OPTIMIZATION OF GREEN INFRASTRUCTURE PRACTICES FOR INDUSTRIAL AREAS

By

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Abstract

Industrial areas are environmentally degraded land areas with multiple environmental issues. Majority of industrial areas are surrounded by residential and commercial areas due to the ease of access for material and human resources. Annual discharge of larger volumes of contaminated stormwater to receiving water bodies and the air pollution are two major environmental problems for such areas. Green Infrastructure (GI) practices are known as a land conservation strategy which introduces green space in urban areas. These practices also contain various components that can improve the quality of stormwater discharges and air quality in urban areas.

For optimization of GI for a particular area, several studies have been conducted in the past by addressing the problem as a single objective optimization problem by minimizing the associated costs. For a complex land use like an industrial area, the reality in optimizing GI can incorporate several other aspects related to environmental, economic and social objectives which are expected of GI through their implementation.

The optimization process of GI practices for a specific area includes the selection of most suitable practices that provides the required benefits for the area alongside with their optimal sizing. In the current practice, optimal selection and sizing of GI practices is generally conducted based on the expert judgement, and there are no systematic methodologies currently available for this process. Especially for a complex land use like an industrial area where there exist high environmental demands, methodologies should be developed for the optimum selection and sizing of GI practices.

This research was aimed at developing a novel methodology to optimize GI practices to mitigate stormwater and air pollution in industrial areas by combining several techniques such as mathematical optimization, simulation modelling, performance measure analysis, Delphi survey and Multi Criteria Decision Analysis. The proposed methodology considered various important aspects during the optimization process such as addressing the required environmental demands in industrial areas, land area constraints, stakeholder

opinions and multiple environmental, economic and social benefits of GI practices.

The generic methodology proposed in this study has been successful in identifying the optimum GI practices and their optimum sizes to treat stormwater and improve air quality for a case study industrial area in Melbourne, Australia. The results of this innovative methodology applied to the case study area demonstrated its applicability and efficiency in optimizing GI practices for industrial areas. This research has contributed to the current knowledge base on GI by introducing an innovative approach to enhance the optimization and decision making of GI planning process.

Declaration

I, Varuni Maheshika Jayasooriya, declare that the PhD thesis entitled 'Optimization of Green Infrastructure Practices for Industrial Areas' is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

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Varuni Jayasooriya

2016

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This thesis is not only an outcome of years of hard work but also a milestone in my life which wouldn't be possible without the guidance, support and affection of several amazing individuals whom I'm forever grateful. I would like to express my sincere gratitude to all the people who supported me throughout this mentally and emotionally challenging journey of PhD.

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List of Publications

Journal papers

- Jayasooriya, V.M., Ng, A.W.M, Muthukumaran S, Perera B.J.C. (2017). Decision Making in Selecting Stormwater Management Green Infrastructure for Industrial Areas Part 1: Stakeholder Preference Elicitation Using a Delphi Survey. *(Under preparation)*
- Jayasooriya, V.M., Ng, A.W.M, Muthukumaran S, Perera B.J.C. (2017). Decision Making in Selecting Stormwater Management Green Infrastructure for Industrial areas Part 2: An Australian Case Study Using TOPSIS. *(Under preparation)*
- Jayasooriya, V. M., Ng, A. W. M., Muthukumaran, S., & Perera, B. J. C. (2017). Green infrastructure practices for improvement of urban air quality. *Urban Forestry & Urban Greening*, 21, 34-47
- Jayasooriya, V. M., Ng, A. W. M., Muthukumaran, S., & Perera, B. J. C. (2016). Optimal Sizing of Green Infrastructure Treatment Trains for Stormwater Management. *Water Resources Management*, 30(14), 5407-5420.
- Jayasooriya, V. M., & Ng, A. W. M. (2014). Tools for modelling of stormwater management and Economics of Green Infrastructure practices: A review. *Water, Air, & Soil Pollution*, 225(8), 1-20.

Conference papers

- Jayasooriya, V.M., Ng, A.W.M, Muthukumaran S, Perera B.J.C (2015), Sizing of Green Infrastructure Treatment Trains for Stormwater Management, *36th Hydrology and Water Resources Symposium*, Hobart, Tasmania, 7-10 December, 2015
- Jayasooriya, V.M., Ng, A.W.M. (2013) Development of a Framework for the Valuation of Eco System Services of Green Infrastructure Practices, *20th International Congress on Modelling and Simulation*, Adelaide, Australia, 1–6 December 2013, pp3155-3161

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Abbreviation

AHP	-	Analytic Hierarchy process
ANP	-	Analytic Network Process
BMP	-	Best Management Practices
BR	-	Bioretention
CNT	-	Centre for Neighbourhood Technology
CO	-	Carbon Monoxide
Cu	-	Copper
DNR	-	Department of Natural Resources
EEA	-	European Environmental Agency
EIA	-	Environmental Impact Assessment
EIP	-	Eco Industrial Park
GAIA	-	Geometrical Analysis for Interactive Aid
GDSS	-	Group Decision Support System
GHG	-	Green House Gas
GI	-	Green Infrastructure
GIS	-	Geological Information Systems
GVC	-	Green Values Calculator
LID	-	Low Impact Development
LIDRA	-	Low Impact Development Rapid Assessment Tool
L-THIA	-	Long Term Hydrologic Impact Assessment
MAUT	-	Multi Attribute Utility Theory
MAVT	-	Multi Attribute Value Theory
MCDA	-	Multi Criteria Decision Analysis
MUSIC	-	Model for Urban Stormwater Improvement Conceptualization
NO_2	-	Nitrogen Dioxide
O3	-	Ozone
Pb	-	Lead
PD	-	Retention Pond
PM	-	Particulate Matter
PROMETHEE	-	Preference Ranking Organization METHod for Enrichment of Evaluations
ELECTRE	-	ELimination and Choice Expressing Reality
SCS	-	Soil Conservation Service
SDB	-	Sedimentation Basin
SME	-	Small to Medium Industries
SO_2	-	Sulfer Dioxide
STRATUM	-	Street Tree Resource/ Analysis Tool for Urban Forest Managers
SUDS	-	Sustainable Urban Drainage Systems
SUSTAIN	-	System for Urban Stormwater Analysis and Integration
SW	-	Vegetated Swale
SWMM	-	Stormwater Management Model
SWOT	-	Strengths, Weaknesses, Opportunities and Threats

TBL	-	Triple Bottom Line Criteria
TN	-	Total Nitrogen
TOPSIS	-	The Technique for Order of Preference by Similarity to Ideal Solution
TP	-	Total Phosphorous
TR-55	-	Technical Release
TSS	-	Total Suspended Solids
UFORE	-	Urban Forest Effects Model
UNEP	-	United Nations Environmental programme
UNEP	-	United States Environmental Program
USEPA	-	United States Environmental Protection Agency
VU	-	Victoria University
WERF	-	Water Environment Research Foundation
WinSLAMM	-	Windows Source Loading and Management Model
WL	-	Wetland
WQI	-	Water Quality Index
WSUD	-	Water Sensitive Urban Design
Zn	-	Zinc

CHAPTER 1

Introduction

1.1 Background

Rapid advancement of industrialization has become one of the major threats to the natural environment over the years. Infrastructure development as a consequence of industrialization creates enormous pressures on natural green space, in urban areas. The reduction of pervious surfaces associated with green space creates several adverse impacts on land surface characteristics, water cycle and the atmosphere. Most of the industrial areas are located within urban areas, surrounded by commercial and residential areas, due to easy access for human resources, transportation and materials supply (The Brooklyn Evolution, 2012). Therefore, these areas increase the tendency of human exposure to various environmental impacts occurred by industrial activities.

Among the number of environmental problems present in industrial areas, water resource contamination and air pollution are identified as key concerns which can create severe long term impacts for human and ecosystem health (Alshuwaikhat, 2005, Ghasemian et al., 2012). Industrial areas are identified as hot spots which generate highly polluted stormwater runoff, mainly consist of sediments, nutrients and heavy metals due to the presence of large impervious areas (Woodard, 2001). Furthermore, industrial activities increase the air pollution by emitting various gaseous pollutants and dust generation (Bamniya et al., 2012).

During the past decade, Green Infrastructure (GI) practices have been evolved as successful measures in restoring urban green space across many countries around the world (Allen, 2012). Though these practices have been earlier identified as a replacement for conventional stormwater management strategies, GI in broader terms can be defined as an "interconnected network of green space that conserves natural systems and provides assorted benefits to human populations" (Benedict and McMahon, 2006). There are several different GI practices available which can provide these benefits. Some of the examples for widely applied GI practices are green roofs, trees, green walls, wetlands, bioretention, pervious pavements, infiltration trenches, retention ponds, sedimentation basins and vegetated swales (Elliott and Trowsdale, 2007).

Whilst investigating the numerous benefits of GI, researchers have identified that, apart from the application as a stormwater management strategy that manage both water quantity and quality within the water cycle, GI practices can also provide other important ecosystem services. Ecosystem services can be defined as "benefits of ecosystems to households, communities, and economies" (Boyd and Banzhaf, 2007). Some of these other ecosystem services that GI practices provide are, energy savings, air quality improvement, reducing greenhouse gases, reduction of urban heat island, improvement of community liveability which includes aesthetics, recreation, and improvement of habitats amongst others (CNT, 2010).

GI practices play a significant role in the well-known Eco Industrial Park (EIP) concept in industrial ecology. EIP is an industrial area that is designed to encourage the businesses to share infrastructure as a strategy for enhancing production, minimizing costs, managing the environmental and social issues (Dinep and Schwab, 2010). Lowe et al. (1996) define the term Eco Industrial park (EIP) as follows.

> *"An Eco Industrial Park is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resources issues including energy, water and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would have realized if it optimized its individual interests."*

GI practices are widely used within the EIP planning to manage the issues related to stormwater, wastewater, air pollution and energy consumption. Furthermore, GI can improve the social and community dimension of the industrial areas by providing measurements to enhance the community liveability within and its surroundings (Côté and Cohen-Rosenthal, 1998). However, there are yet debates exist in ways of designing GI practices within industrial areas that can provide the optimum benefits to achieve the goals of the EIP concept (Mitchell, 2002, Lowe, 2005). Since there is a pool of different GI practices available that can produce several different combinations of interconnected networks of green space, it is a difficult task to assess which individual GI or combinations are the most suitable practices for a particular area. According to the definition of Lowe et al. (1996), it is always important to optimize the benefits that can be gained through designing ecologically sustainable industrial areas, as a collective benefit rather than the individual benefits. Hence, innovative methodologies should be developed to identify ways of optimum selection and planning of GI practices within industrial areas that can provide more globalized benefits.

Even though the research on optimization of GI practices within the industrial areas is still in its infancy stage, there are several examples of the applications of the EIP concept particularly in heavy industrial areas across the world. Some of the prominent international examples of EIPs are Kalundborg (Denmark), Forth Valley (Scotland, UK), Kawasaki (Japan), Rotterdam (The Netherlands), Map Ta Phut (Thailand), and North Texas (TX, USA) (Golev, 2012). Majority of the development of these EIPs were gradually evolved in brownfield areas (Corder et al., 2014).

The first EIP in Australia is recorded as the “steel river’ project which is located in Newcastle, New South Wales. This project included several GI practices to landscape streets, provide recreational and community livability benefits, and to manage the water resources within the site (Yapa, 2004). Some of the other leading examples for the applications of GI practices in heavy industrial areas in Australia are Kiwinana (Western Australia), Gladstone (Queensland) and Geelong (Victoria) (Corder et al., 2014). The selection of different GI practices in these EIP are generally conducted through the expert judgement and assessing the numerous other factors such as availability of funds, land area and other resources. There is no systematic methodology currently available to identify the optimum GI practices for different industrial areas (Gibbs and Deutz, 2005, Gibbs and Deutz, 2007, Breuste et al., 2015, Mathey et al., 2015).

Åstebøl et al. (2004) has proposed a stormwater management plan for an industrial site in Norway by considering a set of GI practices. The proposed stormwater solution from this study has concentrated mainly on vegetation structure of the GI practice and the amount of stormwater managed on site. Chen et al. (2012) developed a model to study the air pollution of industrial sites according to the land use changes. When assessing the role of GI practices in improving the environmental quality of industrial areas, limited number of studies has looked at the methods of optimizing GI for such areas (Breuste et al., 2015, Mathey et al., 2015). Therefore, this research will focus on proposing a methodology for the selection of optimum GI practices for industrial areas, to fill the above discussed research gaps.

1.2 Research Significance and Innovation

Based on the previous studies on greening the industrial areas, it is evident that the possibilities of implementing GI practices within industrial areas are well acknowledged. However, there is yet a research gap exist in identifying the optimum GI practices from the pool of different practices available, which are most suitable for these areas (Kopperoinen et al., 2014, Wolch et al., 2014). Unlike residential or commercial areas where a limited number of GI practices can be implemented due to space restrictions, industrial areas may have opportunities in implementing several different types of GI (Rowe and Bakacs, 2012, US EPA, 2014). To date, limited studies have been conducted on identifying optimum GI practices for industrial areas. Hence, this research is particularly targeted on identifying optimum GI practices that can be implemented to manage stormwater and improve the air quality, which are two major environmental problems occurred within the industrial areas (Bamniya et al., 2012, Odefey et al., 2012).

The mathematical optimization techniques have been widely used by several researchers in environmental optimization applications. However, in the optimization of GI practices for a particular area, majority of studies have been conducted by addressing the problem as a single objective optimization problem in minimizing the associated costs (Kaini et al., 2007, Kaini et al., 2012, Montaseri et al., 2015). For a complex land use like an industrial area, the reality in optimizing GI practices can incorporate several other aspects such as environmental, economic and social objectives that are expected by their implementation (Maes et al., 2015, Veleva et al., 2015). Another complexity that can be associated with the optimization of GI is to achieve their optimal sizing (Jayasooriya et. al, 2016). The sizing may influenced by several constraints that are forced by the land itself and the required environmental standards. These constraints may require identifying the GI practices that can be implemented with the available funds to provide expected outcomes (Szulczewska et al., 2014, Loures, 2015). Furthermore, unlike residential or commercial areas, industrial areas may have high environmental, economic and social demands to be addressed by GI implementation, which can be assessed through several performance measures (Kousky et al., 2013, Long, 2014, Wolch et al., 2014). In addition, the stakeholder preferences on GI implementation also play a major role in the optimization process, in reaching for a more realistic and compromise solution (Roe and Mell, 2013, Hansen and Pauleit, 2014). Hence, it is evident that optimization of GI practices for an industrial area is a complex problem that combines each of the above discussed aspects. Currently, there are no comprehensive studies conducted in developing a methodology to address the problem. Thus, this research will develop an innovative methodology to optimize GI practices for industrial areas by incorporating several methodologies such as mathematical optimization, performance measure analysis, Delphi survey, Multi Criteria Decision Making (MCDA) and scenario analysis. However, the optimization in this research is limited to identify optimum GI practices for industrial areas based on managing the stormwater and mitigating the air pollution individually (not combined). The methodology developed in this study also can provide valuable insights for the EIP concept in optimizing the GI practices for industrial areas.

1.3 Research Aims

The identification of the optimum GI practices for an industrial area from the pool of different practices is a complex procedure that involves several individual tasks. The three major aims considered in this study in optimizing the

GI practices for an industrial area are, improving the environmental quality of the area, achieving the economic feasibility and improving the social context. These aims can be also categorized under the Triple Bottom Line (TBL) criteria in environmental decision making. A generic systematic methodology has been developed in this research to identify optimum GI practices based on these aims to manage stormwater and mitigate air pollution in industrial areas individually.

The method has been demonstrated by applying it to a major heavy industrial area located in Melbourne, Australia. Further details of the case study area will be discussed on Section 1.4. The research has been conducted using the mix methods (e.g. mathematical optimization, performance measure analysis, Delphi survey, MCDA, scenario analysis) based research approach.

The objectives which were followed in the present study to achieve the above mentioned research aims are listed below.

- Developing a systematic methodology to optimize the selection and sizing of stormwater management GI treatment trains for industrial areas.
    - Developing a methodology to optimally size GI treatment trains for stormwater management using simulation-optimization modelling approach
    - Stakeholder preference elicitation for the identification of environmental, economic and social performance measures related to GI optimization for industrial areas
    - Using Multi Criteria Decision Analysis (MCDA) techniques to optimize the selection and sizing of GI treatment trains for stormwater management
    - Demonstration of the methodology for a case study area
- Identification of optimized GI scenarios to mitigate air pollution in industrial areas
    - Assessment of the applicability of simulation models to quantify the air quality improvement of GI practices in Australia
    - Performing a scenario analysis to identify the optimum GI scenario to mitigate the air pollution in industrial areas
    - Demonstration of the methodology for a case study area

1.4 Study Area

The aims of this study which are discussed under Section 1.3 were demonstrated using a case study industrial area located in Australia, known as the Brooklyn Industrial Precinct. The Brooklyn Industrial Precinct is located in the Brimbank City Council, Victoria, as shown in Figure 1.1. The area covers a total of 262 ha land area which consists of numerous heavy and light industries. The Brooklyn Industrial Precinct is located approximately 12 km west to Melbourne Central Business District, and is a part of the Western Industrial Node which plays a significant role of supporting the economy of metropolitan Melbourne (The Brooklyn Evolution, 2012). The area comprises of over 60 industries and 200 businesses located within the precinct (Jones and Ooi, 2014).

Figure 1.1 – Study Area

The Brooklyn Industrial Precinct is surrounded by the residential and commercial areas which also represent the large potential labour pool and commercial market attracted to the area. The area predominantly consists of industrial lots which are used for heavy and light industrial use including materials recycling, warehousing logistics, manufacturing uses and, new available lots which will be subjected to further development. Some of other major industries found within this area are quarrying, former landfills, abattoirs, composting, tallow producers, container storage, former chemical manufacturing and retail manufacturing businesses (The Booklyn Evolution, 2012, Jones and Ooi, 2014, Leadwest, 2016) .

The Brooklyn Industrial Precinct is a triangular shaped land, bordered by Kororoit creek to the west (flows from north to south) and Geelong road to the south. The eastern boundary of the precinct consists with a freight railway line. Figure 1.2 shows the study area including land use breakdown. The northern and southern land uses adjacent to the precinct comprises of residential land areas which are affected by the poor environmental quality of the industrial activities within the area. The creek corridor which is in the western side of the area has been substantially environmentally degraded and has identified with the potential of enhancements for the public recreation and environmental value. The road network of the area is coarse grained and poorly connected (The Brooklyn Evolution, 2012).

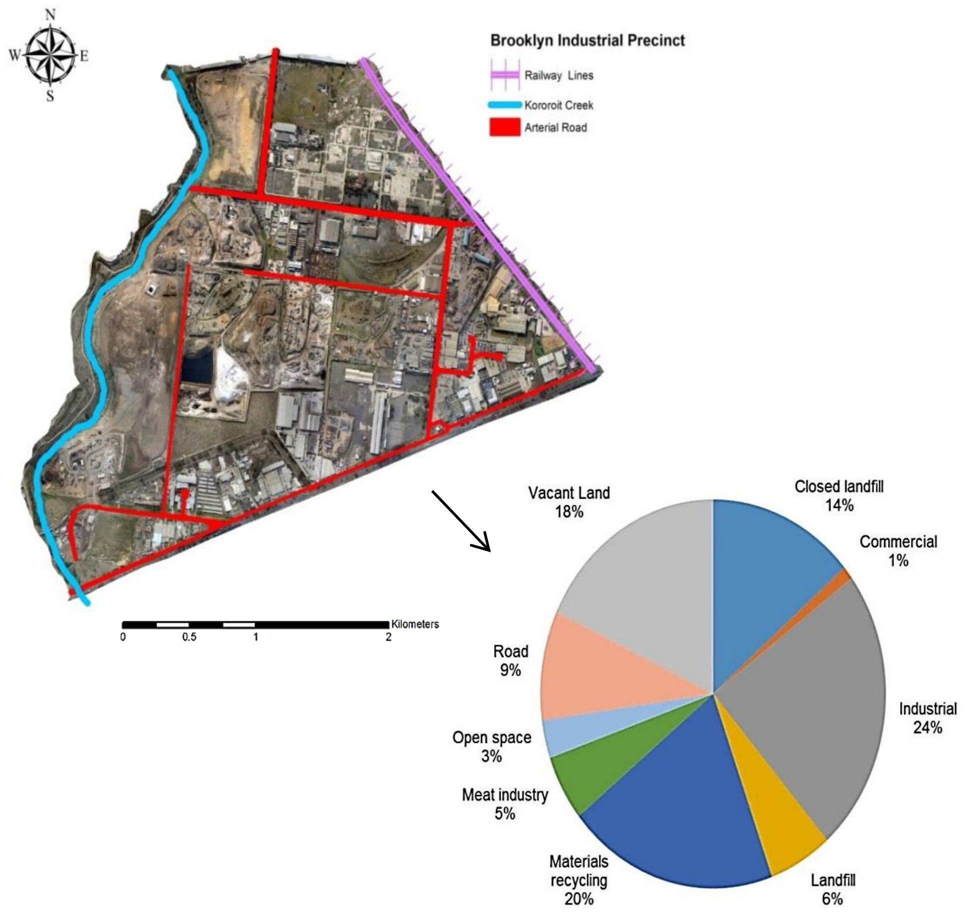


Figure 1.2 – Land Use Breakdown, Brooklyn Industrial Precinct (The Brooklyn Evolution, 2012)

The topography of the area is generally flat, with the exception of substantial mounding and excavation associated with the quarries and landfills (The Brooklyn Evolution, 2012). Figure 1.3 shows the topographic map generated by Geographical Information Systems for the study area. The area is also characterized by poor shallow soils. The average annual rainfall of the area is around 400-500 mm. The groundwater profile of the area is shown in Figure 1.4.

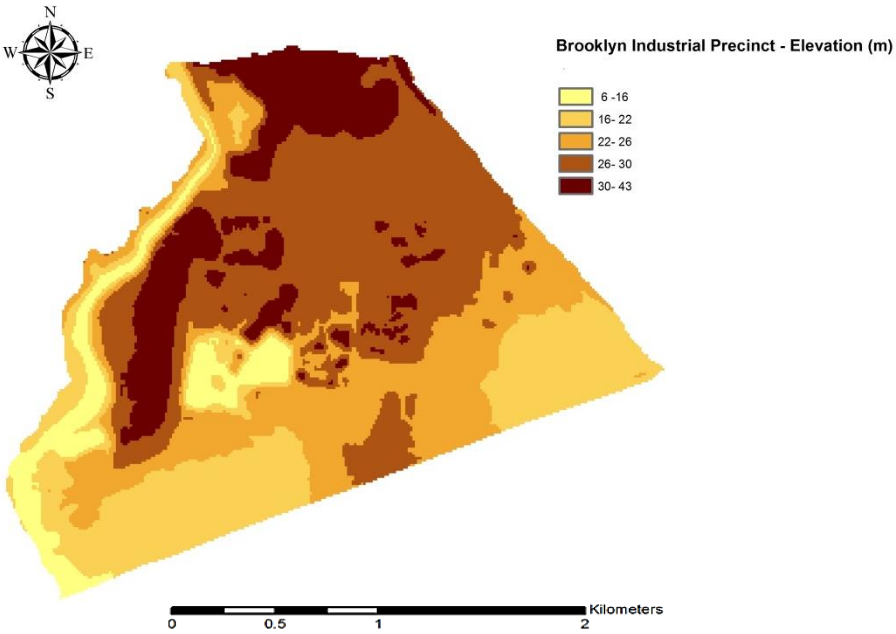


Figure 1.3 – Topography of the Study Area

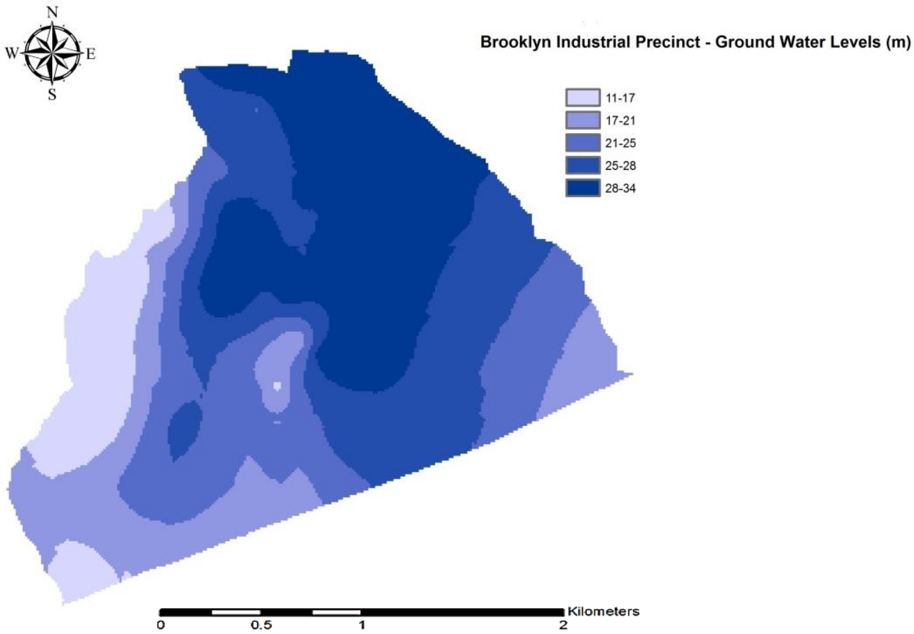


Figure 1.4 – Groundwater Profile of the Study Area

1.4.1 Environmental Issues

The environmental issues related to amenity and poor liveability, air quality and the pollution of Kororoit Creek are the major environmental issues prevailed in the area since the beginning of its industrial development (The Brooklyn Evolution, 2012). The limited water infrastructure onsite leads to poorly controlled drainage and flooding and high sediment loads to the Kororoit Creek (Jones and Ooi, 2014). Furthermore, the discharge of high levels of runoff consists with nutrients and heavy metals have deteriorated the water quality and aquatic eco systems of the Kororoit creek. The Kororoit creek has also been identified as a river with low a river quality index ranked by Melbourne Water due to the stormwater pollution caused by the industrial activities in Brooklyn Industrial Precinct (River Health Data, 2014).

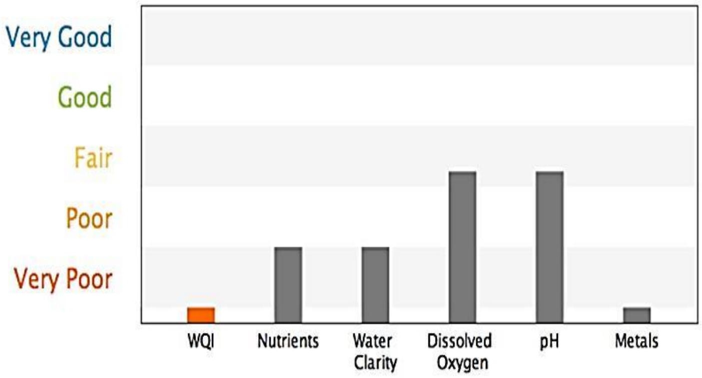


Figure 1.5 – 2012 -2013 Water Quality Parameter Scores – Kororoit Creek near Brooklyn Industrial Precinct (Yarra and Bay, 2014)

Figure 1.5 shows the water quality parameter scores measured in the Kororoit creek near Brooklyn for nutrients, water clarity, dissolved oxygen, pH and heavy metals in 2012-2013. Even though the dissolved oxygen levels and pH values of the river has remained in fair conditions, the water clarity, nutrient and heavy metal quality show that the creek should be given a high priority in protection and improving its water quality. Furthermore, the water quality data of "Kororoit Creek" close to "Brooklyn Precinct" analyzed by Melbourne Water (2013a) had identified that heavy metals 'Copper (Cu)' and 'Zinc (Zn)' levels at the Kororoit Creek close to Brooklyn have exceeded the guidelines for fresh and marine water quality (ANZECC, 2000). According to Figure 1.6 which shows the water quality index history of the creek over the years, it has been evident that strategies should be implemented to manage the industrial stormwater pollution of the area.

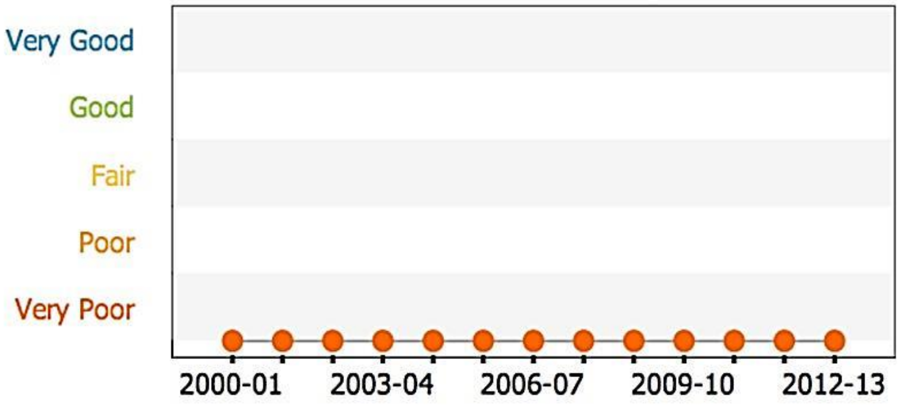


Figure 1.6 – Water Quality Index History – Kororoit Creek near Brooklyn Industrial Precinct (Yarra and Bay, 2014)

The air quality of the area is particularly affected by excessive dust production which has adversely influenced the health and wellbeing of the residents of the adjacent residential areas (Cook, 2014). The particulate matter (PM10) levels of the Brooklyn Industrial Precinct are particularly high due to various industrial activities and the constant vehicular movement on the unsealed roads of the area (Jones and Ooi, 2014).Brooklyn experiences an average of 28 days per year of PM10 exceeding 50 $\mu g/m^3$, which exceeds the recommended limit of 5 days per year by EPA Victoria (EPA Victoria, 2016). The EPA Victoria has also analysed the PM 2.5 levels for Brooklyn Industrial precinct for one year period in 2010-2011, with sampling in every 3 days. The results of the sampling program identified that the maximum permissible limits for PM 2.5 levels were exceeded in Brooklyn for 107 times per year (Jones and Ooi, 2014).

Figure 1.7 shows the total number of days with poor air quality from October 2009 to February 2014 in Brooklyn, compared to its surrounding suburbs. The air quality of the Brooklyn Industrial precinct shows a significant deterioration compared to some of the major commercial and industrial suburbs in Melbourne.

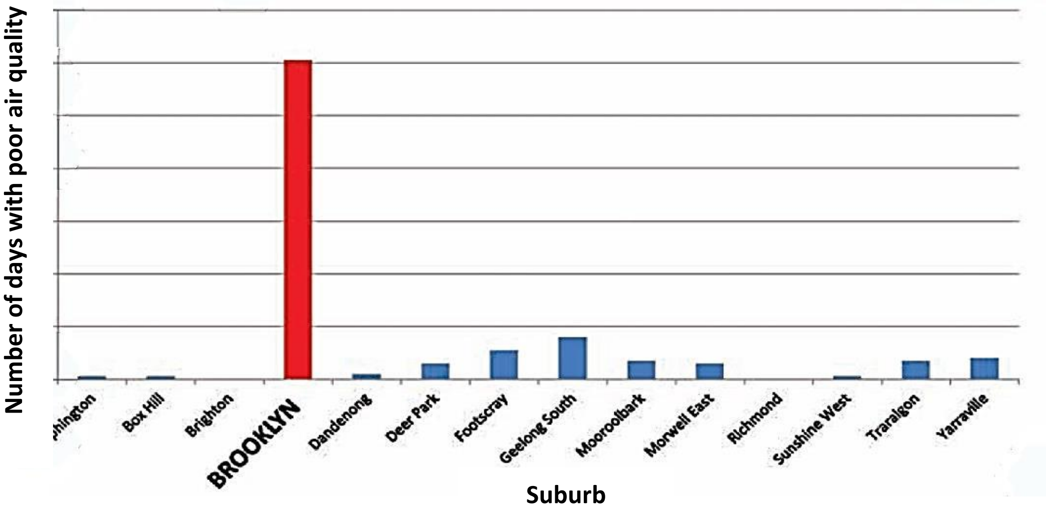


Figure 1.7 – Total Poor Air Quality Days October 2009 – February 2014 (EPA Victoria, 2016)

1.4.2 Long Term Planning

Since the Brooklyn Industrial Precinct has been recognized as a prime industrial land area which affects the human wellbeing not only within the area itself but also in the surroundings, long term planning activities have been implemented under the vision of converting it to a more "clean and green" area within the next 20 years (Browne and Brookes, 2014). These long term planning activities were initially developed under five key structural planning themes which are, improving the land use, employment and economic activity, access and connection, environmental condition, image and identity, and development and staging. To achieve the goals of this strategic plan in an economically feasible way, the Brooklyn Industrial Precinct also has received government support through various funding programs (Jones and Ooi, 2014).

One of the major aims considered within the scope of the current long term framework plan for the Brooklyn Industrial Precinct is, implementing GI practices to improve the image and the environmental quality of the area. Currently, the land areas along the Kororoit creek corridor have been identified which has the potential to implement GI practices to reduce the stormwater pollution in the creek by heavy industrial activities of the nearby areas. Moreover, these GI practices are intended to provide slow release of stormwater to the creek and to save potable water that is currently used for the dust suppression of the area. Enhancing the creek corridor as a key environmental and recreation asset, and improving the habitats for various species are some of the other objectives which are planned to achieve in the long term framework. Within these objectives, some of the GI practices currently being considered in this area are wetlands, rain gardens, sedimentation basins and retention ponds (The Brooklyn Evolution, 2012). Furthermore, the areas within the precinct which also cover the sideways of the road network have been identified with the opportunities for future tree plantation, to improve the air quality and the overall image of the area. The overall vision of the long term planning framework for the Brooklyn Industrial Precinct is to convert it to a world class EIP within the next 20 years (Dixon, 2014).

1.5 Outline of the Thesis

To achieve the major aims discussed in Section 1.3, the research has been designed as illustrated in Figure 1.8. The various steps followed in the research are presented in this thesis by including them in to 6 chapters.

The Chapter 2 presents a general literature review on the research problem and various concepts associated with it. It contains a literature review on GI practices and the ecosystem services provided by GI. The chapter also discusses about two major environmental problems which are generic to the industrial areas; stormwater and air pollution. The strengths, weaknesses, opportunities and threats in implementing GI practices to mitigate these problems were discussed to identify the research gaps in the area. In the second part of the literature review, the software tools that are used to model and quantify the ecosystem services of GI practices are discussed by presenting a critical review on each of the different tools. Finally, a critical review of MCDA methods and their applications in environmental decision making is presented in Chapter 2.This review will lead to identify the most suitable MCDA method for the present problem that has been analysed.

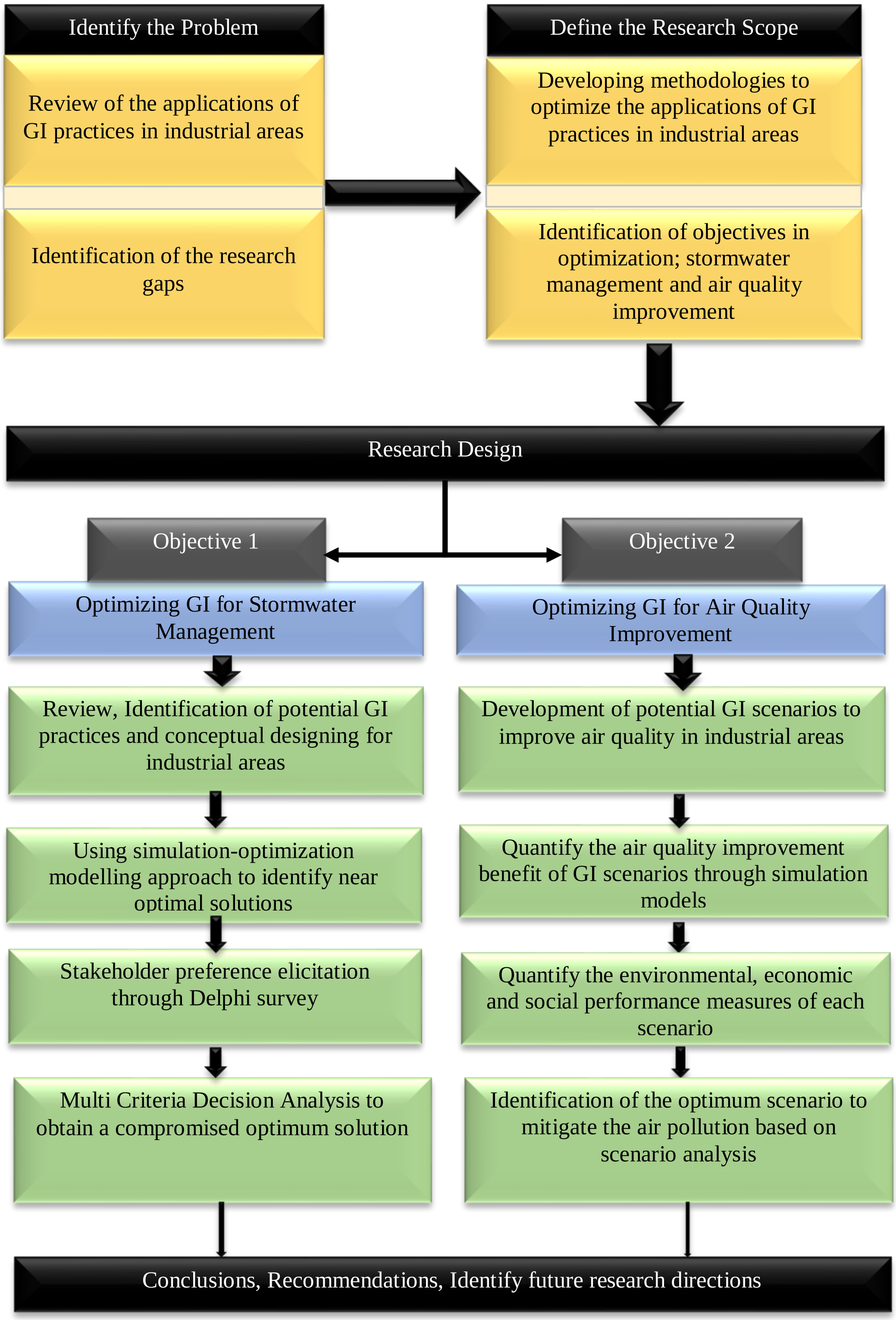


Figure 1.8 – Research Design

Chapter 3 comprises the first steps of the development of systematic methodology in identifying the optimum GI practices for an industrial area based on stormwater management. This chapter includes the steps in using single objective optimization to identify the optimum sizing of GI treatment trains, which are currently practiced in the industry to treat and manage stormwater. Furthermore, this chapter explains the innovative simulation-optimization modelling approach that has been adapted to identify the optimal sizing for treatment measures in a GI treatment train.

Chapter 4 contains the steps followed in stakeholder preference elicitation and MCDA, to obtain a compromised optimum GI practices for the study area. The chapter includes the findings of the 4-rounded Delphi survey conducted with a panel of experts to confirm and identify the performance measures related to the stormwater management GI selection in an industrial area. In summary, the chapter discusses about the importance in incorporating multi-disciplinary stakeholders in the GI optimization.

Chapter 5 discusses the procedure followed to identify the optimum GI scenarios in an industrial area to mitigate the air pollution, which is the second objective of this research. The results obtained through each of the steps in Figure 1.8 are presented in Chapter 5.

Chapter 6 which is the final chapter of the thesis presents the summary of the thesis, the conclusions which are drawn from the study and the limitations of the study. This chapter concludes by presenting the recommendations for the future research in the area.

CHAPTER 2

Optimization of Green Infrastructure Practices to Mitigate Major Environmental Issues in Industrial Areas: a Review

2.1 Introduction

With the rapid urban growth and development, the quality of green space available on the earth surface is degrading. Furthermore, many land characteristics have been altered such that the whole water cycle has significantly changed. Some of the adverse effects occurred by these changes include the increase of runoff which can lead to flooding and the poor quality of receiving waters. Therefore, to improve the quality of prevailing surface conditions while managing the stormwater, Green Infrastructure (GI) practices have been introduced which is currently becoming one of the most promising strategies of nonpoint source stormwater pollution control measures, by restoring the natural environment across many countries around the world. Having evolved since the 20th century, GI today has become the centrepiece of smart regional and metropolitan planning, which ensures environmentally friendly and cost effective solutions for generations to come (Youngquist, 2009, ASLA, 2015).

Even though GI practices are currently popular as a stormwater management strategy, the first reference of the term "Green Infrastructure" was found in a report produced in Florida in 1994, which was sent to the governor on land conservation strategies (Firehock, 2010). The intention of using the notion 'Green Infrastructure' in this report was to indicate that the natural systems are equally important or even more important components of the general 'infrastructure'. Since its introduction, the term 'Green Infrastructure' was frequently used in land development and land conservation discussions across the world which later evolved as a promising stormwater management strategy. The GI practices have been widely defined in two different ways in the literature. In some contexts GI practices have been referred to trees that provide ecological benefits to urban areas whereas some refer them to engineered structures (such as stormwater management or water treatment facilities) that provides environmentally friendly solutions to the communities (Heisler, 1986, Marsalek and Chocat, 2002, Benedict and McMahon, 2006, Dunn, 2010). In general, Benedict and McMahon (2012) define GI practices as an ecological framework, which can be simply explained as a natural life support system.

The applications and the importance of GI practices to improve the environmental quality of various land use types are well discussed in the literature (De Sousa, 2003, Carter and Fowler, 2008, Schilling and Logan, 2008). However, to date, the optimum planning for GI practices has not yet been discussed comprehensively for land use types such as industrial areas, which are complex and dynamic components in urban areas (Mathey et al., 2015). Industrial areas are environmentally degraded areas which also consist of brownfield lands that are known as abandoned or underused sites that have tremendous opportunities of redevelopment by introducing urban green space (Fleming, 2012).

The optimum planning of GI practices in such areas in the past and even now has been largely opportunistic, taking advantage of the funding opportunities, rather than looking at the reasons for implementing them in these areas and their actual long term benefits (Young et al., 2014). From the selection of suitable GI practices to the sizing of these practices, various decisions should be made to achieve the environmental sustainability in an optimum way. The decision makers often find it difficult to assess the nature of these decisions due to multiple objectives associated with them (Naumann et al., 2011). One of the other major problems in this process is the lack of the utilization of various tools and methods that can be used to support the GI optimization decision making.

This chapter provides a literature review of GI practices, with the different ecosystem services they provide. Furthermore, the literature review will discuss the two major industrial environmental problems which are the focus of this study, industrial stormwater and air pollution. The role of GI practices in industrial areas is discussed by looking at the issues and challenges for their optimization. Multiple objectives associated with the decision making of GI optimization for industrial areas is also discussed in this chapter, by focussing on different tools and methods that can be used to provide the support for the decision makers.

2.1.1 Green Infrastructure Practices

Infrastructure systems are essential components in the modern high density cities. The Oxford dictionary defines the term infrastructure as “the basic physical and organizational structures and facilities (e.g. buildings, roads, and power supplies) needed for the operation of a society or enterprise”. These infrastructure systems that are often referred as traditional “grey” infrastructure, consists of engineered networks of roads and services, which provide range of services for the communities in urban areas (Wolf, 2003, Benedict and McMahon, 2006, Ely and Pitman, 2012). The ‘grey infrastructure’ systems generally provide a single functionality for a community. However, with the constant pressure that has been forced by the urbanization upon traditional infrastructure, people have explored alternative systems which can provide multiple functions in cities within the same spatial area (European Commission, 2013). As a result of these efforts, the concept of GI was introduced, which comprises of various elements that are capable of effectively responding to the environmental, economic and social pressures that are forced upon public by the urbanization.

Various scholars have provided different definitions for the term GI. Some of the definitions which are used in literature for GI are,

> *“Green Infrastructure is an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations.”* ***(Benedict and McMahon, 2006)***

> *“Green Infrastructure is the network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services.”* ***(Naumann et al., 2011)***

"Green Infrastructure is an approach to water management that protects, restores, or mimics the natural water cycle. Green infrastructure is effective, economical, and enhances community safety and quality of life." ***(American Rivers, 2010)***

*"Green Infrastructure is a design strategy for handling runoff that reduces runoff volume and distribute the flows by using vegetation, soils and natural processes to manage water and create healthier urban and suburban environments."****(USEPA, 2014a)***

As can be seen from these different definitions, the more recent focus of GI practices has been concentrated towards its applications as a stormwater management strategy. However, in summary, the underlying idea of these definitions portrays that GI practices can provide multiple benefits that can contribute to develop resilient cities. This also implies that GI practices are intended to serve human settlement, to meet their needs, in addition to the benefit to the environment.

GI practices can be implemented within urban areas in different scales from the local level through engineered structures to a broader level through landscaping (Naumann et al., 2011). The GI practices which are implemented at local level are known as structural GI. Some of the examples of structural GI practices are wetlands, green roofs, rain gardens/bioretention systems, vegetated swales, permeable pavements, infiltration trenches, retention ponds, sedimentation basins and green walls. At the broader level, GI practices are considered as non-structural components such as preservation and restoration of natural landscapes (e.g. forests and floodplains) (American Rivers, 2010, Foster et al., 2011, Ellis, 2013). The major focus of the research presented in this thesis will be on structural GI practices.

GI practices can be integrated into the existing features of the built environment such as streets, buildings, parking lots and landscaped areas

(USEPA, 2015). One of the important features of GI practices compared to traditional grey infrastructure is the cost effectiveness during their operational period. Even though the initial installation costs of GI can be potentially high in redevelopment and retrofit settings, from their life cycle perspective, the long term operational and maintenance costs make them economically feasible than the conventional infrastructure in stormwater management. A study conducted by United states Environmental Protection Agency (USEPA) considering 17 projects which used local scale GI practices found that, in majority of occasions GI provided a cheaper and more environmentally friendly performance in managing stormwater compared to the conventional methods (USEPA, 2007, USEPA, 2014b, USEPA, 2015).

The costs and benefits of GI practices compared to grey infrastructure as a stormwater management strategy has been well discussed in the literature for various development types (e.g. residential, commercial and industrial areas). Table 2.1 shows the cost savings associated with stormwater management GI practices used in various commercial and industrial facilities in USA and Canada (MacMullan and Reich, 2007). These case studies have used combinations of several different types of GI practices for different facilities and have achieved significant amount of cost savings. It is evident that even though investing on GI practices can be initially costly when compared to the traditional infrastructure, they can be more favourable when looking at their long term benefits (Dunec, 2012, USEPA, 2013). Moreover, apart from the major environmental benefits that GI practices provide as a stormwater management strategy, these practices provide several other services such as air quality improvement, energy savings, urban heat island reduction, providing habitats, improving the liveability of the areas, urban food production, recreational opportunities and reducing the Green House Gas (GHG) emissions. These services are also known as ecosystem services (Tzoulas et al., 2007, Benedict and McMahon, 2012, Lennon and Scott, 2014). These ecosystem services are further discussed in Section 2.1.1.1 in more detail.

Decision making in GI planning compared with grey infrastructure, involves multiple objectives (European Commission, 2013). Furthermore, GI is fairly a new concept compared with the grey infrastructure. Thus it faces several challenges related to scientific uncertainty, socio-political uncertainty/acceptance, which create uncertainties in decision making compared to grey infrastructure (Thorne et al., 2015). In the planning principles of GI, stakeholder engagement has been identified as one of the important processes that is required to achieve the expected outcomes of implementing the GI practices (Hansen and Pauleit, 2014, De Bellis et al., 2015). These stakeholders may include public entities or individuals who own or manage the land in the areas which fall within the GI network and the people who invest on the future of the communities. The decisions for the initiation of GI practices can be immensely benefitted from these stakeholders by integration of their knowledge, experience and resources (Benedict and McMahon, 2012, Roe and Mell, 2013, Norton et al., 2015). There are several tools available to evaluate the performance of GI practices (i.e. various ecosystem services) and the potential cost savings which also support the planning of GI (USEPA, 2014b). These tools will be discussed in detail in Section 2.6.

2.1.1.1 Ecosystem Services of Green Infrastructure Practices

The modern concept of ecosystem services and its importance in decision making was first emerged in 1970's through an idea presented by Westman (1977). However, the actual development of the idea of ecosystem services only began to emerge in 1990s, where number of researchers from diverse backgrounds started to adopt the ecosystem services in a perspective of facilitating better decision making (Daily, 1997, Gómez-Baggethun et al., 2010, Scott et al., 2013). Since then, several definitions have been presented for the term "ecosystem services". One of the widely used definitions for ecosystem services in recent literature is presented by Millennium Ecosystem Assessment (2005) as "ecosystem services are the benefits people obtain from ecosystems" (p.49).

Table 2.1 – Cost Savings through Installing GI as Stormwater Management Strategies in Commercial and Industrial Developments (MacMullan and Reich, 2007)

Location	**Description of GI used**	**Cost Savings through GI (annual)**	**Reference**
Parking Lot Retrofit Largo, Maryland	One-half acre of impervious surface. Stormwater directed to central bioretention.	$10,500 - $15,000	USEPA (2005)
Old Farm Shopping Centre , Maryland	Site redesigned to reduce impervious surfaces, added bioretention, filter strips, and infiltration trenches.	$36,230	Zielinski (2000)
270 Corporate Office Park, Maryland	Site redesigned to eliminate pipe and ponds, stormwater system, reduce impervious surface, added bioretention, swales, and permeable pavers.	$27,900	Zielinski (2000)
OMSI Parking Lot Portland, Oregon	Parking lot incorporated bio-swales into the design, and reduced piping and catch basin infrastructure.	$78,000	Liptan and Brown (1996)
Light Industrial Parking Lot, Portland, Oregon	Site incorporated bio swales into the design, and reduced piping and catch basin infrastructure.	$11,247	Liptan and Brown (1996)
Point West Shopping Center, Lexana, Kansas	Reduced curb and gutter, reduced storm sewer and inlets, reduced grading, and used porous pavers, added bioretention cells, and native plantings.	$168,898	Beezhold and Baker (2006)
Vancouver Island Technology Park Redevelopment British Columbia, Canada	Constructed wetlands, grassy swales and open channels, rather than piping to control stormwater. Also used native plantings, shallow stormwater ponds within forested areas, and permeable surfaces on parking lots.	$530,000	Tilley (2003)

GI practices provide several ecosystem services throughout their entire life cycle. Through functionally and spatially connected natural systems, GI practices ensure the provision of ecosystem goods and services for the society (Karhu, 2011). Some of the ecosystem services of GI practices can be listed as;

Improved water quality

GI practices can improve the water quality by filtering the pollutants in stormwater. The vegetation and the soil system associated with GI practices can affect in improving the quality and reducing quantity of stormwater. The water quality improvement benefits of GI practices include effectively capturing sediments, oil and other common pollutants found in urban stormwater that typically wash into sewers and receiving water bodies during the storm events (MacMullan and Reich, 2007, Jaffe et al., 2010, Yang et al., 2015).

Reduced flooding

GI practices can mitigate the effects of floods by managing the stormwater close to its source, including reducing the frequency, area and impact of the flooding events. The reduced flood related benefits can also lead to the reduced expenditure on maintenance of bridges, culverts and other water related infrastructure (Braden and Johnston, 2004, MacMullan and Reich, 2007).

Groundwater recharge

The GI practices that infiltrates stormwater to the ground, contributes to recharge deep aquifers and subsurface groundwater (CNT, 2010). The increase of the pervious areas through GI practices can significantly improve the groundwater recharge and increase the associated water supplies for drinking and irrigation. A study conducted by Otto et al. (2002) shows that the impermeable areas of Atlanta reduce the groundwater infiltration which contains water that can serve for household needs up to 3.6 million people per year.

Air quality improvement

GI practices improve the air quality through uptake and deposition of atmospheric air pollutants through vegetation. GI practices such as trees and green roofs support in uptaking air pollutants such as Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Ozone (O_3) and Particulate Matter (PM2.5,PM10) (Currie and Bass, 2008). Studies have shown that a single tree can remove around 0.44 pounds of atmospheric air pollutants per year (MacMullan and Reich, 2007, Plumb and Seggos, 2007). Moreover, the cooling provided by vegetation in GI also support to reduce the smog formation by lowering the reaction rate of nitrogen oxides and volatile organic compounds (CNT, 2010).

Urban heat island reduction

The urban heat island effect is a phenomenon which occurs when metropolitan areas are significantly warmer than its surrounding areas. The amount of hard surface areas in cities is generally higher than that of rural areas. Urban heat island is caused by these hard surface areas which absorb and store the solar energy and radiate it as heat (USACE, 2014). GI practices replace hard heat absorbing surfaces with soils and vegetation. The shade and the water vapour produced by GI practices help to reduce the ambient temperatures that can regulate the urban heat island effect (European Commission, 2013).

Reduced energy use

The shading properties and insulating properties of GI practices such as green roofs can provide cooling effects and reduce the energy demand in warmer months (MMSD, 2013). Furthermore, GI practices in general can reduce the off-site energy use by preventing the runoff and reducing the demands for potable water (e.g. through groundwater recharge) (CNT, 2010).

Reduced Green House Gas (GHG) emissions

The ability of GI practices to sequestrate carbon through vegetation can support to achieve the greenhouse gas emission goals, which can contribute to the carbon sink (USEPA, 2015). Furthermore, by the reduction of energy consumption and the urban heat island effect, GI practices can also reduce the carbon dioxide emissions from regional electricity generation (CNT, 2010). It has been estimated that, through both carbon sequestration and avoided emissions, GI practices can reduce around total of 73,000 tons of carbon dioxide per year which is similar to removing the emissions of 14,000 vehicles in US (MMSD, 2013).

Enhanced aesthetics and property values

The natural features and the vegetative cover provided by GI practices enhance the aesthetics of the areas which can lead to the increase of adjacent property values. GI practices provide structural and visual interest to otherwise open spaces. They can also provide amenities for people living and working in these areas that can further complement the economic vitality of sites (MacMullan and Reich, 2007).

Creating recreational opportunities

Larger scale GI practices which have public access such as wetlands are shown to provide recreational opportunities that can lead to the improvement of the liveability in urban areas. A study in Philadelphia has estimated that over a 40 year period, areas where GI practices have been implemented showed an increase of almost 350 million worth of recreational trips (CNT, 2010).

Providing habitats

Vegetation in GI practices can provide habitats for wide variety of flora and fauna even from the smaller scales of implementation. GI practices enhance the natural habitats by provisioning living space for both resident and migratory species such as wildlife, birds and insects. GI practices can also act as nurseries for various plant species (CNT, 2010, USEPA, 2015).

2.2 Industrial Stormwater Pollution

Rapid urbanization and the reduction of permeable surfaces can contribute to the generation of stormwater runoff that can enter the receiving water bodies such as rivers, streams, lakes and coastal waters. In urban areas, stormwater can be generated from residential, commercial and industrial areas which are contributors for non-point source pollution. Among these different source categories, runoff generated from industrial areas have been identified with elevated levels of excess nutrients, sediments, heavy metals, hydrocarbons and other substances (Duke and Chung, 1995, Duke and Beswick, 1997). Furthermore, industrial runoff is the predominant contributor of Zinc (Zn) and Copper (Cu) loadings in receiving waters. Industrial areas in combination with the commercial land, produces the highest pollutant loading among of all stormwater sources (Horner, 1994).

Industrial activities such as material handling and storage, and equipment cleaning and maintenance, can interact with rainfall and build up the pollutants that can degrade the water quality of natural waterways (USEPA, 2016). Stormwater discharges from small to medium enterprises (SME) are largely unregulated and are not receiving treatment before entering the rivers or coastal waters. In Australia, 75% of the industrial areas are comprised with SME's which largely accounts for the industrial stormwater pollution (City of Kingston 2005). According to the study done by City of Kingston (2005), stormwater from approximately 4500 businesses drain into the Port Philip Bay.

Even though the stormwater contamination has been identified as non-point source pollution for majority of land use types, industrial areas can also contribute to the point source discharges. The point source pollution in industrial areas can be attached to a single activity which has a one clear source. Some of the examples are the accidental discharges or deliberate disposal (Novotny, 1995, City of Kingston 2005, Zgheib et al., 2012). However, stormwater contamination through point sources is considered as not very difficult problem to mitigate in industrial areas since the source is identifiable whereas non- point source pollution is difficult to control due to their diffuse nature. Table 2.2 shows the sources of different stormwater pollutants based on the types of industry. Furthermore, past studies have highlighted that, there exists a lack of guidelines to regulate the non-point stormwater pollution in industrial areas considering its harmful impacts compared to runoff of other land use types

(Griffen, 2005, Al Bakri et al., 2008). Implementation of GI practices in industrial land areas can provide benefits in improving the runoff quality. The development of proper methodologies to identify the optimum GI practices in such areas can further provide opportunities to develop the guidelines in runoff management.

Table 2.2 – Relationship between Industry Type and the Pollutant Groups in Stormwater (Water by Design, 2011)

Industry type	Litter	Sediments	Oil, Grease, hydrocarbons	Organic Toxicants	Other Toxicants
Food beverage and tobacco manufacturing	☑			☑	
Textile clothing, footwear and leather manufacture	☑				
Wood and paper product manufacture	☑			☑	
Printing, publishing and recorded media	☑				
Petroleum, coal chemicals, product manufacturing			☑		☑
Non-metallic mineral product manufacturing		☑			☑
Manufacturing (Other)	☑		☑		☑
General construction	☑	☑			
Construction trade services	☑	☑			
Basic material wholesaling	☑	☑			
Motor vehicle retailing and services			☑		☑
Transport and storage		☑	☑		

2.3 Industrial Air Pollution

One of the major impacts of world's industrial growth is the pressure that it has forced upon the atmospheric environment (Zwickl and Moser, 2014). Air pollution can be explained as the emissions of hazardous chemicals, particulate matter, toxic substances and biological organisms to the atmosphere (Salgueiro-

González et al., 2015, Griffin, 2016). Among the different land use types, industrial areas and associated activities are known to be the major contributor of the global air pollution. According to a study conducted by USEPA, industrial air pollution has accounted to 50% from the total air pollution reported in America (ECO, 2010).

Air pollution in industrial areas originates from various sources such as industrial processes, paved and unpaved road ways, construction and demolition sites, parking lots, storage piles, handling and transferring the materials, and from the open areas (Sharma, 2009). According to an assessment conducted by the European Environment Agency (EEA), the costs of the industrial air pollution caused by Europe's largest industrial facilities have been estimated around \$59 - \$189 billion in 2012. These estimates were based on various costs associated with premature deaths, hospital costs, lost work days, health problems, damage to buildings and reduced agricultural yields due to the industrial air pollution (EEA, 2014). Table 2.3 shows different air pollutants, their sources based on industrial activities, health effects and the types of vulnerable communities associated with these pollutants.

2.4 Role of GI Practices in Industrial Areas

The industrial sector plays a major role in country's economy (Wu and Chen, 2012). Several industrial areas are located within urban areas surrounded by residential and commercial areas due to easy acquisition of materials and human resources. Contamination of surrounding water bodies from the runoff generated from larger impermeable areas and air pollution are identified as major environmental issues related to majority of these industrial areas (Alshuwaikhat, 2005, water by design, 2011, Ghasemian et al., 2012). In addition to these major environmental impacts, some of the other issues associated with the industrial areas are high energy consumption, GHG Emissions, threats to the natural ecosystems and habitats, and reduced community liveability (Paull, 2008). Lack of measures for the proper restoration of environmental quality within these areas can affect workers, surrounding communities and the ecosystems in long term. Strategically planned GI practices have an enormous potential to meet the environmental demands forced by industrial areas through providing diverse range of ecosystem services (De Sousa, 2003, Dorsey, 2003, Mathey et al., 2015). Hence, it is important to look at the methodologies to strategically plan GI practices to address these environmental issues in industrial areas.

In urbanized areas, the abandoned or underutilized industrial areas which are known as ‘brownfields’ are considered as major liabilities to a county’s economy (Greenberg and Lewis, 2000, Davis, 2002, Hand and Rebert, 2006). These brownfield areas are known to provide ideal opportunities for redevelopment using sustainable initiatives such as GI practices. Sustainable brownfield redevelopment techniques are intended to achieve cleaner water, substantial energy savings, restoration of the ecosystems and increased diverse economic service and increased production efficiencies of these areas (Lewis, 2008, Fenwick and Center, 2012). It is evident that GI practices can not only provide means of reducing the environmental threat posed to the neighbourhood communities by these areas, but also provide numerous economic benefits for the industries or individual businesses. However, there is yet limited information available on applications of GI practices in such areas due to the general lack of systematic knowledge on the optimal applications of these practices, shortage of awareness and the perspectives on the potential of integrating these strategies in such land areas (De Sousa, 2006). The potential benefits of GI practices for such brownfields can only be understood if they are accepted as the vital land areas that can support applications of urban GI practices (Mathey et al., 2015).

Table 2.3 – Sources, Health Effects and Vulnerable Populations to Different Pollutants (Kampa and Castanas, 2008, Environmental Justice Australia, 2014)

Pollutant	Sources	Health Effects	Vulnerable Populations
Particulate Matter (PM10 and PM2.5)	Mining activities, motor vehicle emissions, wood burning, unflued gas heating, coal dust and coal burning	Upper respiratory tract irritation and infection, exacerbation of asthma, decreased lung function, myocardial infarction, premature mortality	Elderly people with respiratory and cardiovascular conditions, children with asthma
Ozone (O_3)	Vehicle or industrial emissions and their reactions to sunlight, hydrocarbons and emissions of oxides of Nitrogen	Decreased lung and pulmonary function, upper respiratory tract infection, exacerbation of chronic respiratory conditions including asthma. Emphysema and chronic bronchitis	People with chronic respiratory conditions (especially children with asthma)
Oxides of Nitrogen (NO_X)	Energy generation, mining and other industrial operations, unflued gas appliances, motor vehicle emissions	Upper respiratory tract infection, exacerbation of chronic respiratory conditions including asthma, eye irritation, reduced immunity to lung infection	People with chronic respiratory conditions (especially children with asthma)
Sulfer Dioxide (SO_2)	Fossil fuel combustion, metal smelting or photochemical industries	Throat irritation, exacerbation of cardiovascular diseases including asthma	Elderly people with respiratory and/or cardiovascular diseases
Carbon monoxide (CO)	Biomass and fossil fuel combustion, vehicle exhaust emissions	Reduction of Oxygen carrying capacity of blood, resulting in headache, nausea, dizziness, breathlessness, fatigue, visual disturbance, angina, coma	People with ischaemic heart disease, pregnant women
Lead (Pb)	Smelting	Neuropsychological and cognitive effects, hypertension	Children and pregnant women

The need for the environmentally sustainable strategies which supports the efficient use of resources in industrial areas are becoming increasingly evident (Vey, 2007, UNIDO, 2011, Dunec, 2012). GI practices form an essential element in increasing the resilience of industrial businesses by providing places where people meet and interact, increasing physical and social connectivity, and strengthening community bonds and values in the long term (Jones et al., 2015). Furthermore, GI practices demonstrate several financial advantages when compared to the traditional grey infrastructure in runoff management due to their potential for reducing initial capital expenditure, ongoing operation and maintenance expenses (Naumann et al., 2011, Young et al., 2014). Moreover, strategically planned GI practices can also be used to recapitalize aging assets. Another important factor associated with GI practices is that since they leverage existing natural resources, their regeneration process consume less energy and reduce the financial burden forced upon the industrial businesses (The Nature Conservancy, 2013). In addition, GI practices offer numerous opportunities to enhance the communication within industries to effectively manage socio-political risks through the innovative collaboration of stakeholders (The Nature Conservancy, 2013).

Apart from the several benefits discussed, the implementation of GI practices within industrial areas has been also identified with the potential to treat wastewater discharged from the industrial plants by using them as source control treatment measures (Mcllvaine, 2014). Furthermore, alongside with the treatment of runoff, GI practices support the food mitigation by reducing the volume of runoff generated in site through the capture and storage of stormwater. GI practices also provide opportunities to reduce the high potable water demands in industrial areas by promoting the reuse of water for activities such as cooling, cleaning the equipment and product processing (Clements et al., 2013).

In 2011, the United Nations Environmental programme (UNEP) has defined the term "Green Economy" which is explained as an economy that is achieved by improved human well-being and social equity while significantly reducing environmental risks and ecological scarcity (UNEP, 2011). The industries and businesses are predominant drivers of a country's economic growth which provide food, transport, technologies, infrastructure, housing, and other goods and services to the communities (UNIDO, 2011). Greening the industries through sustainable practices such as GI therefore can also create an important contribution to the green economy.

2.4.1 Case Studies

There are several examples where GI practices have been used in industrial areas to mitigate the environmental degradation and to improve the quality of life in these areas. This section presents some of the overseas and Australian case studies where GI practices have been successfully implemented or currently being considered for various industrial areas.

Milwaukee's 30th Street Industrial Corridor, Milwaukee, Wisconsin

The Milwaukee 30th Street Industrial Corridor located in the State of Wisconsin encompasses of 880 acre land area that is surrounded by several residential and commercial neighbourhoods (City of Milwaukee, 2014). This area has been highly utilized by manufacturing activities until the industry started declining in 1980's. After the decline of the manufacturing industry, many industries along the 30th Street Industrial Corridor were downsized and the area has remained with significant environmental issues that are affecting for the surrounding communities (USEPA, 2014c). In 2005 and 2007, the United States Environmental Protection Agency (USEPA) granted funds for City of Milwaukee to resolve a number of major environmental, economic, and social issues, and improve the overall quality of life for local area residents and businesses by revitalizing the area. Several GI practices were considered in the site redevelopment planning, specifically to mitigate floods and to improve the stormwater quality for receiving waters (DNR, 2012, DNR, 2014).

This area has suffered from severe flooding in July 2010 which caused over $30 million damages in private sector alone and the loss of 250 jobs in the local area (The Corridor, 2014). To alleviate stormwater contamination and the flooding of this area, GI practices which promote detention and constructed wetlands are proposed that provides storage and delay of water entering into the sewer system (MMSD, 2015). With the area wide development plan, sections of the corridor are planned to be developed into linear parks through promoting more urban green space. This has been intended to provide recreational opportunities and amenities for the area that could be beneficial for the residents of the adjacent residential area. Furthermore, these land areas were designed to connect with waterways through strategically planned bio swales, wetlands and infiltration based GI practices (USEPA, 2014c).

Genetta Park and Stream Restoration Project, Montgomery, Alabama

The master plan for the restoration of Genetta Park in Montgomery in Alabama, USA, was initiated in 2010, to transform an unattractive industrial land into an attractive environmental amenity by implementing GI practices (Fenwick and Center, 2012). The park area covered around 4 acre land area with Genetta stream travelling across the area. The land use of the area has been creating negative impacts for the Genetta stream by creating floods downstream, impaired water quality, reduced stream biodiversity and reduced groundwater recharge (Fenwick and Center, 2012). The budget allocated for the restoration project was $4 million and the project was completed in 2014 (2D Studio, 2015).

This project was carried under three phases where phase one and two consisted of utilizing the elements of GI practices to enhance the neighbourhood amenity with green space, and designing important GI features to address areas stormwater issues (USEPA, 2014c). The first phase of the restoration project was to implement a wetland to manage stormwater generated from the 4 acre catchment area, specifically to handle very large amounts of runoff that occur during larger storm events. One of the major constraints occurred during the design of the wetland was the limited land area available for its construction with the major expectation of managing the flooding in the area (Fenwick and Center, 2012).

In the second phase of the project, several other GI practices were added to the park. In this stage, permeable surfaces for the area were designed to infiltrate runoff to the ground naturally (USEPA, 2014c). Another component of this design included a tree lined alley which added benefits by providing safer walking paths to the neighborhood residents (2D Studio, 2015).

Dow's Texas Operations, Freeport, Texas

Dow's Texas operations located at Freeport in Texas, USA is a large integrated manufacturing site and the largest complex for the manufacturing of chemical products in North America. This site is located at the intersection of the Gulf of Mexico, the lower Brazos river and the Columbia bottomlands, which integrate a network of freshwater, marsh and forest ecosystems that are critical not only to the company's operations but also to the fish, wildlife, agriculture and the local communities (Hawkins and Prickett, 2012, Hawkins and Prickett, 2014). One of the major environmental issues this area has been facing since 1979 was the exceedences of the limits of ground level Ozone (O_3) by failing to meet the national ambient air quality standards. Dow and other companies in the area have invested on highly expensive source control engineered solutions for years to reduce the threatening levels of ground level O_3.

In 2011, the Nature Conservancy and the Dow chemical company collaborated to conduct a 5 year project (2011-2015) to identify methodologies for companies to recognize, value and incorporate biodiversity and ecosystem services into business goals, decisions and strategies (Molnar and Kubiszewski, 2012). Under this project, major attention was given to reduce the ground level O_3 limits through reforestation by increasing the tree coverage of the area (Browning et al., 2014). The team identified the importance of trees as a GI strategy not only to reduce the O_3, but also to provide several additional benefits to the area such as avoided climate change costs (e.g. health costs, costs for lost outputs, infrastructure damage costs) due to Carbon storage, compared to traditional engineered solutions. Furthermore, being a low cost air pollution control strategy, increasing the tree cover in this area is also intended to improve the habitats of the area, increase the property values and create recreational opportunities for the local communities (Hawkins and Prickett, 2012, Hawkins and Prickett, 2014).

City of Rome, New York

City of Rome in New York, USA is an area with a population of 35,000 people. This area consists of abandoned brownfield properties around 500 acres of its municipality. A key parcel area of city of Rome has been utilized as former general cable complex, a wire roping manufacturing plant which occupied 17 acres. This area has been abandoned since 1950s and included several abandoned buildings, extensive impervious cover and high level of material contamination. At present, this site is operated by American Alloy Steel, which occupies 58,000 square foot area. This industrial facility is being operating today as a clean manufacturing company by utilizing GI practices to safely filter and manage 100% of the site's stormwater without adding them into combined sewer overflow facilities of the area (Fenwick and Center, 2012).

The transformation of this site area was started in 1996 after receiving the USEPA brownfield pilot program grant. This area has been further awarded a total of $8.4 million to remediate and redevelop 13 municipally owned abundant industrial sites, including $1.6 million for the former Rome Cable site (Rome Sentinal, 2015). During the redevelopment process, a substantial effort was made to manage the runoff of the site. GI practices were used alongside with the conventional practices to achieve this goal. The engineered structures, driving lanes and parking lots were identified as hot spots of generating contaminated runoff. These were directed into and extensive network of bio swales landscaped with various plant species to filter and treat the pollutants (Fenwick and Center, 2012).

Victorian Desalination Project, Wonthaggi, Victoria

The Victorian desalination plant located in Wonthaggi, Australia provides a source of drinking water which is independent of rainfall for Melbourne and several other regional communities. This plant is capable of supplying 150 billion litres of water per year to Melbourne, Geelong and South Gippsland towns. The Victorian desalination project is an outcome of a public private partnership which delivered the biggest desalination plant in Australia and is the world's one of the biggest reverse osmosis plants (Degrémont, 2012). The Victorian desalination plant incorporates the southern hemisphere's largest green roof which occupies 26,000 square meters. The green roof construction was carried out during 2009 to 2012 with a budget of $4 million by the technical design guidance of ASPECT studios and installation and maintenance support of Fytogreen Australia (Aspects Studios, 2013, Green roofs Australasia, 2013).

The focus of this green roof project was to soften the visual impact for the area forced by process plant and other industrial infrastructure. Some of the other objectives considered by implementing the green roof were ecological restoration of the area, improvement of the thermal performance of the building, minimization of the noise impacts from the desalination process plant and the protection of the roof from the harmful effects of solar radiation (Gledhill, 2011, Growing Green Guide, 2012).

2.4.1.1 Concluding Remarks on Case Studies

By analysing these different case studies where GI practices were successfully implemented in industrial areas, it is evident that these practices can provide a wide range of benefits for such areas. The major objectives of implementing GI practices in each of these sites were different, however targeted on improving the overall environmental quality of these areas. One of the important factors that could be identified through reviewing these different case studies is the importance of the availability of funds for the GI implementation. The allocated funds highly influence the GI planning process and it is important to optimally plan the GI implementation to obtain the maximum benefit with economic feasibility. Further complexity is added to the planning process by various constraints such as land area availability to implement GI to achieve required environmental, economic and social demands in such areas. The review of these different case studies further stresses the importance of identifying methodologies to optimally plan GI practices for complex land uses such as industrial areas, to achieve the long term sustainability goals.

2.5 Optimization of Green Infrastructure Practices for Industrial Areas: Opportunities Issues and Challenges

It has been evident that during the past few years, GI practices have gradually become a vital component in the sustainable urban planning (Andersson et al., 2014). In the context of designing sustainable cities, applications of GI practices for several residential, commercial and industrial developments are well discussed in the literature (De Sousa, 2003, Williamson, 2003, Schilling and Logan, 2008). However, the implementation of GI practices in majority of these studies was conducted only based on trial and error or expert judgement without giving a comprehensive attention to the land use type. According to the existing industrial GI implementation case studies reviewed in Section 2.4, it is further evident that the GI selection for particular industrial areas has rather been an ad hoc process and there were no systematic methodologies involved for the optimization of GI practices for such areas.

The impact of land use changes in urban planning has become a focal point of scientific interest due to the fact that different land use types show different degrees of threats to the communities and ecosystems (Nijkamp, 2000, Nijkamp et al., 2002). The uniqueness of each land use type exhibits various types of environmental externalities and should be treated cautiously during the implementation of GI practices (Mathey et al., 2015). According to the land surface characteristics, industrial areas can be divided in to three major land use types as brownfields, existing industrial lands, and mixed land use of brownfields and existing industrial lands (Lambert and Boons, 2002). Thus, these land surface variations create the need for more careful selection and optimization of the best option for industrial areas from a number of different GI practices available, when compared with the other land use types.

Optimization of GI practices in industrial areas incorporates several challenges when compared to residential, commercial or open spaced areas, mainly due to the presence of land contamination. The presence of various industrial activities and considerably larger impermeable surfaces in industrial areas can lead to diffuse stormwater pollution and the selected GI practices for such areas should have the ability to limit these pollutants entering the receiving water bodies (Todorovic et al., 2008). Some of the other challenges include, the lack of financial resources for undertaking soil remediation for the GI implementation, risk of dealing with contamination (e.g. groundwater pollution), legal restrictions, and lack of tools and methodologies to identify optimum GI practices which are suitable for industrial areas (De Sousa, 2003, Atkinson et al., 2014).

Furthermore, one of the major drawbacks of GI practices compared to grey infrastructure is the large land area requirement to achieve the intended environmental or socio economic outcome. Hence the achievement of optimum results through GI implementation should be accomplished within existing land area constraints (Kaini et al., 2012). This creates a challenge in identifying the optimum GI practices for an industrial area to meet the environmental demand forced by the land use type. The other barriers in optimum application of GI practices in industrial areas are, lack of facilities for long term monitoring and evaluation, insufficient supporting and ongoing maintenance funds, failure of highlighting and addressing the real issues of the sites through GI practices, and ultimately a lack of success with project's objectives and the site sustainability (Doick et al., 2009). Figure 2.1 shows the analysis of strengths, weaknesses, opportunities and threats (SWOT), in applications of GI practices within industrial areas (The Nature Conservancy, 2013).

Application of GI practices for industrial areas

Strengths

- Provides nature's inherent resource-efficiency and multi-functionality (water purification, air quality improvement, flood protection etc.)
- Requires low initial expenses and operating expenses (only monitoring, feedback and control)
- Appreciates over time as it grows more interconnected with the local environment
- Is less sensitive to increases in the cost of raw materials, cost of power, power interruption, etc.

Weaknesses

- Often requires a large physical footprint to provide the expected outcomes
- Ecosystem services are currently not comprehensively valued or quantified as part of project technical and non-technical evaluations
- Requires time for proper site investigation and performance maturation
- Engineering community has little expertise in designing GI practices to achieve ecosystem services

Threats

- Can be susceptible to seasonal weather changes and extreme weather conditions
- Can be subjected to unforeseen stresses over its lifetime
- There is generally insufficient understanding of the ecosystem control variables
- There is a lack of recognized ecosystem-related industry design standards
- May require time (years) to mature and to provide the required functionality
- Can pose challenges to obtain permits or regulatory approvals.

Opportunities

- Offers opportunities for innovative non-technical risk management by active local stakeholder participation in the design and operation of the GI solution
- Offers opportunities to partner with local landowners in the use of land areas
- Offers opportunities to boost the local economy by offering valuable by-products like fresh water and biomass that can be used for local food production
- Offers opportunities to create resource efficient systems with minimal waste streams through by-product optimization
- Offers low-cost risk mitigation opportunities

Figure 2.1 – SWOT Analysis on Applications of GI Practices for Industrial Areas (Adapted from The Nature Conservancy (2013))

According to this SWOT analysis, the implementation of GI practices in industrial areas incorporates a unique set of issues including the lack of knowledge on evaluating ecosystem services provided by them for such areas, the lack of expertise in designing GI practices to optimally achieve these ecosystem services, the large physical footprint required for their construction, the lack of proper industry design standards and the challenges in obtaining the permits or regulatory approvals. Another layer of complexity is added to the problem due to the perspectives of the industrial land owners on GI practices as a sustainable solution. There can be issues raised due to their lack of interest on negotiating for the land areas for GI construction. Moreover, there are particularly many different types of stakeholders involved in managing GI projects in industrial areas (Chiu and Yong, 2004, Baas and Boons, 2004). These stakeholders also play a significant role in identifying potential stresses forced upon the area and how the GI practices can be optimally utilized to overcome them. In summary, there exists a wide range of opportunities for GI practices to provide resilience in industrial and business operations when they are optimally designed. However, the knowledge base on their optimal applications should be further enhanced to assess the ways of overcoming the potential challenges and barriers of their implementation. The present research work had made a contribution to the knowledge in the area of GI optimization, by addressing number of these challenges.

2.5.1 Multiple Objectives in Green Infrastructure Decision Making

The rise of GI strategies has started in 1990's when the environmental sustainability was becoming a national and international goal in the world. The growing interest of GI practices during this period was mainly concentrated around the objective of land conservation in urban areas in order to transform them into more sustainable cities (Benedict and McMahon, 2006). However, the pressures forced upon land through urbanization and industrialization have provided the opportunity to look at the multifunctionality of GI practices not only as a land conservation strategy, but also as a means of providing wide range of ecosystem services. The ability of GI practices to provide several functions and ecosystem services within the same spatial area has been then identified with multiple objectives of different perspectives such as environmental, social and economic point of view (European Commission, 2012). In the current context, a major focus is given for the ecosystem services provided by GI practices in the decision making of GI planning process (Hansen and Pauleit, 2014).

The are several objectives associated in decision making when selecting optimum GI practices for a particular site from the pool of different alternatives available (Jia et al., 2013). The process in selecting potential GI practices for a site is further governed by the site specific planning, environmental, institutional and regulatory constraints (Ellis et al., 2004). One of the major challenges faced by the decision maker during the GI selection process is to select the most cost effective and practically best achievable strategy for the site, which also provides benefits in terms of other multiple objectives considered (Lee et al., 2012a). Especially for industrial areas, these objectives can be further complex due to the higher environmental demands, impacts enforced by different GI practices on industry or business operations and the perspectives of variety of stakeholders associated in the project (Todorovic et al., 2008, Chen et al., 2009, UNIDO, 2011, The Nature Conservancy, 2013). Hence, it is always important to maintain the balance between environmental and economic goals of GI implementation while achieving the optimal implication among the multiple objectives (Maringanti et al., 2009).

2.5.2 Stakeholder Participation in Green Infrastructure Decision Making

When optimizing GI practices for a particular area by considering their multiple objectives, studies have highlighted the importance of stakeholder engagement due to the diverse nature of the problem (Young et al., 2010, Jia et al., 2013). These stakeholders may be engineers, planners and environmentalists who can directly or indirectly have an impact on the GI selection (Martin et al., 2007). An engineer who represents a local government agency can have a higher preference on minimizing the costs of the GI strategy while a planner will prefer on improving the amenity of the area. Furthermore, an environmentalist may have an entirely different priority such as reducing the environmental impacts occurred by uncontrolled stormwater. Thus, to provide a reasonable balance between these conflicting objectives of different stakeholders, it is important to incorporate their preferences in the decision making process (Tompkins et al., 2008, Kodikara et al., 2010).

GI planning requires the knowledge from different disciplines such as landscape ecology, urban/regional planning, landscape architecture and engineering which rely on the partnership between different local authorities and stakeholders for its successful implementation. The preferences of these different stakeholders are elicited in the planning process to support the knowledge transfer and ensure environmental justice (Hansen and Pauleit, 2014).

Martin et al. (2007), Young et al. (2010), Chan et al. (2012), Sanon et al. (2012) and Jia et al. (2013) have studied the importance of the stakeholder participation in GI planning for urban areas by considering their ecosystem services as multiple objectives that support the decision making. However, none of these studies have extensively studied the importance of stakeholder participation to identify the objectives or criteria relevant to the GI planning in industrial areas. The industrial areas are complex land use types which can include wide range of different GI practices with different impacts for water quality and quantity, air quality, which are subjected to different constraints and entailing variable costs. Unfamiliarity or lack of the knowledge on stakeholders on the specific objectives for such areas could negatively influence the decision making process of optimum GI planning (Thomas, 2002, Viavattene et al., 2008). It had been argued that transferring corporate and social responsibility (that includes environmental, economic and social performances) into industry's objectives is best undertaken through the stakeholders point of view (Sharma and Henriques, 2005). Hence, the strategies that promote sustainability for industrial areas such as GI practices should be given careful attention in terms of identifying their particular objectives and the influences of stakeholders for their optimum applications.

2.6 Tools and Techniques Used for the Green Infrastructure Optimization

Software tools have been used for water resource management since the mid-1960s and the modelling tools that have the ability of simulating the runoff quality and quantity started emerging from 1970s (Zoppou, 2001). After the GI practices were identified as vital components in managing urban stormwater, these tools were updated with the components that can evaluate the effectiveness of GI practices. The primary goal of most of these tools was to assess the ability of GI practices in managing urban runoff quality and quantity (Jayasooriya and Ng, 2014). The cost modules of these tools include measures for cost benefit analysis, and assessment of operation, installation and maintenance costs of GI practices. In selecting the GI practices for a particular area, these different types of tools are widely used in different contexts to obtain information on assessing the performance of different GI practices (Eliot and Trowsdale, 2007). In addition, there are different techniques which are used in decision making problems with multiple objectives and performance measures that involve stakeholders. This section will review various modelling tools that can assess the performances of different GI practices and Multi Criteria Decision Analysis (MCDA) techniques which can be used as decision support techniques for the GI optimization problems.

2.6.1 Review of Green Infrastructure Modelling Tools

GI practices attempt to replicate the pre development conditions of a site, which has been subjected to develop by reducing the runoff quantities and improving the runoff quality (Davis, 2005). The models which have the ability for predicting the responses of different GI practices on stormwater management and costs of GI are discussed within this section. Table 2.4 shows some of the modelling tools that have the ability to assess the performances and costs of various GI practices and references to the case studies they have been previously applied. Ten modelling tools among this list which are widely used with published work in the literature are reviewed below. This review is also published in Jayasooriya and Ng (2014).

Table 2.4 – GI Modeling Tools (Jayasooriya and Ng, 2014)

Modelling Tools	**References and Case Studies**	**Supported GI Practices**	**Comments**
Environmental Protection Agency (EPA) Green Long Term Control- EZ Template	(Schmitt et al., 2010)	Green Roofs, Vegetated Swales, Bio Retention Basins, Permeable Pavements, Rain Barrels	• Planning tool for combined sewer overflow control. • Can be used in small communities.
Water Environmental Research foundation (WERF) Best Management Practices (BMP) SELECT Model	(Reynolds et al., 2012)	Extended Detention ,Bio retention, Wetlands, Swales, Permeable Pavements	• Examines the effectiveness of alternative scenarios for controlling stormwater pollution. • Water quality parameters that can be simulated are Total Suspended Solids, Total Nitrogen, Total Phosphorus and Total Zinc.
RECARGA	(Dietz, 2007, Atchison et al., 2006)	Bio Retention, Rain Garden, Infiltration	• Performance evaluation of bio retention rain garden and infiltration practices.
Virginia Runoff Reduction Method (VRRM)	(Bork and Franklin, 2010)	Green Roofs, Downspout Disconnection, Permeable Pavements, Grass Channels, Dry Swales, Bio Retention, Infiltration, Extended Detention Ponds, Wet Swales, Constructed Wetlands, Wet Ponds	• Incorporates built-in incentives for environmental site design, such as forest preservation and the reduction of soil disturbance and impervious surfaces.
Program for Predicting Polluting Particle Passage through Pits, Puddles, & Ponds (P8 *Urban Catchment Model)*	(Elliott and Trowsdale, 2007, Obeid, 2005)	Detention Tanks, Ponds, Wetlands, Infiltration Trenches, Swales, Buffer Strips	• Model the generation and transportation of pollutants through urban runoff and the effectiveness of GI for improving the water quality.
Delaware Urban Runoff Management Model (DURMM)	(Lucas, 2004, Lucas, 2005)	Filter Strips, Bio Retention Swales, Bio Retention, Infiltration Swales	• Spreadsheet tool to assist GI design.

Modelling Tools	References and Case Studies	Supported GI Practices	Comments
Stormwater Investment Strategy Evaluator (StormWISE) Model	(McGarity, 2006, McGarity, 2010, McGarity, 2011)	Riparian Buffers ,Filter Strips, Wetland/Rain Garden, Bio Retention/Infiltration Pits, Rain Barrel/Cisterns, Land Restoration By Impervious Surface Removal, Permeable Pavements, Green Roofs	• Studies on GI projects based on pollutant load reduction and cost benefits.
EPA Stormwater Management Model (SWMM)	(Huber and Singh, 1995, Tsihrintzis and Hamid, 1998, Huber, 2001, Khader and Montalto, 2008, Rossman, 2010)	Bio Retention, Infiltration Trenches, Porous Pavement, Rain Barrels, Vegetative Swales, Green Roofs, Street Planters, Amended Soils	• Planning, analysis and design related to stormwater runoff, combined sewer overflows and drainage systems. • Complex model with variety of features. • One of the most popular software.
WERF BMP and Low Impact Development (LID) Whole Life Cycle Cost Modelling Tools	(Reynolds et al., 2012)	Green Roof, Planters, Permeable Pavements, Rain Gardens, Retention Ponds, Swales, Cistern, Bio Retention, Extended Detention Basins	• Planning level cost estimation for GI practices. • Different spreadsheet tools are designed for different practices.
Centre for Neighborhood Technology(CNT) Green Values National Stormwater Management Calculator	(Jaffe, 2011, Guo and Correa, 2013)	Green Roofs, Planter Boxes, Rain Gardens, Cisterns, Native Vegetation, Vegetation Filter Strips, Amended Soils, Swales, Trees, Permeable Pavements	• Allows the user to select a runoff reduction goal and select the combination of GI practices that provides the optimum runoff reduction in a cost effective way.
CNT Green Values Stormwater Management Calculator	(Kennedy et al., 2008, Wise et al., 2010, Jaffe et al., 2010)	Roof Drains, Rain Gardens, Permeable Pavements, Trees, Porous Pavements, Drainage Swales	• Tool which helps to get an approximation of financial and hydrologic conditions for a user defined site.

Modelling Tools	References and Case Studies	Supported GI Practices	Comments
Chicago Department of Environment Stormwater Ordinance Compliance Calculator	(Emanuel, 2012)	Green Roofs, Planter Boxes, Rain Gardens, Native Vegetation, Vegetated Filter Strips, Swales, Trees	• Used to evaluate the opportunities of GI with regard to the guidelines of Chicago's stormwater management ordinance.
Long-Term Hydrologic Impact Assessment (L-THIA)	(Tang et al., 2005, Bhaduri, 1998, Bhaduri et al., 2001, Engel et al., 2003)	Bio Retention/Rain Gardens, Grass Swale, Open Wooded Space, Permeable Pavement, Rain Barrel/Cisterns, Green Roof.	• Consists of calculations for Stormwater runoff and pollutant loading.
GI Valuation Tool Kit	(GiVAN, 2010)	Green Cover	• Evaluate the dollar value of environmental and social benefits.
EPA System for Urban Stormwater Treatment Analysis and Integration (SUSTAIN)	(Lai et al., 2006, Lai et al., 2007, Lai et al., 2009, Lai et al., 2010, Shoemaker et al., 2013)	Bio Retention, Cisterns, Constructed Wetlands, Dry Ponds, Grassed Swales, Green Roofs, Infiltration Basins, Infiltration Trenches, Permeable Pavements, Rain Barrels, Sand Filters (Surface And Non-Surface),Vegetated Filter Strips ,Wet Ponds	• Implementation planning for flow and pollution control. • Selects the most cost effective solution in stormwater quality and quantity management.
Model for Urban Stormwater Improvement Conceptualization(MUSIC)	(Wong et al., 2002, Deletic and Fletcher, 2004, Wong et al., 2006, Dotto et al., 2011)	Bio Retention Systems, Infiltration Systems, Media Filtration Systems, Gross Pollutant Traps, Buffer Strips, Vegetated Swales, Ponds, Sedimentation Basins, Rainwater Tanks, Wetlands, Detention Basins.	• Assists in decision making of GI selection for stormwater management in urban development.
Low Impact Development Rapid Assessment (LIDRA)	(Montalto et al., 2007, Behr and Montalto, 2008, Yu et al., 2010)	Green Cover	• Evaluates the effectiveness of green space in reducing stormwater runoff.

Modelling Tools	References and Case Studies	Supported GI Practices	Comments
WinSLAMM (*Source Loading and Management Model* for Windows)	(Pitt and Voorhees, 2002)	Infiltration/Bio filtration Basins, Street Cleaning, Wet Detention Ponds, Grass Swales, Filter Strips, Permeable Pavement	• Evaluates how effective the GI practices in reducing runoff and pollutant loadings. • The cost effectiveness of practices and their sizing requirements can also be modeled.
Street Tree Resource i-Tree i-Tree Streets /Analysis Tool for Urban Forest Managers (STRATUM)	(McPherson et al., 2005, Soares et al., 2011)	Street Trees	• Assessment of the street trees in terms of current benefits, costs and management needs.
i-Tree Hydro	(Kirnbauer et al., 2013)	Trees, Green Cover	• Simulate the effect of trees and green cover on water quality.

RECARGA

RECARGA is a tool that was mainly developed to estimate the reduction of runoff volume through GI, which also indirectly supports to improve the water quality (Wang et al., 2013). The tool can be used to size and evaluate the performance of bio retention facilities, rain gardens and infiltration practices. This modelling tool simulates infiltration of water through three distinct soil layers with user defined climatic conditions (Atchison and Severson, 2004).

RECARGA is used to size individual GI practices and therefore it is one of the popular tools used in site or neighborhood scale GI planning. The equations presented in Technical Release-55 (TR-55) (SCS, 1986) are used for runoff calculation in RECARGA for impervious and pervious areas (Gaffield et al., 2008). The Green-Ampt infiltration model is used to estimate the initial infiltration into the soil surface and the van Genuchten relationship is used for drainage between soil layers (POTTER, 2005, Montgomery et al., 2010, Brown et al., 2013). One of the important features of this modelling tool is that it can capture the soil moisture and evapotranspiration during a storm event (Atchison and Severson, 2004, Atchison et al., 2006).

The inputs to the tool include hourly precipitation or event precipitation, hourly evapotranspiration, drainage area, impervious area, previous area curve number, soils properties and properties of the GI feature. Specific design parameters for different GI such as ponding zone depth, root zone thickness and properties and under drain flow rate should also be provided to assess the performance of the GI practice. The outputs are ponding times, number of overflows, water balance and total tributary runoff from both impervious and pervious areas. Though RECARGA is developed using the MATLAB computer program, it has been incorporated into a graphical user interface which provides more user friendliness.

P8 Urban Catchment Model

P8 is a model developed to predict runoff generation and transportation from urban catchments (Walker Jr, 1990). The tool is primarily applied to evaluate the design requirements for GI practices in order to achieve 70-85% of Total Suspended Solids (TSS) removal. The GI practices that can be modeled using the tool are retention ponds, infiltration basins, swales and buffer strips. P8 is identified as a tool that is best suited for the conceptual level preliminary design of GI practices for a catchment scale (Elliott and Trowsdale, 2007). The modelling tool can be applied for either site or catchment scale GI planning activities.

The underlying runoff modelling algorithms of P8 are derived from a number of other catchment models such as SWMM, STORM, Hydrological Simulation Program – Fortran (HSPF) and TR-20. Runoff generated from the pervious areas is calculated from the Soil Conservation Service (SCS) curve number method and runoff from the impervious areas is assumed to be the rainfall once the depression storage is achieved. The classes of particles treated by various GI practices are defined by factors which control catchment export and behavior of treatment measures such as settling velocity, decay rate and filtration efficiency. The treatment of water quality components are defined by their weight distributions across particle classes (Walker Jr, 1990).

The major inputs to the model are; characteristics of the catchment and the GI practices, particle and water quality component characteristics, precipitation and air temperature (Palmstrom and Walker, 1990, Walker Jr, 1990). The simulations of the model are based on continuous hourly rainfall data. The model outputs are, water and mass balances, removal efficiencies, comparison of flow, loads and concentration across the GI, elevation and outflow ranges for each GI, sediment accumulation rates, mean inflow or outflow concentration, detailed statistical summaries , continuity checks on simulation data and time series graphs. P8 is a user friendly tool with several tabular and graphic formats which could be easily adapted by engineers and planners.

SWMM

SWMM is one of the most popular runoff modelling tools among water resource professionals and researchers. SWMM has the capability of evaluating the performance of several GI practices such as permeable pavements, rain gardens, green roofs, street planters, rain barrels, infiltration trenches and vegetated swales. SWMM can be applied in a wide range of spatial scales varying from site to catchment scale. SWMM incorporates a sub catchment based approach to simulate runoff generated from rainfall where the runoff can be diverted to different storage or treatment devices (Rossman, 2010).

SWMM consists of four components: “RUNOFF”, EXTRAN”, “TRANSPORT” and “STORAGE/TREATMENT (S/T)” blocks which are used to simulate different stages of the hydrological cycle (Tsihrintzis and Hamid, 1998). Storage processes are well simulated within all the blocks while the S/T block is used for the modelling of a majority of the processes occurring in GI for water quality improvement. First order decay processes are applied in RUNOFF, TRANSPOSRT and S/T blocks. Settling velocities are used in the TRANSPORT block when simulating the sedimentation process that occurs in GI. Biological processes can be only simulated by first order decay or removal equations through RUNOFF, TRANPORT or S/T blocks (Huber et al., 2004).

The catchment characteristics need to be first defined as the input data for SWMM which are, area, width and slope of the sub catchment, rainfall data, percentage imperviousness, manning’s “n” values and depression storage for pervious and impervious areas. Finally, the sizing characteristics of different GI practices are required to simulate their effectiveness on managing urban runoff. An output report file is generated from the data used for each model run which also contains the status of the simulation. The output report file is used by the model interface to create time series graphs, tables and statistical analysis of the simulation results. Handling of SWMM requires knowledge of fundamental processes related to hydrological modelling which limits its application for specific user groups (Huber et al., 1988, Huber and Singh, 1995, Huber, 2001, Huber et al., 2004, Abi Aad et al., 2010).

WERF BMP and LID Whole Life Cycle Cost Modelling Tools

WERF modelling tools contain a set of excel spread sheets which facilitate the evaluation of whole life cycle costs of GI practices for stormwater management. These tools have the ability to express monetary values associated with GI practices with regards to capital outlay, operation and maintenance costs. The modelling tools are developed for nine GI practices, them being; extended detention basin, retention pond, swale, permeable pavement, green roof, large commercial cisterns and residential rain garden, curb-contained bio retention and in-curb planter vault. WERF tools are mainly suitable for conducting planning level cost estimates (Water Environment Research Foundation, 2009).

WERF modelling tools contain cost details which are derived from the US literature, interviews and expert judgments. The default values for cost analysis can be altered by users whenever the site specific data are available for the area.

The user inputs for the model are general information of the treatment devices such as system size, drainage area and system type. After evaluating the whole life cycle costs for the construction, operation and maintenance stages, a cost summary is provided to the user. Furthermore, the tool gives users an option of selecting the sensitivity analysis in the planning and designing stage. Illustration of the results by present value graphs is another important output that WERF BMP modelling tools can produce. Three different present value graphs can be obtained from the modelling tools such as annual present value of cost expenditure, cumulative discounted cost with time and discounted costs with time (Houdeshel et al., 2009). The WERF modelling tools for LID and BMP come with an interface for the data entry in the format of an excel spread sheet which makes the handling of software easy for different levels of user groups (Water Environment Research Foundation, 2009).

Green Infrastructure Valuation Toolkit

Green Infrastructure valuation tool kit is an excel spread sheet tool which can calculate the costs and benefits associated with different GI practices. The tool can be used in decision making to select the best investment and compare the benefits of GI over conventional development to select the best practice from a possible set of opportunities. The target user groups are managers, developers or other stakeholders who are interested in investment of GI practices (Ozdemiroglu et al., 2013). The difference between the GI Valuation Toolkit and the other tools reviewed earlier are that, this tool calculates benefits of GI not only for stormwater management but also for ten other different aspects. The eleven different aspects that the tool addresses in evaluating the economic benefit include: stormwater and flood management, climate change adaption and mitigation, place and communities, health and wellbeing, land and property values, investment, labor productivity, tourism, recreation and leisure, biodiversity, and land management (Natural Economy Northwest, 2010, Evans et al., 2012). The tool calculates economic benefits by considering the land area or green space covered with any GI practice.

Costs and benefits related to different services of GI practices are calculated using the market prices of the area. When the market values are not available, the non-market values can be applied. The modelling approach for calculating the economic benefit uses various evaluation methods such as contingent valuation, hedonic pricing, travel cost method, effects on production, preventative expenditure, benefit transfer, and specific values. (Natural Economy Northwest, 2010).

The main input data required for the calculation are the land area covered with green space and the information on species of trees or vegetation used. The cumulative economic benefit of all eleven aspects can be calculated as the final outcome. The return on investment of the GI implementation can be also calculated which can be a decision aid for the stakeholders. Though this is designed as a simple and easy to use spreadsheet tool, the support of an expert such as an economist is recommended during the cost benefit analysis process (Green Infrastructure Valuation Network, 2010).

CNT Green Values National Stormwater Management Calculator

The CNT national stormwater management calculator which is also known as National Green Values Calculator (GVC) is a tool that was developed to compare the performance, costs and benefits of GI practices against conventional stormwater management practices (Kennedy et al., 2008). The step by step procedure of the calculator allows the users to set up a runoff reduction goal for their sites by considering the runoff reduction efficiency through a set of GI practices. The GI practices that are incorporated in the National GVC include; green roof, planter boxes, rain gardens, cisterns/rain barrels, native vegetation, vegetated filter strips, amended soils, roadside swales, trees, swales in parking lot, permeable pavement on parking, permeable pavement on drive ways and alleys, and permeable pavement on sidewalks. The calculator is designed to be used in site scale, and therefore the tool is incapable of handling evaluations from neighborhood scale to catchment scale (Wise, 2008, Center for Neighborhood Technology, 2009).

CNT uses the Soil Conservation Service (SCS) runoff curve number method to calculate the volume of runoff generated. The effect on the GI practices on infiltration, evapotranspiration and reusing the stormwater runoff is calculated by modelling each practice's ability to capture runoff (Kauffman, 2011). The construction and maintenance costs for different GI practices are calculated and added to get the total life cycle cost for the project. The cost module includes the design life cycle of the project and gives the ability for the user to analyze costs and benefits for: 5, 10, 20, 30, 50, and 100 year life spans. The cost valuations for infrastructure maintenance and design are obtained from the relevant literature and the latest industry data for the relevant GI practice (Center for Neighborhood Technology, 2009).

The inputs for the National GVC contains site specific parameters such as the land cover distribution, the soil type, the runoff reduction goal and the attributes of the different GI practices. The National GVC is available as a web based open source tool and the simple interface makes it easier to handle for users with any knowledge level. However, the tool cannot be applied for different geographical regions since it contains inbuilt data for regions in US only.

SUSTAIN

SUSTAIN is an ArcGIS based decision support system developed by the USEPA to guide water resource professionals for the design and implementation of management plans to preserve water and meet water quality goals in catchment scales. It also includes the application of GI practices in stormwater management projects and allows the users to assess these practices in terms of both environmental and economic perspectives. The currently supported GI practices in SUSTAIN include: bioretention, cistern, constructed wetland, dry pond, grassed swale, green roof, infiltration basin, infiltration trench, porous pavement, rain barrel, sand filter (surface and non-surface),vegetated filter strip and wet pond (Lai et al., 2007).

The cost component for GI construction is presented in more sophisticated manner in SUSTAIN compared to the other models, by considering measures to analyze the unit costs of individual segments of the GI. The cost estimation module in SUSTAIN is one of the strongest cost modules available in any similar software to analyze the economic benefits of the GI practices in stormwater management (Lai et al., 2006, Lai et al., 2009, Lai et al., 2010). The cost data in the cost estimation module are obtained directly from industry and the unit cost approach in SUSTAIN is designed to minimize the errors that can result by considering the bulk construction cost of GI practices on a country wide basis.

The input data required for the model are the land use data, catchment data and the design details of different GI practices. The model outputs are the performances of different GI practices in runoff quality improvement and amount of runoff reduction. SUSTAIN integrates GIS data for the analysis which makes the data input to the program more comprehensive with complexity in model handling. Therefore, the end user needs to have sufficient knowledge on stormwater management practices and GIS software packages (Lee et al., 2012b, King Country, 2013). SUSTAIN software program is mainly suitable for large scale projects which need more accuracy on the basis of both environmental and economic aspects.

MUSIC

MUSIC is a conceptual level planning and designing tool used for the performance assessment of different GI practices in improving stormwater quality. This modelling tool enables the users to determine, the quality of runoff produced by catchments, the performances of different GI measures on improving the runoff quality in order to achieve target pollution reduction levels with the option to select the best possible GI scenarios based on their life cycle cost assessment. MUSIC can be operated in a range of spatial scales varying between 0.01 km^2 to 100 km^2 (Wong et al., 2002). MUSIC supports a number of GI practices such as bio retention systems, infiltration systems, media filtration systems, gross pollutant traps, vegetated swales, sedimentation basins, rainwater tanks, wetlands and retention ponds.

The underlying model algorithms of MUSIC were developed by modifying the properties of a previous model known as SimHyd, developed by Chiew and McMahon (1997), which enables the disaggregation of daily runoff into sub-daily temporal patterns. The runoff generation from impervious and pervious areas is modeled separately in MUSIC. A stochastic approach with dry and wet weather event mean concentrations are used for the pollutant generation simulations of MUSIC (Dotto et al., 2011, Dotto et al., 2008). The life cycle costing data were gathered from several case studies in different cities across Australia. These data are further analyzed by means of regression and statistical methods to develop a representative set of data for different GI treatment measures (music by eWater User Manual, 2013).

MUSIC contains inbuilt meteorological data and climatic data for 50 reference areas within Australia. Users also have the opportunity to input meteorological data for specific study areas. Catchment characteristics include impervious area and land use. Design specifications of the device (treatment type, size, area) are the other input data required for the MUSIC modelling tool. The outputs generated from the model are flow reduction capability, pollutant removal efficiencies and the life cycle costs of different GI scenarios. The output is illustrated as time series graphs, tabular statics and cumulative frequency graphs (Wong et al., 2002, Wong et al., 2006). The tool is designed for professionals with more technical knowledge in stormwater management and the target user group includes urban stormwater engineers, planners, policy staff, and state, regional and local government agencies.

LIDRA

LIDRA is a tool that assesses the cost effectiveness of different GI practices using hydrological and cost accounting methods. The modelling tool calculates the hourly water balance with the opportunity of selecting over 30 different GI strategies. Most importantly LIDRA contains a built in database that contains the life cycle costs with a phased life cycle costs algorithm for GI practices for the cost benefit analysis (Spatari et al., 2011). LIDRA is web based online assessment tool and GI planning is done in the catchment scale (Montalto et al., 2007, Montalto et al., 2011).

The model contains a stochastic precipitation generator and the runoff calculation is based on a physically based water budgeting procedure. The precipitation data are stochastically generated by historical rainfall data sets by using a Markov Chain and bootstrapping method. The difference in runoff from pre and post development of different GI scenarios is calculated using a water balance based on the Thornthwaite Mather approach (Aguayo, 2010). For the economic component, the model uses a 30 year life cycle costing algorithm which reports capital, operation and maintenance costs (Yu et al., 2010).

The major data inputs required in LIDRA modelling tool are: hourly precipitation data, parcel characteristics of the area, land use data, soil types and parameters of GI practices. Some of the outputs of this tool are the amount of runoff that can be reduced annually, the annual or cumulative costs for the practices, the comparison of cost effectiveness of different practices and the rate variability of results that the user needs to handle when uncertainty and changes occur in cost, climate and inflation rates (Yu et al., 2010) . LIDRA is an online web based program with a user friendly interface that makes it easy to handle by users of different knowledge groups.

WinSLAMM

WinSLAMM was initially developed as a model to study the relationship between pollutants in urban runoff and runoff quality. With the advancement of GI practices as stormwater source control measures, the tool has been upgraded by adding modules which have the capability of modelling the performances and life cycle costs of different practices such as infiltration/bio filtration basins, street cleaning, wet detention ponds, grass swales, filter strips and permeable pavements (Pitt and Voorhees, 2002, Pitt and Voorhees, 2004). The tool supports modelling in different spatial scales such as site, catchment and regional scales.

WinSLAMM is commonly used as a planning tool which can be applied for the hydrology of different types of storms including small storms. The model can evaluate long series of rainfall events and the impacts of urban soils on runoff are also considered. The biological conditions of the receiving waters are calculated according to the type of GI practice which has been used with the characteristics of the site. Cost details of the different practices can be directly obtained from the model run. WinSLAMM can be integrated with a number of other drainage models when a detailed analysis of runoff is required. The model also contains inbuilt Monte- Carlo components for considering uncertainties (Pitt and Voorhees, 2004, Pitt, 2006).

The tool uses input parameters such as characteristics of contributing catchments and the characteristics of pollutants associated with particulate solids in these areas. The calculated model outputs from the WinSLAMM model are runoff volumes and runoff quality in pre development conditions and post development conditions with total control costs in terms of capital costs, land costs, annual maintenance costs, present value of all costs and annualized value of all costs. One of the important features of this model is that the outputs can be imported to a number of other models and also can be integrated in GIS platform. The users require fundamental knowledge of urban hydrology and stormwater management procedures in order to handle the modelling tool (Pitt and Voorhees, 1995, Pitt and Voorhees, 2002, Pitt and Voorhees, 2004, Pitt, 2006).

2.6.1.1 Comparison of the Modelling Tools

In this section, a comparison has been conducted on the ten modelling tools discussed in Section 2.6.1, in terms of the modelling and simulation approaches, data requirements, accuracy and regional limitations.

Modelling and Simulation Approach

Among the ten models selected for the review, except for WERF and GI Valuation Toolkit, all the other models simulate the rainfall runoff generated by rainfall to assess the performance of GI practices. RECARGA, P8, SWMM, SUSTAIN, MUSIC, LIDRA and WinSLAMM models can facilitate continuous and single event simulation while CNT can be used for event based simulation only. RECARGA, P8 and LIDRA, use hourly time steps for the rainfall runoff simulations. SWMM, SUSTAIN, MUSIC, WinSLAMM can simulate runoff for hourly or shorter time steps.

In the modelling of economic aspects, GI Valuation Toolkit uses complex economic pricing and evaluation methods for the cumulative cost benefit calculations. Tools that have the capability of calculating the lifecycle costs for GI (CNT, MUSIC, LIDRA and WERF) contain inbuilt databases for the construction, maintenance and operation costs for GI practices specifically for the region where the model has been developed.

Data Requirements

The general data requirements for almost all the tools are climatic data, soil profile and land use data. RECARGA, P8, LIDRA and WinSLAMM models require fewer inputs compared to complex hydrologic and hydraulic models such as SWMM. Therefore, these models are suitable for planning level GI implementation activities rather than for detailed design. Most of the input data required for these models can be obtained from literature, drainage plans, local councils or soil surveys. MUSIC and

CNT models also have low input requirements in runoff modelling since most of the regional specific parameters (climatic data, soil types, hydraulic conductivity etc.) are inbuilt with the software as default values. SUSTAIN model inputs are integrated with a GIS interface. Thus the GIS based inputs such as catchment information, land use, land cover and digital elevation profiles are required and this can be found easily from local mapping sources. For the costing data MUSIC, WERF, SUSTAIN, LIDRA and GI Valuation Toolkit comes with inbuilt input databases which makes the data requirements for economic analysis much more user friendly. However, user defined input costing data can also be provided to these models when more specific valuations are required.

Model Accuracy

The uncertainty associated with any modelling tool is an attribute which can have a significant impact on accuracy of the final result. However, uncertainty can be reduced to a certain level by calibrating and validating the model results whenever the data are available. When looking at the accuracy levels of the different models reviewed, SWMM and WinSLAMM provide the highest level of accuracy as detailed design tools. WinSALMM contains built in Monte Carlo sampling procedures to reduce the uncertainties associated with the data inputs. These procedures help to generate the model outcome more accurate by representing them in probabilistic terms (O'Bannon Ph et al., 2008). Several literature studies on SWMM modelling indicate that SWMM can produce reasonably accurate results when the model outcomes are calibrated and validated (Temprano et al., 2005, Barco et al., 2008, Sun et al., 2012).

RECARGA, P8, CNT and LIDRA are most suitable for GI planning level activities, due to the uncertainties and the variation of input parameters in these tools can significantly affect the detailed design process. SUSTAIN model incorporates an aggregated modelling approach to represent distributed GI practices in larger scale catchment planning applications. Though this methodology has been introduced to reduce the computational times and efforts, it can lead to uncertainties in the model output. MUSIC is also a tool that is only accurate as a conceptual designing tool since it does not include the necessary algorithms for the detailed designing of GI practices.

The inbuilt cost data in WERF and GI Valuation Toolkit models have limited accuracy levels to be used in a range of different applications since they are obtained by using a reference data set. Therefore, users need to define their own cost data using a number of references in order to get more accurate results. The GI Valuation Toolkit also does the cost benefit analysis based on a number of other ecosystem services. Therefore, some of the benefits of these services can be subject to the phenomenon of double counting. This can also create some uncertainties in the results by over estimating the benefits of GI practices. The CNT model does not include the costing details for pipes or detention ponds since the model does not predict the peak flow. Therefore, CNT cannot be accurately used to determine the costing required for storage and sizing of the overflows (Center for Neighborhood Technology, 2009).

Regional Applications and Limitations

Though there are several different tools available for GI modelling, one of the major limitations of them are that the majority of the models are designed to be applied within a specific country or region where they were developed. There are very few tools available that can be transferable to any geographic location since most of them contain inbuilt databases related to the region or location where they were developed.

RECARGA is a tool that uses the Department of Natural Resources (DNR) conservation practice standards for Wisconsin, USA and P8 is calibrated with the catchment data of Rhode Island. Therefore, these two tools have limited applications only for a particular area outside of those locations. MUSIC is the most popular tool in Australia for modelling GI practices which contains an inbuilt climatic database. MUSIC can be also used to model the performances of GI practices under UK climatic conditions. WERF, SUSTAIN, and LIDRA are developed with inbuilt databases for a specific context but all three modelling tools have the flexibility for users to include new data for the required modelling purposes. Since CNT is an online tool which comes up with cost benefit data for a range of different cities in US, the usage of the tool is only limited to states in US. The GI Valuation Toolkit which was developed in the UK can also be used in any other region with the inclusion of cost benefit data of the particular region. WinSLAMM was initially developed for use in North America and has recently extended its usage for overseas. Among the ten models, SWMM is one of the most sophisticated models which can be used in any geographic region provided that the wide range of required input data is available.

2.6.2 Multi Criteria Decision Making (MCDA)

Environmental decision making is often complex and requires multi - disciplinary knowledge bases which incorporate, engineering, economics, ethics, physical and social sciences backgrounds (Huang et al., 2011). As the complexity of a decision increases, it becomes a difficult task for the stakeholders to identify the management alternative that maximizes all the benefit criteria. Hence, this difficulty in environmental decision making has demanded more sophisticated analytical methods that can reach for a compromise solution which is based upon the preferences of different stakeholders for the different attributes (Herath and Prato, 2006).

To address problems that involve heterogeneous stakeholder groups with conflicting objectives where ideal solution does not exist which satisfies all the criteria, Multi Criteria Decision Analysis (MCDA) techniques provide means of compromising for a solution based on the subjective preferences of decision makers (Herath and Prato, 2006, Ishizaka and Nemery, 2013a). The term MCDA was defined by Belton and Stewart (2002) as “an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter”. In the water resource and environmental planning applications, MCDA has been widely used in the recent past to provide solutions for water policy evaluation, strategic planning and infrastructure selection (Hajkowicz and Collins, 2007).

Subjective information such as human beliefs and preferences on different criteria or attributes plays a major role in obtaining a solution for a decision making problem. MCDA techniques analyze the decision problems with multiple complex objectives according to a structured framework. Furthermore, the issues in solving the problems such as, uncertainties and risks can also be taken into account while performing a MCDA (Ananda and Herath, 2009).

Over the past few decades, several studies have used MCDA techniques for environmental decision making to optimize the alternatives for natural resources (Hajkowicz and Collins, 2007, Ascough et al., 2008, Steele et al., 2009, Wang et al., 2009). One of the advantages of the MCDA techniques in environmental decision making is that, each of these techniques has the capability of assessing the similarities or potential areas of conflict between stakeholders with different views, which results in more comprehensive understanding of values held by each other (Kiker et al., 2005). Furthermore, MCDA approaches support the policy makers by providing an understanding of strategic planning through communication between stakeholders (Ananda and Herath, 2009). It is also apparent that the proper use of a MCDA model represents adequate environmental- economic implications in an environmental project (Munda et al., 1994). Therefore, it is evident that MCDA is one of the prominent techniques in environmental decision making.

2.6.2.1 Stakeholder preference elicitation in MCDA

Environmental decision making involves numerous stakeholders with conflicting views. The MCDA provides transparent means of communicating with the stakeholders and elicit their preferences (Mustajoki et al., 2004). The notion of 'preference' in the context of MCDA reflects the desires of the decision maker on a set of alternatives or preference parameters such as weights and preference thresholds related to individual performance measures (Kodikara, 2008). The preference elicitation method used in MCDA can have a significant influence on selection of the best solution among competing alternatives.

As noted by Vincke (1992), the preference elicitation for comparing two objects can be present in two different ways as; 1) preference for one of them and 2) indifference between them. In the first instance, the decision maker presumes a numerical representation for the two objects while in the second case, a preference relation is constructed from the knowledge associated to the compared objects. In the first situation, uncertainties can occur due to incomplete and ambiguous information whereas in the second case uncertainties can arise due to the fact that the decision maker may not be able to clearly state the preference relation for the pair of objects. (Figueira et al., 2005a).

Gathering preference data is one of the major difficulties associated with the MCDA process. Previous studies have proven that the preferences of the decision makers can be variable due to several circumstances which could lead to biased outcomes (Lloyd, 2003, Braga and Starmer, 2005). The preference elicitation methods should always attempt to collect the information of user preference as much as possible to achieve the goals of the decision analysis. Furthermore, the preference elicitation methods should be able to avoid preference reversals, discover hidden preferences and assist the users making trade-offs when confronting with competing objectives (Chen and Pu, 2004). Hence, it is evident that selecting the suitable preference elicitation method is also one of the important steps in the MCDA process. A comprehensive review on the stakeholder preference elicitation method used in the present study is presented in Chapter 4.

2.6.2.2 Structure of MCDA

The general steps in performing a MCDA for a problem has been described by several authors (Howard, 1991, Hammond et al., 1999, Yoe, 2002, Gregory et al., 2012, Estévez and Gelcich, 2015). Figure 2.2 shows the flow chart of different stages of the MCDA process. It should be noted that MCDA is not a linear top down process. The modifications can be performed in previous stages according to the requirements of the study (Estévez and Gelcich, 2015). The first step in the process is the definition of the MCDA problem. It is important to have a clear understanding of the decision problem and its goals during this problem definition stage. Involvement of stakeholders during the problem definition stage will also provide the required understanding of the background, expectations through the solutions, and information on potential socio- economic conflicts within the context of the problem (Ehler and Douvere, 2009).

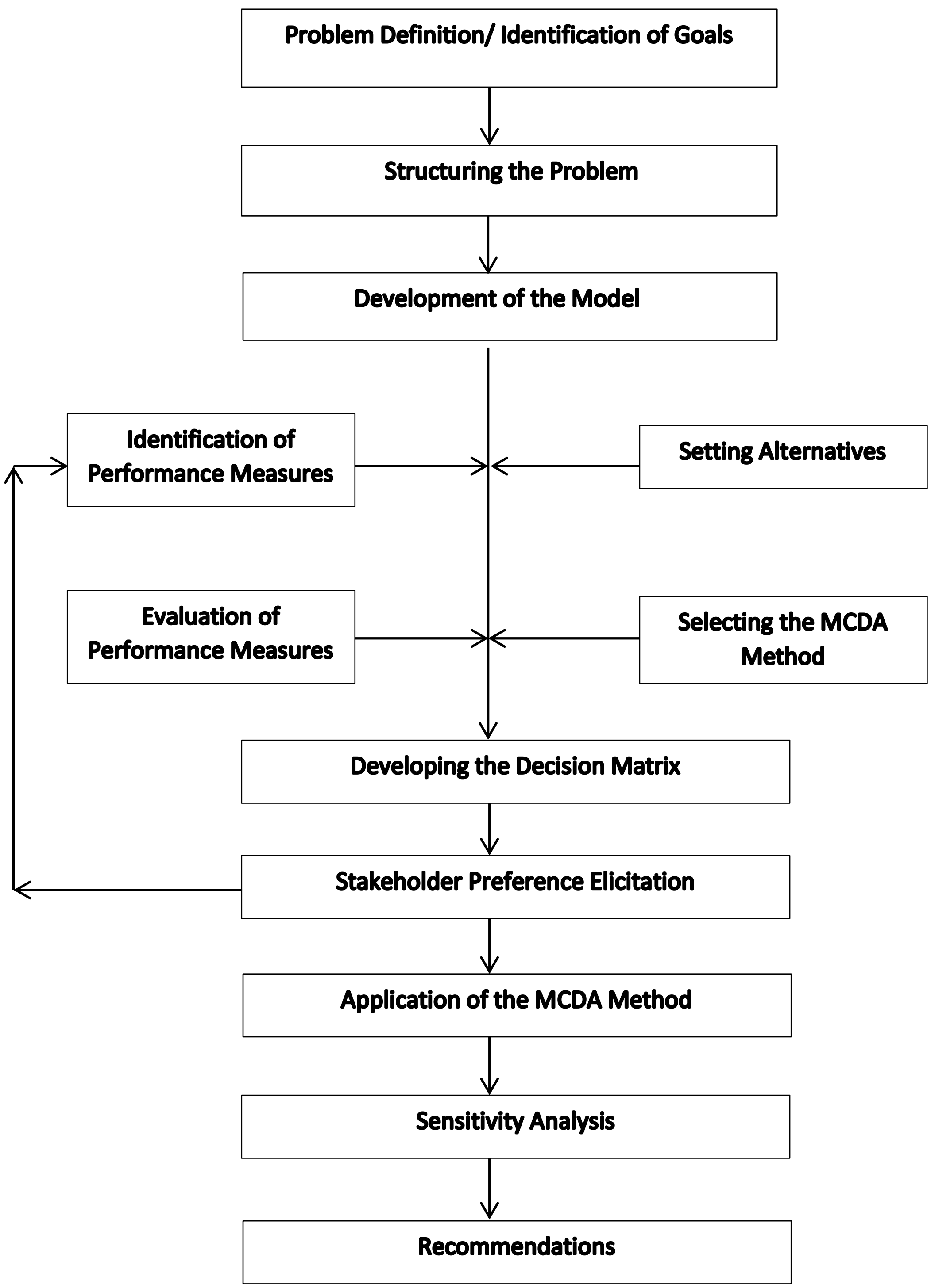


Figure 2.2 - Stages of MCDA Process Adapted from Yatsalo et al. (2015)

The next step involves structuring of the problem which leads to the model development with the identification of performance measures and the alternatives. After this stage, the performance measures should be evaluated using various methods available in literature or stakeholder consultations. These evaluations can be present in various forms such as qualitative or quantitative. In parallel, the selection of a suitable MCDA method for the study could be also performed by assessing the requirements of the study. The governing factors identified in the literature for the selection of a suitable MCDA method for a particular study are, ease of use, understandability of the MCDA method by decision maker and availability of user friendly software packages which incorporate the MCDA technique (Buchanan and Daellenbach, 1987, Olson et al., 1998, Raju and Pillai, 1999, Inamdar, 2014).

Based on the evaluated performance measures on each alternative, the decision matrix should be developed which will be used as one of the inputs for MCDA. Stakeholder preference elicitation is the next step after the development of the decision matrix, which is one of the most important steps conducted in the MCDA process that needs to be performed with care due to associated uncertainties. Different MCDA methods require different types of input information during the preference elicitation. The required type and amount of data in preference elicitation is highly dependent upon the selected MCDA method (Kodikara, 2008). The sensitivity analysis is another important component in the MCDA process. Through the systematic variation of weights, performance measures and ranking algorithms, the sensitivity analysis provides the opportunity to identify instances where model need to be strengthened to obtain more robust results (Hajkowicz and Collins, 2007). After the sensitivity analysis, the decision makers are recommended to proceed with the results or they can return to a previous stage and revise the MCDA process, until the analysis is sufficiently robust in recommending the final result (Yatsalo et al., 2015).

2.6.2.3 Review of MCDA Methods

The MCDA methods are primarily grouped under two major categories as continuous and discrete methods, according to the behaviour of the alternatives to be analyzed (Ananda and Herath, 2009). The continuous MCDA methods involve situations where the number of possible alternatives is infinite. In such occasions, the continuous MCDA methods provide the opportunity to identify a feasible region at which the suitable alternatives lie within, where each point of the region corresponds to a specific alternative (Doumpos and Zopounidis, 2002). The discrete MCDA techniques on the other hand, deal with the problems where there exist a finite number of alternatives and a set of performance measures, by which the alternatives are required to be judged (Hajkowicz et al., 2000). As the proposed methodology in this study is associated with the application of discrete MCDA, the scope of this literature review is only limited to a discussion on discrete MCDA methods used in environmental decision making.

When considering the discrete MCDA methods, there are several different classification systems available in the literature based on their similarities in application for a problem. Belton and Stewart (2002) categorized MCDA in to three broad categories as value measurement models, goal aspiration or reference level models and outranking models. In the first category, values of the alternatives were given a preference order which is consistent with a relatively strong set of axioms. These axioms can provide various functionalities such as, a) ‘‘impose some form of discipline in the building up of preference models’’; (b) ‘‘help the decision-makers to obtain greater understanding of their own values, and to justify their final decisions when required’’; (c) ‘‘encourage explicit statements of acceptable trade-offs between criteria’’ (Mendoza and Martins, 2006). Numerical scores are constructed in this category to assess the degree to which one decision option is better than other. The second category is applied in situations where decision makers find it difficult to trade-off between different alternatives, but are having an understanding about the outcome in terms of satisfying goals of each criterion. As an example, the desirable or satisfactory levels are defined for each criterion in terms of goals and the MCDA techniques in this category discover the options which are closest in achieving these desirable goals. The third category focuses on pairwise comparison of alternatives by assessing preferences and indifferences between them (Belton and Stewart, 2002, Mendoza and Martins, 2006).

Another classification system is presented by Roy (1996) by dividing MCDA methods into three categories as, 1) unique synthesis criteria approach; which consists of aggregating the different points-of-view into a unique function that will be optimized, 2) outranking synthesis approach; which consists of developing a relationship called an outranking relationship, that represents the decision-makers' preferences and 3) interactive local judgement approach; which proposes methods with alternate calculation steps, giving successive compromise solutions, and dialog steps, leading to an extra source of information on the decision-maker's preferences (Vincke, 1992, Schramm and Morais, 2012). Based on these examples, it is evident that there are several classification systems available for MCDA methodologies in literature as such there is no universal system to classify the wide range of techniques. Vincke (1992) explains the reason behind the above discussed inconsistency in MCDA classification as the fuzziness of the boundaries of their families.

Throughout the past 20 years, MCDA has been widely used in environmental decision making in different disciplines such as forest management, food security assessment, energy policy analysis, water resource management, ecosystem management, soil management and wildlife management (Herath and Prato, 2006, Zardari et al., 2014). Table 2.5 shows information on some applications of MCDA in environmental decision making found in literature and the MCDA methods used in these studies. Among the various MCDA methods available, seven most popular and frequently used MCDA methods in environmental decision making are reviewed below.

Table 2.5 – Applications of MCDA in Environmental Decision Making

Area of Application	**MCDA Method**	**Type of the Decision Problem**	**Reference**
Hydropower management	AHP	Identify the best sites to develop hydropower projects with electric power greater than 100 kW.	Supriyasilp et al. (2009)
Petroleum remediation	ELECTRE III	Selection of the remediation techniques for a land contaminated with petroleum.	Balasubramaniam et al. (2007)
River management	MAUT	Ranking five management alternatives for the Missouri River system.	Prato (2003)
Waste management	PROMETHEE	Site prioritization for solid waste management.	Vaillancourt and Waaub (2002)
Environmental Impact Assessment (EIA)	AHP and MAUT	The assessment of the environmental impacts of two water development projects.	Marttunen and Hämäläinen (1995)
Water pollution control	TOPSIS	The selection of the best combat responses to oil spill in the sea.	Krohling and Campanharo (2011)
Wastewater treatment	MAVT, MAUT	Assessment of methods for pharmaceutical removal from hospital wastewater.	Schuwirth et al. (2012)
Irrigation water pricing	AHP and TOPSIS	Choosing the alternatives for the designing and implementing of irrigation water pricing policy.	Gallego-Ayala (2012)
Urban water supply	PROMETHEE	Evaluating alternative operating rules for multi-purpose, multi reservoir urban water supply systems	Kodikara et al. (2010)
Waste management	ANP	Assessment of site suitability for municipal solid waste landfills.	Ferretti (2011)
Energy management	ELECTRE III	Selection and dimensioning of energy systems.	Papadopoulos and Karagiannidis (2008)

Area of Application	MCDA Method	Type of the Decision Problem	Reference
Water resource management	ANP	Ranking water transfer projects	Toosi and Samani (2012)
Groundwater assessment	AHP	Assessment of the impacts of environmental security on groundwater in urban areas.	Bobylev (2009)
Urban water supply	ELECTRE I	Choosing the priority city for the implementation of water supply system.	Morais and Almeida (2006)
Rainwater harvesting	PROMETHEE	Assessment of site suitability for rainwater harvesting.	Inamdar (2014)
Forest management	MAUT	Evaluating the habitat suitability measurements.	Store and Kangas (2001)
Waste management	TOPSIS	Selection of most suitable hazardous waste transportation firm.	Gumus (2009)
EIA	PROMETHEE	Prioritization of EIA and ranking of environmental projects	Al-Rashdan et al. (1999)
Wastewater treatment	ANP and AHP	Selecting the most suitable wastewater treatment system.	Bottero et al. (2011)
Groundwater quality assessment	TOPSIS	Investigating the parameters to develop a groundwater quality assessment system.	Li et al. (2012)
Renewable energy	ELECTRE	Assessment of action plan for the diffusion of renewable energy technologies at regional scale.	Beccali et al. (2003)
Forestry planning	MAVT	Assessment of forestry planning strategies.	Kangas et al. (2001)

AHP = Analytic Hierarchy process, ANP = Analytic Network Process, PROMETHEE = Preference Ranking Organization METHod for Enrichment of Evaluations , ELECTRE = ELimination Et Choix Traduisant la REalité /ELimination and Choice Expressing Reality, TOPSIS= The Technique for Order of Preference by Similarity to Ideal Solution, MAUT= Multi Attribute Utility Theory , MAVT = Multi Attribute Value Theory

Multi Attribute Utility Theory

The Multi Attribute Utility Theory (MAUT) is a MCDA method which is based on the utility theory (Raju and Vasan, 2007). MAUT attempts to maximize decision makers' preference (termed as utility in this method) that is represented by a function named utility function. A utility function is a measure, which quantifies the preferences of a decision maker by assigning a numerical index to varying levels of satisfaction, of a particular criterion. Within MAUT, the researcher's role is to obtain the preferences of decision makers, in order to estimate the utility function. This could be obtained through carefully planned questions which are coherent with the estimation of the uncertain utility function (Torrance et al., 1982, Pirdashti et al., 2009, Ishizaka and Nemery, 2013b).

MAUT has combined advantages of both simple scoring techniques and optimization models (Huber, 1974, Vincke, 1992, San Cristóbal, 2012). Furthermore, the utility function in MAUT has the capability of handling the preference representations which are under risk or uncertainty, which is an inherent component in majority of MCDA problems (Figueira et al., 2005a). However, one of the major drawbacks of MAUT is, the high demand on decision makers due to the complexity of the method and the amount of human judgments that are required to solve the problem (Zeleny, 1982). Keeney and Raiffa (1976) and Von Winterfeldt and Edwards (1986) have provided important contributions to the field of research in MAUT.

Multi Attribute Value Theory

Multi Attribute Value Theory (MAVT) is also based on the utility theory similar to MAUT. In MAVT, there exists a value function as a mathematical representation, which allows an analytical study of preferences and value judgments (Keeney and Raiffa, 1976, Von Winterfeldt and Edwards, 1986, Herath and Prato, 2006). Similar to the utility function in MAUT, MAVT assumes that there exists a value function which represents the decision makers' preferences and to identify the best alternative, the value function has to be determined (Herwijnen, 2007). However, unlike the MAUT where the utility function represents preferences with uncertainty, MAVT value function represents preferences under certainty (Figueira et al., 2005a).

Guidelines for the selection of criteria in MAVT are provided by Gregory et al. (1993). Russell et al. (2001) suggest that the selected number of criteria in MAVT should be small, clearly explainable using simple terms and meaningful. One of the disadvantages of MAVT is that the decision rule of MAVT makes the outcome as a complete compensation between the alternatives. As an example, in MAVT, one good criterion for an alternative can completely rule out all the bad criteria for that alternative (Herwijnen, 2007). MAVT has proven to provide a transparent and a systematic framework for the decision makers involved in the decision problem (Karjalainen et al., 2013, Apperl et al., 2015). The underlying theoretical concepts of MAVT are described in Fishburn (1967), Keeney and Raiffa (1976) and Von Winterfeldt and Edwards (1986).

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a popular decision making model which has been widely used in several environmental and water resource planning applications over the years. The major reasons for the popularity of the AHP are its conceptual simplicity and robustness to handle complex real world problems (Saaty, 1986). The AHP consists of three stage process namely 1) identifying and organizing decision objectives, criteria and alternatives in to a hierarchical structure 2) evaluating the pairwise comparisons between the relevant elements at the each level of hierarchy, and 3) using the priorities obtained from the pairwise comparisons to rank the alternatives in the bottom level of the hierarchy (Saaty, 1988). The AHP is applied to set priorities for the criteria and sub criteria in a decision making problem according to a hierarchy. The alternatives are evaluated through pairwise comparisons. In AHP, the pairwise comparison ratios are estimated with respect to the strength of the decision makers' preferences between the subjects of comparison. Due to the pairwise comparison process which compares every alternative against each other, AHP is considered as a methodology which is highly subjective to the human judgment compared to the other MCDA methods (Mendes Jr, 2011).

It has been proven that AHP is efficient in well-structuring the problem and also tackling one of the major difficulties in MCDA, which is the weight evaluation effectively. Even though, the AHP has been widely used to solve several MCDA problems in environmental decision making and many other fields, the method also has short comings such as forcing the users to follow hierarchical structure, the large amount of information required form the decision maker and the problems occur with the utility normalization (Kodikara, 2008, Pomerol and Barba-Romero, 2012). The complete theoretical interpretation of the AHP can be found in Saaty (1986), Saaty (1988) and Saaty (1990).

Analytic Network Process

One of the drawbacks associated with AHP in the decision making is that, it is incapable of dealing with interactions and interdependencies between the elements of the hierarchy (Zhu et al., 2015). Most of the real world problems are difficult to structure according to a hierarchy due to the involvement of interaction and the dependence of higher-level elements on lower-level elements (Saaty and Vargas, 2006). To overcome this problem, Saaty (2001) introduced Analytic Network Process (ANP), which represents the decision making problem as a network of criteria and alternatives (named as elements), grouped into clusters (Peris et al., 2013). Thus, the feedback structure does not have a top to bottom form like a hierarchy, rather than a form of a network connecting components of each elements, with loops to connect each component to itself.

One of the greatest challenges in ANP is to decide the priorities of the elements in the network, in particular, the alternatives of the decision and to justify the validity of the outcome. The reason for the challenge is explained as; the feedback involves cycles at which cycling is an infinite process. Furthermore, the operations needed to derive the priorities are more demanding compared to those with the hierarchies (Saaty, 2004a, Saaty, 2004b, Saaty, 2005). However, due to the practical integration, the ability to handle complex decisions and complex relationships within the criteria, the ANP has become widely accepted recently in solving MCDA problems (El-Abbasy et al., 2013, Grady et al., 2015).

The Technique for Order of Preference by Similarity to Ideal Solution

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method which is based on synthesizing criterion similar to MAUT and AHP, was first proposed by Hwang and Yoon (1981). The major principle behind the TOPSIS method is that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and farthest distance from the negative ideal solution (NIS) (Opricovic and Tzeng, 2004, Kelemenis and Askounis, 2010). The positive ideal solution can be explained as a solution that maximizes the benefit criteria and minimizes the cost criteria, while the negative ideal solution represents the solution that maximizes cost criteria and minimizes the benefit criteria (Wang and Elhag, 2006). The TOPSIS makes full use of criteria/attribute information, provides a cardinal ranking of alternatives, and does not require attribute/criteria preferences to be independent. To apply TOPSIS for a MCDA problem, the criteria values have to be numeric, monotonically increasing or decreasing, and should have commensurable units (Chen et al., 1992, Yoon and Hwang, 1995, Behzadian et al., 2012).Though TOPSIS was initially used for MCDA; Lai et al. (1994) also extended its applications to provide solutions for Multi Objective Optimization problems.

One of the major advantages of the TOPSIS method is that limited requirements of subjective information from the decision makers. The only subjective data required for TOPSIS are the weights for each criterion (Olson, 2004). The methods such as AHP can be restricted in applications due to the capacity of humans in information processing and could only be effectively used for problems with limited number of criteria or alternatives. Methods such as TOPSIS therefore, are identified as more suitable for problems with large number of criteria and alternatives, especially when objective or quantitative data are available (Shih et al., 2007).

Preference Ranking Organization METHod for Enrichment of Evaluations

The Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) is a outranking MCDA method which was first published by Brans et al. (1984), with extensions by Brans et al. (1986). The outranking methods provide opportunity to conduct pairwise comparison of alternatives for each criterion systematically, to establish the ranking order of alternatives. PROMETHEE, similar to all outranking methods, consists of two major phases as; the construction of the outranking relation and the exploitation of this relation in order to assist the decision maker (Brans and Vincke, 1985). The outranking methods such as PROMETHEE are known as appropriate for situations where criteria matrices are not easily aggregated, measurement scales vary over wide ranges and units are incommensurate or incomparable (Linkov et al., 2004).

The PROMETHEE family of outranking methods includes, PROMETHEE I for the partial outranking of alternatives, PROMETHEE II for the complete outranking of alternatives, PROMRTHEE III for ranking based on interval, PROMETHEE IV for complete or partial ranking of the alternatives when the set of viable solutions is continuous, the PROMETHEE V for problems with segmentation constraints, PROMETHEE VI for the human brain representation, and PROMETHEE GDSS (Group Decision Support System) for the group decision making (Brans et al., 1998, Brans and Mareschal, 2005, Behzadian et al., 2010). PROMETHEE has been widely applied recently in many different areas for solving MCDA problems due to its transparent computational procedure and the user friendliness (Figueira et al., 2005a, Brans and Mareschal, 2005).

The PROMETHEE method introduces six preference function types which describes the decision makers' preferences (Kodikara, 2008). The preference modelling information required from the decision makers to apply PROMETHEE are particularly known as clear and understandable for both the decision makers and the analyst, which consists of information between the criteria and information within each criteria (Brans and Mareschal, 2005). However, one of the limitations of the PROMETHEE method is that it can be used for the MCDA problems with limited number of alternatives, due to the requirement of pairwise comparison of alternatives (Vetschera and De Almeida, 2012).

ELimination Et Choix Traduisant la REalité /ELimination and Choice Expressing Reality

The ELimination Et Choix Traduisant la REalité /ELimination and Choice Expressing Reality (ELECTRE) is another MCDA method which belongs to the family of outranking methods. Therefore, similar to PROMETHEE, pair wise comparison of alternatives is used in ELECTRE for aggregating the decision makers' preferences on each of the criteria. The first version of ELECTRE was introduced as ELECTRE I by Roy (1968) which was followed by different extended versions such as ELECTRE II (Roy and Bertier, 1973), ELECTRE III (Roy, 1978), ELECTRE IV (Roy and Hugonnard, 1982) and ELCTRE IS (Roy and Skalka, 1985).

ELECTRE builds one or several outranking relations based on two major concepts known as 'concordance' and 'discordance'. The major advantage of ELECTRE over other MCDA methods discussed is that ELECTRE incorporates the measures to handle the uncertainty and vagueness of the decision problem (Velasquez and Hester, 2013). The ELECTRE methods can take the imperfect knowledge of the data into account and the arbitrariness occurs during construction of the family of criteria. This is modelled by the indifference and preference thresholds (Figueira et al., 2005b). Some of the other strong features of ELECTRE are the ability to deal with strongly heterogeneous criteria (e.g. combination of cardinal and ordinal criteria) which complicates the aggregation of criteria into a common scale and the capability to handle the qualitative criteria well (Guarnieri and Almeida, 2015). However, some of the drawbacks of the ELECTRE method are, the complexity of the method with the requirement of larger amounts of input data and the high sensitivity of the model outcome to the weights which requires the precise measurement of criteria weights (Beccali et al., 1998, Figueira et al., 2010, Govindan et al., 2010).

2.6.2.4 Applications of MCDA in GI Decision Making

For the past 20 years, MCDA has been widely applied for water resource management applications (Hajkowicz and Collins, 2007). Among these applications, selecting the most suitable stormwater management GI from the pool of alternatives is one of the decision problems where MCDA methods have been applied previously. Implementing GI practices as source control measures to manage stormwater has been identified to provide various other ecosystem services for the urbanized areas while demonstrating some barriers economically, related to their associated costs (Barbosa et al., 2012). Thus, it creates the optimum selection of GI practices as a platform for a typical MCDA problem.

Martin et al. (2007) used ELECTRE III method, to select the most suitable GI practice among 8 individual alternatives based on their technical and hydraulic capabilities, environmental impacts, social perception and maintenance and economic aspects. The preference elicitation of stakeholders such as local government agencies, departmental public works authorities and private developers was conducted through a questionnaire survey, to include subjective information in the decision analysis.

Young et al. (2010) performed a MCDA to select the best GI practice among 14 different alternatives. The criteria considered were geologic factors, contributing area, site slope/topography, soil type, water quality improvement, installation costs, annual maintenance, public safety, aesthetic benefits and ability to recharge groundwater. Objective weight elicitation was performed in this study to rank the most suitable GI practice for the study area among the pool of alternatives, using AHP.

All above studies have generally focused on optimizing GI practices for urban areas to manage stormwater and have not specifically assessed their importance based on the land use type. Furthermore, they were performed to identify optimum stormwater management GI practices by assessing them as individual measures and no studies have proposed methodologies to optimize them when they are considered as combinations of practices (i.e. as treatment trains). Therefore, the present study has made an attempt to address these research gaps by developing a methodology to optimize GI practices, when they are combined as 'treatment trains' for industrial areas. The developed methodology has been tested by applying it to a case study area in Melbourne. The methodology developed for the stormwater management GI optimization for industrial areas by incorporating various tools and techniques discussed here is explained in Chapters 3 and 4 respectively.

2.7 Summary

GI practices which were initially introduced as land conservation strategies, are currently becoming increasingly popular due to their stormwater management aspects and several other ecosystem services (Allen, 2012). In urbanized land uses, industrial areas are generally located close to residential and commercial areas due to the ease of access for material and human resources (The Brooklyn Evolution, 2012). These industrial areas can pose several threats to the environment and surrounding communities in the long term. GI practices can be implemented in industrial areas to mitigate major environmental problems that occur in these areas such as degradation of water resource through contaminated runoff and air pollution (Alshuwaikhat, 2005, Ghasemian et al., 2012).

Several previous studies in the literature have highlighted the importance and the benefits that can be achieved for industrial areas by implementing GI practices (Åstebøl et al., 2004, Chen et al., 2012). There are several different GI practices available which can provide different benefits for industrial areas with different associated costs for their implementation. Regardless of the wide acknowledgement of the applications of GI practices within industrial areas in the literature, there are no systematic methods available in the current practice to identify optimum GI practices suitable for such areas. In the current practice, the GI optimization for such land areas is performed through expert judgement and simulation models which are an ad-hoc process (Jayasooriya et al., 2016). The analysis of strengths, weaknesses, opportunities and threats (SWOT) conducted for the assessment of the applications of GI practices within industrial areas further highlighted the lack of knowledge and research gaps in GI optimization for industrial areas.

Apart from the main objectives of implementing GI practices in industrial areas which is enhancing the overall environmental quality, there are several other multiple objectives associated in the optimization process. Another layer of complexity is added for the GI optimization process in industrial areas due to the views of various stakeholders who influence the process of GI implementation in such areas. When optimizing GI practices for an industrial area, all of these factors should be considered to identify the optimum GI practices which will ensure maximum benefits with minimum costs. The chapter highlighted the importance of a systematic methodology to optimize GI practices for industrial areas which also involve multi-disciplinary stakeholders. This chapter further provided a comprehensive literature review on various tools and techniques which can be used to develop a methodology for the GI optimization in industrial areas. Various software tools which have the ability to model ecosystem services and the associated costs of GI practices were also reviewed. Moreover, a review on the MCDA methods which can be used for the decision making problems that involve multiple stakeholders was also presented in this chapter.

The review presented herein shows that, GI practices can provide multiple benefits for industrial areas. It further stresses the importance of identifying the most suitable GI practices for such areas. There are various complexities associated with selecting GI for industrial areas and there is a lack of systematic methodologies to perform this task. Therefore, this study will focus on addressing these research gaps by developing an innovative methodology to optimize GI practices for industrial areas.

CHAPTER 3

Optimal Sizing of Green Infrastructure Treatment Trains for Stormwater Management

3.1 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 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 and Jackson, 1997, Walsh, 2000, Booth et al., 2002, Gaffield et al., 2003). 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 (Allen, 2012). GI practices can provide stormwater treatment functionalities and several other environmental, economic and social objectives specifically beneficial for environmentally degraded land uses such as industrial areas (De Sousa, 2003, Gill et al., 2007).

As mentioned in previous chapters, GI practices provide several ecosystem services. However, when they are implemented as stormwater management strategies, they are also known in synonyms as Low Impact Development (LID), Low Impact Urban Design and Development (LIUDD), Sustainable Urban Drainage Systems (SUDS) and Water Sensitive Urban Design (WSUD) (Elliott and Trowsdale, 2007). Some of the widely used GI treatment measures are wetlands, retention ponds, bioretention basins, permeable pavements, infiltration trenches, swales and sedimentation ponds (Dietz, 2007, Ahiablame et al., 2012). These different GI practices can be implemented as individual measures or as combinations of measures (which are also known as "treatment trains") to treat the runoff generated from different land uses. However, the implementation of GI practices as treatment trains requires larger land areas and also requires the identification of most suitable types of GI practices to use as a combination to achieve the maximum water quality improvement benefits. Compared to land uses such as residential or commercial areas where limited number of GI practices (e.g. swales, bioretention) can be used due to space restrictions, industrial areas have the potential of implementing several large scale GI practices (e.g. wetlands, retention ponds) as treatment trains that could also provide a range of water quality improvement benefits.

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. After the GI selection, the sizing is generally obtained with the aid of simulation software. US Environmental Protection Agency (US EPA) Stormwater Management Model (SWMM) (Huber and Dickinson, 1988), Model for Urban Stormwater Improvement Conceptualization (MUSIC) (Wong et al., 2002), Source Loading and Management Model (SLAMM) (Pitt and Voorhees, 2002) and Urban Volume and Quality (UVQ) (Diaper and Mitchell, 2006) are some of the simulation models that have been used for sizing of GI practices for stormwater management (Elliott and Trowsdale, 2007, Jayasooriya and Ng, 2014).

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. 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).

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 considering multiple environmental, economic and social objectives is a tedious process even for an individual treatment measure, 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. Another important factor which needs to be considered is the different cost elements associated with different GI practices with different sizes. Different GI practices incorporate various costs associated with different phases in their life cycle. When optimally sizing the GI practices in a treatment train, all these factors should be assessed to obtain economically feasible options with water quality improvement benefits.

To optimize the sizes of individual GI practices, 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.

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 different sizing combinations for individual treatment measures that achieve the target pollution reduction levels. Furthermore, in minimizing the cost as a single objective, these 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 sizing combination for a particular area (Martin et al., 2007, Young et al., 2009, Jia et al., 2013). Currently, there are no systematic methodologies available for sizing of GI when they are implemented as a treatment train. Therefore, the current chapter describes an innovative methodology developed in this study for the size optimization of GI practices in a treatment train. The sizing of the treatment train was formulated as a single objective optimization in this study. Minimizing the Equivalent Annual Cost (EAC) of the treatment train was considered as the objective function, with the constraints of target reduction levels of pollutants (TSS, TP and TN) and available land area. Though the results of the single objective optimization should produce a single optimum result, this study has produced a set of least cost solutions within the constraints, which are close to the minimum cost solution, but with vastly different sizes of different treatment measures. These least cost solutions were further assessed with different performance measures related to economic, social and environmental objectives to provide decision support in selecting the most suitable GI treatment trains for an industrial area. The methodology developed in this study was demonstrated by using two sample treatment trains, for the case study area of the Brooklyn Industrial Precinct (Section 1.4). The methodology and the application described in this chapter is already published in Jayasooriya et al (2016).

3.1.1 Types of Green Infrastructure Practices in Treating Stormwater

GI practices provide a resilient approach which is cost effective in managing wet weather impacts while accommodating several other community benefits (US EPA, 2015). There are several GI practices available which are used as stormwater treatment measures worldwide. This section provides a brief overview of the GI stormwater treatment measures which are widely used in Australia. The key features of the selected GI practices are reviewed in this section with some of their technical and maintenance considerations.

3.1.1.1 Sedimentation Basins

Stormwater runoff consists with sediment loads that can impose adverse impacts to the downstream waterways. Sedimentation basins provide functionalities in reducing sediment loads to protect downstream water ways and ensure the long term efficiency of other downstream treatment measures (Melbourne Water, 2013). Sedimentation basins are effective in reducing the coarser sediments which are larger than 125µm and they can reduce up to 70%-90% of sediments above this particle size (WBM, 2009). They are widely used in land use areas that generate larger sediment loads to trap the sediments. The sedimentation basins operate by reducing the flow velocities and allowing the sediments to settle down the water column (DEP, 2006).

Some of the sedimentation basins are designed to maintain the saturated or shallow flooded soil conditions and they are planted with wetland plant species (Hogan and Walbridge, 2007). Apart from its roles on water quality improvement and flood protection, sedimentation basins have the ability to mimic some the ecosystem service provided by wetlands such as ground water recharge and biodiversity support (Johnston, 1991, Walbridge and Struthers, 1993, Zedler, 2003).

The maintenance of the sedimentation basins should be done approximately once in every five years which includes dewatering and dredging of collected sediments. However, this maintenance requirement depends on the nature of the catchment. As an example, industrial areas which produce larger sediment loads may require the desilting of sediments from sedimentation basins more frequently (Francey, 2005).

3.1.1.2 Bioretention (Rain Garden)

Bioretention systems which are also known as rain gardens are depressed areas created in landscapes which are designed to receive stormwater. The bioretention systems are typically covered with vegetation such as shrubs and perennials (Dietz, 2007).

Bioretention systems can effectively capture runoff, promote evapotranspiration, promote infiltration, recharge groundwater, protect stream channels, reduce peak flow and treat the stormwater through variety of treatment mechanisms (Ahiablame et al., 2012). The runoff passes through the filtration media of bioretention with vegetation providing functions such as extended detention, fine filtration and biological uptake. Bioretention systems are particularly found to be effective in removing nutrients in stormwater runoff (Francey, 2005, Hunt et al., 2006, Davis et al., 2009).

Bioretention systems are suitable for a range of scales and shapes, thus create flexible treatment measures for any area. Bioretention can be used to treat stormwater prior to entry into an underground drainage system. Furthermore, they can be located at drainage system outfalls to provide treatment for larger areas (Melbourne Water, 2013). The most important period of maintenance for bioretention is the first two years of its construction during the establishment of its plants. The vegetation in bioretention plays a major role in maintaining the porosity of the filter media and a healthy growth of its vegetation is crucial for its satisfactory performance. Sediment accumulation should also be monitored to ensure long term efficient performance of the bioretention (Francey, 2005).

3.1.1.3 Wetlands

Wetland is one of the widely used stormwater treatment measures which is popular among many countries in the world. Wetlands are shallow detention systems which are vegetated with emergent aquatic macrophytes (Persson et al., 1999). Wetlands are generally less than 2 m deep and represent the interference between the permanent water bodies and the land environment (Wong et al., 1999). They generally have fluctuating water levels with regular filling and draining of water. One of the major reasons of wetlands becoming a popular treatment measure is that, they are used as landscape amenities in urban design. Apart from flood protection and stormwater treatment, wetlands provide several other ecosystem services such as improving the community liveability in land areas which leads to the increase in property values, providing recreational opportunities and creating habitats for flora and fauna (Hoehn et al., 2003, Zedler and Kercher, 2005, Mitsch et al., 2015).

The vegetation present in wetlands can provide a wide range of water quality management objectives through a variety of biological and chemical treatment mechanisms. The runoff passing through the wetland macrophyte zone is subjected to processes such as biological uptake of nutrients, coagulation of small particles, filtration and surface adhesion of small particles, enhanced sedimentation, decomposition of accumulated organic matter and physical sedimentation of particles (Wong et al., 1999). The major maintenance considerations for the wetlands are maintaining the vegetation and the wetland flow conditions. Furthermore, the wetland inlet zone should be maintained regularly to prevent from sediment and debris build up (Francey, 2005).

3.1.1.4 Retention Ponds

Retention ponds are reservoir systems with permanent pool of water, which are used to store stormwater, reduce flooding by controlling peak flows and enhance the water quality by various physical, biological and chemical processes (Marsalek and Chocat, 2002). The depth of the water level in retention ponds is typically greater than 1.5 m with a small range of water level fluctuation. Retention ponds often form a part of flood retarding system however they also provide a surface for the absorption of dissolved nutrients (Francey, 2005). Some of the other advantages of the retention ponds are the ability to provide support in improving the runoff quality for small areas and the ability to collect runoff from larger areas such as several developments or parts of a city (McComas, 2003). The stormwater treatment mechanisms and the functionalities of retention ponds are almost similar to those of wetlands. However, the major difference between these two practices is that wetlands only store runoff for a certain retention time whereas the retention ponds maintain a permanent pool of water.

The retention ponds are also known as a GI practice that is providing a high aesthetic value for the properties which also provides recreational opportunities. It has been also found that retention ponds have significantly increased the adjacent property values in urban areas (Wakelin et al., 2003). However, retention ponds are also known as a treatment measure which has high maintenance requirements compared to many other GI practices. Without the proper maintenance, the retention ponds can become a liability to the environment. The poorly maintained retention ponds can become sources of several water quality issues such poor water colour, clarity and odour, and prevalence of algal blooms. Furthermore, the flood protection and water quality improvement functionalities of retention ponds can decrease due to sediment accumulations which reduce the storage volume, debris blocks at the outlet structure, damage of pipes or the loss of slope stabilizing vegetation (US EPA, 2009).

3.1.1.5 Vegetated Swales

Vegetated swales are one of the most widely used low cost GI treatment measures which are particularly developed along roadsides to attenuate flows and to reduce the pollutant loads from upstream land uses (Fletcher et al., 2002). These are shallow, open vegetated drains, channels or ditches which are designed to convey, filter and infiltrate stormwater (Barrett et al., 1998, Deletic and Fletcher, 2006, Ahmed et al., 2015). The swale systems use mild slopes and over land flow to gradually convey runoff to the downstream (Francey, 2005). Vegetated swales are designed to treat runoff through the use of vegetation (through filtering and reducing the pollutants), biological and chemical processes of soils and infiltration.

Vegetated swales reduce the pollutants mainly through filtering out the sediments and other pollutants, and also provide support in lowering the runoff velocities and volumes generated from impervious urban areas. The areas where vegetated swales are widely applied are adjacent to roads which also provides an aesthetic value to the roadways along highways or local streets (Lantin and Barrett, 2005).

The treatment efficiency of stormwater from vegetated swales mainly relies upon the vegetation. Hence, it is important to maintain the growth of the vegetation of the vegetated swale. The potential for erosion along the swale should also be monitored particularly during the establishment stage of the swale. Some of the other maintenance requirements which are primarily associated with vegetated swales the are removal of accumulated sediments, the removal of litter and debris, and the prevention of the undesirable vegetation and weeds (Francey, 2005).

3.1.1.6 Infiltration Practices

Infiltration practices capture and store stormwater, and slowly infiltrate runoff into the underground soil. The infiltrated water is then used as groundwater recharge or collected through underdrains. Similar to other GI practices previously discussed, the infiltration practices also provide two fundamental functions, the attenuation of runoff volume and the treatment of runoff. Infiltration practices use various porous media to facilitate the infiltration of runoff to the ground. Infiltration facilitates the treatment of runoff through several other treatment mechanisms such as chemical and bacterial degradation, sorption and filtering (Gulliver et al., 2011). Some of the examples of the infiltration practices are infiltration basins, infiltration trenches and permeable pavements.

When implementing infiltration practices to manage stormwater, a careful consideration should be given to the type of runoff generated or the type of land use that runoff is originated. The implementation of the infiltration practices for a site should be determined by analyzing the quality of runoff generated from the site and looking at the potential threats of polluting the groundwater in the area. The environmental and human health risks should be assessed before implementing infiltration practices at any site (US EPA, 2013). The maintenance of infiltration practices should be done regularly to remove the clogged sediments of the system to maintain an appropriate infiltration rate (Francey, 2005).

3.1.2 Green Infrastructure Treatment Trains

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, Koch et al., 2014, Loperfido et al., 2014). The treatment train method has several advantages over implementing a single treatment measure at the catchment outlet. These advantages 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).

GI treatment measures can vary from simple treatment measures that support direct infiltration of stormwater, to complex measures such as wetlands that incorporate processes of biological uptake. The treatment trains can combine GI with several of these different mechanisms to improve the pollutant removal of stormwater. Moreover, the stormwater treatment mechanisms incorporated in each GI, play a major role in identifying their location in the treatment train. GI are categorized as primary, secondary and tertiary treatment measures according to the particle size ranges they remove in the treatment process. A primary treatment measure is required in any treatment train to avoid clogging created by coarse particles and to maintain proper functionality of other treatment measures in pollutant removal (Melbourne Water, 2005). Hence, treatment trains can be developed by combining primary and secondary, primary and tertiary, or primary, secondary and tertiary measures together, to achieve the target reduction levels of pollutants. The relationships between particle size range, pollutants and treatment mechanisms are shown in Table 3.1. The teratment mechanisms secreening and sedimentation is performed by the primary treatment measures whereas functionalities such as enhanced sedimentation, adhension and fliteration are provided by secondary treatment measures. For further treatment of dissolved particles, tertiary treatment measures can be impleneted which invlove mechanisms such as biological uptake.

Table 3.1- Relationships between Particle Size Range, Pollutants and Treatment Mechanisms (Breen, 1999)

Size range (µm)	Pollutant					Treatment mechanism
	Litter	Sediment	Nutrients	Organics	Metals	
>5000 (gross solids)						Screening
5000–125 (coarse)						Sedimentation
125–10 (fine)						Enhanced sedimentation
10–0.45 (colloidal)						Adhesion and filtration
<0.45 (dissolved)						Biological uptake

Another important factor that needs to be considered in selecting a treatment train is the physical site characteristics of the area. Selecting a potential set of GI practices for a site depends on the type of land use or activities that are associated with the particular catchment. Some of the treatment measures which incorporate mechanisms such as infiltration are not recommended to treat hotspot runoff (e.g.

runoff from heavy industrial land use) due to the potential groundwater contamination (US EPA, 2012). Table 3.2 shows the typical GI treatment measures that provide functionalities for primary, secondary and tertiary treatment in the stormwater treatment process. By combining these treatment measures based on the physical site characteristics, several different treatment train configurations can be developed for a given area.

Table 3.2 - GI Treatment Measures in Treatment Trains (Melbourne Water, 2005)

Treatment	Pollutants	Typical Treatment Measures
Primary Treatment	Gross pollutants and coarse sediments	Gross polluant traps, Sédimentation basins, Vegetated swales
Secondary Treatment	Fine sediments and attached pollutants	Vegetated swales, Infiltration trenches, Permeable pavement, Bioretention
Tertiary Treatment	Nutrients and dissolved heavy metals	Bioretention, Bio- infiltration systems, Wetlands, Retention ponds

3.2 Optimal Sizing of Treatment Trains – Methodology

The generic methodology developed in this study for the optimum sizing of GI treatment trains consists of three broad steps: (1) Development of potential treatment trains, (2) Optimization of the sizing of treatment trains, and (3) Assessment of treatment trains with performance measures.

3.2.1 Development of Potential Treatment Trains

For the development of potential treatment trains, GI practices suitable for the study area were first identified. The selection of GI was based on the land use and physical site characteristics, and the availability of land of the area. Geographical Information Systems (GIS) based physical site assessment was used in this study to identify a set of potential GI for the area. The major parameters considered in the physical site assessment were slope, geology, groundwater level, soil type and the land use type of the area. Once the potential GI measures were identified, the treatment trains were developed considering their treatment mechanisms and the related particle size removal ranges. Treatment trains were developed by combining primary and secondary treatment measures; primary and tertiary treatment measures; and primary secondary and tertiary treatment measures in series.

3.2.2 Optimization of Sizing of Treatment Trains

Once the potential treatment trains were developed for the study area, size optimization was achieved in two steps as explained in Sections 3.2.2.1 and 3.2.2.2.

3.2.2.1 Formulation of Single Objective Optimization Problem

There can be several alternative size combinations of GI in the treatment train that achieve the required target reduction levels of pollutants, with costs close to that of the minimum cost but with vastly different sizing combinations for individual treatment measures. 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 study) - Cost for activities such as additional landscaping, improving the access track for maintenance, replacing filtration media on a bioretention system and 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). However, it should be noted that there can be instances where this cannot be achieved in real world conditions. In the present study, it has been assumed that the GI is well maintained and therefore, decommissioning cost was excluded from the life cycle costing analysis. Thus, capital cost and annual operation and maintenance costs were used in computing the life cycle cost of treatment trains. The Equivalent Annual Cost (EAC), which is 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 train 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,

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

Subject to $g_{TSS}(x_i) \geq TR_{TSS}$

$g_{TP}(x_i) \geq TR_{TP}$

$g_{TN}(x_i) \geq TR_{TN}$

$h(x_i) \leq LAA$

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 Total Suspended Solids (TSS), Total phosphorous (TP) and Total Nitrogen (TN); TR = target reduction level corresponding to pollutants TSS, TP and TN; h(x) = land area required for GI, and 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 the 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 modelling standard in Australia which is used for conceptual design of GI for stormwater treatment. MUSIC has been calibrated using rainfall and 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. Additional details of MUSIC were described in Section 2.6.1.

3.2.2.2 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 study (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 Figure 3.1. Even though the optimization within the defined scenarios is explained here, this methodology is generic and can be applied for any treatment train. Figure 3.1a shows the procedure for sizing a treatment train with two treatment measures, while Figure 3.1a and 3.1b together show how the sizing was done for a treatment train with three treatment measures.

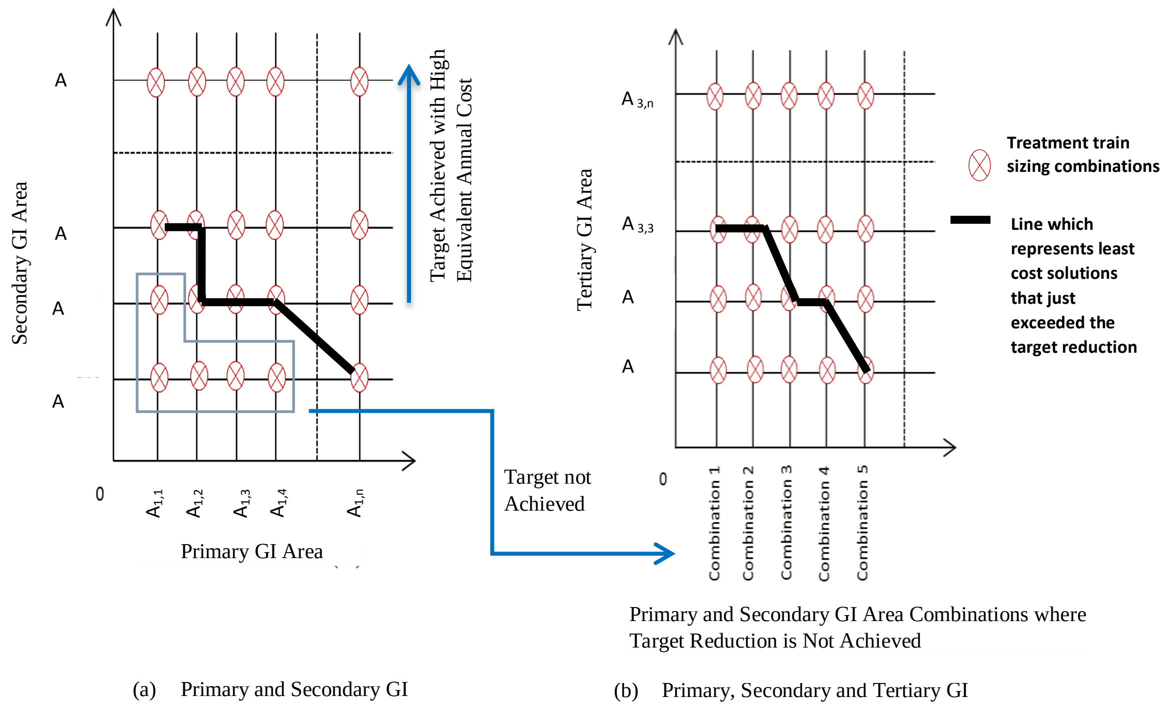


Figure 3.1 – Size Combinations of GI in Treatment Trains

First, the grid was formed by considering the areas of primary and secondary GI, subject to the available land area, as shown in Figure 3.1a. 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 Figure 3.1a. The sizing combinations above the line achieved more than 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 Figure 3.1b, the sizing combinations that do not achieve the pollutant target reduction levels (solutions below the black line in Figure 3.1a) were further considered by adding a tertiary treatment measure. Figure 3.1b 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 Figure 3.1a and the area of the tertiary treatment measure; the area interval for the tertiary treatment measure in the grid was selected as in Figure 3.1a by performing several initial simulations of the treatment measure individually. Then the treatment measures defined by the grid points in Figure 3.1b were simulated using MUSIC. The solutions along the frontier (black line in Figure 3.1b) 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.

An automated computer program was developed to simulate the treatment train efficiencies with different sizing, by combining MUSIC simulation software with Matlab Integrated Development Environment (IDE). This computer program was used to simulate all size combinations defined by the grid to evaluate the target pollutant removal efficiencies and EAC.

3.2.3 Assessment of Treatment Trains with Performance Measures

The optimization in Section 3.2.2 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 also 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 these 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 description of the performance measures considered, and the methods and tools used to compute them are presented in Table 3.3.

Table 3.3– Objectives and Performance Measures

Objective	Performance Measure	Unit	Maximize or Minimize	Method of Evaluation
Environmental	Annual TSS Load Reduction	(Kg)	Maximize	MUSIC Output
	Annual TP Load Reduction	(Kg)	Maximize	MUSIC Output
	Annual TN Load Reduction	(Kg)	Maximize	MUSIC Output
	Cu Removal	(%)	Maximize	MUSIC Output
	Zn Removal	(%)	Maximize	MUSIC Output
	Peak Flow Reduction	(%)	Maximize	MUSIC Output
	Habitat Creation	Ratio	Maximize	Green Area Ratio Method (Keeley, 2011)
Economic	Potable Water Savings	(ML/Yr)	Maximize	MUSIC Output
	Equivalent Annual Cost	($)	Minimize	MUSIC Output
	Capital Cost	($)	Minimize	MUSIC Output
	Annual Operation and Maintenance Cost	($)	Minimize	MUSIC Output
Social	Improvement of Liveability	Ratio	Maximize	Green Area Ratio Method (Keeley, 2011)

The TSS, TP and TN were identified as three of the major parameters to assess the water quality improvement through GI and were included under the environmental objective. As discussed in Section 1.4, the Kororoit creek in the study area has been contaminated due to industrial land use activities. 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 Strategy, 2006). Several studies have also highlighted that above 70% of industrial facilities have been found to discharge stormwater with elevated levels of 'Copper (Cu)' and 'Zinc (Zn)' amongst other heavy metals (Strecker et al., 1997, Harper, 1998, Golding, 2006, Jurries and Ratliff, 2013). By analysing the water quality data of the area, 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.

As shown in Table 3.3, different tools and methods were used to estimate the values of the selected performance measures. The load reduction of TSS, TP and TN were obtained using 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 (Keeley, 2011) is an urban sustainability metric that measures the enhancement of urban environmental quality through GI practices. This method has been adopted for this study to compute the performance measures for habitat creation and improvement of the liveability of the area. An introduction to the Green Area Ratio Method and a description of data used for the calculations are given in Appendix 3A. By estimating the values of performance measures for each least cost treatment train sizing combination, a matrix of alternatives (i.e. sizing combinations of treatment trains) and performance measures was developed, to identify the most suitable sizing combination of the treatment train among the least cost solutions obtained from the optimization in Section 3.2.2.

3.3 Application of the Methodology

The generic methodology explained in Section 3.2 is demonstrated below by applying it to two sample treatment trains related to the case study area (Brooklyn

Industrial Precinct) which was discussed comprehensively in Section 1.4. The particular information related to the case study area when applying the methodology for the optimization of stormwater management GI practices is explained below.

A 90 ha area within the industrial precinct which is identified as an area that contributes highly contaminated runoff to the Kororoit creek was selected for the application of the proposed methodology (The Brooklyn Evolution, 2012). The study area has been identified as an area which produces highly polluted stormwater runoff due to various industrial activities. A long term development plan has been developed for the study area. In this plan, major attention has been given for the implementation of GI practices to improve stormwater quality of the creek as the major objective. Areas have already been proposed for implementation of GI, close to the boundary of the creek. Land areas of 2000 m^2, 10000 m^2 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 which are represented in green as shown in Figure 3.2. 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 liveability of the area in an economically feasible way (The Brooklyn Evolution, 2012).

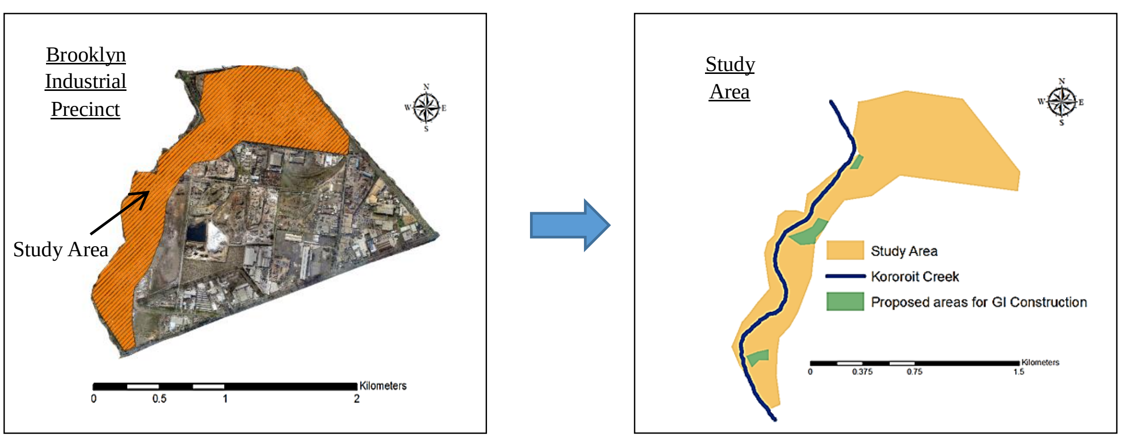


Figure 3.2 – Proposed Land Areas for Potential GI Implementation to Manage Stormwater at Kororoit Creek (The Brooklyn Evolution, 2012)

3.3.1 Development of Treatment Train Configurations

By considering parameters such as slope, geology, groundwater level, soil type and land use type, several potential GI were identified for the study area. They were sedimentation basin, vegetated swale, bioretention, retention pond and wetland. Of these, sedimentation basin and vegetated swale were considered as primary treatment; vegetated swale and bioretention as secondary treatment; and bioretention, retention pond and wetland as tertiary treatment. Vegetated swale demonstrates treatment mechanisms which can be categorized under both primary and secondary treatment levels. Similarly, bioretention has the capability of performing both secondary and tertiary level treatment. Due to the presence of heavy industrial activities within the study area, the practices which support direct infiltration of stormwater to underground such as infiltration practices were excluded as potential GI practices.

Combining the above selected treatment measures, several treatment train configurations (combining primary and secondary, combining primary and tertiary, and combining primary, secondary and tertiary) were developed as potential treatment trains for the study area, as shown in Table 3.4. However, as stated earlier, only two treatment trains consisting of two and three treatment measures are demonstrated below in Sections 3.3.2 and 3.3.3 respectively. Nevertheless, the proposed methodology can be applied to treatment trains with any number of treatment measures according to the requirements of the study area.

Table 3.4 - Development of Treatment Train Configurations for the Study Area

Primary and Secondary Treatment	Primary and Tertiary Treatment	Primary, Secondary and Tertiary Treatment
Sedimentation Basin and Vegetated Swale	Sedimentation Basin and Retention Pond	Sedimentation Basin, Vegetated Swale and Bioretention Sedimentation Basin, Vegetated Swale and Retention Pond Sedimentation Basin, Vegetated Swale and Wetland
*Sedimentation Basin and Bioretention	Sedimentation Basin and Wetland	Sedimentation Basin, Bioretention and Retention Pond *Sedimentation Basin, Bioretention and Wetland
Vegetated Swale and Bioretention	Vegetated Swale and Wetland Vegetated Swale and Retention Pond	Vegetated Swale, Bioretention and Retention Pond Vegetated Swale, Bioretention and Wetland

*Sample treatment trains that are demonstrated in this chapter.

3.3.2 Results for Sample Treatment Train 1 (*two treatment measures*)

The results of the single objective optimization that was performed for the sample treatment train configuration with sedimentation basin and bioretention (treatment train with primary and secondary treatment measures) are discussed in this section.

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). A discount rate of 3.5% was selected to estimate the life cycle cost by referring to the recently published figures for the discount rates in environmental projects (EPA Victoria, 2012, Department of Treasury and Finance, 2014).

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 m^2, 10000 m^2 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 1, first two lots of 2000 m^2 and 10000 m^2 were considered for the construction of primary (sedimentation basin) and secondary (bioretention) treatment measures as the area constraints.

Initial simulations with MUSIC showed that, increasing the sedimentation basin (primary) 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 500m^2 for bioretention (secondary). Therefore, these area intervals were used as the grid intervals to define the potential sizing combinations of GI in the treatment train configuration. Figure 3.3 shows the size combinations of sample treatment train 1 (consists with sedimentation basin and bioretention), analysed with the single objective optimization.

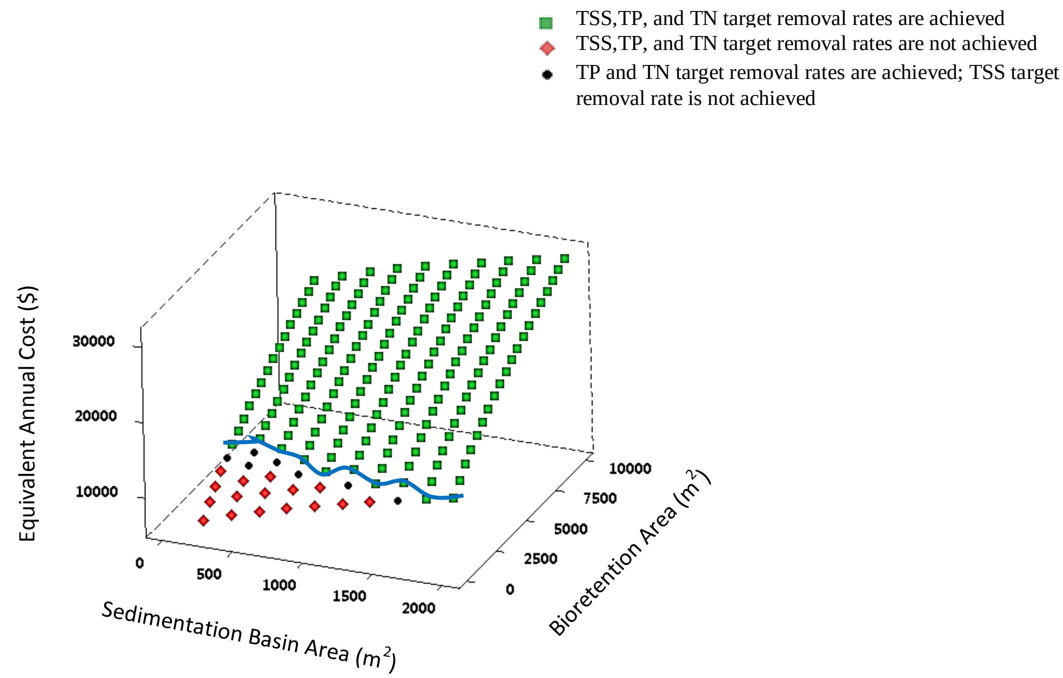


Figure 3.3- Simulation Results for Treatment Train with Sedimentation Basin and Bioretention

This figure also shows the EAC for all size combinations simulated for sample treatment train 1. Different colored symbols represent how the target reduction levels have been achieved for each sizing combination as explained below.

1) Green symbols along the blue line – These are the low EAC size combinations where the 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 target pollutant reduction levels of all three pollutants, but with high EAC, compared to those of (1).
3) Green symbols along the blue line – These are the low EAC size combinations where the target pollution reduction levels were just achieved for all three pollutants.

4) Green symbols above the blue line – The size combinations that achieved more than the target pollutant reduction levels of all three pollutants, but with high EAC, compared to those of (1).
5) 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 unable to achieve the target pollution reduction levels, even though they had a low EAC. The sizing combinations along the blue line were considered as feasible least cost treatment train sizing combinations that achieve the target reduction levels for sample treatment train 1. 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 3.5. It should be noted that the values for costs are related for the year of 2014. The capital cost, sum of operation and maintenance cost, and the EAC related to each of these size combinations are shown in Figure 3.4.

As observed from Table 3.5, for sample treatment train 1, 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 3.5 shows that as 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 Figure 3.4, 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 different sizing combinations may produce different values of the performance measures.

Table 3.5– Least Cost Sizing Combinations Obtained from the Single Objective Optimization, their sizes of Individual Treatment Measures and Removal Efficiencies for Sample Treatment Train 1

Sizing Combination	Sedimentation Basin Area (m^2)	Bioretention Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_BR(1)	2000	500	80.6	69	52.6	14569
SDB_BR (2)	1800	500	80.2	66.3	50.1	13822
SDB_BR (3)	1600	1000	81.9	67.0	52.9	14680
SDB_BR (4)	1400	1000	81.2	63.9	50.3	13881
SDB_BR (5)	1200	1500	82.9	64.2	52.5	14365
SDB_BR (6)	1000	1500	80.6	61.6	49.5	13493
SDB_BR (7)	800	2000	81.7	60.6	51.7	13723
SDB_BR (8)	600	2500	82.7	60.0	53.5	13778
SDB_BR (9)	400	3000	82.7	58.8	53.7	13652
SDB_BR (10)	200	3000	80	55.4	50.7	12354

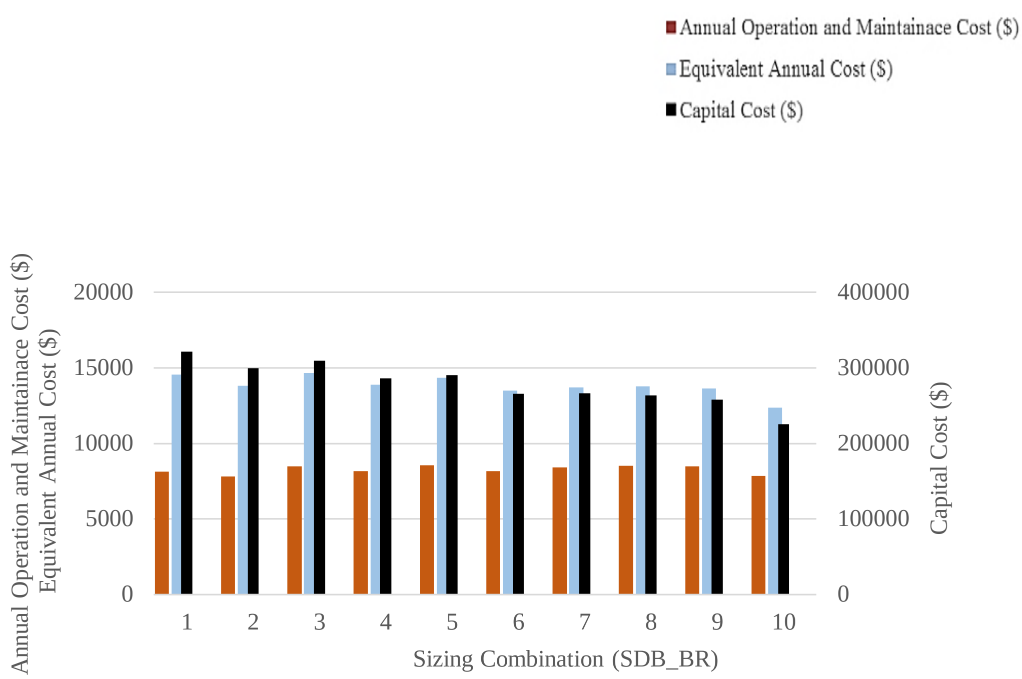


Figure 3.4 - Cost Elements Associated with Sample Treatment Train 1 (Sedimentation Basin and Bioretention)

3.3.3 Results for Sample Treatment Train 2 (*three treatment measures*)

Optimization was conducted further for the infeasible sizing combinations that were below the blue line (solutions which were unable to achieve the target reduction levels) in Figure 3.3 of Section 3.3.2, by adding a tertiary treatment measure for the treatment train. A wetland was added to these infeasible sizing combinations as explained in Section 3.3.1, to demonstrate the methodology for a sample treatment train configuration with primary, secondary and tertiary treatment measures. The sizing interval for the wetland in the grid was identified as 500 m^2 from the initial MUSIC simulations, which has given an increase in removal efficiency of 1-2% for TSS, TP and TN. The 8000 m^2 area available in the third lot was used as the area for the wetland. A similar procedure was followed as in Section 3.3.2 to identify different regions with feasible and infeasible solutions. The individual sizes obtained for each of the three treatment measures in the treatment train that just achieve the target pollutant reduction levels with least EAC (i.e. sizing combinations of the black line in Figure 3.7b) are given in Table 3.6 with their removal efficiencies. The capital cost, sum of operation and maintenance cost and the EAC related to each of these size combinations (of sample treatment train 2) are shown in Figure 3.5.

Similar to sample treatment train 1, there are several treatment train sizing combinations with EAC close to each other but with vastly different sizes of individual treatment measures in sample treatment train 2. Furthermore, as can be seen in Table 3.5, TSS has remained as the critical pollutant in sizing the treatment trains. It is evident from Figure 3.5 that variations of different cost components show a pattern similar to sample treatment train 1. Since the annual operation and maintenance costs remain almost similar for all sizing combinations, the capital cost can be identified as the cost component that makes the highest impact for the variations of EAC of these treatment train sizing combinations. Similar to sample treatment train 1, the maximum difference of EAC of sizing combinations of sample treatment train 2 from the minimum EAC is of the order of 17%, while the sizing combinations are showing variations for all three treatment measures.

Table 3.6- Least Cost Sizing Combinations Obtained from the Single Objective Optimization, their sizes of Individual Treatment Measures and Removal Efficiencies for Sample Treatment Train 2

Sizing Combination	Sedimentation Basin Area (m^2)	Bioretention Area (m^2)	Wetland Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)*
SDB_BR_WL(1)	200	2500	1000	80.1	65.8	55.2	16278
SDB_BR_WL (2)	400	2000	1500	82	70.7	59.9	18137
SDB_BR_WL (3)	200	2000	2000	82	72.3	62.8	18303
SDB_BR_WL (4)	800	1500	1000	80.8	69.5	56.1	17470
SDB_BR_WL (5)	600	1500	1500	80.7	70.6	58.7	18086
SDB_BR_WL (6)	400	1500	2000	80.6	72.9	61.3	18446
SDB_BR_WL (7)	200	1500	2500	81.8	73.2	64.7	18512
SDB_BR_WL (8)	1200	1000	1000	81.6	71.5	57.1	17951
SDB_BR_WL (9)	1000	1000	1000	80	69	54.6	17079
SDB_BR_WL (10)	800	1000	2000	82.7	73.6	62.7	19230
SDB_BR_WL (11)	600	1000	2500	82.3	75.2	64.5	19597
SDB_BR_WL (12)	400	1000	2500	80.2	73.5	63.7	18494
SDB_BR_WL (13)	200	1000	3000	81.6	74.3	66.5	18485
SDB_BR_WL (14)	1400	500	1000	80.4	70	55.5	17154
SDB_BR_WL (15)	1200	500	1500	80	72.3	58.4	17935
SDB_BR_WL (16)	1000	500	2000	80.4	72.7	61.5	18526
SDB_BR_WL (17)	800	500	2500	81.5	74.6	64.1	18965
SDB_BR_WL (18)	600	500	3000	81.3	76	66.3	19258
SDB_BR_WL (19)	400	500	3500	81.3	77	69.4	19386
SDB_BR_WL (20)	200	500	3500	80.7	75.3	67.6	18088

*Cost analysis has been conducted for the year of 2014.

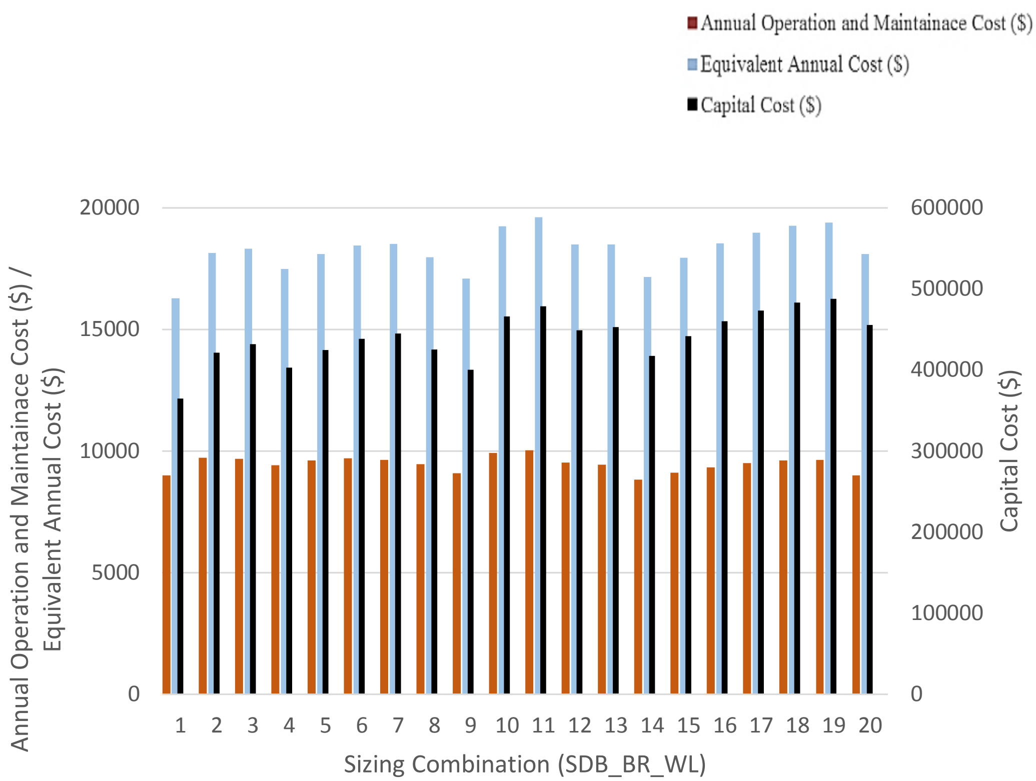


Figure 3.5 - Cost Elements Associated with Sample Treatment Train 2 (Sedimentation Basin, Bioretention and Wetland)

3.3.4 Optimal Treatment Train Sizing Combinations for all Treatment Trains – Summary of Results

Similar procedure was followed for the remaining 12 treatment train configurations which were identified as potential treatment trains for the study area in Table 3.4, to identify near optimal sizing combinations using single objective optimization. Several sizing combinations for different treatment train configurations were identified that achieve the target pollutant reduction levels with close EAC values to each other, however with vastly different sizing combinations of individual treatment measures. The results obtained for the remaining 12 treatment train configurations (individual sizes of treatment measures in the treatment train for near optimal sizing combinations, treatment train efficiency for TSS, TP, TN and the equivalent cost) are shown in Appendix 3B.

3.4 Assessment of Treatment Trains using Performance Measures

As stated in Section 3.2.3, several performance measures based on TBL objectives of environmental, economic and social were identified in relation to treatment train sizing combinations of the study area. These performance measures were confirmed through having several discussions with stakeholders who are currently engaged with the redevelopment operations of Brooklyn Industrial Precinct 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 different assessment methods, these performance measures were computed and a decision matrix was developed which defined the performance measure values for alternative treatment train sizing combinations as described in Section 3.2.3. The assessment with performance measures is comprehensively demonstrated using the sample treatment train 1 and is discussed in this section. The decision matrix developed for the least cost sizing combinations of sample treatment train 1 is shown in Table 3.7. A statistical summary of the performance measure values for all least cost treatment train sizing combinations is given in Appendix 3C.

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 normalize 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. equivalent annual cost, capital cost, operation and maintenance cost),

$$Y = \frac{X_{max} - X}{(X_{max} - X_{min})} \times 100 \qquad (3.1)$$

Table 3.7- Decision Matrix for Sizing Combinations of Sample Treatment Train 1

Sizing Combination	Annual TSS Load Reduction (Kg)	Annual TP Load Reduction (Kg)	Annual TN Load Reduction (Kg)	Cu Removal (%)	Zn Removal (%)	Peak Flow Reduction (%)	Habitat Creation (ratio)	Portable Water Savings (ML/yr)	Equivalent Annual Cost ($)	Capital Cost ($)	Annual Operation and Maintenance Cost ($)	Improvement of Liveability (ratio)
SDB_BR (1)	46600	79	428	74	84	41	0.012	17	14569	321833	8133	0.011
SDB_BR (2)	45600	77	407	72	84	38	0.011	17	13822	299792	7826	0.010
SDB_BR (3)	47100	77	441	75	77	40	0.013	33	14680	309250	8495	0.010
SDB_BR (4)	46100	74	410	73	87	38	0.012	35	13881	286081	8159	0.010
SDB_BR (5)	47100	74	429	75	91	41	0.014	49	14365	290534	8555	0.010
SDB_BR (6)	45900	71	406	72	84	39	0.013	51	13493	265796	8177	0.009
SDB_BR (7)	46600	70	422	74	86	42	0.015	64	13723	266160	8400	0.010
SDB_BR (8)	46900	69	433	75	73	46	0.017	75	13778	263614	8506	0.011
SDB_BR (9)	47200	67	439	75	89	49	0.018	84	13652	257912	8494	0.012
SDB_BR (10)	45800	64	412	72	90	48	0.017	87	12354	225236	7849	0.011
Mean	46490	72.11	422.70	73.7	85.0	42.2	0.014	51.2	13832	278621	8259	0.010
Standard Deviation	597.12	4.88	13.23	1.3	6.0	4.0	0.002	25.9	658	28431	272	0.001
Coefficient of Variation	0.01	0.07	0.03	0.02	0.07	0.10	0.172	0.51	0.05	0.10	0.03	0.081

SDB – Sedimentation Basin BR - Bioretention

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

$$Y = \frac{(X - X_{min})}{(X_{max} - X_{min})} \times 100 \qquad (3.2)$$

Where *Y*= the normalized value; *X* = the performance measure value; X_{min} = the minimum value of the performance measure; and X_{max} = the maximum value of the performance measure.

Table 3.8 shows the normalized values of the performance measures for different sizing combinations of sample treatment train 1. The best and worst performance measure values are represented in green and red respectively. These normalized values are shown in Figure 3.6 for different sizing combinations of sample treatment train 1.

As can be seen from Table 3.8 and Figure 3.6, the sizing combinations SDB_BR (9) and SDB_BR (10) provide best solutions (100 in the scale) in terms of most performance measures. These two sizing combinations have provided 8 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 2 performance measures for size combination 10 has produced the worst value. On the other hand, size combinations 2 and 6 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 best performance measure value for size combination 2 with one performance measure. The size combinations 1, 3, 4, 5, 7, 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. Similarly, the performance measure values (that are converted into 1-100 scale) for the 20 near optimal sizing combinations obtained for the sample treatment train 2 are shown in Figure 3.7. The results obtained for the sample treatment 2 with three treatment measures further shows the complexity of selecting a single optimum sizing combination for the study area by the single objective of minimizing the equivalent annual cost.

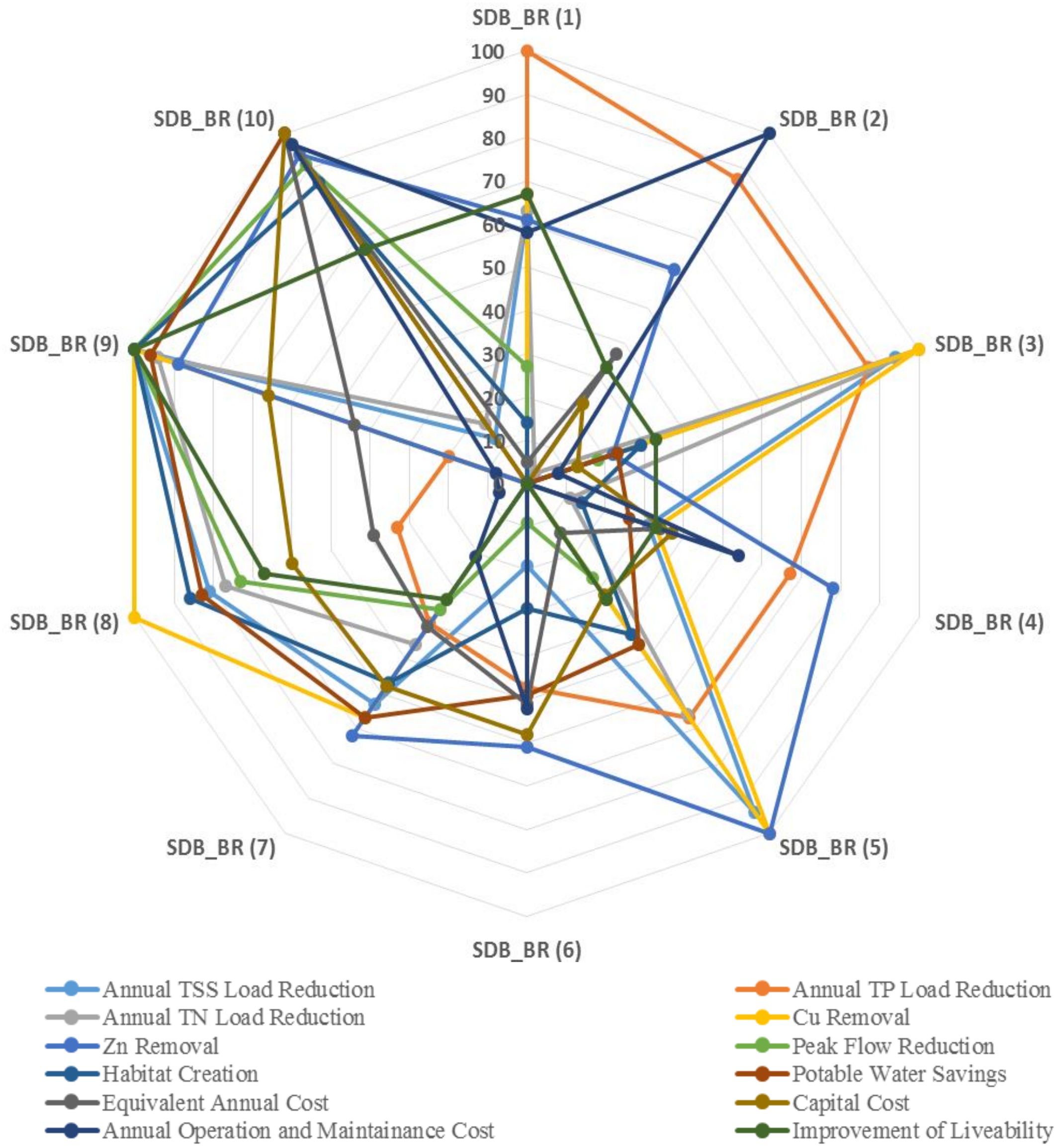
As can be seen from Table 3.8 and Figures 3.6 and 3.7, there is no single sizing combination that could be the best in terms of all performance measures. In addition to this difficulty, different stakeholders have different preferences (in most cases contradictory to each other) on the performance measures. For example, environmentalists would have a preference on the environmental performance measures, while the resource managers might focus on 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 through a Multi Criteria Decision Analysis (MCDA) approach, which considers both the differences in performance measures and the 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 the stakeholder preferences in performance measures will be discussed in Chapter 4.

Table 3.8- Standardized Performance Measures for Sizing Combinations of Sample Treatment Train 1

Sizing Combination	Normalized Scale (0-100)											
	Environmental							Economic				Social
	Annual TSS Load Reduction	Annual TP Load Reduction	Annual TN Load Reduction	Cu Removal	Zn Removal	Peak Flow Reduction	Habitat Creation	Portable Water Savings	Equivalent Annual Cost	Capital Cost	Annual Operation and Maintenance Cost	Improvement of Liveability
SDB_BR (1)	63	**100**	63	67	61	27	14	**0**	5	**0**	58	67
SDB_BR (2)	**0**	87	3	**0**	61	**0**	**0**	**0**	37	23	**100**	33
SDB_BR (3)	94	87	**100**	**100**	22	18	29	23	**0**	13	8	33
SDB_BR (4)	31	67	11	33	78	**0**	14	26	34	37	54	33
SDB_BR (5)	94	67	66	**100**	**100**	27	43	46	14	32	**0**	33
SDB_BR (6)	19	47	**0**	**0**	61	9	29	49	51	58	52	**0**
SDB_BR (7)	63	40	46	67	72	36	57	67	41	58	21	33
SDB_BR (8)	81	33	77	**100**	**0**	73	86	83	39	60	7	67
SDB_BR (9)	**100**	20	94	**100**	89	**100**	**100**	96	44	66	8	**100**
SDB_BR (10)	13	**0**	17	**0**	94	91	86	**100**	**100**	**100**	97	67

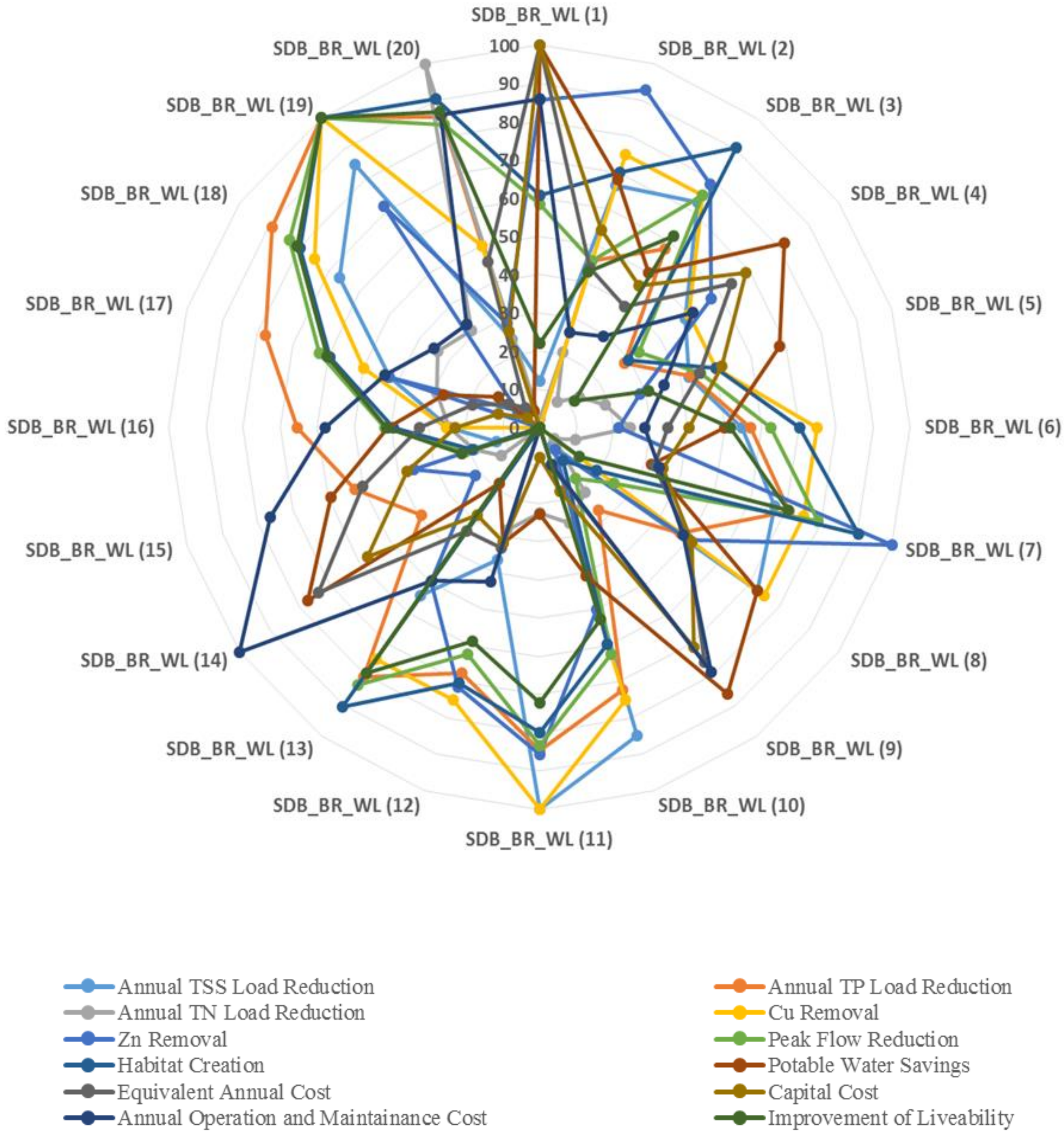
Best Solution **Worst Solution** SDB – Sedimentation Basin BR - Bioretention

Please refer to Table 3.5 for the individual sizes of the treatment measures in the treatment train.



SDB – Sedimentation Basin BR - Bioretention

Figure 3.6 - Performance Measures (1-100 Scale) for Sizing Combinations obtained for Sample Treatment Train 1



SDB – Sedimentation Basin BR – Bioretention WL - Wetland

Figure 3.7 - Performance Measures (1-100 Scale) for Sizing Combinations obtained for Sample Treatment Train 2

3.5 Summary

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. 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 highly different performances in terms of Triple Bottom Line (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 sizing combinations and selecting the best size combination out of the considered sizing combinations. Due to the large number of simulation trials required, all possible treatment train sizing combinations cannot be realistically handled in this approach Moreover, this approach is subjective. Therefore, the present study has proposed a methodology which is an extension of the current approach to size GI treatment trains, by formulating the problem as a single objective optimization problem. Minimizing the Equivalent Annual Cost (EAC) of the treatment train was considered as the objective function in the single objective optimization, and the constraints were the target reduction levels of pollutants (Total Suspended Solids, Total Phosphorous and Total Nitrogen) and the available land area. However, unlike the previous studies where a single optimum solution was obtained in the optimization, several treatment train sizing combinations close to the minimum cost were obtained with these sizing combinations having vastly different performance measure values in terms of TBL objectives. The results of the optimization showed that there are several solutions which have different sizing combinations of individual treatment measures, but with costs close to the minimum and just exceeding the target 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 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 chapter 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. The methodology proposed in this study also showed the difficulty in treatment train size optimization only based on the single objective optimization. Moreover, the optimization of treatment train sizing for an complex land use like industrial area should consider all relevant performance measures (not only EAC) and stakeholder preferences on performance measures. This can be achieved through methodologies such as Multi Criteria Decision Analysis (MCDA) which consider both the differences in performance measures and the stakeholder preferences in these performance measures. The procedures followed for the stakeholder preference elicitation and MCDA will be discussed in Chapter 4.

CHAPTER 4

Stakeholder Preference Elicitation and Multi Criteria Decision Analysis for Optimum Green Infrastructure Selection for Stormwater Management

4.1 Introduction

In the context of Multi Criteria Decision Making (MCDA), the term 'preference' usually refers to the desires of the decision maker, which is one the essential elements in the decision making process (Kodikara, 2008). As discussed in Section 2.6.2.1, gathering preference data which is known as 'preference elicitation' is one of the major difficulties associated with the MCDA process. Previous studies have proven that the preferences of the decision makers can be variable due to several circumstances which could lead to biased outcomes (Lloyd, 2003, Braga and Starmer, 2005). The preference elicitation methods should always attempt to collect the information of user preferences as much as possible to achieve the goals of the decision analysis. Furthermore, the preference elicitation methods should be able to avoid preference reversals, discover hidden preferences and assist the users making trade-offs when confronting with competing objectives (Chen and Pu, 2004). This chapter presents the results of stakeholder preference elicitation and MCDA carried out to identify a compromise optimum stormwater treatment train among the several near optimal solutions obtained from the single objective optimization process described in Chapter 3, for the case study area.

4.2 Optimal Selection of GI Practices: Stakeholder Preference Elicitation

The results obtained from the single objective optimization performed in Chapter 3 showed the difficulty in selecting a single optimum solution from the near optimal sizing combinations. In terms of optimizing GI practices, the optimal selection of GI practices among the pool of alternatives available and the optimal sizing of the selected GI practices are two important stages of the process. In the current practice, there is no systematic methodology available to perform these two tasks simultaneously. Furthermore, it is important to identify the performance measures that influence the optimum selection of GI practices for complex land uses such as industrial areas. Even though the initial selection of various performance measures was conducted through literature review and stakeholder consultations as discussed in Section 3.2.3, a consensus between a panel of experts is further required to identify the redundant or missing performance measures and to provide weights for these performance measures based on their importance for the decision problem.

The investigation of optimum GI practices to manage stormwater in industrial areas requires the preferences of multiple stakeholders to obtain a balance between the conflicting objectives and reach for a compromise solution. Hence, understanding and eliciting the stakeholder preferences is one of the major steps in performing the MCDA to select the most suitable GI treatment trains for the study area. There are many tools that can facilitate the stakeholder preference elicitation in the decision making process. In this study, the Delphi survey technique has been used for stakeholder preference elicitation with the SWING method for weight elicitation embedded in the Delphi survey. A brief introduction and the justifications in selecting these two techniques for the present study are further discussed in Sections 4.2.1 and 4.2.2.

4.2.1 Delphi Survey Method

The Delphi survey technique was first emerged through the military studies conducted by RAND corporation in 1940s and early 1950s (Dalkey and Helmer, 1963). From its introduction to date, the Delphi method has gained a wide popularity among researchers and has been applied for a variety of group decision making problems. The Delphi survey is a group decision making technique that allows interaction between the researcher and a group of experts related to a specific topic through a series of questionnaires. The Delphi survey is used to gain group consensus on a certain aspect, using a systematic process of information gathering (Yousuf, 2007). The structured questionnaires in the Delphi survey are completed anonymously by a panel of experts and the responses of each questionnaire are fed back to the expert panel in the subsequent rounds (Hasson et al., 2000). The participants also get the opportunity to revise or reconsider their responses based on the collective responses of the expert panel during the multiple survey rounds of the Delphi survey (Pulipati and Mattingly, 2013).

One of the key advantages of the Delphi survey is that, it facilitates the independent thinking of the participants and thus avoids the direct confrontation of the experts (Okoli and Pawlowski, 2004). Moreover, the anonymous and confidential nature of this technique overcomes several barriers in traditional communication, such as “peer pressure” and “groupthink” where few people from the group dominates the decision making (Barnes, 1987, Hsu and Sandford, 2007, Yousuf, 2007). Another advantage of the Delphi Survey is that the flexibility provided by the technique for the experts to be participated from a geographically distributed locations and have the convenience on participating within their own time frames (Kenny, 2016). The questionnaires in the Delphi technique are self-explanatory and the multiple iterations of the questionnaires further leads to an increased validity of contents. Due to the above discussed advantages, the Delphi survey has been selected as the stakeholder preference elicitation method for the present study.

One of the most important factors in designing a Delphi survey is to form the expert panel by selecting an appropriate group of experts (Skulmoski et al., 2007).

There are no standards or guidelines available for the selection of experts for a Delphi panel which has been one of the major drawbacks of this method (Baker et al., 2006). Another disadvantage of this method is the drop out of participants due to potential sample fatigue during the several iterative rounds. However, unlike traditional questionnaire methods, the Delphi survey does not require a statistically significant sample of respondents; rather the method relies on the selection of a limited number of high level experts on the area of interest (Dalkey and Helmer, 1963, Kenny, 2016).

There is no standard number of participants in an expert panel for Delphi surveys defined in literature. Majority of the Delphi studies performed in the literature have considered around 10-15 participants for an expert panel (Day and Bobeva, 2005, Gordon and Pease, 2006, Hung et al., 2008, Kenny, 2016). Thus, in the present study, a Delphi Survey was designed by considering 10-15 experts who has the expertise in the industrial GI projects and the study area, to gather information. More information about the experts participated in the study and their expert profile is discussed in Section 4.4.1.2.

4.2.2 SWING Weighting Method

The SWING weighting method which was introduced by von Winterfeldt and Edwards (1986) provides the decision maker the opportunity to swing the weights for criteria from worst outcome to the best (Pöyhönen and Hämäläinen, 2001, Runge et al., 2011). It uses a reference state where all the criteria are at the worst level and the participant assigns 100 points to the most preferred option (Parnell and Trainor, 2009, Gomes et al., 2011). The magnitudes for the other options are expressed in reference to the most preferred option (100 points) through giving them points between 0-100 (the score of the least preferred option may not be 0 points) and are then normalized to yield the final weights (Zardari et al., 2015). One of the advantages of the SWING method is that it does not take the range of each criterion into account. This makes the weights of the criterion independent upon their values. Another important factor is that the method starts with identifying the most important option first, which makes it easier for the decision maker to compare the other options and give them weights with respect to the best option. Hence, this technique provides means of weighing the criteria with simple yet accurate and precise way (Gomes et al., 2011). One of the drawbacks of this method is, it does not allow the participants to directly compare the criterion against each other as each criterion is weighted with respect the best option (Zardari et al., 2015). Due to the simplicity and flexibility for the decision makers to understand the process in a self-understood questionnaire, the SWING weighting method has been embedded with the Delphi survey for the weight elicitation of the performance measures in this study.

4.3 Selection of the Suitable MCDA Technique

There are many MCDA methods described in literature, which can be used for various decision making problems as discussed in Section 2.6.2.3. The decision makers are faced with the challenge of selecting the most appropriate method for their study, which is often difficult to justify (Ishizaka and Nemery, 2013). Ozernoy (1997) states that selecting a suitable MCDA method for a particular study is a MCDA problem itself. Every MCDA technique comes with their own limitations, particularities, hypotheses, premises and perspectives (Ishizaka and Nemery, 2013). Therefore, the selection of a MCDA method for a particular problem strongly depends on type of the problem analyzed, type of information required by the method, methods of preference elicitation, types of decision makers involved, effort and time required for the computations, algorithms used to achieve the final solution, types of uncertainties associated with the problem and the ways of handling them (Guitouni and Martel, 1998, Pomerol and Barba-Romero, 2012). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used as the MCDA method for the current problem and the concepts of the method and justifications in selecting this method are discussed in Section 4.3.1 below.

4.3.1 TOPSIS Method

The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method which is presented by Hwang and Yoon (1981) is a MCDA method that is used to identity solutions from a finite set of alternatives (Jahanshahloo et al., 2006). This method attempts to choose alternatives that simultaneously have the shortest distance from the positive ideal solution (the solution that maximizes benefit criteria and minimizes cost criteria) and the farthest distance from the negative ideal solution (the solution that maximizes the cost criteria and minimizes the benefit criteria). The steps of TOPSIS analysis can be explained as follows (Opricovic and Tzeng, 2004, Jahanshahloo et al., 2006, Behzadian et al., 2012, Li et al., 2013).

- Assume that there is a decision problem with ***m*** alternatives and ***n*** criteria (performance measures) with the score for each alternative with respect to each criterion.
- Let x_{ij} is the score of ***alternative i*** with respect to ***criterion j***, where there exist a decision matrix, $X = (x_{ij})$, ***m×n matrix***.
- Let ***J*** be the criteria to be ***maximized***.
- Let ***J'*** is the criteria to be ***minimized***.

Step 1 - Construct the normalized decision matrix

$$r_{ij} = x_{ij}/\sqrt{\sum x_{ij}^2} \tag{4.1}$$

Where r_{ij} = the normalized value and, x_{ij} = observed value for each alternative *i* with respect to each criterion *j*, *i= 1, 2….m, j= 1, 2 …n*

Step 2 - Calculation of the weighted normalized decision matrix

- Assume that there exist a set of weights for each criterion as w_j for ***j= 1, 2 …n***
- Multiply each column of the normalized decision matrix with its associated weight and element of the new matrix is:

$$v_{ij} = w_j \times r_{ij} \tag{4.2}$$

Where v_{ij} = Weighted normalized value, and w_j = Weight of the j^{th} criterion

Step 3 - Determine the positive ideal and negative ideal solution

$$A^+ = \{v_1^+ ,\ldots\ldots\ldots\ldots v_n^+ \}\text{, where}$$

$$v_j^+ = \{max_i\left(v_{ij}\right) \; if \; j \in J; min_i\left(v_{ij}\right) \; if \; j \in J'\} \qquad (4.3)$$

$$A^- = \{v_1^- ,\ldots\ldots\ldots\ldots v_n^- \}\text{, where}$$

$$v_j^- = \{min_i\left(v_{ij}\right) \; if \; j \in J; max_i\left(v_{ij}\right) \; if \; j \in J'\} \qquad (4.4)$$

Where A^+ = positive ideal solution, A^- = negative ideal solution

Step 4 - Calculate the separation measures

The separation of each alternative *i* from the positive and negative ideal solutions is given as follows.

$$S_i^+ = \sqrt{\sum(v_j^+ - v_{ij})^2} \qquad i = 1,2,\ldots, m \qquad (4.5)$$

$$S_i^- = \sqrt{\sum(v_j^- - v_{ij})^2} \qquad i = 1,2,\ldots, m \qquad (4.6)$$

Where S_i^+, S_i^- = separation from positive and negative ideal solutions.

Step 5 - Calculate the relative closeness to the positive ideal solution

The relative closeness is defined by closeness coefficient (C_i^*)as follows.

$$C_i^* = S_i^- / (S_i^- + S_i^+) \qquad (4.7)$$

Step 6 - Rank of the preference order

- Ranking is done based on the relative closeness of alternative *i* to the positive ideal solution. (Higher the relative closeness to the ideal solution, higher the rank of the alternative)

The TOPSIS analysis procedure starts with normalizing the decision matrix. The decision matrix used in the TOPSIS method should only contain quantitative numeric values. The normalization of the decision matrix can reduce the computational problems that can occur due to different units and measurements of the criteria. There are several different normalization techniques that can be used in the TOPSIS method which are introduced by different authors (Hwang and Yoon, 1981, Yoon and Hwang, 1995, Milani et al., 2005). Step 1 above shows the vector normalization technique which is the commonly used normalization method for TOPSIS in the literature (Jahanshahloo et al., 2006, Shih et al., 2007). This method is also used in the present study to normalize the decision matrix. Some of the other normalization techniques used in TOPSIS analysis in the literature are linear normalization and non-monotonic normalization (Shih et al., 2007).

The decision matrix normalization converts the decision matrix into a normalized decision matrix which allows the comparison across the criteria by transforming the values into a common non-dimensional unit (Step 1) In Step 2; the normalized decision matrix is converted into a weighted normalized decision matrix by multiplying each column of the decision matrix with the associated weight. This is followed by determining the positive ideal solution and negative ideal solution (in Step 3) and the calculation of the separation of each alternative from those ideal solutions (in Step 4). The relative closeness expressed by closeness coefficient is then calculated for each alternative (Step 5), and the alternatives are ranked according to the descending order of the closeness coefficient (Step 6) (Behzadian et al., 2012).

The TOPSIS method has several advantages such as the availability of simple computational process that can be easily programmed into a spreadsheet, a sound logic that well represents the rationale of human choice, the existence of a scalar value that represents both the best and worst alternatives simultaneously, and the presence of fewer amounts of rank reversals compared with the popular MCDA methods such as ELECTRE (Roy, 1968) and AHP (Zanakis et al., 1998, Shih et al., 2007). TOPSIS has been identified as a MCDA method which is suitable for problems with large number of criteria and alternatives which are provided with numerical or quantitative data. Due to these advantages, the TOPSIS method was selected as the MCDA technique to obtain a compromise solution in GI optimization for industrial areas.

4.4 Stakeholder Preference Elicitation – Data Analysis and Results

An expert panel who are experienced with industrial GI applications has been consulted through a four rounded Delphi Survey to identify performance measures and to obtain weights for the selection of GI practices for industrial areas. A series of questionnaire surveys was used to identity redundant and missing performance measures from the already identified set of performance measures and for the weight elicitation, which were then used in the TOPSIS analysis to obtain a compromise optimum solution. The complete procedure followed for the stakeholder preference elicitation through the Delphi survey and the results are discussed in this section.

4.4.1 Delphi Survey: Identification of Performance Measures and Weight Elicitation

One of the most important questions which need to be addressed during the design of a Delphi survey is determining the number of questionnaire rounds that is required to achieve the consensus. The number of questionnaire rounds depends on the type of the problem being analysed, the objectives of the Delphi survey (whether the research requires the answers for one broad question or a series of questions), the available time, the resources and the consideration of the levels of sample fatigue (Hasson et al., 2000). According to the literature, the classic Delphi technique generally consists of four rounds (Young and Hogben, 1978), whereas more recent studies have proven that three or two rounds of questionaries are required for majority of Delphi Surveys to reach consensus (Harman et al., 2013, Tolsgaard et al., 2013, McMahon et al., 2014, Thellesen et al., 2015). The major drivers in integrating a Delphi survey in a research is to minimize the biasing effects of dominant panel members, irrelevant communication and the peer pressure towards conformity

(Ganisen et al., 2015). Hence, it is crucial to decide on the appropriate number of rounds considering the fact that stopping the study too soon may yield into inefficient results and continuing it further may cause sample fatigue and waste respondents time (Schmidt, 1997).

There are two major objectives which need to be considered in the Delphi survey for the present study. The first objective is to identify the performance measures which are important in optimizing GI practices for industrial areas. The second objective is to elicit weights for those identified performance measures. By analysing the study objectives, a four round questionnaire series was conducted in the Delphi survey. Figure 4.1 shows the process diagram of the structure of the Delphi survey conducted in the present study with the description of the objectives which were intended to be achieved in each questionnaire round.

As explained in the survey design in Figure 4.1, after deciding on the number of rounds required for the Delphi survey, the structure of the surveys and the timelines for conducting the surveys were finalized. The surveys were structured to have both open ended and closed ended questions when required. To improve the clarity of the questionnaire survey, 3 pilot tests were carried out before distributing the final survey and necessary amendments and refinements were done accordingly.

The identification of the potential members to represent the expert panel is another important step in the Delphi survey process. The selection of the right candidates to form the expert panel in the Delphi survey is important as the validity of the results depends on the expertise of the participants (Ganisen et al., 2015). However, there are no specific standards or guidelines provided in the literature with regard to the selection of the experts for a Delphi Survey (Hsu and Sandford, 2007). In selecting an expert panel, majority of previous studies have used selection criteria which includes knowledge, experience with the problem area which is being investigated, direct involvement with the projects/industry (practitioners), hierarchy or position, relevant publications (if they are academics) and their capacity and willingness to participate (Jeffery, 2000, Powell, 2003, Duncan et al., 2004, Skulmoski et al., 2007, Haughey, 2010, Valerdi, 2011). In this study, several experts were identified who comply with the above selection requirements as potential

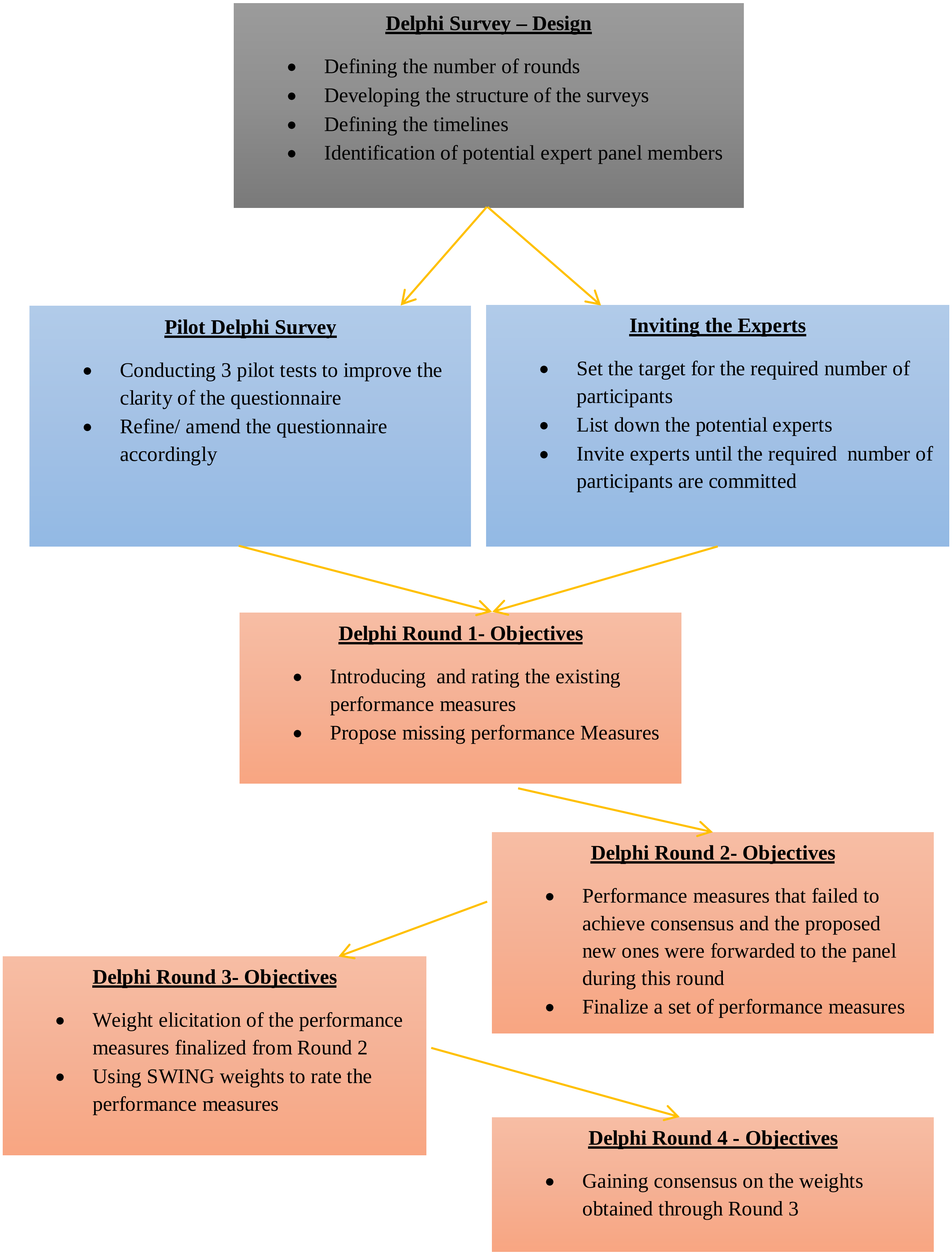


Figure 4.1 – Delphi Process Diagram

participants for the Delphi panel who have experience and/or currently working on projects related to applications of GI practices in industrial areas. The profile of the expert panel members selected for the Delphi survey is further discussed in Section 4.4.1.2.

The questionnaire series was designed to be conducted within an 8 week period (February first week to April first week, 2016) with each expert given 1 week to answer each questionnaire. Due to the ethical conduct of research and human subjects involved in the questionnaire surveys, Victoria University (VU) Ethics Committee clearance was obtained prior to distributing the questionnaire surveys to the participants. Self-explanatory online surveys were identified as the most suitable method of conducting the Delphi survey in this study due to the knowledge and experience of the selected expert panel on the problem and the ease of participation for the panel members within a flexible timeline in distributed geographical locations. The questionnaire surveys were designed using the Qualtrics Online survey software. The software provided the opportunity to send individual link of the questionnaire survey to each expert which has been used in subsequent rounds where each expert was provided feedback of the previous round to compare their individual response with the group's response.

4.4.1.1 Measuring Delphi Consensus

The principle aim of incorporating the Delphi technique for a study is to achieve the consensus among participants on the problem being analysed (Giannarou and Zervas, 2014). However, the measurement of consensus of a Delphi survey is also the most contentious component of the method as there is no universal method currently available for this process (Heiko, 2012). The measurement of consensus in a Delphi survey highly varies due to the controversial understanding of the term and hence there are several methods presented in the literature to assess the level of consensus (Rayens and Hahn, 2000, Yang, 2003). Table 4.1 shows the most widely used methods in the literature to measure the consensus in Delphi surveys with the examples from several previous studies. As shown in Table 4.1, researchers have used methods such as stipulated number of rounds, subjective analysis, certain level of

Table 4.1 – Methods of Measuring Delphi Consensus (Most information extracted from Heiko, 2012)

Measurement of Consensus	Criteria
Stipulated number of rounds	• "Research indicated that three iterations are typically sufficient to identify points of consensus…Thus, three rounds were used in this study." (Fan and Cheng, 2006)
Subjective analysis	• "The expert's rationale for a response had to be consistent with the mean group response" (Mitchell, 1998). • "Overall, it was felt that a third round of the study would not add to the understanding provided by the first two rounds and thus the study was concluded." (MacCarthy and Atthirawong, 2003) • "A consensus…was pursued through a series of personal interviews over several days." (Lunsford and Fussell, 1993)
Certain level of agreement	• "In keeping with most other Delphi studies, consensus was defined as 51% agreement among respondents." (Loughlin and Moore, 1979) • "Consensus was achieved on an item if at least 60% of the respondents were in agreement and the composite score fell in the "agree" or "disagree" range." (on a 5 point likert scale) (Seagle and Iverson, 2001) • "More than 67% agreement among experts on nominal scale was considered consensus" (Alexandrov et al., 1996, Pasukeviciute and Roe, 2001).
APMO Cut-off Rate (average percent of	• "Cottam et al. (2004) calculate an APMO Cut-off Rate of 69.7%, thus, questions having an agreement level below this rate have not reached consensus and are included in the next round."

majority opinions)	• "Islam et al. (2006) calculate APMO Cut-off Rates of 70% (first round) and 83% (second round) for consensus measurement."
Mode, mean/median ratings and rankings, standard deviation	• "In our case, mode was used as an enumeration of respondents who had given 75% or more probability for a particular event to happen. If this value was above 50% of the total respondents, then consensus was assumed." (Chakravarti et al., 1998) • "Mean responses within acceptable range (mean± 0.5) and with acceptable coefficient of variation (50% variation) were identified as opinion of firm consensus." (Sharma et al., 2003). • "Consensus was achieved, if ratings (4-point Likert scale) for the items fell within the range of mean± 1.64 standard deviation." (Rogers and Lopez, 2002, West and Cannon, 1988)
Interquartile range (IQR)	• "Consensus is reached when the IQR is no larger than 2 units on a 10-unit scale. " (Linstone and Turoff, 1975). • "Consensus was obtained, if the IQR was 1 or below on a 7-point likert scale." (De Vet et al., 2005). • "IQR of 1 or less is found to be a suitable consensus indicator for 4- or 5-unit scales." (Raskin, 1994, Rayens and Hahn, 2000)
Coefficient of variation	• "The authors found the coefficient of variation at or below 0.5, which was to them a cut-off point conventionally accepted as indicating reasonable internal agreement" (Zinn et al., 2001). • "A consistent decrease of the coefficients of variation between the first and the second round, indicated an increase in consensus (greater movement toward the mean)." (Buck et al., 1993).

agreement, average percent of majority opinions, mode/mean/median ratings and rankings, standard deviation, inter quartile range and co- efficient of variation. Thus, it is evident from Table 4.1 that selecting a suitable method to analyse the consensus is a subjective process which depends on the nature of the problem being analysed and the Delphi facilitator’s goals that are expected to be achieved through conducting the study.

For the current Delphi study, two methods were used to measure the degree of consensus of the participants which are the certain level of agreement and the coefficient of variation based on the objectives of the survey. The aim of the first two rounds of Delphi survey is to finalize a set of important performance measures in selecting GI practices for industrial areas, among the ones which were identified through initial discussions with stakeholders and through literature as discussed in Section 3.2.3.

To obtain the expert responses for the Delphi surveys, likert scales are used. Majority of the Delphi surveys presented in the literature have considered likert scales with 5 or 7 point scales and there are no specific guidelines available in selecting a suitable scale for a Delphi survey (Williams and Webb, 1994, Verhagen et al., 1998, Birdir and Pearson, 2000, Miller, 2001). A study conducted by Dawes (2008) showed that the 5 and 7 point likert scales produced the same mean score as each other, once they were rescaled. Scales with too many points have identified to be more demanding for the respondents and thus have found to be creating response fatigue and response biases (Hinkin, 1995). Hence, in this study, for the first two rounds, experts were asked to rate the level of importance of the each performance measure using a 5 point likert scale as follows.

- Not Important (1)
- Slightly Important (2)
- Moderately Important (3)
- Very Important (4)
- Extremely Important (5)

In finalizing the set of performance measures, the certain level of agreement which is the most widely used technique for Delphi surveys in literature was selected as the method of determining the degree of consensus for the present study in first two rounds. With regards to the level of agreement, Alexandrov et al. (1996) considered that if two thirds of the panel (67%) have agreed with the offered option, consensus has been achieved. After this study, several researchers have considered the two thirds cut-off as a statistically significant threshold in their Delphi studies (Lehmann et al., 2004, Chang et al., 2009, Juwana, 2012). Thus, 67% (two thirds) cut-off was used as the level of agreement in achieving consensus in the first two rounds of Delphi study. The collapsed category approach which collapses the top and bottom categories to calculate the agreement level was used in this study to determine consensus as was done by Rayens and Hahn, (2000), Keeney et al, (2011) and, Kenny, (2016). The collapsed categories for the first two rounds were defined as follows.

- Not Important (1)
- Slightly Important (2)

Disagree (If sum ≥ 67%)

- Moderately Important (3)

Neutral

- Very Important (4)
- Extremely Important (5)

Agree (If sum ≥ 67%)

If the two thirds of the expert panel selected a performance measure as not important or slightly important, it has been considered as disagreement and the performance measure has been considered as redundant. If two thirds of the expert panel has selected a performance measure as very important or extremely important, it has been considered as an agreement and identified as an important performance measure for the selection of GI. If neither of the above requirements were achieved, it was forwarded to the next round.

The third and fourth rounds were used to obtain the weights by the expert panel for the performance measures (which were finalized through rounds 1 and 2) in GI selection based on their importance for industrial areas. In this round, experts were asked to provide SWING weights for the finalized performance measures through questions which included a numerical output. Hence, to measure the degree of consensus in these two rounds, the 'coefficient of variation' of weights was used. The method of integrating the coefficient of variation which was used to determine the degree of consensus in rounds 3 and 4 is explained in Table 4.2 (Heiko, 2012).

Table 4.2 – Consensus Measurement through Co-efficient of Variation (English and Kernan, 1976)

Coefficient of Variation of Responses (C_V)	Decision Rule
$0 < C_V \leq 0.5$	Good degree of consensus. No need for additional round.
$0.5 < C_V \leq 0.8$	Less than satisfactory degree of consensus. Possible need for additional round.
$C_V > 0.8$	Poor degree of consensus. Definite need for additional round.

4.4.1.2 Expert Profile

The participants in a Delphi study need to be a panel of individuals who has knowledge on the topic being investigated (Hasson et al., 2000). McKenna (1994) defines this as "panel of informed individuals" and thus the term 'experts' has been applied to represent Delphi participants. For a Delphi survey to be successful the commitment of the experts throughout the study is important, and the success is highly dependent upon the expert's interest and involvement with the topic being discussed.

For the current Delphi analysis, the experts who are experienced in applications of GI practices in industrial areas were identified based on their expertise in similar areas. An email was sent to 25 experts who represent local and state government, public and private water utilities, universities, consultancy firms, and urban planning and development authorities. The target was to obtain responses from 10-15 experts. A description of the complete research project, the description of the Delphi survey and the role of the surveys in the research project, the details of research investigators, the research ethics and the confidentiality were explained to these experts before distributing the survey. Furthermore, the experts were also informed that their participation will be requested for all four rounds before starting the questionnaire series. Among the 25 participants that the email invitation was sent, 16 participants agreed to participate in the survey series. Table 4.3 shows the profile of the experts who agreed to participate in the survey series.

Table 4.3 – Profile of the Experts who agreed to Participate in Delphi Survey

ID	Expert Designation	Current Organization Type
1	Project Manager	Public Water Utility
2	Environmental Engineer	Consultancy
3	Senior Design Engineer	Local Government
4	Research Fellow	University
5	Water Resources Engineer	State Government
6	Strategic Supply Planner	Public Water Utility
7	Project Manager	Public Water Utility
8	Water Resources Planner	State Government
9	Senior Water Resource Analyst	Public Water Utility
10	Research Fellow	University
11	Senior Associate	Consultancy
12	Project Manager	Public Water Utility
13	Senior Drainage & Subdivisions Engineer	Local Government
14	Technical Director - Water	Consultancy
15	Design Engineer	Local Government
16	Water Resources Engineer	Local Government

Among the 16 experts who provided their consent to participate in all four rounds, 15 experts completed the first round by maintaining 94% precent of response rate. Each expert was given one week to complete each round and reminders were sent to the experts who did not complete the survey, two days before the closing of the relevant round. Only the experts who completed a round were invited to participate in the subsequent round. Round two was completed by all 15 experts who completed round 1 by providing 100% response rate. Only 13 experts completed round 3 with 87% response rate and the final round was completed by 12 experts by maintaining 92% response rate from round 3 to round

4. The summary of the response rates in each round is shown in Table 4.4. The dropped out experts mentioned time and other commitments as the reasons to drop out from the successive questionnaire rounds.

Table 4.4 – Summary of Response Rates

Round	Invited	Completed	Response Rate (By round)
Round 1	16	15	94%
Round 2	15	15	100 %
Round 3	15	13	87%
Round 4	13	12	92%

The percentage years of experience of the experts who participated at the beginning of the survey and the end of the survey is shown in Figure 4.2. This shows that the above 50% of the participants had 10-20 years' experience on the field and thus it can be considered as a panel of high expertise.

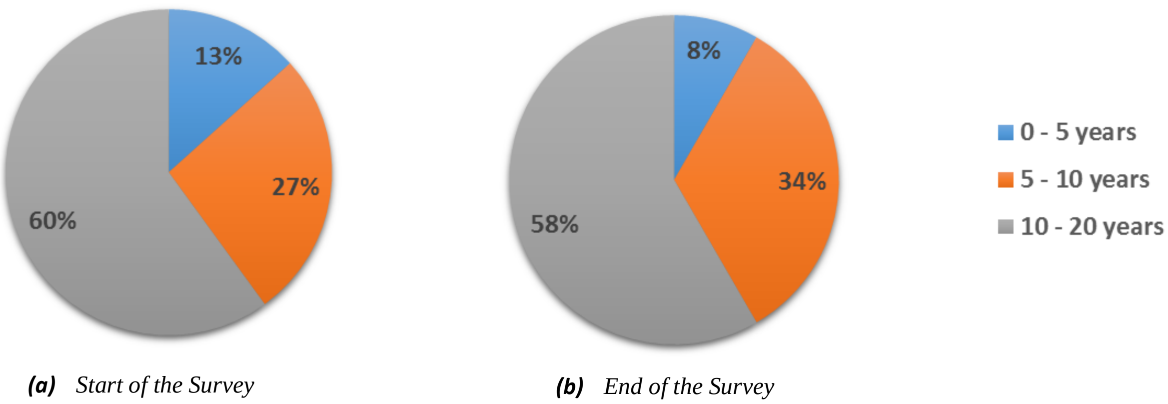


Figure 4.2 – Expert Panel – Years of Experience (Percentage)

4.4.1.3 Round 1 of Delphi Survey

Based on an extensive literature review and initial discussions with stakeholders, the objectives and some of the important performance measures in selecting GI for industrial areas were already identified as discussed in Section 3.2.3. These initial discussions were conducted with various stakeholders who are currently involved with the project such as project managers, urban planners, environmental engineers and stormwater professionals. Several individual interviews and meetings were conducted with these stakeholders to identify and short list the most important performance measures in selecting GI for industrial areas. The description of the 12 performance measures which were initially selected are shown in Table 4.5. In Round 1, the objective was to ensure whether there are any redundant or missing performance measures. The experts were provided with the description of the current performance measures and they were asked to rate the importance of objectives and performance measures in 1-5 scale through close ended questions. Furthermore, they were asked to suggest any missing performance measures that they think which should be included in the list as an open ended question. The complete questionnaire distributed to the participants in Round 1 is shown in Appendix 4A.

Figures 4.3 and 4.4 show the percentage responses of the expert panel on the TBL objectives (environmental, economic and social) and performance measures in GI selection for industrial areas. As shown in Figure 4.3, 87%, 73% and 73% of expert panel agreed (selected 4 or 5 in a 5 point likert scale) on the environmental, economic and social objectives respectively. Among the environmental performance measures considered, the consensus has been achieved for TSS and TN load reduction and peak flow reduction by the percentage expert agreement of 80%, 73% and 67% respectively. There were no disagreement responses for both TSS reduction and peak flow reduction, which shows that these environmental performance measures are well preferred by the expert panel.

The annual TP load reduction, Cu and Zn removal and habitat creation among environmental performance measures did not reach the 67% cut off rate with expert consensus. The annual TP reduction and habitat creation have exhibited the same pattern of expert responses with 60% agreement, 20% neutral and 20% disagreement. Both Zn and Cu removal had less disagreement level of 7% however had high neutral response rate of 33% and 40% respectively. As these four performance measures did not achieve consensus in Round 1 and showed high level of neutral response rate and level of disagreement up to 20%, they were forwarded into the next round. All economic and social performance measures achieved the 67% of consensus in Round 1.

Table 4.5 – Performance Measures and their Description

Objective	Performance Measure		
	ID	**Name**	**Description**
Environmental	PM-1	Annual TSS Load Reduction	The removal ability of TSS, TP and TN through GI. Environmental Impacts TSS – Reducing the visibility and absorbance of light, which can increase stream temperatures and reduce photosynthesis TP and TN – Generation of toxic algal blooms, decreasing the dissolved oxygen, light and habitat available for other aquatic species
	PM-2	Annual TP Load Reduction	
	PM-3	Annual TN Load Reduction	
	PM-4	Heavy Metal Removal (Cu)	The removal ability of heavy metals through GI. Above 70% of industrial facilities have been found to discharge stormwater with elevated levels Zn and Cu amongst heavy metals. Environmental Impacts Cu – Interference with fish sensory systems, migration and behaviours related to predator avoidance of aquatic life Zn – Impaired reproduction and reduced growth in aquatic life
	PM-5	Heavy Metal Removal (Zn)	
	PM-6	Peak Flow Reduction	Ability to attenuate peak flows to reduce flood risks and harmful impacts to the surrounding water bodies
	PM-7	Habitat Creation	Ability for creating or preserving habitats (animals, plants or other organisms) to support biodiversity.
Economic	PM-8	Potable Water Savings	Ability to save potable water which is used for various industrial activities.
	PM-9	Equivalent Annual Cost	Annualized form of the total life cycle cost of GI. This is obtained as the total life cycle cost divided by number of years in the life cycle.
	PM-10	Capital Cost	Capital cost of the stormwater management GI.
	PM-11	Annual Operation and Maintenance Cost	Operation and maintenance costs incurred annually for the GI.
Social	PM-12	Improvement of Liveability	Improvement of the quality of life in the area (e.g. creating leisure/recreational opportunities, visual and aesthetic appeal) through urban greening

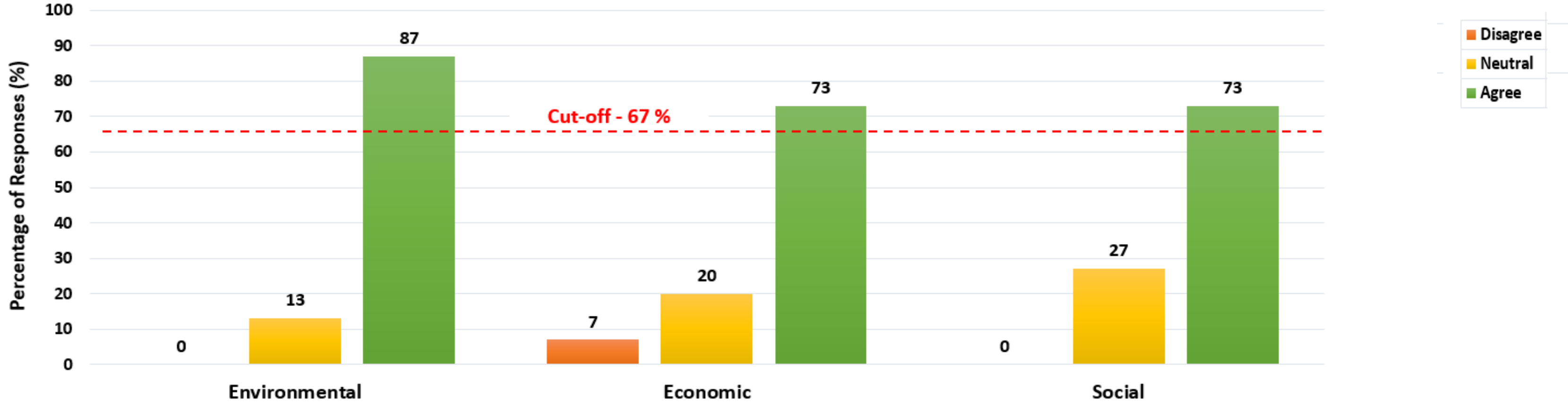


Figure 4.3 – Expert ratings for Objectives – Round 1

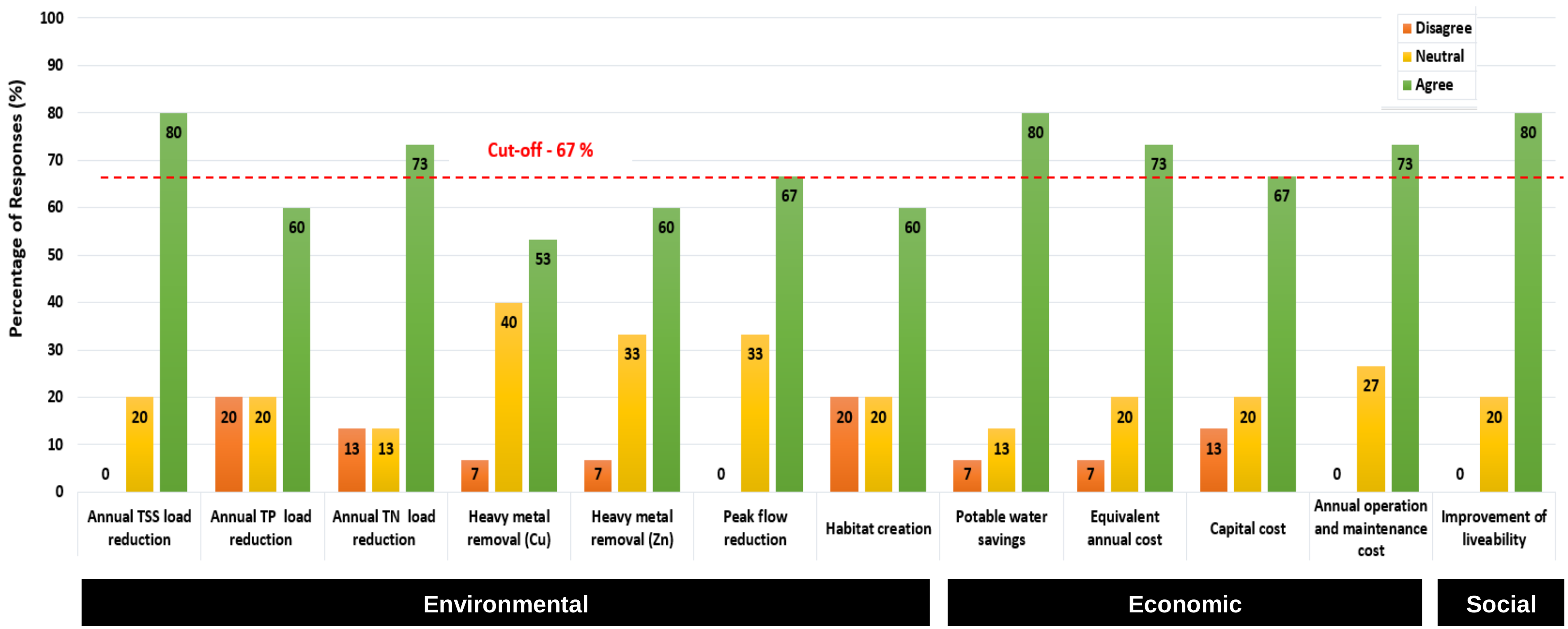


Figure 4.4 – Expert Ratings for Performance Measures – Round 1

Furthermore in Round 1, experts were also asked to suggest performance measures that they thought were missing in the current list of performance measures. They were also asked to provide the reasons on why they thought these new performance measures should be included as importance performance measures in GI selection for industrial areas. Several suggestions were made by the expert panel as new performance measures. Some examples of expert suggestions are shown below.

#Expert 1 - *"Without measuring capacity building - and performance measures to identify the success/ failure uptake of new technologies - we won't know at what stage of the uptake cycle we have successfully shifted behaviour and values towards the new system/ approach. This knowledge is invaluable to ensure can support changes to system /organizational components/ human behaviour where they will have the most impact/ success. Changing technologies and approaches should be supported and measured through considered capacity building techniques. A key performance measure should be how a group/ organization successfully absorbs new approaches/ ways of doing things to then successful change the whole system over time. A performance measure would be good around how a group/ organization etc. can tolerate change and respond effectively to new processes, technologies etc. relating to GI.*"

The statement from #Expert 1 highlights the importance of a performance measure which represents the perceptions of the industries or business in the area, on GI approaches. This statement also draws the attention towards how the behavioural or perspectual aspects of people in these land areas can affect the decision of the process of selecting the optimum or most suitable type of GI practices for such areas. Majority of the GI planning projects for industrial areas begins with the assumption that the industrial organizations/businesses have a clear idea on the environmental, economic and social benefits of implementing such techniques due to their corporate and social responsibilities. However, there can be several perceptual barriers available that can limit the applications of specific types of GI practices based on the stakeholder's conceptions (limited knowledge, scepticism, lack of will to adopt etc.)

for such areas. Therefore, in the process of optimization of the GI practices for industrial areas, the behavioural aspect of the industry/business on accepting the particular GI measures can be considered as one of the important social performance measures. However, the evaluation of such a performance measure requires time, resources and larger amounts of further research which is beyond the scope of this study. Due to the importance of such performance measures suggested by experts, these performance measures were included in the subsequent rounds of the Delphi survey, to improve the knowledge base on expert preferences on them. However, such performance measures were not included in the final MCDA analysis, due to limited data availability on assessing them.

#Expert 2 - *"A measure of total runoff volume reduction that captures reductions due to infiltration and evapotranspiration. Flow volume reduction is a good indicator of improvement in the flow pattern discharged and encourages retention, rather than just detention practices."*

The statement from #Expert 2 highlights another important environmental performance measure which is specifically important for industrial areas. Industrial areas annually generate high volumes of contaminated stormwater compared to other land use types, due to the existence of larger impermeable/hard surface areas. The retention GI practices such as retention ponds or wetlands provide the functionalities in retaining the volumes of stormwater or the contaminants from various mechanisms as discussed in Section 3.1, whereas detention practices such as sedimentation basins do not provide much benefits in runoff volume reduction (Loperfido et al., 2014, Liu et al., 2015). Hence, the total runoff volume reduction can be considered as one of the important performance measures which can be used to identity optimum GI practices for an industrial area.

In addition to these two discussed performance measures, the experts proposed several water quality parameters and other performance measures which can be useful in stormwater management GI selection for industrial areas. A description of the proposed new performance measures from Round 1 is presented in Table 4.6.

Table 4.6 – Proposed New Performance Measures by Experts in Round 1

Objective	Proposed New Performance Measures in Round 1	
	Name	**Description**
Environmental	Total runoff volume reduction	The volume of runoff reduced by capture and storage through GI.
	Hydrocarbon removal	Ability of removing hydrocarbons found in industrial runoff that can cause risk to human and environmental health.
	Organic pollutants removal	Ability of removing organic pollutants found in industrial runoff that can cause risk to human and environmental health.
	Heavy metal removal (other)	Ability of removing other heavy metals found in industrial runoff that can cause risk to human and environmental health.
	Urban cooling effect	The ability of reducing the high urban temperatures present in industrial areas through GI.
Economic	Urban food production	Ability of using GI as a source of urban food production (e.g. GI as a source of urban agriculture) for areas with larger space.
	Energy savings	Energy savings benefits provided for the larger buildings in industrial areas by GI practices through cooling and improved building thermal performance.
Social	Industry/ Business's behaviour on accepting GI measure	Measurements on how a group/ organization successfully absorb new approaches, tolerate the change, and respond effectively to GI practices.
	Risk Assessment	The associated risk of the GI measures, which will impose on environment, economy and the society within the industrial and surrounding communities.
	Life cycle period of the GI measure	Life span of the viable performance of GI practice.
	Public safety	Measure of the potential hazard that can be caused by the GI practices to the general public in the area.

The performance measures that did not achieve the expert consensus from the existing list (Round 1) and the proposed new performance measures in Round 1 were forwarded to Round 2 of the Delphi survey, for further expert feedback.

4.4.1.4 Round 2 of Delphi Survey

In Round 2 of the Delphi survey, each expert was sent a questionnaire which included the summary results of the group's responses from Round 1, together with the individual responses of the specific expert in the same round. This has provided the opportunity for the experts to evaluate their own opinions with respect to the group's opinion. The four performance measures that didn't achieve consensus in Round 1 and the newly proposed performance measures were included in this round, for expert feedback. Figure 4.5 shows an example of an individual question included in Round 2. The complete survey conducted for Delphi round 2 is presented in Appendix 4B.

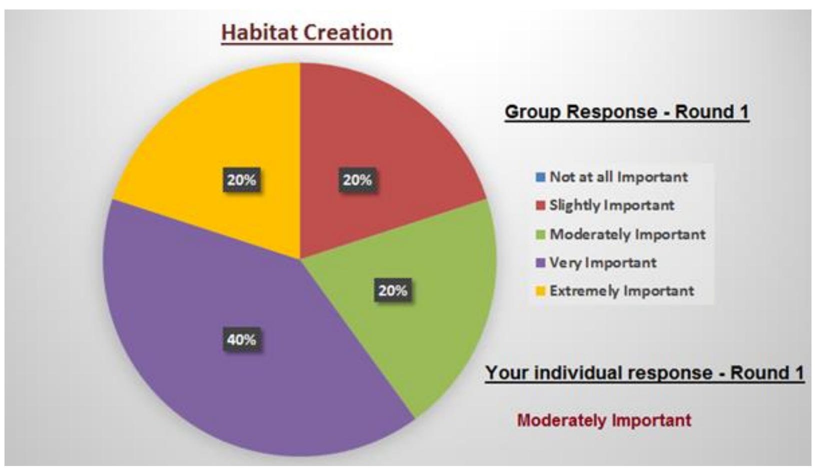


Figure 4.5 – Sample Personalized Question – Delphi Round 2

Each expert on this round was given the opportunity to reconsider their answers based on group response or they could also maintain the same answer as they provided in Round 1. The results obtained for the performance measures that failed to achieve consensus in Round 1 and the newly proposed performance measures are shown in Figures 4.6 and 4.7 respectively. As shown in Figure 4.6, in Round 2, two

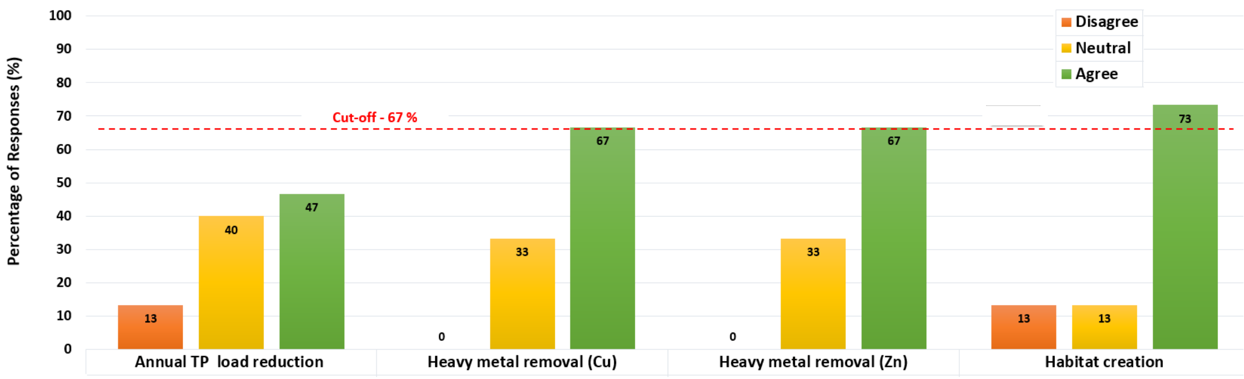


Figure 4.6 – Round 2 Results for the Existing Performance Measures

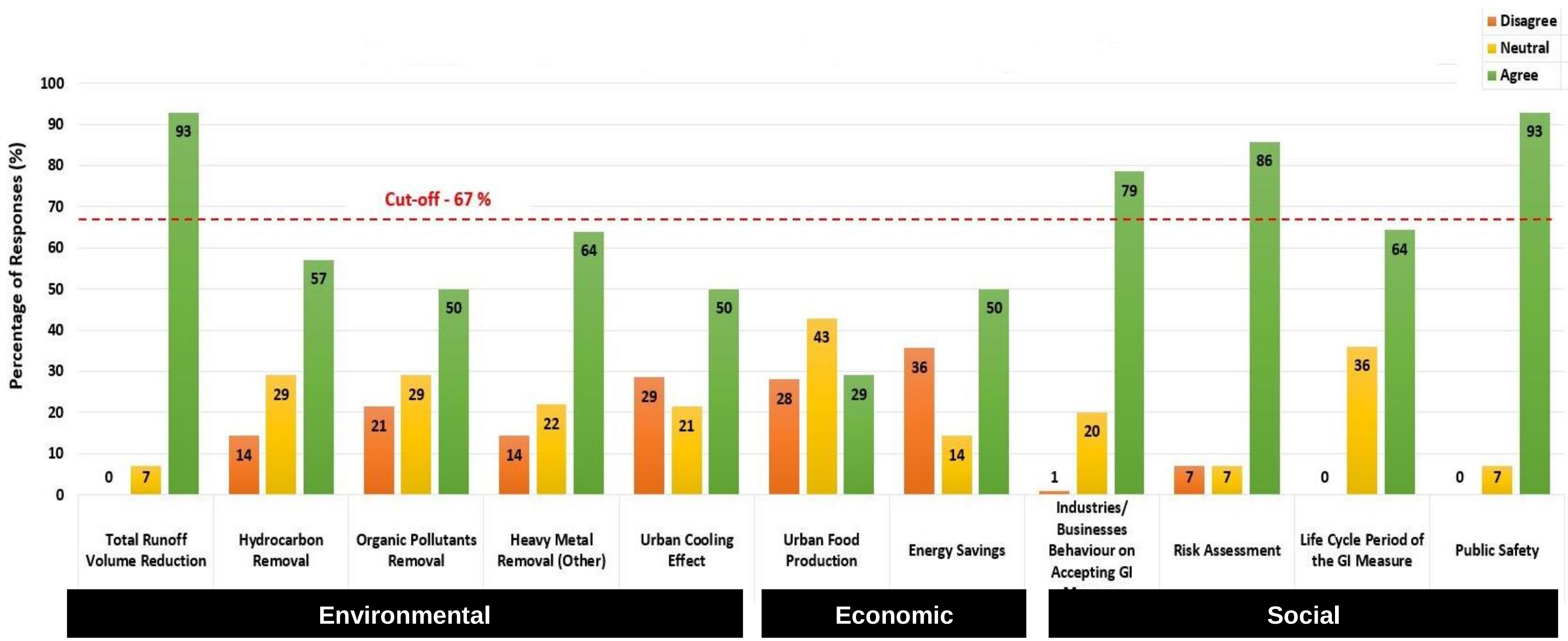


Figure 4.7 – Round 2 Results for New Performance Measures

thirds of expert consensus level was achieved for the performance measures Cu removal, Zn removal and habitat creation. Compared with the Round 1 result for these performance measures, the disagreement responses has been reduced for all these performance measures with zero disagreement levels for heavy metal components in Round 2. However, the TP removal did not achieve the consensus even in Round 2 and has shifted towards the neutral responses from 60% agreement level in Round 1 to 47% in Round 2. The percentage number of responses that disagreed with the performance measure of TP removal in Round 1 has dropped from 20% to 13% in Round 2. The reasons for the change in responses for TP removal were discussed by some experts. Some reasons they have provided for the higher neutral agreement level on TP removal are, the difficulty (or limiting nature) in achieving the TN removal rates through GI compared to TP (in sizing the GI to treat stormwater, the target removal rates of TP is generally achieved when the TN target reduction is achieved), the impacts of TN is higher than TP for freshwater, and the high standards of TN removal required in stormwater discharges in some areas which made them less focused on the importance on TP removal.

The experts also suggested that it would be more meaningful and easier for them to assess the similar types of performance measures when they are grouped together. Based on the suggestions of the expert panel, Cu removal and Zn removal were grouped into a single performance measures named heavy metal removal. Even though the TP removal did not reach the consensus in Round 2, considering the reasons provided by the experts for the lower concern on TP (as majority of their responses for TP removal was based on its importance compared with TN removal), the TN removal and TP removal were grouped into a single performance measure as nutrient removal and was taken into the Round 3.

From the newly proposed performance measures, total runoff volume reduction, industry/businesses behaviour on accepting the GI measures, risk assessment and public safety were agreed by more than 67% of the experts with zero or very low disagreement rate, which indicates a high degree of consensus. All other performance measures such as other water quality components, urban cooling effect, urban food production and energy savings had higher disagreement and neutral response rates except for the life cycle period of GI measure which was close to consensus with 64% expert agreement and zero disagreement. However, as discussed Section 3.2.2.1, well maintained GI practices are considered to have infinite life cycle periods and was assumed likewise in this study. Hence, among the proposed new performance measure list in Round 1, four performance measures that achieved the consensus (i.e. total runoff volume reduction, industry/businesses behaviour on accepting the GI measures, risk assessment and public safety) were added to the existing list and was confirmed as the final set of most important performance measures that influence the optimum GI selection for industrial areas. In Round 3, the experts were asked to provide weights for these final set of performance measures, in order to rank them based on the importance, according to their preferences.

4.4.1.5 Round 3 of Delphi Survey

In Round 3 of the Delphi application, the experts were requested to provide weights (using the SWING method) for the set of performance measures which were finalized through the previous two rounds. They were provided with the finalized set of performance measures from the previous rounds and asked to identify the most important performance measure first and give it a rating of 100. Then based on the most important measure, they were asked to rate the importance of other performance measures in 0-99 scale. The complete questionnaire distributed in Round 3 is shown in Appendix 4C. Figure 4.8 shows the final set of 14 performance measures which were presented to the experts to elicit weights in Round 3.

From the 15 experts who responded to Round 2, only 13 have provided weights for the performance measures in Round 3. The individual SWING weights provided by the experts for the performance measures are shown in Table 4.7. Based on the ratings provided by experts using the SWING method, the percentage weight allocated by the experts for each performance measure was calculated (individual SWING weight provided by the expert for each performance measure divided by total of SWING weights provided by each expert) and is shown in Table 4.8. To obtain a single representative weight for the performance measures, different methods can be used such as mean or median. In this study, the median weight was used as the representative weight as median has proven to be the measure that agrees well with the majority of the views of the group in decision making (Hokkanen et al., 1995, Kodikara, 2008). Furthermore, the median has also been identified as not as sensitive as the mean on extreme values (Keller and Warrack, 2003).

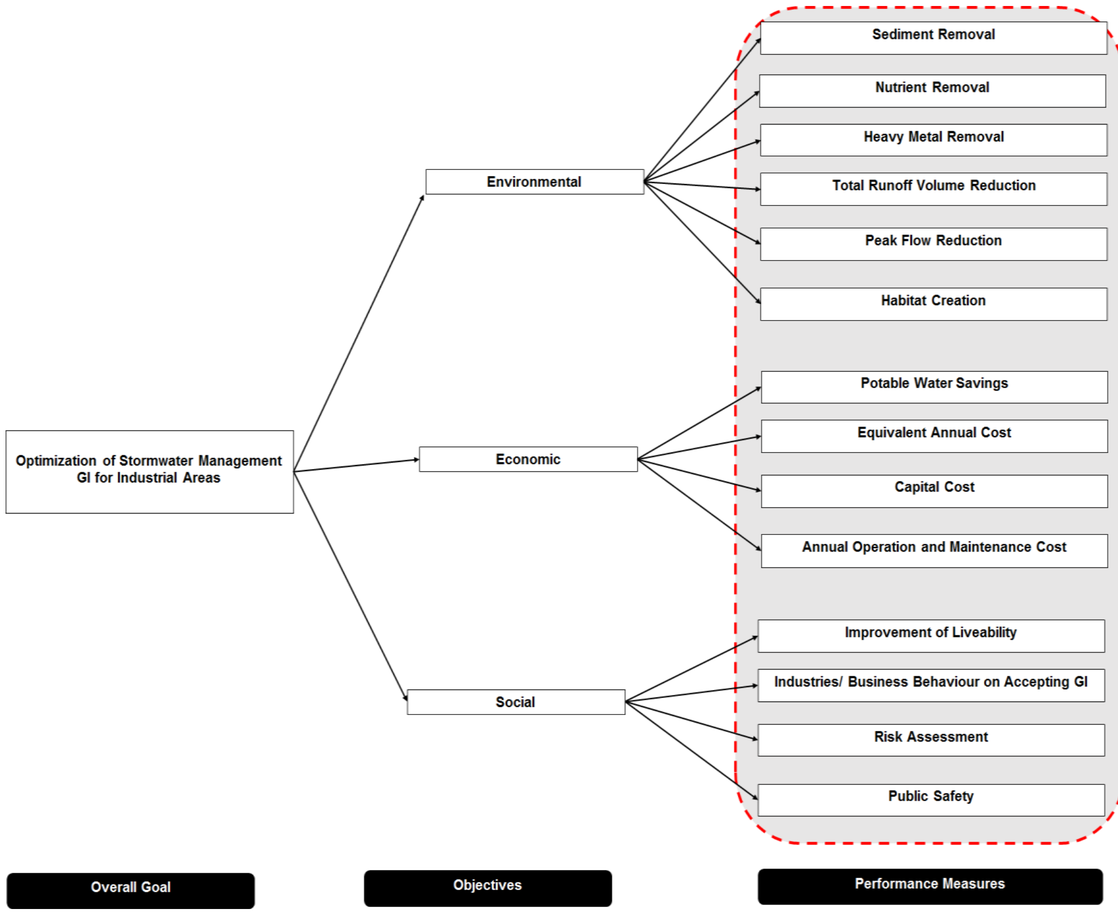


Figure 4.8 – Finalized Performance Measures in Stormwater Management GI Selection for Industrial Areas

The summary of the mean, median, standard deviation and the coefficient of variations of the weights provided by the expert panel in Round 3 is shown in Table 4.9. As discussed in Section 4.4.1.1, the degree of consensus in Round 3 is measured using the coefficient of variation of weights. According to the results in Delphi round 3, the expert's weights provided for all performance measures have shown a coefficient of variation below 0.5 which shows a good degree of consensus (refer to

Table 4.2). Apart from the performance measure of industry/business behaviour on accepting GI measure which had a coefficient of variation of 0.419, all the other performance measure measures had coefficients of variation well below 0.5. Even though this shows that an additional round is not required due to consensus has already been achieved, another round (Round 4) was conducted to confirm and refine the final weights of the performance measures, which are used as the input for the TOPSIS analysis. The ranks of the performance measures based on the median weights provided by the experts in Round 3, is shown in Figure 4.9. The experts have ranked total runoff volume reduction as the most important performance measure in selecting GI practices for industrial areas. Public safety and industry/businesses behaviour on accepting the GI measure were ranked as second and third important performance measures respectively. Habitat creation was ranked as the least important performance measure among the selected the list of performance measures. Even though habitat creation is one of the important performance measures related to GI implementation, this can be explained as the presence of more priority performance measures in the list (e.g. :stormwater quality/quantity and the costs) for industrial areas. Moreover, in Round 3, the experts have provided weights which are fairly close to each other for almost all performance measures. After analysing the results of Round 3, the final round (Round 4) of the Delphi survey was distributed among the participants which included feedback of group's weights and their individual weights on performance measures.

Table 4.7 – SWING Weights Provided by Experts in Round 3 (0-100 Scale)

Performance Measure	SWING Weights – Round 3												
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Expert 6**	**Expert 7**	**Expert 8**	**Expert 9**	**Expert 10**	**Expert 11**	**Expert 12**	**Expert 13**
Sediment Removal	100	70	90	35	55	90	80	81	70	35	90	80	85
Nutrient Removal	90	5	100	35	55	90	80	75	75	40	70	95	50
Heavy Metal Removal	90	80	60	35	71	90	80	74	80	65	95	80	64
Total Runoff Volume Reduction	95	80	90	90	85	80	80	100	85	100	80	90	53
Peak Flow Reduction	80	100	50	45	85	85	80	60	100	30	70	100	72
Habitat Creation	80	0	50	50	90	70	80	80	60	60	70	75	32
Potable Water Savings	90	10	70	55	90	80	90	95	70	45	95	70	95
Equivalent Annual Cost	85	50	80	40	70	95	90	70	80	80	70	95	100
Annual Operation and Maintenance Cost	85	80	50	80	85	95	70	82	80	70	90	60	61
Capital Cost	80	75	60	85	33	95	70	76	85	50	80	90	55
Industry/business Behaviour on Accepting GI Measure	90	5	20	100	100	97	100	69	70	85	90	90	98
Improvement of liveability	85	5	90	60	80	90	80	90	72	55	100	85	85
Risk Assessment	95	80	80	75	70	95	50	68	85	75	70	60	37
Public Safety	85	50	80	70	95	100	50	85	90	95	95	50	48

Environmental Objective

Economic Objective

Social Objective

Table 4.8 – Percentage Weights for the Performance Measures – Round 3

Performance Measure	Percentage Weights (%) – Round 3												
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13
Sediment Removal	8.13	10.14	9.28	4.09	5.17	7.19	7.41	7.33	6.35	3.95	7.73	7.14	9.09
Nutrient Removal	7.32	0.72	10.31	4.09	5.17	7.19	7.41	6.79	6.81	4.52	6.01	8.48	5.35
Heavy Metal Removal	7.32	11.59	6.19	4.09	6.67	7.19	7.41	6.70	7.26	7.34	8.15	7.14	6.84
Total Runoff Volume Reduction	7.72	11.59	9.28	10.53	7.99	6.39	7.41	9.05	7.71	11.30	6.87	8.04	5.67
Peak Flow Reduction	6.50	14.49	5.15	5.26	7.99	6.79	7.41	5.43	9.07	3.39	6.01	8.93	7.70
Habitat Creation	6.50	0.00	5.15	5.85	8.46	5.59	7.41	7.24	5.44	6.78	6.01	6.70	3.42
Potable Water Savings	7.32	1.45	7.22	6.43	8.46	6.39	8.33	8.60	6.35	5.08	8.15	6.25	10.16
Equivalent Annual Cost	6.91	7.25	8.25	4.68	6.58	7.59	8.33	6.33	7.26	9.04	6.01	8.48	10.70
Annual Operation and Maintenance Cost	6.91	11.59	5.15	9.36	7.99	7.59	6.48	7.42	7.26	7.91	7.73	5.36	6.52
Capital Cost	6.50	10.87	6.19	9.94	3.10	7.59	6.48	6.88	7.71	5.65	6.87	8.04	5.88
Industry/business Behaviour on Accepting GI Measure	7.32	0.72	2.06	11.70	9.40	7.75	9.26	6.24	6.35	9.60	7.73	8.04	10.48
Improvement of liveability	6.91	0.72	9.28	7.02	7.52	7.19	7.41	8.14	6.53	6.21	8.58	7.59	9.09
Risk Assessment	7.72	11.59	8.25	8.77	6.58	7.59	4.63	6.15	7.71	8.47	6.01	5.36	3.96
Public Safety	6.91	7.25	8.25	8.19	8.93	7.99	4.63	7.69	8.17	10.73	8.15	4.46	5.13

Environmental Objective   Economic Objective   Social Objective

Table 4.9 – Round 3 Weight Statistics

Performance Measure	Weights – Round 3 (n=13)			
	Mean	Median	Standard Deviation	Coefficient of Variation
Sediment Removal	7.154	7.330	1.888	0.264
Nutrient Removal	6.166	6.787	2.337	0.379
Heavy Metal Removal	7.223	7.188	1.624	0.225
Total Runoff Volume Reduction	8.426	7.989	1.834	0.218
Peak Flow Reduction	7.241	6.789	2.712	0.374
Habitat Creation	5.735	6.009	2.118	0.369
Potable Water Savings	6.938	7.216	2.122	0.306
Equivalent Annual Cost	7.493	7.260	1.518	0.203
Annual Operation and Maintenance Cost	7.482	7.421	1.662	0.222
Capital Cost	7.054	6.867	1.936	0.275
Industry/business Behaviour on Accepting GI Measure	7.434	7.748	3.114	0.419
Improvement of liveability	7.093	7.407	2.127	0.300
Risk Assessment	7.138	7.588	2.012	0.282
Public Safety	7.422	7.987	1.781	0.240

Environmental Objective   Economic Objective   Social Objective

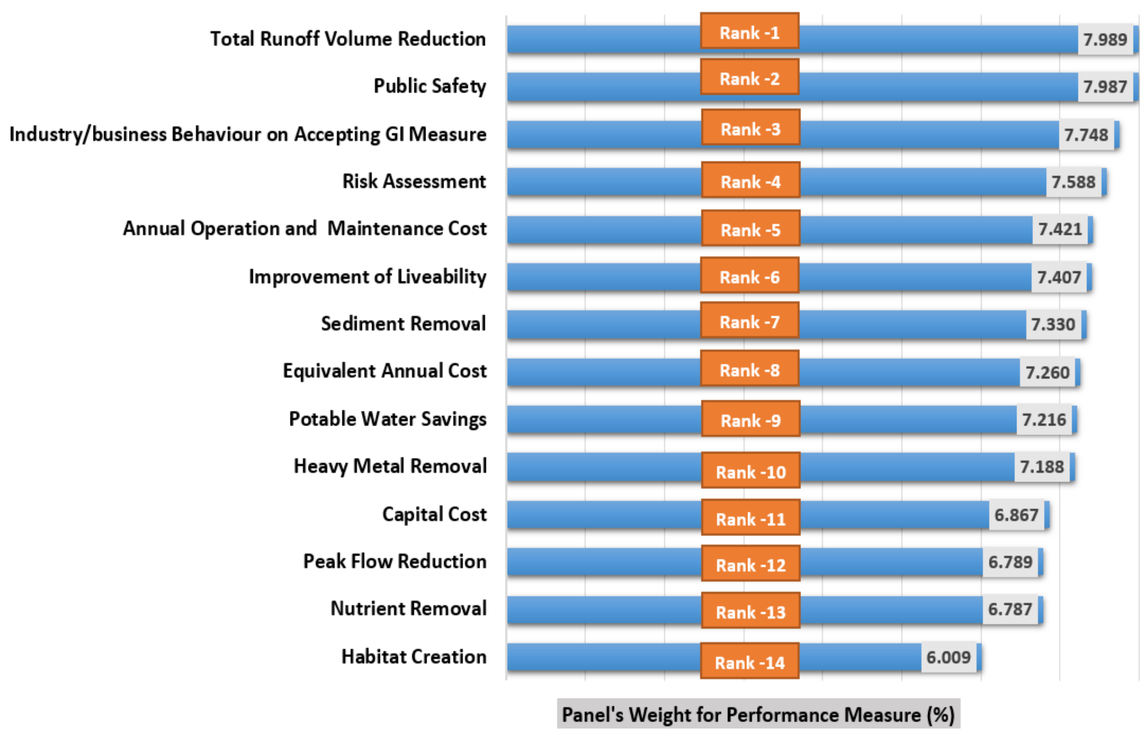


Figure 4.9 – Ranks and Weights of the Performance Measures Based on Expert Opinions – Round 3

4.4.1.6 Round 4 of Delphi Survey

The Round 3 feedback was sent as personalized questionnaire survey to each expert in Round 4 which is the final round of the Delphi survey. Experts were provided with the opportunity to compare their individual weights with the group weights and reconsider their answers in Round 4. The complete questionnaire distributed in Round 4 is shown in Appendix 4D. Among the 13 experts who participated in Round 3, only 12 participants provided their responses for Round 4. Similar to Round 3, the percentage weights for each performance measure were estimated based on SWING weights provided by the experts. The individual SWING weights provided by the experts and the calculated percentage weights for the performance measures are presented in tables 4.10 and 4.11 respectively.

As discussed in Section 4.4.1.5, the consensus has been already achieved in Round 3, with the coefficient of variation below 0.5 for all performance measures. Hence, this round was used to confirm the final weights of the performance measures. Moreover, in both Round 3 and Round 4, the experts were also asked to provide their weights for the TBL (environmental, economic, social) objectives considered. Based on the SWING weights provided by the experts for the objectives, the percentage weights were calculated and the summary of mean and median weights for each objective is shown in Table 4.12. According to Table 4.12, the experts have valued the environmental objectives the most (40% median weight at the end of Round 4) followed by social objectives (28% median weight at the end of Round 4) and economic objectives (32% median weight at the end of Round 4).

The median weights were taken as the representative group weights for the performance measures and the weight statistics of Round 4 is shown in Table 4.13. As it can be seen from the Table 4.13, the total weight experts provided for environmental, economic and social objectives are around 41%, 26% and 31% respectively. These weights are also consistent with the stakeholder weights presented in round 4 in Table 4.12 for each objective.

Table 4.10 – SWING Weights Provided by Experts – Round 4 (0-100 scale)

Performance Measure	SWING Weights – Round 4											
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Expert 6**	**Expert 7**	**Expert 8**	**Expert 9**	**Expert 10**	**Expert 11**	**Expert 12**
Sediment Removal	100	80	85	45	76	80	80	70	70	94	60	82
Nutrient Removal	70	55	100	65	78	80	79	70	62	97	90	78
Heavy Metal Removal	75	100	60	70	77	80	78	70	80	98	80	100
Total Runoff Volume Reduction	90	80	95	95	79	50	100	84	100	96	95	98
Peak Flow Reduction	65	80	55	60	78	60	74	100	50	93	100	70
Habitat Creation	60	35	60	40	95	80	75	50	60	100	72	68
Potable Water Savings	70	45	65	55	75	90	95	58	75	99	70	92
Equivalent Annual Cost	65	65	80	50	70	90	71	55	82	85	62	70
Annual Operation and Maintenance Cost	75	60	80	83	80	90	85	60	90	92	45	83
Capital Cost	60	60	80	85	60	85	70	60	65	80	40	71
Industry/business Behaviour on Accepting GI Measure	85	40	50	100	80	95	99	60	95	90	65	98
Improvement of liveability	80	40	77	75	100	95	90	75	55	99	75	88
Risk Assessment	85	70	95	80	88	95	91	95	85	91	30	85
Public Safety	80	65	97	90	90	100	89	90	98	95	35	87

Environmental Objective   Economic Objective   Social Objective

Table 4.11 – Percentage Weight for Performance Measures – Round 4

Performance Measure	Percentage Weights (%) – Round 4											
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12
Sediment Removal	9.43	9.14	7.88	4.53	6.75	6.84	6.80	7.02	6.56	7.18	6.53	7.01
Nutrient Removal	6.60	6.29	9.27	6.55	6.93	6.84	6.72	7.02	5.81	7.41	9.79	6.67
Heavy Metal Removal	7.08	11.43	5.56	7.05	6.84	6.84	6.63	7.02	7.50	7.49	8.71	8.55
Total Runoff Volume Reduction	8.49	9.14	8.80	9.57	7.02	4.27	8.50	8.43	9.37	7.33	10.34	8.38
Peak Flow Reduction	6.13	9.14	5.10	6.04	6.93	5.13	6.29	10.03	4.69	7.10	10.88	5.98
Habitat Creation	5.66	4.00	5.56	4.03	8.44	6.84	6.38	5.02	5.62	7.64	7.83	5.81
Potable Water Savings	6.60	5.14	6.02	5.54	6.66	7.69	8.08	5.82	7.03	7.56	7.62	7.86
Equivalent Annual Cost	6.13	7.43	7.41	5.04	6.22	7.69	6.04	5.52	7.69	6.49	6.75	5.98
Annual Operation and Maintenance Cost	7.08	6.86	7.41	8.36	7.10	7.69	7.23	6.02	8.43	7.03	4.90	7.09
Capital Cost	5.66	6.86	7.41	8.56	5.33	7.26	5.95	6.02	6.09	6.11	4.35	6.07
Industry/business Behaviour on Accepting GI Measure	8.02	4.57	4.63	10.07	7.10	8.12	8.42	6.02	8.90	6.88	7.07	8.38
Improvement of liveability	7.55	4.57	7.14	7.55	8.88	8.12	7.65	7.52	5.15	7.56	8.16	7.52
Risk Assessment	8.02	8.00	8.80	8.06	7.82	8.12	7.74	9.53	7.97	6.95	3.26	7.26
Public Safety	7.55	7.43	8.99	9.06	7.99	8.55	7.57	9.03	9.18	7.26	3.81	7.44

Environmental Objective   Economic Objective   Social Objective

Table 4.12 – Round 3 and 4 Mean and Median Weights for Objectives

Objective	Weight Statistics			
	Mean		Median	
	Round 3	**Round 4**	**Round 3**	**Round 4**
	(n)=13	(n)=12	(n)=13	(n)=12
Environmental	39.93	41.67	38.46	40.00
Economic	30.15	27.95	30.36	28.81
Social	29.93	30.38	32.69	32.30

Table 4.13 – Round 4 Weight Statistics

Performance Measure	**Weights – Round 4 (n=12)**			
	Mean	Median	Standard Deviation	Coefficient of Variation
Sediment Removal	7.140	6.925	1.269	0.178
Nutrient Removal	7.157	6.780	1.180	0.165
Heavy Metal Removal	7.557	7.065	1.475	0.195
Total Runoff Volume Reduction	8.304	8.495	1.560	0.188
Peak Flow Reduction	6.954	6.210	2.012	0.289
Habitat Creation	6.069	5.735	1.418	0.234
Potable Water Savings	6.803	6.845	0.992	0.146
Equivalent Annual Cost	6.532	6.355	0.873	0.134
Annual Operation and Maintenance Cost	7.100	7.095	0.950	0.134
Capital Cost	6.307	6.080	1.090	0.173
Industry/business Behaviour on Accepting GI Measure	7.349	7.560	1.659	0.226
Improvement of liveability	7.282	7.550	1.221	0.168
Risk Assessment	7.627	7.985	1.523	0.200
Public Safety	7.821	7.780	1.466	0.187

Environmental Objective Economic Objective Social Objective

According to Table 4.13, it is evident that in Round 4, the coefficient of variation has further converged towards zero compared to Round 3 and well below 0.5. Thus, in Round 4 consensus of weights of all performance measures have improved and further reached towards a very good degree of consensus. It should be noted that the sample fatigue has also started to occur with participants dropping out from the surveys when the number of rounds are becoming higher. Figure 4.10 shows the comparison of the degree of consensus for the performance measures in Round 3 and Round 4.

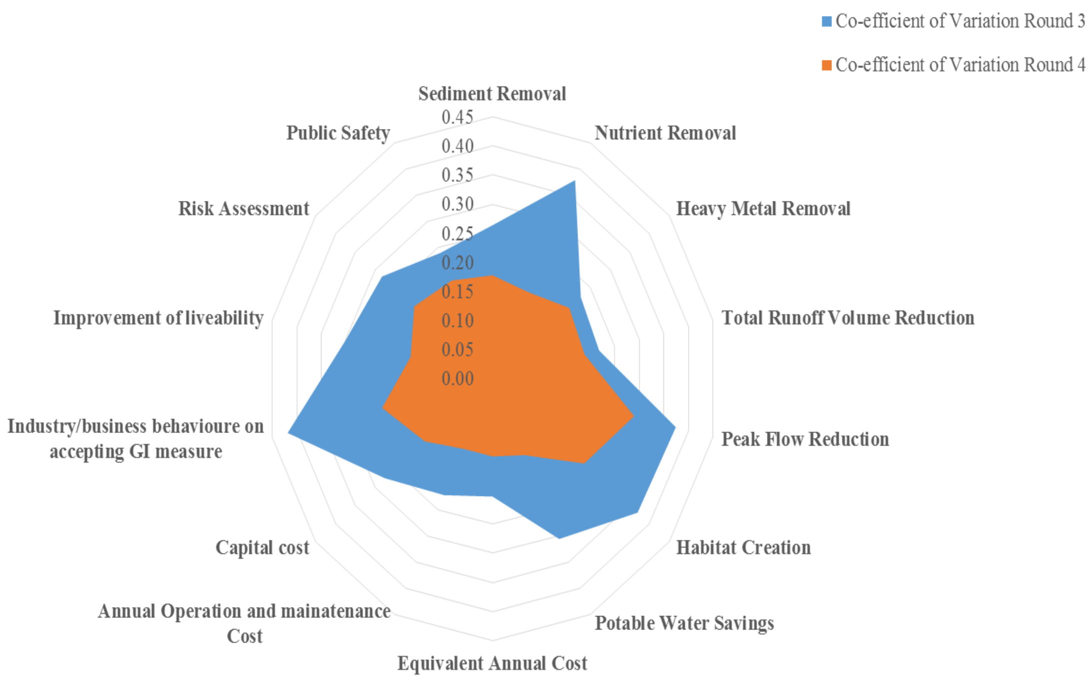


Figure 4.10 – Degree of Consensus based on Coefficient of Variation of Weights – Round 3 and Round 4

Based on the SWING weights provided for the performance measures in Round 4, the final median weights are shown in Figure 4.11. When compared with the Round 3, the highest and lowest ranked performance measures have not changed, however the rank order of the other performance measures have slightly changed. Moreover, the weight values were changed for almost all performance measures with higher variation among them compared to Round 3. These final weights were used as the input for MCDA, which will be discussed in Section 4.5.

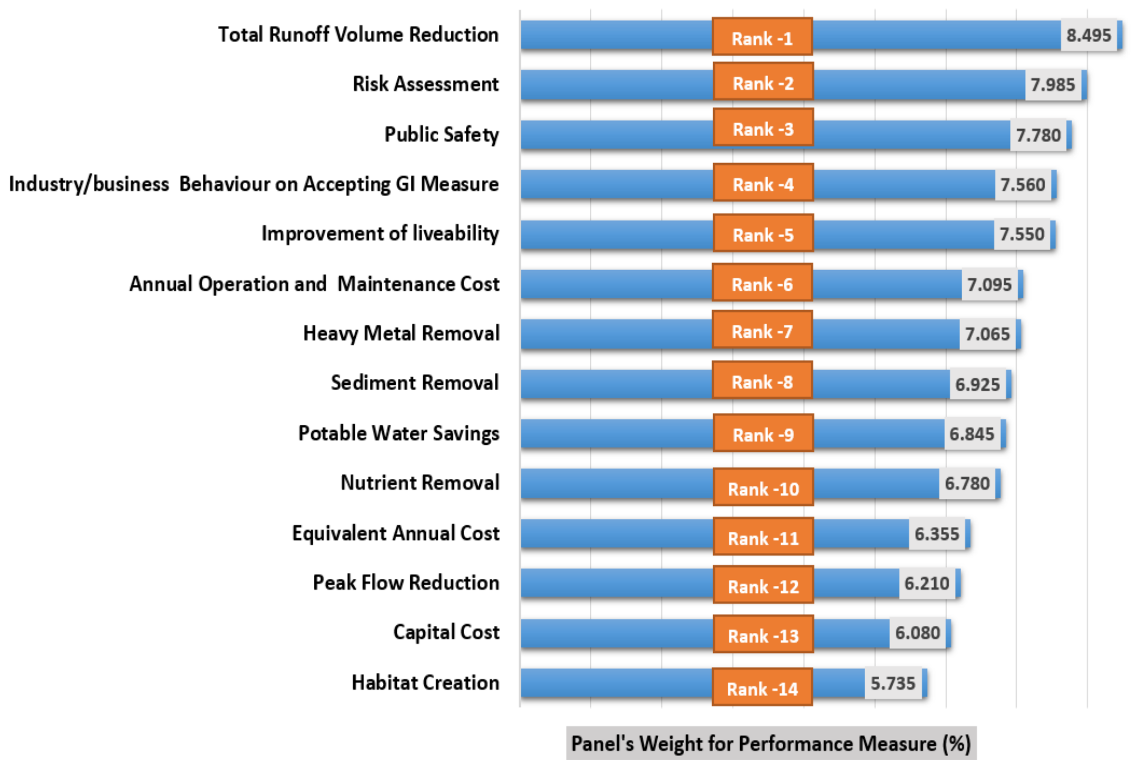


Figure 4.11 – Final Weights and Ranks for Performance Measures – Round 4

4.5 Application of TOPSIS to Select Optimum GI Practices and Their Sizing Combinations

The weights obtained for the performance measures in the previous section were then used as input in the MCDA to identify compromise optimum treatment trains and their sizing combinations for the study area. As discussed in Section 4.3.1, the TOPSIS method has been selected as the most suitable MCDA method for the current problem. The only subjective information used in TOPSIS is the weights obtained from the stakeholder preference elicitation. However, one of the important factors in TOPSIS is that, the method requires the values of the performance measures used in the decision matrix to be quantitative. Among the important performance measures identified by the experts, risk assessment, public safety and industry/business behaviour on accepting the GI measure cannot be quantified explicitly due to their qualitative nature. Thus, when applying the TOPSIS method for this study, these qualitative performance measures were not considered in the final analysis. The SWING weights for the performance measures are obtained with reference to the best performance measure and the SWING weights of each performance measures are based only on the reference point of best performance measure. Therefore, removing the three qualitative performance measures does not impact the original weights of the remaining performance measures obtained through stakeholder preference elicitation. However, when using the weights of remaining performance measures for TOPSIS, the final weights should be normalized to get a sum of one. Hence, based on the expert weights elicited from Delphi survey, new percentage weights were derived again (as explained in Section 4.4.1.5) by considering 11 quantifiable performance measures which are shown in Table 4.14. The weights were then normalized to get a sum of one, which were then used as the input in the TOPSIS analysis. The new weights which were derived for the 11 quantifiable performance measures to be used in TOPSIS analysis are shown in Table 4.15.

Table 4.14 – New Percentage Weights obtained from SWING weights after Removing Qualitative Performance Measures

Performance Measure	New Percentage Weights (%) – Round 4											
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Expert 6**	**Expert 7**	**Expert 8**	**Expert 9**	**Expert 10**	**Expert 11**	**Expert 12**
Sediment Removal	12.35	11.43	10.16	6.22	8.76	9.09	8.92	9.31	8.87	9.10	7.60	9.11
Nutrient Removal	8.64	7.86	11.95	8.99	8.99	9.09	8.81	9.31	7.86	9.39	11.41	8.67
Heavy Metal Removal	9.26	14.29	7.17	9.68	8.87	9.09	8.70	9.31	10.14	9.49	10.14	11.11
Total Runoff Volume Reduction	11.11	11.43	11.35	13.14	9.10	5.68	11.15	11.17	12.67	9.29	12.04	10.89
Peak Flow Reduction	8.02	11.43	6.57	8.30	8.99	6.82	8.25	13.30	6.34	9.00	12.67	7.78
Habitat Creation	7.41	5.00	7.17	5.53	10.94	9.09	8.36	6.65	7.60	9.68	9.13	7.56
Potable Water Savings	8.64	6.43	7.77	7.61	8.64	10.23	10.59	7.71	9.51	9.58	8.87	10.22
Equivalent Annual Cost	8.02	9.29	9.56	6.92	8.06	10.23	7.92	7.31	10.39	8.23	7.86	7.78
Annual Operation and Maintenance Cost	9.26	8.57	9.56	11.48	9.22	10.23	9.48	7.98	11.41	8.91	5.70	9.22
Capital Cost	7.41	8.57	9.56	11.76	6.91	9.66	7.80	7.98	8.24	7.74	5.07	7.89
Improvement of Liveability	9.88	5.71	9.20	10.37	11.52	10.80	10.03	9.97	6.97	9.58	9.51	9.78

Table 4.15 – Final Weights for TOPSIS Analysis

Performance Measure		**New Weight (Median) from Stakeholder Preference Elicitation**
Rank (New)	Name	
1	Total Runoff Volume Reduction	11.16
2	Improvement of liveability	9.83
3	Annual Operation and Maintenance Cost	9.24
4	Heavy Metal Removal	9.4
5	Sediment Removal	9.1
6	Potable Water Savings	8.76
7	Nutrient Removal	8.99
8	Equivalent Annual Cost	8.04
9	Peak Flow Reduction	8.27
10	Capital Cost	7.93
11	Habitat Creation	7.58

4.5.1 Sample Treatment Train 1 *(two treatment measures)*

Various steps involved in the TOPSIS analysis were comprehensively discussed earlier in Section 4.3.1. The application of the TOPSIS to rank the near optimal sizing combinations obtained in Section 3.3 is explained for a sample treatment train with two treatment measures. This treatment train consists of a sedimentation basin and bioretention (same sample treatment train demonstrated in Section 3.3.2).

A decision matrix was initially developed for the 10 near optimal sizing combinations of the above sample treatment train in Section 3.4, based on the performance measures identified through stakeholder discussions and literature review. However, after the Delphi survey, new performance measures were added to this list. Thus, before starting the TOPSIS analysis, a modified decision matrix was developed with the finalized performance measures and their derived weights from the stakeholder preference elicitation. The modified decision matrix is shown in Table 4.16.

Table 4.16 – Modified Decision Matrix for TOPSIS (Sample Treatment Train 1)

Near Optimum Treatment Train Sizing Combination	Performance Measures										
	Environmental						**Economic**				**Social**
	Total Runoff Volume Reduction (m^3)	Sediment Removal (Kg)	Nutrient Removal (Kg)	Heavy Metal Removal (ratio)	Peak Flow Reduction (%)	Habitat Creation (ratio)	Potable Water Savings (ML/yr)	Equivalent Annual Cost ($)	Capital Cost ($)	Operation and Maintenance Cost ($)	Improvement of Liveability (ratio)
SDB_BR (1)	2001	46600	507	0.0061	41.3	0.0117	17	14569	321833	8133	0.011
SDB_BR (2)	2001	45600	484	0.0057	38.4	0.0108	17	13822	299792	7826	0.010
SDB_BR (3)	4003	47100	518	0.0069	40.0	0.0127	33	14680	309250	8495	0.010
SDB_BR (4)	4003	46100	484	0.0064	37.7	0.0118	35	13881	286081	8159	0.010
SDB_BR (5)	6004	47100	503	0.0077	40.9	0.0137	49	14365	290534	8555	0.010
SDB_BR (6)	6004	45900	477	0.0072	38.8	0.0128	51	13493	265796	8177	0.009
SDB_BR (7)	8005	46600	492	0.0084	42.3	0.0147	64	13723	266160	8400	0.010
SDB_BR (8)	10006	46900	502	0.0097	45.8	0.0166	75	13778	263614	8506	0.011
SDB_BR (9)	12008	47200	506	0.0109	49.2	0.0184	84	13652	257912	8494	0.012
SDB_BR (10)	12008	45800	476	0.0104	48.7	0.0176	87	12354	225236	7849	0.011

SDB – Sedimentation Basin BR - Bioretention

In the modified decision matrix, annual stormwater volume reduction was added as a new performance measure. This was estimated by using the equations proposed by CNT (2010) to estimate the runoff volume reduction through GI practices. The equations and the other information used for the runoff volume calculation are explained in Appendix 4E. The annual nutrient load reduction was taken as the sum of annual TP and TN load reduction obtained through MUSIC simulation in Section 3.4. The total heavy metal removal ability of different GI treatment trains was estimated using the green area ratio method (Keeley, 2011) (Refer Appendix 3A for the demonstration of the method and Appendix 4F for the ratings used for the total heavy removal ability of GI practices). The methods of estimating the remaining performance measures were previously discussed in Section 3.2.3.

As discussed in Section 4.3.1, the first step in TOPSIS is to normalize the decision matrix using Equation 4.1. The intention of the normalization is to convert the performance measure values with different units into a common scale. Table 4.17 shows the normalized decision matrix for the near optimal sizing combinations of sample treatment train 1. After normalizing the decision matrix, the next step is to obtain the weighted normalized decision matrix by multiplying the decision matrix by the weights for each of the performance measure (Equation 4.2). The weighted normalized decision matrix for sample treatment train 1 is shown in Table 4.18. In the weighted normalized decision matrix, the positive ideal solution (which maximizes benefit and minimizes cost) and the negative ideal solution (which minimizes the benefit and maximizes the cost) were also identified for different criteria (Equations 4.3 and 4.4), and are highlighted in Table 4.18.

Table 4.17 – Normalized Decision Matrix for TOPSIS (Sample Treatment Train 1)

Near Optimum Treatment Train Sizing Combination	**Performance Measures**										
	Environmental						**Economic**				**Social**
	Total Runoff Volume Reduction	Sediment Removal	Nutrient Removal	Heavy Metal Removal	Peak Flow Reduction	Habitat Creation	Potable Water Savings	Equivalent Annual Cost	Capital Cost	Operation and Maintenance Cost	Improvement of Liveability
SDB_BR (1)	0.027	0.123	0.110	0.067	0.090	0.068	0.026	0.095	0.085	0.102	0.091
SDB_BR (2)	0.027	0.120	0.104	0.063	0.083	0.063	0.027	0.090	0.080	0.098	0.083
SDB_BR (3)	0.053	0.124	0.112	0.076	0.087	0.074	0.052	0.095	0.082	0.106	0.090
SDB_BR (4)	0.053	0.121	0.105	0.071	0.082	0.068	0.055	0.090	0.076	0.102	0.082
SDB_BR (5)	0.080	0.124	0.109	0.085	0.089	0.079	0.078	0.093	0.077	0.107	0.089
SDB_BR (6)	0.080	0.121	0.103	0.080	0.084	0.074	0.081	0.088	0.071	0.102	0.081
SDB_BR (7)	0.107	0.123	0.106	0.093	0.092	0.085	0.101	0.089	0.071	0.105	0.088
SDB_BR (8)	0.133	0.124	0.108	0.107	0.099	0.096	0.119	0.089	0.070	0.107	0.095
SDB_BR (9)	0.160	0.124	0.109	0.120	0.107	0.107	0.133	0.089	0.068	0.106	0.101
SDB_BR (10)	0.160	0.121	0.103	0.115	0.106	0.102	0.137	0.080	0.060	0.098	0.094

SDB – Sedimentation Basin   BR - Bioretention

Table 4.18 – Weighted Normalized Decision Matrix for TOPSIS (Sample Treatment Train 1)

Near Optimum Treatment Train Sizing Combination	**Performance Measures**										
	Environmental						**Economic**				**Social**
	Total Runoff Volume Reduction	Sediment Removal	Nutrient Removal	Heavy Metal Removal	Peak Flow Reduction	Habitat Creation	Potable Water Savings	Equivalent Annual Cost	Capital Cost	Operation and Maintenance Cost	Improvement of Liveability
SDB_BR (1)	0.0030	0.0113	0.0099	0.0063	0.0074	0.0052	0.0024	0.0080	0.0069	0.0096	0.0091
SDB_BR (2)	0.0030	0.0111	0.0094	0.0059	0.0069	0.0048	0.0025	0.0076	0.0064	0.0093	0.0084
SDB_BR (3)	0.0060	0.0114	0.0101	0.0071	0.0072	0.0056	0.0048	0.0081	0.0066	0.0100	0.0090
SDB_BR (4)	0.0060	0.0112	0.0094	0.0067	0.0068	0.0052	0.0050	0.0076	0.0061	0.0096	0.0083
SDB_BR (5)	0.0090	0.0114	0.0098	0.0080	0.0073	0.0061	0.0071	0.0079	0.0062	0.0101	0.0089
SDB_BR (6)	0.0090	0.0112	0.0093	0.0075	0.0070	0.0057	0.0074	0.0074	0.0057	0.0097	0.0082
SDB_BR (7)	0.0121	0.0113	0.0096	0.0088	0.0076	0.0065	0.0092	0.0075	0.0057	0.0099	0.0088
SDB_BR (8)	0.0151	0.0114	0.0098	0.0100	0.0082	0.0073	0.0108	0.0076	0.0057	0.0101	0.0095
SDB_BR (9)	0.0181	0.0115	0.0099	0.0113	0.0088	0.0082	0.0121	0.0075	0.0055	0.0100	0.0102
SDB_BR (10)	0.0181	0.0111	0.0093	0.0108	0.0087	0.0078	0.0125	0.0068	0.0048	0.0093	0.0094
Positive Ideal Solution (A^+)	0.0181	0.0115	0.0101	0.0113	0.0088	0.0082	0.0125	0.0068	0.0048	0.0093	0.0102
Negative Ideal Solution (A^-)	0.0030	0.0111	0.0093	0.0059	0.0068	0.0048	0.0024	0.0081	0.0069	0.0101	0.0082

According to Table 4.18, the sizing combination SDB_BR (9) has the highest number of positive ideal solutions. Majority of the positive ideal solutions of this combination is for the performance measures related to the environmental objective. SD_BR (10) also have few positive ideal solutions which are related to the economic objective. To have an idea about selecting the most suitable sizing combination among these 10 combinations, the values of the weighted normalized decision matrix was standardized in to a 0-100 scale (where 100 represents positive ideal solution and 0 represents negative ideal solution) using Equations 3.1 and 3.2. The standardized performance measures are shown in Figure 4.12.

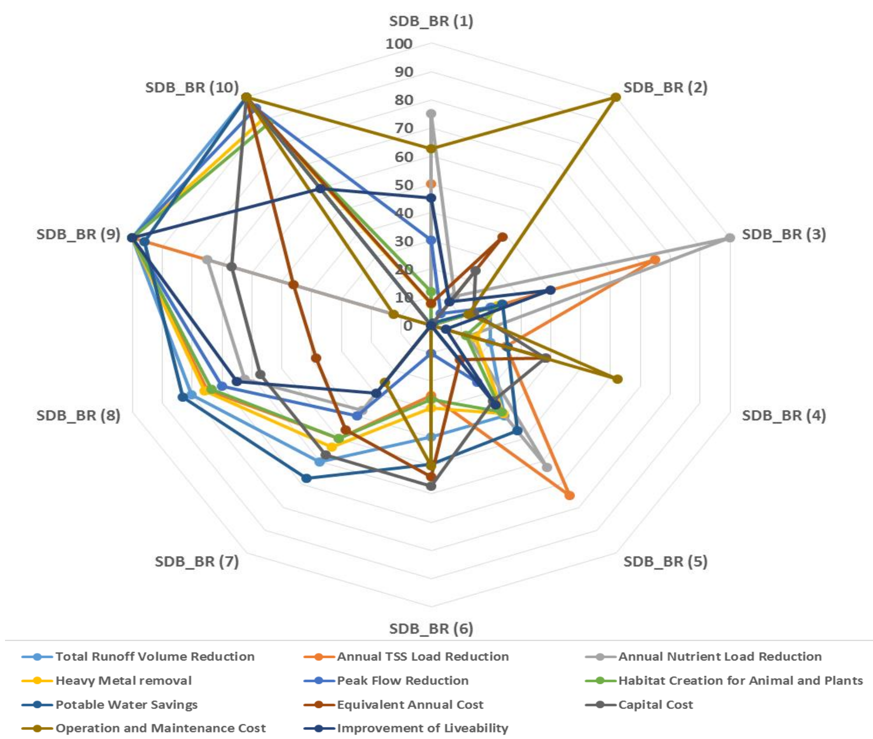


Figure 4.12 – Standardized Values for Weighted Normalized Decision Matrix (Sample Treatment Train 1)

As it can be seen from Figure 4.12, among the two solutions, SDB_BR (9) and SDB_BR (10) can be identified as solutions which are closest to the positive ideal solution. However, since these two sizing combinations consist of positive ideal solutions for different performance measures in terms of different objectives it is important to perform the TOPSIS to identify the most suitable compromised sizing combination for the area. As the next step in TOPSIS, the separation of each alternative sizing combination from the positive and negative ideal solution was calculated and based on these values, the relative closeness to the ideal solution was estimated for each treatment train sizing combination (Equations 4.5-4.7). The results of the separation from the negative and positive ideal solutions and the estimated relative closeness to the positive ideal solution are shown in Table 4.19. The highest relative closeness indicates that the solution is farthest from the negative ideal solution and is closest to the positive ideal solution. The treatment train sizing combinations for the sample treatment train 1 were ranked based on their relative closeness to the positive ideal solution. For this treatment train, the sizing combination number 9 (SDB_BR 9) is the highest ranked solution among the 10 solutions, which can be considered as the compromise optimum solution. This treatment train consists with a larger surface for the bioretention compared to the sedimentation basin area (refer Table 3.5). Bioretention provides more environmental and economic advantages compared with the sedimentation basin (Millen et al., 1997, Roy-Poirier et al., 2010). This shows that the results of the methodology are highly influenced by the areas of the individual GI in the treatment train. It further shows the importance of the optimal sizing of individual treatment measures in GI treatment train design.

4.5.2 Sample Treatment Train 2 *(three treatment measures)*

A similar TOPSIS analysis was conducted for the sizing combinations of sample treatment train 2. This treatment train consisted of three treatment measures which are sedimentation basin, bioretention and wetland. As explained in Section 3.3.3, 20 near optimal sizing combinations were identified for the sample treatment train 2 from the single objective optimization. Similar to the sample treatment train 1, the normalized decision matrix and the weighted normalized decision matrix was obtained for this treatment train. The standardized values of the performance measures based on the weighted normalized decision matrix are shown in Figure 4.13. As can be seen in the plot, SDB_BR_WL (1) and SDB_BR_WL (19) consist of highest number of positive ideal solutions for different performance measures.

Table 4.19 – Separation Measures, Relative Closeness and Ranks of Near Optimal Sizing Combinations – Sample Treatment Train 1

Treatment Train Sizing Combination	**Separation Measure of the Group**		**Relative Closeness**	**Rank**
	Positive Ideal	Negative Ideal	Closeness Coefficient	
SDB_BR (1)	0.01932	0.00120	0.0583	9
SDB_BR (2)	0.01948	0.00115	0.0559	10
SDB_BR (3)	0.01548	0.00423	0.2145	7
SDB_BR (4)	0.01560	0.00424	0.2136	8
SDB_BR (5)	0.01162	0.00808	0.4101	5
SDB_BR (6)	0.01178	0.00818	0.4097	6
SDB_BR (7)	0.00783	0.01196	0.6041	4
SDB_BR (8)	0.00417	0.01564	0.7893	3
SDB_BR (9)	0.00129	0.01928	0.9372	1
SDB_BR (10)	0.00136	0.01933	0.9341	2

(Refer Section 3.3.2 for the individual sizing of the near optimal sizing combinations in sample treatment train 1)

SDB – Sedimentation Basin BR - Bioretention

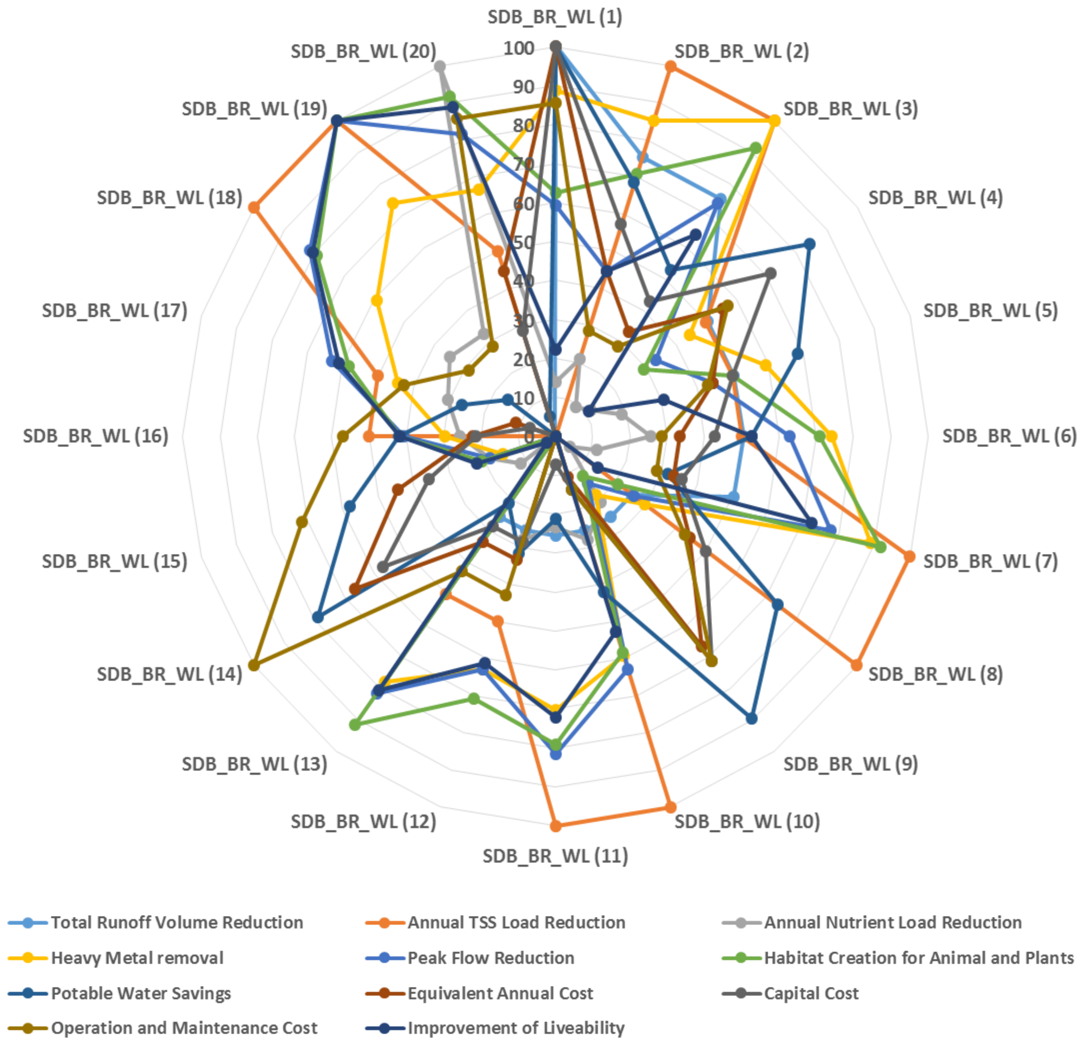


Figure 4.13 – Standardized Values for Weighted Normalized Decision Matrix (Sample Treatment Train 2)

Similar to the previous example, it is difficult to identify which sizing combination among these two solutions is best for the area. The separation measures from the ideal solutions and the relative closeness to the positive ideal solution were calculated using TOPSIS to obtain the compromise optimum sizing combination. Table 4.20 shows the results of the TOPSIS analysis for these 20 near optimal sizing combinations. According to the TOPSIS results, SDB_BR_WL (1) can be identified as the compromise optimum solution which is closest to the positive ideal solution.

Table 4.20 – Separation Measures, Relative Closeness and Ranks of Near Optimal Sizing Combinations – Sample Treatment Train 2

Treatment Train Sizing Combination	**Separation Measure of the Group**		**Relative Closeness**	**Rank**
	Positive Ideal	Negative Ideal	Closeness Coefficient	
SDB_BR_WL (1)	0.0054	0.0081	0.6003	1
SDB_BR_WL (2)	0.0048	0.0065	0.5729	3
SDB_BR_WL (3)	0.0048	0.0070	0.5932	2
SDB_BR_WL (4)	0.0067	0.0044	0.3935	11
SDB_BR_WL (5)	0.0061	0.0047	0.4351	7
SDB_BR_WL (6)	0.0055	0.0052	0.4879	5
SDB_BR_WL (7)	0.0056	0.0059	0.5093	4
SDB_BR_WL (8)	0.0082	0.0027	0.2493	17
SDB_BR_WL (9)	0.0082	0.0030	0.2666	16
SDB_BR_WL (10)	0.0069	0.0040	0.3673	14
SDB_BR_WL (11)	0.0067	0.0048	0.4181	8
SDB_BR_WL (12)	0.0067	0.0043	0.3896	12
SDB_BR_WL (13)	0.0071	0.0050	0.4148	10
SDB_BR_WL (14)	0.0098	0.0020	0.1716	20
SDB_BR_WL (15)	0.0091	0.0020	0.1792	19
SDB_BR_WL (16)	0.0086	0.0027	0.2358	18
SDB_BR_WL (17)	0.0082	0.0036	0.3064	15
SDB_BR_WL (18)	0.0080	0.0047	0.3707	13
SDB_BR_WL (19)	0.0080	0.0057	0.4150	9
SDB_BR_WL (20)	0.0073	0.0065	0.4682	6

(Refer Section 3.3.3 for the individual sizing of the near optimal sizing combinations in sample treatment train 2)

SDB – Sedimentation Basin BR – Bioretention WL - Wetland

4.5.3 TOPSIS Results Summary for All Treatment Trains

For the treatment trains which included two treatment measures (primary and secondary treatment measures and primary and tertiary treatment measures), 7 potential configurations were developed for the study area by combining two GI practices in a series (i.e. combinations of sedimentation basin, vegetated swale, bioretention, wetland and retention pond), as discussed in Section 3.3 (including sample treatment train 1). From these 7 potential treatment trains, 66 near optimal sizing combinations that achieved the required pollutant target reduction levels with minimum cost were identified for the study area (refer to Section 3.3). A TOPSIS analysis was then performed for these 66 near optimal alternative sizing combinations to select the most suitable GI treatment train with two treatment measures for the study area, and optimum individual treatment measure sizing. The alternative treatment train sizing combinations were ranked from best combination to the worst by considering the relative closeness to the positive ideal solution as demonstrated in Section 4.5.1 using the TOPSIS method. Among these 66 solutions, the results for the 10 best treatment trains (as per the rank order obtained through TOPSIS) are shown in Table 4.21. This table shows the treatment measures in the configuration and their individual sizing combinations with their relative closeness to the positive ideal solution.

Similarly, for the treatment trains which consisted of three treatment measures (as a combination of primary, secondary and tertiary), 7 potential treatment train configurations were developed (including sample treatment train 2), and using these treatment train configurations, 219 near optimal sizing combinations were identified through the single objective optimization (refer to Section 3.3).TOPSIS was used to identify the most suitable treatment train configuration for the study area and the potential sizing combinations of its individual treatment measures. The results obtained for the highest ranked 10 treatment trains which had the closest distance to the positive ideal solution are shown in Table 4.22.

Table 4.21 – TOPSIS Ranking of the Treatment Trains with Two Treatment Measures (Results for 10 Highest Ranked Sizing Combinations)

Treatment Train Sizing Combination	**Area of the Treatment Measure (m^2)**		**Separation Measure of the Group**		**Relative Closeness**	**Rank**
	Treatment Measure 1	Treatment Measure 2	Positive Ideal	Negative Ideal	Closeness Coefficient	
SW_BR (10)	500	3500	0.03174	0.01998	0.6137	1
SW_BR (1)	5000	1500	0.03661	0.02354	0.6086	2
SW_BR (4)	3500	2000	0.03327	0.02266	0.5949	3
SW_BR (2)	4500	1500	0.03427	0.02404	0.5877	4
SDB_SW (1)	1000	4500	0.03200	0.02314	0.5803	5
SW_PD (1)	5000	1500	0.02999	0.02186	0.5783	6
SW_BR (9)	1000	3000	0.03011	0.02199	0.5780	7
SW_BR (7)	2000	2500	0.03042	0.02283	0.5712	8
SW_BR (5)	3000	2000	0.03111	0.02362	0.5684	9
SW_BR (3)	4000	1500	0.03202	0.02481	0.5634	10

SW – Vegetated Swale SDB – Sedimentation Basin BR – Bioretention PD – Retention Pond

Table 4.22 – TOPSIS Ranking of the Treatment Trains with Three Treatment Measures (Results for 10 Highest Ranked Sizing Combinations)

Treatment Train Sizing Combination	**Area of the Treatment Measure (m^2)**			**Separation Measure of the Group**		**Relative Closeness**	**Rank**
	Treatment Measure 1	Treatment Measure 2	Treatment Measure 3	Positive Ideal	Negative Ideal	Closeness Coefficient	
SW_BR_PD (9)	5000	500	1000	0.0109	0.0173	0.6128	1
SDB_SW_BR (42)	200	4500	1500	0.0122	0.0179	0.5946	2
SW_BR_PD (16)	3500	1000	1000	0.0110	0.0157	0.5887	3
SW_BR_PD (23)	500	2500	1500	0.0105	0.0149	0.5856	4
SW_BR_WL (1)	5000	500	1000	0.0118	0.0160	0.5764	5
SDB_SW_BR (39)	200	4000	1500	0.0125	0.0165	0.5691	6
SDB_SW_PD (20)	400	5000	1000	0.0120	0.0157	0.5667	7
SW_BR_PD (8)	4000	500	1000	0.0118	0.0152	0.5632	8
SDB_SW_BR (1)	200	500	3000	0.0114	0.0147	0.5618	9
SW_BR_PD (22)	1000	2000	1500	0.0112	0.0142	0.5583	10

SW – Vegetated Swale　　SDB – Sedimentation Basin　　BR – Bioretention　　PD – Retention Pond　　WL- Wetland

The results of the TOPSIS analysis presented in Table 4.21 shows that the combination of vegetated swale and bioretention is the most suitable treatment train configuration for the study area to implement a treatment train with two treatment measures. The optimum sizing combination for this treatment train configuration is 500 m^2 surface area for the swale and 3500 m^2 surface area for the bioretention. This treatment train configuration with the above mentioned sizing combination maximizes the benefit criteria and minimizes the cost criteria, based on their performance measure values and the stakeholder preferences on performance measures. Among the 10 highest ranked alternative treatment trains shown in Table 4.21, 8 configurations consists of swale and bioretention, which shows that it is one of the most environmentally, economically and socially beneficial treatment train configuration for the study area.

As shown in Table 4.22, it is evident that the best treatment train configuration with three treatment measures for the study area is a combination of vegetated swale, bioretention and a retention pond. The optimal sizing combination for this treatment train configuration of 5000 m^2 surface area for vegetated swale, 500 m^2 surface area for bioretention and 1500 m^2 surface area for retention pond.

From the results obtained for treatment trains with both two and three treatment measures show that the vegetated swale and bioretention configuration is the best option for the area with higher relative closeness to the positive ideal solution and its performance can also be complemented by adding a retention pond as a tertiary treatment measure.

4.5.4 Sensitivity Analysis

Uncertainty is an inherent component in methods such as MCDA, which involves human judgment in decision making. In any MCDA process, uncertainty can appear in various stages from selecting a suitable MCDA method until providing the recommendations based on the results. Thus, in MCDA studies where subjective information is involved, it is important to have an idea about the implications of these uncertainties in order for the decision makers to make certain decisions with caution and confidence (Kodikara, 2008, Triantaphyllou and Sánchez, 1997). As discussed in Section 2.6.2.2, sensitivity analysis is conducted as the final step of the MCDA process, to have an understanding of these potential uncertainties.

Generally in the MCDA process, the inconsistencies in input data can bring uncertainty to the final results. Insua (1990) classifies these input data into two categories as,

1. Objective data – e.g. the performance characteristics/evaluations of performance measures of the alternatives
2. Subjective data – e.g. the judgemental input of the decision makers/weights of performance measures

Furthermore, Mareschal (1986) suggests that there are two reasons for the uncertainties that occur in decision making; 1) the technical reasons involved in the evaluation process (e.g. the errors in measurement instruments or human judgement), and 2) the difficulty of quantifying and representing the performance measures in a single value. The objective data in this study were estimated using software or other methods available in literature and therefore considered as data with less uncertainty. Hence, in this study, a sensitivity analysis was conducted to study the uncertainties that occur due to subjective data (which are the weights of the performance measures).

To investigate the sensitivity to the weight changes, the 10 highest ranked treatment train sizing combinations with two treatment measures were used which are shown in Table 4.21. The changes in the closeness coefficient and the rank order for these treatment trains were analysed using the change of weights for all performance measures. The method used for the sensitivity analysis and the results are discussed in Section 4.5.4.1.

4.5.4.1 Results of the Sensitivity Analysis

The sensitivity analysis is demonstrated by considering the 10 highest ranked treatment train sizing combinations (with two treatment measures) presented in Table

4.21. Ten weight variation ratios were defined to assess the impact of changes weight for the final rank order as 0.01, 0.05, 0.1, 0.5, 1, 1.5, 2, 2.5, 3 and 3.5. In these weight variation ratios, 1 represented the original weights of the performance measures obtained from the preference elicitation. While changing the weights of one performance measure at a time according to these weight variation ratios, the changes in closeness coefficient and the changes in rank order were analysed for the 10 treatment trains. When changing the weights of performance measures according to the weight variation ratios, the original weights of the selected performance measure was multiplied by the related weight variation ratio to recalculate the new weight for that performance measure. The final weights of the rest of the performance measures were recalculated to get a normalized sum of 1.

Figure 4.14 shows how the closeness coefficient varied according to the changes of weights in total runoff volume reduction for the 10 treatment trains. According to Figure 4.14, the closeness coefficients for treatment trains SW_PD (1), SW_BR (5), SDB_SW (1), SW_BR (3) and SW_BR (9) started to gradually increase when the variation ratios become higher. The closeness coefficients gradually decreased for SW_BR (1), SW_BR (2), SW_BR (4), SW_BR (10) and SW_BR (7) with the increase of variation ratios. The results obtained for the variation of weights of total runoff volume reduction shows that the reduction of the weights from the original weight (variation ratio =1) did not impact much on the rank order, however the increasing weights have an impact on the final rank order. The rapid changes in the rank order have started around variation ratio of 1.2 according to Figure 4.14. This shows that the rank order start to change when the weights of the runoff volume reduction starts to increase from around 20%. However, it should be noted that this conclusion has reached under the assumption of changing the weights of one performance measure at a time while keeping the weights of all other performance measures almost constant but adjusted to get a normalized sum of 1. Similar analysis (as explained previously) was performed by changing the weights of other performance measures to assess the variation of the closeness coefficient. The results obtained for the weight changes of other performance measures and the comments are shown in Figure 4.15.

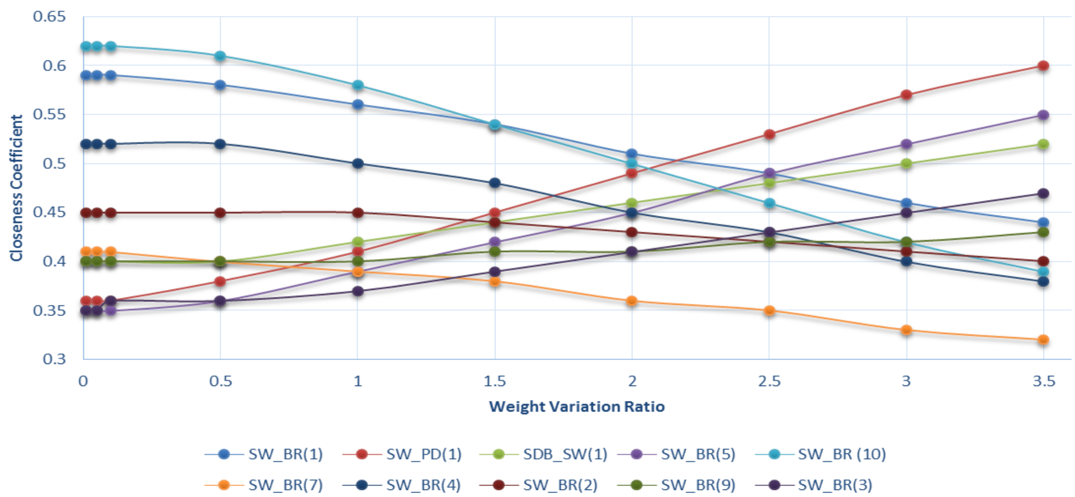
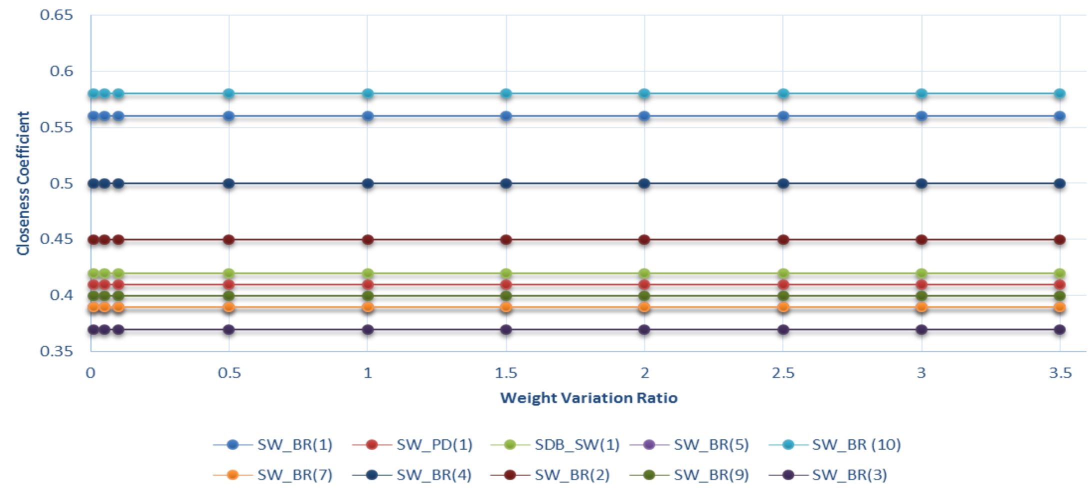


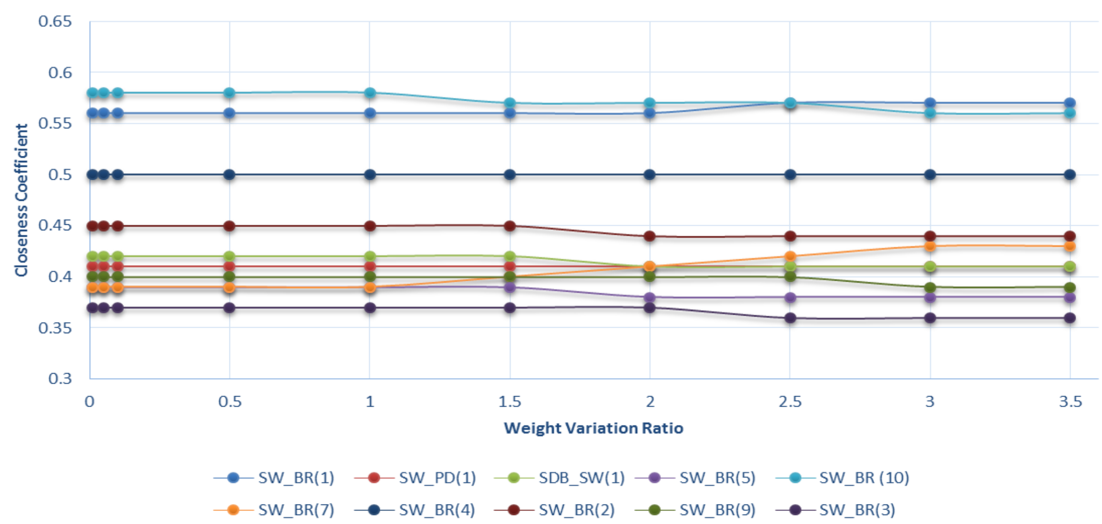
Figure 4.14 – Closeness Coefficients under Different Weight Variation Ratios for Total Runoff Volume Reduction

In summary, the results obtained from the sensitivity analysis for treatment train sizing combinations with two treatment measures showed that different treatment trains are sensitive to the different weights of different performance measures. The treatment trains SW_BR (10) and SW_BR (7) are the two most sensitive treatment trains which affected the rank order based on the weights changes for majority of performance measures. One of the important observations about these two treatment trains is that the bioretention has a larger area compared to the vegetated swale. Hence, it is evident that the sensitivity of the rank order also depends on the type of the GI used and its area. Sediment removal and nutrient removal are the least sensitive performance measures for the weight changes whereas weight changes of all other performance measures showed a moderate rate of sensitivity for the final rank order. Furthermore, the rank order for most of the performance measures starts to change around weight variation ratio of 1.2, when compared with the original weight (weight variation ratio =1). This shows that the final rank order of the treatment trains start to change when the weights of the performance measures increases from 20%. However, these conclusions are based on assumption of varying the weights of one performance measure at a time while keeping the weights of other performance measures almost constant, but changed accordingly to make the sum of weights to 1.

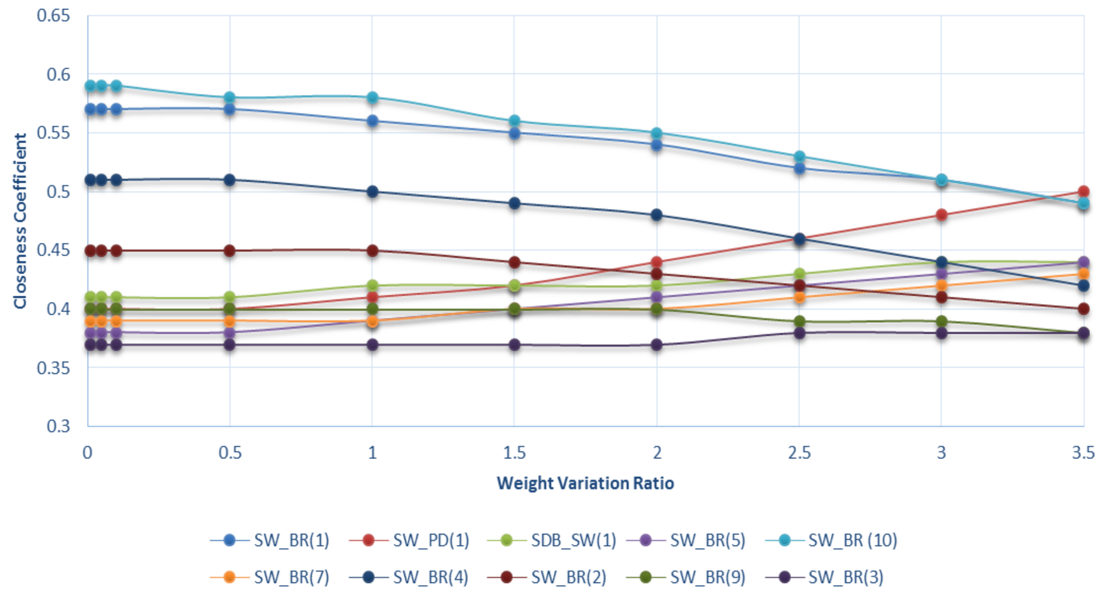
Figure 4.15- Closeness Coefficients under Different Weight Variation Ratios for Different Performance Measures and Comments



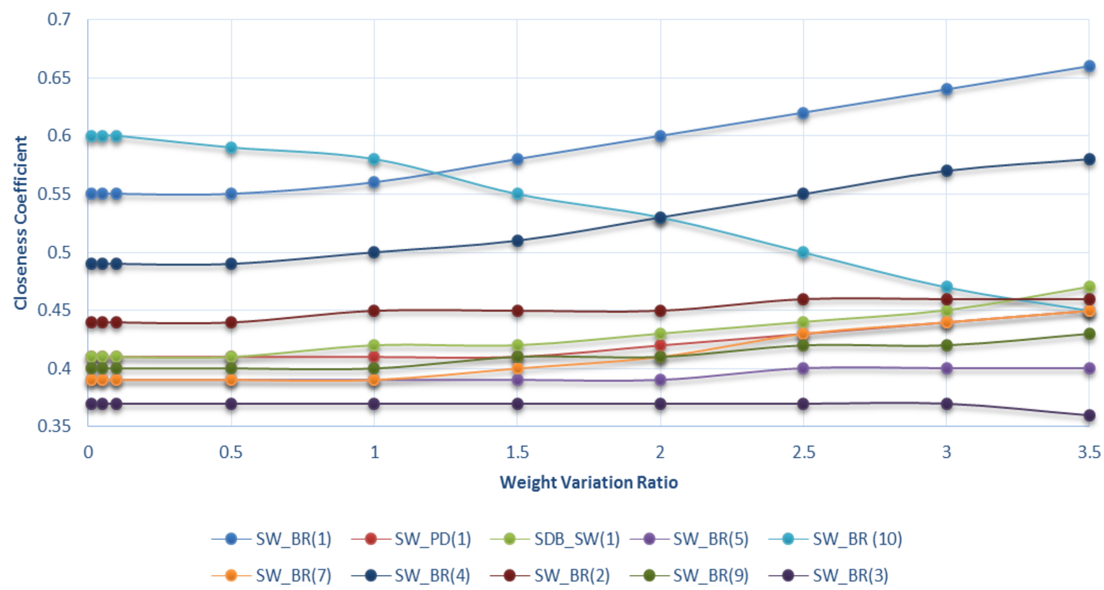
a) Sediment Removal - *The weight changes of sediment removal are insensitive to the final rank order of treatment trains.*



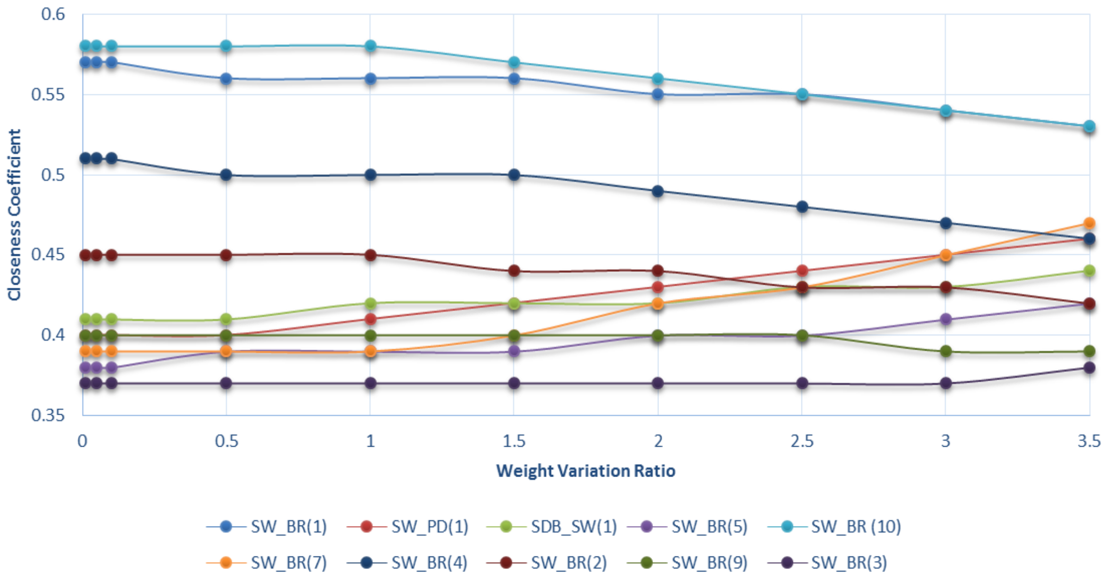
b) Nutrient Removal - *Similar to the sediment removal, the weight changes of nutrient removal also did not impact much on the final rank order.*



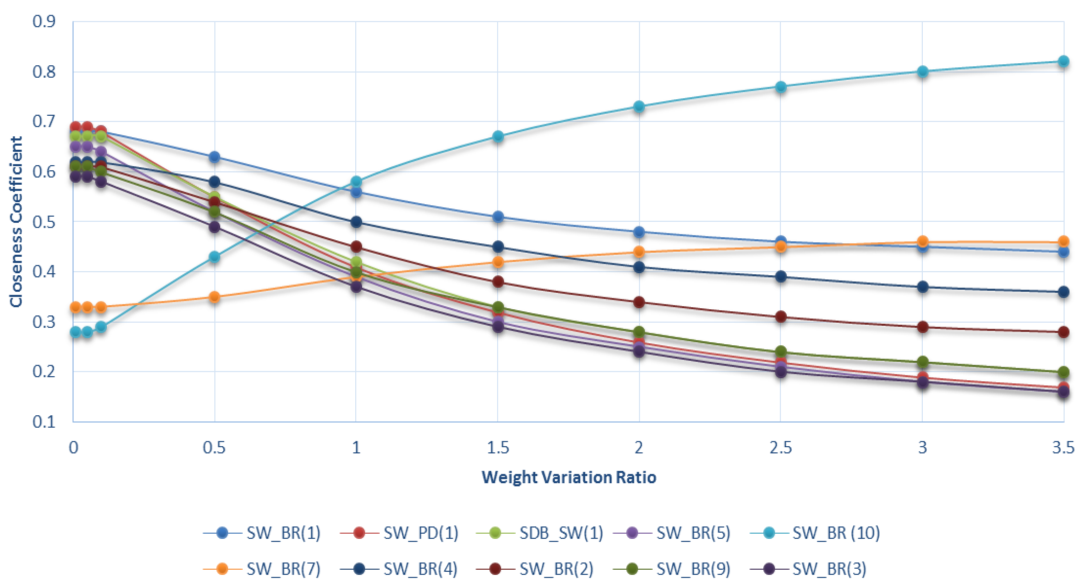
c) Heavy Metal Removal - *The changes of weights for heavy metal removal show slight variations of rank order starting from around the variation ratio of 1.4.*



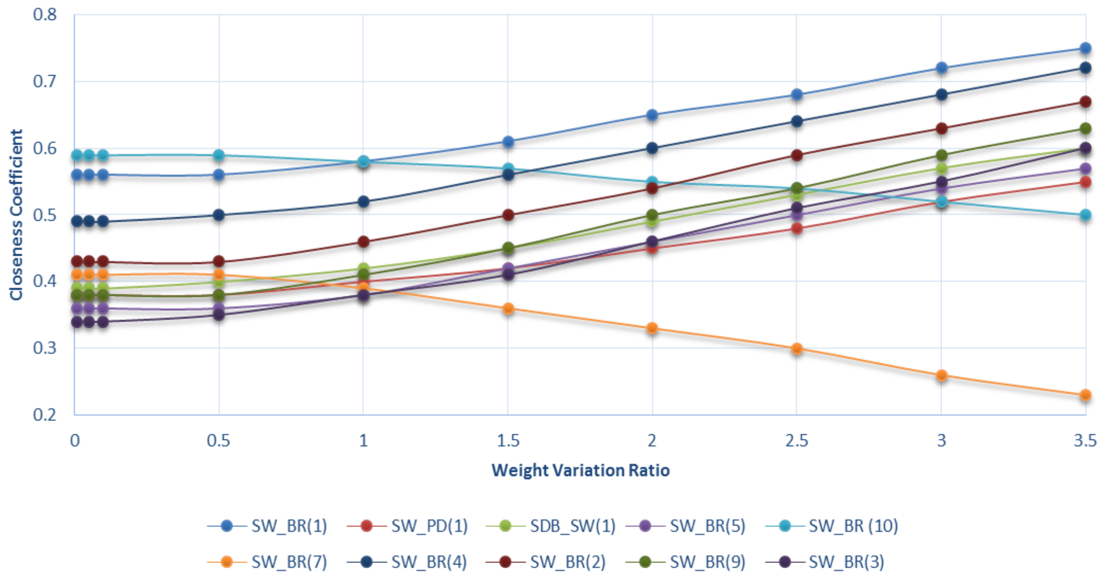
d) Peak Flow Reduction - *For the weight changes of peak flow reduction, the rank order of majority of the treatment trains remained the same. However, the rank order is slightly affected by treatment trains SW_BR (10) and SW_BR (7) starting from the weight variation ratio around 1.2.*



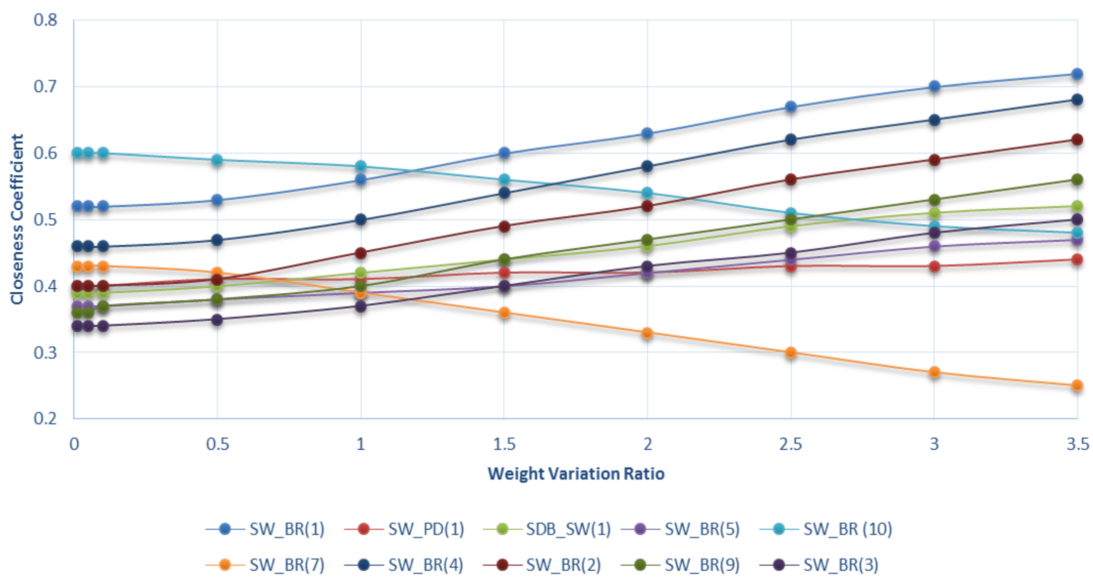
e) Habitat Creation - *The highest ranked treatment train has remained the same throughout the weight changes for habitat creation. The rank order of the rest of the treatment trains are slightly changed starting from the weight variation ratio of 1.5.*



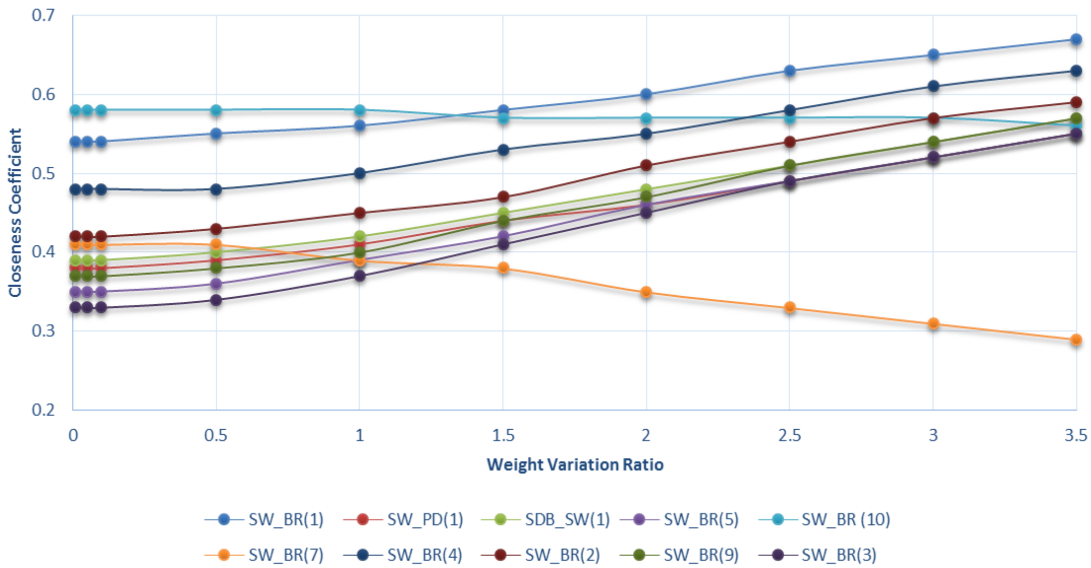
f) Potable Water Savings - *The treatment trains SW_BR (10) and SW_BR (7) show the highest sensitivity to the weight changes of potable water savings. The rank order of the other treatment trains remained almost the same with the weight changes.*



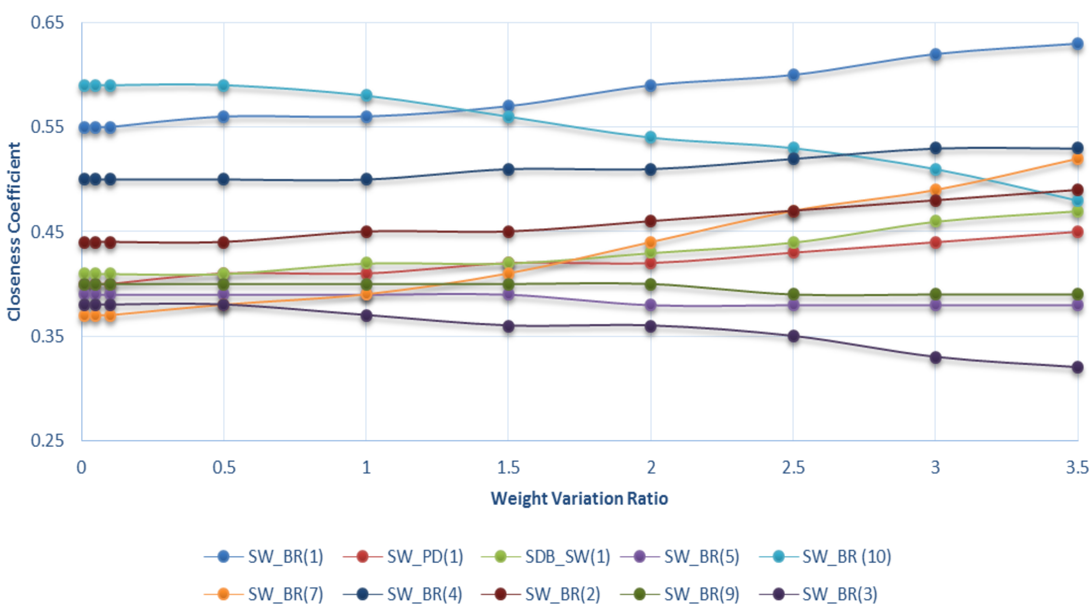
g) Equivalent Annual Cost - *Similar to the potable water savings, the treatment trains SW_BR (10) and SW_BR (7) show the highest sensitivity to the weight changes.*



h) Capital Cost - *The rapid changes of rank order starts from the weight variation ratio around 1.2. Similar to potable water savings and equivalent annual cost, treatment trains SW_BR (10) and SW_BR (7) show the highest sensitivity to the weight changes of capital cost.*



i) Annual Operation and Maintenance Cost - *Shows a similar trend to equivalent annual cost and capital cost.*



j) Improvement of Liveability - *Similar to most of the performance measures, treatment trains SW_BR (10) and SW_BR (7) are sensitive to the weight changes. The changes in rank order starts from around weight variation ratio of 1.2, for improvement of liveability.*

4.6 Summary

Stakeholder opinions play a major role when selecting optimum GI practices for an industrial area to reach for a compromise optimum solution based on the Triple Bottom Line (TBL) objectives (environmental, economic and social). Stakeholder preference elicitation is one of the major steps of the decision making process that should be performed with care due to the sensitivity of their preferences to the final compromise solution. This chapter explained the stakeholder preference elicitation and Multi Criteria Decision Analysis (MCDA) carried out for an industrial area to select the compromise optimum GI treatment trains.

In this study, a four rounded Delphi survey was performed to finalize a set of performance measures that are useful in selecting optimal GI practices for industrial areas which also included the weight elicitation for these performance measures using the SWING weighting method. A panel of experts who have experience in different sectors such as government, industry and research related to industrial GI implementation were consulted using a series of online questionnaire surveys to identify relevant performance measures and elicit their weights for the performance measures.

The results of the Delphi survey showed that, the experts valued the total runoff volume reduction as the most preferred performance measure in GI selection for an industrial area. Furthermore, the Delphi survey with the subsequent rounds showed a very good degree of consensus among the expert panel however showed some sample fatigue. The weights elicited for performance measures through the SWING weighting method were used as input for the TOPSIS analysis, which was used as the MCDA method in this study. The TOPSIS analysis was conducted for various near optimal treatment train sizing combinations with low equivalent annual costs which were obtained through the single objective optimization in Chapter 3. The MCDA analysis was conducted for various treatment train configurations which consisted with two and three treatment measures respectively. A treatment train configuration with a vegetated swale and bioretention was identified to be the compromise optimum treatment train with two treatment trains for the case study area considered. Adding a retention pond as a tertiary treatment measure for this treatment train configuration also complimented its performance for the study area. The method used in the present study was successful in identifying compromise optimum treatment train configurations and their individual sizing simultaneously.

As the final step of the MCDA process, a sensitivity analysis was performed to identify the weight sensitivity of the performance measures which are the only subjective data used in the study. Various weight variation schemes were developed by changing the weights of different performance measures and the changes of the closeness coefficient of the treatment trains were assessed. The results from the sensitivity analysis showed that different performance measures had low to moderate levels of sensitivity to the weight changes for the final rank order.

The methodology proposed in this study proved the importance of the optimal sizing of individual measures in the treatment train which is not explicitly addressed in the current sizing approaches for GI. The size changes of individual treatment measures showed variations in their performances though they had cost elements which were close to each other. The complexity in addressing this issue was handled using a Delphi survey followed by MCDA, which provided valuable insights to the existing knowledge on GI selection for industrial areas. The stakeholder preference elicitation, MCDA and the sensitivity analysis performed in this chapter with the integration of single objective optimization has proven efficient in optimizing GI treatment trains for an industrial area in terms of both selection and sizing.

CHAPTER 5

Green Infrastructure Practices to Mitigate Air Pollution in Industrial Areas

5.1 Introduction

Over the years, anthropogenic activities associated with industrialization are generating pressure on the natural environment. Air quality deterioration is one of the major environmental problems stressed upon industrial communities, which can cause hazardous consequences for human health in the long term (Faiz, 1993, Akbari et al., 2001, Akimoto, 2003, Wang et al., 2004). According to the estimates of World Health Organization (WHO), urban air pollution accounts for 6.4 million years of life lost annually worldwide (Cohen et al., 2004, Chen and Whalley, 2012).

Industrial areas are one of the major contributors to urban air pollution through sources such as heavy industrial activities, vehicular movement and power generation (Worland, 2016). Industrial areas largely contribute to air pollution in urban areas when compared with residential and commercial areas. Even though Australia has been able to maintain reasonable air quality levels compared to many other countries, 3000 premature deaths occur in Australia annually due to air pollution (Environmental Justice Australia, 2014). Air pollution can trigger cardio vesicular and respiratory diseases that can lead to increased mortality rates (Dominici et al., 2006).

Though it is inevitable that the degradation of air quality is a consequence of urban development, it is well-known that urbanization and associated activities are vital for the world’s growth. Thus, researchers, ecologists and urban planners have identified the need to reduce air pollution resulting from urbanization (Saunders et al., 2011). As a low cost mitigation strategy, several researchers have studied the role of urban greening for air quality improvement in urban areas (Beckett et al., 1998, Nowak et al., 2006). As an initiative of introducing urban greening concepts to reduce the impacts of harmful pollutants in the atmosphere, GI practices have been widely used in various urban areas across the world (Nowak et al., 1998, Yang et al., 2005, Nowak et al., 2006). However, there are yet limited studies conducted to investigate how well these different GI practices perform in improving the air quality and which practices would be optimum for a particular area to mitigate air pollution while providing other environmental, economic and social benefits.

This chapter describes the application of an air quality modeling tool i-Tree Eco, to quantify air quality improvement for several GI scenarios through a scenario analysis. The i-Tree Eco model has not been widely used in Australia to date (Saunders et al., 2011). The study has two major aims. The first aim is to assess the applicability of the i-Tree Eco software in Australia to quantify the air quality improvement from different GI (i.e. trees, green roofs and green walls) using a case study industrial area. The second aim is to assess GI scenarios using various environmental, economic and social performance measures to identify the optimum GI among several alternatives, for an industrial area. The work presented in this chapter has been already published in Jayasooriya et al., (2017).

5.1.1 Measuring Air Quality

There are six major constituents that are specified as air quality indicators based on their effects on health or environment, which are named as criteria air pollutants. Carbon Monoxide (CO), Ozone (O_3), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Particulate Matter (PM10 and PM2.5) and Lead (Pb) are defined as criteria air pollutants in ambient conditions (USEPA, 2015). Among these pollutants, PM10 and O_3 are identified as the pollutants that are of major concern in affecting the health and environmental conditions in Australia, having concentrations above the ambient air quality standards for major cities such as Melbourne, Brisbane, Perth and Sydney (Department of the Environment and Heritage, 2001, Simpson et al., 2005).

Table 5.1 shows the national ambient air quality standards in Australia for criteria air pollutants and their adverse health and environmental impacts. This shows that exceeding the critical levels of the various air pollutants can create various adverse impacts for the human health.

Table 5.1 – National Ambient Air Quality Standards for Criteria Pollutants (NEPM, 2003) and Impacts on Health and Environment (US EPA, 2015)

Criteria air pollutant	Averaging period	Maximum (ambient) concentration during averaging period	Impacts on health and environment
Carbon Monoxide (CO)	8 hours	9.0 ppm	Reducing the oxygen carrying capacity to body's organs, heart disease, chest pain (angina)
Nitrogen Dioxide (NO_2)	1 hour	0.12 ppm	Increasing susceptibility to respiratory diseases such as asthma, emphysema and bronchitis, heart disease
	1 year	0.03 ppm	
Ozone (O_3)	1 hour	0.10 ppm	Difficulties in breathing, cough, sore throat, asthma, emphysema and chronic bronchitis, interfering with the ability of sensitive plants to produce and store food, visibility damage of tree leaves, adverse impacts on ecosystems, loss of species diversity and habitat quality
	4 hours	0.08 ppm	
Sulfur Dioxide (SO_2)	1 hour	0.20 ppm	Respiratory diseases such as bronchoconstriction and asthma, hearth diseases
	1 day	0.08 ppm	
	1 year	0.02 ppm	
Lead (Pb)	1 year	0.50 $\mu g/m^3$	Affecting nervous system, kidney function, immune system, reproductive system, cardiovascular system, losses of biodiversity, decreased growth of plants and animals
Particulate Matter (PM10)	1 day	50 $\mu g/m^3$	Premature death, non-fatal heart attacks, irregular heartbeat, aggravated asthma, decrease lung function, respiratory symptoms
Particulate Matter (PM2.5)	1 day	25 $\mu g/m^3$	
	1 year	8 $\mu g/m^3$	

5.1.2 Role of Green Infrastructure Practices in improving Air Quality

GI practices such as trees, shrubs, lawns, green roofs and green walls have been proven efficient in reducing the harmful air pollutants and regulating the Green House Gas (GHG) emissions within the cities (Akbari et al., 2001, Baró et al., 2014). The vegetation in GI intercepts gaseous air pollutants through the leaf stomata as the primary way of improving air quality. Furthermore, the vegetation can intercept particulate matter by absorbance or adherence to the surface with the aid of the wind currents (Currie and Bass, 2008).

Direct air quality improvement is achieved by the uptake and deposition of the pollutants through GI. However, GI practices can also contribute to the energy savings by providing cooling during summer months, which can lower the emissions of power plants as indirect air quality improvement benefits. Therefore, the cumulative air quality improvement obtained from GI can be estimated as the total of direct and indirect benefits in resource units or monetary terms (Akbari et al., 2001, Foster et al., 2011).

5.2 Modelling of Air Quality Improvement of Green Infrastructure Practices

One of the widely used techniques to assess the pollution reduction capability of GI is through the use of dry deposition models (Yang et al., 2008). Models such as Urban Forest Effects Model (UFORE) that use the concepts of dry deposition modeling, were used in several case studies in the United States to quantify the air quality improvement through GI such as trees, green roofs and green walls (Nowak and Crane, 2000, Nowak et al., 2005). More recently, i-Tree Eco was introduced as an enhanced version of UFORE, which can also evaluate the monetary values of environmental services of GI (Martin, 2011, Hirabayashi et al., 2012). The i-Tree Eco is a peer reviewed open source software which is developed by the United States Forest Service. This has been initially used for several cities in United States to assess the air quality improvement and numerous ecosystem services of GI such as carbon storage, carbon sequestration and energy savings (Nowak and Crane, 2000, Hirabayashi et al., 2012). In 2011, i-Tree Eco was introduced as an Australian compatible version which includes integrated air quality and local weather data for New South Wales, Australian Capital Territory and Victoria (i-Tree Eco Australia, 2012).

There are several studies presented in the literature which quantify the air quality improvement through GI. Currie and Bass (2008) used UFORE to analyze the air quality improvement by different GI such as green roofs, trees and green walls in Toronto, Canada. This study showed that green roofs can significantly improve the urban air quality. A study conducted in Portland Oregon in USA using UFORE showed that green roofs can contribute to a direct air quality improvement of 3.5 Kg per acre annually with a GHG reduction of 7100 Kg per year (City of Portland, 2010). Nowak (1994a,b) used dry deposition modeling to estimate the air quality improvement of urban trees in Chicago, USA, which is equivalent to 9.2 million dollars and removal of 5575 metric tons of air pollutants annually. Using i-Tree Eco, Baró et al. (2014) estimated that the urban forest in Barcelona, Spain, removes 305 tons of air pollutants annually. Saunders et al. (2011) used UFORE in Perth, Australia to assess the differences of pollutant removal for different tree species and identified that, trees with needle like leave forms are more effective in air pollutant uptake.

Although i-Tree Eco has been widely acknowledged in literature for its capabilities in quantifying the air quality improvement through different GI, there are yet limited studies conducted in Australia on its applications (Saunders et al., 2011, Amati et al., 2013). Furthermore, it is evident that GI practices such as green roofs and green walls are not yet popular in Australia, despite their wider applications in US and Europe (Wilkinson and Reed, 2009). Furthermore, GI practices such as green roofs and green walls have a high potential on being implemented as air quality improvement strategies especially in industrial areas with poor air quality and less green space. Thus, quantifying the air quality improvement of GI within the Australian context will provide more information on developing policies and guidelines on future applications of GI practices for such areas. Studies on quantifying the air quality improvement will also raise the awareness among the stakeholders on more tangible and long term benefits of GI practices. Moreover, assessing the air quality improvement, its economic value and other ecosystem services, can provide information on selecting the most suitable GI for an industrial area based on the various benefits they can provide for individual industries and also for the surrounding communities in such areas. Potential GI practices that are used for air pollution mitigation may have different performance measures related to environmental, economic and social objectives which can be of high relevance for industrial areas. Hence, comparison of the performance measures of these different GI practices used for air pollution mitigation will provide assistance in selecting the most suitable GI for an industrial area.

5.2.1 i-Tree Eco Model

The i-Tree Eco software provides functionalities to analyze the urban forest structure including the species composition, tree health and leaf area. It estimates the amount of pollution removed by urban forest within a year for criteria pollutants (O_3, SO_2, NO_2, CO, PM10 and PM2.5) except for Pb, through dry deposition modeling. The i-Tree Eco software can also assess the air quality improvement by different tree species through the species list included in the model. Additionally, i-Tree Eco is capable of evaluating other ecosystem services provided by urban forests such as the effects of trees on building energy use, avoided runoff and the economic value of air quality improvement, carbon storage and carbon sequestration (Nowak and Crane, 2000). The i-Tree Eco model is developed by United States Department of Agriculture (USDA) Forest Service and initially was used in US to model the air quality improvement of GI. Currently the model is fully functional for Australia. Even though the model is fully functional for Australia, there are limitations exist such as the human health impacts of the air pollution removal are based on the US specific model and the energy effect model is adopted from the US based research (i-Tree Eco Users Manual, 2014). Hence, a care must be taken when interpreting the human health and energy efficiency data for Australia using the i-Tree Eco model.

5.2.2 i-Tree Eco Model Development

The i-Tree Eco software estimates hourly dry deposition of pollutants from trees for O_3, SO_2, NO_2, CO, PM2.5 and PM10 throughout a year. The i-Tree Eco model development and calculation for air quality improvement can be explained in four major steps as shown in Figure 5.1.

5.2.2.1 Field Data Requirements

The first step in the i-Tree Eco model development is to identify the suitable sampling method to define the plots. Plot is a hypothetical area within the study area which is used to define the existing land use and vegetation. Locating the plots for field sampling in a study area can be done by three different approaches namely random, stratified random or grid. The random sampling is done by laying random plots throughout the study area without any stratification. Within the stratified random sampling process, the area is stratified (e.g. based on their land use classes) and the plots are located randomly within each of the strata. In the grid based sampling, the plots are located within a predefined grid, which enables to distribute the plots evenly within the study area (i-Tree Eco Users Manual, 2014).After identifying the suitable field sampling method, the number of plots required should be decided by considering factors such as the model accuracy and the time and resources required for the data collection. Higher accuracy can be achieved when the number of plots within the area is increased, however the time and cost required for the data collection can be increased accordingly. The minimum number of plots required for an accurate i-Tree Eco model is considered to be 30 (i-Tree Eco Users Manual, 2014). According to the recommendations provided by Nowak et al. (2008) for the field data collection, larger plot areas are recommended for the model outcomes with lower standard error. However, larger plot areas also can increase the time and resources required for the measurement of plot variables.

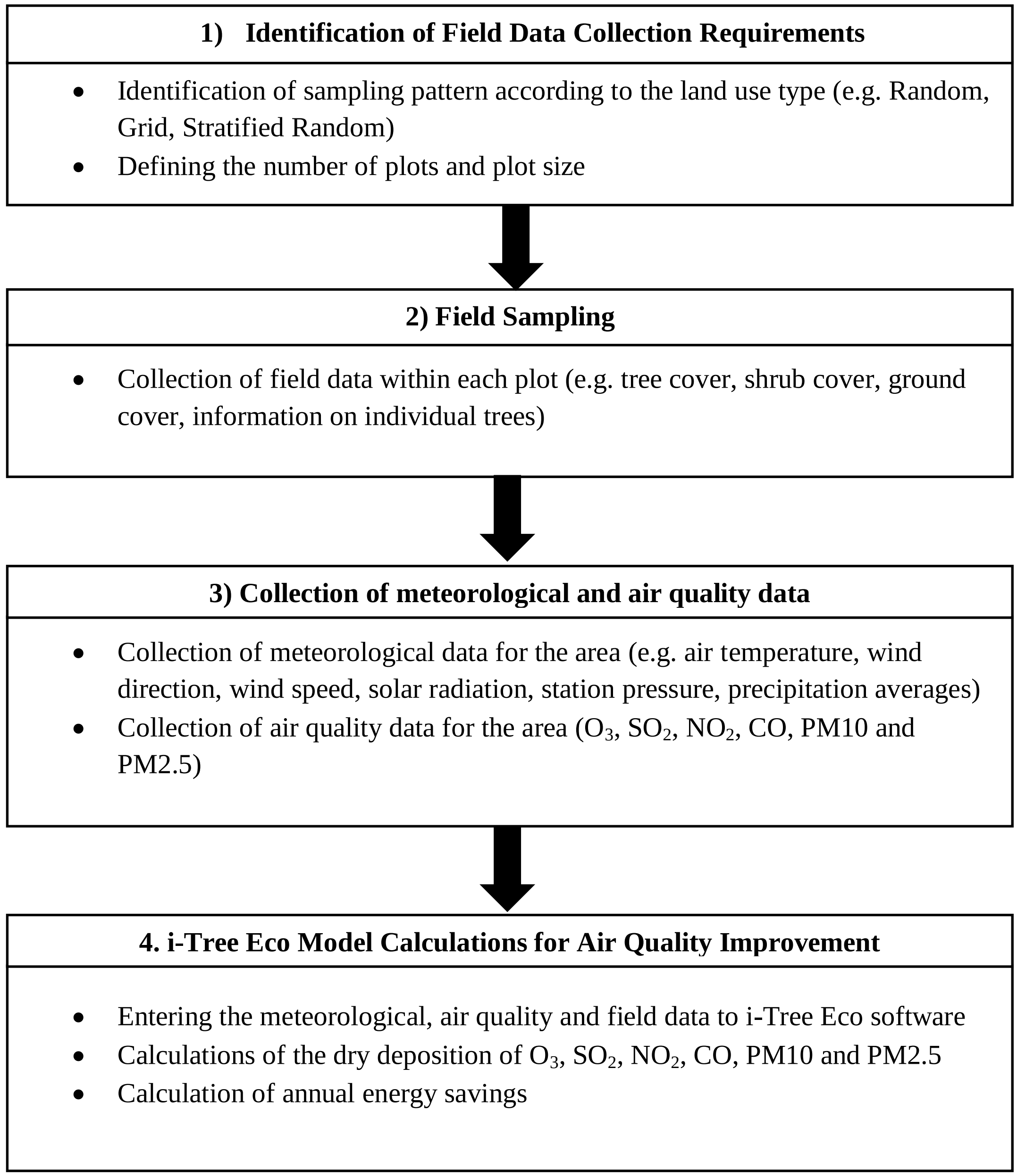


Figure 5.1 - Steps Involved in Modeling Air Quality Improvement Using i-Tree Eco

5.2.2.2 Field Sampling

After the plots are defined for the study area as explained in Section 5.2.2.1, field data are collected for each of the plot as shown in Table 5.2. For each plot, field data such as land use, ground, tree and shrub cover are required (Nowak and Crane, 2000). Models can be developed with or without shrub information according to the user requirements. More information on collecting these data in the field can be found in the i-Tree Eco Users Manual (2014).

Table 5.2 – Information Required For Each Plot to Develop an i-Tree Eco Model

Information Type	Parameters
Plot Information (Percentage)	Land Use Tree Cover
Ground Cover Information (Percentage)	Buildings Cement Surface Other Impervious Surface Soil Surface Shrub Cover Grass Cover Water Surface
Shrub Information	Species Height Missing Shrub Percentage Percentage Area
Tree Information	Direction and Distance to Plot Centre Species Diameter at the Breast Height (DBH) Height to Live Top Height to Crown Base Crown Width (NS, EW) Missing Tree Precentage Die Back Distance to the Buildings (For Energy Savings Calculations)

5.2.2.3 Collection of Meteorological and Air Quality Data

Metrological data such as air temperature, wind direction, wind speed, solar radiation, station pressure, precipitation averages and the air quality data for criteria pollutants (O_3, SO_2, NO_2, CO, PM2.5 and PM10) are required to develop the i-Tree Eco model. The i-Tree Eco software includes an inbuilt database for meteorological and air quality data for US, Canadian and Australian users (i-Tree Eco Users Manual, 2014). For the present study, the inbuilt meteorological data in the model was used to assess the air quality improvement through GI.

5.2.2.4 i-Tree Eco Model Calculations for Air Quality Improvement

Based on the inputs of field data and metrological and air pollution data, i-Tree Eco quantifies the air quality improvement by urban forests through dry deposition. The air quality improvement per unit tree cover due to dry deposition of pollutants I_{unit} *(%)* is estimated as,

$$I_{unit} = \frac{F}{F + M_{total}} \times 100 \qquad (5.1)$$

where F = pollutant flux ($gm^{-2}\ h^{-1}$) and M_{total} = total air pollutant mass per unit tree cover ($gm^{-2}\ h^{-1}$).

The model estimates the pollutant flux (F) for O_3, SO_2, NO_2 and CO as a product of deposition velocity and input air pollutant concentration.

$$F = V_d \times C \times 3600 \qquad (5.2)$$

where V_d = deposition velocity (ms^{-1}) and C = air pollutant concentration (gm^{-3}). The deposition velocities *(V_d)* for O_3, SO_2, NO_2 and CO are calculated as the inverse sum of the aerodynamic resistance, quasi laminar boundary layer resistance, and canopy resistance (Baldocchi et al., 1987).

$$V_d = \frac{1}{R_a + R_b + R_c} \qquad (5.3)$$

where R_a = aerodynamic resistance (sm^{-1}); R_b = quasi laminar boundary layer resistance for the air pollutant (sm^{-1}); and R_c = canopy resistance (sm^{-1}).

The aerodynamic resistance is calculated only using meteorological data and therefore it is independent of the type of pollutant. The quasi laminar boundary layer and canopy resistances are calculated separately for O_3, SO_2, NO_2 and CO (Hirabayashi et al., 2012). Meteorological data are also used to calculate these two parameters. The equations that are used to calculate R_a , R_b and R_c are explained in Nowak et al. (1997). The equations used for the calculation of pollutant flux and deposition velocity for the pollutants PM10 and PM 2.5 are given in Hirabayashi et al. (2012).

M_{total} for all the criteria pollutants considered is calculated as,

$$M_{total} = H \times C \qquad (5.4)$$

where H = urban mixing height (m) and C = air pollutant concentration ($gm^{-3} h^{-1}$).

The mixing height (*H)* is defined as the height of the layer adjacent to the ground, over which pollutants or any constituents emitted within the layer become vertically dispersed by convection or mechanical turbulence (Seibert et al., 2000). Metrological data are used to determine the mixing height. The mixing height in i-Tree Eco is calculated based on the United States Environmental protection Agency's (US EPA) mixing height program. The mixing heights for twice daily (morning and afternoon) are first calculated using surface weather and upper air data for the particular stations and then interpolated hourly (Hirabayashi and Endreny, 2015). The estimation of mixing heights using this method is an objective way of simplify and homogenize the estimation of mixing heights under convective conditions (Seibert et al., 2000). These values are then used in the i-Tree Eco model to quantify the air quality improvement by the pollutant uptake through vegetation (Hirabayashi, 2011; Hirabayashi and Endreny, 2015).

5.2.3 Modeling Green Roofs and Green Walls Using i-Tree Eco

Even though the preliminary functionality of i-Tree Eco is to assess the air quality improvement of urban forests which consist of trees, it has been also used for the simulation of air quality improvement benefits of GI such as green roofs and green walls (Deutsch et al., 2005, Currie and Bass, 2008). The i-Tree Eco software models the air pollutant removal based on the type of vegetation and its structure. Hence, manipulating the type of species and the structure of vegetation used, i-Tree Eco can simulate the air pollutant removal by green roofs and green walls for a particular area. Growing Green Guide (2014) suggests a set of species suitable for green roofs and green walls constructed in Victoria, Australia. Thus, replacing the conventional roof and wall areas by roofs and walls of these recommended species, i-Tree Eco can be used to simulate the air quality improvement through green roofs and green walls.

5.2.4 Estimation of Building Energy Savings of Green Infrastructure Practices

The i-Tree Eco software can also estimate the building energy savings through trees by using the inputs of distance and direction from buildings to trees, and hourly weather data (McPherson.,1994, McPherson and Simpson.,1999). However, i-Tree Eco cannot be used for the energy savings estimations through green roofs and green walls. CNT (2010) proposed equations to estimate the building energy savings using annual heating and cooling degree days and the changes in thermal resistance of GI and conventional practices. These equations were used in the present study to quantify the energy savings from green roofs and green walls. A description of the equations and the data used for the calculation of building energy savings from green roofs and green walls are given in Appendix 5A.

It should be noted that the methods and equations which are used for the energy estimation in this study should be only used to get an approximation on the real energy savings benefit of GI. There is very limited research available yet to accurately determine the energy savings benefits by GI practices. Hence, the results presented in this study with regard to the energy savings should be treated cautiously and only be used as a way of aiding the decision making.

5.3 Use of i-Tree Eco to Identify Optimum Green Infrastructure Scenarios

Figure 5.2 – Case Study Area (Brooklyn Industrial Precinct)

The i-Tree Eco model has been applied to identify the optimum GI scenarios for air quality improvement in the case study area of the *Brooklyn industrial Precinct* (Figure 5.2). The *Brooklyn industrial precinct* has been identified as one of Victoria's major hot spots for poor air quality. Even though the majority of other air pollutants are within their permissible levels, dust and aerosol production are identified as most critical contribution of air pollution within the area due to industrial activities such as quarry operations and materials recycling. Furthermore, due to heavy vehicular movement in the unsealed roads of the area, high emissions of dust particulates were reported during day time (The Brooklyn Evolution, 2012).

Figure 5.3 shows the daily PM10 levels in the *Brooklyn Industrial Precinct* from 2010 to 2014. The PM10 levels of the area have exceeded the maximum allowable value of 50 µg/m^3 more than 5 days per year which is the national ambient air quality standard (NEPM, 2003). The elevation of poor air quality levels in the area has also reported an increase of heart related diseases and asthma conditions among the neighborhood communities (EPA Victoria, 2013).

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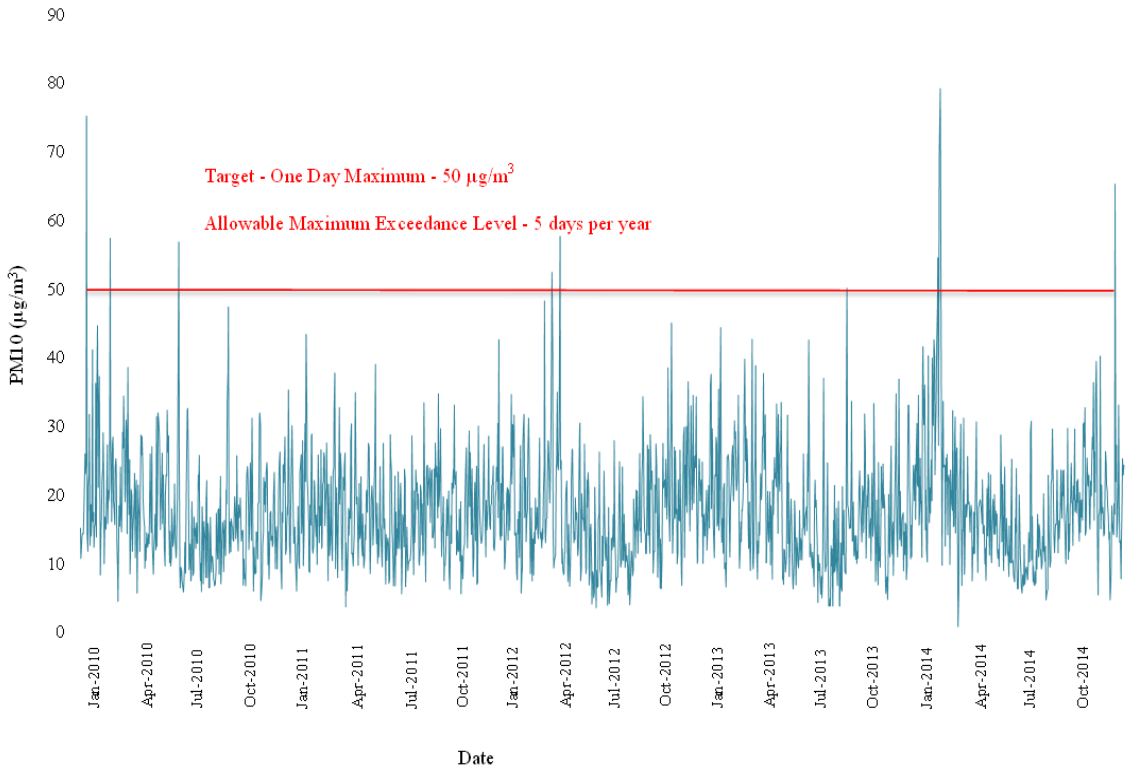


Figure 5.3 - PM10 Levels of Brooklyn Industrial Precinct– 2010-2014 (EPA Victoria, 2015)

The *Brooklyn industrial precinct* is identified as an area with limited green space. Therefore, long term planning activities are being carried out within the area to increase the potential of more urban greening opportunities by implementing GI. As a result of these planning activities, new areas for tree planting are proposed for the *Brooklyn industrial precinct* (The Brooklyn Evolution, 2012). A scenario analysis has been performed for the *Brooklyn Industrial Precinct* to identify optimum GI practices which improve the air quality of the study area, with the aid of i-Tree Eco software.

5.3.1 Data Collection and Model Set up

The instructions given in the i-Tree Eco Users Manual (2014) were followed to collect the field data of the study area. As the Brooklyn Industrial Precinct is a zoned industrial land area, the total area consists of a single land use type. Hence, the grid based sampling procedure was followed to locate plots for field data collection. A 200 m × 200 m grid was superimposed on the GIS map of the area, to establish the plots. The plot centers were established at the intersection points of the grid and 88 plots were considered to collect the field data of the study area. The plot distribution based on the 200 m × 200 m grid, for the study area is shown in Figure 5.4. Each plot had an area of 1000 m^2 (0.1 ha) as recommended by Nowak et al. (2008). Field data such as plot information, and ground cover information (Table 5.2) were collected for the 88 plots located throughout the study area using high resolution GIS mapping. The tree information for each of the 88 plots were also collected which are, distance and direction of trees to the plot center, number of trees, tree species types, diameter at the breast height (dbh), missing percentage, height to crown base, crown width and distance from trees to the buildings. Field work and the Brimbank City Council tree information database were used to collect the tree information for each plot.

Local hourly meteorological (i.e. air temperature, wind direction, wind speed, solar radiation, station pressure and precipitation averages) and air quality data (i.e. O_3, SO_2, NO_2, CO, PM10 and PM2.5) were used as the other input data for the study area (i-Tree Eco Users Manual, 2014).

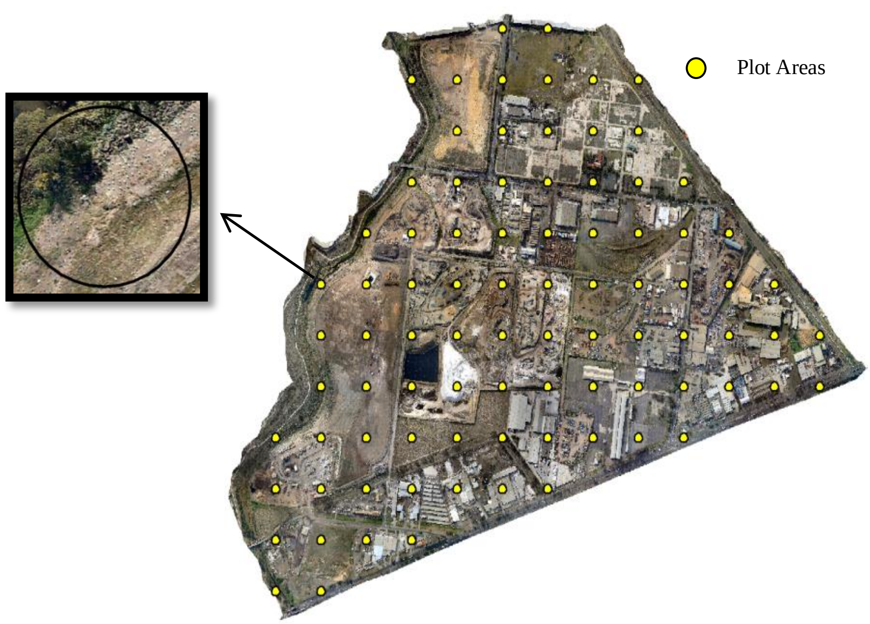


Figure 5.4 – Plot Distribution of the Study Area

5.3.1.1 Model set up - Baseline Scenario (Existing)

The existing tree scenario of the study area was used as the baseline, which was used to conduct the comparisons of pollutant removal and energy savings with several other GI scenarios. For each of the 88 field plots defined in Section 5.3.1, local meteorological data, air quality data and tree information currently available within the plot (collected in Section 5.3.1) were used as the input data for the baseline scenario.

5.3.1.2 Model set up - New Scenarios

Trees, green roofs and green walls are GI, which provide significant air quality improvement and building energy saving benefits. Therefore, different GI scenarios consisting of trees, green roofs and green walls were simulated separately by increasing the number of trees and manipulating the species to model green roofs and green walls, in the 88 plots of the baseline scenario.

(a) New Tree Scenario

In the *Brooklyn industrial precinct*, the areas available for the additional tree plantation were already identified in its long term planning framework (The Brooklyn Evolution, 2012). The baseline (existing) scenario was updated with the new trees to simulate the new tree scenario. The plot distribution map (Figure 5.4) was superimposed with the identified additional tree plantation map to develop the new tree scenario as shown in Figure 5.5.

Figure 5.5 – Proposed Tree Plan for New Tree Scenario

The number of trees in each of the plot area was updated according to the new tree plan (Figure 5.5). The current dominant tree species of the area was identified to be *Eucalyptus cladocalyx* during the model setup for the baseline scenario in Section 5.3.1. Thus, in the new tree scenario, the baseline scenario was updated with the additional trees of *Eucalyptus cladocalyx* to estimate the air quality improvement and building energy savings.

(b) Green Roof Scenario

For the green roof scenario, the roof areas of all industrial and commercial buildings of the study area were replaced with intensive green roofs of *Eucalyptus macrocarpa*, which is one of the recommended species for green roofs in Victoria, Australia (Growing Green Guide, 2014). Similar to the new tree scenario, the baseline scenario was updated with the new green roofs. Figure 5.6 shows the superimposed plot distribution map with the green roof scenario simulated for the study area. The baseline scenario was updated with additional green roofs with the information of *Eucalyptus macrocarpa* to simulate the air quality improvement.

Figure 5.6 – Green Roof Scenario

The i-Tree Eco software does not have capabilities to simulate the building energy saving effects of green roofs. Therefore, the equations suggested by CNT (2010) were used to estimate the building energy savings of GI for the study area.

(c) Green Wall Scenario

For the green walls scenario, vertical walls of plantation were added for the walls of industrial and commercial buildings (boundaries of the buildings) as shown in Figure 5.7. Hedges of 2m high *Laurus nobilis* species (Growing Green Guide, 2014) were added around commercial buildings as green walls. Similar to the new tree and green roof scenarios, the baseline scenario was updated with green walls of *Laurus nobilis*. As per the green roof scenario, the equations suggested by CNT (2010) were used to estimate the building energy savings of green walls.

Figure 5.7 - Green Wall Scenario

(d) Other Scenarios

The above three scenarios are combined to develop three other scenarios as 1) new trees and green roof scenario, 2) new trees and green wall scenario, and 3) green roof and green wall scenario. These scenarios were also simulated using the i-Tree Eco software, to estimate their performances in improving air quality. The building energy savings estimations were conducted using i-Tree Eco and equations of CNT (2010).

5.3.2 Identification and Evaluation of Performance Measures

Each GI scenario simulated in Section 5.3.1.2 performs differently in improving air quality. For each different scenario, the differences in performance can be measured through performance measures under environmental, economic and social objectives. These performance measures can provide assistance to decision makers to select the most suitable GI scenarios for the study area. Based on literature and having discussions with various stakeholders such as project managers, urban planners and engineers who work in areas of industrial GI implementation, several performance measures were identified as shown in Table 5.3. The table also shows how the performance measures are estimated.

The environmental performance measures (which are all air quality improvement measures) were obtained from the i- Tree Eco output. The building energy savings was identified as an important economic performance measure of GI, especially for industrial areas. The energy savings from trees were also estimated from the i-Tree Eco model output. The energy savings from green roofs and green walls were estimated from equations proposed by CNT (2010).

Different cost components associated in the life cycle of GI such as capital cost and annual operation and maintenance costs were identified as the other important economic performance measures. Equivalent Annual Cost (EAC), which is the annual form of the life cycle cost, was considered as an economic performance measure to assess the annual recurrent costs of different GI scenarios. The costs of trees were calculated based on the information from Brimbank City Council Street Tree Policy (2010). Cost components for green roofs and green walls were estimated using Growing Green Guide (2014).

Table 5.3 - Environmental, Economic and Social Performance Measures for GI Scenarios

Objective	Performance Measure	Unit	Maximize or Minimize	Method of Estimation
Environmental	Annual NO_2 removal	(Kg/Yr.)	Maximize	i- Tree Eco
	Annual SO_2 removal	(Kg/Yr.)	Maximize	i- Tree Eco
	Annual PM10 removal	(Kg/Yr.)	Maximize	i- Tree Eco
	Annual CO removal	(Kg/Yr.)	Maximize	i- Tree Eco
	Annual PM2.5 removal	(Kg/Yr.)	Maximize	i- Tree Eco
	Annual O_3 removal	(Kg/Yr.)	Maximize	i- Tree Eco
Economic	Energy savings	($)	Maximize	i-Tree Eco, CNT (2010)
	Equivalent annual cost	($)	Minimize	Growing Green Guide (2014), Brimbank City Council Street Tree Policy (2010)
	Capital cost	($)	Minimize	Growing Green Guide (2014), Brimbank City Council Street Tree Policy (2010)
	Annual operation and maintenance cost	($)	Minimize	Growing Green Guide (2014), Brimbank City Council Street Tree Policy (2010)
Social	Improvement of liveability	-	Maximize	Keeley, (2011)

The stakeholders have identified the improvement of the livability of an industrial area and its surroundings as of major importance, which is considered as a social performance measure. The Green Area Ratio method (Keeley, 2011) (Appendix 3A) was used to estimate the improvement of the liveability of the area. The improvement of community health or the reduction of the health related costs due to air pollution reduction is another important social performance measure that can measure the success of air quality improvement strategies for such areas (McCubbin and Delucchi, 1999, Künzli et al., 2000). However, due to insufficient data availability, the reduction of health costs due to air quality improvement was not considered in the present study.

5.4 Results from Scenario Analysis

The results obtained from the i-Tree Eco analysis for different GI scenarios in the case study area are presented in this section. This section also provides a discussion of the results of the present study by comparing them with several GI case studies across the world for air quality improvement.

5.4.1 Air Quality Improvement from Existing Trees (Baseline Scenario)

The i-Tree Eco modeling of the existing tree scenario (baseline) has provided information on the urban forest structure such as tree density, percentage leaf area and the specie types in Brooklyn Industrial Precinct. From inputs of existing tree information, the tree density for the existing tree coverage was reported as 10 trees per hectare with the dominant tree species of *Eucalyptus cladocalyx*. The percentage tree population and percentage leaf area with respect to the total tree coverage for 10 most dominant species for the study area is shown in Figure 5.8. As can be seen from Figure 5.8, the dominant species type of the area is *Eucalyptus cladocalyx*. Hence, trees of *Eucalyptus cladocalyx were* added as new trees to model new tree scenario in Section 5.3.1.2.

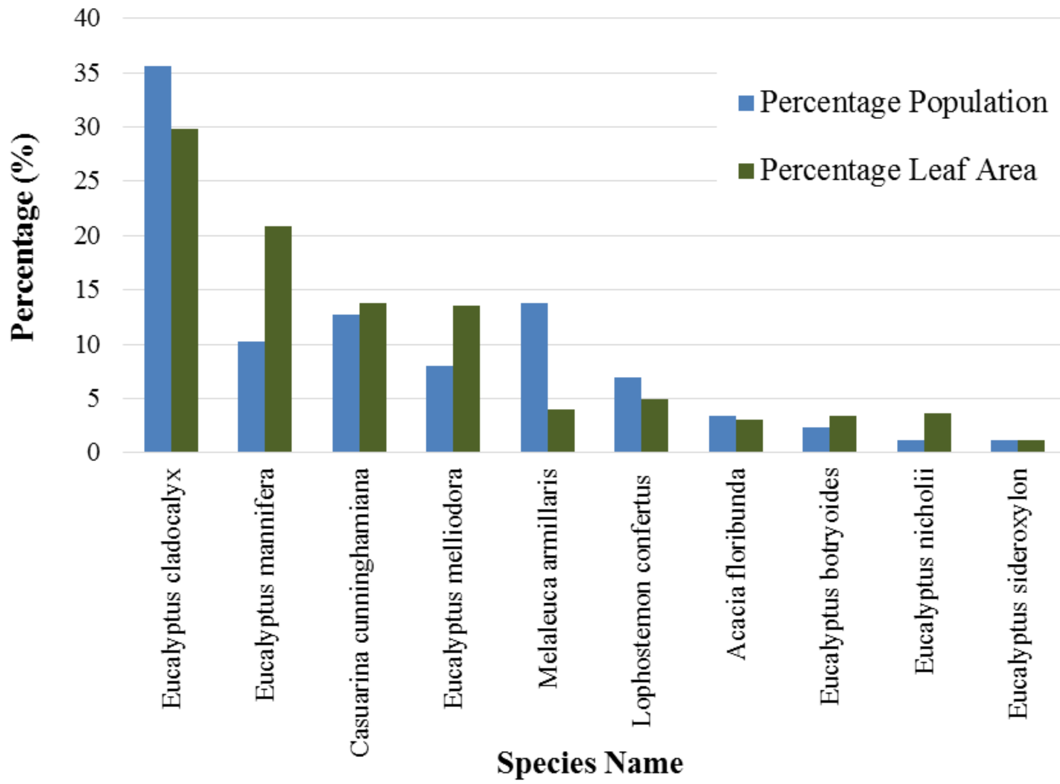


Figure 5.8 – Dominant Tree Species in the Brooklyn Industrial Precinct

The air quality improvement through the existing trees was estimated using the i-Tree Eco model based on tree information, local hourly meteorological (i.e. air temperature, wind direction, wind speed, solar radiation, station pressure, precipitation averages) and air quality data (O_3, SO_2, NO_2, CO, PM10 and PM2.5). The model estimations showed that the urban forest in the Brooklyn Industrial Precinct removes 68 kg of NO_2, 22 kg of SO_2, 225 kg of PM 10, 9 kg of CO, 7 kg of PM 2.5 and 246 kg of O_3 annually. Table 5.4 provides the information on the total air quality improvement together with the tree density for several cities around the world. The Brooklyn Industrial Precinct has the lowest number of trees per hectare compared with other cities around world and as well as Perth, Australia. The increase of a tree density of the study area can lead to greater annual air quality improvement benefits.

Table 5.4 also shows that there are large variations occurring in the pollutant removal quantities even when the number of trees per hectare is close to each other for different cities. Nowak (1994a) and Yang et al. (2005) state that the variations of the air pollutant uptake for different study areas occur due to seasonal variations in air pollutant concentrations and the biological cycle of the tree species. The capability of urban trees to remove the air pollutants is significantly affected by factors such as tree health, soil health, soil moisture availability, leaf period (e.g. evergreen species retains green leaves throughout all seasons), leaf area index (LAI), meteorology and pollution concentrations which are vastly varied across the regions (Baró et al., 2014). Furthermore, there are more complex factors that can affect the results, which are unknown or difficult to model such as dispersion of pollutants at different scales, physiological differences in vegetation between climatic regions and the effects of resource limitations on plant growth (Saunders et al., 2011).

5.4.2 Air Quality Improvement through New Tree Scenario

Adding new trees in the proposed tree planting areas has increased the tree density of the area as 80 trees per hectare. Figure 5.9 shows the annual air pollutant removal for the new tree scenario and its comparison to the baseline scenario for the study area. The new scenario with additional trees has provided a removal of 964 kg of NO_2, 125 kg of SO_2, 1474 kg of PM 10, 10 kg of CO, 43 kg of PM 2.5 and 1885 kg of O_3 annually.

Table 5.4 - Tree Density and Annual Quality Improvement for Different Cities

Study Area	**Country**	**Area Hectare (ha)**	**Number of Trees Per Hectare**	**Total Annual Pollutant Removal (kg/Yr)**	**Total Annual Pollutant Removal per Hectare (kg/Yr)/ha**	**Reference**
Calgary	Canada	82500	165	4,000	0.05	Nowak et al, (2006)
Toronto	Canada	712400	119	17,500	0.02	Nowak et al, (2006)
Atlanta	United States	2169400	276	44,200	0.02	Nowak et al, (2006)
New York	United States	3449400	65	19,100	0.01	Nowak et al, (2006)
Baltimore	United States	23900	126	18,600	0.78	Nowak et al, (2006)
Philadelphia	United States	36930	62	15,200	0.41	Nowak et al, (2006)
Washington	United States	1441200	121	23,800	0.02	Nowak et al, (2006)
Boston	United States	23210	83	17,900	0.77	Nowak et al, (2006)
Woodbridge	United States	2797	164	31,800	11.37	Nowak et al, (2006)
Minneapolis	United States	15130	65	18,400	1.22	Nowak et al, (2006)
Syracuse	United States	6630	135	15,200	2.29	Nowak et al, (2006)
Morgantown	United States	2751	296	26,700	9.71	Nowak et al, (2006)
Moorestown	United States	3864	153	28,200	7.30	Nowak et al, (2006)
Jersey City	United States	5460	35	9,600	1.76	Nowak et al, (2006)
Freehold	United States	10030	95	337,700	33.67	Nowak et al, (2006)
Barcelona	Spain	10100	143	305,000	30.20	Baros et al, (2014)
Western Suburbs of Perth	Australia	6320	83	294,000	46.52	Saunders et al, (2011)
Brooklyn Industrial Precinct	**Australia**	**262**	**10**	**577**	**2.20**	**Present study**

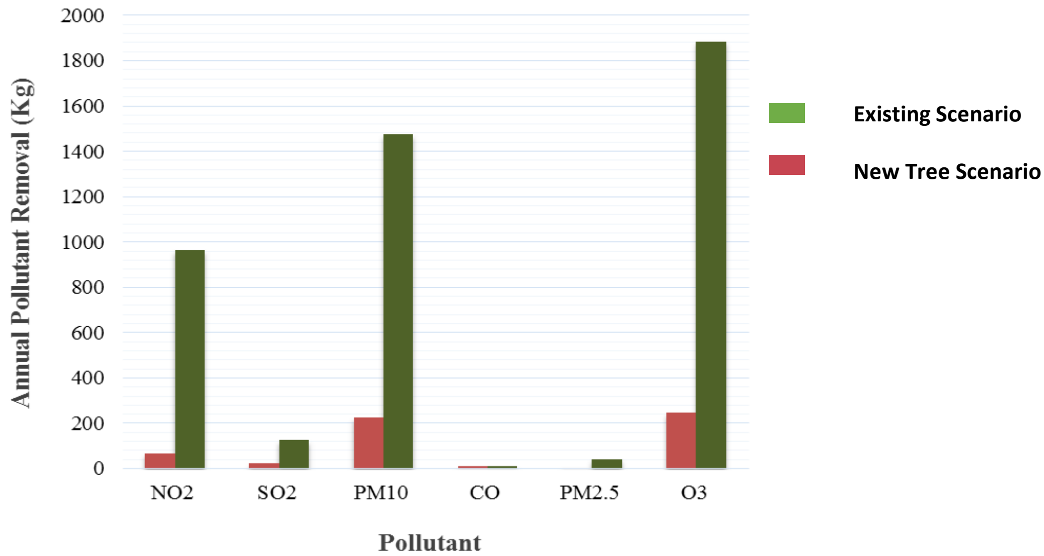


Figure 5.9 – Annual Air Pollutant Removal for Baseline (Existing) and New Tree Scenario

Figure 5.10 shows the average monthly removal rates of the six pollutants assessed. The removal rates in the colder months May-August have shown an increase compared to the other months for almost all pollutants. These results have shown a similar trend to the i-Tree Eco assessment conducted in the suburbs of Perth, Australia (Saunders et al., 2011), where the urban forest consisted with evergreen dominant species similar to the present study. However, the temporal variations of monthly removal rates for the Brooklyn Industrial Precinct have shown a different trend to those of the cities of Philadelphia in North America (Gryning and Chaumerliac, 2013), Barcelona in Spain (Baró et al., 2014) and Beijing in China (Yang et al., 2005). These three cities have recorded low pollutant removal rates in colder months compared to warmer months. The dominant tree species in Philadelphia, Barcelona and Beijing were non evergreen. Therefore, it can be observed that the growth cycle and the characteristics of the species type selected can play a major role in the pollutant removal process especially in areas where seasonal climatic variations exist. The, assessment of air quality improvement of GI due to variations of vegetation species is beyond the scope of this study.

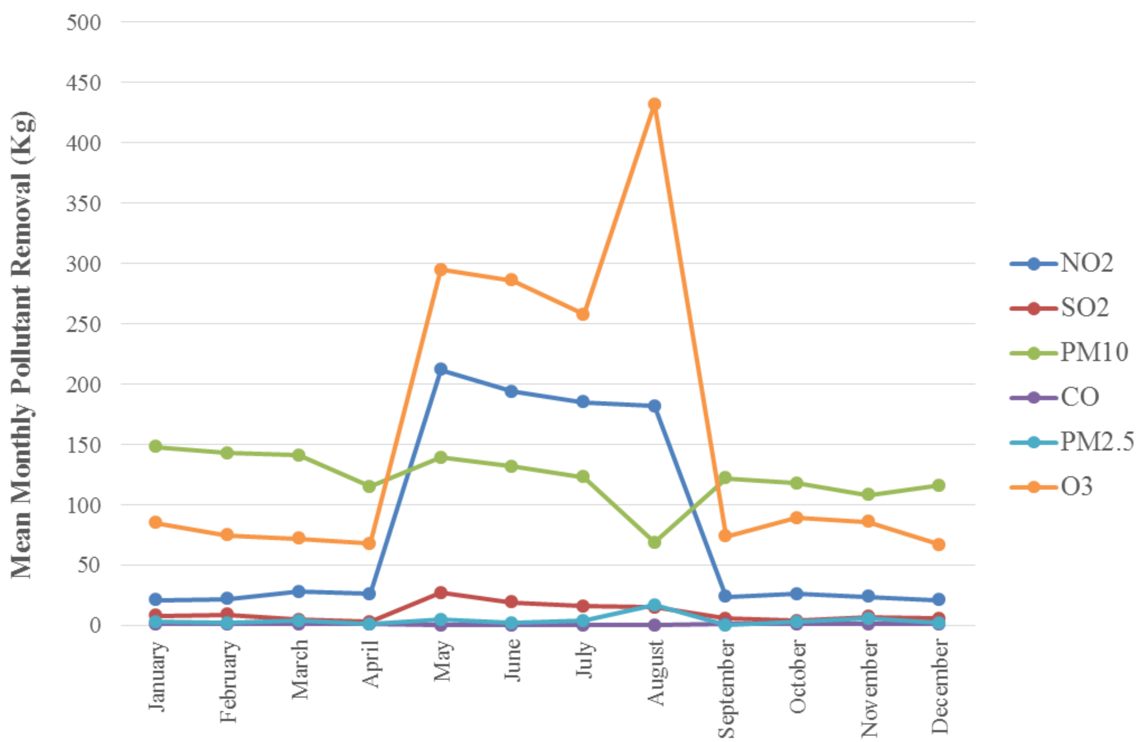


Figure 5.10 – Monthly Air Pollutant Removal Trends for New Tree Scenario

5.4.3 Air Quality Improvement through Green Roof Scenario

The Brooklyn Industrial Precinct consists of commercial and industrial buildings which covers a total roof area of 288,788 m^2. Replacing the roof areas of these buildings through intensive green roofs in combination with the existing trees has provided an annual uptake of 109 kg of NO_2, 30 kg of SO_2, 443 kg of PM10, 10kg of CO, 14 Kg of PM 2.5 and 357 kg of O_3. Figure 5.11 shows the air pollutant uptake through the green roof scenario compared to the baseline scenario.

5.4.4 Air Quality Improvement through Green Wall Scenario

Replacing the building walls by green walls improved the air quality annually by up taking 87 kg of NO_2, 26 kg of SO_2, 314 kg of PM10, 10kg of CO, 10 Kg of PM

2.5 and 298 kg of O_3. Figure 5.12 shows the air pollutant uptake through green wall scenario compared to the baseline scenario.

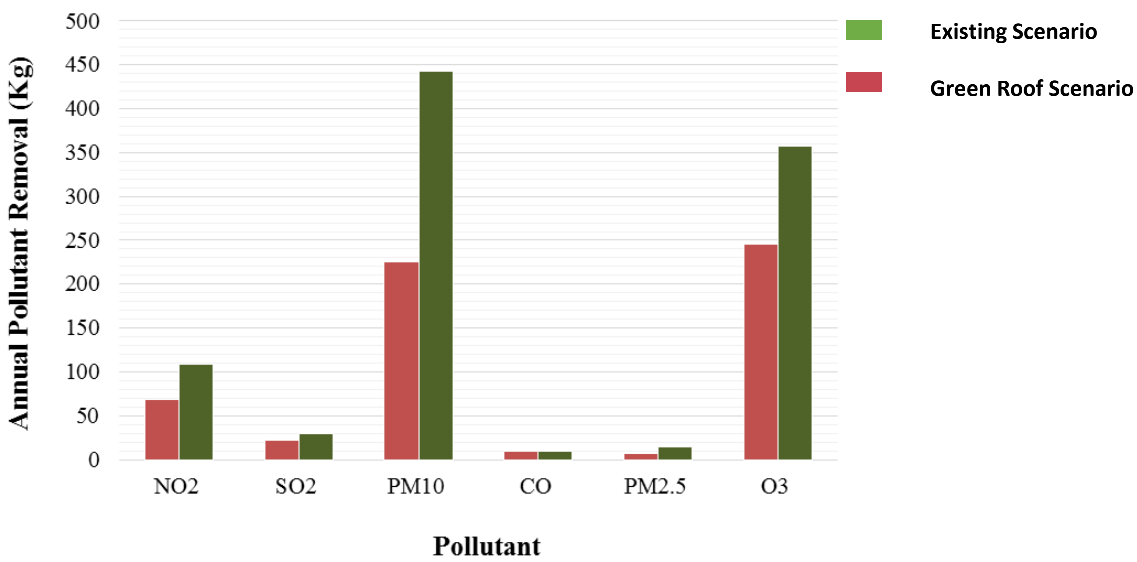


Figure 5.11 – Annual Air Pollutant for Baseline (Existing) and Green Roof Scenario

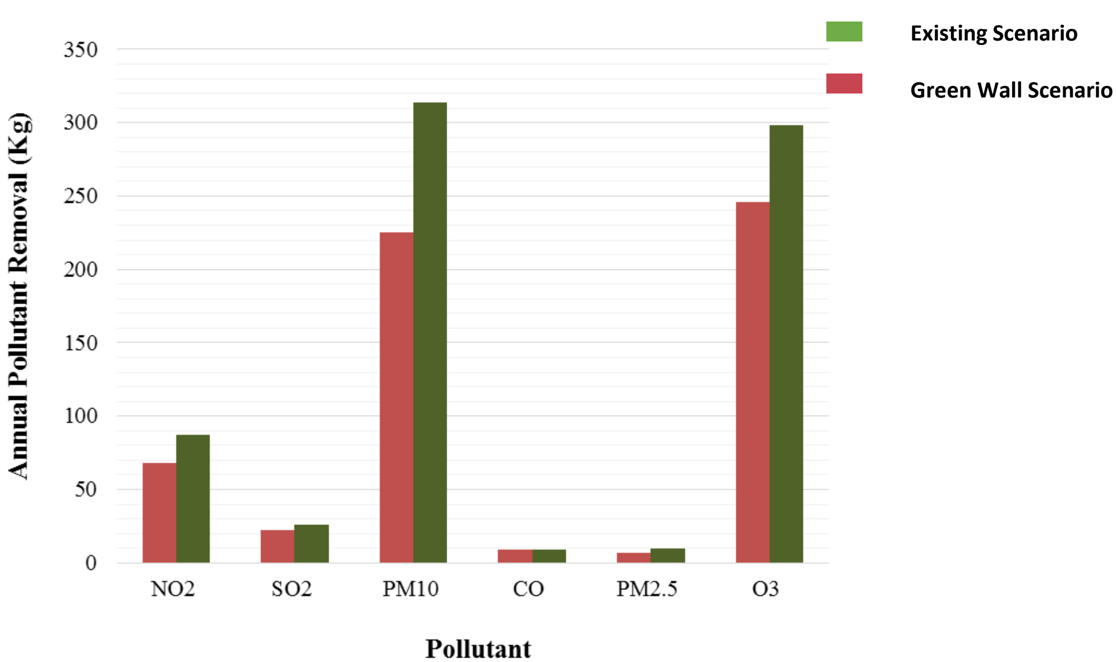


Figure 5.12 – Annual Air Pollutant for Baseline (Existing) and Green Wall Scenario

Even though the air quality improvement through green roofs and green walls was relatively lower compared to trees, they can be identified as potential GI scenarios that can provide significant benefits for industrial areas with less open space to implement trees.

5.4.5 Air Quality Improvement through Other Scenarios

Figure 5.13 shows the summary of the pollutant removal for combinations of scenarios with trees and green roofs, trees and green walls, and green walls and green roofs for the study area.

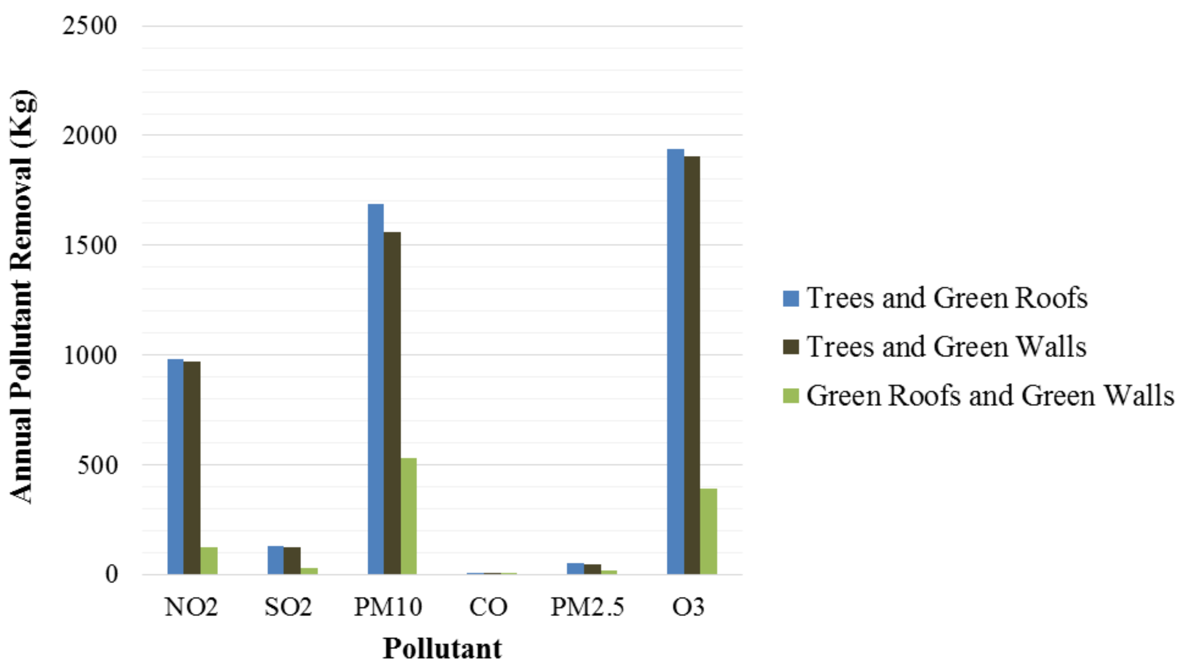


Figure 5.13 – Annual Air Pollutant Removal for Other Scenarios

The combination of green roofs and green walls has shown relatively low air quality improvement benefits compared to other two combined scenarios. Moreover, combining the green roofs and green walls with trees has provided almost similar air quality improvement results for the Brooklyn Industrial Precinct. Hence it can be observed that, in combined scenarios where trees are included, the trees dominate the pollutant removal process. Combining green roofs or green walls with trees have increased the air pollutant uptake for the area but have not provided the sum of air pollutant uptake they have shown, when they were considered individually. One of the reasons for this phenomenon can be the air pollutant uptake reaching its maximum uptake limit through both the GI practices for the study area.

5.4.6 Summary of Individual Air Pollutant Uptake through Different GI Scenarios

The i-Tree Eco model results obtained for different GI scenarios considered with trees, green roofs and green walls individually and in combination show that the different scenarios uptake different pollutants differently. Table 5.5 shows the summary results for the annual air pollutant uptake and the percentage of uptake with respect to the total pollutant uptake for individual pollutants in each of the GI scenarios considered for the study area.

O_3, PM10 and NO_2 are the pollutants which have the highest uptake rates through GI. SO_2 and PM2.5 uptake occurred in smaller quantities while CO removal rate has remained constant throughout all scenarios. The lower deposition velocity of CO compared to other pollutants may have influenced the low removal rates of CO by GI (Lovett, 1994, Nowak et al., 2006). Trees have the highest percentage uptake for O_3 from the total pollutant uptake while green roofs and green walls had the highest rates of uptake for PM10 from the total pollutants. Hence, even though green roofs and green walls have not provided higher air pollutant removal compared to the trees, they can be identified as GI with a greater potential for the implementation for industrial areas like the *Brooklyn industrial precinct* where there exist air quality problems with particulate matter such as dust.

Table 5.5 – Summary of Individual Air Pollutant Uptake from Different GI Scenarios

Scenario	Annual air pollutant removal summary	NO_2	SO_2	PM10	CO	PM2.5	O_3
Existing (Baseline)	Removal (Kg)	68	22	225	9	7	246
	Percentage from the total uptake (%)	11.79	3.81	38.99	1.56	1.21	42.63
New Trees	Removal (Kg)	964	125	1474	10	43	1885
	Percentage from the total uptake (%)	21.42	2.78	32.75	0.22	0.96	41.88
Green Roofs	Removal (Kg)	109	30	443	10	14	357
	Percentage from the total uptake (%)	11.32	3.12	46	1.04	1.45	37.07
Green Walls	Removal (Kg)	87	26	314	10	10	298
	Percentage from the total uptake (%)	11.68	3.49	42.15	1.34	1.34	40
Trees and Green Roofs	Removal (Kg)	982	129	1691	10	50	1937
	Percentage from the total uptake (%)	20.46	2.69	35.24	0.21	1.04	40.36
Trees and Green Walls	Removal (Kg)	971	126	1562	10	46	1906
	Percentage from the total uptake (%)	21.01	2.73	33.8	0.22	1	41.25
Green Roofs and green Walls	Removal (Kg)	123	33	530	10	17	393
	Percentage from the total uptake (%)	11.12	2.98	47.92	0.9	1.54	35.53

5.4.7 Energy Savings by GI scenarios

For the estimation of energy savings through different GI scenarios, a cost of $ 349 per Mega Watt hour (Mwh) as recommended by the i- Tree Eco Model was used (i-Tree Eco Australia, 2012). Figure 5.14 shows the annual energy saving benefits provided by different GI scenarios considered.

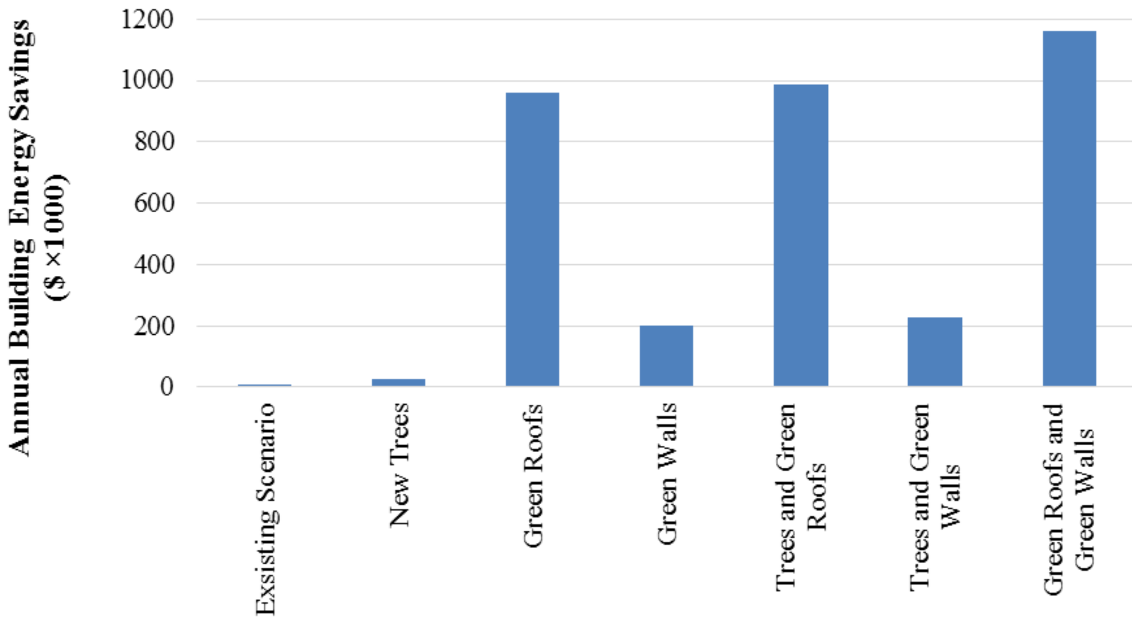


Figure 5.14 – Building Energy Savings for Different GI Scenarios

Highest energy savings were provided by green roofs compared to trees and green walls. Combination of green roofs and green walls has provided the highest annual energy saving of 3324 Mwh which is equivalent to an economic benefit of $ 1,160,076 for the study area. The electricity is generated in Victoria primarily through brown coal, which is considered as a major contributor for GHG emissions. Therefore, reducing the energy use in industrial areas which has higher energy consumption compared to other land uses, can indirectly contribute to the improvement air quality and GHG emission.

5.4.8 Assessment with Performance Measures

To identify the most suitable GI scenario for the study area, the different scenarios identified and modeled were assessed with several environmental, economic and social performance measures. These performance measures were selected through literature and by having discussions with stakeholders such as urban planners, project managers and engineers who are engaged in improving the urban greening within the study area. The performance measures were estimated using the methods discussed in Section 5.3.2. The summary results of the performance measures estimated for six different GI scenarios in the study area are shown in Table 5.6.

When comparing the different individual GI scenarios with the performance measures related to air pollutant removal (environmental objective), trees have provided the highest benefits in terms of pollutants. Moreover, the cost components, capital cost and equivalent annual costs, are lower for trees compared to both green roofs and green walls. Trees also have provided high livability benefits. However, green roofs and green walls have provided more local benefits such as building energy savings for the study area, compared to trees. The difference between equivalent annual cost and the cost of annual energy savings is almost similar in trees and green walls. Hence it can be observed that, if the local benefits are more preferred for a building with relatively lower costs, green walls can be a potential GI.

When looking at the combined scenarios of GI, it is evident that combining the different scenarios has not significantly increased the air pollutant uptake. The scenarios where trees are included (trees and green roofs, and trees and green walls), the air pollutant uptake has been dominated by the trees and has not provided the sum of pollutant removal of the individual scenarios. The combination of green roofs and green walls has provided highest energy savings benefits however has the highest capital and equivalent annual cost. Even though all of the combined scenarios have provided high livability and energy savings benefits, they have considered as inferior for the study area due to the high costs associated with them.

Table 5.6 – Assessment with Performance Measures for New GI Scenarios

The GI Scenario	Environmental						Economic				Social
	Annual NO_2 Removal (Kg)	Annual SO_2 Removal (Kg)	Annual PM10 Removal (Kg)	Annual CO Removal (Kg)	Annual PM2.5 Removal (Kg)	Annual O_3 Removal (Kg)	Annual Building Energy Savings ($)	Capital Cost ($)	Annual Operation and Maintenance Cost ($)	Equivalent Annual Cost ($)	Liveability Improvement (Green Area Ratio)
Trees Only	964	125	1474	10	43	1885	26200	2305600	491630	537742	0.77
Green Roof Only	109	30	443	10	14	357	960911	43318200	2032110	2898474	0.44
Green Wall Only	87	26	314	10	10	298	199307	16958855	384949	724126	0.06
Trees and Green Roofs	982	129	1691	10	50	1937	987111	45623800	2523740	3436216	1.21
Trees and Green Walls	971	126	1562	10	46	1906	225507	19264454	876579	1261868	0.83
Green Roofs and Green Walls	123	33	530	10	17	393	1160076	60277054	2417059	3622600	0.50

5.5 Summary

Industrial areas are identified as hotspots in generating various air pollutants due to ongoing industrial activities. GI practices have been identified as strategies that can improve the air quality levels by uptaking the harmful air pollutants while providing several other beneficial ecosystem services. There are limited studies conducted in Australia to quantify the air quality improvement through different GI such as trees, green roofs and green walls which have the potential of improving air quality specifically in industrial areas. Therefore, this study has made an attempt to quantify the air quality improvement through different GI scenarios and evaluated them using several performance measures related to environmental, economic and social objectives, to identify the most suitable scenarios for an industrial area.

The suitability of the i-Tree Eco software to quantify the air quality improvement through several GI scenarios was assessed by applying it to a case study industrial area in Victoria, Australia. It should be noted that the i-Tree Eco software has been used only in a limited number of studies in Australia. The comparison of the results of the present study with other studies across the world showed that the i-Tree Eco software can be successfully applied to an Australian case study area. From the six different GI scenarios that were assessed through i-Tree Eco, trees were found to be the most suitable GI for the study area which has the highest air pollutant uptake and lower costs compared to green roofs and green walls. However, green roofs and green walls found to have more local benefits in terms of energy savings which can indirectly lead to air quality improvement by reducing the GHG emissions. Furthermore, combining green roofs or green walls with trees did not provide a significant increase in air pollutant uptake, however has provided more energy and livability benefits compared to trees only scenario.

Even though the cost components associated with green roofs and green walls are higher, these GI can be also identified as practices which could provide greater local benefits especially for industrial areas, where energy consumption can be particularly high. The analysis conducted in this chapter has provided new insights in modeling the green roofs and green walls ability of air quality improvement, using a simulation model which not widely in Australia. The methodologies used in this study were further validated by comparing them against various international case studies. The values obtained through the simulation for Australia have proven that the i-Tree Eco model can be successfully applied within Australian context. The results obtained in this study can also be beneficial in promoting more green roofs and green walls in Australian industrial areas and also to develop planning and policies related to these practices.

CHAPTER 6

Summary, Conclusions and Recommendations

6.1 Summary

With the rapid urban growth and development, the natural green space available in urban areas is consequently been degraded. These changes of land surface characteristics leads to various environmental problems such as increasing the runoff which can lead to flooding and the poor quality of receiving waters, degradation of air quality and threats to the natural habitats. Among different land uses in urban areas, the industrial areas are highly environmentally degraded land areas due to ongoing industrial activities which pose numerous threats to natural ecosystems (Alshuwaikhat, 2005, Ghasemian et al., 2012). However, industrial areas plays major role in a country's economy and therefore it is important to identify optimum strategies to improve the environmental quality of such areas (The Brooklyn Evolution, 2012). Green Infrastructure (GI) practices integrate measures which are implemented to restore the green space in urban areas and are currently becoming one of the promising strategies around the world of restoring the natural environment (Jayasooriya and Ng, 2014).

The current practice of selection of GI for a particular area is an ad-hoc process which is mainly based on the expert judgement (Jayasooriya et al., 2016). Different types of GI practices provide different functionalities and there is limited number of studies available in literature on assessing the optimum GI practices for an industrial area to mitigate the various environmental problems that occur in these areas. Furthermore, there exists a research gap in a systematic methodology, which could be applied for an industrial area to identify the optimum GI practices. Thus, this study has made an attempt to strengthen the knowledge base on identifying the methodologies to optimize GI practices, specifically for industrial areas. In implementing GI practices for industrial areas, the current study has considered two major aims which are optimizing GI practices for stormwater management in industrial areas and identifying most suitable GI practices for the air quality improvement in industrial areas. To achieve these aims, this research has used a mix methods based research approach. The research has proposed systematic methodology by integrating several existing methodologies to support the professionals in decision making related to optimal GI planning for industrial areas. The proposed systematic methodology in this study has contributed to enhance the current knowledge base in GI optimisation specifically for industrial lands and also showed the inadequacies and inaccuracies of the current ad-hoc process of GI optimisation.

In the first part of the study, a methodology was developed to optimally size and select the GI treatment trains to manage stormwater. A simulation-optimization based modelling approach was used by integrating both single objective optimization and simulation modelling using the Model for Urban Stormwater Improvement Conceptualization (MUSIC). Several potential treatment train configurations were developed for an industrial case study area in Melbourne and for each of the configurations, the methodology was developed to obtain the optimal sizing combinations of individual treatment measures in the treatment train. A single objective optimization problem was formulated by minimizing the Equivalent Annual Cost (EAC) as the objective function and available land area and the target pollution removal rates for the pollutants of Total Suspended Solids (TSS), Total Phosphorous (TP) and Total Nitrogen (TN) as the constraints. Even though a single objective optimization should produce a single optimum solution, in this study, instead of a single solution, several near optimal solutions were obtained which are close to the single optimum solution and were separately analysed. Each of the near optimal sizing combination had almost similar EAC; however had vastly different sizing combinations for the individual treatment measures and quite different values of performance measures. For the assistance of obtaining the optimum treatment train sizing combination from the near optimal solutions for the study area, the treatment train sizing combinations were assessed using several performance measures associated with triple bottom line (TBL) criteria (environmental, economic and social). Even though the performance measure assessment provided an idea of loosely identifying some of the suitable treatment trains for the study area, it also highlighted the importance of integrating stakeholder preferences for the study to obtain a compromise optimum solution for the study area. This component of the research contributed to the knowledge on stakeholder integration in GI decision making by proposing a methodology to integrate their opinions in a more structured and systematic way than the existing ad-hoc approach.

As the next phase of the methodology in optimizing stormwater management GI practices, a four rounded Delphi survey was conducted with a panel of experts to identify the performance measures that influence the GI selection for industrial areas. Furthermore, these Delphi surveys were used for weight elicitation using the SWING weighting method for each of the identified performance measures, which were then used as the input data for a Multi Criteria Decision Analysis (MCDA). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981) was used as the MCDA method in this study to reach for a compromise optimum treatment train configuration and the sizing combination of the individual measures of the treatment train. The integration of TOPSIS with the results of the mathematical optimisation showed that this method has the ability to assess the larger volumes of data in decision making and could be integrated more frequently in the GI planning process. Moreover, a sensitivity analysis was performed to validate the results obtained through TOPSIS by considering several weighting schemes for different performance measures. The results of the sensitivity analysis assessed the most sensitive performance measures for the weight changes. The methodology proposed in this study was successful in optimizing both the selection and sizing of a treatment train for an industrial area simultaneously which is not addressed in the current GI treatment train optimisation. This has provided contribution to the knowledge by enhancing the efficiency of current GI optimisation process.

The next aim of the research was to identify methodologies to obtain most suitable GI practices to improve the air quality in industrial areas. A scenario analysis was performed which integrated different GI scenarios, to identify optimum the GI practices for the case study industrial area. The simulation software i-Tree Eco was used to simulate the air quality improvement benefits of different potential GI scenarios. Even though the i-Tree Eco software has been introduced as an Australian compatible version in 2012, there is yet very limited number of comprehensive studies conducted in Australia to assess the air quality improvement benefits of GI using i-Tree Eco (Saunders et al., 2011, Amati et al., 2013). Therefore, this component of the study also assessed the suitability of the i-Tree Eco software in an Australian context to quantify the air quality improvement benefits of GI practices. The results obtained for the case study area were compared with several previous studies across the world to assess the suitability of i-Tree Eco in the Australian context. The results also showed that the i-Tree Eco can be successfully applied in Australia to assess various GI scenarios. Furthermore, these scenarios were assessed with performance measures of TBL to identify the optimum GI practices for the study area. The results obtained from this research component was beneficial in strengthening the knowledge base on optimum applications of the GI practices in Australia, especially in industrial areas where the air quality is significantly degraded. Moreover, this study has provided information on improving the understanding of the modelling concepts of the i-Tree Eco model and enhancing its applications in the Australian context.

6.2 Conclusions

The conclusions which are obtained through various components of the research are summarized below by considering them as four major sections.

6.2.1 Optimization of Treatment Train Sizing

The innovative methodology proposed in this study by integrating mathematical optimization and simulation modelling has demonstrated the capability of identifying the optimal low cost treatment trains with the sizes for the individual treatment measures. In the current practice, this process is conducted through a trial and error process and several simulation runs are needed to perform to obtain the sizing combinations that achieve the target reduction levels of pollutants. However, even after obtaining the sizing combinations through the trial and error process, there are no measures provided in the current approach to assess whether these sizing combinations are optimum for the study area (Jayasooriya et al., 2016). The methodology proposed in this study identified the potential near optimal sizing combinations that could be implemented within the area with low EAC which are the most economically feasible treatment train sizing combinations for the study area. The initial driver for the implementation of GI practices for any area is the funds allocated for the project. Thus, using the EAC as the objective function, the proposed methodology has provided means of screening out the optimal sizes of individual treatment measures in a treatment train that provides the same stormwater treatment benefit within the available land area constraints with the minimal costs. Unlike in the current approach where the single optimum solution is selected which minimises the cost, the proposed methodology provided the opportunity to the decision on maker to select several near optimal low cost solutions and assess them over the other performance measures.

Even though the single objective optimization should produce a single optimum result (which is the treatment train sizing combination with least EAC in this study), the proposed methodology obtained several solutions which are close to the single optimum solution. Analysing these near optimal solutions further showed that even though all these sizing combinations have EAC which are close to each other, the individual treatment measures in the treatment train had vastly different sizing combinations. Assessment of these near optimal sizing combinations with various performance measures related to industrial areas further showed the difficulty in selecting a single optimum solution for a treatment train sizing problem due to the vastly different sizing of individual treatment measures. The results of the performance measure assessment related to environmental, economic and social aspects further stressed the importance of the involvement of stakeholders of multi-disciplinary groups related to GI implementation in reaching for a compromise optimum solution based on their preferences.

At present, the sizing of these treatment trains are performed using the simulation models and it does not provide any means of assessing whether the chosen size through the model provides the optimum benefits for a particular area. The methodology proposed in this study showed the capability of obtaining the optimal sizing combinations for treatment trains which incorporate number of treatment measures that integrates primary, secondary and tertiary treatment. Furthermore, the proposed method in this study has showed specifically beneficial for industrial areas, where there exist a potential to consider different types GI practices due to high environmental demands of these areas (e.g.: treatment of specific pollutants, improving the environmental quality of the areas, improving the liveability etc.), compared to other urban land uses such as commercial or residential areas. However it should be noted that the methodology proposed in this study for optimal treatment train sizing can also be adopted for any land use based on the requirements of the study.

6.2.2 Stakeholder Preference Elicitation through Delphi Survey

The results obtained from the proposed methodology discussed in the Section 6.2.1 showed the importance of integrating the opinions of different stakeholders in selecting the most suitable treatment trains for the study area. Four rounded Delphi survey process used in this study for the stakeholder preference elicitation was proven to be a robust technique to elicit preferences from an expert panel without having face to face interactions, which reduced issues that occur in group discussions such as "peer pressure" or "group think". The Delphi survey used in this study provided a flexible and economically feasible way of eliciting stakeholder preferences by considering the consensus of the expert panel for the problem being discussed. The initial two rounds of the Delphi surveys were used to finalize a set of performance measures which are important for industrial areas in selecting GI practices for stormwater management.

At the end of the Round 2 of the Delphi survey, the consensus was reached for all the performance measures which were initially identified through literature and stakeholder discussions. This also shows that, for a Delphi survey to be successful, the selection of the expert panel plays a major role. It is important to select the experts who have the expertise on the specific topic which is been discussed. In addition to the existing performance measures, the experts identified several other environmental economic and social measures which are important in optimizing GI practices for an industrial area. From the suggestions received by the experts, it was evident that they showed major interest in the water quality improvement functionality in GI practices for industrial areas. Generally in GI implementation, a major attention is given to the water quality parameters of TSS, TP and TN in stormwater. However, for industrial areas the panel proposed additional water quality parameters to be considered in stormwater such as hydrocarbons, organic pollutants and different types of heavy metals. Moreover, they also identified the industry or businesses behaviour on accepting the GI measures as one of the important social performance measures which influences the implementation of GI within such areas. These types of different suggestions showed the importance of integrating experts with multiple disciplines in GI selection decision problems.

The SWING weighting method which was used for the weight elicitation in the final rounds of the Delphi survey was proven to be simple and robust weighting technique to be used in a self-explanatory survey. Even though the Delphi survey was planned with four rounds, at the end of Round 3, a high degree of consensus has been achieved for weights of all the parameters. However, final round was conducted to further validate the results and it showed that at the end of Round 4, the results were further converged towards the consensus however has started showing sample fatigue. Thus, this also showed that for a Delphi survey to be successful, the number of rounds should be appropriately decided based on the study requirements.

The experts valued the environmental objective as the most important objective followed by social and economic objectives for industrial areas in GI implementation for stormwater management. They also preferred the total runoff volume reduction as the most important performance measure in selecting a GI for an industrial area. Habitat creation was the least preferred performance measure from the list of finalized performance measures. This also suggests that the reduction of stormwater volume is important for industrial areas that annually generate larger quantities of contaminated stormwater. The importance of social performance measures in GI optimization process for such areas was also shown by the higher weights provided for performance measures such as public safety, industry/businesses behaviour on accepting the GI and risk assessment.

Even though, stakeholder opinions are used in the current approach in GI optimisation, this study has proposed a methodology to perform it in a more systematic way rather than the traditional ad-hoc process. Moreover, the method proposed herein by integration of the SWING weights with the Delphi survey proved to provide high degree of expert consensus in the optimisation process which is lacking in the current approach. The generic methodology proposed in this study for the stakeholder consultation and GI decision making by combining mathematical optimisation and MCDA can be applied for any industrial area for GI optimisation.

6.2.3 MCDA to Select Optimum GI for Stormwater Management and Sensitivity Analysis

The TOPSIS method was used in this study as the MCDA technique to identify the optimum GI treatment train configurations and the sizing combinations for stormwater management. The TOPSIS method has proven to be a simple but robust MCDA technique which uses the weights of the performance measures as the only subjective data. As the weights provided by the experts are the only subjective data used in this method, care must be taken to obtain the weights of the performance measures accurately to use in TOPSIS. The relative closeness to the positive ideal solution (the solution that minimizes the costs and maximizes the benefit) is used to rank the most suitable treatment trains (configuration and sizing combination) for the study area.

From the TOPSIS analysis conducted for the case study area of the Brooklyn Industrial Precinct, among the treatment trains with two treatment measures, a treatment train configuration with vegetated swale and bioretention showed the highest benefits with a low cost. Experts have also weighted total runoff volume reduction as the most preferred performance measure. Furthermore, the TOPSIS analysis also showed the optimum individual sizing combinations of the treatment measures of the above treatment train configuration for the study area. This showed that, the proposed methodology in combination with MCDA was successful in selecting and sizing the optimum GI treatment trains for the study area simultaneously. As there are no systematic methods available in the current practice to perform these tasks simultaneously (expert judgement and simulation models are used currently for the selection and sizing of GI treatment trains), it is evident that the proposed methodology can provide assistance for engineers and planners in optimizing GI treatment trains for industrial areas.

A similar TOPSIS analysis was also performed for the near optimal sizing combinations of treatment train configurations with three treatment measures. The results from this analysis showed that when considering three treatment measures, a treatment train configuration of vegetated swale, bioretention and retention pond also provide the required benefits for the study area with a lower cost. Even though the results were demonstrated using treatment trains with two and three treatment measures in this study, the methodology can be adopted to identify the optimal treatment trains with any number of treatment measures.

As any MCDA method that incorporates subjective data, the TOPSIS method also include uncertainties in its application (Stewart, 2005, Boran et al., 2009, Awasthi et al., 2011). As the only subjective data used in this method are the weights provided by experts, a sensitivity analysis was conducted to assess the impact of the weights and the effects of change of the weights on the final rank order. Based on the sensitivity analysis performed for the treatment trains with two treatment measures with variable weighting schemes, performance measures of sediment removal and nutrient removal showed the least sensitivity to the change of rank order, whereas all other performance measures showed moderate levels of sensitivity for the final rank order. Moreover, some of the treatment trains also showed high sensitivity to the change of the weights compared to other treatment trains considered in the analysis and had an impact on the final rank order. The results of the sensitivity analysis provided the opportunity to identify the performance measures which should be carefully assessed during the performance measure evaluation process and weight elicitation process, which can have an impact on the final rank order. This assessment showed the level of uncertainty that can occur during the expert consultation due to the subjectivity.

6.2.4 Air Quality Improvement Modelling of GI, Scenario Analysis and Identification of Optimum GI Practices

Degradation of air quality is one of the major environmental problems in industrial areas (Bamniya et al., 2012). Even though many countries in the world have already identified the importance of GI practices in mitigating the air pollution, there are yet limited studies and limited knowledge available in the Australian context related the benefits of GI practices for air quality improvement (Jayasooriya et al, 2017). The scenario analysis conducted in this research by considering several GI scenarios consists of trees, green roofs and green walls showed that they can provide a wide range of air quality improvement benefits in Australian context especially for industrial areas. The i-Tree Eco model used in this study to quantify the air quality improvement benefits of different GI scenarios is not yet widely applied in Australia. The reason for this can be explained as the lack of understanding about the model concepts and the data requirements within Australia. Another important fact related to the limited applicability of the model is the limitation of data sets to validate the results obtained from the model (Saunders et al., 2011, Jayasooriya et al., 2017). Hence, this study also aimed on providing data sets for the validation of models in the future applications of i-Tree Eco within Australia. The current model validation is done by comparing them with various international case study areas. The comparison of the results obtained from i-Tree Eco for the case study area with other international case studies showed that, i-Tree Eco can be successfully applied in Australia to assess the air quality improvement benefits of GI practices. The results obtained in this study will strengthen the applications of i-Tree Eco in Australia and as well as provide more information on validating the model outcomes.

Among the deferent GI scenarios modelled using i-Tree Eco, the trees provided the highest air quality improvement benefit for the study area followed by green roofs and green walls. Different scenarios were assessed using performance measures of TBL criteria to identify the optimum GI scenarios for the study area. Even though green roofs had high costs for implementation, operation and maintenance, they also had high annual energy savings benefits. The energy savings can further lead to improve the air quality by reducing the emissions. Thus, green roofs were also identified as a potential GI for industrial areas where energy consumption is particularly high, as a GI practice that provides more local benefits. Moreover, when analysing the percentage uptake of individual criteria pollutants by each GI scenario, the green roofs showed a high percentage uptake of particulate matter (PM10) compared to other pollutants. This also shows that green roofs can be a potential GI for industrial areas such as the Brooklyn Industrial precinct which has air quality problems associated with PM10. In summary, the analysis conducted using i-Tree Eco to identify the optimum GI scenarios for the case study area has contributed to provide information on applications of GI practices for air quality improvement and developing polices related to these practices in Australian industrial areas when developing them into Eco Industrial Parks (EIP).

6.3 Limitations of the Study

While the present study has provided several contributions in identifying methodologies to optimize GI practices for industrial areas, it should be also noted that there are few limitations present in the research scope and the methodology. It is important to have a clear idea about the limitations of the research during the application of the methodologies proposed as it will provide more transparency in interpreting the final results. Some of the limitations of the scope and methods which are used in this study are explained as follows.

1. Even though this research investigated the methodologies of identifying optimum GI practices for industrial areas, the main scope was only limited to two objectives which are the optimization of GI practices for stormwater management and air quality improvement. However, there are many other environmental issues in industrial areas that GI practices can provide benefits such as Urban Heat Island effect, Green House Gas emissions etc. These environmental issues were not considered during the optimization process and no assessment has been performed to optimize GI practices based on these objectives.
2. In the process of obtaining the optimal sizing combinations for treatment trains, the research has only focussed on optimizing based on the surface area of the treatment measures. However, several other parameters may influence the performance of GI treatment measures such as storage properties of the treatment measures (e.g. extended detention depth, permanent pool volume, exfiltration rates), filter media properties and the properties of the plant species used. The impact on these parameters on the final results was not addressed during the optimization process.
3. When selecting the objectives for the assessment with performance measures, technical aspects (e.g. system reliability, problems associated with implementation) of the treatment measures were not taken into consideration even though it can be an influential objective in GI treatment train optimization.
4. When selecting the expert panel for the Delphi survey, the experts were selected based on their expertise on the areas on various disciplines as industry, government and research. It did not include the perspectives of public such as industry land owners who can also influence the GI optimization in industrial areas.
5. The sensitivity analysis performed for the TOPSIS method only considered changing weights of a single performance measure at a time while keeping the weights of all the other performance measures constant. The study did not

assess the model sensitivity while weights of all the performance measures are changed at the same time.

6. The optimization of GI practices to improve the air quality was conducted by using plant species which can be used in the Australian context. However, the results of the study are highly dependent on the types of plant species used. There can be different plant species that can provide different air quality improvement benefits and this study did not address the impacts of the plant species on identifying optimum GI for air quality improvement.

6.4 Recommendations for Future Research

Even though the ecosystem services of GI practices are widely acknowledged in the literature, there are limited studies conducted on optimizing these practices based on their benefits for specific land use areas (De Sousa, 2003, Weber et al., 2006, La Rosa and Privitera, 2013). This study has made an attempt to identify optimum GI practices for an industrial area based on their performances with the involvement of multi-disciplinary stakeholders. As discussed in the previous section, there are few limitations present in this study. Future studies in this area should further focus on identifying methodologies to address these specific limitations presented. Moreover, one of the major issues in conducting this research was the limited data availability, especially for assessing the ecosystem services of GI practices. Based on these factors, recommendations for the future research in this area are provided as follows.

1. As previously discussed, there are several other benefits of GI practices for industrial areas such as Urban Heat Island reduction and reducing Green House Gas emissions. In future studies, these benefits could be also added to the MVDA process as performance measures. However, there is yet limited knowledge available on quantifying these benefits for different types GI

practices. Therefore, more research should be conducted in identifying methodologies to quantify these benefits of GI practices to strengthen the optimization process.

2. Even though a high degree of consensus has been achieved through the four rounded Delphi survey in this study, conducting a post Delphi focus group discussion can be recommended to further verify the results obtained from the Delphi study.

3. During the Delphi survey process, the experts have proposed several important social performance measures for the GI selection for industrial areas for stormwater management such as industry/ businesses behaviour in accepting GI, public safety and risk assessment. However, due to the limited data availability in evaluating these performance measures, they were not included in the MCDA analysis. Thus, future studies can be focused on identifying ways to quantify these social performance measures of GI practices for industrial areas. Investigating on the quantification of these social performance measures can provide more information for the GI optimization process.

4. The study has assessed the suitability of the i-Tree Eco software in the Australian context. Even though i-Tree Eco software has introduced in Australia in 2012, there are very limited studies conducted in Australia using this software. The i-Tree Eco software integrates a database of air quality and climate data in Australia; however is limited for certain regions in Australia. This can be one of the reasons the model has not yet been used extensively. Hence, future studies could be conducted to update i-Tree Eco with more comprehensive data for other regions of Australia to assess the air quality improvement benefits of GI practices in the Australian context.

5. Finally, this study focused on identifying the optimal GI practices to mitigate stormwater and air pollution in industrial areas separately. In the future, studies can be conducted to introduce methodologies that can assess the combined benefits of GI and identify optimal practices that provide both the benefits together for a particular area.

In summary, the research presented in this thesis has contributed to the knowledge by 1) introducing an innovative methodology that strengthens the current optimisation process of GI treatment trains and 2) improving the current understanding of air quality improvement and modelling aspects related to GI for industrial areas. Even though various complex techniques such as mathematical optimization and MCDA were used in this process, the major focus of this research was given to develop a methodology which involves simplified application of these techniques in order to introduce them in real world decision making. Thus, in a practical point of view, this research has attempted and successfully identified the flaws of current GI optimisation procedure and proposed an innovative methodology that improves decision making of GI.

References

2D STUDIO. 2015. *Fairview Environmental Park – Montgomery, AL* [Online]. Available: http://2dstudiollc.com/projects/genetta-park-stream-restoration/ [Accessed 28th February 2016].

ABI AAD, M., SUIDAN, M. & SHUSTER, W. 2010. Modeling Techniques of Best Management Practices: Rain Barrels and Rain Gardens Using EPA SWMM-5. *Journal of Hydrologic Engineering,* 15**,** 434-443.

ABILY, M., DULUC, C., FAES, J. & GOURBESVILLE, P. 2013. Performance assessment of modelling tools for high resolution runoff simulation over an industrial site. *Journal of Hydroinformatics,* 15**,** 1296-1311.

AGUAYO, M. 2010. *Development of a Database and Website for Low Impact Development Rapid Assessment (LIDRA) tool version 2.0* Master of Science Drexel University

AHIABLAME, L. M., ENGEL, B. A. & CHAUBEY, I. 2012. Effectiveness of low impact development practices: literature review and suggestions for future research. *Water, Air, & Soil Pollution,* 223**,** 4253-4273.

AHMED, F., GULLIVER, J. S. & NIEBER, J. L. Estimating swale performance in volume reduction. World Environmental and Water Resources Congress 2015, 2015. 255-260.

AKBARI, H., POMERANTZ, M. & TAHA, H. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar energy,* 70**,** 295-310.

AKIMOTO, H. 2003. Global air quality and pollution. *Science,* 302**,** 1716-1719.

AL BAKRI, D., RAHMAN, S. & BOWLING, L. 2008. Sources and management of urban stormwater pollution in rural catchments, Australia. *Journal of Hydrology,* 356**,** 299-311.

ALEXANDROV, A. V., PULLICINO, P. M., MESLIN, E. M. & NORRIS, J. W. 1996. Agreement on disease-specific criteria for do-not-resuscitate orders in acute stroke. *Stroke,* 27**,** 232-237.

ALLEN, W. L. 2012. Environmental Reviews and Case Studies: Advancing Green Infrastructure at All Scales: From Landscape to Site. *Environmental Practice,* 14**,** 17-25.

AL-RASHDAN, D., AL-KLOUB, B., DEAN, A. & AL-SHEMMERI, T. 1999. Environmental impact assessment and ranking the environmental projects in Jordan. *European Journal of Operational Research,* 118**,** 30-45.

ALSHUWAIKHAT, H. M. 2005. Strategic environmental assessment can help solve environmental impact assessment failures in developing countries. *Environmental impact assessment review,* 25**,** 307-317.

AMATI, M., BRACK, C., GHOSH, S., KACHENKO, A., MCMANUS, P., SALDARIAGGA, N., SHRESTHA, K., WANG, M. & YUNG, S.-H. 2013. Understanding the carbon and pollution mitigation potential of Sydney's urban forest.

AMERICAN RIVERS. 2010. *What is Green Infrastructure?* [Online]. Washington. Available: http://www.americanrivers.org/initiatives/pollution/green-infrastructure/what-is-green-infrastructure/ [Accessed 17th October 2015].

ANANDA, J. & HERATH, G. 2009. A critical review of multi-criteria decision making methods with special reference to forest management and planning. *Ecological economics,* 68**,** 2535-2548.

ANDERSSON, E., BARTHEL, S., BORGSTRÖM, S., COLDING, J., ELMQVIST, T., FOLKE, C. & GREN, Å. 2014. Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services. Ambio, 43, 445-453.

ANZECC, A. 2000. Australian and New Zealand guidelines for fresh and marine water quality. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra, 1-103.

APPERL, B., PULIDO-VELAZQUEZ, M., ANDREU, J. & KARJALAINEN, T. 2015. Contribution of the multi-attribute value theory to conflict resolution in groundwater management–application to the Mancha Oriental groundwater system, Spain. *Hydrology and Earth System Sciences,* 19**,** 1325-1337.

ASCOUGH, J., MAIER, H., RAVALICO, J. & STRUDLEY, M. 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecological modelling,* 219**,** 383-399.

ASLA. 2015. *Green Infrastructure* [Online]. Americal Society of Landscape Architechts. Available: https://www.asla.org/greeninfrastructure.aspx [Accessed 23rd November 2015].

ASPECTS STUDIOS. 2013. *Victorian Desalination Project Green Roof* [Online]. Available: http://aspect.net.au/?p=181 [Accessed 29th December 2015].

ÅSTEBØL, S. O., HVITVED-JACOBSEN, T. & SIMONSEN, Ø. 2004. Sustainable stormwater management at Fornebu—from an airport to an industrial and residential area of the city of Oslo, Norway. *Science of the total environment,* 334**,** 239-249.

ATCHISON, D. & SEVERSON 2004. “RECARGA User’s Manual, Version 2.3”. University of Wisconsin – Madison ,Civil & Environmental Engineering Department ,Water Resources Group.

ATCHISON, D., POTTER, K. W. & SEVERSON, L. 2006. *Design guidelines for stormwater bioretention facilities,* Water Resources Institute.

ATKINSON, G., DOICK, K., BURNINGHAM, K. & FRANCE, C. 2014. Brownfield regeneration to greenspace: Delivery of project objectives for social and environmental gain. *Urban Forestry & Urban Greening,* 13**,** 586-594.

AWASTHI, A., CHAUHAN, S. S. & GOYAL, S. K. 2011. A multi-criteria decision making approach for location planning for urban distribution centers under uncertainty. Mathematical and Computer Modelling, 53, 98-109.

BAAS, L. W. & BOONS, F. A. 2004. An industrial ecology project in practice: exploring the boundaries of decision-making levels in regional industrial systems. *Journal of Cleaner Production,* 12**,** 1073-1085.

BAKER, J., LOVELL, K. & HARRIS, N. 2006. How expert are the experts? An exploration of the concept of ‘expert’within Delphi panel techniques. *Nurse researcher,* 14**,** 59-70.

BALASUBRAMANIAM, A., BOYLE, A. R. & VOULVOULIS, N. 2007. Improving petroleum contaminated land remediation decision-making through the MCA weighting process. *Chemosphere*, 66**,** 791-798.
BALDOCCHI, D. D., HICKS, B. B. & CAMARA, P. 1987. A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. *Atmospheric Environment (1967),* 21**,** 91-101.
BAMNIYA, B., KAPOOR, C., JAIN, S. & KAPOOR, K. 2012. Impact assessment of air pollution in industrial areas of Rajasmand and Udaipur Districts. *Journal of Environmental Science, Computer Science and Engineering & Technology,* 1**,** 411-417.
BARBOSA, A., FERNANDES, J. & DAVID, L. 2012. Key issues for sustainable urban stormwater management. *Water research,* 46**,** 6787-6798.
BARCO, J., WONG, K. M. & STENSTROM, M. K. 2008. Automatic calibration of the US EPA SWMM model for a large urban catchment. Journal of Hydraulic Engineering, 134, 466-474.

BARNES, J. L. 1987. An international study of curricular organizers for the study of technology.
BARÓ, F., CHAPARRO, L., GÓMEZ-BAGGETHUN, E., LANGEMEYER, J., NOWAK, D. J. & TERRADAS, J. 2014. Contribution of ecosystem services to air quality and climate change mitigation policies: The case of urban forests in Barcelona, Spain. *Ambio,* 43**,** 466-479.
BARRETT, M. E., WALSH, P. M., JR, J. F. M. & CHARBENEAU, R. J. 1998. Performance of vegetative controls for treating highway runoff. *Journal of environmental engineering,* 124**,** 1121-1128.
BARRETT, P., J 2001. LIFE–CYCLE COSTING. *BETTER PRACTICE GUIDE.* Australian National Audit Office.
BASTIEN, N., ARTHUR, S., WALLIS, S. & SCHOLZ, M. 2009. The best management of SuDS treatment trains: a holistic approach. *Water science and technology: a journal of the International Association on Water Pollution Research,* 61**,** 263-272.
BATTIATA, J., COLLINS, K., HIRSCHMAN, D. & HOFFMANN, G. 2010. The runoff reduction method. Journal of Contemporary Water Research & Education, 146, 11-21.
BECCALI, M., CELLURA, M. & ARDENTE, D. 1998. Decision making in energy planning: the ELECTRE multicriteria analysis approach compared to a fuzzy-sets methodology. *Energy Conversion and Management,* 39**,** 1869-1881.
BECCALI, M., CELLURA, M. & MISTRETTA, M. 2003. Decision-making in energy planning. Application of the Electre method at regional level for the diffusion of renewable energy technology. *Renewable Energy,* 28**,** 2063-2087.
BECKETT, K. P., FREER-SMITH, P. & TAYLOR, G. 1998. Urban woodlands: their role in reducing the effects of particulate pollution. *Environmental pollution,* 99**,** 347-360.
BEEZHOLD, M. T. & BAKER, D. W. 2006. Rain to Recreation: Making the Case for a Stormwater Capital Recovery Fee. *Proceedings of the Water Environment Federation,* 2006**,** 3814-3825.

BEHR, C. & MONTALTO, F. Risk Analysis Application for Assessing the Cost-Effectiveness of Low Impact Development for CSO Control Using LIDRA. Low Impact Development for Urban Ecosystem and Habitat Protection, 2008. ASCE, 1-10.

BEHZADIAN, M., KAZEMZADEH, R. B., ALBADVI, A. & AGHDASI, M. 2010. PROMETHEE: A comprehensive literature review on methodologies and applications. *European journal of Operational research,* 200**,** 198-215.

BEHZADIAN, M., OTAGHSARA, S. K., YAZDANI, M. & IGNATIUS, J. 2012. A state-of the-art survey of TOPSIS applications. *Expert Systems with Applications,* 39**,** 13051-13069.

BELTON, V. & STEWART, T. 2002. *Multiple criteria decision analysis: an integrated approach*, Springer Science & Business Media.

BENEDICT, M. A. & MCMAHON, E. T. 2006. Green infrastructure. *Linking landscapes and communities, Washington-Covelo-London*.

BENEDICT, M. A. & MCMAHON, E. T. 2012. *Green infrastructure: linking landscapes and communities*, Island Press.

BHADURI, B. L. 1998. A geographic information system-based model of the long-term impact of land use change on nonpoint-source pollution at a watershed scale.

BHADURI, B., MINNER, M., TATALOVICH, S. & HARBOR, J. 2001. Long-term hydrologic impact of urbanization: a tale of two models. *Journal of Water Resources Planning and Management,* 127**,** 13-19.

BIRDIR, K. & PEARSON, T. E. 2000. Research chefs' competencies: A Delphi approach. *International Journal of Contemporary Hospitality Management,* 12**,** 205-209.

BOBYLEV, N. 2009. *Decision support for natural disasters and intentional threats to water security*, Springer Science & Business Media.

BOOTH, D. B. & JACKSON, C. R. 1997. URBANIZATION OF AQUATIC SYSTEMS: DEGRADATION THRESHOLDS, STORMWATER DETECTION, AND THE LIMITS OF MITIGATION1. *JAWRA Journal of the American Water Resources Association,* 33**,** 1077-1090.

BOOTH, D. B., HARTLEY, D. & JACKSON, R. 2002. FOREST COVER, IMPERVIOUS-SURFACE AREA, AND THE MITIGATION OF STORMWATER IMPACTS1. *JAWRA Journal of the American Water Resources Association,* 38**,** 835-845.

BORAN, F. E., GENÇ, S., KURT, M. & AKAY, D. 2009. A multi-criteria intuitionistic fuzzy group decision making for supplier selection with TOPSIS method. Expert Systems with Applications, 36, 11363-11368.

BORK, D. R. & FRANKLIN, J. 2010. Revitalizing Urbanized Watersheds through Smart Growth: The Fairfax Boulevard Case Study.

BOTTERO, M., COMINO, E. & RIGGIO, V. 2011. Application of the analytic hierarchy process and the analytic network process for the assessment of different wastewater treatment systems. *Environmental Modelling & Software,* 26**,** 1211-1224.

BOYD, J. & BANZHAF, S. 2007. What are ecosystem services? The need for standardized environmental accounting units. *Ecological Economics,* 63**,** 616-626.

BRADEN, J. B. & JOHNSTON, D. M. 2004. Downstream economic benefits from storm-water management. *Journal of Water Resources Planning and Management,* 130**,** 498-505.

BRAGA, J. & STARMER, C. 2005. Preference anomalies, preference elicitation and the discovered preference hypothesis. *Environmental and Resource Economics,* 32**,** 55-89.

BRAND, U. 2012. Green economy–the next oxymoron? No lessons learned from failures of implementing sustainable development. *GAIA-Ecological Perspectives for Science and Society,* 21**,** 28-32.

BRANS, J. P., MACHARIS, C., KUNSCH, P. L., CHEVALIER, A. & SCHWANINGER, M. 1998. Combining multicriteria decision aid and system dynamics for the control of socio-economic processes. An iterative real-time procedure. *European Journal of Operational Research,* 109**,** 428-441.

BRANS, J., P, MARESCHAL, B. & VINCKE, P. 1984. PROMETHEE a new family of outranking methods in multi criteria analysis. *Operational Research'84***,** 408-421.

BRANS, J.-P. & MARESCHAL, B. 2005. PROMETHEE methods. *Multiple criteria decision analysis: state of the art surveys.* Springer.

BRANS, J.-P. & VINCKE, P. 1985. Note—A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making). *Management science,* 31**,** 647-656.

BRANS, J.-P., VINCKE, P. & MARESCHAL, B. 1986. How to select and how to rank projects: The PROMETHEE method. *European journal of operational research,* 24**,** 228-238.

BREEN, P. F. 1999. Assembling the Stormwater Treatment Train, Lecture Notes, Shortcourse on Planning and Design of Stormwater Management Measures. Cooperative Centre for Catchment Hydrology and Department of Civil Engineering: Monash University.

BREUSTE, J., ARTMANN, M., LI, J. & XIE, M. 2015. Special issue on green infrastructure for urban sustainability. Journal of Urban Planning and Development, 141, A2015001.

BRIMBANK CITY COUNCIL STREET TREE POLICY. 2010. *Brimbank City Council* [Online]. Available: http://www.brimbank.vic.gov.au/COUNCIL/Council_Policies_Strategies_and_Plans/Council_Policies/Street_Tree_Policy [Accessed 20th June 2015].

BROWN, R., SKAGGS, R. & HUNT III, W. 2013. Calibration and validation of DRAINMOD to model bioretention hydrology. *Journal of Hydrology*.

BROWNE, D. & BROOKES, K. 2014. Living Brooklyn Integrated Water Cycle Management Strategy. E2 Design Lab, Melbourne.

BROWNING, P., GONG, M., HU, T., MARX, C. & NATAKE, T. 2014. Valuing Nature in Business. *A Case Study of Chemical Manufacturing and Forest Products Industries.* Nicholas school of environment.

BUCHANAN, J. T. & DAELLENBACH, H. G. 1987. A comparative evaluation of interactive solution methods for multiple objective decision models. *European Journal of Operational Research,* 29**,** 353-359.

BUCK, A. J., GROSS, M., HAKIM, S. & WEINBLATT, J. 1993. Using the Delphi process to analyze social policy implementation: A post hoc case from vocational rehabilitation. *Policy Sciences,* 26**,** 271-288.

CARTER, T. & FOWLER, L. 2008. Establishing green roof infrastructure through environmental policy instruments. *Environmental management,* 42**,** 151-164.

CENTER FOR NEIGHBORHOOD TECHNOLOGY. 2009. *National Green Values Calculator Methodology* [Online]. Available: http://greenvalues.cnt.org/national/downloads/methodology.pdf [Accessed 12th Jan 2014].

CHAKRAVARTI, A., VASANTA, B., KRISHNAN, A. & DUBASH, R. 1998. Modified Delphi methodology for technology forecasting case study of electronics and information technology in India. *Technological Forecasting and Social Change,* 58**,** 155-165.

CHAN, K. M., SATTERFIELD, T. & GOLDSTEIN, J. 2012. Rethinking ecosystem services to better address and navigate cultural values. *Ecological economics,* 74**,** 8-18.

CHANG, W.-L., LO, Y.-P. & HONG, Y.-T. A heuristic model of network-based group decision making for E-Services. Information Technology: New Generations, 2009. ITNG'09. Sixth International Conference on, 2009. IEEE, 326-331.

CHEN, L. & PU, P. Survey of Preference Elicitation Methods. Ecole Politechnique Federale de Lausanne (EPFL), IC/2004/67, 2004.

CHEN, L., WANG, Y., LI, P., JI, Y., KONG, S., LI, Z. & BAI, Z. 2012. A land use regression model incorporating data on industrial point source pollution. *Journal of Environmental Sciences,* 24**,** 1251-1258.

CHEN, S.-J., HWANG, C.-L. & HWANG, F. P. 1992. Fuzzy multiple attribute decision making(methods and applications). *Lecture Notes in Economics and Mathematical Systems*.

CHEN, Y. & WHALLEY, A. 2012. Green infrastructure: The effects of urban rail transit on air quality. *American Economic Journal: Economic Policy***,** 58-97.

CHEN, Y., HIPEL, K. W., KILGOUR, D. M. & ZHU, Y. 2009. A strategic classification support system for brownfield redevelopment. *Environmental Modelling & Software,* 24**,** 647-654.

CHIEW, F. H. S. & MCMAHON, T. A. 1997. Modelling Daily Runoff and Pollutant Load from Urban Catchments. *Water (AWWA Journal)* 24:16-17.

CHIU, A. S. & YONG, G. 2004. On the industrial ecology potential in Asian developing countries. *Journal of Cleaner Production,* 12**,** 1037-1045.

CITY OF KINGSTON 2005. Coastal Catchments Initiative Industry Stormwater Project

CITY OF MELBOURNE WSUD GUIDELINES 2005. Applying the Model WSUD Guidelines. *An Initiative of the Inner Melbourne Action Plan.* Melbourne Water.

CITY OF MILWAUKEE. 2014. *Welcome to the 30th Street Industrial Corridor* [Online]. Available: http://city.milwaukee.gov/Projects/30thStreetIndustrialCorridor.htm#.VvIl4eJ95D8 [Accessed 23rd March 2016].

CITY OF PORTLAND 2010. Portland's Green Infrastructure. *Quantifying the Health, Energy and Commiunity Liveability Benefits.* Environmnetal Services City of Portland: City of Portland Bureau of Environmental Sevices.

CLARK, C., ADRIAENS, P. & TALBOT, F. B. 2008. Green roof valuation: a probabilistic economic analysis of environmental benefits. *Environmental science & technology,* 42**,** 2155-2161.

CLEMENTS, J., ST JULIANA, A. & DAVIS, P. 2013. The Green Edge: How Commercial Property Investment in Green Infrastructure Creates Value. *Natural Resources Defense Council*.

CNT. 2010. The Value of Green Infrastrcuture. *A Guide to Recognizing Its Economic, Environmental and Social Benefits* [Online].

COHEN, A. J., ANDERSON, H. R., OSTRO, B., PANDEY, K. D., KRZYZANOWSKI, M., KÜNZLI, N., GUTSCHMIDT, K., POPE III, C. A., ROMIEU, I. & SAMET, J. M. 2004. Urban air pollution. *Comparative quantification of health risks,* 2**,** 1353-1433.

COOK, H. 2014. Brooklyn dust pollution worsening, Says EPA. The Age.

CORDER, G. D., GOLEV, A., FYFE, J. & KING, S. 2014. The status of industrial ecology in Australia: Barriers and enablers. *Resources,* 3**,** 340-361.

CÔTÉ, R. P. & COHEN-ROSENTHAL, E. 1998. Designing eco-industrial parks: a synthesis of some experiences. *Journal of cleaner production,* 6**,** 181-188.

COTTAM, H., ROE, M. & CHALLACOMBE, J. 2004. Outsourcing of trucking activities by relief organisations. *Journal of Humanitarian Assistance,* 1.

CURRIE, B. A. & BASS, B. 2008. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosystems,* 11**,** 409-422.

DAILY, G. 1997. *Nature's services: societal dependence on natural ecosystems*, Island Press.

DALKEY, N. & HELMER, O. 1963. An experimental application of the Delphi method to the use of experts. *Management science,* 9**,** 458-467.

DAVIS, A. P. 2005. Green engineering principles promote low-impact development. *Environmental science & technology,* 39**,** 338A-344A.

DAVIS, A. P., HUNT, W. F., TRAVER, R. G. & CLAR, M. 2009. Bioretention technology: Overview of current practice and future needs. *Journal of Environmental Engineering,* 135**,** 109-117.

DAVIS, T. S. Brownfields: A comprehensive guide to redeveloping contaminated property. 2002. American Bar Association.

DAWES, J. G. 2008. Do data characteristics change according to the number of scale points used? An experiment using 5 point, 7 point and 10 point scales. *International journal of market research,* 51.

DAY, J. & BOBEVA, M. 2005. A generic toolkit for the successful management of Delphi studies. *The Electronic Journal of Business Research Methodology,* 3**,** 103-116.

DE BELLIS, Y., SANTOS, A., TOSICS, I., DAVIES, C., HANSEN, R., RALL, E., PAULEIT, S. & LAFORTEZZA, R. 2015. Green infrastructure planning and implementation.

DE SOUSA, C. A. 2003. Turning brownfields into green space in the City of Toronto. *Landscape and urban planning,* 62**,** 181-198.

DE SOUSA, C. A. 2003. Turning brownfields into green space in the City of Toronto. Landscape and urban planning, 62, 181-198.

DE SOUSA, C. A. 2006. Unearthing the benefits of brownfield to green space projects: An examination of project use and quality of life impacts. *Local Environment,* 11**,** 577-600.

DE VET, E., BRUG, J., DE NOOIJER, J., DIJKSTRA, A. & DE VRIES, N. K. 2005. Determinants of forward stage transitions: a Delphi study. *Health Education Research,* 20**,** 195-205.

DEGRÉMONT 2012. Victorian Desalination Project (VDP). *Delivering a safe and reliable desalination water supply to Victoria.* Melbourne.

DELETIC, A. & FLETCHER, T. D. 2006. Performance of grass filters used for stormwater treatment—a field and modelling study. *Journal of Hydrology,* 317**,** 261-275.

DELETIC, A. & FLETCHER, T. Modelling performance of stormwater grass swales-application of simple and complex models. WSUD 2004: Cities as Catchments; International Conference on Water Sensitive Urban Design, Proceedings of the, 2004. Engineers Australia, 713.

DEP 2006. WSUD Engineering Guidelines. Tasmania: Derwent Estuary Program.

DEPARTMENT OF THE ENVIRONMENT AND HERITAGE 2001. State of the Air. *Commiuinity Summary 1991-2001.*

DEPARTMENT OF TREASURY AND FINANCE 2014. Victorian Guide to Regulation. *Toolkit 2: Cost-benefit analysis.*

DEUTSCH, B., WHITLOW, H., SULLIVAN, M. & SAVINEAU, A. Re-Greening Washington, DC: A green roof vision based on environmental benefits for air quality and storm water management. Proc. of 3rd North American Green Roof Conference: Greening rooftops for sustainable communities, Washington, DC, 2005. 4-6.

DIAPER, C. & MITCHELL, G. 2006. Urban volume and quality (UVQ). *Urban Water Resources Toolbox: Integrating Groundwater into Urban Water Management. L. Wolf, B. Morris and S. Burn (eds). London, IWA*.

DIETZ, M. 2007. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution,* 186**,** 351-363.

DINEP, C. & SCHWAB, K. 2010. *Sustainable site design: criteria, process, and case studies for integrating site and region in landscape design*, John Wiley & Sons.

DIXON, T. 2014. LIVING BROOKLYN. *A Path to Health & Prosperity at Brooklyn Industrial Estate through Integrated Water Management*

DNR 2012. EPA Assessment Funding Final Report. *30th Street Industrial Corridor.* City of Milwaukee.

DNR. 2014. *Milwaukee's 30th Street Industrial Corridor project* [Online]. Available: http://dnr.wi.gov/topic/Brownfields/Corridor.html [Accessed 23rd March 2016].

DOICK, K., SELLERS, G., CASTAN-BROTO, V. & SILVERTHORNE, T. 2009. Understanding success in the context of brownfield greening projects: The requirement for outcome evaluation in urban greenspace success assessment. *Urban Forestry & Urban Greening,* 8**,** 163-178.

DOMINICI, F., PENG, R. D., BELL, M. L., PHAM, L., MCDERMOTT, A., ZEGER, S. L. & SAMET, J. M. 2006. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. Jama, 295, 1127-1134.

DORSEY, J. W. 2003. Brownfields and greenfields: the intersection of sustainable development and environmental stewardship. *Environmental Practice,* 5**,** 69-76.

DOTTO, C., DELETIC, A. & FLETCHER, T. Analysis of uncertainty in flow and water quality from a stormwater model. 11th International Conference on Urban Drainage, 2008.

DOTTO, C., KLEIDORFER, M., DELETIC, A., RAUCH, W., MCCARTHY, D. & FLETCHER, T. 2011. Performance and sensitivity analysis of stormwater models using a Bayesian approach and long-term high resolution data. *Environmental Modelling & Software,* 26**,** 1225-1239.

DOUMPOS, M. & ZOPOUNIDIS, C. 2002. *Multicriteria decision aid classification methods*, Springer Science & Business Media.

DUKE, L. D. & BESWICK, P. G. 1997. Industry compliance with storm water pollution prevention regulations: the case of transportation industry facilities in california and the los angeles region1. Wiley Online Library.

DUKE, L. D. & CHUNG, Y. J. 1995. Industrial storm water pollution prevention: Effectiveness and limitations of source controls in the transportation industry. *Waste Management,* 15**,** 543-558.

DUNCAN, E. A., NICOL, M. M. & AGER, A. 2004. Factors that constitute a good cognitive behavioural treatment manual: A Delphi study. *Behavioural and Cognitive Psychotherapy,* 32**,** 199-213.

DUNEC, J. L. 2012. Banking on green: A look at how green infrastructure can save municipalities money and provide economic benefits community-wide. JSTOR.

DUNN, A. D. 2010. Siting green infrastructure: legal and policy solutions to alleviate urban poverty and promote healthy communities. *BC Envtl. Aff. L. Rev.,* 37**,** 41.

ECO. 2010. *Air Pollution Caused by Industries* [Online]. Available: http://www.ecocoalition.org/air-pollution-caused-by-industries.

EEA. 2014. Industrial air pollution has high economic cost. Available: http://www.eea.europa.eu/media/newsreleases/industrial-air-pollution-has-high.

EHLER, C. & DOUVERE, F. 2009. Marine spatial planning, a step-by-step approach towards ecosystem-based management.

EL-ABBASY, M. S., ZAYED, T., AHMED, M., ALZRAIEE, H. & ABOUHAMAD, M. 2013. Contractor selection model for highway projects using integrated simulation and analytic network process. *Journal of Construction Engineering and Management,* 139**,** 755-767.

ELLIOTT, A. & TROWSDALE, S. 2007. A review of models for low impact urban stormwater drainage. *Environmental modelling & software,* 22**,** 394-405.

ELLIS, J. B. 2013. Sustainable surface water management and green infrastructure in UK urban catchment planning. *Journal of Environmental Planning and Management,* 56**,** 24-41.

ELLIS, J. B., DEUTSCH, J.-C., MOUCHEL, J.-M., SCHOLES, L. & REVITT, M. 2004. Multicriteria decision approaches to support sustainable drainage options for the treatment of highway and urban runoff. *Science of the total Environment,* 334**,** 251-260.

ELY, M. & PITMAN, S. 2012. Green Infrastructure: Life support for human habitats. *Prepared for the Green Infrastructure Project, Botanic Gardens of Adelaide*.

EMANUEL, R. 2012. City of Chicago Stormwater Management Ordinance Manual. *City*.

ENGEL, B. A., CHOI, J.-Y., HARBOR, J. & PANDEY, S. 2003. Web-based DSS for hydrologic impact evaluation of small watershed land use changes. *Computers and Electronics in Agriculture,* 39**,** 241-249.

ENGLISH, J. M. & KERNAN, G. L. 1976. The prediction of air travel and aircraft technology to the year 2000 using the Delphi method. *Transportation research,* 10**,** 1-8.

ENVIRONMENTAL JUSTICE AUSTRALIA 2014. Clearing the air. *Why Australia urgently needs effective national air pollution laws.*

EPA VICTORIA 2012. ENVIRONMENT PROTECTION (FEES) REGULATIONS. *REGULATORY IMPACT STATEMENT.* EPA Victoria, 200 Victoria Street, Carlton.

EPA VICTORIA 2013. EPA Victoria submission to senete inquiry into the impact on health of air quality in Australia. EPA Victoria, 200 Victoria Street, Carlton.

EPA VICTORIA. 2015. Monitoring the environment [Online]. Available: http://www.epa.vic.gov.au/our-work/monitoring-the-environment/air-quality-bulletins/hourly-air-quality-data-table [Accessed 25th August 2015].

EPA VICTORIA. 2016. Brooklyn Industrial Precinct [Online]. Available: http://www.epa.vic.gov.au/our-work/current-issues/odour-and-air-quality/brooklyn-industrial-precinct [Accessed 01 st July 2016].

ESTÉVEZ, R. A. & GELCICH, S. 2015. Participative multi-criteria decision analysis in marine management and conservation: Research progress and the challenge of integrating value judgments and uncertainty. *Marine Policy,* 61**,** 1-7.

EUROPEAN COMMISSION 2012. The Multifunctionality of Green Infrastructure *Science for Environment Policy.*

EUROPEAN COMMISSION. 2013. Building a Green Infrastructure for Europe. Available: http://ec.europa.eu/environment/nature/ecosystems/docs/green_infrastructure_broc.pdf.

EVANS, B., CROOKES, L. & COAFFEE, J. 2012. Obesity/Fatness and the City: Critical Urban Geographies. *Geography Compass,* 6**,** 100-110.
EWATER. 2013. *MUSIC by eWater user manual* [Online].
FAIZ, A. 1993. Automotive emissions in developing countries-relative implications for global warming, acidification and urban air quality. *Transportation Research Part A: Policy and Practice,* 27**,** 167-186.
FAN, C. K. & CHENG, C. L. 2006. A study to identify the training needs of life insurance sales representatives in Taiwan using the Delphi approach. *International Journal of Training and Development,* 10**,** 212-226.
FENWICK, R. & CENTER, N. E. E. F. 2012. Sustainable Water Management on Brownfields Sites.
FERRETTI, V. 2011. A multicriteria spatial decision support system development for siting a landfill in the province of Torino (Italy). *Journal of Multi‐Criteria Decision Analysis,* 18**,** 231-252.
FIGUEIRA, J. R., GRECO, S., ROY, B. & SŁOWIŃSKI, R. 2010. ELECTRE methods: main features and recent developments. *Handbook of multicriteria analysis.* Springer.
FIGUEIRA, J., GRECO, S. & EHRGOTT, M. 2005. *Multiple criteria decision analysis: state of the art surveys,* Springer Science & Business Media.
FIREHOCK, K. 2010. A Short history of the term green infrastructure and selected literature. *Green Infrastructure Center*.
FISHBURN, P. C. 1967. Methods of estimating additive utilities. *Management science,* 13**,** 435-453.
FLEMING, N. 2012. Green shoots from brownfield roots. *ECOS,* 2012.
FLETCHER, T. & TAYLOR, A. 2007. Estimating life cycle costs of stormwater treatment measures. *Australian Journal of Water Resources,* 11**,** 79.
FLETCHER, T. D., PELJO, L., FIELDING, J., WONG, T. H. & WEBER, T. The performance of vegetated swales for urban stormwater pollution control. Global Solutions for Urban Drainage, Proc. of the Ninth Int. Conf. on Urban Drainage, Sept 8-13 2002, Portland, OR, 2002.
FOSTER, J., LOWE, A. & WINKELMAN, S. 2011. The value of green infrastructure for urban climate adaptation. *Center for Clean Air Policy, February*.
FRANCEY, M. 2005. WSUD Engineering Procedures: Stormwater. *Melbourne Water, Melbourne*.
GADDIS, E. J. B., VOINOV, A., SEPPELT, R. & RIZZO, D. M. 2014. Spatial optimization of best management practices to attain water quality targets. *Water resources management,* 28**,** 1485-1499.
GAFFIELD, S. J., GOO, R. L., RICHARDS, L. A. & JACKSON, R. J. 2003. Public Health Effects of Inadequately Managed Stormwater Runoff. *American Journal of Public Health,* 93**,** 1527-1533.
GAFFIELD, S., MONTGOMERY, R., SEVERSON, L. & SIGMARSSON, S. Infiltration Modeling to Evaluate Tradeoffs in Planning for Future Development. Proceedings of the 11th International Conference on Urban Drainage, 2008.

GALLEGO-AYALA, J. 2012. Selecting irrigation water pricing alternatives using a multi-methodological approach. *Mathematical and Computer Modelling,* 55**,** 861-883.

GANISEN, S., MOHAMMAD, I. S., NESAN, L. J., MOHAMMED, A. H. & KANNIYAPAN, G. 2015. The Identification Of Design For Maintainability Imperatives To Achieve Cost Effective Building Maintenance: A Delphi Study. *Jurnal Teknologi,* 77.

GHASEMIAN, M., POURSAFA, P., AMIN, M. M., ZIARATI, M., GHODDOUSI, H., MOMENI, S. A. & REZAEI, A. H. 2012. Environmental impact assessment of the industrial estate development plan with the geographical information system and matrix methods. *Journal of environmental and public health,* 2012.

GIANNAROU, L. & ZERVAS, E. 2014. Using Delphi technique to build consensus in practice. *Int. Journal of Business Science and Applied Management*, 9.

GIBBS, D. & DEUTZ, P. 2005. Implementing industrial ecology? Planning for eco-industrial parks in the USA. Geoforum, 36, 452-464.

GIBBS, D. & DEUTZ, P. 2007. Reflections on implementing industrial ecology through eco-industrial park development. Journal of Cleaner Production, 15, 1683-1695.

GILL, S. E., HANDLEY, J. F., ENNOS, A. R. & PAULEIT, S. 2007. Adapting cities for climate change: the role of the green infrastructure. *Built environment*, 33**,** 115-133.

GIVAN. 2010. *Building Natural Value for Sustainable Economic Development:*

GLEDHILL, H. 2011. *Victorian Desalination Project Coastal Park* [Online]. ASPECT Studios: Landscape Architechture, Urban Design. Available: http://www.depi.vic.gov.au/__data/assets/pdf_file/0005/190481/ASPECT-Studios-presentation-May-2011.pdf.

GOLDING, S. 2006. Zinc and Copper Concentrations in an Industrial Area Creek during Storm Events. *Watershed Ecology Section.* Watershed Ecology Section: Washington State Department of Ecology.

GOLEV, A. 2012. Application of industrial ecology principles for enhanced resource efficiency in heavy industrial areas.

GOMES, L. F. A. M., RANGEL, L. A. D., JUNIOR, L. & DA ROCHA, M. 2011. Treatment of uncertainty through the interval smart/swing weighting method: a case study. *Pesquisa Operacional,* 31**,** 467-485.

GÓMEZ-BAGGETHUN, E., DE GROOT, R., LOMAS, P. L. & MONTES, C. 2010. The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. *Ecological economics,* 69**,** 1209-1218.

GORDON, T. & PEASE, A. 2006. RT Delphi: an efficient,"round-less" almost real time Delphi method. *Technological Forecasting and Social Change,* 73**,** 321-333.

GOVINDAN, K., GRIGORE, M. C. & KANNAN, D. Ranking of third party logistics provider using fuzzy Electre II. Computers and Industrial Engineering (CIE), 2010 40th International Conference on, 2010. IEEE, 1-5.

GRADY, C. A., HE, X. & PEETA, S. 2015. Integrating social network analysis with analytic network process for international development project selection. *Expert Systems with Applications,* 42**,** 5128-5138.

GREEN INFRASTRUCTURE VALUATION NETWORK 2010. Building Natural Value for Sustainable Economic Development: The Green Infrastructure Valuation Toolkit User Guide. *Green Infrastructure Valuation Network*.

GREEN ROOFS AUSTRALASIA. 2013. *Victorian Desalination Project* [Online]. Fytogreen. Available: https://greenroofsaustralasia.com.au/projects/victorian-desalination-project [Accessed 15th November 2015].

GREENBERG, M. & LEWIS, M. J. 2000. Brownfields redevelopment, preferences and public involvement: a case study of an ethnically mixed neighbourhood. *Urban Studies,* 37**,** 2501-2514.

GREGORY, R., FAILING, L., HARSTONE, M., LONG, G., MCDANIELS, T. & OHLSON, D. 2012. *Structured decision making: a practical guide to environmental management choices*, John Wiley & Sons.

GREGORY, R., LICHTENSTEIN, S. & SLOVIC, P. 1993. Valuing environmental resources: a constructive approach. *Journal of Risk and Uncertainty,* 7**,** 177-197.

GRIFFEN, L. M. 2005. Reducing pollutants in industrial stormwater runoff: Improved water quality protection using prioritized facility regulation.

GRIFFIN, R. D. 2016. Principles of air quality management, CRC Press.

GROWING GREEN GUIDE 2014. A guide to green roofs,walls and facades. *In Melbourne and Victoria, Australia.* Department of Environment and Primary Industries.

GROWING GREEN GUIDE. 2012. *Victorian Desalination Project Green Roof* [Online]. Available: http://www.growinggreenguide.org/victorian-case-studies/victorian-desalination-project-green-roof/ [Accessed 5th October 2015].

GRYNING, S.-E. & CHAUMERLIAC, N. 2013. *Air pollution modeling and its application XII*, Springer Science & Business Media.

GUARNIERI, P. & ALMEIDA, A. T. D. 2015. Framework to manage suppliers for strategic alliances with a multicriteria method. *Production,* 25**,** 713-724.

GUITOUNI, A. & MARTEL, J.-M. 1998. Tentative guidelines to help choosing an appropriate MCDA method. *European Journal of Operational Research,* 109**,** 501-521.

GULLIVER, J., ERICKSON, A. & WEISS, P. 2011. Stormwater treatment: Assessment and maintenance.

GUMUS, A. T. 2009. Evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS methodology. *Expert Systems with Applications,* 36**,** 4067-4074.

GUO, Q. & CORREA, C. 2013. The Impacts of Green Infrastructure on Flood Level Reduction for the Raritan River: Modeling Assessment. *World Environmental and Water Resources Congress 2013.*

HAJKOWICZ, S. & COLLINS, K. 2007. A review of multiple criteria analysis for water resource planning and management. *Water resources management,* 21**,** 1553-1566.

HAJKOWICZ, S., YOUNG, M. & MACDONALD, D. H. 2000. Supporting decisions: understanding natural resource management assessment techniques. Policy and Economic Research Unit, CSIRO Land and Water, Adelaide, Australia.

HAMMOND, J. S., KEENEY, R. L. & RAIFFA, H. 1999. *Smart choices: A practical guide to making better decisions*, Harvard Business Press.

HAND, K., L & REBERT, A. 2006. Brownfields to Green Spaces. Available: http://www.dcnr.state.pa.us/cs/groups/public/documents/document/d_001041.pdf.

HANSEN, R. & PAULEIT, S. 2014. From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. *Ambio,* 43**,** 516-529.

HARMAN, N. L., BRUCE, I. A., CALLERY, P., TIERNEY, S., SHARIF, M. O., O'BRIEN, K. & WILLIAMSON, P. R. 2013. MOMENT–Management of Otitis Media with Effusion in Cleft Palate: protocol for a systematic review of the literature and identification of a core outcome set using a Delphi survey. *Trials,* 14**,** 70.

HARPER, H. H. 1998. Stormwater chemistry and water quality.

HASSON, F., KEENEY, S. & MCKENNA, H. 2000. Research guidelines for the Delphi survey technique. *Journal of advanced nursing,* 32**,** 1008-1015.

HATT, B. E., DELETIC, A. & FLETCHER, T. D. 2006. Integrated treatment and recycling of stormwater: a review of Australian practice. *Journal of Environmental Management,* 79**,** 102-113.

HAUGHEY, D. 2010. Delphi technique a step-by-step guide. *Project Smart. com. uk***,** 1-2.

HAWKINS, N. & PRICKETT, G. 2012. The Nature Conservancy•DOW COLLABORATION. *2012 PROGRESS REPORT.* The Dow Chemical Company: The Nature Conservancy.

HAWKINS, N. & PRICKETT, G. 2014. 2014 Annual Progress Report. *The Nature Conservancy & Dow.*

HEIKO, A. 2012. Consensus measurement in Delphi studies: review and implications for future quality assurance. *Technological forecasting and social change,* 79**,** 1525-1536.

HEISLER, G. M. 1986. Effects of individual trees on the solar radiation climate of small buildings. *Urban Ecology,* 9**,** 337-359.

HERATH, G. & PRATO, T. 2006. *Using multi-criteria decision analysis in natural resource management,* Ashgate Publishing, Ltd.

HERWIJNEN, M. V. 2007. Multiple− attribute value theory (MAVT).

HINKIN, T. R. 1995. A review of scale development practices in the study of organizations. *Journal of management,* 21**,** 967-988.

HIRABAYASHI, S. & ENDRENY, T. A. 2015. Surface and upper weather pre-processor for i-Tree Eco and Hydro.

HIRABAYASHI, S. 2011. Urban Forest Effects-Dry Deposition (UFORE-D) Model Enhancements. Citeseer.

HIRABAYASHI, S., KROLL, C. N. & NOWAK, D. J. 2012. i-Tree Eco Dry Deposition Model Descriptions. Citeseer.

HOEHN, J. P., LUPI, F. & KAPLOWITZ, M. D. 2003. Untying a Lancastrian bundle: valuing ecosystems and ecosystem services for wetland mitigation. *Journal of Environmental Management,* 68**,** 263-272.

HOGAN, D. M. & WALBRIDGE, M. R. 2007. Best management practices for nutrient and sediment retention in urban stormwater runoff. *Journal of Environmental Quality,* 36**,** 386-395.

HOKKANEN, J., SALMINEN, P., ROSSI, E. & ETTALA, M. 1995. The choice of a solid waste management system using the ELECTRE II decision-aid method. *Waste management & research,* 13**,** 175-193.

HORNER, R. R. 1994. Fundamentals of urban runoff management: technical and institutional issues.

HOUDESHEL, C., POMEROY, C., HAIR, L. & GOO, R. 2009. Cost Estimating Tools for Low-Impact Development Best Management Practices. *World Environmental and Water Resources Congress 2009.*

HOWARD, A. F. 1991. A critical look at multiple criteria decision making techniques with reference to forestry applications. *Canadian Journal of Forest Research,* 21**,** 1649-1659.

HSU, C.-C. & SANDFORD, B. A. 2007. The Delphi technique: making sense of consensus. *Practical assessment, research & evaluation,* 12**,** 1-8.

HUANG, I. B., KEISLER, J. & LINKOV, I. 2011. Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. *Science of the total environment,* 409**,** 3578-3594.

HUBER, G. P. 1974. Multi-Attribute Utility Models: A Review of Field and Field-Like Studies. *Management Science,* 20**,** 1393-1402.

HUBER, W. & DICKINSON, R. 1988. Stormwater Management Model (SWMM) User's Manual, Version 4.0. *United States Environmental Protection Agency, Athens, Georgia*.

HUBER, W. & SINGH, V. 1995. EPA Storm Water Management Model-SWMM. *Computer models of watershed hydrology.***,** 783-808.

HUBER, W. C. 2001. New options for overland flow routing in SWMM. *Urban Drainage Modeling***,** 22-29.

HUBER, W. C., CANNON, L. & STOUDER, M. 2004. BMP modeling concepts and simulation.

HUBER, W. C., DICKINSON, R. E., BARNWELL JR, T. O. & BRANCH, A. 1988. *Storm water management model, version 4,* US Environmental Protection Agency, Environmental Research Laboratory.

HUNG, H.-L., ALTSCHULD, J. W. & LEE, Y.-F. 2008. Methodological and conceptual issues confronting a cross-country Delphi study of educational program evaluation. *Evaluation and Program Planning,* 31**,** 191-198.

HUNT, W., JARRETT, A., SMITH, J. & SHARKEY, L. 2006. Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. *Journal of Irrigation and Drainage Engineering,* 132**,** 600-608.

HWANG, C., L & YOON, K. 1981. *Muliple attributes decision making methods and applications and applications,* Berlin, Springer.

INAMDAR, P. M. 2014. *Selection and Evaluation of Potential Stormwater Harvesting Sites in Urban Areas.* Victoria University.

INSUA, D. R. 1990. Sensitivity analysis in multi-objective decision making. *Sensitivity Analysis in Multi-objective Decision Making.* Springer.

ISHIZAKA, A. & NEMERY, P. 2013a. *Multi-criteria decision analysis: methods and software*, John Wiley & Sons.

ISHIZAKA, A. & NEMERY, P. 2013b. Multi-attribute utility theory. *Multi-Criteria Decision Analysis: Methods and Software***,** 81-113.

ISLAM, D. M., DINWOODIE, J. & ROE, M. 2006. Promoting development through multimodal freight transport in Bangladesh. *Transport Reviews,* 26**,** 571-591.

I-TREE ECO AUSTRALIA 2012. Users Manual. ENSPEC: Arboriculture Australia.

I-TREE ECO USERS MANUAL. 2014. Available: https://www.itreetools.org/resources/manuals/Eco_Manual_v5.pdf [Accessed 30 January 2015].

JAFFE, M. 2011. Environmental Reviews & Case Studies: Reflections on Green Infrastructure Economics. *Environmental Practice,* 12**,** 357-365.

JAFFE, M. S., ZELLNER, M., MINOR, E., GONZALEZ-MELER, M., COTNER, L., MASSEY, D., AHMED, H., ELBERTS, M., SPRAGUE, H. & WISE, S. 2010. *Using green infrastructure to manage urban stormwater quality: a review of selected practices and state programs*, Illinois Environmental Protection Agency.

JAHANSHAHLOO, G. R., LOTFI, F. H. & IZADIKHAH, M. 2006. An algorithmic method to extend TOPSIS for decision-making problems with interval data. *Applied mathematics and computation,* 175**,** 1375-1384.

JÄNICKE, M. 2012. "Green growth": From a growing eco-industry to economic sustainability. *Energy Policy,* 48**,** 13-21.

JAYASOORIYA, V. & NG, A. 2013. Development of a framework for the valuation of Eco-System Services of Green Infrastructure.

JAYASOORIYA, V. M. & NG, A. W. M. 2014. Tools for Modeling of Stormwater Management and Economics of Green Infrastructure Practices: a Review. *Water, Air, & Soil Pollution,* 225**,** 1-20.

JAYASOORIYA, V., NG, A., MUTHUKUMARAN, S. & PERERA, B. 2017. Green infrastructure practices for improvement of urban air quality. Urban Forestry & Urban Greening, 21, 34-47.

JAYASOORIYA,V.M., NG, A.W.M.,MUTHUKUMARAN, S.,PERERA, B.J.C. 2016. Optimial Sizing of Green Infrastructure Treatment Trains for Stormwater Management. *Water Resources Management*, 1-14.

JEFFERY, A. L., IAN BENNUN, STUART MCLAREN, DAVID 2000. Delphi survey of opinion on interventions, service principles and service organisation for severe mental illness and substance misuse problems. *Journal of Mental Health,* 9**,** 371-384.

JIA, H., YAO, H., TANG, Y., SHAW, L. Y., ZHEN, J. X. & LU, Y. 2013. Development of a multi-criteria index ranking system for urban runoff best management practices (BMPs) selection. *Environmental monitoring and assessment,* 185**,** 7915-7933.

JOHNSTON, C. A. 1991. Sediment and nutrient retention by freshwater wetlands: effects on surface water quality. *Critical Reviews in Environmental Science and Technology,* 21**,** 491-565.
JOHNSTON, F., HANIGAN, I., HENDERSON, S., MORGAN, G. & BOWMAN, D. 2011. Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007. *Environmental research,* 111**,** 811-816.
JONES, R., N & OOI, D. 2014. Living Brooklyn: Baseline report on the economics of the urban water cycle in the Brooklyn Industrial Precinct. Victoria Institute of Strategic Economic Studies: Victoria University, Melbourne.
JURRIES, D. & RATLIFF, K. 2013. Industrial Stormwater Best Management Practices Manual. Citeseer.
JUWANA, I. 2012. *Development of a Water Sustainability Index for West Java, Indonesia.* Victoria University, Australia.
KAINI, P., ARTITA, K. & NICKLOW, J. 2012. Optimizing Structural Best Management Practices Using SWAT and Genetic Algorithm to Improve Water Quality Goals. *Water Resources Management,* 26**,** 1827-1845.
KAINI, P., ARTITA, K. & NICKLOW, J. Evaluating optimal detention pond locations at a watershed scale. World environmental and water resources congress, 2007.
KAMPA, M. & CASTANAS, E. 2008. Human health effects of air pollution. Environmental pollution, 151, 362-367.
KANGAS, J., KANGAS, A., LESKINEN, P. & PYKÄLÄINEN, J. 2001. MCDM methods in strategic planning of forestry on state-owned lands in Finland: applications and experiences. *Journal of Multi-Criteria Decision Analysis,* 10**,** 257-271.
KARHU, J. 2011. Green Infrastructure Implementation: Proceedings of the European Commission Conference, 19 November 2010. *Brussels: European Commission*.
KARJALAINEN, T., ROSSI, P., ALA-AHO, P., ESKELINEN, R., KLOVE, B., PULIDO-VELAZQUEZ, M. & YANG, H. 2013. A decision analysis framework for stakeholder involvement and learning in groundwater management. *Hydrology and Earth System Sciences,* 17**,** 1-13.
KAUFFMAN, G. J. 2011. Economic Value of Stormwater in Delaware.
KEELEY, M. 2011. The Green Area Ratio: an urban site sustainability metric. Journal of environmental planning and management, 54, 937-958.
KEENEY, R. L. & RAIFFA, H. 1976. *Decisions with multiple objectives: preferences and value trade-offs,* Cambridge university press.
KEENEY, S., HASSON, F. & MCKENNA, H. 2011. The Delphi Technique in Nursing and Health Research. 2011 Chichester. *UK Wiley-Blackwell*.
KELEMENIS, A. & ASKOUNIS, D. 2010. A new TOPSIS-based multi-criteria approach to personnel selection. *Expert Systems with Applications,* 37**,** 4999-5008.
KELLER, G. & WARRACK, B. 2003. Statistics for management and economics. Thomson, USA.

KENNEDY, J., HAAS, P. & EYRING, B. 2008. Measuring the Economic Impacts of Greening: The Center for Neighborhood Technology Green Values Calculator. *Growing Greener Cities: Urban Sustainability in the Twenty-First Century***,** 326-345.

KENNY, J. 2016. *Exploring elements for innovation in the Australian water sector.* Doctor of Philosophy, Queensland Univerisity of Technology.

KHADER, O. & MONTALTO, F. A. Development and calibration of a high resolution SWMM model for simulating the effects of LID retrofits on the outflow hydrograph of a dense urban watershed. Proceedings of the 2008 International Low Impact Development Conference, Organized by the American Society of Civil Engineers, 2008.

KIKER, G. A., BRIDGES, T. S., VARGHESE, A., SEAGER, T. P. & LINKOV, I. 2005. Application of multicriteria decision analysis in environmental decision making. *Integrated environmental assessment and management,* 1**,** 95-108.

KIM, S.-W., PARK, J.-S., KIM, D. & OH, J.-M. 2014. Runoff characteristics of non-point pollutants caused by different land uses and a spatial overlay analysis with spatial distribution of industrial cluster: a case study of the Lake Sihwa watershed. *Environmental earth sciences,* 71**,** 483-496.

KING COUNTRY 2013. Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9: SUSTAIN Model Pilot Study. Prepared by Curtis DeGasperi, Water and Land Resources Division. Seattle, Washington. *King County i July 2013*.

KIRNBAUER, M., BAETZ, B. & KENNEY, W. 2013. Estimating the stormwater attenuation benefits derived from planting four monoculture species of deciduous trees on vacant and underutilized urban land parcels. *Urban Forestry & Urban Greening*.

KOCH, B. J., FEBRIA, C. M., GEVREY, M., WAINGER, L. A. & PALMER, M. A. 2014. Nitrogen removal by stormwater management structures: A data synthesis. JAWRA Journal of the American Water Resources Association, 50, 1594-1607.

KODIKARA, P. N. 2008. *Multi-objective optimal operation of urban water supply systems.* Victoria University.

KODIKARA, P. N., PERERA, B. & KULARATHNA, M. 2010. Stakeholder preference elicitation and modelling in multi-criteria decision analysis–A case study on urban water supply. *European Journal of Operational Research,* 206**,** 209-220.

KOPPEROINEN, L., ITKONEN, P. & NIEMELÄ, J. 2014. Using expert knowledge in combining green infrastructure and ecosystem services in land use planning: an insight into a new place-based methodology. Landscape Ecology, 29, 1361-1375.

KOUSKY, C., OLMSTEAD, S. M., WALLS, M. A. & MACAULEY, M. 2013. Strategically placing green infrastructure: cost-effective land conservation in the floodplain. Environmental science & technology, 47, 3563-3570.

KROHLING, R. A. & CAMPANHARO, V. C. 2011. Fuzzy TOPSIS for group decision making: A case study for accidents with oil spill in the sea. *Expert Systems with Applications*, 38**,** 4190-4197.

KÜNZLI, N., KAISER, R., MEDINA, S., STUDNICKA, M., CHANEL, O., FILLIGER, P., HERRY, M., HORAK, F., PUYBONNIEUX-TEXIER, V. & QUÉNEL, P. 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment. *The Lancet*, 356**,** 795-801.

LA ROSA, D. & PRIVITERA, R. 2013. Characterization of non-urbanized areas for land-use planning of agricultural and green infrastructure in urban contexts. Landscape and Urban Planning, 109, 94-106.

LAI, F., ZHEN, J., RIVERSON, J., ALVI, K. & SHOEMAKER, L. 2009. Multiple watershed scales approach for placement of best management practices in SUSTAIN. *Proc. 2009 ASCE Environ. and Water Resour. Cong.*

LAI, F.-H., DAI, T., ZHEN, J., RIVERSON, J., ALVI, K. & SHOEMAKER, L. 2007. SUSTAIN-AN EPA BMP process and placement tool for urban watersheds. *Proceedings of the Water Environment Federation,* 2007**,** 946-968.

LAI, F.-H., SHOEMAKER, L., ALVI, K., RIVERSON, J. & ZHEN, J. Current Capabilities and Planned Enhancements of SUSTAIN. World Environmental and Water Resources Congress 2010@ sChallenges of Change, 2010. ASCE, 3271-3280.

LAI, F.-H., ZHEN, J., RIVERSON, J. & SHOEMAKER, L. SUSTAIN–An Evaluation and Cost-Optimization Tool for Placement of BMPs. Proceedings of the ASCE EWRI World Water and Environmental Congress, 2006. 21-25.

LAI, Y.-J., LIU, T.-Y. & HWANG, C.-L. 1994. Topsis for MODM. *European Journal of Operational Research,* 76**,** 486-500.

LAMBERT, A. & BOONS, F. A. 2002. Eco-industrial parks: stimulating sustainable development in mixed industrial parks. *Technovation,* 22**,** 471-484.

LANTIN, A. & BARRETT, M. Design and pollutant reduction of vegetated strips and swales. Impacts of Global Climate Change, 2005. ASCE, 1-11.

LE BLANC, D. Special issue on green economy and sustainable development. Natural Resources Forum, 2011. Wiley Online Library, 151-154.

LEADWEST. 2016. Brooklyn Evolution [Online]. Available: http://www.leadwest.com.au/Melbournes-West/Liveability-and-Sustainability-in-Melbournes-west/Brooklyn-Evolution [Accessed 10th August 2016].

LEE, J. G., SELVAKUMAR, A., ALVI, K., RIVERSON, J., ZHEN, J. X., SHOEMAKER, L. & LAI, F.-H. 2012a. A watershed-scale design optimization model for stormwater best management practices. *Environmental Modelling & Software,* 37**,** 6-18.

LEHMANN, H., KUHN, J. & LEHNER, F. The future of mobile technology: findings from a European Delphi study. System Sciences, 2004. Proceedings of the 37th Annual Hawaii International Conference on, 2004. IEEE, 10 pp.

LENNON, M. & SCOTT, M. 2014. Delivering ecosystems services via spatial planning: reviewing the possibilities and implications of a green infrastructure approach. *Town Planning Review,* 85**,** 563-587.

LEWIS, G. 2008. Brown to Green: Sustainable Redevelopment of America's Brownfield Sites. Northeast - Midwest Institute

LI, P., QIAN, H., WU, J. & CHEN, J. 2013. Sensitivity analysis of TOPSIS method in water quality assessment: I. Sensitivity to the parameter weights. *Environmental monitoring and assessment,* 185**,** 2453-2461.

LI, P., WU, J. & QIAN, H. 2012. Groundwater quality assessment based on rough sets attribute reduction and TOPSIS method in a semi-arid area, China. *Environmental Monitoring and Assessment,* 184**,** 4841-4854.

LINKOV, I., VARGHESE, A., JAMIL, S., SEAGER, T. P., KIKER, G. & BRIDGES, T. 2004. Multi-criteria decision analysis: a framework for structuring remedial decisions at contaminated sites. *Comparative risk assessment and environmental decision making,* 38**,** 15-54.

LINSTONE, H. A. & TUROFF, M. 1975. *The Delphi method: Techniques and applications*, Addison-Wesley Reading, MA.

LIPTAN, T. & BROWN, C. K. 1996. A cost comparison of conventional and water quality-based stormwater designs. *City of Portland. Bureau of Environmental Services. Portland, OR*.

LIU, Y., AHIABLAME, L. M., BRALTS, V. F. & ENGEL, B. A. 2015. Enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff. Journal of environmental management, 147, 12-23.

LLOYD, A. J. 2003. Threats to the estimation of benefit: are preference elicitation methods accurate? *Health economics,* 12**,** 393-402.

LLOYD, S. D., WONG, T. H. & CHESTERFIELD, C. J. 2002. Water sensitive urban design: a stormwater management perspective.

LONG, H. 2014. Land consolidation: An indispensable way of spatial restructuring in rural China. Journal of Geographical Sciences, 24, 211-225.

LOPERFIDO, J. V., NOE, G. B., JARNAGIN, S. T. & HOGAN, D. M. 2014. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. Journal of Hydrology, 519, 2584-2595.

LOUGHLIN, K. G. & MOORE, L. F. 1979. Using Delphi to achieve congruent objectives and activities in a pediatrics department. *Academic Medicine,* 54**,** 101-6.

LOURES, L. 2015. Post-industrial landscapes as drivers for urban redevelopment: Public versus expert perspectives towards the benefits and barriers of the reuse of post-industrial sites in urban areas. Habitat International, 45, 72-81.

LOVETT, G. M. 1994. Atmospheric deposition of nutrients and pollutants in North America: an ecological perspective. *Ecological Applications***,** 630-650.

LOWE, E. 2005. An eco-industrial park definition for the circular economy. *Retrieved October*, 24**,** 2011.

LOWE, E. A., MORAN, S. R., HOLMES, D. B. & MARTIN, S. A. 1996. *Fieldbook for the Development of Eco-Industrial Parks: Final Report*, Indigo Development.

LUCAS, W. 2005. Developing an Effective Urban Runoff Management Approach. *Impacts of Global Climate Change.*

LUCAS, W. C. Delaware Urban Runoff Management Model: Hydrology and Hydraulics. World Water & Environmental Resources Congress 2003, 2004. ASCE, 1-10.

LUNSFORD, D. A. & FUSSELL, B. C. 1993. Marketing business services in central Europe: the challenge: a report of expert opinion. *Journal of Services Marketing,* 7**,** 13-21.

MACCARTHY, B. L. & ATTHIRAWONG, W. 2003. Factors affecting location decisions in international operations-a Delphi study. *International Journal of Operations & Production Management,* 23**,** 794-818.

MACMULLAN, E. & REICH, S. 2007. The economics of low-impact development: A literature review. *ECONorthwest, Eugene, OR*.

MAES, J., BARBOSA, A., BARANZELLI, C., ZULIAN, G., E SILVA, F. B., VANDECASTEELE, I., HIEDERER, R., LIQUETE, C., PARACCHINI, M. L. & MUBAREKA, S. 2015. More green infrastructure is required to maintain ecosystem services under current trends in land-use change in Europe. Landscape ecology, 30, 517-534.

MARESCHAL, B. 1986. Stochastic multicriteria decision making and uncertainty. *European Journal of Operational Research,* 26**,** 58-64.

MARINGANTI, C., CHAUBEY, I. & POPP, J. 2009. Development of a multiobjective optimization tool for the selection and placement of best management practices for nonpoint source pollution control. *Water Resources Research,* 45.

MARSALEK, J. & CHOCAT, B. 2002. International report: stormwater management. *Water science and technology,* 46**,** 1-17.

MARTIN, C., RUPERD, Y. & LEGRET, M. 2007. Urban stormwater drainage management: The development of a multicriteria decision aid approach for best management practices. *European journal of operational research,* 181**,** 338-349.

MARTIN, N. A. 2011. A 100% tree inventory using i-Tree Eco protocol: A case study at Auburn University, Alabama.

MARTTUNEN, M. & HÄMÄLÄINEN, R. P. 1995. Decision analysis interviews in environmental impact assessment. *European journal of operational research,* 87**,** 551-563.

MATHEY, J., RÖßLER, S., BANSE, J., LEHMANN, I. & BRÄUER, A. 2015. Brownfields as an element of green infrastructure for implementing ecosystem services into urban areas. Journal of Urban Planning and Development, 141, A4015001.

MCCOMAS, S. 2003. *Lake and pond management guidebook*, CRC Press.

MCCUBBIN, D. R. & DELUCCHI, M. A. 1999. The health costs of motor-vehicle-related air pollution. *Journal of Transport Economics and Policy***,** 253-286.

MCGARITY, A. E. 2006. Screening optimization model for watershed-based management of urban runoff nonpoint pollution. *US Environmental Protection*

Agency, Office of Wetlands, Oceans, and Watersheds, final report for project AW-83238401-0.
MCGARITY, A. E. 2011. Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds. *Journal of Water Resources Planning and Management,* 138**,** 111-124.
MCGARITY, A. E. Watershed-based Optimal Stormwater Management: Part 1-Application of StormWISE to Little Crum Creek in Suburban Philadelphia. Proceedings of the World Environmental & Water Resources Congress, 2010.
MCKENNA, H. P. 1994. The Delphi technique: a worthwhile research approach for nursing? *Journal of advanced nursing,* 19**,** 1221-1225.
MCLLVAINE, R. 2014. Green Infrastructure for Industrial Water & Wastewater. *Industrial water & wastes digest.*
MCMAHON, S., CUSACK, T. & O'DONOGHUE, G. 2014. Barriers and facilitators to providing undergraduate physiotherapy clinical education in the primary care setting: a three-round Delphi study. *Physiotherapy,* 100**,** 14-19.
MCPHERSON, E. G. & SIMPSON, J. R. 1999. Carbon Dioxide Reduction Through Urban Forestry. *Gen. Tech. Rep. PSW-171, USDA For. Serv., Pacific Southwest Research Station, Albany, CA*.
MCPHERSON, E. G. 1994. Energy-saving potential of trees in Chicago. *Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor [Newtown Square], PA: US Department of Agriculture, Forest Service, Northeastern Research Station***,** 95-113.
MCPHERSON, E. G., NOWAK, D. J. & ROWNTREE, R. A. 1994. Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project.
MCPHERSON, G., SIMPSON, J. R., PEPER, P. J., MACO, S. E. & XIAO, Q. 2005. Municipal forest benefits and costs in five US cities. *Journal of Forestry,* 103**,** 411-416.
MELBOURNE WATER 2005. *WSUD Engineering Procedures: Stormwater: Stormwater*, CSIRO PUBLISHING.
MELBOURNE WATER 2013a. Annual Water Quality Factsheet. Long Term Water Quality Monitoring Sites 2013. Melbourne Water.
MELBOURNE WATER 2013b. Water Sensitive Urban Design Guidelines. *South Eastern Councils.*
MENDES JR, P. 2011. Analytic Hierarchy Process. *Demand Driven Supply Chain.* Springer.
MENDOZA, G. & MARTINS, H. 2006. Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. *Forest ecology and management,* 230**,** 1-22.
MILANI, A., SHANIAN, A., MADOLIAT, R. & NEMES, J. 2005. The effect of normalization norms in multiple attribute decision making models: a case study in gear material selection. *Structural and multidisciplinary optimization,* 29**,** 312-318.
MILLEN, J., JARRETT, A. & FAIRCLOTH, J. 1997. Experimental evaluation of sedimentation basin performance for alternative dewatering systems. Transactions of the ASAE, 40, 1087-1095.

MILLENNIUM ECOSYSTEM ASSESSMENT 2005. *Ecosystems and human well-being: desertification synthesis*, World Resources Institute.
MILLER, G. 2001. The development of indicators for sustainable tourism: results of a Delphi survey of tourism researchers. *Tourism management,* 22**,** 351-362.
MITCHELL, L. 2002. Resource Manual on Infrastructure for Eco-Industrial Development. *University of Southern California, Center for Economic Development, School of Policy, Planning, and Development, CA, USA*.
MITCHELL, M. P. 1998. Nursing education planning: a Delphi study. *Journal of Nursing Education,* 37**,** 305-307.
MITSCH, W. J., BERNAL, B. & HERNANDEZ, M. E. 2015. Ecosystem services of wetlands. *International Journal of Biodiversity Science, Ecosystem Services & Management,* 11**,** 1-4.
MMSD 2013. Green Infrastructure Benefits and Costs. *MMSD Regional Green Infrastructure Plan.* The Milwaukee Metropolitan Sewerage District.
MMSD 2015. 30th Street Industrial Corridor Greenway Corridor Report. *MMSD Contract M03062P01/M03062P02.* Milwaukee Metropolitan Sewerage District

MOLNAR, J. L. & KUBISZEWSKI, I. 2012. Managing natural wealth: Research and implementation of ecosystem services in the United States and Canada. *Ecosystem Services,* 2**,** 45-55.
MONTALTO, F. A., BEHR, C. T., YU, Z. & THURSTON, H. 2011. Accounting for uncertainty in determining green infrastructure cost-effectiveness. *Economic incentives for stormwater control***,** 246.
MONTALTO, F., BEHR, C., ALFREDO, K., WOLF, M., ARYE, M. & WALSH, M. 2007. Rapid assessment of the cost-effectiveness of low impact development for CSO control. *Landscape and urban planning,* 82**,** 117-131.
MONTASERI, M., AFSHAR, M. H. & BOZORG-HADDAD, O. 2015. Development of Simulation-Optimization Model (MUSIC-GA) for Urban Stormwater Management. *Water Resources Management,* 29**,** 4649-4665.
MONTGOMERY, R., GAFFIELD, S., SIGMARRSON, S., SEVERSON, L. & LEFERS, J. The challenges of mitigating hydrologic impacts of development: lessons learned in Dane County, Wisconsin. Innovations in Watershed Management under Land Use and Climate Change. Proceedings of the 2010 Watershed Management Conference, Madison, Wisconsin, USA, 23-27 August 2010., 2010. American Society of Civil Engineers (ASCE), 807-816.
MORAIS, D. C. & ALMEIDA, A. T. 2006. Water supply system decision making using multicriteria analysis. *Water Sa,* 32**,** 229-236.
MUNDA, G., NIJKAMP, P. & RIETVELD, P. 1994. Qualitative multicriteria evaluation for environmental management. *Ecological economics,* 10**,** 97-112.
MUSIC BY EWATER USER MANUAL. 2013. *eWater* [Online].
MUSTAJOKI, J., HÄMÄLÄINEN, R. P. & MARTTUNEN, M. 2004. Participatory multicriteria decision analysis with Web-HIPRE: a case of lake regulation policy. *Environmental Modelling & Software,* 19**,** 537-547.
NATURAL ECONOMY NORTHWEST. 2010. *Building natural value for sustainable economic development* [Online]. Available:

http://www.greeninfrastructurenw.co.uk/resources/Green_Infrastructure_Valuation_Toolkit_UserGuide.pdf [Accessed 18th Jan 2014].
NAUMANN, S., DAVIS, M., KAPHENGST, T., PIETERSE, M. & RAYMENT, M. 2011. Design, implementation and cost elements of Green Infrastructure projects. *Final report, European Commission, Brussels***,** 138.
NEPM. 2003. *National Environment Protection (Ambient Air Quality) Measure* [Online]. Australian Government. Available: https://www.comlaw.gov.au/Details/C2004H03935 [Accessed 30th March 2015].
NIJKAMP, P. 2000. Critical Success Factors for Sal Remediation Policy: A Meta-Analytic Comparison of Dutch Experiences.
NIJKAMP, P., RODENBURG, C. A. & WAGTENDONK, A. J. 2002. Success factors for sustainable urban brownfield development: A comparative case study approach to polluted sites. *Ecological Economics,* 40**,** 235-252.
NORTON, B. A., COUTTS, A. M., LIVESLEY, S. J., HARRIS, R. J., HUNTER, A. M. & WILLIAMS, N. S. 2015. Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and Urban Planning,* 134**,** 127-138.
NOVOTNY, V. 1995. *Non point Pollution and Urban Stormwater Management*, CRC Press.
NOWAK, D. J. & CRANE, D. E. 2000. The Urban Forest Effects (UFORE) Model: quantifying urban forest structure and functions.
NOWAK, D. J. 1994A. Air pollution removal by Chicago's urban forest. *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project***,** 63-81.
NOWAK, D. J. 1994B. Urban forest structure: the state of Chicago's urban forest. Chaper.
NOWAK, D. J., CRANE, D. E. & STEVENS, J. C. 2006. Air pollution removal by urban trees and shrubs in the United States. *Urban forestry & urban greening,* 4**,** 115-123.
NOWAK, D. J., CRANE, D. E., STEVENS, J. C. & HOEHN, R. E. 2005. The urban forest effects (UFORE) model: Field data collection manual. *USDA Forest Service, Northern Research Station*.
NOWAK, D. J., MCHALE, P. J., IBARRA, M., CRANE, D., STEVENS, J. C. & LULEY, C. J. 1998. Modeling the effects of urban vegetation on air pollution. *Air pollution modeling and its application XII.* Springer.
NOWAK, D. J., WALTON, J. T., STEVENS, J. C., CRANE, D. E. & HOEHN, R. E. 2008. Effect of plot and sample size on timing and precision of urban forest assessments. *Arboriculture and urban forestry,* 34**,** 386-390.
NOWAK, D., MCHALE, P., IBARRA, M., CRANE, D., STEVENS, J. & LULEY, C. 1997. Modeling the effects of urban vegetation on air pollution. 22nd NATO/CCMS International Technical Meeting on Air Pollution Modeling and its Application. *Clermont-Ferrand, France*.
O'BANNON PH, D., ERICH SCHMITZ, P. & M ASCE, K. S. 2008. Advanced Drainage Concepts Using Green Solutions for CSO Control-the KC Approach.

OBEID, N. 2005. *Modeling and analysis of phosphorus reduction by rain gardens and other BMPs in stormwater runoff from small urban developments.* Massachusetts Institute of Technology.

ODEFEY, J., DETWILER, S., ROUSSEAU, K., TRICE, A., BLACKWELL, R., O'HARA, K., BUCKLEY, M., SOUHLAS, T., BROWN, S. & RAVIPRAKASH, P. 2012. Banking on Green.

OKOLI, C. & PAWLOWSKI, S. D. 2004. The Delphi method as a research tool: an example, design considerations and applications. *Information & management,* 42**,** 15-29.

OLSON, D. L. 2004. Comparison of weights in TOPSIS models. *Mathematical and Computer Modelling,* 40**,** 721-727.

OLSON, D. L., MECHITOV, A. I. & MOSHKOVICH, H. M. 1998. Cognitive effort and learning features of decision aids: Review of experiments. *Journal of Decision Systems,* 7**,** 129-146.

OPRICOVIC, S. & TZENG, G.-H. 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research,* 156**,** 445-455.

OTTO, B., RANSEL, K., TODD, J., LOVAAS, D., STUTZMAN, H. & BAILEY, J. 2002. Paving our way to water shortages: How sprawl aggravates the effects of drought. *Paving our way to water shortages: how sprawl aggravates the effects of drought.* American Rivers.

OZDEMIROGLU, E., CORBELLI, D., GRIEVE, N., GIANFERRARA, E. & PHANG, Z. 2013. Green Infrastructure –Valuation Tools Assessment.

OZERNOY, V. 1997. Some Fundamental Problems in the Selection and Justification of Discrete Alternative MCDM Methods. *In:* CLÍMACO, J. (ed.) *Multicriteria Analysis.* Springer Berlin Heidelberg.

PALMSTROM, N. & WALKER, W. 1990. The P8 urban catchment model for evaluating nonpoint source controls at the local level. *Enhancing States' Lake Management Programs, US EPA*.

PAPADOPOULOS, A. & KARAGIANNIDIS, A. 2008. Application of the multi-criteria analysis method Electre III for the optimisation of decentralised energy systems. *Omega,* 36**,** 766-776.

PARNELL, G. S. & TRAINOR, T. E. 2.3. 1 Using the Swing Weight Matrix to Weight Multiple Objectives. INCOSE International Symposium, 2009. Wiley Online Library, 283-298.

PASUKEVICIUTE, I. & ROE, M. 2001. The politics of oil in Lithuania:: strategies after transition. *Energy policy,* 29**,** 383-397.

PAULL, E. 2008. The environmental and economic impacts of brownfields redevelopment. *Northeast Midwest*.

PERIS, J., GARCÍA-MELÓN, M., GÓMEZ-NAVARRO, T. & CALABUIG, C. 2013. Prioritizing Local Agenda 21 Programmes using Analytic Network Process: A Spanish Case Study. *Sustainable Development,* 21**,** 338-352.

PERSSON, J., SOMES, N. & WONG, T. 1999. Hydraulics efficiency of constructed wetlands and ponds. *Water science and technology,* 40**,** 291-300.

PIRDASHTI, M., GHADI, A., MOHAMMADI, M. & SHOJATALAB, G. 2009. Multi-criteria decision-making selection model with application to chemical engineering management decisions. *World Academy of Science, Engineering and Technology,* 49**,** 54-59.

PITT, R. & VOORHEES, J. 2002. SLAMM, the source loading and management model. *Wet-weather flow in the urban watershed: technology and management***,** 103-139.

PITT, R. & VOORHEES, J. 2004. WinSLAMM and low impact development. *Putting the LID on Stormwater Management, College Park, MD*.

PITT, R. & VOORHEES, J. Source loading and management model (SLAMM). Seminar Publication: National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels, 1995. 225-243.

PITT, R. 2006. Module 4: Stormwater Controls and WinSLAMM.

PLUMB, M. & SEGGOS, B. 2007. Sustainable Raindrops: Cleaning New York Harbor by Greening the Urban Landscape. Available: http://www.riverkeeper.org/wp-content/uploads/2009/06/Sustainable-Raindrops-Report-1-8-08.pdf.

POMEROL, J.-C. & BARBA-ROMERO, S. 2012. *Multicriterion decision in management: principles and practice*, Springer Science & Business Media.

POTTER, K. W. 2005. Stormwater infiltration and focused groundwater recharge in a rain garden: simulations for different world climates. *Sustainable water management solutions for large cities***,** 178.

POWELL, C. 2003. The Delphi technique: myths and realities. *Journal of advanced nursing,* 41**,** 376-382.

PÖYHÖNEN, M. & HÄMÄLÄINEN, R. P. 2001. On the convergence of multiattribute weighting methods. *European Journal of Operational Research,* 129**,** 569-585.

PRATO, T. 2003. Multiple-attribute evaluation of ecosystem management for the Missouri River system. *Ecological Economics,* 45**,** 297-309.

PULIPATI, S. B. & MATTINGLY, S. P. 2013. Establishing criteria and their weights for evaluating transportation funding alternatives using a Delphi survey. *Procedia-Social and Behavioral Sciences,* 104**,** 922-931.

RAGSDALE, M., WUETHRICH, B. & GRANJU, C. P. E. 2008. Knox County, Tennessee Stormwater Management Manual AMEC EARTH & ENVIRONMENTAL, INC: KNOX COUNTY, TENNESSEE DEPARTMENT OF ENGINEERING AND PUBLIC WORKS

RAJU, K. S. & PILLAI, C. 1999. Multicriterion decision making in river basin planning and development. *European Journal of operational research,* 112**,** 249-257.

RAJU, K. S. & VASAN, A. 2007. Multi attribute utility theory for irrigation system evaluation. *Water resources management,* 21**,** 717-728.

RASKIN, M. S. 1994. The Delphi study in field instruction revisited: Expert consensus on issues and research priorities. *Journal of Social Work Education,* 30**,** 75-89.

RAYENS, M. K. & HAHN, E. J. 2000. Building consensus using the policy Delphi method. *Policy, politics, & nursing practice,* 1**,** 308-315.

REYNOLDS, S., POMEROY, C., ROWNEY, A. & ROWNEY, C. 2012. Linking Stormwater BMP Systems Water Quality and Quantity Performance to Whole Life Cycle Cost to Improve BMP Selection and Design. *World Environmental and Water Resources Congress 2012*.

RIVER HEALTH DATA. 2014. *Melbourne Water* [Online]. Available: http://www.melbournewater.com.au/waterdata/riverhealthdata/werribee/Pages/Werribee-catchment.aspx [Accessed 25th June 2014].

ROE, M. & MELL, I. 2013. Negotiating value and priorities: evaluating the demands of green infrastructure development. *Journal of Environmental Planning and Management*, 56**,** 650-673.

ROE, M. & MELL, I. 2013. Negotiating value and priorities: evaluating the demands of green infrastructure development. Journal of Environmental Planning and Management, 56, 650-673.

ROGERS, M. R. & LOPEZ, E. C. 2002. Identifying critical cross-cultural school psychology competencies. *Journal of school psychology*, 40**,** 115-141.

ROME SENTINAL. 2015. *Rome Cable site gets $1.6M for cleanup* [Online]. Available: http://romesentinel.com/rome/rome-cable-site-gets-1-6m-for-cleanup/QBqoai!toXply7GkfQpS8xcVa2ynw/ [Accessed 25th January 2016].

ROSSMAN, L. A. 2010. *Storm water management model user's manual, version 5.0*, National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

ROWE, A. & BAKACS, M. 2012. An Introduction to Green Infrastructure Practices. Available: http://njaes.rutgers.edu/pubs/fs1197/intro-to-green-infrastructure.asp.

ROY, B. & BERTIER, P. 1973. La Méthode ELECTRE II(Une application au média-planning...).

ROY, B. & HUGONNARD, J.-C. 1982. Ranking of suburban line extension projects on the Paris metro system by a multicriteria method. *Transportation Research Part A: General*, 16**,** 301-312.

ROY, B. & SKALKA, J.-M. 1985. *ELECTRE IS: Aspects méthodologiques et guide d'utilisation*, LAMSADE, Unité associée au CNRS no 825, Université de Paris Dauphine.

ROY, B. 1968. Classement et choix en présence de points de vue multiples (la méthode ELECTRE), Rev. Française Automat., Informat. *Recherche Opérationnelle*, 8.

ROY, B. 1968. Classement et choix en présence de points de vue multiples. *Revue française d'automatique, d'informatique et de recherche opérationnelle. Recherche opérationnelle*, 2**,** 57-75.

ROY, B. 1978. ELECTRE III: Un algorithme de rangement fonde sur une representation floue des preferences en presence de criteres multiples. *Cahiers du Centre d'etudes de recherche operationnelle***,** 3-24.

ROY, B. 1996. *Multicriteria methodology for decision aiding*, Kluwer Academic Publishers, Dordrecht.

ROY-POIRIER, A., CHAMPAGNE, P. & FILION, Y. 2010. Review of bioretention system research and design: past, present, and future. Journal of Environmental Engineering, 136, 878-889.

RUNGE, M. C., CONVERSE, S. J. & LYONS, J. E. 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. *Biological Conservation,* 144**,** 1214-1223.

RUSSELL, C., DALE, V., LEE, J., JENSEN, M. H., KANE, M. & GREGORY, R. 2001. Experimenting with multi-attribute utility survey methods in a multi-dimensional valuation problem. *Ecological Economics,* 36**,** 87-108.

SAATY, T. 2004a. Fundamentals of the analytic network process — multiple networks with benefits, costs, opportunities and risks. *Journal of Systems Science and Systems Engineering,* 13**,** 348-379.

SAATY, T. L. & VARGAS, L. G. 2006. *Decision making with the analytic network process*, Springer.

SAATY, T. L. 1986. Axiomatic foundation of the analytic hierarchy process. *Management science,* 32**,** 841-855.

SAATY, T. L. 1988. *What is the analytic hierarchy process?*, Springer.

SAATY, T. L. 1990. How to make a decision: the analytic hierarchy process. *European journal of operational research,* 48**,** 9-26.

SAATY, T. L. 2001. Analytic network process. *Encyclopedia of Operations Research and Management Science.* Springer.

SAATY, T. L. 2004b. Fundamentals of the analytic network process—Dependence and feedback in decision-making with a single network. *Journal of Systems science and Systems engineering,* 13**,** 129-157.

SAATY, T. L. 2005. The analytic hierarchy and analytic network processes for the measurement of intangible criteria and for decision-making. *Multiple criteria decision analysis: state of the art surveys.* Springer.

SALGUEIRO-GONZÁLEZ, N., DE ALDA, M. L., MUNIATEGUI-LORENZO, S., PRADA-RODRÍGUEZ, D. & BARCELÓ, D. 2015. Analysis and occurrence of endocrine-disrupting chemicals in airborne particles. TrAC Trends in Analytical Chemistry, 66, 45-52.

SAN CRISTÓBAL, J. R. 2012. *Multi criteria analysis in the renewable energy industry*, Springer Science & Business Media.

SANON, S., HEIN, T., DOUVEN, W. & WINKLER, P. 2012. Quantifying ecosystem service trade-offs: The case of an urban floodplain in Vienna, Austria. *Journal of environmental management,* 111**,** 159-172.

SAUNDERS, S., DADE, E. & VAN NIEL, K. An Urban Forest Effects (UFORE) model study of the integrated effects of vegetation on local air pollution in the Western Suburbs of Perth, WA. 19th International Congress on Modelling and Simulation, 2011.

SCHILLING, J. & LOGAN, J. 2008. Greening the rust belt: A green infrastructure model for right sizing America's shrinking cities. *Journal of the American Planning Association,* 74**,** 451-466.

SCHMIDT, R. C. 1997. Managing Delphi surveys using nonparametric statistical techniques*. *decision Sciences,* 28**,** 763-774.

SCHMITT, T., BILLAH, M., COLLINS, J., SULLIVAN, M. & BUSIEK, B. 2010. EPAs Response to the Current Status of CSO Control Efforts Development of New Tools and Guidance. *Proceedings of the Water Environment Federation,* 2010**,** 1399-1405.

SCHRAMM, F. & MORAIS, D. C. 2012. Decision support model for selecting and evaluating suppliers in the construction industry. *Pesquisa Operacional,* 32**,** 643-662.

SCHUWIRTH, N., REICHERT, P. & LIENERT, J. 2012. Methodological aspects of multi-criteria decision analysis for policy support: A case study on pharmaceutical removal from hospital wastewater. *European journal of operational research,* 220**,** 472-483.

SCOTT, M., COLLIER, M., FOLEY, K. & LENNON, M. 2013. Delivering ecosystems services via spatial planning-reviewing the possibilities and implications of a green infrastructure approach. UCD University College of Dublin.

SCS, U. 1986. Urban Hydrology for Small Watersheds (Technical Release 55). *US Department of Agriculture*.

SEAGLE, E. D. & IVERSON, M. 2001. *Characteristics of the turfgrass industry in 2020: a Delphi study with implications for agricultural education programs.* Citeseer.

SEIBERT, P., BEYRICH, F., GRYNING, S.-E., JOFFRE, S., RASMUSSEN, A. & TERCIER, P. 2000. Review and intercomparison of operational methods for the determination of the mixing height. *Atmospheric environment,* 34**,** 1001-1027.

SHARMA, D. P., NAIR, P. C. & BALASUBRAMANIAN, R. 2003. Analytical search of problems and prospects of power sector through Delphi study: case study of Kerala State, India. *Energy policy,* 31**,** 1245-1255.

SHARMA, D., P. 2009. Industrial Dust, Air Pollution and related Occupational Diseases. *Nuisance to be controlled for improvement of general environment, safety and health standard:* [Online]. Available: https://saferenvironment.wordpress.com/2009/09/05/industrial-dust-air-pollution-and-related-occupational-diseases/.

SHARMA, S. & HENRIQUES, I. 2005. Stakeholder influences on sustainability practices in the Canadian forest products industry. *Strategic Management Journal,* 26**,** 159-180.

SHIH, H.-S., SHYUR, H.-J. & LEE, E. S. 2007. An extension of TOPSIS for group decision making. *Mathematical and Computer Modelling,* 45**,** 801-813.

SHOEMAKER, L., RIVERSON, J., ALVI, K., ZHEN, J. X., MURPHY, R. & WOOD, B. 2013. *Stormwater Management for TMDLs in an Arid Climate: A Case Study Application of SUSTAIN in Albuquerque, New Mexico* [Online]. Available: http://nepis.epa.gov/Adobe/PDF/P100GNCZ.pdf.

SIMPSON, R., WILLIAMS, G., PETROESCHEVSKY, A., BEST, T., MORGAN, G., DENISON, L., HINWOOD, A., NEVILLE, G. & NELLER, A. 2005. The short-term effects of air pollution on daily mortality in four Australian cities. *Australian and New Zealand Journal of Public Health,* 29**,** 205-212.

SKARDI, M. E., AFSHAR, A. & SOLIS, S. 2013. Simulation-optimization model for non-point source pollution management in watersheds: Application of cooperative game theory. *KSCE Journal of Civil Engineering,* 17**,** 1232-1240.

SKULMOSKI, G. J., HARTMAN, F. T. & KRAHN, J. 2007. The Delphi method for graduate research. *Journal of information technology education,* 6**,** 1.

SOARES, A. L., REGO, F. C., MCPHERSON, E., SIMPSON, J., PEPER, P. & XIAO, Q. 2011. Benefits and costs of street trees in Lisbon, Portugal. *Urban Forestry & Urban Greening,* 10**,** 69-78.

SPATARI, S., YU, Z. & MONTALTO, F. A. 2011. Life cycle implications of urban green infrastructure. *Environmental Pollution,* 159**,** 2174-2179.

STEELE, K., CARMEL, Y., CROSS, J. & WILCOX, C. 2009. Uses and misuses of multicriteria decision analysis (MCDA) in environmental decision making. *Risk analysis,* 29**,** 26-33.

STEWART, T. J. 2005. Dealing with uncertainties in MCDA. Multiple criteria decision analysis: state of the art surveys. Springer.

STORE, R. & KANGAS, J. 2001. Integrating spatial multi-criteria evaluation and expert knowledge for GIS-based habitat suitability modelling. *Landscape and urban planning,* 55**,** 79-93.

STRECKER, E. W., WU, B. & IANNELI, M. 1997. Analysis of Oregon Urban Runoff Water Quality Monitoring Data Collected from 1990 to 1996. *The Oregon Association of Clean Water Agencies*.

SUN, N., HALL, M., HONG, B. & ZHANG, L. 2012. Impact of SWMM catchment discretization: case study in Syracuse, New York. Journal of Hydrologic Engineering, 19, 223-234.

SUPRIYASILP, T., PONGPUT, K. & BOONYASIRIKUL, T. 2009. Hydropower development priority using MCDM method. *Energy Policy,* 37**,** 1866-1875.

SZULCZEWSKA, B., GIEDYCH, R., BOROWSKI, J., KUCHCIK, M., SIKORSKI, P., MAZURKIEWICZ, A. & STAŃCZYK, T. 2014. How much green is needed for a vital neighbourhood? In search for empirical evidence. Land Use Policy, 38, 330-345.

TANG, Z., ENGEL, B., PIJANOWSKI, B. & LIM, K. 2005. Forecasting land use change and its environmental impact at a watershed scale. *Journal of environmental management,* 76**,** 35-45.

TEMPRANO, J., ARANGO, Ó., CAGIAO, J., SUÁREZ, J. & TEJERO, I. 2005. Stormwater quality calibration by SWMM: A case study in Northern Spain. water SA, 32, 55-63.

THE BROOKLYN EVOLUTION 2012. *Brooklyn Industrial Precinct Strategy.* Brimbank City Council.

THE CORRIDOR. 2014. *Green way corridor - North* [Online]. Available: http://www.thecorridor-mke.org/?page_id=158 [Accessed 02 nd January 2016].

The Green Infrastructure Valuation Toolkit User Guide. [Online]. Available: http://www.greeninfrastructurenw.co.uk/resources/Green_Infrastructure_Valuation_Toolkit_UserGuide.pdf.

THE NATURE CONSERVANCY 2013. The case for Green Infrastrcuture. *Joint Industry White Paper*.

THELLESEN, L., HEDEGAARD, M., BERGHOLT, T., COLOV, N. P., HOEGH, S. & SORENSEN, J. L. 2015. Curriculum development for a national cardiotocography education program: a Delphi survey to obtain consensus on learning objectives. *Acta obstetricia et gynecologica Scandinavica,* 94**,** 869-877.

THOMAS, M. R. 2002. A GIS-based decision support system for brownfield redevelopment. *Landscape and Urban Planning,* 58**,** 7-23.

THORNE, C. R., LAWSON, E., OZAWA, C., HAMLIN, S. & SMITH, L. A. 2015. Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management. Journal of Flood Risk Management.

TILLEY, S. 2003. Natural approaches to stormwater management: low impact development in Puget Sound. *Olympia, WA*.

TODOROVIC, Z., REED, J. & TAYLOR, L. SUDS retrofit for surface water outfalls from industrial estates: Scotland case study. 11th Internationla Conference on Urban Drainage, 2008.

TOLSGAARD, M. G., TODSEN, T., SORENSEN, J. L., RINGSTED, C., LORENTZEN, T., OTTESEN, B. & TABOR, A. 2013. International multispecialty consensus on how to evaluate ultrasound competence: a Delphi consensus survey. *PloS one,* 8**,** e57687.

TOMPKINS, E. L., FEW, R. & BROWN, K. 2008. Scenario-based stakeholder engagement: incorporating stakeholders preferences into coastal planning for climate change. *Journal of environmental management,* 88**,** 1580-1592.

TOOSI, S. R. & SAMANI, J. V. 2012. Evaluating water transfer projects using analytic network process (ANP). *Water resources management,* 26**,** 1999-2014.

TORRANCE, G. W., BOYLE, M. H. & HORWOOD, S. P. 1982. Application of multi-attribute utility theory to measure social preferences for health states. *Operations research,* 30**,** 1043-1069.

TRIANTAPHYLLOU, E. & SÁNCHEZ, A. 1997. A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. *Decision Sciences,* 28**,** 151-194.

TSIHRINTZIS, V. A. & HAMID, R. 1998. Runoff quality prediction from small urban catchments using SWMM. *Hydrological Processes,* 12**,** 311-329.

TZOULAS, K., KORPELA, K., VENN, S., YLI-PELKONEN, V., KAŹMIERCZAK, A., NIEMELA, J. & JAMES, P. 2007. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landscape and urban planning,* 81**,** 167-178.

UNEP. 2011. Setting the stage for a green economy transition. Introduction [Online].

UNIDO 2011. Unido Green Industry Initiative. *for Sustainable Industrial Development.* Vienna: United Nations Industrial Development Organization.

US EPA 2009. Stormwater Wet Pond and Wetland Management Guidebook. *In:* PROTECTION, C. F. W. (ed.). Tetra Tech.

US EPA 2013. Implementing stormwater infiltration practices at vacant parcels at brownfield sites. U S Environemntal Protection Agency: Office of Water.
US EPA. 2014. Greening CSO Plans:. Planning and Modeling Green Infrastructure for Combined Sewer Overflow (CSO) Control [Online]. Available: https://www.epa.gov/sites/production/files/2015-10/documents/greening_cso_plans_0.pdf.

US EPA. 2015. *What Are the Six Common Air Pollutants?* [Online]. Available: http://www.epa.gov/air/urbanair/ [Accessed 20th July 2015].
US EPA. 2015. *What is Green Infrastructure?* [Online]. Available: https://www.epa.gov/green-infrastructure/what-green-infrastructure [Accessed 1st of June 2016].
USACE 2014. Cost-estimation tool for low-impact development stormwater best management practices. *Public Works Technical Bulletin.* Washington, DC US Army Corps of Engineers.
USEPA 2005. Low-Impact Development Pays Off. . *Nonpoint Source News-Notes. No. 75.*
USEPA 2007. EPA. Reducing Stormwater Costs Through Low-Impact Development (LID) Strategies and Practices.
USEPA 2013. Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs. U.S. Environmental Protection Agency.
USEPA 2014a. Coastal Stormwater Management Through Green Infrastructure. *A handbook for municipalities.* Washington DC, USA: United States Environmental Protection Agency.
USEPA 2014b. Enhancing Sustainable Communities with Green Infrastructure. *A guide to help communities better manage stormwater while achieving other environmental, public health, social, and economic benefits*
USEPA 2014c. Green Infrastructure:. *Land Revitalization Success Stories.* Office of Solid Waste and Emergency Response: Washington, DC.
USEPA. 2015. Green Infrastructure Opportunities that Arise During Municipal Operations. Available: http://www.epa.gov/sites/production/files/2015-09/documents/green_infrastructure_roadshow.pdf [Accessed 11th March 2015].
USEPA. 2016. *Industrial overview* [Online]. Available: https://www.epa.gov/npdes/stormwater-discharges-industrial-activities#overview [Accessed 31st January 2016].
VAILLANCOURT, K. & WAAUB, J.-P. 2002. Environmental site evaluation of waste management facilities embedded into EUGENE model: A multicriteria approach. *European Journal of Operational Research,* 139**,** 436-448.
VALERDI, R. Convergence of expert opinion via the wideband delphi method. 21st Annual International Symposium of the International Council on Systems Engineering, INCOSE 2011, 2011.
VELASQUEZ, M. & HESTER, P. T. 2013. An analysis of multi-criteria decision making methods. *International Journal of Operations Research,* 10**,** 56-66.
VELEVA, V., TODOROVA, S., LOWITT, P., ANGUS, N. & NEELY, D. 2015. Understanding and addressing business needs and sustainability challenges:

lessons from Devens eco-industrial park. Journal of Cleaner Production, 87, 375-384.

VERHAGEN, A. P., DE VET, H. C., DE BIE, R. A., KESSELS, A. G., BOERS, M., BOUTER, L. M. & KNIPSCHILD, P. G. 1998. The Delphi list: a criteria list for quality assessment of randomized clinical trials for conducting systematic reviews developed by Delphi consensus. *Journal of clinical epidemiology,* 51**,** 1235-1241.

VETSCHERA, R. & DE ALMEIDA, A. T. 2012. A PROMETHEE-based approach to portfolio selection problems. *Computers & Operations Research,* 39**,** 1010-1020.

VEY, J. S. 2007. *Restoring prosperity: The state role in revitalizing America's older industrial cities*, Brookings Institution Metropolitan Policy Program Washington, DC.

VIAVATTENE, C., SCHOLES, L., REVITT, D. & ELLIS, J. A GIS based decision support system for the implementation of stormwater best management practices. 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008.

VINCKE, P. 1992. *Multicriteria decision-aid*, Chichester [England] ; New York : Wiley.

VON WINTERFELDT, D. & EDWARDS, W. 1986. Decision analysis and behavioral research. 1986. Cambridge University Press, Cambridge.

WAKELIN, S. C., ELEFSINIOTIS, P. & WAREHAM, D. G. 2003. Assessment of stormwater retention basin water quality in Winnipeg, Canada. *Water quality research journal of Canada,* 38**,** 433-450.

WALBRIDGE, M. R. & STRUTHERS, J. P. 1993. Phosphorus retention in non-tidal palustrine forssted wetlands of the mid-atlantic region. *Wetlands,* 13**,** 84-94.

WALKER JR, W. 1990. P8 urban catchment model program documentation, v1. 1. *Prepared for IEP, Inc., Northborough, MA and Narragansett Bay Project, Providence, RI*.

WALSH, C. 2000. Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration. *Hydrobiologia,* 431**,** 107-114.

WANG, H. W., MAO, Y. F., GAO, Y., FAN, J. H., ZHANG, S. F. & MA, L. M. 2013. Analysis of Bioretention Cell Design Elements Based on Fourier Amplitude Sensitivity Test (FAST). *Advanced Materials Research,* 779**,** 1369-1375.

WANG, J.-J., JING, Y.-Y., ZHANG, C.-F. & ZHAO, J.-H. 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews,* 13**,** 2263-2278.

WANG, Y.-M. & ELHAG, T. M. 2006. Fuzzy TOPSIS method based on alpha level sets with an application to bridge risk assessment. *Expert systems with applications,* 31**,** 309-319.

WANG, Z., BAI, Z., YU, H., ZHANG, J. & ZHU, T. 2004. Regulatory standards related to building energy conservation and indoor-air-quality during rapid urbanization in China. *Energy and Buildings,* 36**,** 1299-1308.

WATER BY DESIGN 2011. Water Sensitive Urban Design in Industrial Areas. Healthy waterways.

WATER ENVIRONMENT RESEARCH FOUNDATION 2009. User's Guide to the BMP and LID Whole Life Cycle Cost Modeling tools. Version 2.0. .

WBM, B. 2009. Evaluating options for water sensitive urban design–a national guide. *Joint Steering Committee for Water Sensitive Cities (JSCWSC)*.

WEBER, T., SLOAN, A. & WOLF, J. 2006. Maryland's Green Infrastructure Assessment: Development of a comprehensive approach to land conservation. Landscape and urban planning, 77, 94-110.

WEST, G. I. N. 2011. Building natural value for sustainable economic development: The green infrastructure valuation toolkit user guide.

WEST, J. F. & CANNON, G. S. 1988. Essential collaborative consultation competencies for regular and special educators. *Journal of Learning Disabilities,* 21**,** 56-63.

WEST, M., CLAYTOR, R., ROSEEN, R. & ESTEN, M., E 2010. RHODE ISLAND STORMWATER DESIGN AND INSTALLATION STANDARDS MANUAL. Rhode Island Department Of Environmental Management And Coastal Resources Management Council.

WESTMAN, W. E. 1977. How much are nature's services worth? *Science,* 197**,** 960-964.

WILKINSON, S. J. & REED, R. 2009. Green roof retrofit potential in the central business district. *Property management,* 27**,** 284-301.

WILLIAMS, P. L. & WEBB, C. 1994. The Delphi technique: a methodological discussion. *Journal of advanced nursing,* 19**,** 180-186.

WILLIAMSON, K. S. 2003. *Growing with green infrastructure*, Heritage Conservancy Doylestown,, PA.

Wisconsin Housing and Economic Development Authority.

WISE, S. 2008. Green Infrastructure Rising. *Planning,* 74**,** 14-19.

WISE, S., BRADEN, J., GHALAYINI, D., GRANT, J., KLOSS, C., MACMULLAN, E., MORSE, S., MONTALTO, F., NEES, D. & NOWAK, D. 2010. Integrating valuation methods to recognize green infrastructure’s multiple benefits. *Center for Neighborhood Technology, April*.

WOLCH, J. R., BYRNE, J. & NEWELL, J. P. 2014. Urban green space, public health, and environmental justice: The challenge of making cities ‘just green enough’. Landscape and Urban Planning, 125, 234-244.

WOLF, K. L. Ergonomics of the city: Green infrastructure and social benefits. Engineering Green: Proceedings of the 11th National Urban Forest Conference. Washington DC: American Forests, 2003.

WONG, T. H., BREEN, P. F., SOMES, N. L. & LLOYD, S. D. 1999. Managing urban stormwater using constructed wetlands. *Melbourne, Australia: CRC for Catchment Hydrology and CRC for Freshwater Ecology Industry Report,* 98.

WONG, T. H., FLETCHER, T. D., DUNCAN, H. P. & JENKINS, G. A. 2006. Modelling urban stormwater treatment—A unified approach. *Ecological Engineering,* 27**,** 58-70.

WONG, T. H., FLETCHER, T. D., DUNCAN, H. P., COLEMAN, J. R. & JENKINS, G. A. 2002. A model for urban stormwater improvement conceptualisation. *Global Solutions for Urban Drainage***,** 8-13.

WOODARD, F. 2001. *Industrial waste treatment handbook*, Butterworth-Heinemann.
WORLAND, J. 2016. Air Pollution Kills More Than 5 Million People Around the World Every Year. Research suggests the number of deaths will continue to rise [Online]. [Accessed 19th July 2016].
WU, H. & CHEN, C. Urban "brownfields": An Australian perspective. Proceedings of 18th annual Pacific-rim real estate society conference, 2012. 1-20.
YANG, B., LI, S., WALL, H. A., BLACKMORE, P. & WANG, Z. 2015. Green infrastructure design for improving stormwater quality: Daybreak community in the United States West. Landscape Architecture Frontiers, 3, 12-22.

YANG, J., MCBRIDE, J., ZHOU, J. & SUN, Z. 2005. The urban forest in Beijing and its role in air pollution reduction. *Urban Forestry & Urban Greening,* 3**,** 65-78.
YANG, J., YU, Q. & GONG, P. 2008. Quantifying air pollution removal by green roofs in Chicago. *Atmospheric environment,* 42**,** 7266-7273.

YANG, Y. N. 2003. Testing the Stability of Experts' Opinions between Successive Rounds of Delphi Studies.
YAPA, N. 2004. *STEEL RIVER INDUSTRIAL AND BUSINESS PARK* [Online]. Available: http://www.jacksonteece.com/projects/steel-river-industrial-and-business-park [Accessed 20th January 2016].
YARRA AND BAY. 2014. *Kororoit Creek* [Online]. Available: http://yarraandbay.vic.gov.au/report-card/werribee/wbkor0278

YATSALO, B., DIDENKO, V., GRITSYUK, S. & SULLIVAN, T. 2015. Decerns: a framework for multi-criteria decision analysis. *International Journal of Computational Intelligence Systems,* 8**,** 467-489.
YOE, C. 2002. Trade-off analysis planning and procedures guidebook. *US Army Corps of Engineers,* 310.
YOON, K. P. & HWANG, C.-L. 1995. *Multiple attribute decision making: an introduction*, Sage publications.
YOUNG, C., JONES, R. & SYMONS, J. 2014. Investing in Growth: Understanding the Value of Green Infrastructure. Climate Change Working Paper.
YOUNG, K. D., YOUNOS, T., DYMOND, R. L., KIBLER, D. F. & LEE, D. H. 2010. Application of the analytic hierarchy process for selecting and modeling stormwater best management practices. *Journal of Contemporary Water Research & Education,* 146**,** 50-63.
YOUNG, K., KIBLER, D., BENHAM, B. & LOGANATHAN, G. 2009. Application of the Analytical Hierarchical Process for Improved Selection of Storm-Water BMPs. *Journal of Water Resources Planning and Management,* 135**,** 264-275.
YOUNG, R., ZANDERS, J., LIEBERKNECHT, K. & FASSMAN-BECK, E. 2014. A comprehensive typology for mainstreaming urban green infrastructure. Journal of Hydrology, 519, 2571-2583.

YOUNG, W., H & HOGBEN, D. 1978. An Experimental Study of Delphi Technique. *Educational Research Perspective,* 5**,** 57-62.
YOUNGQUIST, T. D. 2009. What is green infrastructure? An evaluation of green infrastructure plans from across the United States.

YOUSUF, M. I. 2007. Using experts' opinions through Delphi technique. *Practical assessment, research & evaluation,* 12**,** 1-8.

YU, Z., AGUAYO, M., PIASECKI, M. & MONTALTO, F. Developments in LIDRA 2.0: a planning level assessment of the cost-effectiveness of low impact development. Proceedings of the ASCE Environment and Water Resources Institute Conference, Providence, Rhode Island, 2010.

ZANAKIS, S. H., SOLOMON, A., WISHART, N. & DUBLISH, S. 1998. Multi-attribute decision making: A simulation comparison of select methods. *European Journal of Operational Research,* 107**,** 507-529.

ZARDARI, N. H., AHMED, K., SHIRAZI, S. M. & YUSOP, Z. B. 2014. *Weighting Methods and Their Effects on Multi-Criteria Decision Making Model Outcomes in Water Resources Management*, Springer.

ZARDARI, N. H., AHMED, K., SHIRAZI, S. M. & YUSOP, Z. B. 2015. Literature Review. *Weighting Methods and their Effects on Multi-Criteria Decision Making Model Outcomes in Water Resources Management.* Cham: Springer International Publishing.

ZEDLER, J. B. & KERCHER, S. 2005. Wetland resources: status, trends, ecosystem services, and restorability. *Annu. Rev. Environ. Resour.*, 30**,** 39-74.

ZEDLER, J. B. 2003. Wetlands at your service: reducing impacts of agriculture at the watershed scale. *Frontiers in Ecology and the Environment,* 1**,** 65-72.

ZELENY, M. 1982. *Multiple Criteria Decision-making.*, McGraw-Hill, New York

ZGHEIB, S., MOILLERON, R. & CHEBBO, G. 2012. Priority pollutants in urban stormwater: Part 1–Case of separate storm sewers. *water research,* 46**,** 6683-6692.

ZHU, B., XU, Z., ZHANG, R. & HONG, M. 2015. Generalized analytic network process. *European Journal of Operational Research,* 244**,** 277-288.

ZIELINSKI, J. 2000. The benefits of better site design in commercial development. *The Practice of Watershed Protection***,** 277-286.

ZINN, J., ZALOKOWSKI, A. & HUNTER, L. 2001. Identifying indicators of laboratory management performance: a multiple constituency approach. *Health Care Management Review,* 26**,** 40-53.

ZOPPOU, C. 2001. Review of urban storm water models. *Environmental Modelling & Software,* 16**,** 195-231.

ZWICKL, K. & MOSER, M. 2014. Informal environmental regulation of industrial air pollution: Does neighborhood inequality matter?

APPENDICES

Appendix 3A - Green Area Ratio Method

Green Area Ratio (Keeley, 2011) is an urban sustainability matrix that uses to assess the potential environmental, economic and social impacts of Green Infrastructure (GI) practices. This method uses a set of performance ratings and the area of GI to calculate the Green Area Ratio. GI with higher green Area Ratio have a high performance. For this study, the Green Area Ratio Method was used to assess the performance of GI practices on their ability to create habitats and improve the liveability of the area. The equation and the performance ratings for different GI practices adopted for this study are explained as follows.

$$GAR = \sum_{i=1}^{n} \frac{Area_{GI} \times PR_{GI}}{Area_{Parcel}}$$

Where, *GAR = Green Area Ratio, i= GI practice, Area* $_{GI}$ *= Area over GI is applied, PR* $_{GI}$ *= Performance Rating of the GI, Area* $_{parcel}$ *= Total area of the land parcel under consideration*.

Based on the performance ratings proposed by studies in literature (West et al. ,2010, West, 2011, CNT, 2010 and Keeley, 2011), the rating system below was developed in this study to estimate the Green Area Ratio to assess the performances of GI practices on their ability to create habitat and improve liveability of the area.

<u>Performance Ratings</u>

GI Practice	**Habitat Creation**	**Improvement of Liveability**
Sedimentation Basin	High	High
Vegetated Swale	Moderate	None
Wetland	Very High	High
Bioretention	Very High	Moderate
Retention Pond	Very High	High

➡

Performance Rating	
None	**1**
Little	**2**
Moderate	**3**
High	**4**
Very High	**5**

Appendix 3B - Least Cost Sizing Combinations Obtained from the Single Objective Optimization, their sizes of Individual Treatment Measures and Removal Efficiencies for all Treatment Trains for Study Area

Table 3B.1 – Treatment Train Sizing Combinations with Sedimentation Basin and Retention Pond

Sizing Combination	Sedimentation Basin Area (m^2)	Retention Pond Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_PD (1)	2000	2000	80.3	75.4	65	21258
SDB_PD (2)	1800	2500	81.2	75.9	67.2	22295
SDB_PD (3)	1600	3000	81.2	77.2	69.1	23212
SDB_PD (4)	1400	3000	81.1	75.9	68	22414
SDB_PD (5)	1200	3500	80.3	76.6	69.2	23195
SDB_PD (6)	1000	4000	81.1	77.3	70.8	23875
SDB_PD (7)	800	4500	80.5	77.9	72.6	24451
SDB_PD (8)	600	5000	81.5	78.6	74.1	24912
SDB_PD (9)	400	5500	82.4	79.8	76	25229
SDB_PD(10)	200	5500	80.4	77.9	75	23931

Table 3B.2 – Treatment Train Sizing Combinations with Sedimentation Basin and Wetland

Sizing Combination	Sedimentation Basin Area (m^2)	Wetland Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_WL(1)	2000	2000	82.8	78	66.6	18606
SDB_WL(2)	1800	2000	81.4	75.5	65	17859
SDB_WL(3)	1600	2000	80.2	74.3	63.3	17088
SDB_WL(4)	1400	2500	81.1	75.3	66	17653
SDB_WL(5)	1200	3000	81.5	77.1	68.5	18111
SDB_WL(6)	1000	3500	82.3	77.8	70.3	18470
SDB_WL(7)	800	3500	80	76.8	68.7	17545
SDB_WL(8)	600	4500	82.3	79.3	73.8	18877
SDB_WL(9)	400	4500	81.3	78.3	73.2	17774
SDB_WL(10)	200	5000	81	79.5	74.7	17586

Table 3B.3 – Treatment Train Sizing Combinations with Sedimentation Basin and Vegetated Swale

Sizing Combination	Sedimentation Basin Area (m^2)	Vegetated Swale Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_SW(1)	1000	4500	86.2	71.8	46.1	18451
SDB_SW(2)	1200	3500	84.8	72	46.3	20848
SDB_SW(3)	1400	2500	84	70.9	46.2	16263
SDB_SW(4)	1600	1500	81.5	69.6	45.7	19011
SDB_SW(5)	1800	1000	81.3	69.2	46.9	14064
SDB_SW(6)	2000	1000	82.6	71.3	49.6	19397

Table 3B.4 – Treatment Train Sizing Combinations with Vegetated Swale and Bioretention

Sizing Combination	Vegetated Swale Area (m^2)	Bioretention Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SW_BR(1)	5000	1500	85.5	64.2	48.7	16227
SW_BR (2)	4500	1500	84.2	62.8	46.7	15641
SW_BR (3)	4000	1500	83.4	61.7	45.0	15034
SW_BR (4)	3500	2000	84.1	61.6	48.7	15557
SW_BR (5)	3000	2000	83.1	60.2	47.4	14895
SW_BR (6)	2500	2000	82.3	58.7	45.6	14195
SW_BR (7)	2000	2500	83.7	58.5	48.8	14497
SW_BR (8)	1500	2500	81.8	56.8	47.5	13679
SW_BR (9)	1000	3000	81.6	56.2	50.4	13733
SW_BR(10)	500	3500	82.5	56.2	52.8	13528

Table 3B.5 – Treatment Train Sizing Combinations with Vegetated Swale and Wetland

Sizing Combination	Vegetated Swale Area (m^2)	Wetland Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SW_WL(1)	5000	1000	80.1	68.8	45.3	18390
SW_WL (2)	4500	1500	81.5	71.4	51.5	19195
SW_WL (3)	4000	1500	80.3	70	49.8	18357
SW_WL (4)	3500	2000	81.7	72.6	54.4	18946
SW_WL (5)	3000	2500	82	75.3	59.7	19390
SW_WL (6)	2500	2500	81.2	73.6	58.5	18415
SW_WL (7)	2000	3000	81.5	75.6	62.6	18654
SW_WL (8)	1500	3500	82.1	76.2	65.8	18732
SW_WL (9)	1000	4000	81.7	77.1	69.5	18602
SW_WL(10)	500	4500	80.5	78.3	71.4	18121

Table 3B.6 – Treatment Train Sizing Combinations with Vegetated Swale and Retention Pond

Sizing Combination	Vegetated Swale Area (m^2)	Retention Pond Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SW_PD(1)	5000	1500	81.7	71.2	52.2	22204
SW_PD (2)	4500	1500	80.6	70.4	51	21397
SW_PD (3)	4000	1500	80.1	68.1	49.5	20560
SW_PD (4)	3500	2500	82	74.1	59.3	23382
SW_PD (5)	3000	2500	80.3	72.3	58.1	22463
SW_PD (6)	2500	3000	80.7	74.5	61.6	23175
SW_PD (7)	2000	3500	81.6	75.3	64.7	23738
SW_PD (8)	1500	4000	81.1	76.1	68	24137
SW_PD (9)	1000	5000	81.9	78.4	72.7	25782
SW_PD (10)	500	5500	80.3	77.9	74.7	25576

Table 3B.7 – Treatment Train Sizing Combinations with Sedimentation Basin, Vegetated Swale and Bioretention

Sizing Combination	Sedimentation Basin Area (m^2)	Vegetated Swale Area (m^2)	Bioretention Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_SW_BR(1)	200	500	3000	82.3	57.1	51.2	16286
SDB_SW_BR(2)	400	500	2500	82.4	58.7	51.5	16607
SDB_SW_BR(3)	600	500	2000	81.8	59.8	50.3	16659
SDB_SW_BR(4)	800	500	1500	80.8	61.6	48.6	16500
SDB_SW_BR(5)	1000	500	1500	82.9	63.9	51.1	17425
SDB_SW_BR(6)	1200	500	1000	80.9	64.5	49.5	16981
SDB_SW_BR(7)	1400	500	1000	83.1	66.9	52	17813
SDB_SW_BR(8)	1600	500	500	81.9	67.5	49.7	16983
SDB_SW_BR(9)	200	1000	2500	82.4	57.9	49.3	16934
SDB_SW_BR(10)	400	1000	2000	81.8	59.4	48.4	17181
SDB_SW_BR(11)	600	1000	1500	80.3	60.9	47.2	17130
SDB_SW_BR(12)	800	1000	1500	83.3	63.4	50	18126
SDB_SW_BR(13)	1000	1000	1000	83	64.7	48	17735
SDB_SW_BR(14)	1200	1000	500	81.1	65.5	45.4	16979
SDB_SW_BR(15)	200	1500	2000	81.3	58.2	46	17197
SDB_SW_BR(16)	400	1500	2000	83.5	61.6	49	18495
SDB_SW_BR(17)	600	1500	1500	82.8	62.4	48.6	18444
SDB_SW_BR(18)	800	1500	1000	82.5	63.9	46.6	18124
SDB_SW_BR(19)	1000	1500	1000	84.5	66.9	49.5	19048
SDB_SW_BR(20)	1200	1500	500	83.2	67.4	46.7	18293
SDB_SW_BR(21)	200	2000	2000	82.5	60	47.5	18350
SDB_SW_BR(22)	400	2000	1500	82.5	61.4	46.7	18493
SDB_SW_BR(23)	600	2000	1500	84.6	64.6	49.9	19596
SDB_SW_BR(24)	800	2000	1000	84.1	65.7	48	19277
SDB_SW_BR(25)	1000	2000	500	83.2	67.1	45.1	18573
SDB_SW_BR(26)	200	2500	2000	84.3	61.8	48.4	19399

SDB_SW_BR (27)	400	2500	1500	83.4	63.3	48.1	19543
SDB_SW_BR (28)	600	2500	1000	83.9	64.9	46	19330
SDB_SW_BR (29)	800	2500	1000	85.6	67.3	49.4	20326
SDB_SW_BR (30)	1000	2500	500	84.5	68.4	46.8	19623
SDB_SW_BR (31)	200	3000	1500	83.2	61.5	45.5	19221
SDB_SW_BR (32)	400	3000	1500	85.2	64.5	49.1	20519
SDB_SW_BR (33)	600	3000	1000	85.4	65.7	47.4	20306
SDB_SW_BR (34)	800	3000	500	83.6	67.2	45.4	19674
SDB_SW_BR (35)	200	3500	1500	84.5	63.3	47.4	20140
SDB_SW_BR (36)	400	3500	1000	83.8	64.9	45.6	20123
SDB_SW_BR (37)	600	3500	1000	85.7	66.9	49.4	21226
SDB_SW_BR (38)	800	3500	500	85.2	68.3	46.8	20594
SDB_SW_BR (39)	200	4000	1500	85.3	64.1	48.4	21015
SDB_SW_BR (40)	400	4000	1000	85.2	66.4	47.3	20997
SDB_SW_BR (41)	600	4000	500	83.6	67.2	45.1	20472
SDB_SW_BR (42)	200	4500	1500	86.4	65.6	49.7	21853
SDB_SW_BR (43)	400	4500	1000	85.7	66.7	48.5	21835
SDB_SW_BR (44)	600	4500	500	85.4	68.5	46.8	21310

Table 3B.8 – Treatment Train Sizing Combinations with Sedimentation Basin, Vegetated Swale and Retention Pond

Sizing Combination	Sedimentation Basin Area (m^2)	Vegetated Swale Area (m^2)	Retention Pond Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_SW_PD(1)	2000	500	1000	81.7	73.5	58.9	21170
SDB_SW_PD (2)	1800	500	1500	81.8	74.9	60.7	22529
SDB_SW_PD (3)	1600	500	1500	80.7	73	59	21759
SDB_SW_PD (4)	1400	500	2000	80.2	73.7	61.5	22874
SDB_SW_PD (5)	1200	500	3000	81.9	77	67.2	25514
SDB_SW_PD (6)	1000	500	3000	80.1	75.6	65.8	24641
SDB_SW_PD (7)	800	500	3500	81.5	76	67.8	25330
SDB_SW_PD (8)	600	500	4000	80.4	76.8	69.6	25886
SDB_SW_PD (9)	1200	500	3000	81.9	77	67.2	25514
SDB_SW_PD (10)	1000	500	3000	80.1	75.6	65.8	24641
SDB_SW_PD (11)	800	500	3500	81.5	76	67.8	25330
SDB_SW_PD (12)	600	500	4000	80.4	76.8	69.6	25886
SDB_SW_PD (13)	400	500	4500	80.9	77.9	71	26284
SDB_SW_PD (14)	200	500	5000	81.4	78	72.5	26443
SDB_SW_PD (15)	400	1500	3000	81	74.3	63	24557
SDB_SW_PD (16)	400	2000	2500	81.6	73.9	59.8	24022
SDB_SW_PD (17)	400	2500	2000	81.1	72.4	55.8	23288
SDB_SW_PD (18)	400	3000	1500	80.2	70.8	52.1	22350
SDB_SW_PD (19)	400	3500	1000	81.5	68.8	46.9	21163
SDB_SW_PD (20)	400	5000	1000	84.3	72.6	50.8	23682
SDB_SW_PD (21)	400	4500	1000	83.5	71.3	49.7	22875
SDB_SW_PD (22)	600	1500	2500	81.4	74.6	60.6	23972
SDB_SW_PD (23)	600	2000	2000	81.6	73.1	57.2	23341
SDB_SW_PD (24)	600	2500	1500	81.8	71.8	53.3	22478
SDB_SW_PD (25)	600	3000	1000	81.7	70	48.6	21347

SDB_SW_PD (26)	800	2500	1000	81.8	70.6	49.9	21367
SDB_SW_PD (27)	800	2000	1500	81.4	72	54.6	22424
SDB_SW_PD (28)	800	1500	2000	81.1	73.1	58.2	23184
SDB_SW_PD (29)	800	1000	2500	80.8	73.4	61.1	23654
SDB_SW_PD (30)	1000	500	3000	80.1	75.6	65.8	24641
SDB_SW_PD (31)	1000	1500	1500	81	72.4	55.3	22196
SDB_SW_PD (32)	1000	1000	2000	80.7	72.6	59.2	22795
SDB_SW_PD (33)	1000	2000	1000	81.1	71.3	51	21242
SDB_SW_PD (34)	1200	500	3000	81.9	77	67.2	25514
SDB_SW_PD (35)	1200	1000	1500	80.5	71.6	56.3	21754
SDB_SW_PD (36)	1200	1500	1000	81.7	71.4	52.3	20961
SDB_SW_PD (37)	1800	500	1500	81.8	74.9	60.7	22529
SDB_SW_PD (38)	2000	500	1000	81.7	73.5	58.9	21170
SDB_SW_PD (39)	1400	500	2000	80.2	73.7	61.5	22874
SDB_SW_PD (40)	1400	1000	1000	80.9	70.8	53.5	20479
SDB_SW_PD (41)	1600	500	1500	80.7	73	59	21759

Table 3B.9 – Treatment Train Sizing Combinations with Sedimentation Basin, Vegetated Swale and Wetland

Sizing Combination	Sedimentation Basin Area (m^2)	Vegetated Swale Area (m^2)	Wetland Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_SW_WL (1)	400	5000	1000	84.4	73.6	51.4	21975
SDB_SW_WL (2)	200	5000	1000	82.1	71	48.2	20677
SDB_SW_WL (3)	200	4500	1000	81.2	69.6	47.3	19870
SDB_SW_WL (4)	400	4500	1000	82.1	72.1	50	21168
SDB_SW_WL (5)	600	4500	500	84.1	70.8	46.3	20395
SDB_SW_WL (6)	200	4000	1500	82	72.5	52.5	20644
SDB_SW_WL (7)	400	4000	1000	81.6	70.8	48.9	20330
SDB_SW_WL (8)	600	4000	1000	83.8	72.8	51.6	21433
SDB_SW_WL (9)	200	3500	1500	80.5	70.7	51.1	19769
SDB_SW_WL (10)	400	3500	1000	80.9	69.4	47.4	19455
SDB_SW_WL (11)	600	3500	1000	83.5	71.4	50	20559
SDB_SW_WL (12)	200	3000	2000	82.6	73	56.1	20314
SDB_SW_WL (13)	400	3000	1500	81.2	71.1	52.9	20148
SDB_SW_WL (14)	600	3000	1000	81.2	70.8	48.9	19639
SDB_SW_WL (15)	800	3000	1000	83.5	72.8	51.8	20635
SDB_SW_WL (16)	200	2500	2000	80.2	72.1	54.7	19338
SDB_SW_WL (17)	600	2500	1000	80.2	68.9	47.4	18663
SDB_SW_WL (18)	800	2500	1000	81.8	71.5	50.1	19659
SDB_SW_WL (19)	200	2000	2500	81	73.7	59.2	19652
SDB_SW_WL (20)	400	2000	2000	80.9	71.8	56.5	19586
SDB_SW_WL (21)	600	2000	1500	80.4	70.9	53.1	19226
SDB_SW_WL (22)	800	2000	1000	80.4	69.3	48.9	18610
SDB_SW_WL (23)	200	1500	3000	81.6	75.2	63.2	19788
SDB_SW_WL (24)	400	1500	2500	81.2	73.7	60.3	19797
SDB_SW_WL (25)	600	1500	2000	80.8	72.6	57.1	19536
SDB_SW_WL (26)	800	1500	2000	82.1	74.4	59.8	20532

SDB_SW_WL (27)	1000	1500	1500	81.5	73.6	56.3	19994
SDB_SW_WL (28)	1200	1500	1000	81.9	71.8	52.7	19254
SDB_SW_WL (29)	200	1000	3500	81.4	76.7	66.4	19705
SDB_SW_WL (30)	400	1000	3000	80.5	74.8	64.3	19772
SDB_SW_WL (31)	600	1000	2500	80.5	73.4	61.8	19586
SDB_SW_WL (32)	800	1000	2000	80.1	72.7	58.2	19219
SDB_SW_WL (33)	1000	1000	2000	81.9	74.2	60.5	20143
SDB_SW_WL (34)	1200	1000	1500	81.7	72.8	56.7	19552
SDB_SW_WL (35)	1400	1000	1000	81.1	72.2	53.9	18771
SDB_SW_WL (36)	200	500	4000	80.6	77.1	69.5	19264
SDB_SW_WL (37)	400	500	3500	80.2	75.4	66.6	19378
SDB_SW_WL (38)	600	500	3500	81.7	77.1	68.3	20481
SDB_SW_WL (39)	800	500	3000	81	75.7	66	20246
SDB_SW_WL (40)	1000	500	2500	80.6	74.2	63.8	19881
SDB_SW_WL (41)	1200	500	2000	80.3	73.4	61	19390
SDB_SW_WL (42)	1400	500	2000	81.6	75.8	63.1	20222
SDB_SW_WL (43)	1600	500	1500	81.2	74	60	19556
SDB_SW_WL (44)	1800	500	1000	81.3	72.8	57	18715

Table 3B.10 – Treatment Train Sizing Combinations with Sedimentation Basin, Bioretention and Retention Pond

Sizing Combination	Sedimentation Basin Area (m^2)	Bioretention Area (m^2)	Retention Pond Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SDB_BR_PD (1)	200	500	4500	81.7	77.6	71.7	24994
SDB_BR_PD (2)	400	500	3500	80	74.7	67	23239
SDB_BR_PD (3)	600	500	3500	82.2	75.6	68.1	24342
SDB_BR_PD (4)	800	500	3000	81	75.2	66.8	23725
SDB_BR_PD (5)	1000	500	2500	81.1	74.1	64.3	22962
SDB_BR_PD (6)	1200	500	2000	80.9	73.2	62.4	22051
SDB_BR_PD (7)	1400	500	1500	80.3	71.4	59.6	20969
SDB_BR_PD (8)	1600	500	1000	80.6	71.4	57.3	19660
SDB_BR_PD (9)	1000	1000	1000	80.3	68.3	54.7	18786
SDB_BR_PD (10)	800	1000	2000	81.8	72.5	61.9	21882
SDB_BR_PD (11)	600	1000	2500	81.7	73.2	64.4	22669
SDB_BR_PD (12)	400	1000	3000	81.5	74.6	65.9	23254
SDB_BR_PD (13)	200	1000	3500	81.5	75.1	68.1	23569
SDB_BR_PD (14)	800	1500	1000	80.9	68.5	56	19177
SDB_BR_PD (15)	600	1500	1500	80.5	68.9	58.9	20288
SDB_BR_PD (16)	400	1500	2000	80.1	70.4	60.8	21098
SDB_BR_PD (17)	200	1500	2500	80.3	72.1	62.7	21584
SDB_BR_PD (18)	400	2000	1000	80	65.1	54.8	18233
SDB_BR_PD (19)	200	2000	2000	81.5	71	61.8	20955
SDB_BR_PD (20)	200	2500	1000	80.5	64.8	55.6	17985

Table 3B.11 – Treatment Train Sizing Combinations with Vegetated Swale, Bioretention and Retention Pond

Sizing Combination	Vegetated Swale Area (m^2)	Bioretention Area (m^2)	Retention Pond Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SW_BR_PD (1)	500	500	4500	81.5	77.3	71.2	26639
SW_BR_PD (2)	1000	500	3500	80.9	75	66.2	25211
SW_BR_PD (3)	1500	500	3000	81.3	74.2	63.5	24912
SW_BR_PD (4)	2000	500	2500	80.9	73.1	60.1	24377
SW_BR_PD (5)	2500	500	2000	80.1	70.9	56	23643
SW_BR_PD (6)	3000	500	1500	80.3	69	51.7	22706
SW_BR_PD (7)	3500	500	1000	80	67.4	47	21518
SW_BR_PD (8)	4000	500	1000	81.1	68	48.5	22393
SW_BR_PD (9)	5000	500	1000	83.6	70.8	51.4	24037
SW_BR_PD (10)	500	1000	3500	81	75.1	67.7	25214
SW_BR_PD (11)	1000	1000	3000	81.4	74.2	64.8	25226
SW_BR_PD (12)	1500	1000	2500	81.2	73.5	61.7	24852
SW_BR_PD (13)	2000	1000	1500	80.3	68.3	53.4	22308
SW_BR_PD (14)	2500	1000	1000	80.5	66.1	48.7	21251
SW_BR_PD (15)	3000	1000	1000	81.8	67.6	49.8	22227
SW_BR_PD (16)	3500	1000	1000	83.2	68.6	51.1	23146
SW_BR_PD (17)	500	1500	2500	80.4	70.9	62.2	23229
SW_BR_PD (18)	1000	1500	2000	80.1	70.4	59	23071
SW_BR_PD (19)	1500	1500	1500	80.7	68.3	55.1	22471
SW_BR_PD (20)	2000	1500	1000	81.1	66.4	51.3	21517
SW_BR_PD (21)	500	2000	2000	80.7	70	61.6	22600
SW_BR_PD (22)	1000	2000	1500	82.3	68.3	57.1	22312
SW_BR_PD (23)	500	2500	1500	81.5	68.1	59.3	21737

Table 3B.12 – Treatment Train Sizing Combinations with Swale, Bioretention and Wetland

Sizing Combination	Swale Area (m^2)	Bioretention Area (m^2)	Wetland Area (m^2)	TSS Removal Efficiency (%)	TP Removal Efficiency (%)	TN Removal Efficiency (%)	Equivalent Annual Cost ($)
SW_BR_WL (1)	5000	500	1000	84	71.3	51	22330
SW_BR_WL (2)	4500	500	1000	82.3	69.4	49.7	21523
SW_BR_WL (3)	4000	500	1000	81.2	68.4	47.9	20685
SW_BR_WL (4)	3500	500	1500	81.8	71.3	53.1	21423
SW_BR_WL (5)	3000	500	1500	80.7	70.1	52	20503
SW_BR_WL (6)	2500	500	2000	82	72.9	56.4	20991
SW_BR_WL (7)	2000	500	2500	82.9	74.3	61	21305
SW_BR_WL (8)	1500	500	2500	81	72.7	60.5	20152
SW_BR_WL (9)	1000	2500	1000	81.8	67.1	55	19548
SW_BR_WL (10)	500	2500	1500	81.7	69.5	59.6	19535
SW_BR_WL (11)	1000	500	3500	83.4	77.8	68.6	21359
SW_BR_WL (12)	500	500	4000	82.6	78.4	70.6	20917
SW_BR_WL (13)	1500	2000	1000	81.1	67.8	52.9	19811
SW_BR_WL (14)	1000	2000	1500	82	69.6	57.8	20110
SW_BR_WL (15)	500	2000	2000	82.1	71.5	61.8	19948
SW_BR_WL (16)	2500	1500	1000	82.4	68.5	52	20859
SW_BR_WL (17)	2000	1500	1000	80.5	67	50.6	19810
SW_BR_WL (18)	1500	1500	1500	80.6	69.4	55.8	20269
SW_BR_WL (19)	1000	1500	2000	81.7	71.9	60	20419
SW_BR_WL (20)	500	1500	2500	80.8	73.5	63.6	20157
SW_BR_WL (21)	3500	1000	1000	82.6	68.8	51	21439
SW_BR_WL (22)	3000	1000	1000	81.6	68	48.8	20519
SW_BR_WL (23)	2500	1000	1500	82.3	71.2	54.7	21156
SW_BR_WL (24)	2000	1000	1500	81.2	69.6	53.1	20106
SW_BR_WL (25)	1500	1000	2000	80.7	71.7	58.2	20417
SW_BR_WL (26)	1000	1000	2500	80.9	73.2	61.6	20466
SW_BR_WL (27)	500	1000	3000	81.4	74.6	65.6	20130

Appendix 3C - Statistical summary of the Performance Measures for all Treatment Trains

Treatment Train	Statistics	Objectives											
		Environmental							Economic				Social
		Performance Measures											
		Annual TSS Load Reduction (Kg)	Annual TP Load Reduction (Kg)	Annual TN Load Reduction (Kg)	Cu Removal (%)	Zn Removal (%)	Peak Flow Reduction (%)	Habitat Creation	Potable Water Savings (ML/yr)	Equivalent Annual Cost ($)	Capital Cost ($)	Annual Operation and Maintainace Cos	Improvement of Liveability
	Number of Treatment Trains	10											
	Mean	46490.00	72.11	422.70	73.57	84.23	42.31	0.014	51.16	13831.70	278620.74	8259.29	0.010
	Standard Deviation	597.12	4.88	13.23	1.34	5.57	4.19	0.003	25.88	657.98	28431.14	272.13	0.001
	Co efficient of Variation	0.01	0.07	0.03	0.02	0.07	0.10	0.189	0.51	0.05	0.10	0.03	0.070
	Minimum	45600.00	63.80	406.00	71.50	72.70	37.70	0.011	16.50	12353.73	225236.12	7826.29	0.009
Sedimentation Basin and Bioretention	Maximum	47200.00	79.20	441.00	75.20	90.50	49.20	0.018	86.50	14679.52	321833.18	8554.78	0.012
	Number of Treatment Trains	10											
	Mean	46850.00	88.45	581.50	83.32	84.78	80.32	0.026	68.50	23477.20	627231.30	10932.50	0.022
	Standard Deviation	594.89	1.38	25.09	4.50	7.78	5.41	0.004	6.31	1249.12	44595.50	385.64	0.003
	Co efficient of Variation	0.01	0.02	0.04	0.05	0.09	0.07	0.163	0.09	0.05	0.07	0.04	0.132
	Minimum	45400.00	86.60	543.00	76.30	66.20	69.30	0.020	60.00	21258.00	552442.00	10209.00	0.018
Sedimentation Basin and Retention Pond	Maximum	47400.00	90.90	615.00	88.70	91.30	85.00	0.032	79.00	25229.00	691340.00	11402.00	0.026
	Number of Treatment Trains	10											
	Mean	45360.00	86.65	557.70	77.06	82.95	62.90	0.014	44.73	17956.90	511037.60	7736.30	0.007
	Standard Deviation	944.22	2.22	29.54	1.52	8.82	6.09	0.003	4.67	553.03	15341.60	248.51	0.004
	Co efficient of Variation	0.02	0.03	0.05	0.02	0.11	0.10	0.189	0.10	0.03	0.03	0.03	0.572
	Minimum	44200.00	82.90	514.00	74.80	69.20	51.90	0.011	36.88	17088.00	485989.00	7369.00	0.002
Sedimentation Basin and Wetland	Maximum	47200.00	90.10	607.00	79.30	92.40	71.40	0.018	51.01	18877.00	535445.00	8168.00	0.013
	Number of Treatment Trains	6											
	Mean	46991.67	80.43	381.83	75.93	91.23	34.07	0.014	156.73	18005.67	363686.00	10731.83	0.009
	Standard Deviation	1083.34	1.22	13.01	2.03	4.62	2.58	0.003	6.06	2441.20	28841.48	2221.43	0.000
	Co efficient of Variation	0.02	0.02	0.03	0.03	0.05	0.08	0.222	0.04	0.14	0.08	0.21	0.046
	Minimum	45600.00	78.80	374.00	73.70	83.80	31.70	0.011	146.25	14064.00	331815.00	7428.00	0.009
Sedimentation Basin and Swale	Maximum	48300.00	81.60	407.00	78.60	96.50	38.50	0.019	162.79	20848.00	406018.00	13096.00	0.010
	Number of Treatment Trains	10											
	Mean	47992.00	69.74	389.20	75.94	91.35	44.58	0.021	68.08	14698.60	305092.50	8596.80	0.010
	Standard Deviation	681.14	3.46	16.45	1.57	3.52	3.66	0.002	15.92	927.88	42362.77	152.76	0.001
	Co efficient of Variation	0.01	0.05	0.04	0.02	0.04	0.08	0.088	0.23	0.06	0.14	0.02	0.080
	Minimum	47000.00	65.40	366.00	73.50	83.60	40.60	0.019	49.54	13528.00	248625.00	8416.00	0.009
Swale and Bioretention	Maximum	49160.00	75.20	425.00	78.40	95.20	52.60	0.025	96.01	16227.00	372887.00	8854.00	0.012

Statistical Summary Continued..

	Number of Treatment Trains							10					
	Mean	46530.00	85.05	491.60	74.76	88.70	44.12	0.024	49.30	18680.20	458773.50	9504.90	0.015
	Standard Deviation	449.81	3.80	70.86	2.34	6.31	9.82	0.002	10.18	397.31	16012.17	423.26	0.003
	Co efficient of Variation	0.01	0.04	0.14	0.03	0.07	0.22	0.067	0.21	0.02	0.03	0.04	0.236
	Minimum	45800.00	78.80	383.00	71.60	73.50	35.10	0.022	31.70	18121.00	429759.00	8636.00	0.010
Swale and Wetland	Maximum	47200.00	90.10	598.00	78.20	95.50	63.10	0.027	64.83	19390.00	474997.00	10044.00	0.021
	Number of Treatment Trains							10					
	Mean	46790.00	84.95	507.60	75.04	85.40	62.91	0.026	87.20	23241.40	542925.80	12382.90	0.017
	Standard Deviation	517.37	3.99	72.31	2.17	8.04	17.09	0.003	17.45	1675.04	71645.18	333.42	0.005
	Co efficient of Variation	0.01	0.05	0.14	0.03	0.09	0.27	0.127	0.20	0.07	0.13	0.03	0.288
	Minimum	45700.00	78.70	412.00	71.30	71.90	40.70	0.022	59.00	20560.00	445027.00	11659.00	0.011
Swale and Retention Pond	Maximum	47400.00	91.00	617.00	78.40	93.30	84.90	0.032	109.00	25782.00	659405.00	12843.00	0.025
	Number of Treatment Trains							44					
	Mean	48062.50	76.83	368.50	78.43	91.10	37.08	0.021	31.33	21367.50	393579.25	13495.90	0.010
	Standard Deviation	451.03	1.40	17.60	1.35	3.60	5.45	0.002	13.05	647.80	10985.92	454.83	0.001
	Co efficient of Variation	0.01	0.02	0.05	0.02	0.04	0.15	0.110	0.42	0.03	0.03	0.03	0.094
	Minimum	47450.00	75.00	348.00	76.40	87.60	31.80	0.019	20.83	20472.20	377322.00	12925.70	0.009
Sedimentation Basin, Swale and Bioretention	Maximum	48470.00	78.40	388.00	79.20	95.70	43.80	0.024	47.96	21852.80	401371.00	13912.30	0.011
	Number of Treatment Trains							41					
	Mean	46560.00	83.90	460.60	74.32	83.28	54.84	0.017	93.14	21762.20	495018.20	11861.80	0.010
	Standard Deviation	492.95	1.57	26.83	1.31	11.66	10.13	0.002	6.30	977.42	33384.35	330.12	0.001
	Co efficient of Variation	0.01	0.02	0.06	0.02	0.14	0.18	0.090	0.07	0.04	0.07	0.03	0.091
	Minimum	46200.00	81.40	416.00	72.70	63.00	37.70	0.015	87.40	20479.00	445909.00	11537.00	0.008
Sedimentation Basin, Swale and Retention Pond	Maximum	47100.00	85.50	483.00	76.20	92.70	63.10	0.019	103.36	22874.00	530279.00	12268.00	0.011
	Number of Treatment Trains							44					
	Mean	46700.00	85.70	459.00	74.20	87.95	39.15	0.016	55.22	19135.50	475621.50	9623.00	0.014
	Standard Deviation	141.42	0.99	16.97	0.85	5.44	4.03	0.001	2.52	594.68	18371.34	227.69	0.001
	Co efficient of Variation	0.00	0.01	0.04	0.01	0.06	0.10	0.083	0.05	0.03	0.04	0.02	0.069
	Minimum	46600.00	85.00	447.00	73.60	84.10	36.30	0.015	53.43	18715.00	462631.00	9462.00	0.013
Sedeimentation Basin, Swale and Wetland	Maximum	46800.00	86.40	471.00	74.80	91.80	42.00	0.017	57.00	19556.00	488612.00	9784.00	0.014
	Number of Treatment Trains							20					
	Mean	50904.00	94.20	607.65	80.48	89.38	67.35	0.021	63.85	21571.05	485268.36	11865.69	0.016
	Standard Deviation	751.85	3.13	55.02	1.34	4.26	11.62	0.003	10.87	2062.96	71656.78	659.10	0.003
	Co efficient of Variation	0.01	0.03	0.09	0.02	0.05	0.17	0.164	0.17	0.10	0.15	0.06	0.170
	Minimum	50260.00	87.60	539.00	77.90	76.70	50.90	0.015	43.90	17985.47	361517.61	10755.12	0.012
Sedimentation Basin, Bioretention and Retention Pond	Maximum	53880.00	99.20	801.00	82.90	96.90	84.80	0.029	82.95	24993.91	614365.47	12706.60	0.023
	Number of Treatment Trains							23					
	Mean	47221.74	79.17	447.74	74.62	87.26	51.35	0.023	101.23	23330.30	469752.30	13935.35	0.014
	Standard Deviation	481.99	4.58	58.98	1.70	3.61	14.67	0.002	14.47	1469.73	58036.18	399.39	0.003
	Co efficient of Variation	0.01	0.06	0.13	0.02	0.04	0.29	0.102	0.14	0.06	0.12	0.03	0.224
	Minimum	46500.00	70.10	353.00	72.00	81.10	32.20	0.019	68.05	21251.00	394283.00	13287.00	0.010
Swale, Bioretention and Retention Pond	Maximum	48550.00	86.10	570.00	78.80	94.30	82.70	0.029	128.58	26639.00	615107.00	14592.00	0.022
	Number of Treatment Trains							27					
	Mean	47239.63	80.31	453.89	74.47	89.26	40.37	0.023	59.41	20588.41	440030.59	11787.85	0.014
	Standard Deviation	535.76	4.24	58.82	1.73	4.32	8.14	0.001	7.80	683.79	24331.42	447.81	0.002
	Co efficient of Variation	0.01	0.05	0.13	0.02	0.05	0.20	0.064	0.13	0.03	0.06	0.04	0.172
	Minimum	46200.00	70.30	381.00	71.30	80.00	13.00	0.021	41.00	19535.00	397294.00	11061.00	0.011
Swale Bioretntion and Wetland	Maximum	48240.00	89.00	601.00	78.40	98.40	53.00	0.027	71.00	22330.00	488586.00	12823.00	0.020
	Number of Treatment Trains							20					
	Mean	46602.50	82.75	504.35	75.25	86.82	47.50	0.020	53.40	18269.00	440722.45	9454.50	0.015
	Standard Deviation	474.75	3.22	79.17	1.29	4.30	6.47	0.003	6.32	833.84	31042.51	321.02	0.002
	Co efficient of Variation	0.01	0.04	0.16	0.02	0.05	0.14	0.140	0.12	0.05	0.07	0.03	0.130
	Minimum	45800.00	75.10	418.00	72.90	79.60	34.00	0.015	43.00	16278.00	364529.00	8816.00	0.012
Sedimentation Basin, Bioretention and Wetland	Maximum	47450.00	88.10	801.00	77.30	94.40	58.00	0.024	65.00	19597.00	487802.00	10035.00	0.019

Appendix 4A - Delphi Survey – Round 1

Online Survey

Investigation of the performance measures in selecting stormwater management Green Infrastructure (GI) practices for industrial areas

Title of the broader research: Optimization of Green Infrastructure (GI) Practices for Industrial Areas

Investigator: Victoria University (VU), Melbourne

Questionnaire – Round 1 (of 4)

Based on an extensive literature review and having initial discussions with several stakeholders, some of the most important performance measures considered in stormwater management GI selection for an industrial area were identified.

Considering three broad objectives (environmental, economic and social), 12 performance measures which influence the GI selection are initially identified. The performance measure names and their descriptions are shown in the following table.

Note: These performance measures may vary for different sites. The major aim of these questionnaires is to identify a set of performance measures that could assist in stormwater management GI selection for industrial areas in general.

Objective	Performance Measure		
	ID	Name	Description
Environmental	PM-1	Annual TSS Load Reduction	The removal ability of TSS, TP and TN through GI. Environmental Impacts TSS – Reducing the visibility and absorbance of light, which can increase stream temperatures and reduce photosynthesis TP and TN – Generation of toxic algal blooms, decreasing the dissolved oxygen, light and habitat available for other aquatic species
	PM-2	Annual TP Load Reduction	
	PM-3	Annual TN Load Reduction	
	PM-4	Heavy Metal Removal (Cu)	The removal ability of heavy metals through GI. Above 70% of industrial facilities have been found to discharge stormwater with elevated levels Zn and Cu amongst heavy metals. Environmental Impacts Cu – Interference with fish sensory systems, migration and behaviours related to predator avoidance of aquatic life Zn – Impaired reproduction and reduced growth in aquatic life
	PM-5	Heavy Metal Removal (Zn)	
	PM-6	Peak Flow Reduction	Ability to attenuate peak flows to reduce flood risks and harmful impacts to the surrounding water bodies
	PM-7	Habitat Creation	Ability for creating or preserving habitats (animals, plants or other organisms) to support biodiversity.
Economic	PM-8	Potable Water Savings	Ability to save potable water which is used for various industrial activities.
	PM-9	Equivalent Annual Cost	Annualized form of the total life cycle cost of GI. This is obtained as the total life cycle cost divided by number of years in the life cycle.
	PM-10	Capital Cost	Capital cost of the stormwater management GI.
	PM-11	Annual Operation and Maintenance Cost	Operation and maintenance costs incurred annually for the GI.
Social	PM-12	Improvement of Liveability	Improvement of the quality of life in the area (e.g. creating leisure/recreational opportunities, visual and aesthetic appeal) through urban greening

Within this round the panel members are expected to,

- Provide some general background information on their expertise in the area
- Rate the above selected performance measures on their importance, which can be used to identify redundant performance measures among them and
- Identify any missing performance measures and propose additional performance measures according to your opinion.

Part One: General Information

This section aims to obtain some basic information on your professional background and experience with stormwater management Green Infrastructure (GI) Practices.

1. Please specify your gender:

○ Male
○ Female

2. What is the sector which best describes your experience related to the study?

○ Public Water Utility
○ Private Water Utility
○ State Government
○ Local Government
○ Urban Planning and Development
○ Consulting
○ Research
○ Other (Please Specify)

3. How many years of experience do you have in the above sector?

- 0 - 2 years
- 2 - 5 years
- 5 - 10 years
- 10 - 20 years
- 20+ years

Part Two: Objectives and Performance Measures

Instructions to participants

In this section, you will be asked to assess the importance of each of the objectives and performance measures we have previously identified as important indicators in selecting GI for an industrial area.

Rate their importance based on your opinion, on 1-5 scale where 1 indicates least important and 5 indicates the most important.

4. Rate the importance of following objectives based on 1-5 scale in selecting GI for stormwater management in an industrial area.

	Not at all Important (1)	Slightly Important (2)	Moderately Important (3)	Very Important (4)	Extremely Important (5)
Environmental Objective	○	○	○	○	○
Economic Objective	○	○	○	○	○
Social Objective	○	○	○	○	○

5. Rate the importance of following performance measures based on 1-5 scale in selecting GI for stormwater management in an industrial area.

	Not at all Important (1)	Slightly Important (2)	Moderately Important (3)	Very Important (4)	Extremely Important (5)
Annual TSS Load Reduction	○	○	○	○	○
Annual TP Load Reduction	○	○	○	○	○
Annual TN Load Reduction	○	○	○	○	○
Heavy Metal Removal (Cu)	○	○	○	○	○
Heavy Metal Removal (Zn)	○	○	○	○	○
Peak Flow Reduction	○	○	○	○	○
Habitat Creation	○	○	○	○	○
Potable Water Savings	○	○	○	○	○
Equivalent Annual Cost	○	○	○	○	○
Capital Cost	○	○	○	○	○
Annual Operation and Maintenance Cost	○	○	○	○	○
Improvement of Liveability	○	○	○	○	○

6. Do you think there are any missing performance measures that should be added to the list of the above identified performance measures?

Please indicate the missing performance measures if there are any, and the reasons why you think the new performance measures should be included in the list.

Dear Panellist,

You have reached the end of questionnaire Round 1 (of 4) of the online Delphi Survey on "Investigation of the performance measures in selecting stormwater management Green Infrastructure practices for industrial zones". Thank you very much for spending your valuable time on this survey. The results of this questionnaire will be analysed soon, and will be included in the development of the Round 2 questionnaire.

We hope that as a respondent of Round 1, you will also provide more inputs and suggestions by participating in Round 2 questionnaire which will be distributed to you within next two weeks.

Thank You.

Best Regards

Research Team,

College of Engineering and Science

Victoria University

Melbourne

Appendix 4B - Delphi Survey – Round 2 (Sample Questionnaire)

Online Survey Round 2 (of 4)

Investigation of the performance measures in selecting stormwater management Green Infrastructure (GI) practices for industrial areas

Title of the broader research: Optimization of Green Infrastructure (GI) Practices for Industrial Areas

We would like to thank you for your responses and input provided through Round 1. The responses provided by expert panel members in Round 1 were used to formulate the questions in this questionnaire (Round 2).

Results Summary - Round 1

- In Round 1, panel members were asked to rate objectives and performance measures in selecting stormwater management Green Infrastructure (GI) for industrial areas, based on 1-5 point rating scale where 1 indicated least important and 5 indicated most important.

Not at all Important (1) Slightly Important (2) Moderately Important (3) Very Important (4) Extremely Important (5)

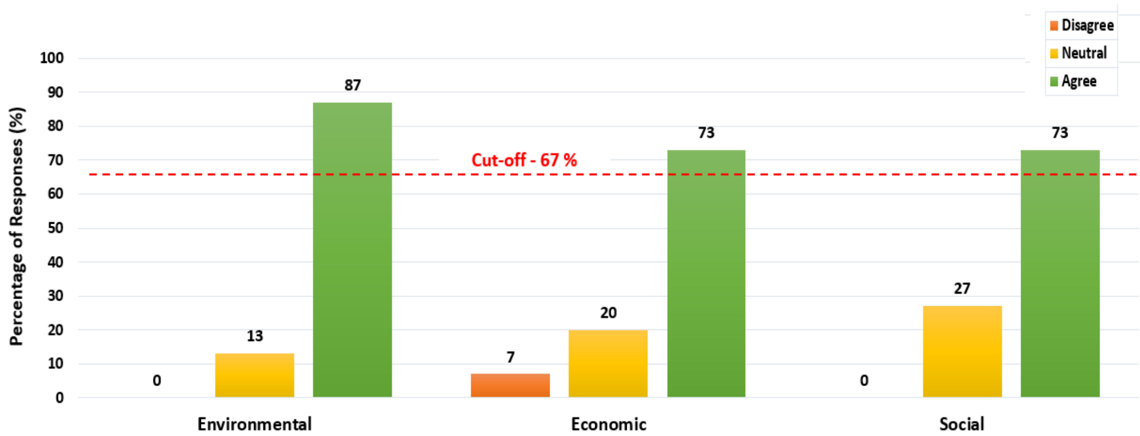
- The responses were categorized as agree, neutral or disagree as follows.

If respondents selected,

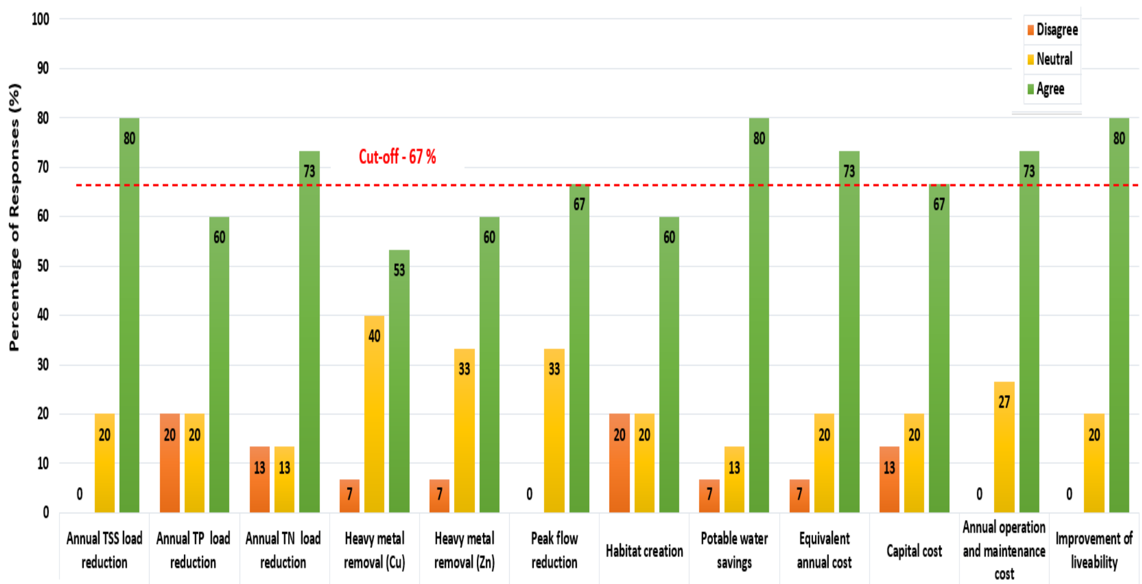
Ratings 1 and 2 - Considered to be "Disagree" with the option
Rating 3 - Considered to be "Neutral" with the option
Ratings 4 and 5 - Considered to be "Agree" with the option

- If 'two thirds' or above from the expert panel (67% or above), 'agreed' with an option it has been considered as important and included in the study.
- If 'two thirds' or above from the expert panel (67% or above) 'disagreed' with an option, it has been considered as redundant.

- The options where 67% of agreement or disagreement level not achieved are forwarded in to this round.



- The expert panel has agreed that all three objectives are important.



- The expert panel members agreed with all the economic and social performance measures.
- The expert panel members have neither agreed or nor disagreed with the environmental performance measures Annual total Phosphorous (TP) load reduction, Heavy metal removal (Cu), Heavy metal removal (Zn), and Habitat creation. These performance measures are further assessed in this round.

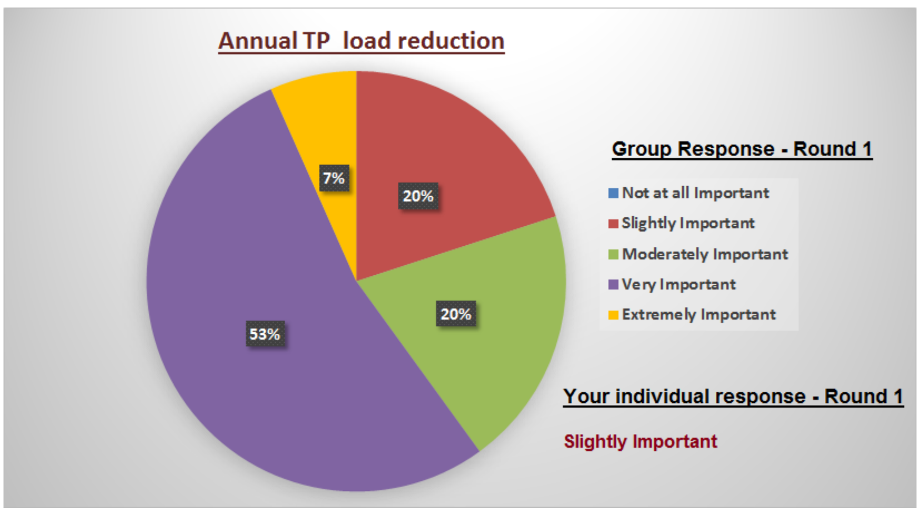
- Furthermore, the additional performance measures proposed by panel members in Round 1 are also assessed in this round.

Questionnaire – Round 2

Instructions to participants

- This section aims to reassess the 4 performance measures that expert consensus has been not achieved in Round 1.
- Your individual feedback from Round 1 is compared with the groups' response and listed for the elements.
- Please reconsider your responses to the elements in the context of group feedback provided.
- You can newly select your responses from the options provided.
- Note: You may select the same rating as you did in Round 1.

1.



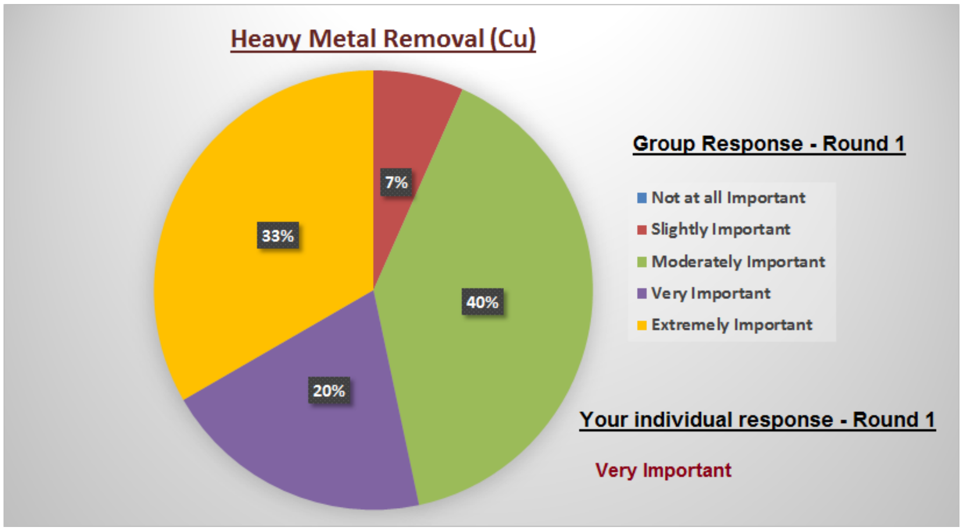
Your Response - Round 2

(You can reconsider your response or you may select the same response as you provided in Round 1)

- Not at all Important
- Slightly Important
- Moderately Important

- Very Important
- Extremely Important

2.

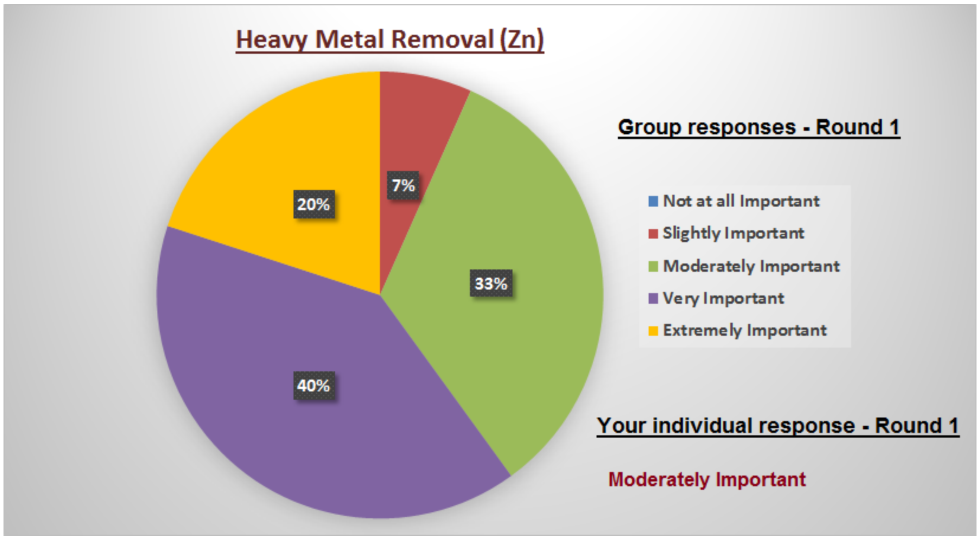


Your Response - Round 2

(You can reconsider your response or you may select the same response as you provided in Round 1)

- Not at all Important
- Slightly Important
- Moderately Important
- Very Important
- Extremely Important

3.

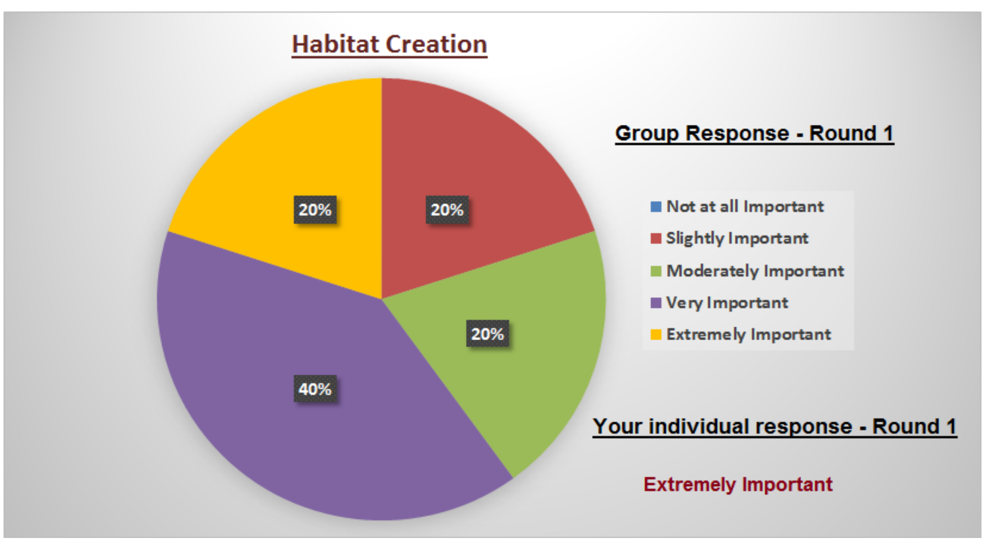


Your Response - Round 2

(You can reconsider your response or you may select the same response as you provided in Round 1)

- Not at all Important
- Slightly Important
- Moderately Important
- Very Important
- Extremely Important

4.



Your Response - Round 2

(You can reconsider your response or you may select the same response as you provided in Round 1)

- o Not at all Important
- o Slightly Important
- o Moderately Important
- o Very Important
- o Extremely Important

Assessment of the additional performance measures proposed in Round 1

Based on the feedback provided by the experts in Round 1, we have identified several new performance measures which can influence the GI selection for industrial areas. The proposed additional performance measures and their descriptions are shown in the following table.

Objective	Proposed New Performance Measures in Round 1	
	Name	**Description**
Environmental	Total runoff volume reduction	The volume of runoff reduced by capture and storage through GI.
	Hydrocarbon removal	Ability of removing hydrocarbons found in industrial runoff that can cause risk to human and environmental health.
	Organic pollutants removal	Ability of removing organic pollutants found in industrial runoff that can cause risk to human and environmental health.
	Heavy metal removal (other)	Ability of removing other heavy metals found in industrial runoff that can cause risk to human and environmental health.
	Urban cooling effect	The ability of reducing the high urban temperatures present in industrial areas through GI.
Economic	Urban food production	Ability of using GI as a source of urban food production (e.g. GI as a source of urban agriculture) for areas with larger space.
	Energy savings	Energy savings benefits provided for the larger buildings in industrial areas by GI practices through cooling and improved building thermal performance.
Social	Industry/ Business's behaviour on accepting GI measure	Measurements on how a group/ organization successfully absorb new approaches, tolerate the change, and respond effectively to GI practices.
	Risk Assessment	The associated risk of the GI measures, which will impose on environment, economy and the society within the industrial and surrounding communities.
	Life cycle period of the GI measure	Life span of the viable performance of GI practice.
	Public safety	Measure of the potential hazard that can be caused by the GI practices to the general public in the area.

5. Rate the importance of the proposed new performance measures for selecting stormwater management GI in an industrial area, based on 1-5 scale.

	Not at all Important (1)	Slightly Important (2)	Moderately Important (3)	Very Important (4)	Extremely Important (5)
Total Runoff Volume Reduction	○	○	○	○	○
Hydrocarbon Removal	○	○	○	○	○
Organic Pollutants Removal	○	○	○	○	○
Heavy Metal Removal (Other)	○	○	○	○	○
Urban Cooling Effect	○	○	○	○	○
Urban Food Production	○	○	○	○	○
Energy Savings	○	○	○	○	○
Industries/ Businesses Behaviour on Accepting GI Measure	○	○	○	○	○
Risk Assessment	○	○	○	○	○
Life Cycle Period of the GI Measure	○	○	○	○	○
Public Safety	○	○	○	○	○

Dear Panellist,

You have reached the end of questionnaire Round 2 (of 4) of the online Delphi Survey on "Investigation of the performance measures in selecting stormwater management Green Infrastructure practices for industrial Areas". Thank you very much for spending your valuable time on this survey. Based on the results of this round, a final set of performance measures will be confirmed. The next round (Round 3) will be used to weight these performance measures and the final round (Round 4) will be conducted to validate the weights. We hope that as a respondent of Round 2, you will also provide your input by participating in Round 3 questionnaire which will be distributed to you within next week.

Thank You.
Best Regards
Research Team,
College of Engineering and Science
Victoria University

Appendix 4C - Delphi Survey – Round 3

Online Survey Round 3 (of 4)

Investigation of the performance measures in selecting stormwater management Green Infrastructure (GI) practices for industrial areas

Title of the broader research: Optimization of Green Infrastructure (GI) Practices for Industrial Areas

- We would like to thank you for your responses provided in identifying the performance measures to select stormwater management GI for industrial areas in Round 1 and Round 2.
- Based on the results of Round 1 and Round 2, we have finalized a set of most important performance measures that can be used to provide decision support in selecting GI for industrial areas.
- In this round, expert panel will be asked to assign weights for each these finalized performance measures.

Results Summary - Round 1 and Round 2

- Based on initial discussions with stakeholders and the review of literature, we have identified objectives (environmental, economic and social) and a set of performance measures that can be used provide decision support for the selection of stormwater management GI for industrial areas.
- In Round 1, panel members were asked to rate these objectives and performance measures, based on 1-5 point rating scale where 1 indicated least important and 5 indicated most important.

The responses were categorized as agree, neutral or disagree as follows.

If respondents selected,

Ratings 1 and 2 - Considered to be " Disagree " with the option

Rating 3 - Considered to be " Neutral " with the option

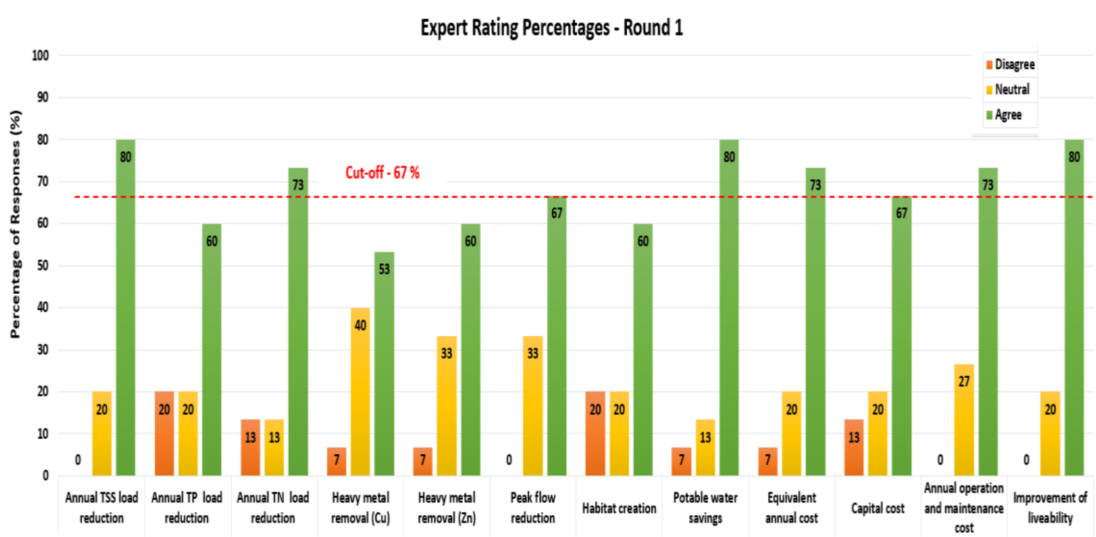
Ratings 4 and 5 - Considered to be " Agree " with the option

- If 'two thirds' or above from the expert panel (67% or above), 'agreed' with an option it has been considered as important and included in the study.
- If 'two thirds' or above from the expert panel (67% or above) 'disagreed' with an option, it has been considered as redundant.
- The options where 67% of agreement or disagreement level not achieved were forwarded in to Round 2.
- After two rounds, the expert panel agreed that almost all the performance measures we initially identified are important.

Furthermore, experts were asked to propose additional or missing performance measures that can be included in the study and rate them into 1-5 scale.

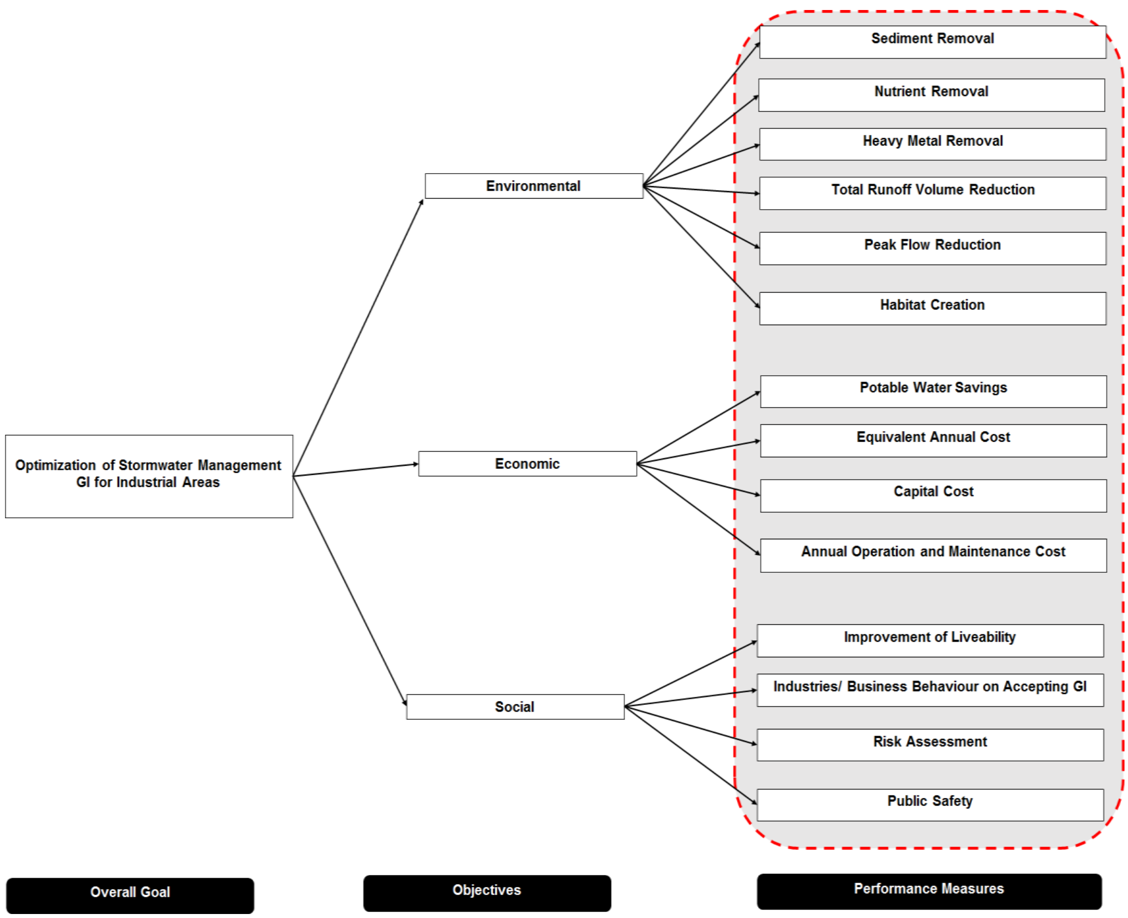
Following bar chart shows the results obtained in Round 2 for the additional performance measures proposed by the expert panel.

Performance Measures



- From the additional performance measures proposed by experts, majority have agreed that Total runoff volume reduction, Industries/ Businesses behaviour on accepting GI measure, Risk assessment and the Public safety are important amongst others.
- Therefore, these performance measures were also included in the existing list of performance measures.
- All the other performance measures will be discussed in details in the next phase of the research.

After the results from Round 1 and Round 2 the finalized set of objectives and performance measures that can influence the selection of stormwater management GI for industrial areas can be represented in a tree diagram as follows.



- The overall goal of this study is to identify optimum stormwater management GI for industrial areas.
- In this round, you will be asked to assign weights for the objectives and performance measures in order to provide decision support in achieving the above mentioned overall goal.

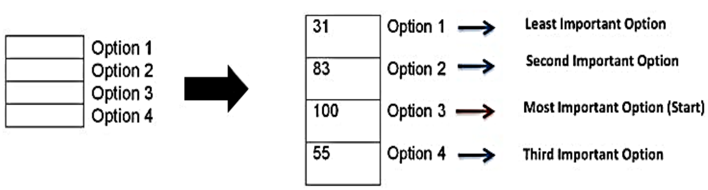
Questionnaire – Round 3

Instructions to Participants

- Please identify the MOST important option from the list below and give it a rating of 100.
- Next, rate each of the other options in turn on a scale of 0–99, to indicate how important they would be compared to the MOST important option in YOUR decision.
- A high rating score means that the option would be important and the value represent how important is the option compared to the MOST important option.

Note: The score of the least important option may not be 0.

Example: Suppose you have asked to rate four options as follows. The ratings can be given as,



When selecting optimum GI for an Industrial area, how do you rate the importance of following objectives?

Please type your rating in each box according to the above instructions, for the following list of objectives.

[ ] Environmental Objective
[ ] Economic Objective
[ ] Social Objective

When the performance measures are considered, how do you rate their importance in selecting optimum GI for an industrial area?

Please type your rating in each box according to the above instructions, for the following list of performance measures.

[ ] Sediment Removal
[ ] Nutrient Removal
[ ] Heavy Metal Removal
[ ] Total Runoff Volume Reduction
[ ] Peak Flow Reduction
[ ] Habitat Creation
[ ] Potable Water Savings
[ ] Equivalent Annual Cost
[ ] Capital Cost
[ ] Annual Operation and Maintenance Cost
[ ] Improvement of Liveability
[ ] Industry/ Business Behaviour on Accepting GI Measure
[ ] Risk Assessment
[ ] Public Safety

Dear Panellist,

You have reached the end of questionnaire Round 3 (of 4) of the online Delphi Survey on "Investigation of the performance measures in selecting stormwater management Green Infrastructure practices for industrial Areas". The weights provided by the expert panel members in this round will be analyzed and the final round (Round 4) will be used to refine and validate these weights. The final round of survey series will be distributed in the first week of April. Thank you very much for spending your valuable time and taking part of this survey series.

Best Regards
Research Team,
College of Engineering and Science
Victoria University
Melbourne

Appendix 4D - Delphi Survey – Round 4 (Sample Questionnaire)

Online Survey Round 4 (of 4)

Investigation of the performance measures in selecting stormwater management Green Infrastructure (GI) practices for industrial areas

Title of the broader research: Optimization of Green Infrastructure (GI) Practices for Industrial Areas

We would like to thank you for your responses provided in identifying and ranking the performance measures to select stormwater management GI for industrial areas in Rounds 1, 2 and 3.

This is the final round (Round 4) of this survey series.

Survey Summary - Rounds 1, 2 and 3

- In Rounds 1 and 2, panel members finalized the objectives and a set of performance measures which are important in selecting stormwater management GI for industrial areas.
- In Round 3, the panel members were asked to provide scores (0-100 scale where 100 represented the most important option) for the objectives and performance measures based on their importance.

Round 3 Results

- Based on your responses in previous round (Round 3), we have calculated the weights of the each option and ranked them.
- This round will present you the group's ranking for each of the options and your individual rankings in the previous round.

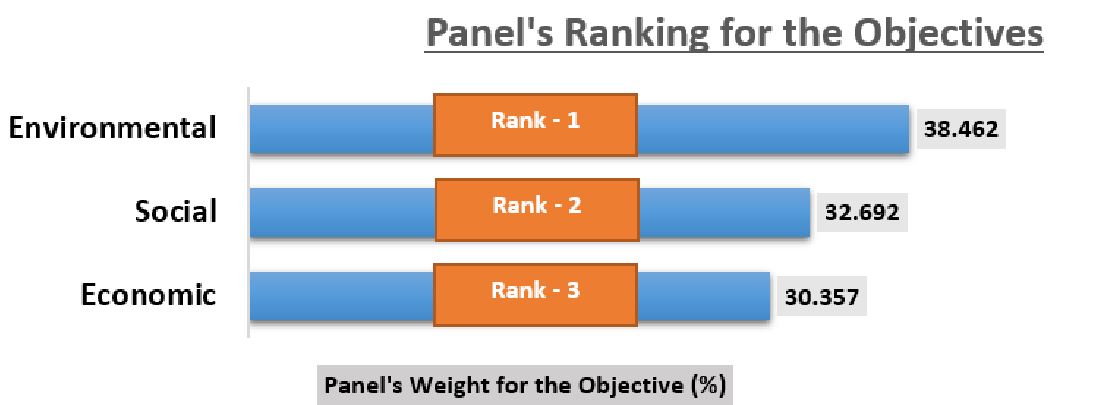
This Round

- In this round, you will be asked to newly rank the options by considering the feedback provided from the previous round. (You may also have the same ranking as you had in previous round.)

Questionnaire – Round 4

Ranking the Objectives

- Based on the scores you have provided for each objective in previous round, we have calculated the weight you have allocated for each of the objective.
- The objective with the highest weight was given the rank 1, which is the most important objective followed by, second important objective as rank 2, third important as rank 3 etc..



- According to the group's response in previous round, environmental objective has ranked as the most important objective (Rank 1), whereas social objective, the second important (Rank 2) and economic objective as the third important objective (Rank 3).
- Following is your individual response in the previous round.

- In the context of group's feedback provided from earlier round, please answer the question 1 given below.
- When answering the question 1, please follow the instructions to the participants which are shown below.

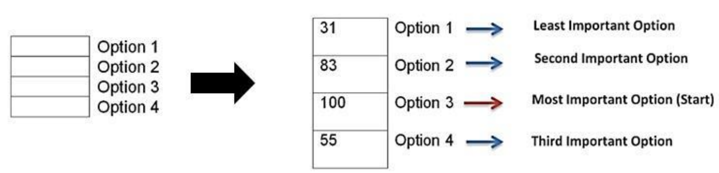
Question 1

Instructions to Participants

- Please identify the MOST important option from the list below and give it a rating of 100.
- Next, rate each of the other options in turn on a scale of 0–99, to indicate how important they would be compared to the MOST important option in YOUR decision.
- A high rating score means that the option would be important and the value represent how important is the option compared to the MOST important option.

Note: The score of the least important option may not be 0.

Example: Suppose you have asked to rate four options as follows. The ratings can be given as,



When selecting optimum GI for an Industrial area, how do you rate the importance of following objectives?

Please type your rating in each box according to the above instructions, for the following list of objectives.

☐ Environmental Objective

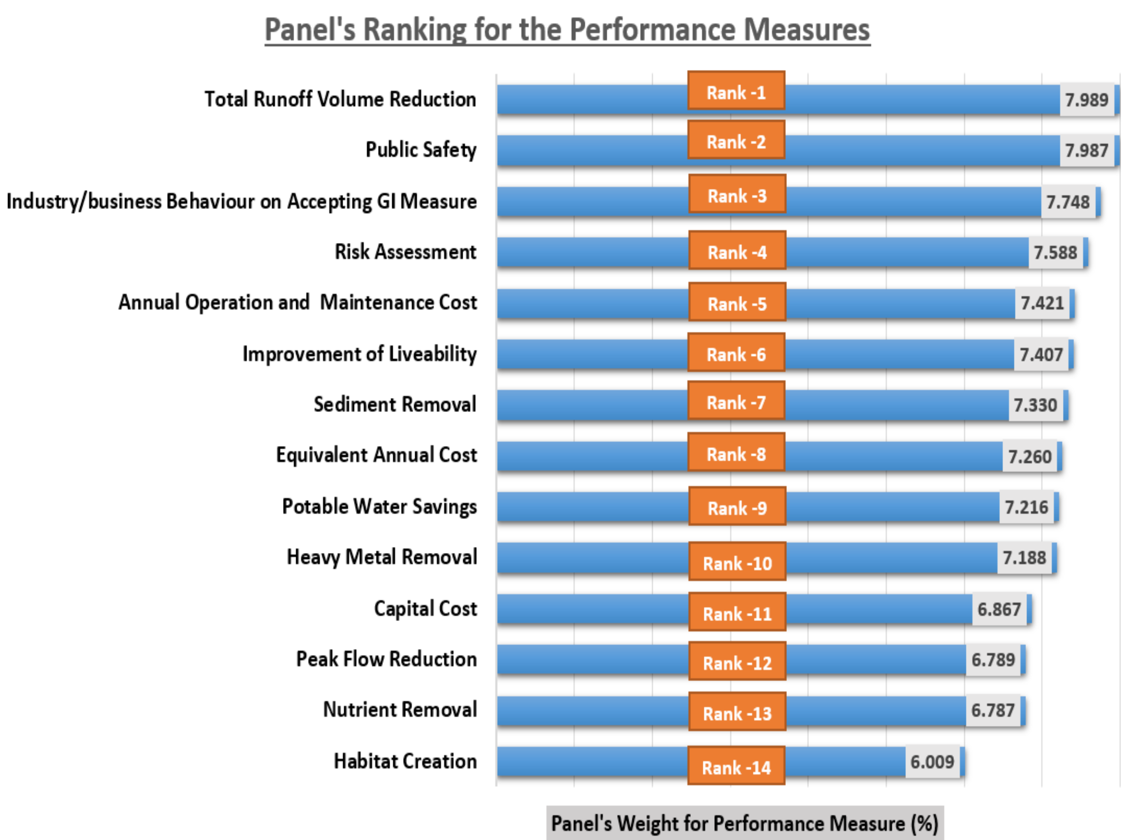
☐ Economic Objective

☐ Social Objective

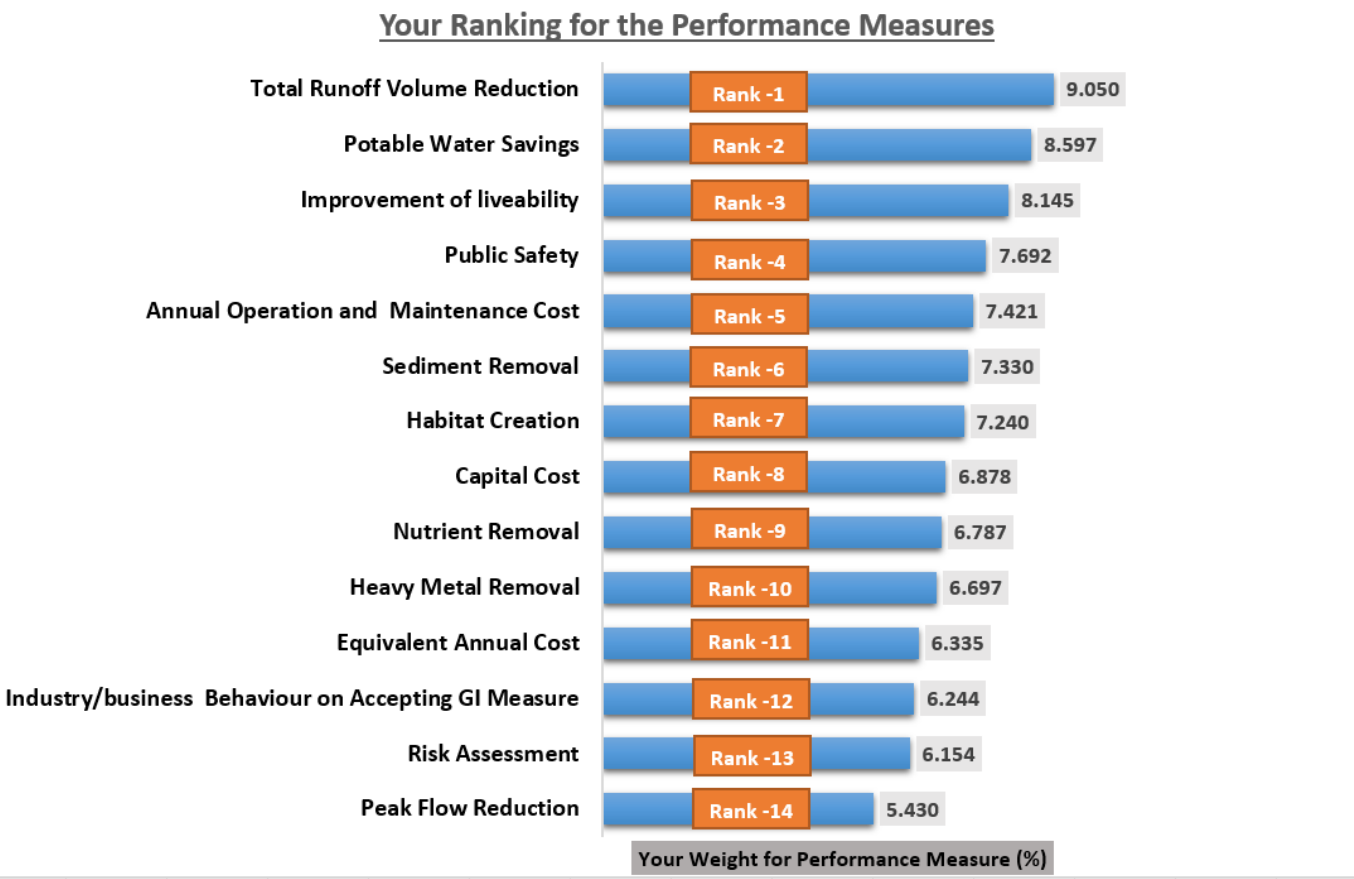
Questionnaire – Round 4

Ranking the Performance Measures

- Based on the scores you have provided for each performance measure in previous round, we have calculated the weight you have allocated for each of the performance measure.
- The performance measure with the highest weight was given the rank 1, which is the most important followed by second important as rank 2, third important as rank 3 etc..



- According to the group's response in previous round, Total Runoff Volume Reduction has ranked as the most important performance measure (Rank 1), whereas habitat creation has ranked as the least important performance measure (Rank 14).
- Following is your individual response in the previous round.



- In the context of group's feedback provided from earlier round, please answer the question 2 given below.
- When answering the question 2, please follow the instructions to the participants which are shown below.

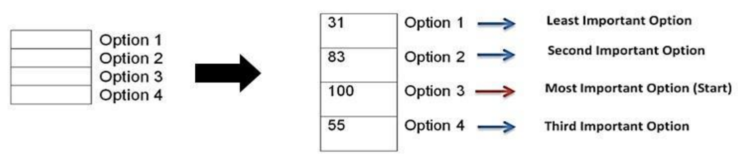
Question 2

Instructions to Participants

- Please identify the MOST important option from the list below and give it a rating of 100.
- Next, rate each of the other options in turn on a scale of 0–99, to indicate how important they would be compared to the MOST important option in YOUR decision.
- A high rating score means that the option would be important and the value represent how important is the option compared to the MOST important option.

Note: The score of the least important option may not be 0.

Example: Suppose you have asked to rate four options as follows. The ratings can be given as,



When all of these performance measures are considered, how do you rate their importance in selecting optimum GI for an industrial area?

Please type your rating in each box according to the above instructions, for the following list of performance measures.

- [ ] Sediment Removal
- [ ] Nutrient Removal
- [ ] Heavy Metal Removal
- [ ] Total Runoff Volume Reduction
- [ ] Peak Flow Reduction
- [ ] Habitat Creation
- [ ] Potable Water Savings
- [ ] Equivalent Annual Cost
- [ ] Capital Cost
- [ ] Annual Operation and Maintenance Cost
- [ ] Improvement of Liveability
- [ ] Industry/ Business Behaviour on Accepting GI Measure
- [ ] Risk Assessment
- [ ] Public Safety

Dear Panellist,

You have reached the end of the questionnaire series on "Investigation of the performance measures in selecting stormwater management Green Infrastructure practices for industrial Areas".

The results of these surveys will be used to identify important parameters in developing a methodology to optimize Green Infrastructure for industrial areas, which is the focus of my PhD research.

Thank you very much for spending your valuable time and taking part of all four rounds of the survey series. Your continuous support provided for my study throughout the last two months is highly appreciated.

Best Regards

Varuni Jayasooriya,
PhD Student,
College of Engineering and Science
Victoria University
Melbourne

Appendix 4E - Calculation of Total Runoff Volume Reduction (Annual) Through GI Practices

Total runoff reduction estimation (CNT, 2010)

$$\textit{Total runoff reduction } (m^3) = \textit{Annual Precipitation } (m) \times \textit{Area of GI practice } (m^2) \times \textit{Percentage Runoff Retained by the GI Practice } (\%)$$

Data used for the calculation

Average annual precipitation (Melbourne) = 650mm

Average annual runoff reduction percentages for various GI Practices (Battiata et al., 2010)

GI Practice	**Annual Percentage Runoff Reduction (%)**
Sedimentation Basin	0
Vegetated Swale	40-60
Bioretention	40-80
Wetland	0
Retention Pond	0

Appendix 4F - Calculation of Total Heavy Metal Removal Ability of GI Practices

Performance Ratings used for the Green Area Ratio Method (refer Appendix 3A) to estimate the heavy metal removal ability of different GI practices (Ragsdale et al., 2008)

Practice	**Heavy Metal Removal Ability**	**Annual Percentage Removal (%)**
Sedimentation Basin	Moderate	50
Vegetated Swale	Moderate	40
Wetland	Moderate	50
Bioretention	High	80
Retention Pond	Moderate	50

Rating	**Percentage Removal**
Low (1)	< 30% Reduction
Moderate (2)	30 % - 80 % Reduction
High (3)	> 80% Reduction

Appendix 5A - Calculation of Building Energy Savings Through Green Roofs And Green Walls

CNT, (2010), Jayasooriya and Ng, (2013)

Annual number of cooling/heating savings (KWh/m^2) = Annual number of cooling / heating degree days (^0C days) × 24 (hrs/day) × Difference between heat transfer coefficients of conventional and green practice ($KWh/m^2 \times {}^0C$ days)

<u>Data used for the calculation</u>

- Annual number of heating and cooling degree days
  - Melbourne - Annual heating degree days 1809 (°C Days)
    - Source : http://www.degreedays.net/
  - Melbourne - Annual Cooling Degree Days 371 (°C Days)
    - Source : http://www.degreedays.net/
- The difference between heat transfer coefficients of conventional and GI practices were obtained from Clark, Adriaens, and Talbot (2008).