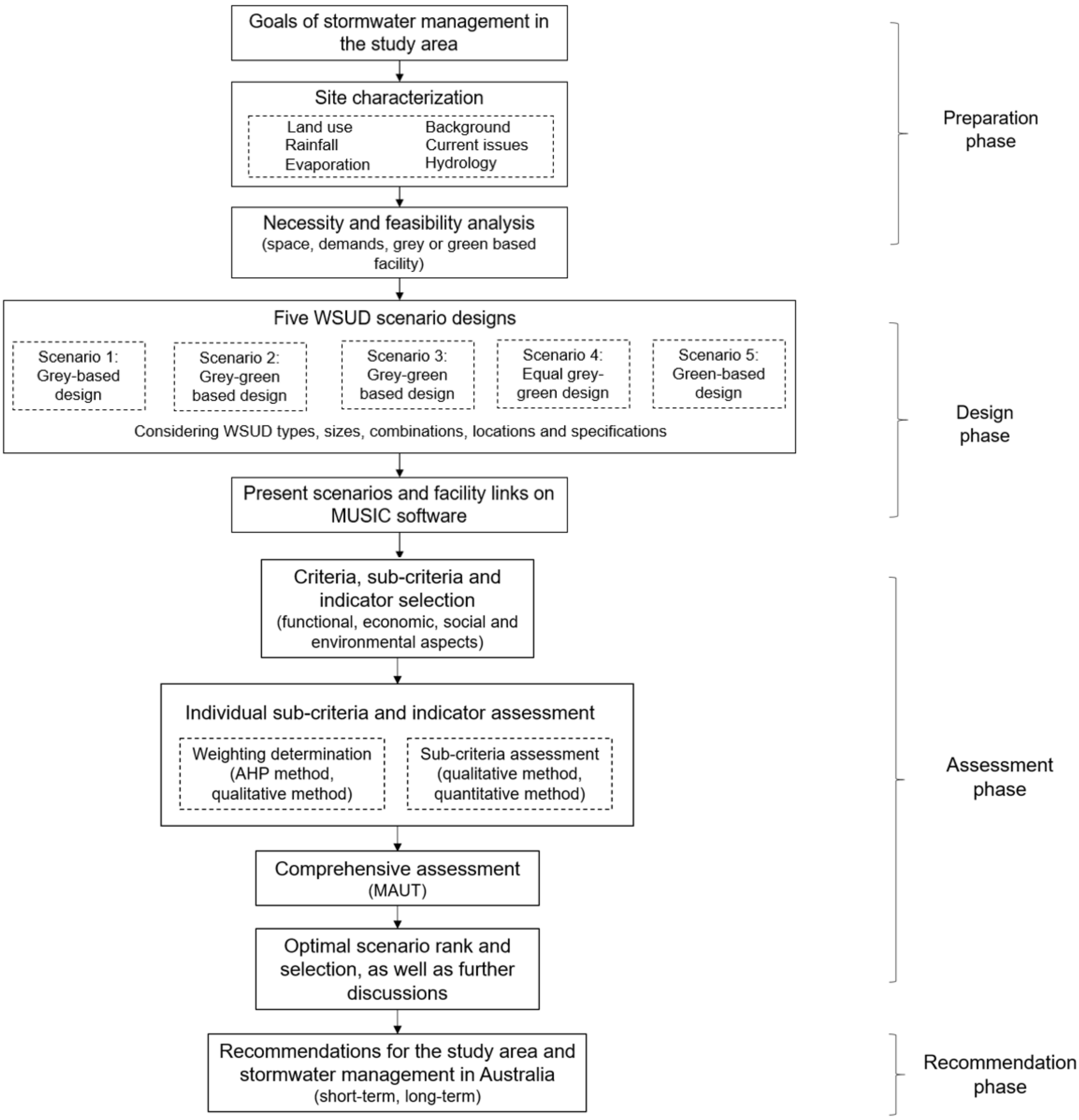

Figure 8. The framework of comprehensive assessment for five WSUD scenarios.

3. Results and Discussion

3.1. Indicator Weights

Table 9 shows the weights of different criteria, sub-criteria, and indicators calculated by AHP method. The higher weight of a sub-criteria represents the higher importance for stormwater management in the study area. The CI determined by AHP is 0.0171 (less than 0.1). This means that the AHP results for weight determination are reasonable (see Appendix C).

Table 9. The weights of criteria, sub-criteria, and indicators.

Criteria	Weights	Sub-criteria	Weights	Indicators	Weights
Functional aspect	22.73%	Flooding control	12.44%	Total water quantity	6.22%
				Surface runoff	6.22%
		Water quality improvement	10.29%	TSS reduction	3.43%
				TP reduction	3.43%
				TN reduction	3.43%
Economic aspect	11.91%	Capital cost	2.60%		
		O&M cost	1.91%		
		Land use cost	7.40%		
Social aspect	43.56%	Water reuse function	15.31%		
		Livability	13.78%		
		Water retaining function	14.47%	Retaining provided by stormwater tank and pond	8.68%
				Retaining provided by bioretention areas	5.79%
Environmental aspect	21.80%	Carbon emission	14.78%		
		Ecosystem value	7.03%		
Total	100.00%		100.00%		

The social aspect is assigned the highest weight (43.56%) and all the three sub-criteria of the social aspect have relative high weights (15.31% for water reuse function, 13.78% for livability, and 14.47% for water retaining function). This is reasonable because many development goals and strategies of stormwater management in the study area emphasized the improvement of the social values such as water reuse and water retaining. Melbourne Water [83] and Wong [30] reported that the performance of tank and pond is better than bioretention areas and swales in water retaining function. Therefore, their weights are quantitively assigned as 8.68% and 5.79%, respectively. In contrast, the economic aspect is ranked fourth with a 11.91% weight, and the weights of O&M cost and capital cost are very low (1.91% and 2.60%, respectively). Considering the importance of open space for other uses, the weight of land use cost (7.40%) is higher than capital cost and O&M cost. Meanwhile, the weights of the functional aspect (22.73%) and the environmental aspect (21.80%) are similar. Flooding control (12.44%) and water quality improvement (10.29%) are the functions that all stormwater infrastructures must consider regardless of grey or green facilities. The former is given a higher weight because of the severe flooding risks in the area. The carbon emission is assigned 14.78%, which is higher than ecosystem values (7.03%) because "zero-emission" in the water sector has been emphasized many times by stakeholders [92]. It is an essential environmental indicator in the infrastructure construction.

3.2. Individual Results

3.2.1. Functional Aspect

Table 10 presents the initial results and normalized results of the functional aspect simulated by MUSIC. Surface runoff, as a non-beneficial indicator, has been transferred to beneficial form before normalization by Equation (3). As the MUSIC software cannot directly calculate the surface runoff, its values were taken from the amount of weir out flow of the South Lawn treatment node. The flooding control and water quality improvement for five scenarios can be further calculated by Equation (1) and are shown in Table 11. It was found that the differences of five scenarios in flooding control are not obvious, except that scenario 2 is slightly better than other alternatives. For the water quality aspect, scenario 5 obtained the highest score in water quality improvement because the large proportion of bioretention areas and swales have pollution removal mechanisms and play a considerable role in improving stormwater quality. Similarly, as an equal grey-green design, the performance of water quality improvement for scenario 4 is also outstanding due to the large size of green-based facilities. On the country, the grey-based scenario's assessment score in water quality improvement is not satisfactory. Scenario 2 performs better in water quality improvement than scenario 3, although the green facility proportion of the latter is higher. This may be because bioretention areas are more efficient than swales in improving stormwater quality.

3.2.2. Economic, Social, and Environmental Aspect

Table 12 summarizes the individual results of eight sub-criteria of economic, social, and environmental aspects and the calculation procedures are provided in the Supplementary Materials. In the calculation, the normal level of stormwater tank and pond is assumed as 1 m. Scenario 1 and 2 have higher capital cost because the cost of stormwater tank is quite high and up to $1000 per kiloliter. Additionally, the two scenarios also perform well in water reuse and retaining function because of the higher performance of these grey facilities in the two indicators, while the bioretention areas and swales cannot contribute to the water reuse. Scenario 3 is relatively average in all the sub-criteria, and there is no one criterion that performs best or worst. Scenario 4 has the highest score among the three economic sub-criteria and also performs satisfactorily in other factors, particularly in carbon emission and ecosystem value. As a green-based option, the pros and cons of scenario 5 are very clear. Its performances in carbon emission, livability improvement, and ecological value are the best among the five alternatives, but the scores of water reuse and retaining function are not satisfactory.

3.3. Comprehensive Results

The values of 10 sub-criteria have been determined qualitatively and quantitatively, as shown in Tables 11 and 12. Calculated using Equations (5) and (6), the normalized results of these sub-criteria as well as their weights are presented by spider diagrams (Figure 9). The calculation procedures are enclosed in Appendix D and the Supplementary Materials.

The scores of functional, economic, social, and environm cvental aspects can be calculated respectively by Equation (4), and the overall scores of five scenarios can be further calculated (Table 13). After the comprehensive assessment based on MAUT, scenario 4 (0.771 out of 1), as the equal grey-green strategy, is the optimal option for stormwater management in the University of Melbourne. It provides maximum comprehensive benefits, although it does not perform best in the functional, social, and environmental aspects. It had the highest economic benefits (0.119) because of the smallest areas of WSUD facilities and the relative few stormwater tanks in design. The optimal scenario comprised 250 m^2 stormwater tanks (including 225 m^2 existing tanks), 50 m^2 pond, 170 m^2 bioretention areas, and 150 m^2 swales. The proportion of grey and green facilities are approximately half (52% green facilities).

Table 10. The individual and normalized results of the functional aspect.

		Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Initial values	Total water quantity reduction	%	1.5	1.6	1.4	1.2	1.1
	Surface runoff	m^3/year	56,300	50,800	55,560	50,540	50,100
	TSS reduction	%	38.5	62.3	58.5	76.9	82.1
	TP reduction	%	20.9	37.1	35.7	44.0	48.3
	TN reduction	%	15.7	26.8	24.7	29.9	36.5
Normalized values	Total water quantity reduction	-	0.2206	0.2353	0.2059	0.1765	0.1618
	Surface runoff	-	0.2359	0.2618	0.2394	0.2630	0.2651
	TSS reduction	-	0.1210	0.1957	0.1838	0.2416	0.2579
	TP reduction	-	0.1124	0.1995	0.1919	0.2366	0.2597
	TN reduction	-	0.1175	0.2006	0.1849	0.2238	0.2732

Table 11. The results of flooding control and water quality improvement for scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Flooding control	0.0284	0.0309	0.0277	0.0273	0.0265
Water quality improvement	0.0120	0.0204	0.0192	0.0241	0.0271

Table 12. The results of sub-criteria in economic, social, and environmental aspects.

Sub-criteria	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Capital cost *	AU$	675,000	631,250	453,750	238,750	420,000
O&M cost *	AU$/year	3900	3575	3650	2775	3000
Land use cost *	m^2	705	750	695	620	650
Water reuse function	m^3	1800	1550	1400	1050	400
Livability	-	10.914	14.62	17.476	16.286	21.59
Water retaining function	-	158.00	146.13	137.16	109.67	60.77
Carbon emission *	kg CO_2-equivalent	43,290	37,360	31,635	21,355	13,730
Ecosystem value	-	0.0120	0.0204	0.0192	0.0241	0.0271

Note: * refers to the non-beneficial sub-criteria.

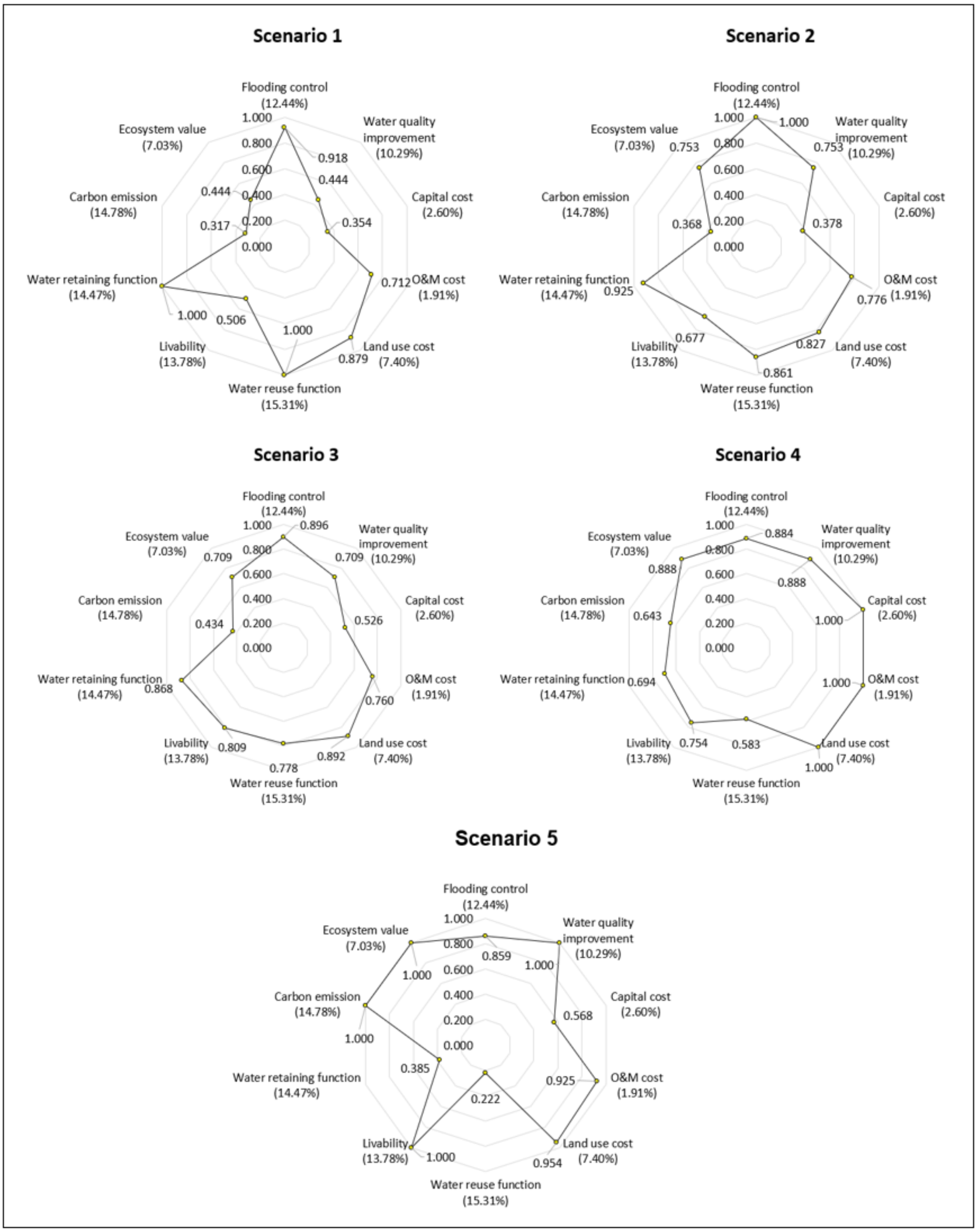

Figure 9. The spider diagrams of normalized results and weights.

In contrast, scenario 1 (0.693 out of 1), as a grey-based strategy with 4.3% green facilities, had a considerable gap for achieving the sustainable stormwater management goals. Its social benefits are excellent but cannot counteract the deficits in terms of functionality and the environmental aspect. Scenario 2 (26.7% green facilities) and scenario 3 (31.7% green facilities) had the approximate 0.75 score but less than scenario 4, which showed the significance of increasing the green WSUD facilities in the study area. If only considering the first four scenarios, we can preliminarily conclude that the overall score increases as the ratio of green facilities gradually increases.

Table 13. Comprehensive results based on multi-attribute utility theory (MAUT).

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Functional aspect	0.160	0.202	0.184	0.201	0.210
Economic aspect	0.088	0.086	0.096	0.119	0.103
Social aspect	0.367	0.359	0.356	0.294	0.227
Environmental aspect	0.078	0.107	0.114	0.157	0.218
Overall score	0.693	0.754	0.749	0.771	0.758

Scenario 5 also had the highest environmental and functional benefits and its green facility areas have reached 69.2%, which was mainly attributed by green facilities' effectiveness in water quality improvement and lower carbon emissions. However, it showed poor social benefits and, thus, caused slightly lower overall score than scenario 4 (0.758 and 0.771). This drag-down is due to its poor social benefits that are strongly related to the "water reuse" and "water retaining" services featured in grey facilities. We must notice herein that scenario 5 has the smallest proportion of grey facilities. Therefore, we can conclude that to keep increasing the green facility is not equal to a better GSI combination design, but there is a trade-off relation we must consider between the proportion of green and grey facilities and also among social, economic, environmental, and functional aspects. A proper combination of grey and green WSUD facilities is the best response to the stormwater management in the study area to achieve the sustainable stormwater management goals.

The results are consistent with the research of Alves et al. [93], Gallo et al. [50], Bakhshipour et al. [94], and Damodram et al. [95]. Alves et al. [93] applied MCDA methods to assess the flooding management in three study areas (Marbella, Ayutthaya, and Sukhumvit) and concluded that the green and grey combination measures provided more advantages compared with previously developed methods. Gallo et al. [50] developed a modeling framework that encompasses green and grey stormwater facilities and was applied into the Berkeley neighborhood. They also reported that the optimal stormwater solution in the study area is a mix of green and grey combination. Bakhshipour et al. [94] illustrated that the hybrid green-blue-grey stormwater infrastructures can economically compete with conventional grey-only pipe networks and the green parts can effectively increase the sustainability and environmental friendliness. The research of Damodram et al. [95] proposed to combine LIDs and BMPs to achieve sustainability goals given limited resources, and its essence is also seeking an optimal combination of grey and green stormwater facilities. Therefore, despite the fact that adopting GSI to manage stormwater has become a worldwide trend, only when a suitable combination of these GSI facilities was applied could their performances be maximized to achieve sustainable development.

3.4. Insights and Practical Significance of the Case Study

Reviewing the entire case study, it was found that setting the sustainable goals for the specified study area can facilitate the effective WSUD design if water managers or local administration can provide a clear statement of commitment towards stormwater water management. These sustainable goals underpin the proposal and determination of criteria and weights by an assessment framework that serves for WSUD scenarios comparison. We must notice herein that there could be large flexibilities between goals and determination of criteria, indicators, and weights. This paper used the methods of questionnaires, discussion with experts, and literature review to transform the qualitative goals into measurable indicators. These methods are worth recommending but entail local water managers having a good understanding of WSUD benefits, sustainable development goals, and GSI principles. In a real case, water managers should not only tightly follow the local stormwater management goals, but also choose sufficient, suitable, and comprehensive criteria and indicators truly matched with the real situation (e.g., from functional, economic, social, and environmental perspectives).

There are many proposed MCDA methods in previous studies, and the combination of two or more MCDA methods can more easily and practically meet the requirements of decision-makers. In this study, the AHP method helps to determine the weights of different sub-criteria, while MAUT standardizes all the criteria and indicators with or without units. It is anticipated that this combined MCDA assessment tool is more practical and convenient for water managers. In terms of this case study, the framework (Figure 8) well contained the stormwater goals, five different scenarios, combined MCDA methods, and sufficient criteria and indicators. This framework should be promoted for the water sector to solve complex decision-making problems.

Since the proportion of green facilities of scenario 4 is 52% (approximately 50%), the "equal green grey" WSUD design philosophy could be empirically applied in some Melbourne campus. This is mainly because these areas have similar external factors such as land use, stormwater goals, and meteorological data, and the optimal results could be similar. However, for an area with different land uses, policies, and meteorological conditions, it is necessary to conduct a comprehensive assessment as described in this paper. By adjusting the proportions of green-grey facilities to generate a number of scenarios, the model can simulate possible WSUD combinations as alternatives. The method of scenario designs can also be used in many other similar cases where both proportions of green and grey facilities play an important role.

3.5. Recommendations and Prospects

The problem that the University of Melbourne urgently needs to solve is related to the implementation of more green stormwater facilities, while the 900 kiloliters existing stormwater tanks basically can meet people's demands of water reusing and retaining. According the results analysis, scenario 4, as "equal grey-green" design, can be applied as a priority design for the University of Melbourne. By comparing scenario 4 and 5, a higher proportion of green WSUD facilities will lower the overall profits. It gives an insight that the performance of WSUD combinations are often not as simple linear relation as the proportional relation, but a more complex mechanism fundamentally associated with criteria, indicators, and weighting systems. Therefore, more scenarios with different green facility proportion are recommended to design for further optimization assessment in the University of Melbourne. In this way, a more accurate optimal result can be further obtained.

As illustrated in Section 3.4, different land uses, policies, and meteorological conditions could lead to various assessment results. In fact, there are many other factors such as stormwater goals, weighting systems, site characteristics, public engagement, and decision-makers' perspectives that should be considered. Taking decision-makers' perspectives as an example, the decision-makers can be engineers, urban planners, and environmentalists who can directly or indirectly impact the assessment of WSUD or GSI [96]. Jayasooriya et al. [47] reported that the priority of the engineers, urban planners, and environmentalists for GSI strategies may be cost-effectiveness, amenity values, and environmental impacts mitigation, respectively. Similarly, for a site with different policies, financial support, location characteristics, public awareness and engagement, etc., the optimal GSI combination may be entirely different. These diversified factors make it a challenge for decision-makers to select the most appropriate stormwater strategy for a site [97].

For the challenge of diversified factors, this paper strongly recommends that a general comprehensive assessment framework can be used to optimize different scenarios based on MCDA methods in Australia or a global scale, rather than the specific case study. In fact, there are several good attempts of combining stormwater management and MCDA to score, rank, and select the optimal option by a more generalizable framework. At the theoretical level, Jayasooriya et al. [47] Sapkota et al. [98], Sapkota et al. [46], and Wu et al. [71] reported that the establishment of a standard comprehensive assessment framework for GSI is significant and it can further assist decision-makers to make a more reasonable, inclusive, and well-informed decision. At the practical level, Morales-Torres et al. [48] reported a decision supported tool called E2STORMED based on MCDA method to assess the multi-benefits of different GSI, and Kuller et al. [31] also developed a rapid

GSI-based MCDA tool for WSUD assets (called SSANTO), to assist stakeholders engaged in the urban planning in focusing on opportunities and needs of WSUD. Additionally, related cases regarding comprehensive assessments for GSI have also been published in recent years [42,99–102]. Importantly, such a framework can well integrate current or future sustainable strategies by questionnaire or other methods, thereby promoting sustainable development in a site [103]. Specifically, when the sustainable policies and strategies change, the goals to be achieved and the indicators to be assessed will change accordingly [104]. Under various external conditions, the framework will continuously help water managers to make informed and inclusive decisions and play a role in achieving sustainable environmental development involving a variety of factors.

In 2019, Dandy et al. [105] proposed a general comprehensive assessment framework for the assessment of the performance of different stormwater harvesting alternatives based on MCDA (Figure 10), which is similar but more generalizable with the framework described in Figure 8. It has guiding significance for the establishment and promotion of general WSUD or GSI assessment framework for stormwater management. Four main steps shown in Dandy et al.'s framework [105] include problem definition, option design, performance evaluation, and option selection, which could be recommended for GSI assessment framework establishment. The future work will continue to develop the assessment framework on the basis of the four-step theory. As the knowledge in GSI and MCDA progresses, the future research for developing the framework and promoting sustainable stormwater management may include the following aspects. These aspects are also shown and illustrated in a variety of publications.

- Propose a clear statement of commitment towards sustainable stormwater water management based on different site characteristics [104].
- Develop a better methodology of transforming the qualitative goals into measurable indicators except for questionnaire [106].
- Develop more reasonable combined scenarios of GSI or WSUD [107].
- Develop more accurate and indicator calculation methods [106].
- Consider the perspectives of all the stakeholders including the public engagement rather than experts only [108,109].
- Select more appropriate MCDA methods for water managers in decision-making processes [110].

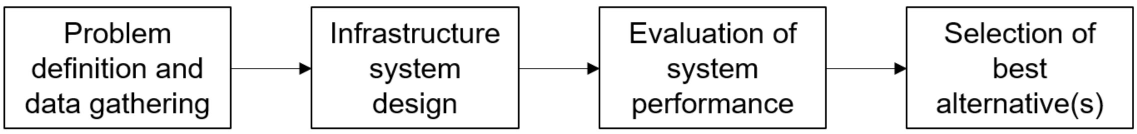

Figure 10. Comprehensive assessment framework for stormwater harvesting alternatives provided by Dandy et al. [105].

3.6. Limitations

The limitations of this paper included MUSIC modeling restrictions, subjectivity of experts in the AHP method, and uncertainty of indicator values. For the MUSIC modeling design, firstly, the campus was divided into seven sub-areas to build the model in MUSIC as shown in Figure 1, where it was assumed that these separate areas are independent. In fact, the seven sub-areas constitute the whole campus and they can influence each other. Additionally, the rainfall events used in the model is of a one-day interval, while a long-term and high intensity of rainfall data (e.g., one-hour interval) are preferable for assessment. Meanwhile, the results produced from MUSIC do not consider the underground pipes and it assumed that these existing conventional approaches have no influence on the facilities performance. Finally, MUSIC is a software only applicable to Australia and New Zealand, and the regional limitations will make it difficult to extend to the global scale [71]. Subjectivity of experts is another limitation of the study. Despite the fact that this study invited a total of six experts to conduct the questionnaire and peer view, this sample size is not sufficient to eliminate the subjectivity of influence. When conditions permit, it would more accurate if more numbers of relevant experts and scholars can participate in the weight determination. For the indicator values, many unit values of indicators such as carbon emission, construction cost, O&M cost, and livability are extracted from previous research and may be out of date. Also, the qualitative assessment method of indicators will also cause some errors.

4. Conclusions

It is a worldwide trend for city planners to select a GSI philosophy rather than "rapid-draining"-based traditional approaches in stormwater management. In Australia, WSUD facilities are designed to accelerate economic, social, and environmental development while dealing with a series of stormwater functional problems. Current stormwater management assessments sometimes ignore the economic and social benefits and there is a lack of a comprehensive selection framework to optimize the stormwater facility combinations based on various criteria. This paper focuses on assessing and optimizing WSUD facility combinations based on AHP and MAUT through a case study of Melbourne University's Parkville Campus. Based on the results, the key findings and conclusions are summarized as follows.

Scenario 4 (equal grey-green design) containing 52% green WSUD facilities obtained the highest scores (0.771) among five designed scenarios. It provides maximum comprehensive benefits although it does not perform best in the functional, social, and environmental aspects. It can be applied as a priority design for achieving the goals of stormwater management in the University of Melbourne. Implementing more green stormwater facilities is an urgent issue in the study area. Meanwhile, considering the similar land uses, stormwater goals and meteorological data in most of Melbourne campuses, the "equal green grey" WSUD design philosophy could be empirically applied in these areas.

Scenario 5 came second with a score of 0.758 despite the fact that the green facility proportion reached 69%. It indicates that to keep increasing the green facility is not equal to a better GSI combination design, but there is a trade-off relation we must consider between the proportion of green and grey facilities and also among social, economic, environmental, and functional aspects. Therefore, more scenarios with different green facility proportion are recommended for further optimization assessment to obtain a more accurate result.

The methods of questionnaires, discussion with experts, and literature review can transform the qualitative goals into measurable indicators, but it is inevitable that the subjectivity of experts will cause some errors. It would more accurate if more numbers of relevant experts and scholars can participate in the weight determination. Also, the combination of two or more MCDA methods can more easily and practically meet the requirements of decision-makers. It is anticipated that this combined MCDA assessment tool is more practical and convenient for water managers.

It is highly possible that a general comprehensive WSUD or GSI assessment framework can be used to optimize different scenarios based on MCDA methods in Australia or a global scale. In recent years, there are several good attempts of assessments combining stormwater management and MCDA in a framework from the theoretical level to the practical level. Four steps including problem definition, option design, performance evaluation, and option selection are recommended to form the GSI assessment framework structure. The future work will continue to develop GSI assessment framework based on the four-step theory. When such a more applicable framework is broadly promoted, it can further promote sustainable development by helping water managers to make informed and inclusive decisions involving a variety of factors.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/10/2885/s1, Section A: Questionnaire results, Section B: Calculation procedures for sub-criteria in economic, social, and environmental aspect.

Author Contributions: Conceptualization, H.X.; Data curation, H.X. and Y.S.; Formal analysis, H.X.; Investigation, H.X. and Y.S.; Methodology, H.X. and Y.S.; Project administration, X.R.; Supervision, X.R.; Writing—original draft,

H.X.; Writing—review & editing, H.X., Y.S. and X.R. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: We declare that there are no conflict of interest relevant to this paper, and there is no significant financial support for this paper that influenced its outcomes.

Appendix A The Descriptions, Functions, and Specifications of Different WSUD Technologies Selected for Designs

Appendix A.1 Stormwater Tank

The stormwater tank schematic diagram is shown in the following Figure A1. It is mainly used for rain harvesting and stormwater reusing, which produces positive impacts on reducing demand on portable water resources. Rainwater tank is widely accepted for a long time and can help households reduce the inconvenience resulted from water restrictions [111]. In MUSIC modeling, the inflow of rainwater tanks is assumed from building roofs. Four types of rainwater tanks are designed in the scenarios, and corresponding parameters are summarized in Table A1.

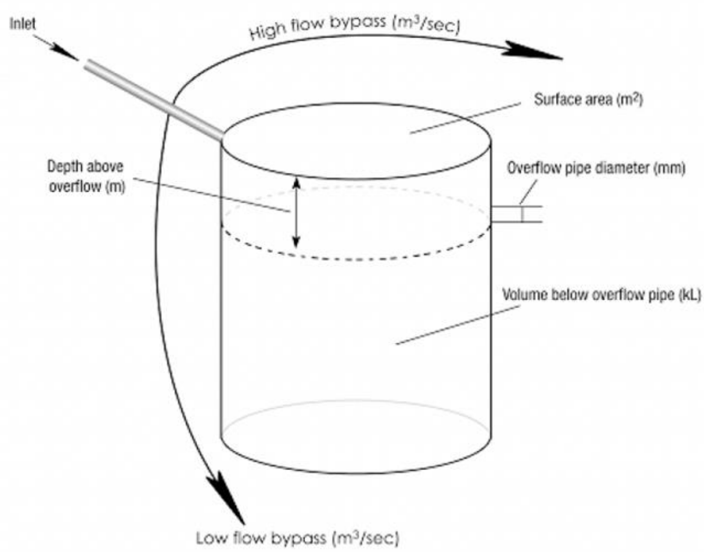

Figure A1. The schematic diagram of stormwater tank [112].

Table A1. Parameters of four types of stormwater tanks in MUSIC.

	Stormwater Tank (50 kL)	Stormwater Tank (100 kL)	Stormwater Tank (750 kL)
Low flow bypass (m^3/s)	0	0	0
High flow bypass (m^3/s)	100	100	100
Volume below overflow pipe (kL)	50	100	750
Depth above overflow (m)	0.2	0.2	0.2
Surface area (m^2)	25	50	150
Initial volume (kL)	25	50	375
Overflow pipe diameter (mm)	250	500	1000

Appendix A.2 Pond

Pond is a simple basin for open water body, which is quite useful for water temporary storage, reuse, and extended detention [113]. At the same time, pond removes particles in inflow by gravity [114]. Figure A2 presents the scheme of a pond and Table A2 summarizes the design parameters of two types of ponds in MUSIC.

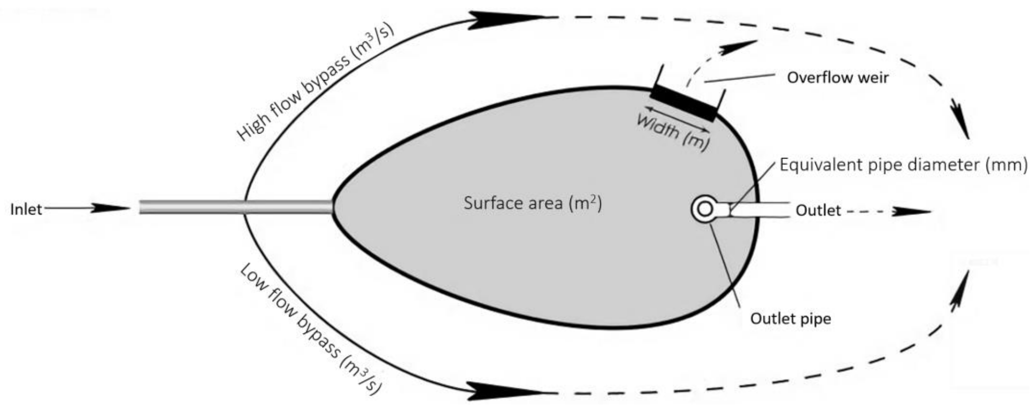

Figure A2. The schematic diagram of pond [112].

Table A2. Parameters of two types of ponds in MUSIC.

	Pond (50 m^2)	Pond (100 m^2)
Low flow bypass (m^3/s)	0	0
High flow bypass (m^3/s)	100	100
Surface area (m^2)	50	100
Extended detention depth (m)	2.0	2.0
Initial volume (kL)	50	100
Exfiltration rate (mm/hr)	0	0
Evaporative loss as % of PET	100	100
Equivalent pipe diameter (mm)	300	300
Overflow weir width (m)	2.0	2.0

Appendix A.3 Bioretention Areas

Bioretention areas treat stormwater by vegetated filter media to remove pollutants, and at the same time store stormwater and allow infiltration into the ground [115]. The vegetation types and media properties can clearly impact bioretention areas' performance [116]. A typical example of a bioretention system is a rain garden. In MUSIC modeling, three types of bioretention areas with different sizes were selected. We assume that vegetation and media properties are the same and all bioretention systems are square. Figure A3 and Table A3 show the schematic diagram and design parameters of bioretention areas, respectively.

Appendix A.4 Swales

Vegetated swales are open water channels covered with vegetation. Swales can remove suspended solids effectively by sedimentation and vegetation trapping [117]. The performance of vegetated swales can be impacted by vegetation density and heights. In MUSIC modeling, the cross section of swales is assumed to be trapezoid. Two types of swales including 50 m^2 size and 100 m^2 size were selected for design. Figure A4 and Table A4 show the schematic diagram and design parameters of swales, respectively.

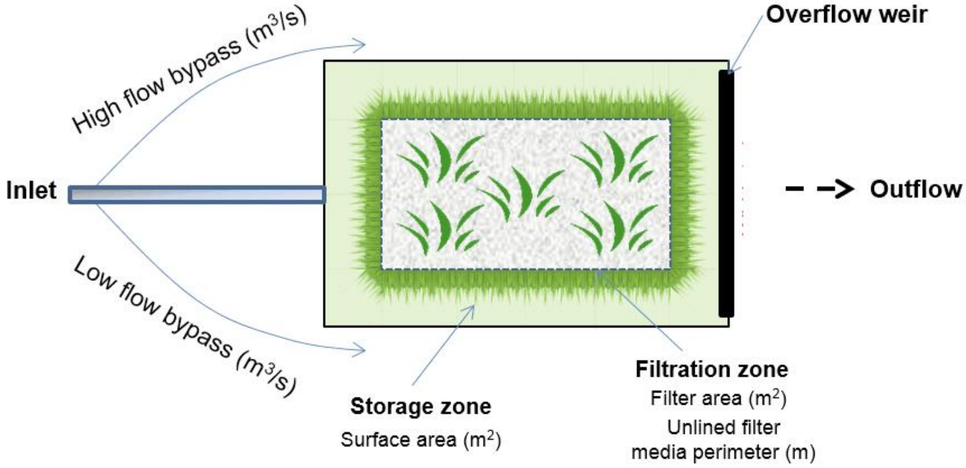

Figure A3. The schematic diagram of bioretention areas [112].

Table A3. Parameters of three types of bioretention areas in MUSIC.

	Bioretention Areas (20 m^2)	Bioretention Areas (30 m^2)	Bioretention Areas (50 m^2)
Low flow bypass (m^3/s)	0	0	0
High flow bypass (m^3/s)	100	100	100
Extended detention depth (m)	0.2	0.2	0.2
Surface area (m^2)	20	30	50
Filter area (m^2)	20	30	50
Unlined filter media perimeter (m)	17.89	21.91	28.28
Saturated hydraulic conductivity (mm/hour)	100	100	100
Filter depth (m)	0.5	0.5	0.5
TN content of filter media (mg/kg)	800	800	500
Orthophosphate content of filter media (mg/kg)	55	55	55
Exfiltration rate (mm/hour)	0	0	0

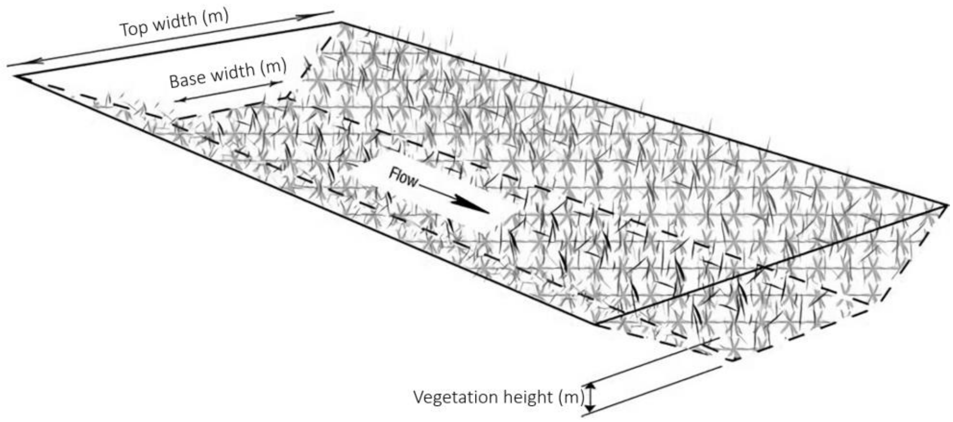

Figure A4. The schematic diagram of swales [112].

Table A4. Parameters of two types of swales in MUSIC.

	Swales (50 m^2)	Swales (100 m^2)
Low flow bypass (m^3/s)	0	0
Length (m)	100	50
Bed slope (%)	3.0	2.0
Base width (m)	1.0	1.0
Top width (m)	5.0	4.0
Depth (m)	0.5	0.4
Vegetation height (m)	0.25	0.25
Exfiltration rate (mm/hour)	0	0

Appendix B Questionnaire Template of Initial AHP Value Determination

Stormwater Management Questionnaires for the University of Melbourne

This questionnaire is to determine the relative importance for 10 sub-criteria in terms of Melbourne University's stormwater management in the future. The questionnaire results will be used as the raw data of AHP (analytic hierarchy process) method for Hanxiang Xiong, Yafei Sun, and Xinwei Ren's paper. Please refer to the examples below, compare the sub-criteria's relative importance of table's each row and column, and use numbers (from 1 to 9) to represent different relative importance (see Table A5) in terms of stormwater management development in the study area (Fractions are ALLOWED to use to express more accurately). More information about site's stormwater goals and strategies are summarized as follows.

Table A5. Scale of relative importance for 1 to 9.

Number	Scale of Relative Importance
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values
Fractions	More detailed intermediate values

If you think flooding control is of extreme importance than capital cost, write the number "9" in the form as shown in Table A6.

Table A6. Writing example (flooding control is of extreme importance than capital cost).

ATTRIBUTE	Flooding Control	Capital Cost
Flooding control	1	9
Capital cost		1

If you think capital cost is of between equal importance and moderate importance than flooding control, write the number "2" or other fractions in the form as shown in the Table A7.

Table A7. Writing example (capital cost is of between equal importance and moderate importance than flooding control).

ATTRIBUTE	Flooding Control	Capital Cost
Flooding control	1	
Capital cost	2	1

More information: Elizabeth Street catchment integrated water cycle management plan (City of Melbourne)
Municipal integrated water management plan (City of Melbourne)
Water for Victoria - Water Plan 2018 (Victoria Department of Environment, Land, Water and Planning)
Victoria's Climate Change Adaptation Plan (Victoria Department of Environment, Land, Water and Planning)
Melbourne Planning Scheme Clause 56.07 (Victoria Department of Environment, Land, Water and Planning)
Melbourne Planning Scheme Clause 22.23 (Victoria Department of Environment, Land, Water and Planning)
Flood Management Strategy Port Phillip and Westernport (Melbourne Water)
Date: ___/___/___

Question 1: Are you familiar with the stormwater management in the study area or have you read the provided information at the first page?
□ Yes □ No

Question 2: What is/are your best field(s)? (can choose more than one option)
□ Urban Water Management □ Green Stormwater Infrastructure □ Sustainable Development □ Water Resource management
□ Water Policy and Governance □ Flooding Issues □ Waste Water Management □ Water Supply and Network
□ Underground Water □ Water Quality and Biodiversity □ Urban Water Planning □ Ecosystem
Other fields ____________________

Question 3: Complete Table A8.

As the value of CI is less than 0.1, the initial pair-wise comparison matrix determined my questionnaires are reasonable. Therefore, the following comprehensive assessment can be further conducted.

Table A8. Relative importance questionnaire of 10 sub-criteria.

ATTRIBUTE	Flooding Control	Water Quality Improvement	Capital Cost	O&M Cost	Land Use Cost	Water Reuse Function	Livability	Water Retaining Function	Carbon Emission	Ecosystem Value
Flooding Control	1									
Water Quality Improvement		1								
Capital Cost			1							
O&M Cost				1						
Land Use Cost					1					
Water Reuse Function						1				
Livability							1			
Water Retaining Function								1		
Carbon Emission									1	
Ecosystem Value										1

Signature:______________

Appendix C The Detailed Description and Procedures of AHP Method

Table A9. Initial pair-wise comparison matrix.

ATTRIBUTE	Flooding Control	Water Quality Improvement	Capital Cost	O&M Cost	Land Use Cost	Water reuse Function	Livability	Water Retaining Function	Carbon Emission	Ecosystem Value
Flooding control	1.000	1.000	5.000	7.000	2.000	0.833	0.800	0.833	0.833	2.000
Water quality improvement	1.000	1.000	4.000	6.000	1.000	0.750	0.800	0.800	0.800	1.000
Capital cost	0.200	0.250	1.000	1.500	0.500	0.167	0.143	0.125	0.143	0.500
O&M cost	0.143	0.167	0.667	1.000	0.333	0.111	0.143	0.143	0.111	0.333
Land use cost	0.500	1.000	2.000	2.000	1.000	0.500	0.667	0.750	0.500	1.000
Water reuse function	1.200	1.333	6.000	9.000	2.000	1.000	1.250	1.250	1.000	2.000
Livability	1.250	1.250	7.000	7.000	1.500	0.800	1.000	1.000	1.000	2.000
Water retaining function	1.200	1.250	8.000	7.000	1.333	1.250	1.000	1.000	1.000	2.000
Carbon emission	1.200	1.250	7.000	9.000	2.000	1.000	1.000	1.000	1.000	2.000
Ecosystem value	0.500	1.000	2.000	3.000	1.000	0.500	0.500	0.500	0.500	1.000

Table A10. Normalized pair comparison matrix.

ATTRIBUTE	Flooding Control	Water quality Improvement	Capital Cost	O&M Cost	Land Use Cost	Water reuse Function	Livability	Water Retaining Function	Carbon Emission	Ecosystem Value
Flooding control	0.122	0.105	0.117	0.133	0.158	0.121	0.110	0.113	0.121	0.145
Water quality improvement	0.122	0.105	0.094	0.114	0.079	0.109	0.110	0.108	0.116	0.072
Capital cost	0.024	0.026	0.023	0.029	0.039	0.024	0.020	0.017	0.021	0.036
O&M cost	0.017	0.018	0.016	0.019	0.026	0.016	0.020	0.019	0.016	0.024
Land use cost	0.061	0.105	0.047	0.038	0.079	0.072	0.091	0.101	0.073	0.072
Water reuse function	0.146	0.140	0.141	0.171	0.158	0.145	0.171	0.169	0.145	0.145
Livability	0.153	0.132	0.164	0.133	0.118	0.116	0.137	0.135	0.145	0.145
Water retaining function	0.146	0.132	0.188	0.133	0.105	0.181	0.137	0.135	0.145	0.145
Carbon emission	0.146	0.132	0.164	0.171	0.158	0.145	0.137	0.135	0.145	0.145
Ecosystem value	0.061	0.105	0.047	0.057	0.079	0.072	0.068	0.068	0.073	0.072

Table A11. Obtaining the results by AHP.

ATTRIBUTE	Flooding Control	Water Quality Improvement	Capital Cost	O&M Cost	Land Use Cost	Water Reuse Function	Livability	Water Retaining Function	Carbon Emission	Ecosystem Value	Normalized Weighted Sum
Flooding control	0.122	0.105	0.117	0.133	0.158	0.121	0.110	0.113	0.121	0.145	12.44%
Water quality improvement	0.122	0.105	0.094	0.114	0.079	0.109	0.110	0.108	0.116	0.072	10.29%
Capital cost	0.024	0.026	0.023	0.029	0.039	0.024	0.020	0.017	0.021	0.036	2.60%
O&M cost	0.017	0.018	0.016	0.019	0.026	0.016	0.020	0.019	0.016	0.024	1.91%
Land use cost	0.061	0.105	0.047	0.038	0.079	0.072	0.091	0.101	0.073	0.072	7.40%
Water reuse function	0.146	0.140	0.141	0.171	0.158	0.145	0.171	0.169	0.145	0.145	15.31%
Livability	0.153	0.132	0.164	0.133	0.118	0.116	0.137	0.135	0.145	0.145	13.78%
Water retaining function	0.146	0.132	0.188	0.133	0.105	0.181	0.137	0.135	0.145	0.145	14.47%
Carbon emission	0.146	0.132	0.164	0.171	0.158	0.145	0.137	0.135	0.145	0.145	14.78%
Ecosystem value	0.061	0.105	0.047	0.057	0.079	0.072	0.068	0.068	0.073	0.072	7.03%

Consistency Index (CI) = 0.0171 (less than 0.1).

Appendix D MAUT Calculation Procedures

Table A12. The initial values of each scenario.

Sub-criteria	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Flooding control	-	0.0284	0.0309	0.0277	0.0273	0.0265
Water quality improvement	-	0.0120	0.0204	0.0192	0.0241	0.0271
Capital cost	AU$	675,000	631,250	453,750	238,750	420,000
O&M cost	AU$/year	3900	3575	3650	2775	3000
Land use cost	m^2	705	750	695	620	650
Water reuse function	m^3	1800	1550	1400	1050	400
Livability	-	10.914	14.62	17.476	16.286	21.59
Water retaining function	-	157.995	146.131	137.161	109.671	60.767
Carbon emission	kg CO_2-e	43,290	37,360	31,635	21,355	13,730
Ecosystem value	-	0.0120	0.0204	0.0192	0.0241	0.0271

Table A13. The normalized values of each scenario as well as its weight.

Sub-criteria	Weights	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Flooding control	12.44%	0.918	1.000	0.896	0.884	0.859
Water quality improvement	10.29%	0.444	0.753	0.709	0.888	1.000
Capital cost	2.60%	0.354	0.378	0.526	1.000	0.568
O&M cost	1.91%	0.712	0.776	0.760	1.000	0.925
Land use cost	7.40%	0.879	0.827	0.892	1.000	0.954
Water reuse function	15.31%	1.000	0.861	0.778	0.583	0.222
Livability	13.78%	0.506	0.677	0.809	0.754	1.000
Water retaining function	14.47%	1.000	0.925	0.868	0.694	0.385
Carbon emission	14.78%	0.317	0.368	0.434	0.643	1.000
Ecosystem value	7.03%	0.444	0.753	0.709	0.888	1.000

Table A14. Obtaining the criteria and overall results.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Functional aspect	0.160	0.202	0.184	0.201	0.210
Economic aspect	0.088	0.086	0.096	0.119	0.103
Social aspect	0.367	0.359	0.356	0.294	0.227
Environmental aspect	0.078	0.107	0.114	0.157	0.218
Overall score	0.693	0.754	0.749	0.771	0.758

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