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Optimal Sizing of Green Infrastructure Treatment Trains for Stormwater Management

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Abstract Green Infrastructure (GI) practices are widely used as source control measures in treating the stormwater. When treating stormwater, application of several GI practices in series as a treatment train has become popular over the implementation of a single treatment measure due to several advantages. However, the optimum sizing of the treatment trains has become an ongoing challenge for stormwater professionals due to various treatment measures and their different sizing combinations producing similar stormwater management benefits. Therefore, the present study proposes a novel methodology to optimize the sizing of GI treatment trains by formulating the problem as a single objective optimization. Minimization of Equivalent Annual Cost (EAC) was used as the objective function, while the target pollution reduction levels and available land area were used as constraints. Although the results of the single objective optimization should produce a single optimum result, this study has produced a set of treatment train sizing combinations which are close to the minimum cost, but with vastly different sizes of individual treatment measures in the treatment train. These sizing combinations had produced varied values for performance measures related to environmental, economic and social objectives, which made the selection of an optimum treatment train sizing combination difficult, for a particular study area. The methodology was demonstrated by using a sample treatment train, for a case study area in Melbourne, in Australia.

Keywords Green infrastructure · Optimization · Stormwater · Performance measures · Treatment train sizing

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1 Introduction

In recent years, the urbanization has become one of the major threats to the natural environment. Infrastructure development as a consequence of urbanization creates enormous pressures on natural green space available in land areas. The reduction of pervious areas associated with urbanization increases the potential of generating stormwater runoff with high velocities and degraded quality, which can cause harmful impacts on the human wellbeing and the health of aquatic ecosystems (Booth et al. 2002; Gaffield et al. 2003; Nikolic and Simonovic 2015). Green Infrastructure (GI) practices are currently gaining wide attention among localities due to their ability in reducing stormwater peak flows, reducing the volume of stormwater discharge and improving the quality of runoff whilst restoring the urban green space. Some of the widely used GI treatment measures are wetlands, retention ponds, bioretention basins, permeable pavements, infiltration trenches, swales and sedimentation ponds (Tsihrintzis and Hamid 1997; Ahiablame et al. 2012; Jayasooriya and Ng 2014).

Implementing of GI in series as a “treatment train” has gained wide acceptance in stormwater management, over the last few years (Benedict and McMahon 2012). The treatment train method has several advantages over implementing a single treatment measure at the catchment outlet, which include the enhanced pollutant removal with the number of different processes provided by several GI treatment measures and the reduced risk of the system failure when one treatment measure fails. Moreover, the treatment trains can augment, the ability of recreating the natural flow regime, the reduction of acute toxicity levels of stormwater for downstream aquatic ecosystems, the improvement of biodiversity by providing stable habitat, the improvement of liveability, and the improvement of treatment levels achieved by treating the pollutants close to their source (Hatt et al. 2006; Bastien et al. 2009).

When a decision has been made to implement GI treatment measures for a particular site, a procedure should be followed for the selection and their sizing. The selection of potential GI for the area is generally obtained by professional judgement. Water resource professionals assess the physical characteristics (e.g. site geology, slope, land use etc.) and available space for GI, to identify the treatment measures suitable for the area. GI can be then constructed as individual measures or treatment trains to achieve the target reduction levels of pollutants in terms of water quality. Some of the most commonly used water quality constituents for the target reduction level assessment in stormwater are, Total Suspended Solids (TSS), Total Phosphorous (TP) and Total Nitrogen (TN) (Melbourne Water, 2005). After the GI selection, the sizing is generally obtained with the aid of simulation models. Once the suitable simulation model is selected for a particular study, a trial and error process is used to obtain the sizing of GI that achieves the target reduction levels of pollutants. Even though the trial and error approach is successfully used for the sizing of individual treatment measures (Lloyd et al. 2002), obtaining the optimum size is a tedious process due to large number of simulation runs that are required to be performed. Furthermore, it has been an ongoing challenge for water resource professionals to perform the size optimization of a treatment train compared to an individual treatment measure, through the trial and error approach. The availability of many combinations of GI and their sizes in a treatment train can result in a considerably large number of simulation runs, which are required to be performed in order to obtain the optimum size combination of a treatment train.

To optimize the sizes of individual GI, several researchers have used single objective optimization models. Kaini et al. (2012) used a genetic algorithm to identify optimum sizes for several individual GI measures with the objective function of minimizing the construction cost. Land use, water balance and pollutant reduction criteria were used as constraints. Similar studies were conducted for the size optimization of wetlands using a genetic algorithm (Montaseri et al. 2015) and for the detention ponds using ant colony optimization (Skardi et al. 2013). In both of these studies, the total life cycle cost of treatment measures was used as the objective function. The constraint used in the former study was the target removal rates of stormwater pollutants. Total Suspended Solids (TSS) load, surface area and the pond storage were used as constraints in the latter study. Gaddis et al. (2014) used spatial optimization techniques for sizing of several individual GI, by considering associated cost as the objective function and the Phosphorous load reduction as the constraint. However, all these studies used single objective optimization to obtain the optimal sizing of individual GI treatment measures and have obtained a single solution which minimized the cost as the objective function within the constraints. None of these studies have comprehensively considered the application of single objective optimization for the sizing of GI treatment trains which combines two or more individual treatment measures. Unlike for the individual GI, it is difficult to obtain a single optimum sizing combination for a treatment train through single objective optimization due to several treatment measures in the treatment train can have vastly different sizing combinations that achieve the target pollution reduction levels. Furthermore, in minimizing the cost as a single objective, these vastly different sizing combinations may have costs which are close to the minimum. These different sizing combinations may also have different environmental, economic and social objectives that can be further assessed through relevant performance measures to select the most suitable treatment trains for a particular area (Martin et al. 2007; Young et al. 2009; Jia et al. 2013).

The major initiative for the implementation GI practices in any real world case study is the funds allocated for the specific project. Therefore, the costs associated with GI determine the design considerations of treatment measures which incorporate economic feasibility as the primary objective in the optimization process for their sizing. Hence, it can be identified that, for the sizing of individual treatment measure or a treatment train, the associated cost is the most suitable objective function which can be used in the optimization. However, some of the above comments also state the difficulty of using the costs as an objective function for the treatment train sizing as vastly different sizing combinations can present within the constraints that are close to the "minimum cost" which is the solution to the single objective optimization. Currently, there are no systematic methodologies available for the sizing of GI when they are implemented as treatment trains. Therefore, the present study proposes a novel methodology for the size optimization of GI in a treatment train. The proposed methodology in this study presents an application of single objective optimization for a treatment train size optimization problem in an innovative way by obtaining several near optimal sizing combinations as the output of single objective optimization instead of a single solution. To obtain the single optimum solution among the near optimal solutions, the present study has proposed a performance measure analysis which considers several environmental, economic and social objectives. The methodology developed in this study was demonstrated by using a sample treatment train, for a case study area in Melbourne, Australia.

2 Study Area

The *Brooklyn Industrial Precinct* is located in Brimbank City Council, Victoria, Australia. The precinct covers 262 ha of total area which predominantly consists of heavy and light industries.

The area is also characterized by poor shallow soils. The average annual rainfall of the area is around 400–500 mm. A 90 ha area within the industrial precinct was selected as the study area for the application of the methodology, which is shown in Fig. 1.

A long term development plan has been already developed for the study area by the Brimbank City Council. In this plan, major attention has been given for the implementation of GI practices to improve stormwater quality of the creek. Areas have already been proposed for implementation of GI, close to the boundary of the creek. Land areas of 2000, 10,000 and 8000 m^2 from upstream to downstream, close to the creek, have been identified in the development plan as potential locations for GI implementation. Some of the other objectives for long term planning of GI within this area are to reduce stormwater peak flows to the creek, improve the river habitats and improve the livability of the area in an economically feasible way (The Brooklyn Evolution 2012).

3 Methodology

The generic methodology developed for the optimum sizing of GI treatment trains consists of two broad steps as, 1) Optimization of the sizing of treatment trains and 2) Assessment of treatment trains with performance measures.

3.1 Optimization of the Sizing of Treatment Trains

In the proposed methodology, the size optimization of a treatment train is achieved in two steps as explained in Sections 3.1.1 and 3.1.2.

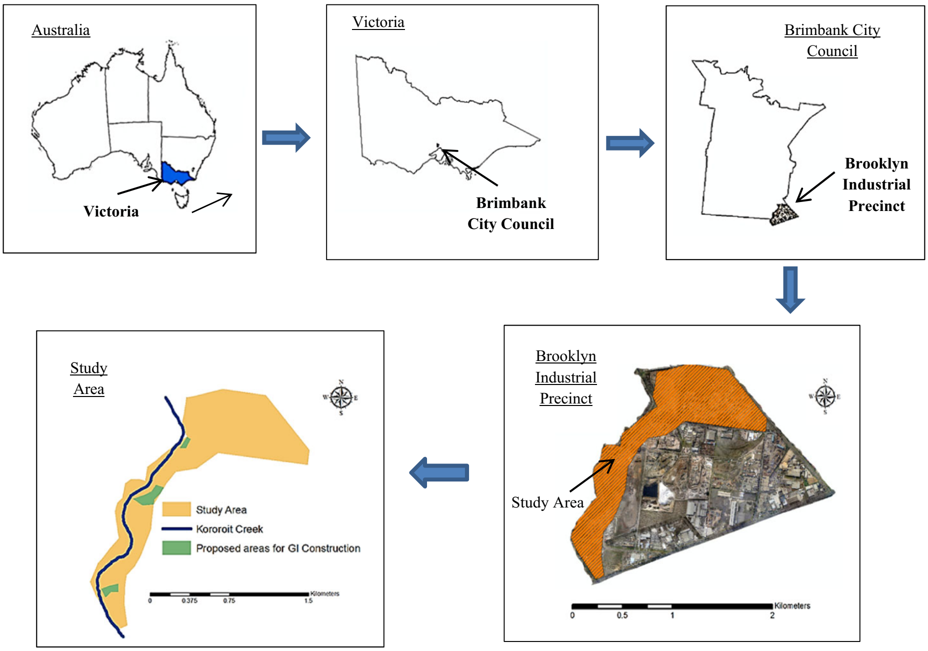

Fig. 1 Study area

3.1.1 Formulation of Single Objective Optimization Problem

As discussed in Section 1, the associated costs of GI play a major role in their planning and designing process. The optimal sizing of GI can be achieved when they are designed to provide maximum benefits with the minimum costs. The life cycle costs of GI represent total costs associated with the treatment measures throughout their life cycle. Hence, the life cycle cost can be identified as a cost element that can represent the total economic considerations of GI implementation. The costs occurred throughout the life cycle must be minimized in order for a treatment train to be economically feasible.

GI practices have several cost elements which occur throughout their life cycle, as listed below.

1. Capital cost - The cost for feasibility studies, conceptual design, preliminary design and construction. The capital cost also includes overheads such as contract and project management costs.
2. Annual maintenance cost - The cost that accounts for the routine maintenance including all costs associated with inspections, training, administration and waste disposal.
3. Annual renewal and adaptation cost (This cost element is referred as "annual operation cost" in this paper) - Cost for activities such as additional landscaping, improving the access track for maintenance, replacing filtration media on a bioretention system, re-contouring and replanting a wetland's macrophyte zone etc.
4. Decommissioning cost - The cost of removing the asset, at the end of the asset's useful life.

Generally, GI practices are known to have infinite life cycles when they are well maintained (Barrett 2001; Fletcher and Taylor 2007). Therefore, in the present study, decommissioning cost was excluded from the life cycle costing analysis. Thus, capital cost, annual maintenance and annual operation costs were used in computing the life cycle cost of treatment trains. The Equivalent Annual Cost (EAC), which represents the annualized form of the life cycle cost, was considered as the objective function in the optimization problem. EAC is defined as the costs incurred per year for the ownership and the operation of an asset during its complete lifespan. EAC is computed by dividing the life cycle cost of the treatment measures by the number of years considered in the life cycle.

The problem of sizing the GI in a treatment was formulated as minimizing the EAC, subject to the constraints of achieving the target reduction levels of pollutants and the available land area. Mathematically, the problem was formulated for a single treatment train as,

$$\text{Minimise} \quad f(x_i) \quad i = 1.2, \ldots..n$$

$$\begin{aligned} \text{Subject to} \quad & g_{TSS}(x_i) > TR_{TSS} \\ & g_{TP}(x_i) > TR_{TP} \\ & g_{TN}(x_i) > TR_{TN} \\ & h(x_i) < LAA \end{aligned}$$

Where

N number of sizing combinations
i sizing combination
f(x) Equivalent Annual Cost (EAC) of the treatment train

g(x) treatment train efficiency corresponding to pollutants TSS, TP and TN
TR target reduction level corresponding to pollutants TSS, TP and TN
h(x) land area required for GI
LAA land area available.

Model for Urban Stormwater Improvement Conceptualization (MUSIC) was used in this study to compute EAC and removal efficiencies of TSS, TP and TN which define the objective function and the constraints of optimization problem. MUSIC is a conceptual planning and designing tool which was developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH) (Wong et al. 2002). MUSIC is the current modeling standard in Australia which is used for conceptual design of GI for stormwater treatment. MUSIC has been calibrated using rainfall runoff properties of different regions of Australia by considering several case studies. Thus, the default runoff parameters of the model were used for the simulation of treatment trains in this study. MUSIC also contains a life cycle costing module which is inbuilt with costing data for different GI practices that are implemented within Australia. The concepts of simulating the treatment efficiencies of GI in MUSIC are presented in Wong et al. (2006). The algorithms used for the life cycle costing calculation of different GI practices are explained by Taylor and Wong (2002) and Taylor (2005).

3.1.2 Obtaining Near Optimum Solutions

The potential sizing combinations of GI within the treatment trains were defined based on a simple grid. The sizing procedure followed for two GI sample treatment trains which is demonstrated in this section (i.e. two treatment measures with primary and secondary treatment measures, and three treatment measures with primary secondary and tertiary treatment measures) is shown in Fig. 2. Figure 2a shows the procedure for sizing a treatment train with two treatment measures, while Fig. 2a and b together show how the sizing was done for a treatment train with three treatment measures.

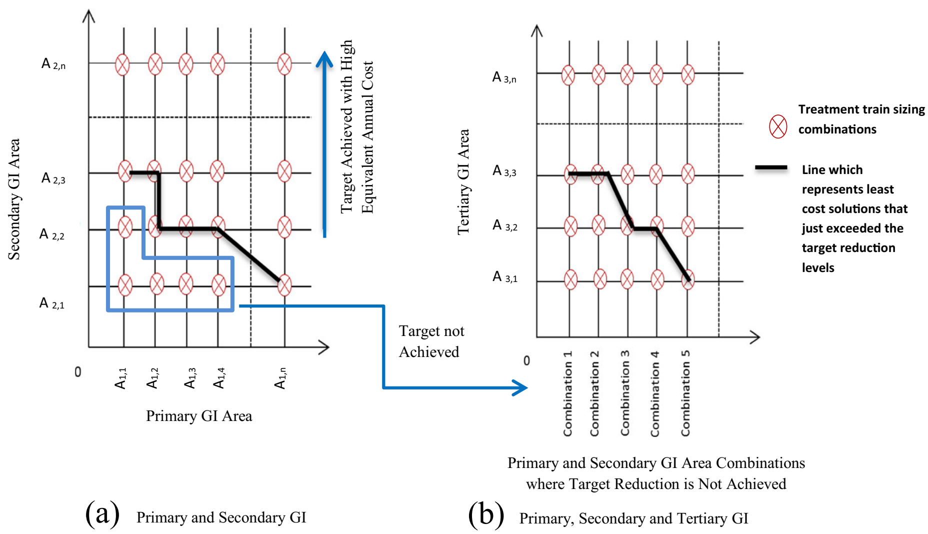

Fig. 2 Size combinations of GI in treatment trains

First, the grid was formed by considering the areas of primary and secondary GI, subject to the available land area, as shown in Fig. 2a. The suitable area intervals of the grid were obtained by performing several initial simulations for each of the treatment measure individually and obtaining pollutant removal efficiencies. The suitable grid interval then was determined as the interval which provides 1–2 % increase in removal efficiencies. Then using MUSIC, target pollutant removal efficiencies and EAC for each of the sizing combinations at the grid points were obtained.

From the simulations, a frontier between the sizing combinations that achieve the pollutant target reduction and that do not achieve the target reduction was identified. The set of sizing combinations on the frontier are represented by the black line in Fig. 2a. The sizing combinations above the line achieved the target reduction levels with high EAC, while the combinations below the line were incapable of achieving the target reduction levels. The sizing combinations along the black line have just exceeded the target pollutant reduction efficiency. Therefore, the sizing combinations along the line were considered as the feasible solutions for the single objective optimization problem that are the close to the optimum. In the next step as shown in Fig. 2b, the sizing combinations that do not achieve the pollutant target reduction levels (solutions below the black line in Fig. 2a) were further considered by adding a tertiary treatment measure. Figure 2b then represents the sizing procedure that is followed for a treatment train with three treatment measures. First, a grid was formed by considering the sizing combinations that do not achieve the target pollution reduction levels in Fig. 2a and the area of the tertiary treatment measure; the area interval for the tertiary treatment measure in the grid was selected as in Fig. 2a by performing several initial simulations of the treatment measure individually. Then the treatment measures defined by the grid points in Fig. 2b were simulated using MUSIC. The solutions along the frontier (black line in Fig. 2b) were then identified as the solutions which are close to the optimum that achieve the pollutant target reduction with least EAC, for the treatment train with primary, secondary and tertiary measures.

3.2 Assessment of Treatment Trains with Performance Measures

The optimization has produced a set of least cost sizing combinations of treatment trains, which achieve the target reduction of pollutants that can be constructed in the available land area. Among the least cost solutions, there may be a solution that is most suitable for the study area when the other important objectives associated with GI implementation are considered. Hence, to select the most suitable solution for the study area, the sizing combinations of treatment trains were assessed with additional performance measures considering three broad objectives commonly known as Triple Bottom Line (TBL) criteria (i.e. environmental, economic and social), which are widely used in water resource planning. Several performance measures for the criteria were identified, which are related to the study area by referring to literature and having discussions with various stakeholders of the study area. A detailed description about these performance measures and the methods of evaluation are discussed in Section 4.2. The evaluations of these various performance measures were used to further identify the most suitable sizing combination of the treatment train among the least cost solutions obtained from the optimization in Section 3.1.2.

4 Application of the Methodology

The generic methodology explained in Section 3 is demonstrated below by applying it to a sample treatment train consists of two treatment measures (sedimentation basin and bioretention) for the study area.

4.1 Sample Treatment Train: Sedimentation Basin and Bioretention

For the EAC estimation, the number of years in the life cycle was set as 50 years as per the expert judgment recommendation in MUSIC software (eWater 2013). As other input data for MUSIC simulation, the rainfall data and the data on soil properties of the study area were obtained from Melbourne Water (MW) and Australian Soil Resources System (ASRIS) respectively. The target reduction levels defined for the study area were 80 % reduction in Total suspended Solids (TSS) and 45 % reduction in Total Phosphorous (TP) and Total Nitrogen (TN) (City of Melbourne WSUD Guidelines 2005).

Available land area for each of the treatment measures were obtained by referring to the long term development plans of the study area (The Brooklyn Evolution 2012). According to the proposed areas for GI implementation, lot areas of 2000, 10,000 and 8000 m^2 were available for the construction of treatment measures. The plans suggest on having single treatment measure at each lot. These land areas were used as area constraints in the study to develop treatment trains. For the sample treatment train demonstrated in this paper, first two lots of 2000 and 10,000 m^2 were considered for the construction of sedimentation basin and bioretention as the area constraints.

Initial simulations with MUSIC showed that, increasing the sedimentation basin area by 200 m^2 has increased the removal efficiency by 1–2 % for TSS, TP and TN. Similar results were obtained by increasing the area by 500 m^2 for bioretention. Therefore, these area intervals were used as the grid intervals to define the potential sizing combinations of GI.

Figure 3 shows the size combinations of sample treatment train, analyzed with the single objective optimization. This figure also shows the EAC for all size combinations simulated for the sample treatment train.

Different colored symbols represent how the target reduction levels have been achieved for each sizing combination. They are;

1) Green symbols along the blue line – These are the low EAC size combinations where the required target pollution reduction levels were just achieved for all three pollutants.
2) Green symbols above the blue line – The size combinations that achieved more than the required target pollutant reduction levels of all three pollutants, but with high EAC, compared to those of (1).
3) Red and black symbols below the blue line – The size combinations where target pollutant reduction levels were not achieved for at least one pollutant (i.e. red – target pollutant reduction levels were not achieved for all three pollutants, black – target pollutant reduction level was not achieved for TSS); the EAC is lower compared to those of both (1) and (2).

Thus, it is evident that the solutions above the blue line were inferior due to high EAC although the target reduction levels of the pollutants have been achieved, in most cases far beyond the required levels. The solutions below the blue line are infeasible since they were

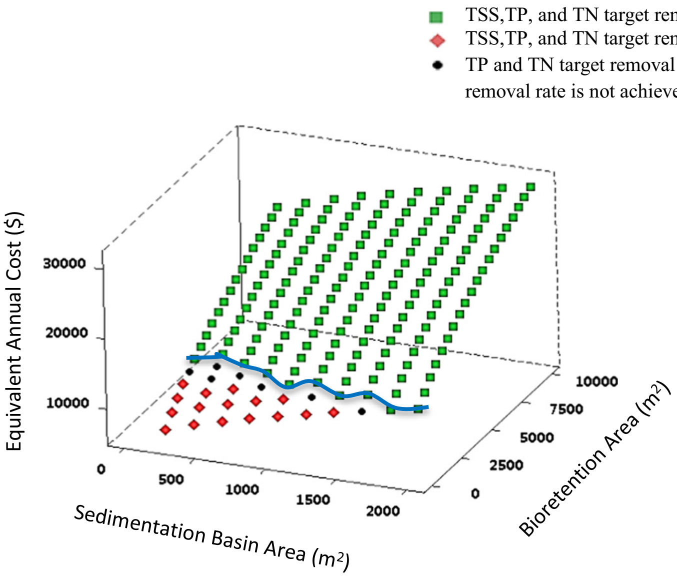

Fig. 3 Simulation results for treatment train with sedimentation basin and bioretention

unable to achieve the target pollution reduction levels, even though they had a low EAC. Hence, the sizing combinations along the blue line were considered as feasible least cost treatment train sizing combinations that achieve the target reduction levels for the sample treatment train. The individual sizes of the treatment measures (i.e. sedimentation basin and bioretention), treatment train removal efficiencies and EAC for these treatment train sizing combinations are shown in Table 1. The capital cost, sum of operation and maintenance cost, and the EAC related to each of these size combinations are shown in Fig. 4.

As observed from Table 1, for this sample treatment train, the TSS removal governs the sizing process. TP and TN removal efficiencies were well above the target reduction levels (45 %), when the required TSS removal rate (80 %) is achieved. Also Table 1 shows that,

Table 1 Least cost sizing combinations obtained from the single objective optimization, their sizes of individual treatment measures and removal efficiencies for sample treatment train

Sizing combination	Sedimentation basin area (m^2)	Bioretention area (m^2)	TSS removal efficiency (%)	TP removal efficiency (%)	TN removal efficiency (%)	Equivalent annual cost ($)
1	2000	500	80.6	69	52.6	14569
2	1800	500	80.2	66.3	50.1	13822
3	1600	1000	81.9	67.0	52.9	14680
4	1400	1000	81.2	63.9	50.3	13881
5	1200	1500	82.9	64.2	52.5	14365
6	1000	1500	80.6	61.6	49.5	13493
7	800	2000	81.7	60.6	51.7	13723
8	600	2500	82.7	60.0	53.5	13778
9	400	3000	82.7	58.8	53.8	13652
10	200	3000	80	55.4	50.7	12354

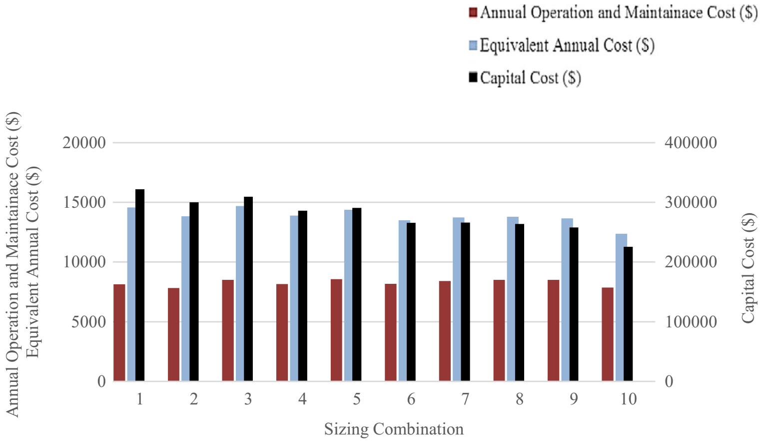

Fig. 4 Cost elements associated with sample treatment train (Sedimentation Basin and Bioretention)

when the bioretention area decreases sedimentation area is increased as expected to achieve the required the pollutant target reduction levels, but EAC also increases. As it can be seen from Fig. 4, the annual operation and maintenance costs remained almost the same for all sizing combinations while the capital costs have shown some differences in their values compared to annual operation and maintenance costs. It should be noted that the maximum difference of EAC of the sizing combinations from the minimum EAC is of the order of 18 %, while the sizing combinations themselves are vastly different. These vastly different sizing combinations may produce vastly different values for the performance measures.

4.2 Assessment of Treatment Trains Using Performance Measures

As stated in Section 3.2, several performance measures based on TBL objectives of environmental, economic and social were identified in relation to treatment train sizing combinations for the study area. These performance measures were confirmed through discussions with stakeholders of the project such as project managers, stormwater engineers and urban planners. These performance measures were used to evaluate the alternative treatment train sizing combinations with the aim of identifying the best sizing combination for the study area. Using the different assessment methods, these performance measures were computed and standardized into a 0–100 scale.

The pollutant load removal of TSS, TP and TN are generally expressed in terms of annualized removal costs which can serve as performance measures in achieving the environmental objectives expected by implementing GI. Therefore, the annual costs for the removal of TSS, TP and TN (i.e. sediments and nutrients) were selected under the category of environmental objective. As noted in Section 2, the Kororoit creek in the study area has been contaminated due to industrial land use activities. Thus, apart from the sediments and nutrients, heavy metals were considered as one of the important water quality parameters that affect the river water quality of the study area (Kororoit Creek Regional 2006). The water quality data of Kororoit Creek close to Brooklyn Precinct analyzed by Melbourne Water (2013) had identified that heavy metals 'Copper (Cu)' and 'Zinc (Zn)' levels have exceeded the guidelines for fresh and marine water quality (ANZECC 2000). Thus, the removal percentages of Cu and Zn were also considered as environmental performance measures. Percentage reduction of the peak flow and the creation of habitats (providing the opportunities to expand the natural habitats of the area through vegetation) are the other two performance measures included in the environmental category.

Potable water savings, capital costs, annual operation and maintenance cost and EAC were identified as economic performance measures. Improvement of the liveability (improving the amenity and providing recreational opportunities) of the area was considered as the social performance measure.

To estimate the values of the selected performance measures, different tools and methods were used. The annual costs of the removal of TSS, TP and TN were obtained using the life cycle costing module of MUSIC. Removal percentages of the selected heavy metals, peak flow reduction, potable water savings and all cost elements were also obtained as the outputs from MUSIC. Green Area Ratio (GAR) (Keeley 2011) which is an urban sustainability metric that measures the enhancement of urban environmental quality through GI, was used to compute the performance measures for habitat creation and improvement of the liveability of the area.

As the next step, the performance measures were standardized in to a 1–100 scale, in order to convert them into a single unit for comparison of alternative treatment train sizing combinations. Following equations were used to standardize the performance measures based on the condition of maximizing or minimizing the performance measure.

For the performance measures that need to be minimized (i.e. annual costs for TSS removal, annual costs for TP removal, annual costs for TN removal, equivalent annual cost, capital cost, operation and maintenance cost),

$$Y = \frac{-(X - X_{max})}{(X_{max} - X_{min})} \times 100 \tag{1}$$

For the performance measures that need to be maximized (i.e. Cu removal, Zn removal, peak flow reduction, habitat creation, potable water savings, and improvement of liveability),

$$Y = \frac{(X - X_{min})}{(X_{max} - X_{min})} \times 100 \tag{2}$$

Where

Y	the standardized value
X	the performance measure value
X_{min}	the minimum value of the performance measure
X_{max}	the maximum value of the performance measure.

Figure 5 shows the standardized values of the selected performance measures for different sizing combinations of the sample treatment train. The best and worst performance measure values are represented as 100 and 0 in the vertical scale respectively.

As can be seen from Fig. 5, the sizing combinations 9 and 10 provide highest standardized values (100) in terms of most performance measures. These two sizing combinations have provided 10 best performance measure values out of 12 performance measures. However, few performance measure values of these two sizing combinations had provided values close to worst performance measure values; even 1 performance measure for size combination 10 has produced the worst value. On the other hand, size combinations 1 and 2 had provided the worst performance measure values for majority of 12 performance measures, most other performance measure values somewhere in the middle range between worst and best values, and the

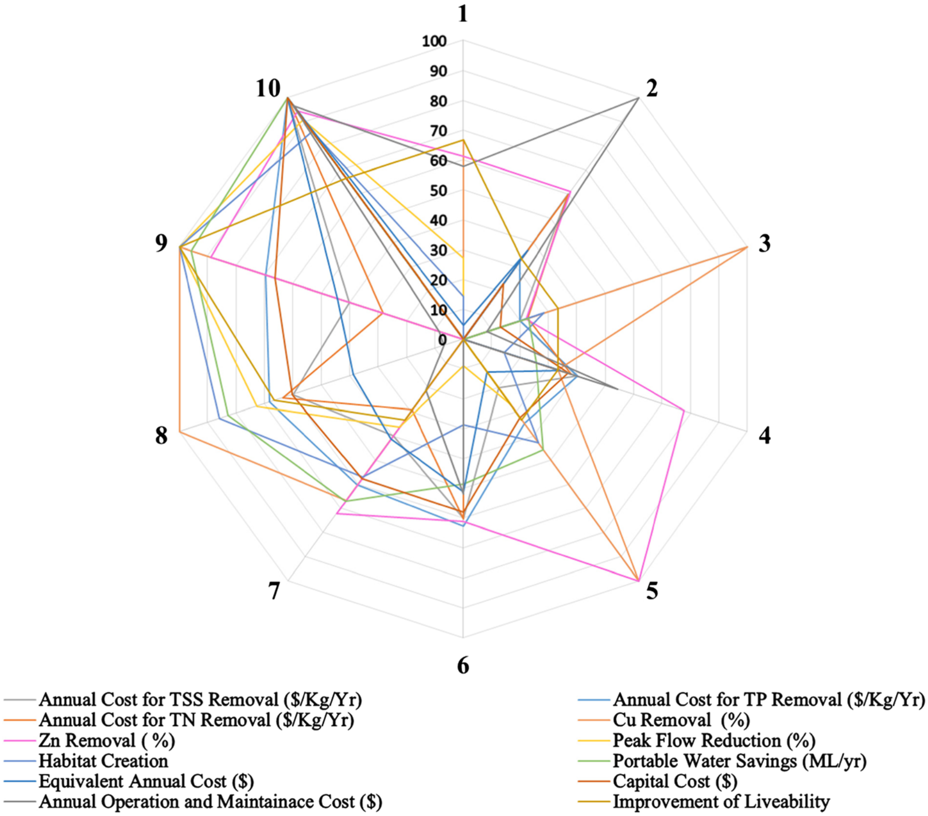

Fig. 5 Performance measures (1–100 Scale) for sizing combinations obtained for sample treatment train (Sedimentation Basin and Bioretention)

best performance measure value for size combination 2 with one performance measure. The size combinations 3–8 had provided performance measure values in the middle range between the worst and best values.

The above comments demonstrate the difficulty in selecting one combination out of the potential sizing combinations of treatment trains considering the performance measures related to TBL criteria. As can be seen from Fig. 5, there is no single sizing combination that could be the best in terms of all performance measures. In addition to this difficulty, different stakeholders have different preferences (in most cases contradictory) on the performance measures. For example, environmentalists would have a preference on the environmental performance measures, while the resource managers might focus in economic measures. The stakeholders with social interests will prefer social performance measures. Opposing differences in performance measure values of treatment train sizing combinations and the different preferences of stakeholders on performance measures need to be considered in selecting the most appropriate treatment train sizing combination for the study area. This can be achieved by Multi Criteria Decision Analysis (MCDA) approach, which considers both the differences in performance measures and stakeholder preferences of performance measures. The application of MCDA in selecting the most appropriate treatment train sizing combination considering both the differences of performance measure values and stakeholder preferences in performance measures will be discussed in a future paper.

5 Summary and Conclusions

Implementation of several GI treatment measures in series as a treatment train has replaced the traditional approach which used a single treatment measure at the catchment outlet. Previous studies have used the cost minimization of GI practices as the objective function in single objective optimization, to optimize the sizing of the individual treatment measures. Even though the single objective optimization methodologies have been successfully used for sizing of individual treatment measures, obtaining a single solution using single objective optimization in conventional form is not possible for a treatment train due to several treatment measures in the treatment train can have vastly different sizing combinations that achieve the target pollution reduction levels within the land area constraints. Furthermore, in minimizing the cost as a single objective, these vastly different sizing combinations may have costs which are close to the minimum, but could have different performances in terms of TBL objectives of environmental, economic and social.

The current approach used in treatment train sizing is trial and error, with the aid of simulation models, considering only a few likely treatment train size combinations and selecting the best size combination out of the considered sizing combinations. Due to the large number of simulation trials required, the all possible treatment train sizing combinations cannot be realistically handled in this approach. Moreover, this approach is subjective. Even though the single objective optimization methodologies can be successfully applied in sizing of the individual GI treatment measures, it might not be feasible to obtain a single optimum solution for the sizing combinations available in a treatment train through single objective optimization. Therefore, the present study has proposed a methodology in obtaining number of sizing combinations for treatment trains which are close to the optimum in terms of EAC, by formulating the problem as a single objective optimization. The results of the optimization showed that there are several solutions available which have vastly different sizing combinations of individual treatment measures, but with costs close to the minimum and just exceeding the removal efficiencies. Even though the optimization has produced a set of least cost sizing combinations, it is difficult to identify the most suitable treatment train sizing combination from this set, since they have produced quite varied TBL performance measure values. No single sizing combination has produced the best performance measure values for all performance measures considered.

In addition, different stakeholders may have different preferences for the performance measures which need to be considered in decision making. Although it can be concluded that the methodology described in this paper was successfully used to identify a set of treatment train sizing combinations close to minimum cost, they consisted of vastly different sizing combinations of individual treatment measures with different TBL performance measure values, which made the selection of single optimum solution further complex. The methodology proposed in this study also showed the difficulty in treatment train size optimization only based on the single objective optimization. Even though the primary objective of optimal sizing of treatment trains is governed by the associated costs, selecting the most suitable treatment train sizing combination should consider all other relevant performance measures and stakeholder preferences on these performance measures. This can be achieved through methodologies such as MCDA that consider both the differences in performance measures and the stakeholder preferences, which will be discussed in a future paper.

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