Selection and Evaluation of Potential Stormwater Harvesting Sites in Urban Areas

By

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Abstract

Urban cities are universally becoming water stressed due to combined pressures of increasing urbanisation, growing populations, and fluctuating climate change regimes. Therefore, water resource managers are globally developing strategies to ensure water security and associated long term sustainable use. Stormwater harvesting represents one of those strategies which reduces pressure on existing urban water resources, and mitigates the detrimental environmental impacts of urban stormwater runoff on receiving water bodies. Selection of suitable urban stormwater harvesting sites and associated project planning are often complex due to spatial, temporal, economic, environmental and social factors, and associated various other variables. Moreover, the planning of stormwater harvesting projects essentially involves the engagement of diverse stakeholders in the decision making, who may have conflicting views on stormwater harvesting sites and approaches.

This research was aimed at developing a comprehensive methodology for evaluating stormwater harvesting sites in urban areas. The methodology provides information on the selection of suitable stormwater harvesting sites, and then facilitates the ranking of those sites from various stakeholder perspectives in a multi-objective environment. At the first phase of the research work, a GIS based screening tool methodology was developed and applied over a highly urbanised area and a semi-urbanised area in Melbourne, Australia. In the second phase, the evaluation methodology ranked the eight short-listed stormwater harvesting sites obtained from the GIS based screening methodology. The Multi Criteria Decision Analysis (MCDA) was used in ranking these sites under economic, environmental and social objectives, representing the sustainability of stormwater harvesting systems. Nine performance measures (PMs) were identified to characterise the objectives and system performance related to the eight alternative stormwater harvesting sites for the demonstration of the application of developed methodology

To represent the diverse perspectives of stakeholders, four major stakeholder groups, namely water authorities, academics, consultants and councils were identified. A workshop was conducted to obtain stakeholder preferences on PMs in terms of

preference functions and weights, as required by the selected MCDA method, PROMETHEE and associated software, D-Sight. The ranking of eight stormwater harvesting sites was obtained under different group decision making situations, mainly comprising of homogenous and heterogeneous groups of selected stakeholders. Finally, rankings were validated by conducting sensitivity analysis and robustness analysis under various compositions of the stakeholder groups.

The major innovation of this research project is the development of comprehensive methodology that assists in the selection of potential sites for stormwater harvesting, and facilitates the ranking in multi-objective and multi-stakeholder environment. Moreover, the proposed research has demonstrated its effectiveness through its successful application in urban stormwater harvesting decision making (by providing insights in terms of site selection and associated multi-objective evaluation). It is expected that the proposed methodology will assist the water professionals and managers with better knowledge, and will reduce the subjectivity in the selection and evaluation of stormwater harvesting sites dealing with different decision making perspectives.

Declaration

I, Prasad Inamdar, declare that the PhD thesis entitled ‘Selection and Evaluation of Potential Stormwater Harvesting Sites in Urban 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.

Acknowledgements

"The greatest part of an adventure isn't being at the destination, it's the journey to get there."

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List of Publications and Awards

Journal Papers

- Inamdar, P.M., Cook, S., Sharma, A.K., Corby, N., O'Connor, J., Perera, B.J.C., 2013. A GIS based screening tool for locating and ranking of suitable stormwater harvesting sites in urban areas. Journal of Environmental Management 128, 363-370.

Conference Papers

- Inamdar, P., Sharma, A.K., Perera, B.J.C., 2012. Evaluation of Urban Stormwater Harvesting Schemes Using Multi-criteria Assessmenta, Paper presented at 34th Hydrology and Water Resources Symposium, 19-22th December, Sydney, Australia.

- Inamdar, P., Cook, S., Sharma, A., Corby, N., O'Connor, J., Perera, B.J.C., 2011. Development of a GIS Based Screening Tool for Evaluating Stormwater Harvesting Sites in Urban Areas, 19th International Congress on Modelling and Simulation, Perth, Australia, pp. 3307-3313.

Awards

- Finalist in Stormwater Victoria's 2013 Excellence Awards in 'Research and Innovation' Category.

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Abbreviations

The following list of abbreviations is used all through in this thesis. The other abbreviations, which were used only in particular sections/chapters, are defined in those sections/chapters.

AC	Academics
AHP	Analytical Hierarchy Process
CGDM	Collective Group Decision Making
CL	Councils
CS	Consultants
CoB	City of Brimbank
CoM	City of Melbourne
CWW	City West Water
DM	Decision Maker
GDM	Group Decision Making
GDSS	Group Decision Support Software
GIS	Geographical Information Systems
HGDM	Homogenous Group Decision Making
LC	Levelised Cost
MCDA	Multi Criteria Decision Analysis
MCE	Multi Criteria Evaluation
NPV	Net Present Value
PF	Preference Function
PMs	Performance Measures
PROMETHEE	Preference Ranking and Organization METHod for Enrichment Evaluation
PWS	Potable Water Savings
TBL	Triple Bottom Line
TSS	Total Soluble Solids
TP	Total Phosphorous
TN	Total Nitrogen
WA	Water Authority
WSUD	Water Sensitive Urban Design

Chapter 1: Introduction

1.1 Background

"The waters which are from heaven, and which flow after being dug, and even those that spring by themselves, the bright pure waters which lead to the sea, may those divine waters protect me here"

Rig-Veda (Ancient Indian Philosophy)

Since ancient times, the utmost importance of water to mankind for mere existence is well understood. The 21st century is essentially the century of cities and urbanisation, where communities make themselves resilient to climate change, particularly allowing for the sustainable management of water resources and the protection of water environments (Lloyd et al., 2012).

Urbanisation, population growth and extended drought periods have forced many urban cities to utilize water resources carefully with supply restrictions (Goonrey et al., 2007; Lloyd et al., 2001). According to the World Health Organization report (2011), water scarcity is a globally significant and accelerating phenomenon where 768 million people rely on unimproved drinking-water sources and 2.5 billion people lack adequate sanitation. Under this scenario, problems associated with food production, human health and economic development will be compounded with increase in per capita water demand in near future.

Australia is the world's driest inhabited continent, with 89% of its population concentrated in urban cities (Grant et al., 2013). Due to prolonged drought period in last decade, six of the seven Australian state capital cities faced water restrictions, affecting an estimated 70% of the Australian population of 21 million people in 2006 (Fletcher et al., 2008). Therefore, finding adequate water resources to sustain Australian cities is a major challenge to Australian policy makers (Grant et al., 2013).

Since 1997, inflows into Melbourne's four major harvesting reservoirs have been below the long-term average, and the annual inflow in 2006 was the lowest on record (1913-

2006) history till date (Tan and Rhodes, 2008). Moreover, it is also projected that water supplies for Melbourne could be reduced by 20 percent by 2050 (Jones et al., 2005). To worsen this situation, there are future projections of frequent droughts in Australia, along with the decrease in annual average rainfalls, and increased evaporation rates, surface temperature, and sea levels (Pearce et al., 2007).

Greater Melbourne's population is projected to increase from 4.1 to 6.4 million between 2010 and 2056, with 39 per cent of this growth occurring by 2026 (DSE, 2011). With existing patterns of water use and supply, demand for potable water in Melbourne could increase from 356 $GL.yr^{-1}$ to more than 534 $GL.year^{-1}$, requiring a major investment in new supply as early as 2024 (DSE, 2011).

Due to aforementioned environmental and social pressures emerging from the impacts of urbanisation, it is now widely acknowledged that a new approach in urban water management must be established for more sustainable use (Brown, 2005). Alternative water resources within the urban boundary are seen as potable water substitutions and therefore means of augmenting the current supply capacity (Fletcher et al., 2008).

Brown et al. (2008) described six different yet cumulative phases of transitions in urban water management. These transitions are shown in Figure 1.1. As seen in Figure 1.1, each phase of transition has a relevant 'cumulative social-political drivers' and associated measures ('service delivery functions') for water management. The first three transition states (i.e. 'Water Supply City', 'Sewered City' and 'Drained City') describe the historical research phase in urban water management. Then 'Waterways City' and part of the 'Water Cycle City' represent the traditional research phase in urban water management since 70s. The rest of the 'Water Cycle City' and 'Water Sensitive City' transitions phase describe the current approaches and future research directions in urban water management.

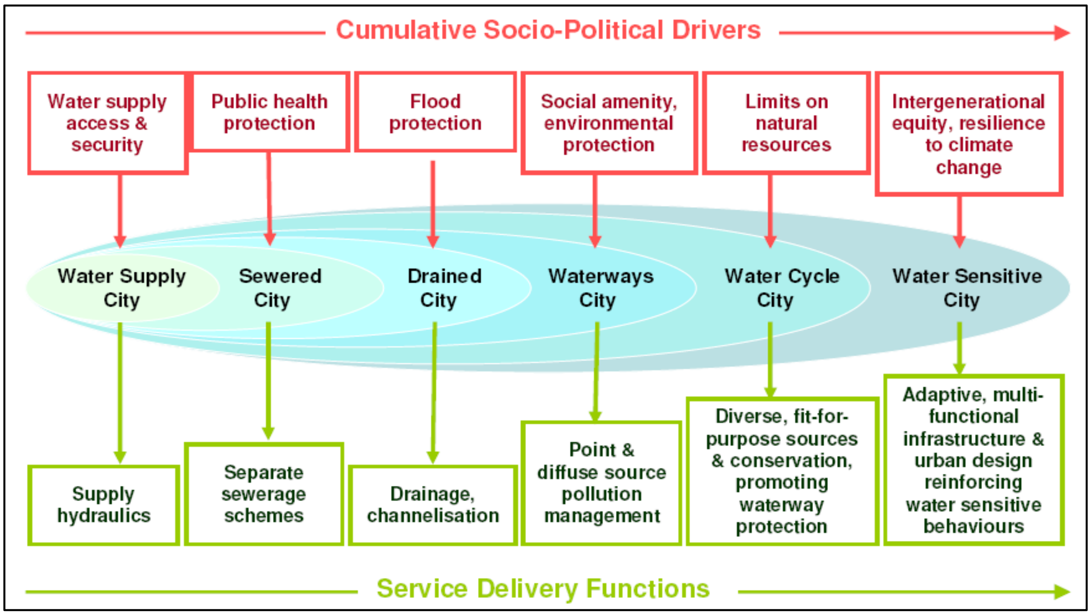

Figure 1.1: Urban Water Management Transitions
[Adopted from (Wong and Brown, 2009)]

Water sensitive cities are defined as the cities which are characterised by principles of Integrated Urban Water Management (IUWM) which include supply security, public health protection, flood protection, waterway health protection, amenity and recreation, greenhouse neutrality, economic vitality, and demonstrable long-term environmental sustainability (Wong and Brown, 2009). Stormwater management is one of key aspects of IUWM which focuses on reusing and recycling of stormwater.

Different countries have defined sustainable stormwater management using different terminologies. The sustainable stormwater management approach has been often termed as ‘LID’ (Low Impact Development) in the USA and Canada, and SUDS (Sustainable Urban Drainage Systems) in the UK. Interestingly, in Japan, ‘LID’ (Land Improvement Districts) stands for the government policies ensuring sustainable use of water and land by establishing sound water circulation systems, providing beautiful landscapes and socioeconomic transformations in rural areas (Swain, 2005). A concept similar to LID (USA) is termed as ‘WSUD’ (Water Sensitive Urban Design) in Australia, which focuses on stormwater quality and flow control before reusing it. WSUD focuses on several structural measures (such as rainwater tanks, infiltration systems, swales, etc.) which are simultaneously used for flood mitigation, water quality improvement and water harvesting. However certain WSUD techniques have been modified and extended for reuse and harvesting of alternative water resources to allow water for multiple purposes such as potable water substitution, flood control and enhanced aesthetics (Mitchell et al., 2007). Furthermore, other non-structural measures (such as community participation, education etc.) are also now included in the WSUD concept.

Stormwater Harvesting: Valuable Alternative Water Resource

Among several alternative water resources available for reuse, stormwater is most preferred by the general public, especially when compared to recycled wastewater (Mitchell et al., 2002). Stormwater harvesting and reuse is a widely used practice which deals with collection, storage, treatment and distribution of stormwater systems (Goonrey et al., 2009; Hatt et al., 2006). Internationally, the terms 'stormwater harvesting', 'rainwater harvesting' and 'water harvesting' have been used interchangeably, whilst they convey similar meaning across different studies (Che-Ani et al., 2009; Hamdan, 2009; Sekar and Randhir, 2007). However, in the Australian context, rainwater harvesting is specifically termed as the collection of rainwater only from rooftops before it hits ground. If not harvested directly from rooftops, rainwater becomes part of stormwater.

According to the literature survey conducted by Philp et al. (2008), many urban water studies focus on wastewater recycling, roofwater harvesting, seawater desalination and groundwater recharge of aquifer compared to stormwater harvesting. Rygaard et al. (2011) analysed 113 urban case studies across different countries related to increasing water self-sufficiency in urban areas. Most of these case studies were in European countries (43%), US (18%) and Australia (17%).

The Santa Monica Urban Runoff Recycling Facility (SMURRF) is one of the prominent stormwater harvesting schemes in California, USA, where stormwater is treated and used for landscape irrigation with dual-pipe reticulation systems (http://www.smgov.net/departments/publicworks/contentciveng.aspx?id=7796). Many of US state governments such as Washington, California, Texas, and Arizona offer financial incentives for localized rainwater harvesting. Roof-rainwater harvesting systems are made compulsory in new construction in Bermuda and the US Virgin Islands (Franca and Anjos, 1998). Stormwater harvesting is also popular in Singapore as this country has implemented a large scale stormwater harvesting scheme through a network of three reservoirs: The Marina Reservoir, The Punggol reservoir and The Serangoon reservoir (PUBoS, 2011). The Australian government strongly encourages the local governments and the water authorities to establish new sources of water including stormwater harvesting through billion dollars of funding annually (DSEWPaC, 2011).

Key benefits of stormwater harvesting have been demonstrated in various studies which include efficient use of existing natural resources, reduction in pollutant loads in the waterways, reduced pressure on existing water infrastructure, and flood control and protection (Mitchell et al., 2007). Frequent changes in flow regime and water quality in urban creeks pose a significant threat to their ecological health and species (Walsh et al., 2005). Stormwater harvesting can assist in the restoration of these urban creeks after careful consideration in design (Fletcher et al., 2007). Stormwater harvesting can reduce the potable water consumption, acting as a supplementary water resource for end uses such as toilet flushing and garden irrigation in the households as well as in the commercial uses.

It is well recognized fact that stormwater harvesting project planning is complex due to many spatial, temporal and social variables such as quantity and quality of runoff, reuse demands, community perceptions, lack of regulations and design criteria, clear design guidelines, and methods to adequately assess costs and benefits of use systems against conventional water supply options (Philp et al., 2008). Furthermore, planning and design process of stormwater harvesting essentially involves engagement of multiple stakeholders in the decision making as different stakeholders have different perceptions on the stormwater harvesting objectives. In this regard, it is imperative that the evaluation of stormwater harvesting sites/schemes should be considered under social, economic and environmental considerations, reflecting the sustainable assessment of schemes.

1.2 Aims of Research

This research is aimed at developing a comprehensive methodology for evaluating stormwater harvesting sites in urban areas. This aim is achieved through conducting research in two key steps.

- Development of a GIS screening tool for obtaining a set of potential stormwater harvesting sites

- Evaluation of these potential stormwater harvesting sites considering economic, environmental and social objectives to facilitate the ranking

In the first phase of the research work, the GIS based screening tool identifies the suitable stormwater harvesting sites in a case study area using innovative concepts of ‘accumulated catchments’ and ‘radius of influence’. In the second phase, the proposed evaluation framework aims to provide recommendations on ranking of stormwater harvesting sites under different perspectives of considered stakeholders. Multi Criteria Decision Analysis (MCDA) evaluation was used to facilitate these rankings under three major objectives representing sustainable stormwater harvesting systems. The long term objectives were considered as follows:

- **Economic:** The stormwater harvesting scheme should be financially viable with acceptable cost to the community.
- **Environmental:** There should be minimum impact on environment and waterways from stormwater harvesting schemes, and water quality of receiving waters should be improved.
- **Social:** The stormwater harvesting scheme should provide maximum benefits to the local community.

The application of the proposed methodology is demonstrated via a case study in the area serviced by City West Water (CWW), one of the local water utility companies in Melbourne. The study additionally considers four stakeholder groups represented by Water Authorities (WA), Academics (AC), Consultants, and City Councils (CL) to reflect the diverse stakeholder preferences in decision making.

This research is expected to assist the water managers in decision making related to selection and evaluation of stormwater harvesting schemes from sustainability perspective.

1.3 Research Methodology

For achieving the aims described in Section 1.2, the key tasks followed were:

1. Development and application of GIS based screening tool methodology
2. Selection of appropriate MCDA method for the study
3. Identification of relevant objectives, alternative sites, and Performance Measures (PMs) for sustainable MCDA evaluation
4. Evaluation of alternative stormwater harvesting sites with respect to selected PMs
5. Preference elicitation from various stakeholder groups
6. Decision analysis of stormwater harvesting sites
7. Sensitivity and robustness analysis for final recommendations

Task 1: Development and application of GIS based screening tool methodology

A critical review of existing GIS based stormwater harvesting site selection approaches was conducted. Based on ideas from existing literature approaches and discussions with water utilities, the GIS based screening tool methodology was proposed. This methodology broadly consists of identification of suitability criteria of runoff and demand, associated data requirements and processing, generation of stormwater harvesting sites through a concept introduced as 'accumulated catchments', consideration of environmental flows, then screening of stormwater harvesting sites through another concept of 'radius of influence', and finally ranking and validation for screened stormwater harvesting sites.

This methodology was applied to two city councils, serviced by City West Water: City of Melbourne (CoM) representing a highly urbanised area and City of Brimbank (CoB) representing a semi urbanised area respectively.

Task 2: Selection of appropriate MCDA method for the study

This task required a comprehensive review of different available MCDA methods/ software. There are no clear guidelines on selecting the single 'best' MCDA method for sustainability analysis of water resource. Moreover, the literature review suggested that, different MCDA methods produce similar ranking results in field of water resource management (Hajkowicz and Higgins, 2008). For the current study, the MCDA method (i.e. PROMETHEE) was selected on the basis of its non-compensatory properties (i.e. not allowing trade-off between objectives), ease of use, and understandability by decision makers. Additionally, there has been a growing trend in the discipline of water resources management to include active engagement and collaboration between stakeholders in policy making and planning processes. The selected MCDA method was found effective in integrating diverse views of stakeholders through its group decision making capabilities.

Task 3: Identification of relevant objectives, alternative sites, and PMs for sustainable MCDA evaluation

In this task, firstly, the long term objectives representing the sustainable stormwater harvesting systems were identified through a literature search and discussions with the officials of the City West Water, who had experience in stormwater harvesting.

The suitable stormwater harvesting sites selected from Task 1 served as alternative sites for the MCDA evaluation. The study selected stormwater harvesting sites from CoM for this task. Then, a complete set of PMs was defined to describe the objectives representing economic, environmental and social aspects of the stormwater harvesting systems. Altogether, a set of nine PMs represented the performance of the stormwater harvesting sites under the three objectives.

The set of nine PMs consisted of two distinct types of PMs: Qualitative and Quantitative. The PMs representing social objectives were qualitative, while PMs representing economic and environmental objectives were quantitative.

Task 4: Evaluation of Performance Measures (PMs)

Performance Measures (PMs) were evaluated to characterise and quantify the alternative stormwater harvesting sites considering economic, environmental and social objectives. The quantification of PMs representing social objectives was based on the qualitative scale derived from the literature review and consultation with City West Water. For quantification of economic and environmental PMs, conceptual designs were developed for all selected alternative stormwater harvesting sites. Conceptual designs evaluation required determining and modelling various infrastructure components of selected alternative stormwater harvesting sites, in terms of sizing, costing, and environmental impacts. Estimated economic, environmental, and social PM values formed an integral part of the 'evaluation matrix', which was used in decision analysis procedure in Tasks 5 and 6.

Task 5: Preference elicitation on PMs from various stakeholder groups

Successful stormwater harvesting schemes essentially require active collaboration between different key stakeholder groups such as local government, the local water authorities and community. To represent the voices of these stakeholders in stormwater harvesting decision making, preference elicitation was conducted. The stakeholder preference parameters served as input for selected MCDA evaluation method, representing the diverse views of stakeholders. Eleven participants belonging to the four identified stakeholder groups namely, Water Authorities (WA), Academics (AC), Consultants (CS), and Councils (CL) expressed their preferences parameters on identified nine PMs. The preference parameters were derived in the form of preference functions and weights, as required by the selected MCDA method.

Task 6: Decision analysis of stormwater harvesting sites

The evaluated PM values of alternative stormwater harvesting sites (Task 4) were combined with preference parameters from stakeholder groups (Task 5) to perform the decision analysis in the form of ranking of stormwater harvesting sites. The decision analysis was conducted under two unique group decision making (GDM) scenarios, namely, Homogeneous Group Decision Making (HGDM) and Collective Group Decision Making (CGDM). The HGDM scenario facilitated decision analysis from each homogenous sub-group of stakeholders (WA, AC, CS and CL), while the CGDM scenario facilitated the collective decision analysis with the selective representative stakeholders from each sub-group of HGDM scenario. The final rankings were derived under the three additional hypothetical yet realistic GDM situations. These GDM situations demonstrated the effectiveness of decision analysis under different compositions and weights assigned to stakeholders, reflecting their importance in decision making.

Task 7: Sensitivity and robustness analysis for final recommendations

In this final task, a sensitivity analysis was carried out to ascertain the validity of ranking results under both GDM situations in Task 6. This procedure briefly consisted of observing the change in final rankings of stormwater harvesting sites with respect to variation in the weights, among group of stakeholders. The sensitivity analysis was followed by a robustness analysis which examined the stability of top ranked stormwater harvesting sites under different group compositions and weights. Finally, recommendations for suitable stormwater harvesting sites for the case study were made based on the results of the decision analysis (Task 6), and sensitivity and robustness analysis.

1.4 Research Significance and Innovation

Urban cities are universally experiencing the water stress due to increased water demand, driven by population growth and fluctuating climate change regimes. These challenges drive the need for a paradigm shift in the management of urban water services, in order to build resilient water sensitive cities which support sustainability and long-term reliability of urban water services.

Stormwater can play a much larger part in meeting Melbourne’s increasing water demands. For example, in year 2009–10, only 10 GL of stormwater was reused out of available 463 GL (DSE, 2011). Moreover, stormwater harvesting and reuse has been emerged as publicly accepted practice of sustainable water management, providing multiple benefits and importantly, securing water supply for cities. Under the *National Urban Water and Desalination Plan,* the Australian Government has committed a minimum of $200 million for urban stormwater harvesting and reuse projects, to ensure the security of water supplies (DEWHA, 2012), Evaluation of stormwater harvesting is often tedious due to significant unpredictability in physical stormwater characteristics, demand patterns and social acceptability, and several institutional and political factors. Moreover, successful stormwater harvesting projects need active collaboration and participation from different stakeholders such as State Governments, water industry, and community. These stakeholders can have their own perceptions, which may cause conflict in the desired economic, environmental, and social objectives expected from stormwater harvesting projects.

The present study has attempted to strengthen the decision making aspect of stormwater harvesting under multi-objective and multi-stakeholder environment. The comprehensive methodology proposed in this study can provide information on suitable stormwater harvesting site selection in urban areas and also can provide multi-objective evaluation of stormwater harvesting sites under the diverse views of stakeholders. The proposed methodology benefits from a combined approach of two distinct and unique methodologies: Geographical Information Systems (GIS), and Multiple Criteria Decision Analysis (MCDA).

The GIS based screening tool methodology developed in the present study has advantages in terms of identifying the suitable stormwater harvesting sites at preliminary investigation level, rather than using existing ad-hoc approaches based on knowledge of the study area. This methodology is substantially innovative as it facilitates the spatial assessment of runoff and demand for stormwater harvesting sites using a concept called ‘accumulated catchment’. The suitable stormwater harvesting sites obtained from the GIS based screening tool can then be used for detailed MCDA assessment.

The MCDA methodology used in the current study has advantages in terms of providing holistic assessment of considered stormwater harvesting sites from economic, environmental and social objectives of sustainability. More importantly, the MCDA evaluation in this study provides the ranking recommendations for considered stormwater harvesting sites from individual and combined perspectives of different stakeholders; represented by water authorities, academics, stormwater consultants and local councils.

The proposed GIS-MCDA evaluation methodology has demonstrated its successful application in urban areas. It is also applicable in peri urbanised/greenfield developments. Existing stormwater harvesting evaluation frameworks lack such comprehensive assessment of stormwater harvesting sites, and hence proposed methodology is innovative in terms of providing conclusive decision aid to stormwater harvesting evaluation in general.

1.5 Thesis Structure

The thesis is organised in seven chapters as shown in Figure 1.2 (end of this Chapter). The detailed explanation of each chapter is explained below.

Chapter 1 describes the challenges of urban water resource management and associated future consequences. In this context, the chapter highlights the importance of stormwater harvesting. Then, it describes the aims of this research project. The chapter further summarises the various tasks associated with the research methodology, providing a brief overview of the whole research project. Finally, significance and innovation of the proposed research is emphasized.

Chapter 2 describes the importance and benefits of the GIS-MCDA approach for evaluation of stormwater harvesting sites. Then, the chapter elaborates on the theoretical foundations of GIS and presents a comprehensive literature review on GIS based site suitability methodologies and their application in stormwater harvesting studies. It then provides a comprehensive literature review of different MCDA methods. Finally, the chapter provides justification for the selected MCDA method along with a description of its methodology and associated software. It should be noted that the relevant literature review associated with different tasks (Section 1.4) is also presented in Chapters 4, 5 and 6.

Chapter 3 is focussed on developing a robust methodology and its application for evaluating and ranking suitable stormwater harvesting sites using GIS at the preliminary level of decision making. The chapter explains in detail the GIS based screening tool methodology developed in the study. Furthermore, the chapter describes the background information on study area of City West Water (CWW), along with description of two councils, City of Melbourne (CoM) and City of Brimbank (CoB) serving as case studies. The chapter then demonstrates the application of the GIS based screening tool to the case study councils representing a highly urbanised area (CoM) and a semi urbanised area (CoB) to short-list and rank suitable stormwater harvesting sites.

Chapter 4 focuses on evaluation of different PMs with respect to selected alternative stormwater harvesting sites. It details the objectives and PMs selected for describing the performance of stormwater harvesting systems in the context of general stormwater harvesting systems and the current case study. Additionally, the chapter elaborates on the alternative stormwater harvesting sites selected for the MCDA assessment, including their site specific characteristics. It then provides a comprehensive methodology including conceptual designs to evaluate the selected PMs. Finally, the results of PM evaluations with respect to alternative stormwater harvesting sites are presented in the form of an evaluation matrix.

Chapter 5 explains the role of stakeholder participation in water resources decision-making, the preference elicitation for MCDA outranking methods, input preference parameters required by the chosen MCDA method and associated software tool used for this study, *D-Sight*. It further describes the detailed preference elicitation procedure used for the case study, and presents the modelling results obtained from selected stakeholder groups (Task 5).

Chapter 6 describes the decision analysis process involved in ranking of stormwater harvesting sites in the case study area. The decision analysis results broadly include ranking of stormwater harvesting sites under different decision making situations, and associated sensitivity and robustness analysis. Finally, the chapter provides recommendations for suitable stormwater harvesting sites in the case study area, based on the decision analysis process.

Chapter 7 provides a summary of conclusions drawn from the study, identified limitations of the study, and potential areas of future research.

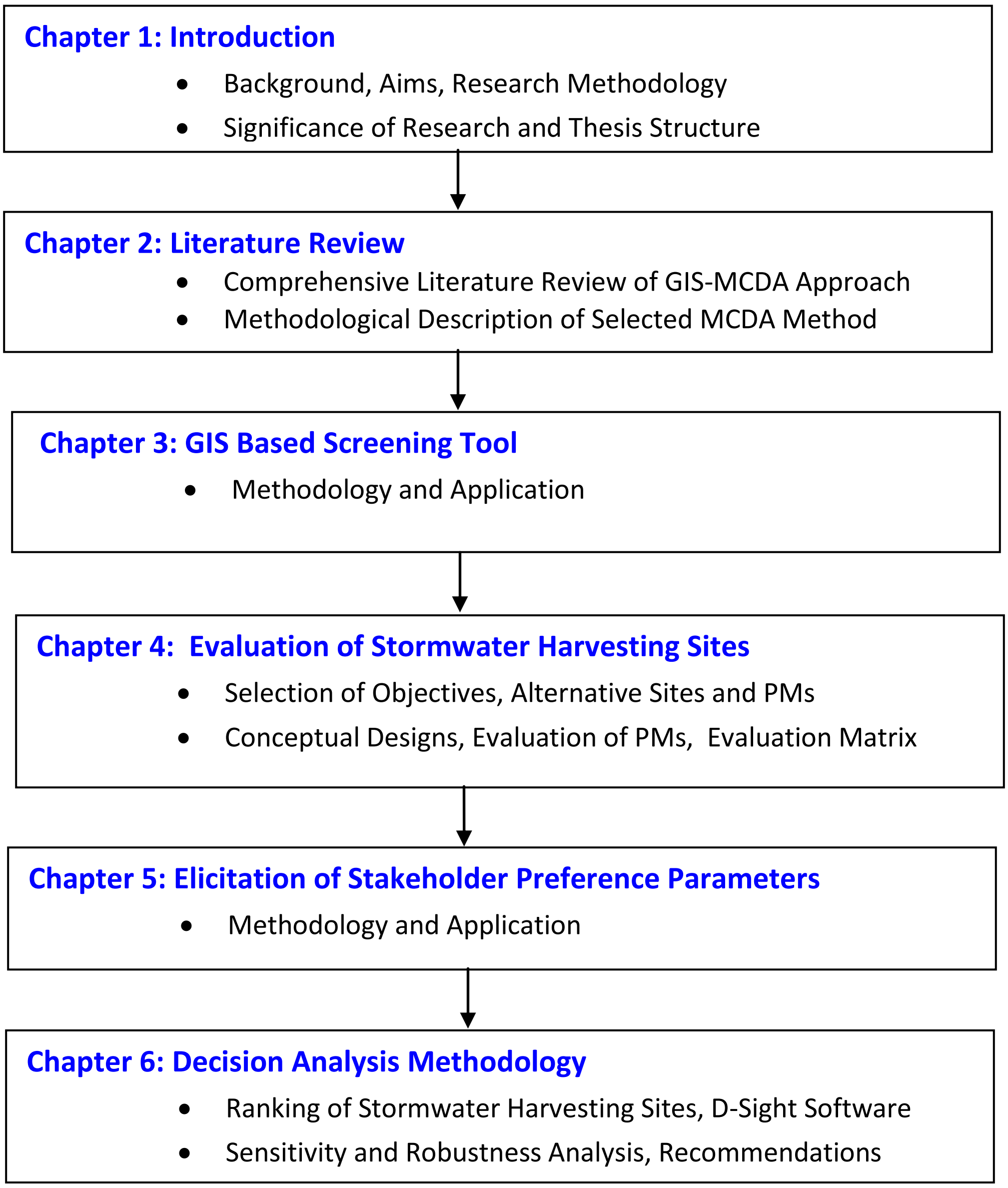

Figure 1.2: Structure of Thesis

Chapter – 2

Evaluation of Stormwater Harvesting Sites: Geographical Information Systems (GIS) and Multi Criteria Decision Analysis (MCDA)

2.1 Introduction

Evaluation of urban water services including stormwater harvesting is generally based on the sustainability principles and certain criteria such that the water systems should be economical, support the environment, and maintain the social acceptability (Sharma et al. 2009). There are various frameworks developed for evaluation of urban water services (Mitchell et al. 2006; Goonrey et al. 2009; Sharma et al. 2009). These frameworks evaluate urban water systems by integrating various analysis methods and tools such as hydrological modelling, water balance analysis, life cycle costing, social analysis as well as stakeholder involvement. These methods and tools are also applicable for the assessment of stormwater harvesting systems.

For evaluation of stormwater harvesting, DEC (2006) broadly classified three major approaches, namely, Economic analysis, Multi Criteria Decision Analysis (MCDA), and Triple Bottom Line (TBL) analysis. Economic analysis methods such as Benefit Cost Analysis (BCA) or Cost Effective Analysis (CEA) are considered as traditional simple evaluation methods. These methods quantify the project costs and benefits in monetary terms for each alternative stormwater harvesting site to facilitate the comparison and consequent decision making. However, economic analysis methods struggle to incorporate the intangibles benefits of stormwater harvesting, such as flood protection, pollution control and societal or aesthetic values of stormwater harvesting schemes (DEC, 2006; Philp et al., 2008; Taylor, 2005).

The MCDA methods provide comprehensive evaluation of stormwater harvesting projects and facilitate the decision aid under considered objectives. This decision aid is facilitated through ranking of stormwater harvesting options under consideration. Furthermore, TBL is a comprehensive approach for assessing costs and benefits of stormwater harvesting schemes in a sustainability context providing equal consideration of environmental, social and economic objectives associated with a given scheme (DEC, 2006).

In Australia, there are TBL guidelines available developed by Taylor (2005), particularly for stormwater management. These guidelines are aimed to assist urban stormwater managers to evaluate the economical, ecological (environmental) and social aspects related to stormwater projects. According to Taylor (2005), all existing TBL studies (related to stormwater management) essentially follow MCDA evaluation methods. However, given the inherent spatial variability of stormwater catchment characteristics, demand patterns and social acceptability, there is no single approach to stormwater harvesting that will be appropriate for all areas (Philp et al., 2008).

Regardless of different approaches used, the evaluation of stormwater harvesting sites is inherently a spatial problem. The performance of stormwater systems in meeting desired objectives will strongly depend on the spatial characteristics of the catchment such as availability of supply (stormwater), intended end use demands, water quality and different distance criteria (e.g. distance to irrigation park/residential area, distance to existing water supply infrastructure etc.) In addition, stormwater harvesting and reuse schemes need significant physical area and financial investment for installing infrastructure systems (i.e. collection, storage, treatment, maintenance systems). Particularly, storage and treatment infrastructure can put constraints on limiting the desired enduses and also may increase the overall costs of the project.

In this regard, the selection of suitable stormwater harvesting sites is of prime importance for urban water infrastructure planners. In Australian cities, generally large scale stormwater harvesting schemes are implemented on existing parks, council reserves, or any other open spaces. Currently, there is no clear guidance available to select the alternative stormwater harvesting sites (and hence the schemes). Existing selection approaches, which are relatively an ad-hoc, use subjective knowledge of urban water managers to shortlist the potential stormwater harvesting schemes. In such context, it is advisable to integrate Geographical Information System (GIS), as they can assist in preliminary decision making through their capability of processing multi-source spatial datasets.

Determining criteria to support a strategy for identifying suitable stormwater harvesting sites requires a biophysical approach, where information based on physically derived catchment characteristics is used for understanding the catchment's hydrological response (De Winnaar et al., 2007). FAO (2003) listed six key factors when identifying water harvesting sites: climate (rainfall), hydrology (rainfall–runoff relationship and intermittent watercourses), topography (slope), agronomy (crop characteristics), soils (texture, structure and depth) and socio-economic (population density, work force, people's priority, experience with rainwater harvesting, land tenure, water laws, accessibility and related costs). Various studies (El-Awar et al. 2000; Mbilinyi et al. 2005; Kahinda et al. 2008) used several physical criteria which deemed to be suitable for stormwater harvesting which included rainfall conditions, runoff, topography, drainage conditions, soil type, distance to storage, etc.

The above criteria are more applicable in rural areas, where there are less spatial constraints for water storages. However, in an urban context, in addition to the issues on less storage space and existing drainage network, the social, institutional and economic factors often put further constraints on locating suitable stormwater harvesting sites. In terms of urban areas, there have been only few studies which provide guidance on GIS based stormwater harvesting site suitability assessment. Thus, there is the need for a GIS based screening tool that can identify sites potentially suited for stormwater harvesting, particularly in urban areas. The current study addresses this issue by developing a GIS based screening tool methodology in Chapter 3.

Apart from site selection, stormwater harvesting project planning is complex and dynamic, where systems are expected to achieve several objectives such as maximizing the reliability, minimizing the public health risks, minimizing the impact on environment, minimizing the supply cost etc. In this context, traditional economic analysis approaches such as BCA/CEA are only useful in assessing the economic viability of stormwater harvesting decisions (DEC, 2006), and these single objective approaches do not consider the dynamics of stormwater harvesting systems. Therefore, focus of urban water managers has been shifted to addressing real world problems with MCDA (Brans, 2002; Kodikara, 2008), which is capable of providing multi-objective assessment of stormwater harvesting systems.

MCDA is a highly recommended popular decision making framework in water resource management decisions including stormwater harvesting (DEC, 2006; Taylor, 2005). As described in Section 2.1, MCDA can provide the ranking of specified stormwater harvesting decisions under conflicting objectives along with different interests of stakeholders. For example, a stormwater harvesting project might have an objective of minimizing the project cost, while at the same time trying to improve aesthetic and social values of the community which may increase the cost of scheme. The MCDA methods can assist decision makers to account for inherent conflicts and trade-offs among such objectives and to rationalize the comparison among different decision options (Kodikara et al., 2010). Moreover, MCDA provides a rich collection of techniques and procedures for structuring the decision problems, and designing, evaluating and prioritizing alternatives (Malczewski, 1999).

Considering the benefits of GIS and MCDA approaches specified above, it is desirable to integrate these approaches in order to develop a comprehensive evaluation framework for stormwater harvesting sites. The GIS can be used to provide information on selection of suitable stormwater harvesting sites and MCDA can facilitate the ranking of sites under economic, environmental and social objectives representing sustainability of stormwater harvesting systems.

The integration of GIS and MCDA has attracted significant interest over the last 15 years despite being two distinctive areas of research (Malczewski, 2006). Malczewski (2006), explained GIS-MCDA approach:

"At the most rudimentary level, GIS-MCDA can be thought of as a process that transforms and combines geographical data and value judgments (the decision-makers preferences) to obtain information for decision making. It is in the context of the synergetic capabilities of GIS and MCDA that one can see the benefit for advancing theoretical and applied research on GIS-MCDA"

The combination of GIS and MCDA thus can considerably enhance the selection process of stormwater harvesting sites, and consequently decision making for stormwater harvesting.

The chapter initially discusses the fundamental GIS concepts, and then elaborates GIS based land use suitability methods. Furthermore, the chapter provides a state of the art literature review of GIS studies in water resource management area with a special focus on stormwater harvesting based site selection. Then the chapter explains the structure of MCDA methods followed by literature review of available MCDA methods. The chapter further emphasizes the importance of selected MCDA method, PROMETHEE along with its justification for current study. The chapter then elaborates the PROMETHEE methodology and associated software selection. Finally, a brief chapter summary is presented.

2.2 Geographical Information Systems (GIS): Concepts, Applications and Software

Geographical Information Systems (GIS) is defined as a system of capturing, storing, manipulating, analysing, and displaying spatial information in an efficient manner (Tsihrintzis et al., 1996). These systems are characterized by standard software packages which offer unique capabilities of automating, managing, and analysing a variety of spatial data (Jankowski, 1995). In early 1980s, GIS systems emerged as a new information processing technology, and since then, GIS has been applied in many environmental decision making situations including water resources (Seth et al., 2006).

GIS software systems principally have four major components (Malczewski, 2004)

- Data input: This component collects and/or processes spatial data from a variety of sources which include manual keyboard entry, digitizers, computer scanning or the importation of existing data files.

- Data storage and retrieval: This component organizes the spatial data in a form of geo-database, which facilitates quick retrieval of data for subsequent analysis, as well as allows further updates and corrections in the spatial dataset.

- Data manipulation and analysis: This component has unique capability of performing an integrated analysis of spatial data and their associated attributes.

Spatial data are manipulated and analysed to obtain information useful for a particular application. There is an enormously wide range of analytical operations available to the GIS users with multiple available toolsets.

- Data Output: The data output component of a GIS provides a way to see the data/information or the results of GIS data analysis in the form of maps, tables, diagrams, etc.

Spatial data in GIS can be represented in two types of data models: raster and vector. The selection of data model depends on the type of specific application of the study. Data in a raster model are stored in a two-dimensional matrix of uniform grid cells (pixels or rasters), usually squares, on a regular grid. Each cell in a raster model has exactly one value (land use, elevation, political division). The size of the grid can vary from meter to many kilometres, and therefore the spatial resolution of data is determined by the grid size. Generally, the grid size determination is based on the desired levels of accuracy of data. Larger cell size yields low resolution for spatial data, losing important information, and conversely small (or fine) cell size improves the data resolution considerably, preserving the data information. However, it should be noted that fine spatial resolution increases the computational time and size of data storage, thereby increasing project costs. In terms of water resource applications, the continuous variables such as elevation and rainfall can be best represented by raster data.

The spatial entities which are finite in nature can be best represented by a vector model. These entities are represented in the form of point, line, and polygon in vector format. For example, a watershed can be represented as a polygon, a river as a line and raingauge station as a point in a given vector model. A polygon of watershed can have various attributes stored in a database representing its area or hydrological information. In the vector model, relationship between the spatial objects (points, lines and polygons) is determined by the term named 'topology'. More details on topology and associated GIS concepts can be found in Davis (2001).

There is an enormous range of GIS commercial software available, which can be used across a range of different platforms including web, computers, mobiles and supercomputers. Steiniger and Hunter (2012) identified several categories of GIS software application as: (i) desktop GIS, used for data creation, editing, analysis and map generation; (ii) Spatial Database Management Systems (Spatial DBMS) that are used for storage of data; (iii) web map server for the delivery of map representations over the internet; (iv) server GIS, that are used to analyse remote spatial data; (v) web GIS clients, to display and query spatial data stored at remote locations that are only accessible via internet or intranet; (vi) mobile GIS, which are most often used for data acquisition in the field; and finally (vii) GIS libraries and extensions, which provide special functions that can enhance standard (desktop) GIS capabilities, or be used to build customized GIS applications, including web mapping applications.

Malczewski (2004) listed major commercial GIS software, on the basis of three application areas i.e. GIS data viewers, desktop GIS, and high-end GIS. This classification, along with its intended use and platform is shown in Table 2.1.

Table 2.1: Major Commercial GIS Software [Adopted from (Malczewski, 2004)]

	GIS Data Viewer	Desktop GIS	High-End GIS
Software	• ArcExplorer, • GeoMedia Viewer, • MapInfo ProViewer	• ArcGIS • Autodesk World, Maptitude, • Idrisi, • GeoMedia, • MapInfo Professional	• ArcGIS (Advanced), • GeoMedia Pro, • MapInfo Professional

The GIS data viewers (such as ArcExplorer) are only used in displaying and querying a specified spatial data set, which usually cannot be further customized by users. The software belonging to this category are usually free and primarily intended for general public and non experts.

The Desktop GIS, as the name suggests, are designed to run on desktop PCs, using the Windows operating system. A full featured desktop GIS includes built-in ability to input, store, manipulate and analyse, and output spatial data. Many desktop GIS software offer a framework for implementing customizations either through a proprietary or third generation programming language such as HTML. The Desktop GIS software require basic to intermediate level of GIS knowledge.

The high-end GIS systems are fully functional GIS toolkits, which often require powerful database and computational facilities. These software are suitable for large commercial enterprises, in a situation where all users of an organization or enterprise have access to a central information resource consisting of spatial data. Furthermore, these software require expert knowledge of GIS systems for their operation.

The current study uses ArcGIS for Desktop (V.9.3) software, developed by ESRI, USA (Ormsby, 2004). This software is primarily selected because its popularity and easy commercial availability.

2.3 GIS based Land Use Suitability Analysis Methods

In broad terms, the GIS based land-use suitability analysis studies aim at identifying the most appropriate spatial pattern for future land uses according to specific requirements or preferences (Malczewski, 2004). The GIS-based land-use suitability analysis has been applied in a wide range of situations such as determining optimal location of animal habitants (Store and Jokimäki, 2003), identifying the suitable crops for agriculture (Ahamed et al., 2000), residential area suitability assessment (Al-Shalabi et al., 2006), locating landfill sites for waste (Sumathi et al., 2008), and urban landscape planning (Dai et al., 2001).

Search for feasible sites, routes, and land use allocations have been traditionally carried out using manual map overlays (Jankowski, 1995). In the GIS environment, the manual map overlay approach has been replaced and refined by Multi-Criteria Evaluation (MCE) methods (Jiang and Eastman, 2000). These MCE methods are essentially similar in concept to the MCDA methods mentioned in Section 2.1. The MCE methods combine information from pre-defined suitability criteria to form a single index of evaluation for GIS based land use/suitability analysis, site selection, and resource evaluation problems (Jankowski and Richard, 1994). Among various MCE methods, Boolean operations and weighted linear combination (WLC) technique are widely used methods, as both methods are simple and easy to implement within GIS environment (Malczewski, 2004).

Boolean operations such as intersection (AND) and union (OR) combine and classify the maps into either suitable or unsuitable (for intended purpose) on the basis of map attributes of pre-defined suitability criteria meeting user defined thresholds. Boolean operations force rigid binary choice of either acceptance or rejection (of a suitable area) to the decision maker which produce doubtful results in estimating the desired suitability (Malczewski, 1999). In WLC, map attributes of different suitability criteria are scaled to a particular common range, as part of the standardization procedure. Weights of relative importance are then assigned to each of the standardized attribute maps. The suitability score is obtained by combining weights and attributes of all standardized maps. High score is interpreted as best suitability of a site (for intended purpose) and vice versa. The WLC retains the variability of continuous criteria (e.g. rainfall, slope, etc.) and allows criteria to trade-off with each other unlike hard Boolean decision of assigning absolute suitability or unsuitability to the criteria (Hossain et al., 2006). However, GIS implementations of WLC often tend to produce uncertain results as weights assigned in WLC are subjective. Similarly, the standardization procedures used such as linear transformation make analysis over-simplified (Malczewski, 2000).

Boolean operations are more suited in vector based data analysis and WLC approaches are dominated in raster based data analysis (Eastman et al., 1998). Either Boolean operations or the WLC approach can be considered superior to each other, as both are different evaluation methods. However, Jiang and Eastman (2000) integrated both Boolean operations and WLC methods, to formulate a new MCE method named as Ordered Weighted Average (OWA). This method performs aggregation similar to WLC, under fuzzy logic operators (such as AND, OR, MIN, MAX) that reflect the degree of risk and tradeoffs in decision making (Jiang and Eastman, 2000).

Both Boolean operations and WLC technique are not considered in the present study, due to limitations described earlier, primarily related to standardization and oversimplification in spatial analysis. The study has developed a GIS based screening tool for stormwater harvesting site suitability analysis, which is described in detail in Section 3.2. In brief, this methodology evaluates suitability criteria for stormwater harvesting by simple overlaying operations available in GIS standard software packages, and potential sites for stormwater harvesting are generated. These sites are then screened, ranked, and validated to shortlist the suitable sites for stormwater harvesting (Chapter 3).

Apart from MCE approaches, Artificial Intelligence (AI) techniques such as Genetic Algorithm (GA), fuzzy logic, Artificial Neural Network (ANN), Cellular Automata have found their applications in GIS based land suitability analysis (Malczewski, 2004). Broadly, AI methods seek to model the complex systems through mimicking human intelligence and they are capable of handling ambiguity and uncertainty associated with underlying process unlike conventional methods. However, due to computation complexities of integrating AI approaches within GIS environment, they found less application in real world GIS land-use suitability analysis (Malczewski, 2004).

2.4 GIS Applications in Water Resource

GIS has demonstrated its effectiveness in the field of water resource management with enormous range of applications, particularly to hydrological modeling (Tsihrintzis et al., 1996). For example, Shamsi (1996) used GIS in combination with a lumped hydrological model to determine various watershed physical parameters such as slope, area, runoff curve numbers, drainage length. The estimation of these parameters using GIS considerabally reduces the calibration time and thus modelling costs can be saved. Furthermore, De Roo (1998) highlighted usefulness of GIS to obtain different parameters such as drainage area, slope gradient, slope direction, and slope length for modelling the erosion potential in Catsop catchment, Netherlands.

Prediction of surface runoff is one of the most useful hydrologic capabilities of a GIS system (Tsihrintzis et al., 1996). Recently, Patil et al. (2008) developed GIS interface based software to predict the surface runoff through the curve number method. In this interface, GIS provided the coding capabilites to implement the curve number algorithm, and also facilitated the thematic mapping of surface runoff. The GIS was also used in deriving the geomorphological characteristics (such as stream ordering and number of streams) and time of concentration, in the flood modelling study conducted by Jain et al. (2000) for Gambhiri River Catchment, India. According to Jain et al. (2000), the estimation of these parameters can be handled easily and more accurately using GIS compared to tedious manual methods.

In terms of application to urban water quality modeling, Vairavamoorthy et al. (2007) developed GIS based software, to predict the risks associated with contaminated intrusion of water, entering into urban water distribution systems. In this study, the GIS based graphical interface served as the spatial database storage, and supported visual representation of modelling outputs in the form of thematic maps.

GIS can be also effective in urban stormwater modelling. Different spatial GIS datasets such as land use maps, digital elevation models, soil imperviousness information maps, contours, digital orthographic aerial photos, and piping network maps of the drainage area can be used to generate input parameters for an urban stormwater model (Seth et al., 2006). The GIS can be also integrated with rainfall-runoff simulation models such as Storm Water Management Model (SWMM) to determine the volumetric runoff and contaminant loadings of storm water (Huber and Singh, 1995).

One of the important applications of GIS in stormwater management is the selection and planning of stormwater Best Management Practices (BMPs). The stormwater BMPs are measures for mitigating nonpoint source (NPS) pollution, caused primarily by stormwater runoff (Zhen et al., 2006). In Australia, the BMPs are known as Water Sensitive Urban Design (WSUD) elements (as explained in Section 1.1) such as infiltration basins, porous paving, swales, infiltration trenches, retentions pond, constructed wetland, and detention basins.

Recently, Viavattene et al. (2008) proposed a GIS based decision support system which enabled stakeholders to identify the potential sites for BMPs, and demonstrated GIS application to a local city council in Birmingham, UK. To determine the suitability of BMPs at a particular site, this study used a certain set of rules based on physical characteristics of study area including land use, slope, soil characteristics, and impervious area. The GIS supported the thematic mapping of physical characteristics and facilitated the visualisation of output results in the form of suitable BMPs.

A similar GIS model was developed by Zhen et al. (2006), which identified the most cost effective combinations of BMPs (such as green roofs and rainwater tanks) based on a meta-heuristic optimization technique. This study assisted to minimize frequency and size of runoff events and resulting combined sewer overflows to the Anacostia River in Washington DC, USA.

2.5 GIS Applications in Stormwater Harvesting

There is extensive literature available on the use of GIS for the assessment of site suitability in rural areas in terms of stormwater harvesting across the world. In India, potential sites for water harvesting structures were identified using the International Mission for Sustainability Developments (IMSD) guidelines within a GIS and remote sensing environment (Kumar et al., 2008; Singh et al., 2009). The use of GIS here assisted both studies (Kumar et al., 2008; Singh et al., 2009) in integrating various maps representing study area characteristics such as landuse/landcover, geomorphology, geology, and drainage conditions to derive suitable water harvesting sites.

In South Africa, similar GIS based decision support systems were developed for identifying suitable locations for water harvesting in several studies. For example, Mbilinyi et al. (2005) used the local indigenous knowledge of local farmers in identifying the factors influencing the rainwater harvesting site suitability (such as slope, soil types, water tables) and used these factors in GIS mapping to identify the suitable stormwater harvesting sites in Tanzania. Kahinda et al. (2008) developed a decision support system in GIS by mapping different physical, ecological and socio-economic factors in combination to identify the suitable rainwater harvesting sites in any given area of South Africa.

Recently, Ziadat et al. (2012) identified the locations for rainwater harvesting in arid watersheds of Jordan, based on GIS mapping of different biophysical and socio-economic criteria. The identified locations were verified from field investigations and local farmers. The study concluded that such participatory GIS approach can be effective in arid regions to mitigate land degradation and promote the water conservation.

There are only few studies reported in literature, which focus on GIS based stormwater harvesting site suitability in urban context. Recently, Chiu (2009) proposed a GIS based rainwater (roof water) harvesting design system in Taipei Metropolitan of Taiwan where spatial technologies, hydraulic simulation and economic feasibility were incorporated in GIS in urban water-energy conservation planning. GIS assisted in identification and estimation of roof area, number of houses, classification of the buildings and spatial interpolation of rainfall, although it was not used in locating suitable sites.

Similarly, Lee et al. (2007) proposed a GIS based methodology for demonstrating the benefits of water harvesting in Chiba city of Japan. The GIS capability in the study was only limited to the classification of the buildings into residential houses, offices, commercial buildings, restaurants, public buildings, which served as a data input for scenario analysis of rainwater harvesting for different end uses.

From an Australian urban area perspective, there have been few GIS studies found in the literature. Shipton and Somenahalli (2010) applied GIS in identifying suitable stormwater harvesting locations in the Central Business District of Adelaide. However, the Shipton and Somenahalli study was limited in identifying stormwater harvesting sites only based on suitable land use and drainage patterns, and the demands for stormwater were not considered. More recently, Chowdhury et al. (2011) developed a new set of bio-physical rules for locating stormwater harvesting sites in greenfield developments from a combination of hydrological modelling, previous feasibility studies and expert opinion workshops. The rules were classified into three categories: (a) catchment rules based on topography of area, (b) development rules based on cost feasibility of stormwater harvesting schemes, and (c) facility rules based on existing infrastructure. However, the study developed only the runoff map in GIS as part of the catchment rules. Technical implementation of linking these biophysical rules within the GIS environment was not considered in the study.

McIntosh et al. (2013) developed a GIS based runoff modelling methodology for assessment of stormwater harvesting options in Ripley Valley, a greenfield development, near Ipswich City in South East Queensland (SEQ), Australia. GIS was particularly useful to characterise the sub-catchment hydrology of the Ripley river basin, and predict the stormwater potential under different stormwater harvesting locations, centralisation/decentralisation strategies, variable rainfall strategies and urban development density scenarios. This study also provided assessment of stormwater harvesting locations based on harvestable volume, supply ratio, and proximity to demand perspectives. However, the methodology proposed by McIntosh et al. (2013) is not yet applicable to existing urban or semi urbanised areas, and limited to greenfield sites.

As described earlier in Section 2.3, the current study has developed and demonstrated a GIS based screening tool methodology (Chapter 3) to identify and rank the suitable stormwater harvesting sites in urban areas.

2.6 Structure of MCDA Methods

The MCDA methods have also been often referred as MCA (Multi Criteria Analysis), MODM (Multi Objective Decision Making), MCDM (Multi Criteria Decision Making), and MADM (Multi Attribute Decision Making) in various literature, essentially covering similar fundamental properties (Hajkowicz, 2007).

A classic MCDA model consists of a finite set of decision options (or alternatives) which need to be ranked or scored by the decision maker and a family of performance measures (or criteria) describing the finite set of decision options from different perspectives. The generic MCDA problem is structured by careful selection of alternatives and performance measures (PMs) representing the objectives of decision problem. Moreover, PMs also describe quantitative/qualitative attributes of alternatives, typically measured in different units. The alternatives and performance measures together form the evaluation matrix (or decision matrix) which can be solved by different MCDA methods.

As stated earlier, for the current project, sites obtained from the GIS based screening tool represent the finite set of alternatives of MCDA which needs to be evaluated through various PMs related to financial, environmental, and social objectives.

Mathematically, the generic MCDA model can be expressed as follows (Pomerol and Barba-Romero, 2000):

Let A= (a_1, a_2, …., a_i) be the finite set of ***i*** possible alternatives which is subjected to a family of ***j*** performance measures, [$f_1(.)$,$f_2(.)$, …. , $f_j(.)$]

Then, Table 2.2 represents the basic dataset of the MCDA model in form of an evaluation matrix. The Decision Maker (DM) wishes to find the 'best choice' of alternatives within the set A. The minimum requirement for evaluation of the MCDA model is to have at least two alternatives and two performance measures i.e. $i \geq 2$ and $j \geq 2$ (Hajkowicz and Collins, 2007). Different MCDA methods further include weights and preferences of DMs on all objectives and PMs.

Table 2.2: Evaluation Matrix of MCDA

Alternatives	Family of Performance Measures			
	$f_1(.)$	$f_2(.)$	…..	$f_j(.)$
a_1	$f_1(a_1)$	$f_2(a_1)$	…..	$f_j(a_1)$
a_2	$f_1(a_2)$	$f_2(a_2)$	…..	$f_j(a_2)$
..	…..	…..	…..	…..
..	…..	…..	…..	…..
a_i	$f_1(a_i)$	$f_2(a_i)$	…..	$f_j(a_i)$

Main Steps in MCDA

The main steps of the MCDA approach are essentially similar for all various MCDA methods. Figure 2.1 explains the common steps in the MCDA approach. These steps are as follows:

1. Problem formulation: The study objectives are formulated for given MCDA problem. For this purpose, relevant stakeholders are identified and consulted.

2. Selection of alternatives and PMs: In this step, finite set of alternatives, relevant to the study, and PMs representing the study objectives with respect to alternatives are identified. Discussions with stakeholders can provide further refinement and agreement in selecting the alternatives and associated PMs.

3. Obtain evaluation matrix: The performance measure values (quantitative or qualitative) for respective alternatives are obtained from various sources such as

expert judgements, literature, community surveys and/or environmental and economic models.

4. Selection and application of MCDA methods: The suitable method for MCDA analysis is chosen depending on the specific problem needs. The different MCDA methods vary according to the additional information (such as weights) they request and the computational procedures they follow in arriving at a solution. This additional information can be treated as ‘preferences’ which are obtained from stakeholders or DMs.

5. Ranking of alternatives and sensitivity analysis: Alternatives under consideration are analysed and ranked with the selected MCDA method. Sensitivity analysis provides robustness in ranking by systematic variation in PMs and preferences of DMs.

6. Results and recommendations: Based on the ranking and relevant sensitivity analysis results, recommendations are made to relevant DMs to make the final decision.

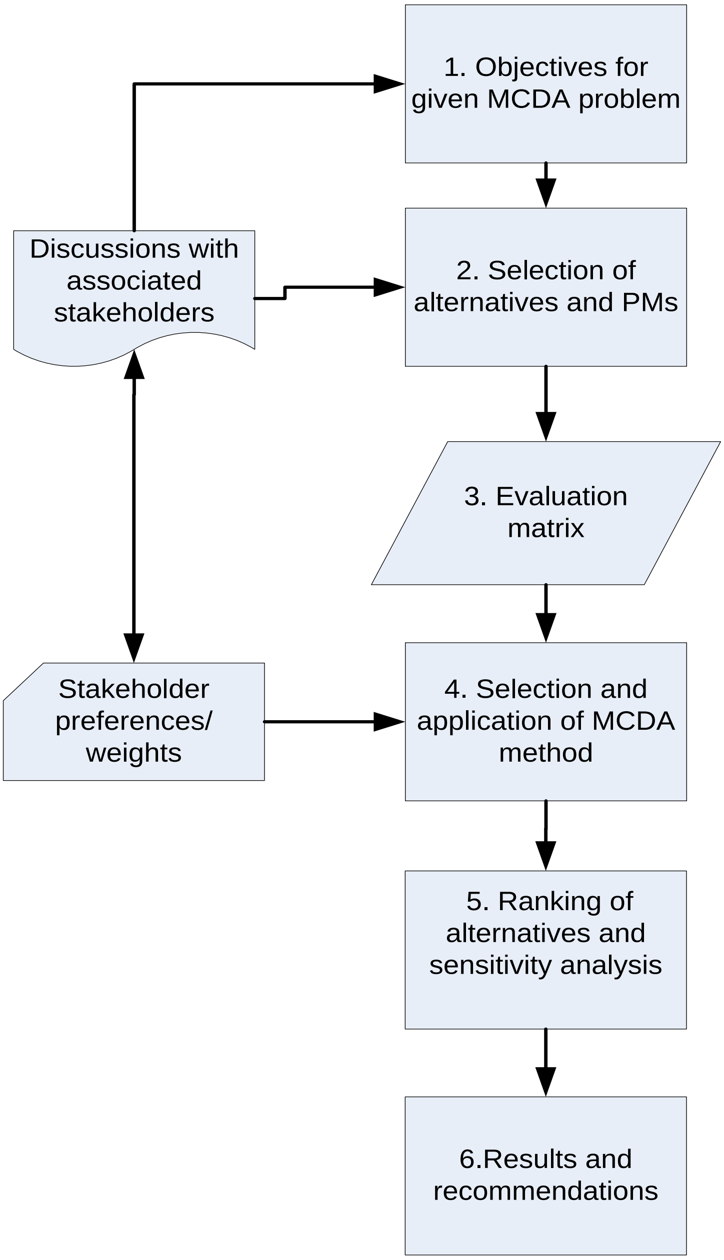

Figure 2.1: Different Steps in Generic MCDA Problem

2.7 Review of MCDA methods

Many authors have classified different MCDA methods in various groups (Hajkowicz and Collins, 2007; Huang et al., 2011; Laia et al., 2008; Pomerol and Barba-Romero, 2000). The main difference in various MCDA methods is based on additional information they request, the methodology they use, their user friendliness, and the sensitivity tools they offer (Brans, 2002).

As described by Pomerol and Barba-Romero (2000), MCDA methods can be broadly categorised as

1. Elementary Methods
2. Utility Methods
3. Outranking methods
4. Other Methods

Each of these methods has their own advantages and disadvantages when applied to a particular decision problem. A brief review of different methods under each category is presented in the next sub-sections.

2.7.1 Elementary Methods

As the name suggests, these methods use the simple preference models for ranking of given alternatives and are widely used in real word applications. Common examples of these methods are weighting (sum or product) methods, conjunctive and disjunctive methods, and ordinal methods such as BORDA, Condorcet methods, Lexicographic methods etc. (Mutikanga et al., 2011; Wang et al., 2009).

The weighting methods derive the ranking of alternatives based on aggregation of DM preferences (specifically weights) on each PM under consideration. Each individual alternative is reduced to single score for ranking purposes, and alternative with highest score is considered as the best. The most common weighting methods are weighted sum or weighted product methods (Pomerol and Barba-Romero, 2000).

Conjunctive and disjunctive methods work on the screening principle such that the acceptable alternatives satisfy the given performance thresholds for all PMs. Ordinal methods derive the rankings by aggregating the individual pre-orders (or ranks) with respect to the PMs for the given set of alternatives. The ordinal methods differ from weighting methods and conjunctive/disjunctive methods from the point of view that ordinal methods do not require any preference information (such as weights/ thresholds) from decision maker.

Elementary methods are barely applied in research problems associated with water resources management due to their inadequacy in handling DM preferences and higher degree of uncertainty (Laia et al., 2008).

2.7.2 Utility Methods

For given alternatives, the utility methods broadly reduce all the PM values to a single score, which enables the comparison (and consequent ranking) of given set of alternatives. These methods are also called as 'single/unique synthesising criterion approach'. These methods were originated from the 'American School of Thinking' (Pomerol and Barba-Romero, 2000) and hence widely used in USA. The major approach of utility methods is Multi-Attribute Utility Theory/Multi-Attribute value theory (MAUT/MAVT).

These methods are based on the principle that if an individual's preferences satisfied certain basic axioms of rational behaviour, and then the person's decisions could be described as the maximisation of the expected utility or probability function. Consequently, these methods model DM's preferences by utility functions or value functions. Von Neumann and Morgenstern (1947) developed the theoretical foundations for MAUT/MAVT methods, but Keeney and Raiffa (1993) made these methods popular through a textbook on multi attribute theory (Dyer, 2005).

In MAUT/MAVT, utility functions are usually generated for each PM by gathering DM's response to make a choice between alternatives. These utility functions can be represented by a utility graph, which is constructed according to the responses of DM for each PM. Once utility functions are set, values of different PMs of a given alternative are converted to one common dimensionless value (0 to 1) to represent the utility score. Finally, the utility scores are combined with weight functions of the PMs using standard mathematical operations (weighted sum or multiplication) to obtain the overall decision score for each alternative. The alternative with the highest score is regarded as the best alternative. It should be noted that the weighting methods (Section 2.7.1) are essentially one form of utility methods as they employ global weighted aggregation of all PMs (to compare the set of alternatives).

Compared to other MCDA methods, the MAUT evaluation method is suitable for complex decisions with multiple criteria and many alternatives (Van Moeffaert, 2002). Detail procedure of constructing these utility functions is explained in the Pomerol and Barba-Romero (2000).

There are diverse applications of MAUT in the water resource area. For example, MAUT was used for selecting the optimum operating rules for the Melbourne water supply system in Australia (Perera et al., 1999), for determining feasible irrigation policies (El-awad et al., 1991; Gómez-Limón and Riesgo, 2004; Raju and Pillai, 1999), and for water quality management (Randhir et al., 2000). Moreover, there are several variant methods of MAUT such as Simple Multi Attribute Rating Technique (SMART), Utility Theory Additive (UTA), etc. (Huang et al., 2011; Pomerol and Barba-Romero, 2000).

Utility methods (such as MAUT) rely on the assumptions that the decision maker is rational, has perfect knowledge (about the given MCDA problem) and is consistent in judgments. Brans (2002) expressed disagreement with the rationality assumption of the MCDA methods, suggesting that utility methods force the optimum solution on decision maker without considering his/her emotions, real life experience and subjectiveness which makes them a compensatory optimization approach. MAUT is majorly criticized for this compensatory nature, where the PMs with high scores dominate the ranking compared to the PMs with low scores, thereby lowering importance of low scored PMs (Brans, 1982). Additionally, the procedures for deriving utility functions (in utility methods) are tedious, and require significant DM input and time, making them less favourable approach for decision making (Pomerol and Barba-Romero, 2000).

2.7.3 Outranking Methods

Outranking methods facilitate pair wise comparison of alternatives, criterion by criterion systematically, to establish the ranking order (of alternatives). This outranking approach is contrary to the utility methods in which alternatives are compared globally considering all criteria (i.e. PMs) simultaneously. The outranking approach seeks to find a compromise for comparing alternatives by balancing the relationship between the alternatives' poor performing PMs and well performing PMs (Roy 1991). These methods belong to the 'European school of thinking' and thus, widely used in Europe (Pomerol and Barba-Romero, 2000).

The outranking approach rejects the fundamental hypothesis of utility methods that all alternatives are comparable. The outranking approach assumes that in some circumstances, a decision maker will be unwilling or unable to compare some alternatives (Butler et al., 2003) and thus, allows incomparability between them. This characteristic is important in situations where some alternatives cannot be compared for various reasons.

Outranking Concept

In general terms, Roy (1968) defined an outranking relation (**S**) as a binary relation, which indicates the strength of the preference for alternative *a* over *b* [*a* **S** *b*, given $(a, b \in A)$]. This strength is defined on the basis of i) existing indications supporting the preference of *a* over *b* (concordance principle), and ii) existing indications supporting the preference of *b* over *a* (discordance principle).

All outranking methods principally work on building and exploiting outranking relations (i.e. **S**) within a given set of alternatives for different PMs. Among various outranking methods, ELECTRE (ELimination and Choice Expressing the REality) and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) methods have wide applications in the area of water resources (Hajkowicz and Collins, 2007). Both ELECTRE and PROMETHEE are based on a pair wise comparison of alternatives and aggregating the DM preferences on each PM, instead of aggregating the global preferences on alternatives as in utility methods (Kodikara, 2008). Among the various outranking methods, PROMETHEE has been used as the MCDA method in the current study. The justification for selecting PROMETHEE method for the current study is described in Section 2.7.5.

2.7.3.1 PROMETHEE Methods: General Information

The PROMETHEE method is one of the most intuitive and popular outranking methods notably, because of its simple mathematical properties and ease of understanding to the decision makers (Brans and Mareschal, 2005; Pomerol and Barba-Romero, 2000). The idea of the PROMETHEE method was first originated by Professor Jean- Pierre in 1982 (Brans, 1982).

The PROMETHEE method works on the principle of establishing and exploiting the outranking relationships among pair wise comparisons of alternatives. PROMETHEE establishes an outranking degree by calculating the positive and negative flow from each alternative with respect to the other alternative. To generate the outranking degree, this method requires a weight and a preference function to be specified by the DM for each PM. The positive flow in outranking degree represents the domination (degree of strength) of a given alternative over the rest of alternatives, and negative flow shows how much alternative is dominated by rest of the alternatives.

In PROMETHEE I, the intersection of these flows induces partial ranking of all alternatives based on preference aggregation (Brans et al., 1986). Pairs of alternatives are categorized by preference (P), indifference (I), or incomparability (R). In PROMETHEE II, the difference of positive and negative flows is considered and termed as ‘net flow’ and absolute ranking of alternatives is achieved by making an ascending order of the net flows, representing best to worst alternatives. The details of the PROMETHEE method can be found in Brans and Mareschal (2005).

Several versions of the PROMETHEE method have been developed over time which include PROMETHEE I, II, III, IV, V, VI, GDSS, and GAIA. PROMETHEE III was developed for ranking based on intervals, and PROMETHEE IV was used for complete or partial ranking of the continuous alternatives (Brans and Mareschal, 2005). PROMETHEE V was an extension of the PROMETHEE II method, where the problem involves the selecting the sub-set of alternatives under set of certain constraints, using linear programming methods (Brans and Mareschal, 1992). PROMETHEE VI (the "Decision-Maker Brain") was developed to represent the human brain representation in decision making (Brans and Mareschal, 1995). PROMETHEE GDSS was developed for group decision making (Macharis et al., 1998). PROMETHEE GAIA (Geometrical Analysis for Interactive Aid) was introduced as a visual interactive module which is a graphical complement to the PROMETHEE rankings (Mareschal and Brans, 1988). Among various variants of PROMETHEE, the PROMETHEE II method is fundamental to implement and used by the majority of researchers among the family of PROMETHEE methods (Behzadian et al., 2010).

2.7.3.2 Recent Applications of PROMETHEE in Water Resources

Behzadian et al. (2010) reviewed 217 scholarly papers which used the PROMETHEE methods in wide application areas such as water resources, environmental management, logistics and transport, forestry, chemistry, finance etc. According to Behzadian et al. (2010), most PROMETHEE based hydrological studies are focussed into the sustainable water resources planning, water management strategies assessment, and irrigation planning. The review further found that the environment management as the most popular topic in PROMETHEE applications, covering several specific areas such as waste management, Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), and land-use planning.

Mutikanga et al. (2011) recently applied PROMETHEE II in ranking of water loss reduction strategies for local urban water utility in Kampala city of Uganda, East Africa. Seven water loss reduction strategies were evaluated with respect to seven PMs representing economic, environmental, public health, technical and social impacts.

Recently, Nasiri et al. (2012) combined GIS and PROMETHEE II approaches to locate the most suitable areas for artificial groundwater recharge in the Garabaygan Basin of Iran to minimize the effect of flooding. The study shortlisted potential suitable areas from GIS based mapping using some exclusionary rules. These suitable areas were ranked using PROMETHEE II under eight different physical criteria to produce the final land suitability map.

PROMETHEE was also used in determining the feasible recycled water management strategies for use in household laundry in Sydney, Australia (Chen et al., 2012). Five alternative strategies considered were based on the combination of different water treatment techniques (such as microfiltration, reverse osmosis, and granular activated carbon) with existing or new washing machines.

Silva et al. (2010) used PROMETHEE in a group decision making framework in ranking of the mitigating strategies to avoid the degradation effects in the Jaboatao River watershed of Brazil. The strategies considered were development of sewage treatment plant, education, sustainable agriculture plan, recovery of native vegetation, and improvement of collection of waste material. These strategies were evaluated with respect to economic, social and environmental aspects.

Kodikara et al. (2010) also used PROMETHEE to evaluate the system performance of Melbourne water supply system under different alternative operating rules and eight performance measures representing economic, environmental and social objectives. The study also provided PROMETHEE preference elicitation methodology for decision making with respect to different stakeholder groups namely; resource managers, water users, and environmental interest groups.

2.7.4 Other Methods

Apart from the elementary, utility and outranking methods, there are several other MCDA approaches that have been proposed and used, in the literature. They are:

- Distance to Idea Point Methods: These methods identify ideal and anti-ideal values for the each PM. The alternatives which are closer to the ideal and furthest from the anti-ideal values of PMs are selected and serve as the basis for distance wise comparison with the rest of alternatives. In case where no ideal or anti-ideal is easily defined, the minimum and maximum PM values may be used for analysis (Hajkowicz and Collins, 2007). Two common techniques of this type are compromise programming (Zeleny, 1982) and TOPSIS (Lai et al., 1994).

- Fuzzy MCDA methods: These methods are introduced by Zadeh (1965) based on fuzzy set theory. The uncertainties involving in a large-scale complex decision making process are properly described via fuzzy membership functions. Fuzzy MCDA methods are not separate MCDA methods, but hybrid methods which combine fuzzy set theory with different MCDA methods. According to the review conducted by Hajkowicz and Higgins (2008), the fuzzy MCDA methods are becoming popular in water resource management due to their effectiveness in handling uncertainty in decision making. More details on fuzzy MCDA methods can be found in Chen et al. (1992).

2.7.5 Selection of the Appropriate MCDA Method and Software

Despite various MCDA methods available in literature, there are no clear guidelines on selecting a particular MCDA method for environmental and sustainability analysis of water resources in general (Rowley et al., 2012). Moreover, the environmental planners usually do not have enough time or economic resources for assessing value/utility functions or performing pair wise comparisons of alternatives and criteria with every DM (Lahdelma et al., 2000). Therefore, ease of use and cognitive ability of the DM are important factors in selecting the appropriate MCDA method for particular application (Kodikara, 2008).

Lahdelma et al. (2000) identified a few requirements for the MCDA method to be used in public environmental problems. These requirements included the ease of understanding ability, the well defined structure, the support to multiple DMs, the ability to handle uncertainty, and the minimal time for preference elicitation information from DM. Additionally, the software availability and the associated costs are also reported as crucial factors in the selection of MCDA method (Pomerol and Barba-Romero, 2000).

Guitouni and Martel (1998) also provided tentative guidelines in selecting the appropriate MCDA methods based on input data requirements (qualitative and quantitative information on PMs), preference elicitation methods, modelling algorithms, and different aggregation procedures. However, this study stressed that none of the MCDA methods can be considered as the ‘super method’ appropriate to all decision-making situations. Likewise, the literature review conducted by Hajkowicz and Higgins (2008) found strong agreement between different MCDA methods producing similar results in water resource management. This review further highlighted the fact that structuring a MCDA problem is more important than the selection of the MCDA method.

Rowley et al. (2012) presented a unique perspective on choosing a suitable MCDA method for environmental and sustainability analysis. The authors discussed various issues related to major methodological choices (utility/outranking methods) required to select and apply the MCDA method, and described theoretical implications of these choices considering needs of DMs. Moreover, authors explicitly recommended outranking methods (non-compensatory aggregation methods) for environmental and sustainability problems, as these methods do not trade-off between the sustainability objectives. Additionally, the authors argued that outranking methods perform better compared to utility methods in terms of addressing preferences, indifferences, incomparability, and data uncertainty (imperfect knowledge) typically associated with sustainability assessment.

PROMETHEE: Selected MCDA Method

As described in Section 2.1, stormwater harvesting decisions are often based on the objectives representing sustainability in terms of economic, environmental and social considerations. The compensatory nature of utility methods allows trade-offs between these considerations. For example, a higher score on financial objectives of stormwater harvesting scheme may be compensated for negative impact on the local environment or social impact on local community. Therefore, such compensatory effect produced by utility methods can lead to adverse impact on final rankings of stormwater harvesting sites.

The current study selected PROMETHEE as the MCDA method, primarily because of its non compensatory properties, simplicity, and algorithm clarity. The non-compensatory character of PROMETHEE is significantly important in the context of the present study as the method retains the sustainability principles of stormwater harvesting sites from economic, environmental and social perspectives.

The PROMETHEE method is also easy to comprehend compared to other outranking methods such as ELECTRE family (Brans and Mareschal, 2005). The study conducted by the Gilliams et al. (2005) pointed out that PROMETHEE has an edge over ELECTRE III, in terms of user friendliness, simplicity of the model strategy, variation of the solution, and implementation. Additionally, the PROMETHEE methods were appeared to be more stable compared to the ELECTRE III in terms of sensitivity analysis (Brans et al., 1986). Furthermore, the PROMETHEE methods are well received by end-users because they are easy to use, intuitive, auditable, and with several graphical and interactive tools (Mutikanga et al., 2011).

Brans and Mareschal (2005) provided certain requisites while selecting appropriate MCDA method. According to these requisites, MCDA methods should meet following considerations for selection.

1. Consideration of magnitude of the deviations between the evaluations of the alternatives within each PM.
2. Avoidance of the normalization effect for different PMs which are expressed in their own units in PROMETHEE.
3. Capability of handling preferences, indifference and incomparability
4. Ease of understanding ability to the DM regarding preference elicitation procedure
5. Avoidance of the ‘Black box’ effects including technical parameters having no significance.
6. Information on the conflicting nature of the criteria.
7. Sensitivity analysis of weights

PROMETHEE is capable of meeting requisite 1, 2, 4 and 5 through the use of simple preference functions. The requisite 3 is handled by PROMETHEE I and II rankings and requisite 6 is addressed by interactive GAIA tool of PROMETHEE. Furthermore, requisite 7 is addressed by the various sensitivity analysis tools that have been developed for PROMETHEE such as ‘weight stability intervals’ and ‘walking weights’ (Refer Section 6.4 for details). The computational procedure of PROMETHEE is given in Section 2.8.

Selection of PROMETHEE Software

One significant reason of selecting PROMETHEE methodology in the current study is the availability of various commercial software packages with various interactive features and sensitivity analysis tools. Table 2.3 describes the chronological development of various software available for PROMETHEE.

Table 2.4 describes the various features of available commercial PROMETHEE software. Among the listed software in the Table 2.4, D-Sight software was selected for the current study. This selection was based on the consideration of various features of D-Sight (Table 2.4) over other PROMETHEE software. The details of *D-Sight* software are given in Section 6.3.

Table 2.3: Available PROMETHEE Software

Year	Name	Developer	Operating System	Source
1990	PromCalc	Bertrand Mareschal and Jean-Pierre Brans	MS-DOS	Discontinued
2000	Decision Lab	ULB and Visual Decision	Windows	Discontinued
2010	D-Sight	Yves De Smet	Windows	http://www.d-sight.com/ Free Demo for 14 days (6 Alternatives, 8 Criteria)
2012	Smart Picker Pro	Philippe Némery	Windows	http://www.smart-picker.com/ Free trial for unlimitied period with limitation in alternatives and criteria (5 Alternatives and 4 Criteria)
2012	Visual Promethee	Bertrand Mareschal	Windows	http://www.promethee-gaia.net/software.html

Table 2.4: Distinct Features of Available PROMETHEE Software

Features	D-Sight	Smart Picker Pro	Visual PROMETHEE**
Group Decision Making	Y	Y	Y
Sensitivity Analysis	Y	Y	Y
Web Integration	Y	N*	N
Module Support	Y	N*	N
GIS Integration	Y	N*	Y
Weight Elicitation Support	Y	Y	N
Utility Method Support	Y	N	N
Price, (AUD)	249	190	Free

**On contact customization is available for these features*
***This software was at beta stage during software selection time of study*

2.8 PROMETHEE Methodology

PROMETHEE methods work on the principle of preference aggregation in pair wise comparison of alternatives against each of defined PMs. All possible combinations of alternatives are evaluated according to different PMs which need to be maximized or minimized. Apart from the basic data required on the evaluation matrix (Table 2.2), PROMETHEE further requires two datasets of additional information (from DMs) in terms of

- Preference Functions
- Weights

2.8.1 Preference Functions

During evaluation of a given pair of alternatives, PROMETHEE considers the magnitude of the deviations (x) between each PM value. If this deviation is large, then higher preference is given to the better alternative. Similarly, smaller deviations on alternatives are treated as weak preference or indifference. To represent this deviation, PROMETHEE uses the concept of preference function, $p(x)$, in pair wise comparison of alternatives. For a given PM, the preference function (PF) translates the deviation (x) between the evaluations of the two alternatives (on that PM), to a preference degree (or preference intensity), which has a value between 0 and 1. The PF concept eliminates the unwanted normalization effects required in utility methods, by comparing different PMs independently in their own measurement units, and also reduces the unwanted compensation effects while aggregating the preferences (Kodikara et al., 2008).

For assignment of preference functions on PMs, the authors of PROMETHEE (Brans et al., 1986) proposed six basic shapes as shown in Figure 2.2. These shapes are named as Usual criterion (Type I), U-shape criterion (Type II), V-shape criterion (Type III), level criterion (Type IV), V-shape with indifference criterion (Type V) and Gaussian criterion (Type VI). Type I, Type II and Type III are variants of Type V.

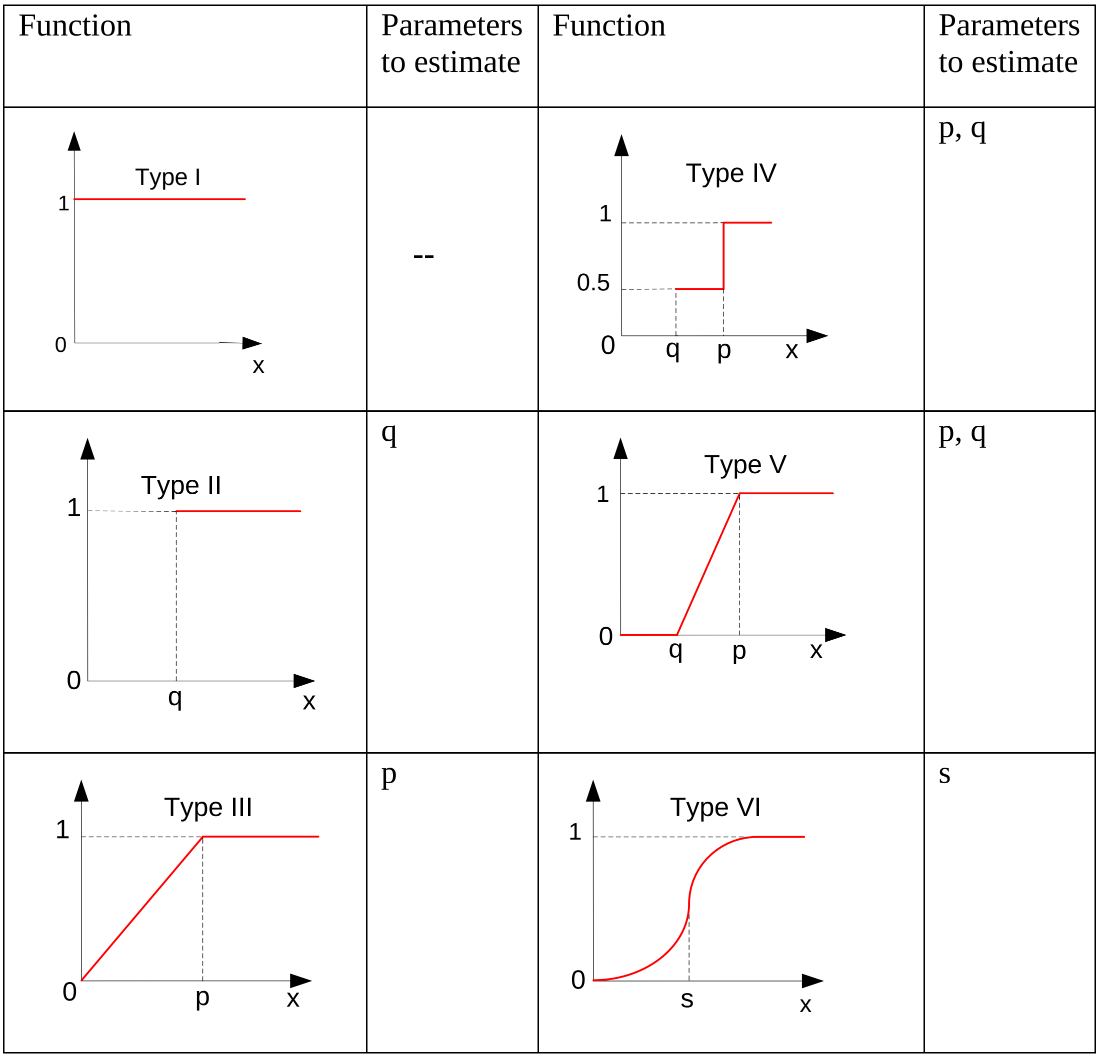

Figure 2.2: Preference Functions used in PROMETHEE

There are three basic thresholds, which can be used to describe each shape of preference functions. These thresholds are: indifference threshold (*q*), preference threshold (*p*) and Gaussian threshold (*s*). However, Type I shape is an exception where no preference threshold is required.

Brans and Mareschal (2005) defined these thresholds as follows:

- The indifference threshold (*q*): The indifference threshold, ***q*** represents the largest difference in PM values until which DM thinks preference between alternatives *a* and *b* is negligible or indifferent.

- The preference threshold (*p*): The preference threshold, ***p***, represents the smallest difference in PM values that is considered as crucial in generating strong preference of one alternative over the other.

- The Gaussian threshold (s): The Gaussian threshold serves as intermediate preference value between *p* and *q*. The *s* value defines the inflection point of preference function Type VI, which remains increasing for all deviations without any discontinuity. The estimation of the *s* value is complex and standard statistical distributions are often employed for its determination.

In the current study, the above thresholds are determined on the set of PMs representing stormwater harvesting objectives (Section 4.2), through a preference elicitation procedure described in Section 5.6.

2.8.2 Weights

Similar to the other MCDA methods, weights in PROMETHEE represent the relative importance of the different PMs from DM perspective. These weights are positive numbers, which are independent from the measurement units of the PM. In PROMETHEE, the set of weight $\{W_j, j = 1,2, \ldots n\}$ for *n* number of PMs is obtained such that, normalised weights add up to 1(i.e. $\sum_{j=1}^{n} W_j$=1). The PMs with higher weights are considered important to the DM and vice versa. PROMETHEE does not provide any specific guidelines on the weight elicitation (Macharis et al., 2004). There are various weighting methods, which can be used for weight elicitation in general MCDA methods including PROMETHEE. More details of these methods are documented in Section 5.4.2.

2.8.3 Principles of PROMETHEE Methodology - Single DM Case

Brans and Mareschal (1994) described two broad steps in PROMETHEE evaluation:

1. Building of outranking relation, and
2. Exploitation for the decision aid.

Step 1: Building of outranking relation

Consider the evaluation of finite set **A** of ***m*** possible alternatives, [a_1, a_2, ...a_i...., a_m] and family of ***n*** PMs,[$f_1(.)$, $f_2(.)$…… $f_j(.)$ .... , $f_n(.)$]. Initially, preference elicitation will be facilitated to derive the set of relative weights, [w_j, $j=1,2,....n$], and set of generalized preference function types, [$F_j(x)$, $j=1,2,...,n$].

As described in Section 2.8.1, for given pair of alternatives (a, b) belonging to set **A**, PF denotes the preference of alternative a over b, and can be expressed $P_j(x)$,
where, $x = f_j(a) - f_j(b)$

The outranking relation for the pair of alternatives (a, b) can be represented by a **multi-criteria preference index** which indicates the degree of preference such that

$$\pi(a,b) = \sum_{j=1}^{n} W_j P_j(a,b)$$

$$\pi(b,a) = \sum_{j=1}^{n} W_j P_j(b,a)$$

Where, $\pi(a, b)$ = Preference degree with which *a* is preferred over *b,*

$\pi(b, a)$ = Preference degree with which *b* is preferred over *a,* and

W_j = Relative weight of importance for PM *j*

Step 2: Exploitation for the decision aid

Decision aid in PROMETHEE can be achieved by either of two approaches of ranking i.e. PROMETHEE I and PROMETHEE II. Both of these approaches are based on estimating and comparing the outgoing flow, Φ^+ *(a)* and incoming flow, Φ^- *(a)* at each alternative. These flows are represented as follows

$$\Phi^+(a) = \frac{1}{n-1}\sum_{i=1}^{n} \pi(\mathrm{a,i})$$

$$\Phi^-(a) = \frac{1}{n-1}\sum_{i=1}^{n} \pi(\mathrm{i,a})$$

The positive flow Φ^+*(a)* defines the strength of alternative *a* in outranking the remaining (n-1) alternatives. Higher the Φ^+*(a),* better is the alternative. Similarly, the negative flow Φ^- *(a)* defines the weakness of alternative *a*, and signifies the degree by which *a* is outranked by other (n-1) alternatives.

PROMETHEE I obtains a partial ranking or pre-order (**P**, **I**, **R**) from the intersection of positive and negative outranking flows, where **P** stands for strict preference, **I** stands for indifference and **R** stands for incomparability. These partial pre-order relations are described as follows:

a **P** b	iff*	Φ^+ (a) > Φ^+ (b) and Φ^- (a) < Φ^- (b), or
		Φ^+ (a) = Φ^+ (b) and Φ^- (a) < Φ^- (b), or
		Φ^+ (a) > Φ^+ (b) and Φ^- (a) = Φ^- (b)
a **I** b	iff	Φ^+ (a) = Φ^+ (b) and Φ^- (a) = Φ^- (b), or
a **R** b	iff	Φ^+ (a) > Φ^+ (b) and Φ^- (a) > Φ^- (b), or
		Φ^+ (a) < Φ^+ (b) and Φ^- (a) < Φ^- (b)

**if and only if*

PROMETHEE II provides complete ranking **(P, I**) to the decision maker through **net outranking flow** Φ (*a*), which can be expressed as

$$\Phi(a) = \Phi^+(a) - \Phi^-(a)$$

considering, a **P** b	iff	Φ (a) > Φ (b), and
a **I** b	iff	Φ (a) = Φ (b)

Higher net outranking flow corresponds to better alternative and vice versa. Compared to PROMETHEE I, PROMETHEE II do not consider incomparability (**R**) between alternatives. Therefore, the authors of PROMETHEE (Brans and Mareschal, 2005) have suggested to consider results obtained from both methods.

The PROMETHEE methodology can be also represented visually better, using GAIA (Graphical Analysis for Interactive Assistance) plane. The GAIA plane interactively provides a systematic visual representation of the main characteristics of the decision problem, such as the conflicts and synergies existing between the PMs or alternatives. This visual display is incorporated in *D-Sight 2012* software. A detailed description of GAIA is given in Section 6.3.

2.8.4 Principles of PROMETHEE Methodology - Group DM Case

PROMETHEE facilitates group decision making through the PROMETHEE GDSS (Group Decision Support System), developed by Macharis et al (1998). The GDSS is particularly useful in terms of handling conflicting opinions of stakeholders and providing consensus solution in the group decision making.

Similar to the single DM case, the method allows each DM (DM = 1, 2, 3 …R) to express his/her own set of preference functions and weights for the same decision problem. Alternatively, GDSS is also capable of evaluating different evaluation matrices obtained by different DMs (with different personal preferences) for the same decision problem. The PROMETHEE GDSS procedure can be conducted through different preference elicitation methods such as video conferencing, surveys, workshops and conferences (Behzadian et al., 2011). More details on preference elicitation methods are covered in Section 5.5.

Specifically, the PROMETHEE GDSS method deals with ranking a finite number of alternatives based on multiple conflicting criteria (or performance measures) with inputs from a group of DMs (Macharis et al. 1998). .

Brans and Mareschal (2005) provide guidelines of the PROMETHEE GDSS procedure, which can have several iterations. The single iteration is comprised of three key phases:

- Phase I: Generation of alternatives and PMs
- Phase II: Individual evaluations by each DM
- Phase III: Global evaluation by the group

Phase I and Phase II are similar to that of the single DM case described earlier. However, Phase II can have several decision matrices (m x n), in case of several DMs, representing their own PM evaluations. Each DM may have different preferences on decisions, represented by a positive weight, ω_r (r = 1, 2,…., R) so that:

$$\sum_{r=1}^{R} \omega_r = 1$$

Phase III deals with computing the net flow vectors, (Φ_1, Φ_2,……,Φ_r,……,Φ_R), of all DMs, which simplifies to a (m x R) matrix shown in the overview of PROMETHEE GDSS procedure in Figure 2.3.

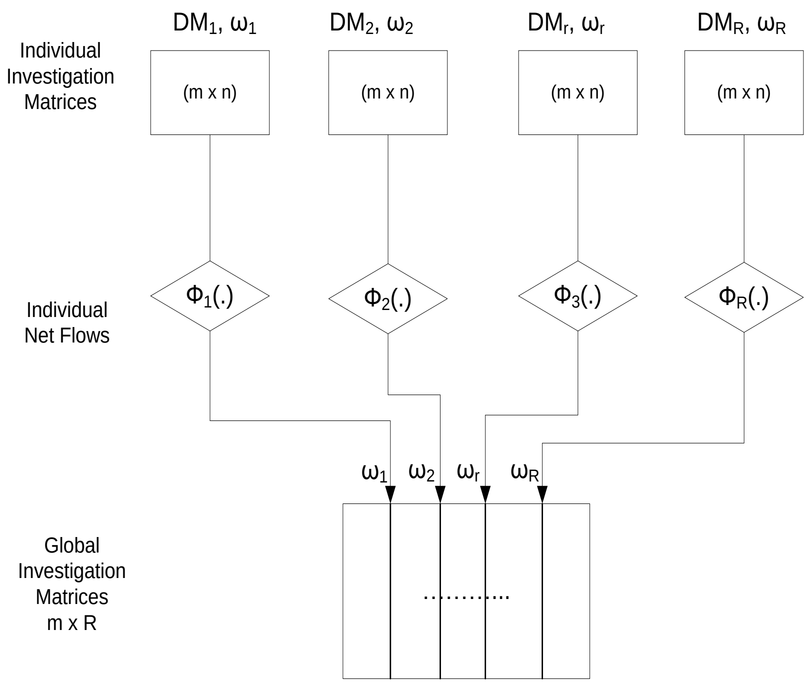

Figure 2.3: PROMETHEE GDSS Methodology

(Source:Brans and Mareschal (2005))

For a given alternative, each column of the global matrix represents a point of view of a particular DM (Figure 2.3). A global PROMETHEE II ranking and the associated GAIA are then computed considering the net flow vectors of all involved DMs. In the current study, the D-Sight software has been used to facilitate the GDSS procedure. A detailed explanation of the group decision making capabilities of *D-Sight* is given in Section 6.3.

2.9 Summary

There are various approaches used in the assessment of stormwater harvesting sites which broadly comprise of Economic Analysis, Multi Criteria Decision Analysis (MCDA) and Triple Bottom Line (TBL). For assessment of stormwater harvesting sites, these approaches use various analysis methods and tools such as hydrological modelling, water balance analysis, life cycle costing, social analysis as well as stakeholder involvement. Also, among these approaches, it was found that MCDA is widely used and recommended approach in the evaluation of stormwater harvesting sites.

Regardless of different evaluation approaches used, there is no common framework available, which can provide assistance in identifying the suitability of stormwater harvesting sites and, further guide on consequent evaluation of stormwater harvesting sites. In this context, this chapter highlighted the importance of GIS-MCDA based evaluation for stormwater harvesting sites. In this combined approach, GIS can serve as a screening tool for preliminary site selection stormwater harvesting, and once sites are identified, they can be evaluated comprehensively with a suitable MCDA method to facilitate decision making.

The chapter elaborated the theoretical foundations of GIS with key concepts and associated software. The two basic data models of GIS i.e. raster and vector can represent spatial information in terms of continuous and discrete variables respectively, and the selection of raster/vector model depends on the type of specific application of the case study. Among variety of GIS software available, the study found that Arc-GIS (V 9.3) was suitable for the proposed GIS screening tool methodology (Chapter 3), primarily due to easy commercial availability and popularity (of Arc-GIS). Furthermore, the chapter detailed briefly on GIS based land use suitability analysis methods.

The chapter also provided a state-of-art literature review on application of GIS in water resource management in general and particularly on stormwater harvesting site selection. This literature review pointed out that there were extensive studies, describing GIS suitability of stormwater harvesting sites in rural areas. However, there have been very few studies where GIS has been used in the urban context, primarily due to multiple factors such as constrained storage space, existing drainage patterns, and other social, institutional and economic factors. To address this research gap, this study has developed a GIS based screening tool methodology which is described in Chapter 3.

The chapter then described the basic terminologies of MCDA approach and presented a brief literature review of different MCDA methods. In terms of broad definition, MCDA is branch of decision science, where a set of finite alternatives and set of performance measures represent the decision problem under evaluation. Additionally, decision maker's preference judgements can be introduced in MCDA. These judgements have a great influence on the final decision, at the same time, bringing in some amount of uncertainty into the decisions.

MCDA methods can be broadly categorised as elementary methods, utility methods, outranking methods, and other methods (ideal distance and fuzzy theory based methods). The outranking methods have advantages over rest of the methods in terms of addressing preferences, indifferences, incomparability and data uncertainty (imperfect knowledge) typically associated with decision makers. Moreover, the outranking methods are highly advised in environment and sustainability decision making problems due to their non-compensatory properties. These non-compensatory properties can retain the sustainability principles of stormwater harvesting sites from economic, environmental and social perspectives.

Selection of the appropriate MCDA method for evaluation depends on its ease of use and understanding ability by the decision maker (DM). Among various MCDA methods, PROMETHEE, an outranking method was deemed as suitable for the current study. This method was selected due to its transparentness, non compensatory properties and the availability of variety of commercial software including the selected ‘D-Sight’ software. The chapter finally detailed the computational aspects of PROMETHEE methodology for single DM case and PROMETHEE GDSS (Group Decision Support System) methodology for group DM case.

Chapter 3: GIS Screening Tool for Stormwater Harvesting - Methodology and Application

3.1 Introduction

As highlighted in Section 2.1, the selection of stormwater harvesting sites is often challenging to water managers due to various factors (such as technical, social, economic and environmental), and this selection is often done on an opportunistic basis using the best judgment of water infrastructure planners. Furthermore, Section 2.1 pointed out that despite recognizing the usefulness of GIS based approaches for site selection, there are very few studies conducted on GIS based stormwater harvesting site selection in urban areas. Considering the above issues and challenges, this chapter discusses a comprehensive GIS based screening tool methodology that was developed for assessment of stormwater harvesting sites in urban areas along with its application to two case study areas.

The chapter first describes the robust GIS based screening methodology for identifying potentially suitable stormwater harvesting sites in urban areas at the preliminary level of decision making. This methodology is structured into four sequential broad steps where each step is explained in detail in the chapter. There steps are:

1. Evaluation of suitability criteria
2. Estimation of environmental flows
3. Evaluation of screening parameters
4. Validation and ranking

Furthermore, the general background information describing climate, hydrology and demand pattern of the two case study areas is presented. Then, the chapter discusses the detailed application of the GIS screening tool methodology to two case study areas to obtain a ranking of suitable stormwater harvesting sites. The chapter further discusses the comparative findings from the two case study areas, highlighting the similarities and differences in the applications, followed by the chapter summary.

3.2 Methodology

The methodology for GIS based screening tool of potential stormwater harvesting sites is described through following four main steps, which can be applied to existing urban areas or semi urbanised areas.

3.2.1 Step 1 - Evaluation of Suitability Criteria

Three tasks are involved in this step: a) Criteria identification for stormwater harvesting suitability, (b) Data acquisition and processing to create spatial maps for identified criteria, and c) Evaluation of suitability criteria.

In task (a), annual runoff and demand are considered as the suitability criteria, as they are the principal drivers for any stormwater harvesting scheme. However, it should be noted that these suitability criteria may not alone provide precise suitability for a given stormwater harvesting site as various other criteria such as technical, social, economic and environmental considerations also play important role in selecting overall suitable stormwater harvesting sites. However, suitability criteria considered in the study are deemed reasonable at the initial screening stage of planning process, conducted through the GIS based screening tool.

The runoff criterion considered runoff generated from both impervious and pervious areas within the study region. The water demand is estimated from potential residential and non-residential water uses (such as irrigation of parks).

The stormwater harvesting catchments can also be considered as the 'accumulating catchments' with their runoff and demand. The accumulated catchments here are defined as aggregated catchments, which increase in size from upstream to downstream. The accumulated catchment concept is explained using Figure 3.1. As depicted in the figure, sub-catchments *a* and *b* are upstream catchments which drain at *outlet-1* and *outlet-2* respectively. The sub-catchment *c* which drains at *outlet-3* is an accumulated catchment, consisting of sub-catchments *a* and *b* with an additional drainage area of *c*. Similarly, the sub-catchment *c* and catchment *d* aggregate themselves together with an incremental drainage area to form the accumulated catchment *e* which drains at *outlet-5*.

Note that the sub-catchments *a*, *b* and *d* are also categorised as accumulated catchments with no upstream catchments contributing to them.

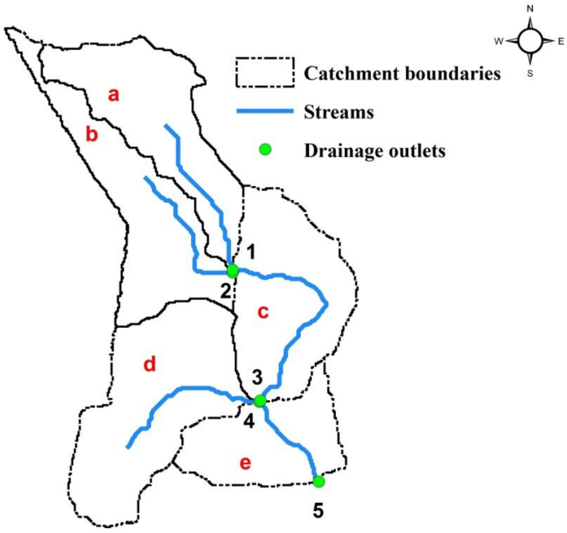

Figure 3.1: Accumulated Catchment

From stormwater harvesting perspective, it is essential to understand the behaviour of the catchment with respect to stormwater flows and respective water demands. The accumulated catchment concept is therefore important, as the decision maker has the preference of implementing stormwater harvesting schemes in various single or accumulated catchments depending on the catchment specific quantity of runoff and the nature of demand. Therefore, this study assesses runoff and demand through accumulated catchments. The drainage outlets of accumulated catchments can be considered as potential stormwater harvesting sites where stormwater can be captured and infrastructure can be built.

In task (b), spatial maps are generated for runoff, demand and accumulated catchments, which require the collection of data such as rainfall, water demands, impervious-pervious areas, digital elevation model (DEM), and digital cadastre. For the GIS based screening tool, an annual time scale for estimating runoff was chosen for both stormwater runoff and demand, as the tool only dealt with preliminary evaluation and ranking of potential stormwater harvesting sites. Thus, the current methodology is designed for a quick and simple investigation of stormwater harvesting suitability across an area. The simple rational method as suggested by Schueler (1987) can be used to generate the runoff map for screening purposes. Thus, yearly rainfall and an impervious-pervious area map can be used to compute yearly runoff. Runoff layer is developed in raster format as software tools such as ‘spatial analyst’ can provide flexibility of interpolation and calculation.

For generating demand maps, the present methodology uses combination of the data of annual demands (spatial point format) and landuse such as park, industrial or household (polygons). Each landuse may have one or more demand points and these demand points are aggregated to represent demand for each landuse (ML/m^2) in the demand map.

In task (c), spatial maps of runoff and demands are overlayed on the accumulated catchments. The accumulated catchments can be obtained from delineation of DEM. Each drainage outlet of these accumulated catchments represents a potential site for stormwater harvesting having attributes of runoff and demand. This task serves as basis for evaluation of suitability criteria with respect to the screening parameters detailed in Step 3 (Section 3.2.3).

3.2.2 Step 2 - Estimation of Environmental Flows

Urbanisation usually doubles runoff volumes, due to impervious surfaces decreasing the infiltration of rainfall (NRMMC et al., 2009). These excessive amounts of urban stormwater runoff can be harmful to the health of stream ecosystems, alter the wet and dry spells that occur in natural wetlands, cause bank erosion, and discharge pollutants to receiving waters (Fletcher et al., 2007). Environmental flows are the flow regimes necessary to maintain or improve the natural ecological health of urban waterways. Stormwater harvesting can be sometimes detrimental to the environment as ‘over extraction’ from the natural waterways may impact on downstream aquatic ecosystems reducing their available aquatic habitat (DEC, 2006). However, stormwater harvesting within an urban catchment has also the potential to mitigate a number of these harmful impacts on the flow regime, including the reduction of the high flow volumes and peak flows, and the reduction in the number of stormwater flow events, and therefore could enhance urban stream health while meeting potable water conservation requirements (Mitchell et al., 2007). These environmental benefits from stormwater harvesting can be achieved by reducing runoff volumes to predevelopment levels (NRMMC et al., 2009), and these reduced runoff volumes can be considered as environmental flows.

In this step, pre-development flows are assumed as environmental flows, which are necessary to maintain natural flow regimes. In the study conducted by Fletcher et al. (2007), pre-development runoff was estimated assuming the catchment as 100% pervious, as the landuse conditions before urban development. The same methodology is used in the present study. This pervious runoff is deducted from the total runoff estimated for each accumulated catchment in Step 1. The resultant runoff is termed as 'harvestable runoff', which is used in later steps.

3.2.3 Step 3 - Evaluation of Screening Parameters

In this step, three screening parameters are identified for screening and ranking of potential stormwater harvesting sites: demand, ratio of runoff to demand and weighted demand distance. All the catchments with harvestable runoff and demands in previous steps are used in the estimation of these screening parameters. The estimation of the values of the screening parameters is conducted through a 'radius of influence' concept (Figure 3.2).

3.2.3.1 Radius of Influence Concept

The harvestable runoff corresponds to an accumulated runoff at the catchment outlet (which is also considered as a potential harvesting site). From the accumulated catchment perspective, runoff at the catchment outlet can be utilized for meeting upstream catchment demands. However, there is the need to consider the distance from the harvesting point (outlet) to the point of demand. Furthermore, there is a possibility that demand locations within adjoining catchments, can be closer to the outlet of the accumulated catchment under consideration. Therefore, the matching of supply from the harvesting site with areas of demand is handled through the 'radius of influence concept' in this methodology.

The physical distance between the stormwater harvesting site and the demand areas is critical for considering the economic feasibility of a stormwater scheme as it determines infrastructure requirements for distribution and associated costs. For example, in Figure 3.2, runoff in the *catchment-b* is draining at *outlet-2* which is intersecting a demand location. Thus, the *outlet-2* is an ideal potential stormwater harvesting site as the catchment outlet and demand is co-located. However, as the distance to demand locations within *catchment-b* increases from *outlet-2* the costs to service this demand increases. From the distance perspective, some of the upstream demands of *catchment-b* can be met by *outlet-1* of the neighbouring upstream *catchment-a* within a certain 'radius of influence', provided adequate runoff is available at *outlet-1*. Thus, with the radius of influence concept, demands within a certain radius of the stormwater harvesting site can be easily satisfied.

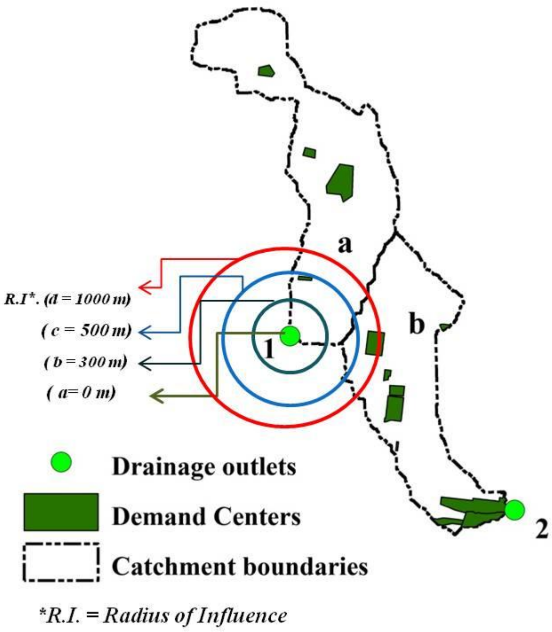

Figure 3.2: Radius of Influence

In Figure 3.2, the radius of influence is shown at four different levels as 0 m, 300 m, 500 m, and 1000 m from the *outlet-1* for demonstration purpose. Under each level, quantity of runoff and demand can be assessed separately and thus decision maker can have flexibility to implement the stormwater harvesting scheme by evaluating the desired runoff and demand match. The radii of influence levels can be altered with the site specific characteristics (such as slope) that may influence the physical distance between supply and demand points.

3.2.3.2 Estimation of Screening Parameters

As stated earlier, the screening parameters used in the study are: a) demand, b) ratio of runoff to demand, and c) weighted demand distance. These parameters are important as they act as key performance indicators for evaluating the suitability of potential stormwater harvesting schemes.

The screening parameter demand can be the aggregated demand (end use specific) within the radius of influence of a stormwater harvesting site. This parameter can identify sites of high demand that should be given higher priority when planning stormwater harvesting schemes to maximise the substitution of potable water demand. Moreover, a stormwater harvesting scheme satisfying relatively small demand may not be cost effective due to the significant capital investment required, particularly in existing urban environments, where retrofitting infrastructure is expensive.

The screening parameter ratio of runoff to demand assesses the match between harvestable runoff and the associated demand. High ratio implies that high amount of runoff is available for meeting the demands regardless of the seasonal fluctuations in summer and winter. If the ratio is low, then the given site may not be able to meet the demands within its radius of influence.

The weighted demand distance refers to the average weighted distance of demand areas from the given stormwater harvesting site. This gives preferences to sites close to high demand areas to minimise transport and water infrastructure costs.

Thus, for each site, potential options for stormwater harvesting can be obtained by computing demands, ratios of runoff to demand and weighted demand distances for all levels considered with different radii of influence. Each site can have ideally *'n'* possible options at *'n'* levels of radii of influence (only four levels are considered in this study). For example, *outlet-2* in Figure 3.2 can have stormwater harvesting options as *2a, 2b,..,2n* based on different demands, different ratios of runoff to demand and different weighted demand distances for *n* levels of radii of influence. However options at all levels of radii of influence are not always possible. For example, for a given stormwater harvesting site, estimation of screening parameters is unrealistic, if there are very low or no demands within the considered level of radii of influence.

3.2.4 Step 4 - Ranking and Validation

The potential stormwater harvesting options generated from all sites can be grouped together for ranking purposes. Thresholds are then defined for screening parameters to eliminate the inferior sites and shortlist non-inferior sites (i.e. based on demands, ratios of runoff to demand and weighted demand distances). Such sites are ranked with highest demand, highest ratio of runoff to demand and lowest weighted demand distance. The ranking of sites can be done by any one of the three parameters or by combination of any two screening parameters, or all parameters together. The most highly ranked sites can be considered for validation with the stakeholders who have a strong local knowledge of stormwater harvesting potential.

Validation is an essential component of the methodology development, as the stakeholders will provide valuable contextual insight into the feasibility of harvesting stormwater at the ranked sites based on their local knowledge of existing drainage infrastructure, soil and terrain characteristics, local water bodies, and open spaces. This local knowledge can assist in refining the ranking of potentially suitable stormwater harvesting sites. These stakeholders are also likely to be aware of planning and regulatory issues associated with stormwater harvesting at particular sites. Thus, the validation process assists in confirming the ranking of potentially suitable stormwater harvesting sites identified from the GIS based screening tool. Top ranked sites can then be considered for detailed assessment.

3.3 Study Areas

City West Water (CWW) is one of the three water retail authorities in the Melbourne metropolitan area in Australia and is wholly owned by the Victorian State Government. The core business of CWW is the delivery of drinking water and recycled water, and the collection of sewage and trade waste from customers in Melbourne's Central Business District and inner and western suburbs. CWW's servicing area includes nine (9) different city councils with different socio-economic status. CWW works closely with local government councils to develop alternative servicing strategies for their open spaces.

To demonstrate the effectiveness of the GIS based screening tool methodology, the current study considers the application of the GIS screening tool on a highly urbanised area and on a semi urbanised area. For this purpose, two city councils within the CWW servicing area were selected respectively: City of Melbourne (CoM) and City of Brimbank (CoB).

The CoM is a highly urbanised council comprising of mainly commercial and park landuse, while the CoB is developing semi urbanised council compromising of mainly residential and open spaces land use. The details of study area (CoM and CoB) are described in Section 3.3.1 and 3.3.2 respectively.

3.3.1 City of Melbourne (CoM)

The study area for CoM within the CWW servicing region is shown in Figure 3.3. The CoM is the local government municipality covering Melbourne's Central Business District and surrounding inner suburbs.

Geographically, the CoM covers an area of 36.5 Km^2 situated at the downstream end of the following three catchments: the Yarra River catchment, the Maribyrnong River catchment, and the Moonee Ponds creek catchment. The Maribyrnong River and Moonee Ponds creek flow into the Yarra River, which enters Port Phillip Bay. The soils in this area are categorised as heavy clay formed on Basalt Rocks. The topography of the CoM is mostly flat with 70% of its land having slopes less than 5%. The CoM also covers the Central Business District (CBD) of Melbourne with a residential population of 96,552, and approximately 788,000 people use city per day for various purposes (ABS, 2009; CoM, 2010).

Greater Melbourne has a temperate climate which is influenced by topography and seasonal weather patterns. Surface water is the main source of water in Melbourne which comes from mountain ash forest catchments in the Yarra Ranges to the east of the city. The mean maximum temperature of Melbourne is 19.8°C and the mean minimum temperature is 10.2°C.

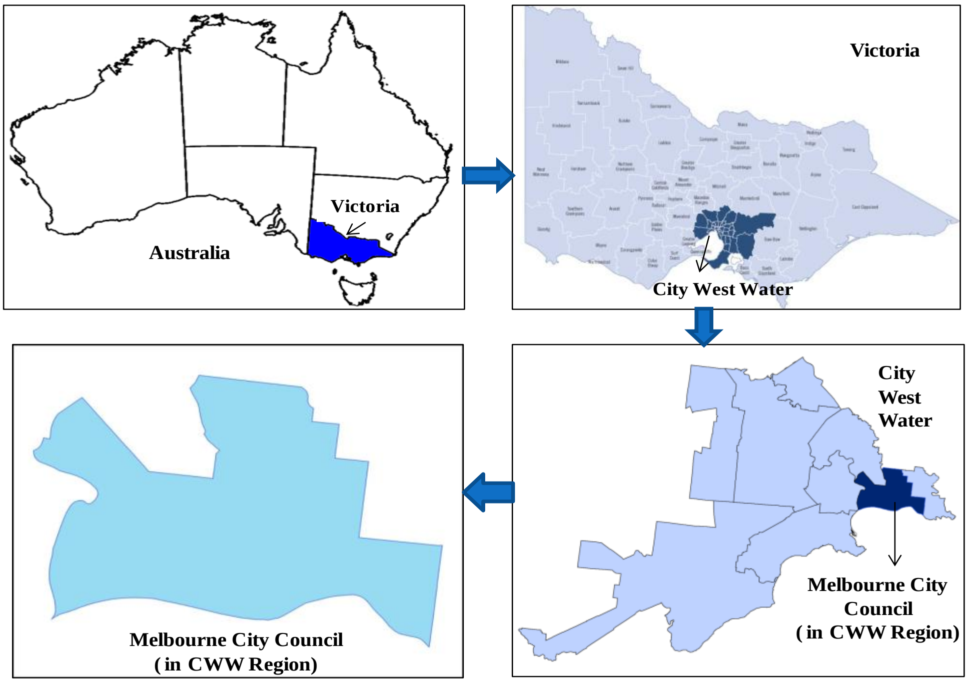

Figure 3.3: City of Melbourne - Case Study

The average annual rainfall of Melbourne is 650 mm (http://www.bom.gov.au/climate/averages/tables/cw_086071_All.shtml) The maximum rainfall occurs during late winter (June, July, August) and early spring (September, October, November), while the minimum occurs during summer (December, January, February) and early autumn (March, April, May).

Melbourne's climate is affected by El Niño wind patterns which caused a severe drought from 1997 until late 2010. Although the Australian Government officially declared cessation of the drought in 2011 (DPI, 2011), the climate change prediction study conducted by Howe et al. (2005) has forecasted higher average temperatures, less rainfall, more frequent hot and dry days, and intense storms in future for Melbourne. Therefore, the City of Melbourne (CoM) is currently taking an active role in saving water, improving water quality and identifying new water sources with an overall target to reduce the per capita potable water consumption by 40 per cent by 2020 (CoM, 2011).

The GIS screening methodology was applied to a portion of the CoM, an area of 26 Km^2 within CWW's service area of 640 Km^2 (Figure 3.3). The rest of the CoM area is separated by the Yarra River and serviced by South East Water (another water retail authority in Melbourne). The study area comprises predominantly commercial land use; other land uses include public parks, reserves, residential and industrial. The total non-residential water demand for the study area in the year 2010 was estimated as 11 GL, where as the total demand including residential demand constituted as 15 GL. This non-residential demand is mainly commercial water use which constitutes 82% (of the total non-residential demand of 11 GL). The next highest non-residential demand results from the irrigation of parks and open spaces accounting for 6%. This high irrigation demand is currently supplied by potable water which is subjected to water supply restrictions.

3.3.2 City of Brimbank (CoB)

The City of Brimbank (CoB) is the second largest municipality in Melbourne with 123 Km^2 of land area. Moreover, CoB boasts its cultural diversity by embracing more than 156 nationalities from around the globe, making it Victoria State’s most culturally diverse municipality (City of Brimbank, 2013). Geographically, CoB is located across western and north-western suburbs of Melbourne. The population in CoB is around 191,084 with population density of 13.3 per ha as of year 2011 estimate (City of Brimbank, 2013). The study area for CoB is shown in Figure 3.4.

The CoB is situated in the Victorian Volcanic Plain, formed from volcanic eruptions and lava flows. The council has many natural features which comprise of grasslands, grassy wetlands, escarpments and riparian sites. Prominent waterways in CoB feature Maribyrnong River, Kororoit Creek, Taylors Creek, Jones Creek, Steele Creek and Stony Creek. The landuse mostly comprised growing residential area (46%) followed by the parklands (20 %) and other areas including industrial and commercial areas. Residential growth is expected to continue in various suburbs in the council (City of Brimbank, 2013)

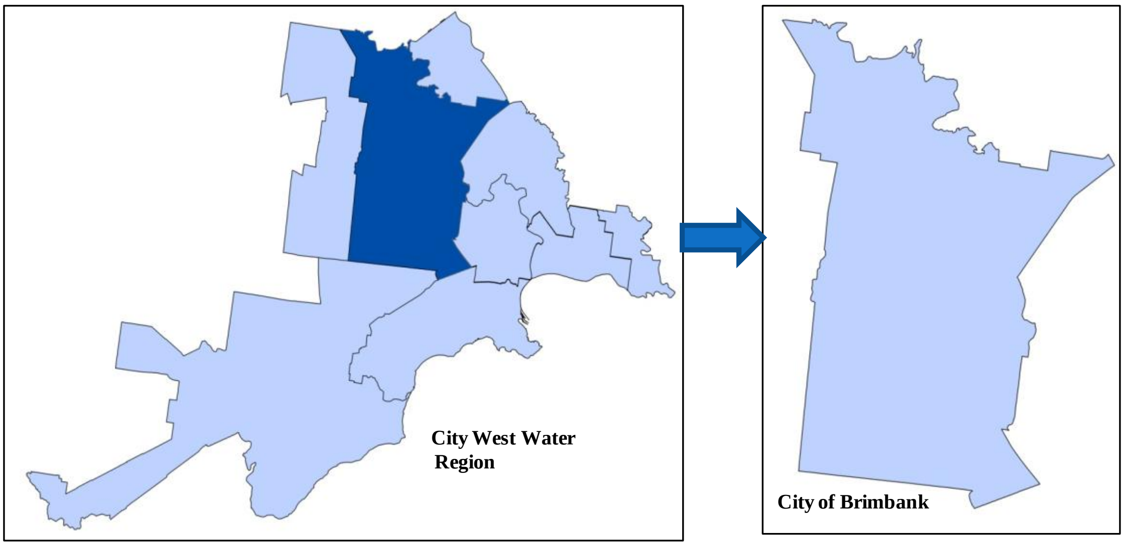

Figure 3.4: City of Brimbank – Case Study

The Brimbank region averages 400-500 mm rainfall a year, which is amongst the lowest in the greater Melbourne area. Having majority of landuse as residential area, CoB had a total water demand (including residential demand) of 12.8 GL in year 2010. The non-residential water demand for same year constituted as 2.8 GL. This non-residential demand was dominated by industries which constituting 82% of total demand, followed by the commercial use (7%) and park irrigation demand (5%) which is subjected to potable water restrictions.

3.4 Application of the Methodology - City of Melbourne (CoM)

The GIS based screening tool methodology described in section 3.2, was applied to the CoM and COB councils within CWW to select and rank the suitable stormwater harvesting sites. The application of the proposed methodology to both these councils served as a measure to compare its effectiveness in highly urbanised and semi urbanised regions. The application of GIS screening tool methodology is presented in more detail for CoM as compared to CoB, to avoid any unnecessary repetition of similar tasks performed in these council case studies.

3.4.1 Evaluation of Suitability Criteria

GIS maps were first developed for the identified suitability criteria of runoff and demand. The accumulated catchment map was also generated for the study area with its drainage network information. Drainage outlets of these accumulated catchments were considered as potential stormwater harvesting sites with runoff generated from the accumulated catchments. Adjacent demands to the drainage outlet were considered as the demands to be supplied from the stormwater harvesting sites.

3.4.2 Data Acquisition and Processing

For developing the spatial maps of runoff, demand and accumulated catchments, necessary data were collected from different Australian institutions and research organizations. The raw datasets included impervious area map, landuse map, study area boundaries, council boundaries, customer demand map, and DEM. Table 3.1 shows some details of these datasets. All raw datasets were processed into the runoff layer, the demand layer and the accumulated catchment layer using Arc GIS version 9.3, Spatial Analyst tools and Arc Hydro tools.

3.4.2.1 Runoff Layer

The drought period of 1997-2009 in Melbourne was considered in developing the runoff layer, as this period provides a conservative estimate for runoff in the assessment of potential stormwater harvesting opportunities. The runoff layer was generated in raster grid format with cell size of 30 m X 30 m.

Table 3.1: Data Description (CoM)

Data	Source	Format	Scale
Rainfall Data	SILO	Text	1:300,000
Impervious Area Map	Melbourne Water	Vector (Polygons)	1:50,000
Customer Demands	CWW	Vector (Point)	1:50,000
Study Area	CWW	Vector (Polygon)	1:300,000 (CWW) 1:50,000 (CoM)
Planning Zone Map (Landuse)	CWW	Vector (Polygon)	1:50,000
DEM (10 m)	Land Victoria	Raster (ESRI grid)	1:60,000

The selected fine resolution was based on the trade-off between spatial scale of rainfall and impervious-pervious area (parcels) map. At low (larger cell size) resolution, the information of pervious-impervious areas may be lost. Although, rainfall may not vary significantly with a relatively larger grid than the 30 m grid, this resolution was considered, so that the information on pervious-impervious areas is considered adequately.

An interpolated rainfall map (or layer) was prepared using SILO data. SILO data provided rainfall values at 0.05 degree (5 km) resolution within the CWW service area which were converted to GIS point format. Rainfall represented by the each of SILO point was the average annual rainfall for the period of 1997-2009. Interpolation of these points was undertaken to represent the rainfall at 30m X 30m resolution using the Inverse Distance Weighting (IDW) method through the spatial analysis tools in Arc GIS 9.3.

The runoff layer for CoM is illustrated in Figure 3.5. The interpolated rainfall map (part ***b*** in Figure 3.5) for the CoM region had a range of annual average rainfall values between 497 mm to 537 mm. The impervious-pervious area map (part ***a*** in Figure 3.5) classified land uses into either impervious (e.g., roads) or pervious (e.g. parks). On the basis of this classification, it was found that CoM (in the CWW region) had 55% of its total area as impervious due to its highly urbanised CBD. The remaining 45% is pervious due to presence of various parks.

The same impervious-pervious map was used to generate the runoff coefficient map where values 0.9 and 0.1 were used as runoff coefficients for impervious areas and pervious areas respectively (Argue et al. 2009). The impervious-pervious map and runoff coefficient map was combined with the rainfall map using the ‘Raster Calculator’ to compute the annual runoff layer (part ***c*** in Figure 3.5). The runoff values were a function of the spatial distribution of impervious areas and pervious areas, generating varied runoff values (between 434mm to 44mm) within the CoM area.

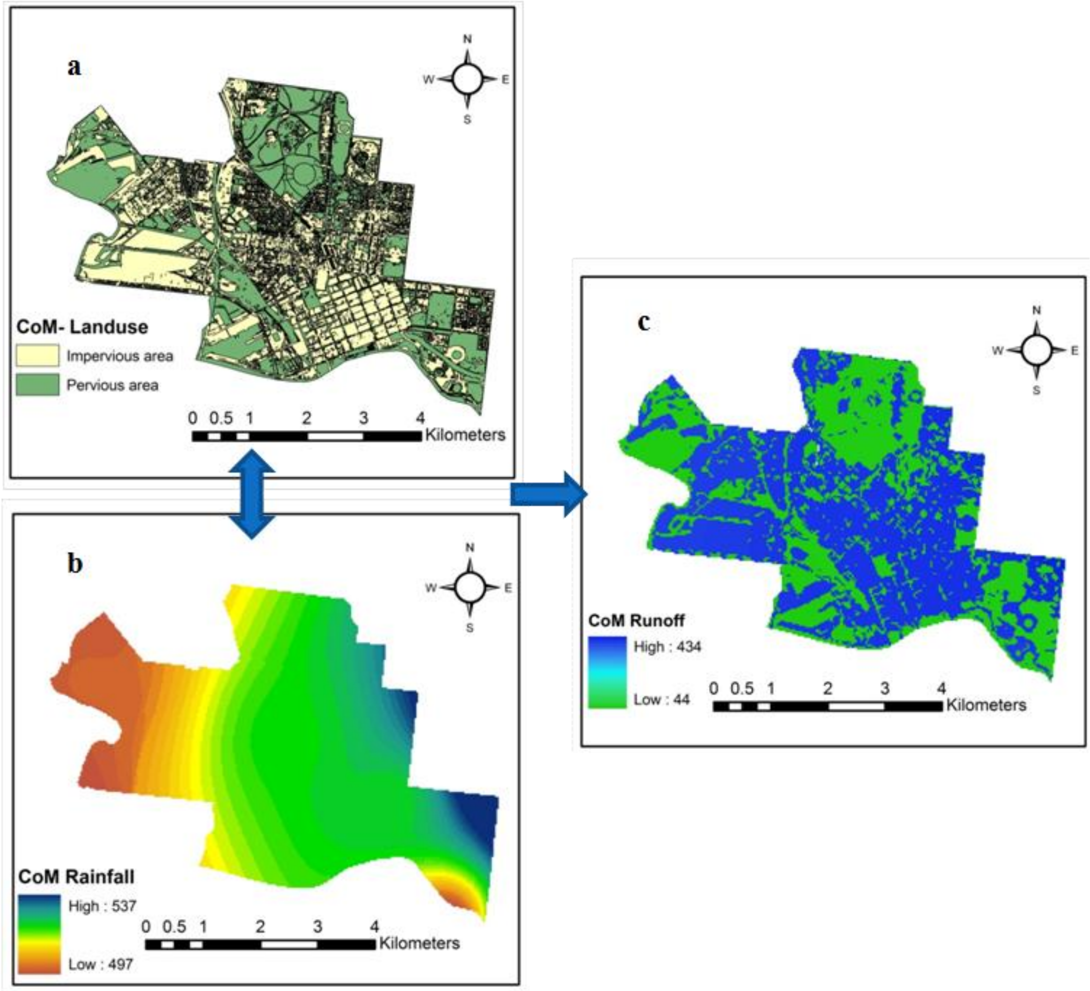

Figure 3.5: Runoff Layer for CoM

a) Impervious-pervious area layer, b) Rainfall layer c) Runoff layer

3.4.2.2 Demand Layer

The study considered two different years of water demands for evaluating the stormwater harvesting sites. The study used year 2010 demands as the base demand case, since they were the most recent data obtained, when the project was started. The total irrigation demand in year 2010 was around 0.65 GL. Also, the study used year 2001 as the maximum demand case as this demand was highest (2.3 GL) during the period of 2001-2010. It should be noted that year 2001 did not have water restrictions as compared to year 2010 which had water restrictions. The comparative analysis of both cases provided an insight into how stormwater harvesting systems would perform with different magnitudes of demands.

CWW provided the data of known individual park demands with their spatial locations in shape file format (spatial points). The annual demands of these parks were in the range of 1 ML to 155 ML with 70% less than 10 ML for year 2010. Similarly, in year 2001, the annual demands for the parks were in range of 1ML to 376 ML with 65% more than 5ML. The spatial demand points were intersected with the park landuse map to identify the demand points within the existing park land use polygons of CoM. This operation resulted into three different types of dataset: (a) demand points intersecting with existing park landuse, (b) demand points not intersecting with existing park landuse, and (c) park landuse not intersecting with demand points. Figure 3.6 illustrates these three cases.

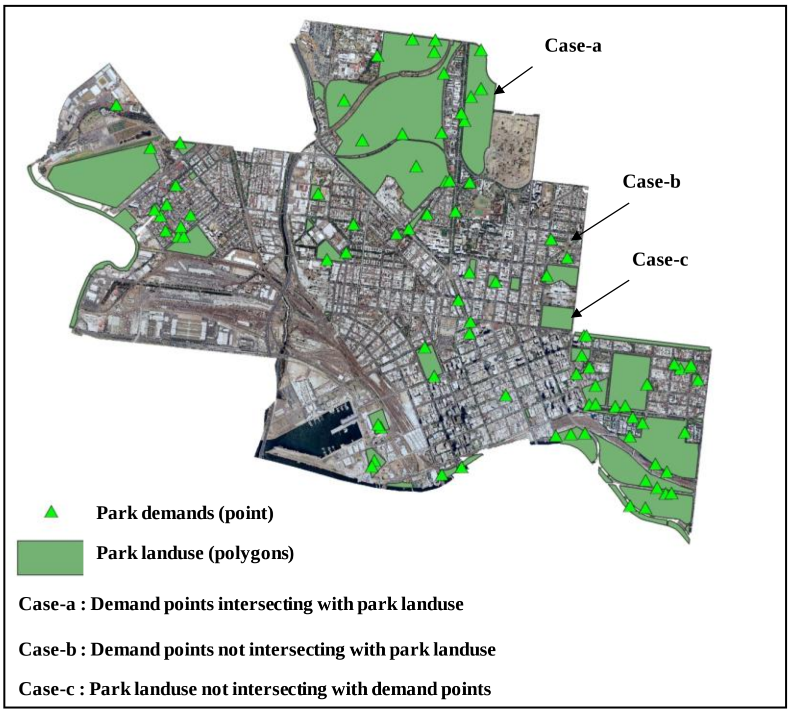

Figure 3.6: Demand Layer of the Parks

For case *(a)* dataset, demand points which intersected with the park landuse area, were summed together to represent a total known demand over a given park landuse area (ML/ m^2). In case *(b)* dataset, the park demand points indicated possibility of recent demand areas which were not present in existing park landuse map. These demand areas were manually digitised with help of aerial imagery to combine into existing park landuse map. Consequently, the similar operation of demand aggregation over park landuse area was performed as with the case *(a)* dataset. The case *(c)* dataset represented the park landuse areas where water demand data is either missing or there is no demand from the corresponding park in both years of 2001 and 2010.

The parks landuse in case *(c)* were authenticated from aerial imagery and CWW officers, to verify whether they are demand areas. For verified parks, the demand was assumed as a minimum of 2 ML per ha after consultations with CWW officers and thus, corresponding demand for all parks in CoM was estimated as 58 ML for year 2010 and 80 ML for year 2001 respectively.

3.4.2.3 GIS Layers for Accumulated Catchments

Using Arc Hydro tools, the DEM of 10 m resolution was processed to delineate the catchments in the study area. The accumulated catchment layer was then generated using the ‘Accumulate Shape’ function of Arc Hydro, resulting in 88 accumulated catchments. With delineation of the catchments, the drainage network along with drainage outlets was populated. Figure 3.7 shows the generated accumulated catchments together with their drainage networks in the CoM region. Additionally, parks in the CoM region are also shown in Figure 3.7

The raster runoff layer was overlayed and aggregated over the accumulated catchment layer to compute the total catchment runoff as the mean annual flow, within the each of 88 accumulated catchments. The total volume of mean annual runoff generated by all catchment outlets was 6.7 GL for the study area. This figure was found to be reasonable by comparing with a study carried out by CoM in 2008 which indicated that mean runoff from CoM was around 13 GL in year 2000 from an area of 36 Km^2 (CoM, 2011). The 6.7 GL figure represents the mean annual runoff from the portion of CoM within the CWW boundary of an area of 26 Km^2 in the drought period of 1997-2009. Furthermore, the mean rainfall in year 2000 (629 mm) was above the mean rainfall over the period 1997-2009 (514 mm) within CoM.

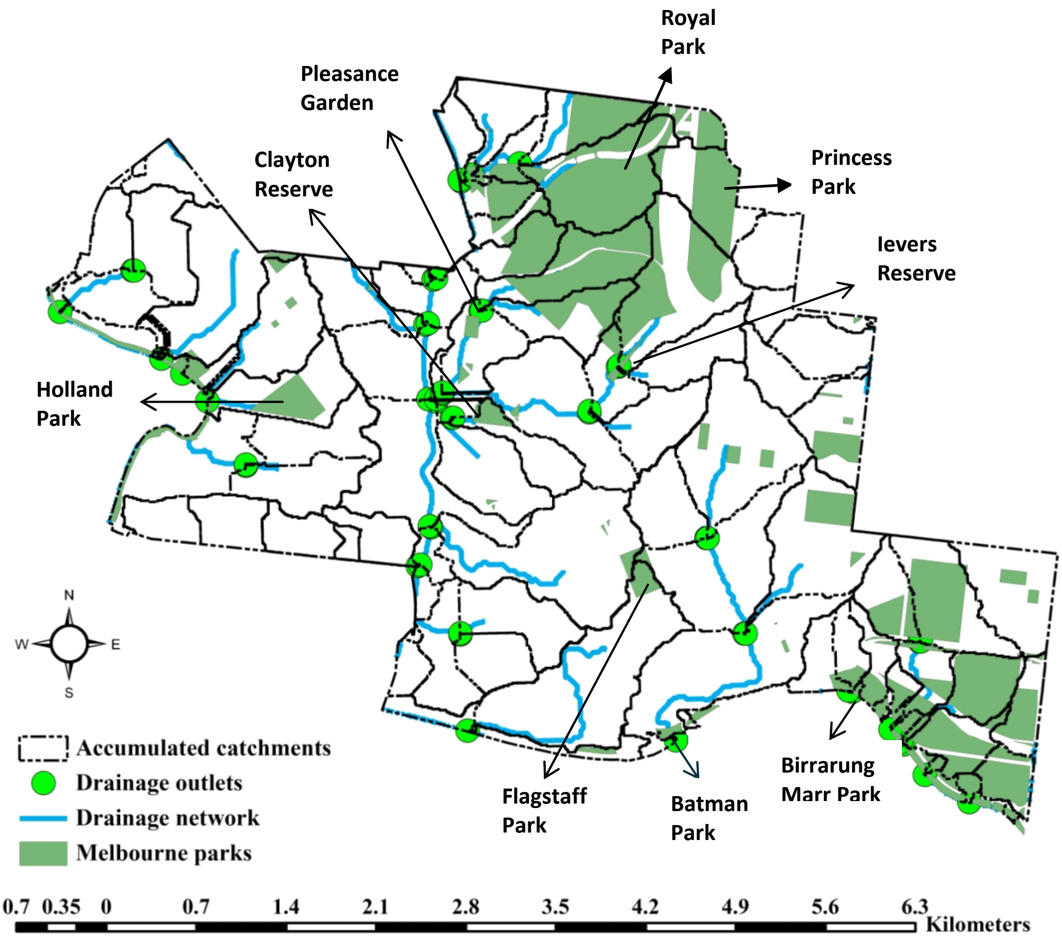

Figure 3.7: Accumulated Catchments and Parks in CoM Region

3.4.3 Estimation of Environmental Flows

This study considered pre-developed flows as environmental flows to be discharged into the waterways. The pre-developed flow was computed for all accumulated catchments using the rational formula. All catchments were assumed as pervious catchments to estimate the pre-developed flows, as pervious catchments reflected landuse conditions of CoM before development.

The runoff coefficient for the pervious areas was assumed as 0.1 after consultation with CWW officers. The pre-developed runoff was subtracted from total runoff for all accumulated catchments (6.7 GL) to obtain the harvestable runoff. The total pre-developed flow was estimated as 4.3 GL and thus the total harvestable runoff was 2.4 GL. The harvestable runoff from each accumulated catchments was used in the screening analysis conducted in later sections.

3.4.4 Evaluation of Screening Parameters

Screening parameters of demand, ratio of runoff to demand and weighted distance were calculated for all 88 stormwater harvesting sites generated from the accumulated catchments. The screening parameters were computed at different radii of influence (i.e. *a = 0 m, b = 300 m, c = 500 m* and *d =1000 m* from each of these sites as described in Figure 3.2) for this study. However, the analyst can select the suitable radii of influence based on their local conditions. The screening parameter calculations were done for both cases of demand as explained in Section 3.2.1. Table 3.2 shows the screening parameters for a sample stormwater harvesting site (ID-22) for year 2010 demands.

Table 3.2: Estimation of Screening Parameters

Site ID	Radius of Influence (m)	Harvestable Runoff (ML)	Demand (ML)	Ratio of Runoff to Demand	Weighted Distance (m)
22	300 (b)	3.28	0.25	13.1	48
	500 (c)		1.91	1.7	390
	1000 (d)		7.02	0.5	596

As the site listed in Table 3.2 did not intersect with any of the parks, the radius of influence 0 m (a) was not applicable in this case. From Table 3.2, it is clear that with an increase in radius of influence, the demand also increased as more demands were aggregated (with increased distance). The ratio of runoff to demand also decreased with the increase in the demand for the same amount of runoff. The nearest park for this site was at 48 m distance.

Theoretically, four stormwater harvesting options were possible for four levels of radii of influence at each site (including the above Site ID-22). However, all four options were not realistic in some cases as absence of demand within certain levels of radii of influence limited the computation of screening parameters and thereby number of options.

For case of the 2010 demand, the analysis generated a total of 97 potential stormwater harvesting options from 88 sites of accumulated catchments. Similarly, for the case of 2001 demand, the analysis generated 100 potential stormwater harvesting options.

3.4.5 Ranking of Stormwater Harvesting Options

The ranking of the options was carried out in two stages. In first stage, set of thresholds were introduced to the screening parameters to shortlist the technically feasible stormwater harvesting options. CWW stormwater professionals were consulted in developing these thresholds for technical feasibility. They were: demands greater than or equal to 5 ML, weighted demand distance less than or equal to 300 m, and ratio of runoff to demand greater than 1.

In second stage, short listed options were ranked based on screening parameters to identify the sites with highest demand, or highest ratio of runoff to demand or lowest weighted demand distance. This approach provided a combined set of stormwater harvesting sites with high demand, high ratio of runoff to demand and low weighted distance.

3.4.6 Ranking Results: Year 2010

All thresholds of screening parameters identified in Section 3.4.5 were applied to all 97 options (Section 3.4.4). The analysis resulted in 33 potential stormwater harvesting options which are represented in Table 3.3. These options are ordered according to their site identification (ID) number.

Among these 33 options, the demands of the sites ranged from 5 ML to 126 ML, the ratios of runoff to demand from 1.3 to 65.1, and the weighted distances from 0 to 300 m. Table 3.3 further shows the number of parks whose demands were considered in this study, within the corresponding radii of influence. Also, in Table 3.3, all drainage locations (i.e. stormwater harvesting sites) have been represented by the nearest park available from the sites. There are nine such stormwater harvesting sites (park locations) which are listed in Table 3.3. It should be noted that *a, b, c* and *d* in Table 3.3 represent the radius of influence levels at distances 0 m, 300 m, 500 m and 1000 m respectively. The 33 options were individually ranked with respect to their demands, ratio of runoff to demands, and weighted demand distance, and they are described under sub-headings (a), (b), and (c) below respectively.

Table 3.3: List of Stormwater Harvesting Options for CoM (Year 2010)
(Demand > =5 ML, Ratio of Runoff to Demand > 1, and
Weighted Demand Distance < =300 m)

Site ID	Possible Options	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
9	9b	38.6	28.7	1.3	0	1	Princes Park
12	12b	228.4	15.9	14.4	210	1	Royal Park South
14	14b	229.4	125.6	1.8	182	2	
17	17a	69.4	23.1	3.0	0	1	Holland Park
	17d		53.8	1.3	112	7	
20	20a	64.5	23.1	2.8	0	1	
26	26b	50.3	19.4	2.6	87	3	Ievers Reserve
28	28b	97.3	6.2	15.8	243	3	Clayton Reserve
29	29a	133.0	23.1	5.8	0	1	Holland Park
	29c		28.9	4.6	80	4	
	29d		31.7	4.2	136	8	
39	39b	31.9	19.4	1.6	87	3	Ievers Reserve
41	41a	67.7	23.1	2.9	0	1	Holland Park
	41c		28.9	2.3	67	4	
	41d		30.7	2.2	103	7	
43	43b	181.5	5.8	31.2	277	2	Clayton Reserve
	43c		6.2	29.4	283	3	
44	44b	402.4	6.2	65.2	250	3	
	44c		6.4	62.6	255	4	
46	46b	104.7	5.8	18.0	182	2	
	46c		6.8	15.3	217	6	
	46d		7.5	14.0	256	7	
47	47b	72.0	5.8	12.4	182	2	
	47c		6.8	10.5	218	5	
	47d		7.5	9.6	256	7	
52	52a	116.5	5.3	21.9	0	1	Victoria Parade Plantation
	52b		13.7	8.5	134	3	
69	69b	948.2	11.6	81.6	175	2	Batman Park
76	76a	62.7	5.3	11.8	0	1	Birrarung Marr Park
	76b		49.0	1.3	300	1	
77	77a	17.2	5.3	3.2	0	1	
78	78a	19.4	5.3	3.7	0	1	
	78b		13.0	1.5	70	2	

a) Ranking Based on (High) Demand

The top 10 stormwater harvesting options ranked according to high demand are listed in Table 3.4. The Royal Park (option *14b*) was ranked high as it had the largest water demand from the golf course, zoo and several playgrounds. Drainage outlets of options *17d*, *29d*, *41d*, *29c*, *41c*, *20a* and *29a* were closely located near Holland Park making the Holland Park another preferable site for stormwater harvesting (Table 3.4).

Stormwater harvesting options *29c* and *41c* had the same amount of demand covered under 300 m radius of influence level due to their close spatial locations. A higher ranking was given to the site with higher ratio of runoff to demand (option *29c* with the ratio of 4.6).

Table 3.4: Ranking Based on Demand (CoM-2010)

Site ID	Harvestable Runoff (ML)	Demand* (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
14b	229.4	**125.6**	1.8	138	2	Royal Park
17d	69.4	**53.8**	1.3	112	7	Holland Park
76b	62.7	**49.0**	1.3	300	1	Birrarung Marr Park
29d	133.0	**31.7**	4.2	136	8	Holland Park
41d	67.7	**30.7**	2.2	103	7	
29c	133.0	**28.9**	4.6	80	4	
41c	67.7	**28.9**	2.3	67	4	
9b	38.6	**28.7**	1.3	0	1	Princes Park
20a	64.5	**23.1**	2.8	0	1	Holland Park
29a	133.0	**23.1**	5.8	0	1	

* *Bold stands for ranking based on high demand*

b) Ranking Based on (High) Ratio of Runoff to Demand

Ranking of the top 10 options on the basis of ratio of harvestable runoff to demand are shown in Table 3.5. The Batman Park was highly ranked stormwater harvesting site (option *69b*), as it had the highest ratio of runoff to demand. The large runoff volume generated at this site was due to high imperviousness of the catchment. However, the Clayton Reserve dominated the ranking with multiple closely spaced drainage outlets with options (*44b, 44c, 43b, 43c, 46b, 46c, 46d and 28b).* The Victoria Parade Plantation (option *52a*) was also a preferable stormwater harvesting site, as it required minimum infrastructure costs at 0 m weighted demand distance.

c) Ranking Based on (Low) Weighted Demand Distance

Table 3.6 shows the top 10 options ranked on the basis of the weighted demand distance. From Table 3.6, it is evident that 9 out of the top 10 options had 0 m weighted demand distance, as the corresponding drainage outlets were intersected with respective parks. Among all options in Table 3.6, Holland Park (*41c* and *20a)* and Princess Park

(*9b*) were preferable choices as they also represent parks with high demands in Table 3.4. Furthermore, the Victoria Parade Plantation *(52a)* was also highly ranked based on the ratio of runoff to demand (Table 3.5). Such commonly ranked sites under different screening parameters provided confidence to stormwater harvesting decision making.

Table 3.5: Ranking Based on Ratio of Runoff to Demand (CoM-2010)

Site ID	Harvestable Runoff (ML)	Demand* (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
69b	948.2	11.7	**81.6**	175	2	Batman Park
44b	402.4	6.2	**65.2**	250	3	Clayton Reserve
44c	402.4	6.4	**62.6**	255	4	
43b	181.5	5.8	**31.2**	277	2	
43c	181.5	6.2	**29.4**	283	3	
52a	116.5	5.3	**21.9**	0	1	Victoria Parade Plantation
46b	104.7	5.8	**18.0**	182	2	Clayton Reserve
28b	97.3	6.2	**15.8**	243	3	
46c	104.7	6.8	**15.3**	217	6	
46d	104.7	7.5	**14.0**	256	7	

* *Bold stands for ranking with high ratio of runoff to demand*

Table 3.6: Ranking Based on Weighted Demand Distance (CoM-2010)

Site ID	Harvestable Runoff (ML)	Demand* (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
52a	116.5	5.3	21.9	**0**	1	Victoria Parade Plantation
76a	62.7	5.3	11.8	**0**	1	Birrarung Marr Park
29a	133.0	23.1	5.8	**0**	1	Holland Park
78a	19.4	5.3	3.7	**0**	1	Birrarung Marr Park
77a	17.2	5.3	3.2	**0**	1	
17a	69.4	23.1	3.0	**0**	1	Holland Park
41a	67.7	23.1	2.9	**0**	1	
20a	64.5	23.1	2.8	**0**	1	
9b	38.6	28.7	1.3	**0**	1	Princes Park
41c	67.7	28.9	2.3	**67**	4	Holland Park

***** *Bold stands for ranking with less demand distance*

3.4.7 Ranking Results: Year 2001

In a similar approach to year 2010 demands, twenty four (24) stormwater harvesting options were shortlisted for year 2001 demand case after application of screening parameter thresholds. These options are ordered in Table 3.7 with respect to site IDs representing six (6) different parks. There were less number of options short listed in 2001 case (24) compared to 2010 (33) as demand magnitudes were high in 2001 (no water restrictions). These higher demands lowered the ratio of runoff to demand, thereby number of viable options.

Among the 24 options for year 2001, the demand of sites were ranged from 5.6 ML to 62.4 ML, the ratios of runoff to demand were ranged from 1.1 to 76.1, and the weighted distances were in range of 0 to 288 m.

a) Ranking Based on Demand

Table 3.8 shows ranking of top 10 sites based on high demand for 2001 case. Option *17d* was highly ranked in both cases of 2001 and 2010 making the Holland Park as natural choice for stormwater harvesting. For the next highly ranked option *69b*, demand was 41.2 ML in 2001 which was reduced to 11.6 ML in 2010 because of water restrictions. The other highly ranked parks with high demand were Clayton Reserve and Victoria Parade Plantation.

b) Ranking Based on Ratio of Runoff to Demand

Ranking of options (Top 10) on the basis of ratio of harvestable runoff to demand are shown in Table 3.9. For highly ranked Batman Park, option *83b* and *69b* represented sufficient availability of stormwater (i.e. ratio) for meeting demands. Similarly, Clayton Reserve had various options such as *44b, 44c, 43b, 43c, 46b,* and *28b* to supply the required demand.

c) Ranking Based on Weighted Demand Distance

Table 3.10 indicates the top 10 options ranked on the basis of the weighted demand distance. The Victoria Parade Plantation (*52a*) was highly ranked site with zero weighted demand distance. Moreover, same park was also ranked as high demand option (*52b*) in Table 3.9. Furthermore, Wellington Parade (*62b*) and Iveres Reserve (*26b* and *39b*) were next best possible locations on the basis of less weighted demand distance ranking.

Table 3.7: List of Stormwater Harvesting Options for CoM (Year 2001)
(Demand > =5 ML, Ratio of Runoff to Demand > 1, and
Weighted Demand Distance < =300 m)

Site ID	Possible Options	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No.of Total Parks	Park Location
17	17d	69.4	62.4	28.8	180	7	Holland Park
26	26b	50.3	11.8	1.1	74	3	Ievers Reserve
28	28b	97.3	13.9	4.3	254	3	Clayton Reserve
	28c		15.0	7.0	271	4	
29	29c	133.0	37.9	6.5	150	4	Holland Park
	29d		40.6	3.5	191	8	
39	39b	31.9	11.8	3.3	74	3	Ievers Reserve
41	41c	67.7	37.9	2.7	157	4	Holland Park
	41d		39.3	1.8	178	7	
43	43b	181.5	13.5	1.7	285	2	Clayton Reserve
	43c		13.9	13.4	288	3	
44	44b	402.4	13.9	13.1	260	3	
	44c		15.0	29.0	273	4	
46	46b	104.7	13.5	26.8	173	2	
	46c		16.4	7.7	218	6	
	46d		18.0	6.4	254	7	
47	47b	72.0	13.5	5.8	173	2	
	47c		16.4	5.3	218	5	
	47d		18.0	4.4	254	7	
52	52a	116.5	10.8	4.0	0	1	Victoria Parade Plantation
	52b		20.6	10.8	96	3	
62	62b	47.9	5.6	5.7	29	2	Wellington Parade South
69	69b	948.2	41.2	8.5	153	2	Batman Park
83	83b	905.7	11.9	23.0	225	2	

Table 3.8: Ranking Based on the Demand (CoM - 2001)

Options	Harvestable Runoff (ML)	Demand* (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
17d	69.4	**62.4**	1.1	180	7	Holland Park
69b	948.2	**41.2**	23.0	175	2	Batman Park
29d	133.1	**40.6**	3.3	191	8	Holland Park
41d	67.7	**39.3**	1.7	178	7	
29c	133.1	**37.9**	3.5	150	4	
41c	67.7	**37.9**	1.8	157	4	
52b	116.5	**20.6**	5.7	96	3	Victoria Parade Plantation
46d	104.7	**18.0**	5.8	254	7	Clayton Reserve
47d	72.0	**18.0**	4.0	254	7	
46c	104.7	**16.4**	6.4	218	6	

** Bold stands for ranking based on high demand*

.

Table 3.9: Ranking Based on Ratio of Runoff to Demand (CoM - 2001)

Options	Harvestable Runoff (ML)	Demand (ML)	Ratio*	Weighted Distance (M)	No. of Total Parks	Park Location
83b	905.7	11.9	**76.1**	225	2	Batman Park
44b	402.4	13.9	**29**	260	3	Clayton Reserve
44c	402.4	15.0	**26.8**	273	4	
69b	948.2	412	**23**	153	2	Batman Park
43b	181.52	13.5	**13.4**	285	2	Clayton Reserve
43c	181.5	13.9	**13.1**	288	3	
52a	116.5	10.8	**10.8**	0	1	Victoria Parade Plantation
62b	478.9	5.6	**8.5**	29	2	Wellington Parade South
46b	104.7	13.5	**7.7**	173	2	Clayton Reserve
28b	97.3	13.9	**7.0**	254	3	

** Bold stands for ranking based on high ratio of runoff to demand*

Table 3.10: Ranking Based on Weighted Demand Distance (CoM - 2001)

Options	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance* (m)	No. of Total Parks	Park Location
52a	116.5	10.8	10.8	**0**	1	Victoria Parade Plantation
62b	47.9	5.6	8.5	**29**	2	Wellington Parade South
26b	50.3	11.8	4.3	**74**	3	Ievers Reserve
39b	31.9	11.8	2.7	**74**	3	
52b	116.5	20.6	5.7	**96**	3	Victoria Parade Plantation
29c	133.0	37.9	3.5	**150**	4	Holland Park
69b	948.2	41.2	23	**153**	2	Batman Park
41c	67.7	37.9	1.8	**157**	4	Holland Park
46b	104.7	13.5	7.7	**173**	2	Clayton Reserve
47b	72.0	13.5	5.8	**173**	2	

*****_Bold stands for ranking based on low weighted demand distance_

3.4.8 Comparative Results of Ranking Corresponding to Year 2010 and 2001 Demands

While comparing the ranking of stormwater harvesting options obtained from year 2010 and 2001 demands (Table 3.4 and 3.7), it was found that five parks represented same options in both years. These parks (or stormwater harvesting sites) are shown in Table 3.11 along with indicative common stormwater harvesting options. Thus, parks representing the common options in Table 3.11 consistently performed well in meeting the screening parameter thresholds under both sets of demands. For rest of the options, demands did not meet the screening thresholds or ceased over period.

Table 3.11: Parks with Common Stormwater Harvesting Options - 2010 and 2001

Parks	Representative Options in 2010 and 2001
Holland Park	17d, 29c,29d, 41c, 41d
Ievers Reserve	26b, 39b
Clayton Reserve	28b, 43b, 43c, 44b, 44c, 46b, 46c, 46d, 47b, 47c, 47d
Batman Park	69b
Victoria Parade Plantation	52a, 52b

Additionally, the comparative ranking results of year 2010 and 2001 were naturally influenced by the shift in demand patterns considering the presence or absence of water restrictions. For both years, Holland Park was ranked highest under high demand category. The Princess Park, Royal Park, and Birrarung Marr Park met the screening thresholds for year 2010 and ranked higher under ‘high demand’ (Table 3.4). However, under no water restrictions in year 2001, same parks did not meet screening thresholds, as ratio of harvestable runoff to demand was lower due to unrestricted demands.

For high ratio of runoff to demand, the Batman Park, Victoria Parade Plantation and Clayton Reserve were highly ranked locations in both years of 2010 and 2001 demands. Similarly, the Victoria Parade Plantation was also emerged as a highly ranked location for weighted demand distance category for demands.

Thus, commonalities of the options (and thereby parks) with respect to high demand, high ratio of harvestable runoff to demand and low weighted demand distance represented the potential opportunity and viability of stormwater harvesting schemes (at the parks) under different magnitudes of demands (2010 and 2001). Thus, ranking of both cases (2010 and 2001) provided insight on the ranking of the parks under varying demand conditions.

3.4.9 Validation

During validation, the CWW officers were consulted to confirm the overall suitability of highly ranked stormwater harvesting sites, based on the ranking results obtained from CoM (both 2010 and 2001 demand cases). The CWW was considered for validation of sites based on their competent experience of stormwater harvesting and physical knowledge of study area. Additionally, the CWW had a good understanding of all stakeholder issues in relation to stormwater harvesting and thus CWW was assumed to represent all stakeholders as they manage the major stormwater harvesting projects in study area.

The stakeholders apart from City West Water (CWW) were not considered for validation as main purpose of GIS analysis was preliminary screening of potentially good stormwater harvesting sites. The validation was one of the most important steps in the methodology as ranking results were authenticated with CWW depending on their sound knowledge of drainage infrastructure, soil and terrain characteristics, local water bodies, and open spaces.

During validation, the suitability of the Royal Park (highest demand site) for stormwater harvesting was confirmed as there was already a stormwater harvesting scheme in operation. However, regardless of the ranking of parks (in both cases of demands), CWW officers identified parks namely, Holland Park, Princess Park, Batman Park, Birrarung Marr Park, Ieveres Reserve, and Clayton Reserve as potentially suitable sites. These parks are shown in Figure 3.7. For these parks, CWW had already given consideration for developing the potential stormwater harvesting schemes. Additionally, despite Victoria Parade Plantation was a highly ranked site in terms of high ratio of runoff to demand and less weighted demand distance, it was not considered suitable by the CWW because of its relatively low demand.

Moreover, apart from ranking results for both demand cases, CWW officers identified few sites namely Flagstaff Park and Pleasance Garden as suitable for stormwater harvesting. These sites were excluded from the GIS ranking analysis (Table 3.3 and 3.7) as they did not meet required the combined threshold of high demand (> 5 ML), high ratio of runoff to demand (> 1) and less weighted distance (< 300 m).

The Flagstaff Park was screened out as it had more weighted demand distance (> 300 m), despite supplying larger demand (> 20 ML) with ratio of runoff to demand (> 8) in 2010. The Pleasance garden was closely located on the boundary of the study area and hence was considered in the analysis.

Local knowledge of study area is desirable in validating the results obtained from GIS screening tool. The decision maker's opinion regarding threshold values would significantly influenced in final short listing of suitable stormwater harvesting sites and it was properly accounted in the proposed methodology. However, the tool enables the decision makers to quickly investigate the outcomes of various threshold values.

Validation of ranking results provided a greater degree of confidence to CWW to investigate the high ranked sites for more detailed investigation. This study also provided flexibility of prioritizing the potential stormwater harvesting sites based on either high demand, high ratio of runoff to demand or low weighted demand distance.

3.5 Application of the Methodology - City of Brimbank (CoB)

The GIS based screening tool methodology described in Section 3.2 was also applied to CoB. The details of application are very similar to that of CoM. The spatial maps of runoff and demand for CoB were evaluated through the accumulated catchment concept, followed by the screening, ranking and validation. A brief overview of application procedure is presented below.

Table 3.12 shows the details of the datasets consisting of data sources, formats and associated (different) scales used in preparing the spatial maps of runoff, demand and accumulated catchments for CoB. Similar to CoM, all spatial maps were processed using Arc GIS version 9.3, Spatial Analyst tools and Arc Hydro tools.

3.5.1 Runoff, Demand and Accumulated Catchment Layers

Initially, annual average rainfall map was prepared for the Brimbank region, where rainfall data for conservative period of 1997-2009 was used. The annual average rainfall values ranged from 427 mm to 470 mm, which were comparatively lesser from CoM (497 mm to 537 mm).

Table 3.12: Data Description (CoB)

Data	Source	Format	Scale
Rainfall Data	SILO	Text	1:300,000
Impervious Area Map	Melbourne Water	Vector (Polygons)	1:178,000
Customer Demands	CWW	Vector (Point)	1: 178,000
Study Area	CWW	Vector (Polygon)	1:300,000 (CWW) 1:178,000 (CoB)
Planning Zone Map (Landuse)	CWW	Vector (Polygon)	1:178,000
DEM (10 M)	Land Victoria	Raster (ESRI grid)	1:200,000

Furthermore, as described in Section 3.2.1, the runoff layer was prepared by combining impervious areas and pervious areas (runoff co-efficient of 0.9 and 0.1 respectively) with rainfall map using the rational method. Similar to CoM, the runoff map was also prepared in raster format at 30 m X 30 m resolution.

The runoff values generated from impervious and pervious area of CoB ranged between 38 mm to 381 mm respectively, reflecting lesser water availability compared to CoM (44 mm to 434 mm respectively). The impervious-pervious area map of CoB had 68.5% of its total area as pervious due to high presence of open spaces. The remaining 31.5% of its area is impervious, majority of which is residential land use.

Similar to CoM, the study considered two irrigation demand years for CoB to evaluate the performance of potential stormwater harvesting sites under different demand conditions. The base case (i.e. year 2010) had a demand of 0.58 GL for all parks in the Brimbank region. Likewise, year 2003 served as maximum demand case with highest demand of 1.05 GL during the period of 2001-2010. The demand layers for both demand cases were generated using the procedure described in Section 3.4.2.2.

The accumulated catchment layer for CoB was processed similar to Section 3.4.2.3 using Arc-Hydro tools. This layer had 120 accumulated catchments along with respective drainage outlets. These drainage outlets represented the 120 potential stormwater harvesting sites. Figure 3.8 illustrates the accumulated catchments for the CoB region:

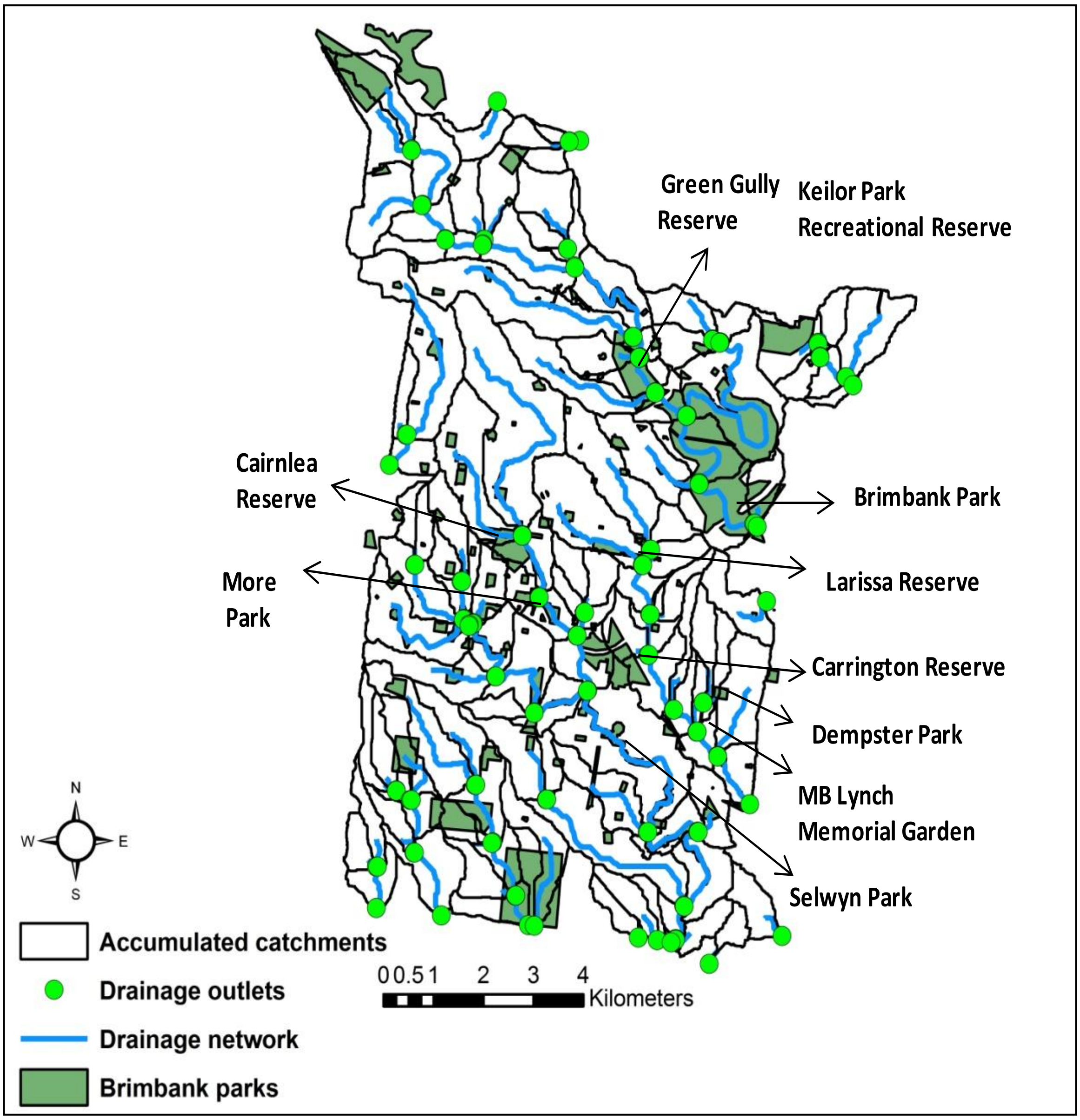

Figure 3.8: Accumulated Catchments and Parks in CoB Region

Furthermore, the integration of runoff layer with the accumulated catchment layer was done to estimate the catchment runoff as the mean annual flow, within each of 120 accumulated catchments. The total annual runoff from all outlets of CoB was estimated as 16.7 GL, of which 10.8 GL was estimated as environmental flow. Thus, the total harvestable amount of runoff from whole CoB was 5.9 GL.

3.5.2 Screening and Ranking of Stormwater Harvesting Sites

The screening procedure similar to Section 3.4.6 was done for all 120 stormwater harvesting sites obtained from the accumulated catchments of the CoB region. The screening parameters (i.e. demand, ratio of harvestable runoff to demand and weighted distance) were computed at four levels of radii of influence (i.e. *a = 0 m, b = 300 m, c = 500 m* and *d =1000 m*) from each of 120 potential stormwater harvesting sites depicted in Figure 3.8.

The screening resulted in generation of 164 stormwater harvesting options for year 2010 and 161 stormwater harvesting options for year 2003. Similar to Section 3.4.5, these screened options were further screened and ranked for evaluating the technical feasibility of stormwater harvesting options for both years. It should be noted that same screening parameter thresholds (demands $\geq$ 5 ML, ratio of harvestable runoff to demand > 1, and weighted demand distance $\leq$ 300 m) were used in ranking of options after consultation with the CWW officials.

After using screening thresholds, 37 options were shortlisted for year 2010 representing 14 different stormwater harvesting sites (or parks). For year 2003, 48 options were shortlisted representing 16 different stormwater harvesting sites. These stormwater harvesting options are shown in Tables 3.13 and 3.14 respectively.

Comparative analysis of Tables 3.13 and 3.14 showed that there were eleven (11) parks represented the same options in both years 2001 and 2003. These parks are shown in Table 3.15 along with common stormwater harvesting options; and Figure 3.8 provides spatial locations of these parks. From Table 3.15, it can be also seen that Green Gully Reserve, Keilor Park Recreational Reserve and Selwyn Park had multiple options which satisfied the screening thresholds of demand, ratio of runoff to demand and weighted demand distance. These parks are shown in Figure 3.8.

Similar to Section 3.4.6, the stormwater harvesting options obtained from both years 2003 and 2010 were further ranked separately for high demand, high ratio of runoff to demand, and low weighted demand distance.

Table 3.13: List of Stormwater Harvesting Options for CoB (Year 2010)
(Demand > =5 ML, Ratio of Runoff to Demand > 1, and Weighted Demand Distance < =300 m)

Site ID	Possible Options	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
20	20c	1585.4	11.1	142.6	266.5	4	Green Gully Reserve
21	21b	18.0	9.5	1.9	125	1	Keilor Park Recreational Reserve
22	22c	678.0	11.1	61	277.6	4	Green Gully Reserve
23	23a	231.6	8.5	27.2	0	1	Keilor Park Recreational Reserve
24	24b	136.4	29.6	4.6	190	1	
	24c		31.3	4.4	197.6	2	
25	26b	2270.3	9.6	236.4	172.6	2	Green Gully Reserve
27	27b	126.5	9.5	13.4	115	1	Keilor Park Recreational Reserve
28	28b	58.8	29.6	2	200	1	
	28c		31.3	1.9	206.5	2	
29	29b	147.8	9.5	15.6	200	1	
33	33b	155.6	9.6	16.2	179	2	Green Gully Reserve
37	37a	388.0	8.5	45.6	0	1	Keilor Park Recreational Reserve
45	45b	29.0	5.5	5.3	120	1	Brimbank Park
46	46b	3423.6	5.5	624.1	130	1	
47	47b	3451.0	5.5	629.1	50	1	
49	49b	363.8	20	18.1	100	3	Cairnlea Reserve
51	51b	32.3	7.5	4.3	136	3	Larissa Reserve
60	60b	44.9	6.0	7.5	148.3	2	Carrington Reserve
	60d		10.1	4.4	163.4	4	
62	62b	24.5	6.0	4.1	151.7	2	
	62d		6.2	4	163.4	3	
63	63b	31.5	6.2	5.1	290	1	Protected Native Grassland
64	64b	77.4	6.2	12.4	290	1	Carrington Reserve
72	72a	488.2	6.5	75.7	0	1	Selwyn Reserve
	72c		6.6	73.9	10.3	2	
	72d		6.6	73.8	11.3	3	
76	76b	55.7	6.1	9.1	235.9	2	Lynch Gardens
77	77a	397.2	6.5	61.5	0	1	More Park
	77c		13.3	29.8	226.9	2	
81	81b	404.4	6.6	61.2	10	2	Selwyn Reserve
	81c		6.6	61.1	11	3	

82	82b	56.9	6	9.3	235.9	2	Dempster Park
90	90a	1002.3	7.5	134.2	0	1	Matthew Hill Reserve
	90c		8.1	124.1	25	4	
101	101b	89.0	10.4	8.6	175.2	2	J.R. Parsons Reserve
102	102b	1133.2	10.4	109.2	181.3	2	Beachley Reserve

Table 3.14: List of Stormwater Harvesting Options for CoB (Year 2003) (Demand > =5 ML, Ratio of Runoff to Demand > 1, and Weighted Demand Distance < = 300 m)

Site ID	Possible Options	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
20	20a	1585.4	44.2	35.9	0	1	Green Gully Reserve
	20c		51.8	30.6	57.2	3	
	20d		55.6	28.5	106.3	6	
21	21b	18.0	16.1	1.1	125	1	Keilor Park Recreational Reserve
22	22a	678.1	44.2	15.4	0	1	Green Gully Reserve
	22c		51.8	13.1	59.6	3	
	22d		55.6	12.2	108.5	5	
24	24b	136.4	110.8	1.2	190	1	Keilor Park Recreational Reserve
	24c		112.4	1.2	192.1	2	
	24d		121.0	1.1	232.8	3	
26	26a	227.0	44.2	51.4	0	1	Green Gully Reserve
	26c		50.3	45.1	33	2	
	26d		55.6	40.8	110	5	
27	27b	126.5	16.1	7.8	115	1	Keilor Park Recreational Reserve
29	29c	147.8	24	6.2	284.7	3	
	29b		16.1	9.2	200	1	
33	33a	155.6	44.2	3.5	0	1	Green Gully Reserve
	33b		50.3	3.1	34.2	2	
	33d		55.6	2.8	102.3	5	
34	34a	2497.4	44.2	56.5	0	1	
36	36c	237.6	5.4	44.2	295.8	2	Lowe Cresent Reserve
38	38a	398.0	44.1	9	0	1	Green Gully Reserve
43	43d	158.5	5.0	31.6	225	5	Larisa Reserve
46	46b	3423.6	5.5	623.6	120	1	Brimbank Park
47	47b	3451.0	5.5	628.6	130	1	
48	48a	138.1	5.5	25.16	50	1	Lowe Cresent Reserve
49	49b	363.8	15.9	22.8	88	3	Cairnlea Reserve
51	51d	32.3	5.0	6.5	235	5	Larissa Reserve
56	56b	405.2	5.0	80.9	107.1	2	Meadowbank, St Albans
64	64b	77.4	18.0	4.3	290	1	Selwyn Reserve
66	66b	467.6	6.9	68.1	270	1	Carrington Reserve
	66c		11.8	63.5	283.4	2	
67	67b	50.0	5.0	10	95.4	2	Meadowbank, St Albans
72	72a	448.2	29.7	16.4	0	1	Selwyn Reserve
	72c		36.7	13.3	80.7	2	
	72d		43.7	11.2	205.4	3	
73	73c	25.0	7.4	3.4	274.8	2	Carrington Reserve
	73b		6.9	3.6	260	1	
74	74b	559.6	13.8	54.9	254.5	2	Barclay Reserve
76	76b	55.7	11.8	4.7	240.3	2	Lynch Gardens
77	77a	397.2	29.7	13.3	0	1	More Park

	77c		36.7	10.9	82.6	2	
79	79b	63.1	10.2	6.2	257.2	2	Barclay Reserve
81	81a	404.4	29.7	13.6	0	1	Selwyn Reserve
82	82b	56.9	11.8	4.8	240.3	2	Dempster Park
90	90a	1002.3	7.5	134.2	0	1	Matthew Hill Reserve
	90b		7.7	131	6.1	2	
	90c		8.1	124.1	25	4	

Table 3.15: Parks with Same Stormwater Harvesting Options - 2010 and 2003

Parks	Representative Options in 2010 and 2003
Green Gully Reserve	20c, 22c, 33b
Keilor Park Recreational Reserve	21b, 24b, 24c, 27b, 29b
Brimbank Park	47b,
Cairnlea Reserve	49b
Larissa Reserve	51b
Carrington Reserve	64b
Selwyn Reserve	72a, 72c, 72d
MB Lynch Memorial Gardens	76b
More Park	77a, 77c
Dempster Park	82b
Matthew Hill Reserve	90a, 90c

For high demand, the top 10 ranked stormwater harvesting options for CoB are shown in Table 3.16 (2010 Demands) and Table 3.17 (2003 Demands). From Tables 3.16 and 3.17, it was evident that Green Gully Reserve, Keilor Park Recreational Reserve, Cairnlea Reserve and More Park were ended up as best stormwater harvesting sites, considering their ranking in both cases.

Table 3.16: Ranking Based on High Demand (CoB - 2010)

Site ID	Harvestable runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
24d	136.4	121.0	1.1	232.8	3	Keilor Park Recreational Reserve
24c		112.4	1.2	192.1	2	
24b		110.8	1.2	190	1	
20d	1585.5	55.6	28.5	106.3	6	Green Gully Reserve
20c		51.8	30.6	57.2	3	
72d	448.2	43.7	11.2	205.4	3	Selwyn Park
72a		29.7	16.4	0	1	
77c	397.2	36.7	10.9	82.6	2	More Park
77a		29.7	13.3	0	1	
49b	363.8	15.9	22.8	88	3	Cairnlea Reserve

Table 3.17: Ranking Based on High Demand (CoB - 2003)

Site ID	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
24c	136.4	31.3	4.4	197.6	2	Keilor Park
28c	58.8	31.3	1.9	206.5	2	
24b	136.4	29.6	4.6	190	1	
28b	58.8	29.6	2	200	1	
49b	363.8	20	18.1	100	3	Cairnlea Reserve
77c	397.2	13.3	29.8	226.9	2	More Park
20c	1585.5	11.1	142.6	266.5	4	Green Gully Reserve
22c	678.1	11.1	61	277.6	4	
101b	89.1	10.4	8.6	175.2	2	J.R. Parsons Reserve
102b	1133.2	10.4	109.2	181.3	2	Beachley Reserve

For high ratio of runoff to demand, the top 10 ranked stormwater harvesting options for CoB are represented in Table 3.18 (2010 demands) and Table 3.19 (2003 demands). The parks namely Brimbank Park and Matthew Hill Reserve were ranked higher in both cases of demand, indicating their larger ability to supply stormwater at varied demand conditions.

Table 3.18: Ranking Based on Ratio of Runoff to Demand (CoB - 2010)

Site ID	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
47b	3451	5.5	628.6	130	1	Brimbank Park
46b	3423.6	5.5	623.6	120	1	
90a	1002.3	7.5	134.2	0	1	Matthew Hill Reserve
90b	1002.3	7.7	131	6.1	2	
90c	1002.3	8.0	124.1	25	4	
56b	405.2	5.0	80.9	107.1	2	Meadowbank, St Albans
66b	467.6	6.9	68.1	270	1	Carrington Reserve
66c	467.6	11.9	63.5	283.4	2	
34a	2497.4	44.2	56.5	0	1	Green Gully Reserve
74b	559.6	13.9	54.9	254.5	2	Barclay Reserve

Table 3.19: Ranking Based on Ratio of Runoff to Demand (CoB - 2003)

Site ID	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
47b	3451.0	5.5	629.1	50	1	Brimbank Park
46b	3423.6	5.5	624.1	130	1	
26b	2270.4	9.6	236.4	172.6	2	Green Gully Reserve
20c	1585.5	11.1	142.6	266.5	4	
90a	1002.3	7.45	134.2	0	1	Matthew Hill Reserve
90c	1002.3	8.1	124.1	25	4	
102b	1133.2	10.4	109.2	181.3	2	Beachley Reserve
72a	488.2	6.5	75.7	0	1	Selwyn Park
72c	488.2	6.6	73.9	10.3	2	
72d	488.2	6.6	73.8	11.3	3	

Tables 3.20 and 3.21 represented the top 10 ranked stormwater harvesting sites, obtained under the weighted demand distance for years 2010 and 2003 respectively. The parks namely Green Gully Reserve, Matthew Hill Reserve, More Park, and Selwyn Reserve emerged out as best stormwater harvesting sites in both cases, indicating minimum infrastructure requirement for developing the stormwater harvesting schemes.

Table 3.20: Ranking Based on Weighted Demand Distance (CoB - 2010)

Site ID	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
90a	1002.3	7.5	134.2	0	1	Matthew Hill Reserve
34a	2497.4	44.2	56.5	0	1	Green Gully Reserve
26a	227.0	44.2	51.4	0	1	
20a	1585.5	44.2	35.9	0	1	
72a	448.2	29.7	16.4	0	1	Selwyn Park
22a	678.1	44.2	15.4	0	1	Green Gully Reserve
81a	404.4	29.7	13.6	0	1	Selwyn Park
77a	397.2	29.7	13.3	0	1	More Park
38a	398.0	44.2	9	0	1	Green Gully Reserve
33a	155.6	44.2	3.5	0	1	

Table 3.21: Ranking Based on Weighted Demand Distance (CoB - 2003)

Site ID	Harvestable Runoff (ML)	Demand (ML)	Ratio	Weighted Distance (m)	No. of Total Parks	Park Location
34a	2497.4	44.2	56.5	0	1	Green Gully Reserve
26a	227.0	44.2	51.4	0	1	
20a	1585.5	44.2	35.9	0	1	
72a	448.2	29.7	16.4	0	1	Selwyn Park
22a	678.1	44.2	15.4	0	1	Green Gully Reserve
81a	404.4	29.7	13.6	0	1	Selwyn Park
77a	397.2	29.7	13.3	0	1	More Park
38a	398.0	44.2	9	0	1	Green Gully Reserve
33a	155.6	44.2	3.5	0	1	
90b	1002.1	7.7	131	6.1	2	Matthew Hill Reserve

Interestingly, for both base (2010) and maximum demand (2003) case, Green Gully Reserve was a commonly ranked suitable location under high demand, high ratio of harvestable runoff to demand and low weighted demand distance.

3.5.3 Validation for CoB Results

Similar to Section 3.4.9, the ranking results obtained from CoB (both 2010 and 2003 demand cases) were presented to CWW officers for the validation. The validation procedure confirmed the overall suitability of highly ranked stormwater harvesting sites in the CoB area, which considered the experience/local knowledge of the CWW officers.

During validation, the CWW officers identified the parks namely Green Gully Reserve, Cairnlea Reserve, and Keilor Park Recreational Reserve as suitable stormwater harvesting sites, regardless of their ranking in respective categories. These parks are shown in Figure 3.8. For these parks, CWW had already initiated developing the stormwater harvesting schemes. The Australian Government has also provided funding of $3.9 Million to develop the stormwater harvesting schemes at the three major recreational areas in CoB which consist of Keilor Park Recreational Reserve, Green Gully Reserve, and Keilor Public Golf Course (DSEWPaC, 2013).

From validation, it was also found that despite high ranking in different categories (Tables 3.16 to 3.21), Selwyn Park, More Park, Dempster Park, Larissa Reserve, Lynch Gardens and Matthew Hill Reserve were not identified as suitable (by the CWW officers) for stormwater harvesting. The primary reason for this was less economic returns on potential financial investment from CWW. However, according to CWW, sites like Carrington Reserve and Brimbank Park were potentially good opportunities for addressing future demands.

3.6 Comparative Findings: CoM and CoB

The applicability of the GIS based Screening tool was tested under base demand and maximum demand conditions for CoM and CoB case studies. The CoM had high impervious area (55%) mainly due to high urbanization (Section 3.4), while CoB was a semi urbanised area (Section 3.5) with majority of landuse as pervious area (68.5%). The harvestable runoff in CoM was sufficiently large (2.4 GL) for a relatively smaller area of 26 Km^2, compared to harvestable runoff (5.9 GL) available from a larger area of CoB (121 Km^2). Such variation in runoff was influenced by the amount of imperviousness in each of the case study areas.

For both base and maximum demand cases, the total park irrigation demands for CoM (0.65 GL and 2.3 GL respectively) were higher than that of CoB (0.58 GL and 1.05 GL respectively). In both cases of demands, the GIS based screening tool identified the common stormwater harvesting sites which satisfied the thresholds for high demand, high ratio of harvestable runoff to demand and low weighted demand distance. This result was applicable to both CoM and CoB case studies.

During validation, CWW officers were consulted for their local knowledge and experience with stormwater harvesting in CoM and CoB areas. In both case studies, validation confirmed the suitability of selected stormwater harvesting sites obtained from the GIS screening tool. After validation, eight sites were found suitable for stormwater harvesting for CoM, while three sites were suitable for CoB. The number of suitable sites for CoB were comparatively less as CoB is a semi urbanised council with lower irrigation demand than CoB. Overall, the application of the GIS methodology over CoM and CoB was effective in identifying the existing and potential stormwater harvesting opportunities.

3.7 Summary

The selection of suitable stormwater harvesting sites is essential and equally challenging for the urban water infrastructure planners. Currently, the selection of these sites is achieved by the intuitive knowledge of water infrastructure planners, which can be subjective. Therefore, the present chapter was focussed on developing a new robust methodology for evaluating and ranking suitable stormwater harvesting sites using GIS at preliminary level of decision making.

The GIS based screening tool methodology required data input in terms of catchment area maps, rainfall, elevation area maps, landuse planning maps, and customer demands maps. Additionally, the ArcGIS software was required to perform spatial operations in GIS environment.

The proposed methodology enabled spatial assessment of runoff and demand for stormwater harvesting sites using a unique concept of accumulated catchments. This accumulated catchment concept enabled decision makers to examine the stormwater catchments on basis of desired quantity of runoff and demand. Drainage outlets of these accumulated catchments were considered as potential stormwater harvesting sites. These sites were further screened and ranked under three screening parameters, namely demand, ratio of harvestable runoff to demand, and weighted demand distance using a 'radius of influence' concept.

The radius of influence concept briefly consisted of matching of supply from the harvesting sites with areas of demand, within a certain physical radius. This physical distance between areas of demand and stormwater harvesting location essentially dictates the economic feasibility of stormwater harvesting scheme, considering the infrastructure and associated distribution costs.

The chapter also demonstrated the application of GIS screening tool methodology over the two councils namely, City of Melbourne (CoM) and City of Brimbank (CoB) representing highly urbanised area and semi urbanised area respectively. For both case studies, the methodology provided sound basis to identify, shortlist, and rank suitable stormwater harvesting sites for further detailed investigation. Additionally, for both case studies, the study analysed the ranking results of stormwater harvesting sites under two varying demand conditions i.e. base demand and maximum demand.

Stormwater harvesting sites obtained from the application of GIS based screening tool were found in well agreement with the stormwater experts from the CWW. After validation, the study found Holland Park, Princess Park, Batman Park, Birrarung Marr Park, Ieveres Reserve, and Clayton Reserve were as suitable stormwater harvesting sites for CoM. Likewise, Green Gully Reserve, Cairnlea Reserve, and Keilor Park Recreational Reserve were found as potentially suitable locations for the CoB.

Thus, the proposed methodology has successfully demonstrated the capability in selecting the priority sites for stormwater harvesting schemes over highly urbanised and semi urbanized areas. Therefore, it is expected that the GIS based screening tool methodology developed and used in this study can benefit the water professionals at early stages of decision making.

Chapter 4 - Evaluation of Performance Measures (PMs) for Stormwater Harvesting Sites

4.1 Introduction

As highlighted in Section 1.3, stormwater harvesting project planning is complex due to different catchment characteristics, and inherent spatial and temporal variability of stormwater and demand. Moreover, it is influenced by the vested interests of different stakeholders. Under such complexity, the evaluation of stormwater harvesting projects through their performance measures (PMs) assists Decision Makers (DMs) to characterise and quantify the system performance from perceived economic, environmental and social objectives. In this context, this chapter describes the generalised evaluation methodology for deriving different PMs representing the system performance of stormwater harvesting sites and the application of this methodology to the current study.

The sustainability assessment of urban water services through the use of performance measures is a well established approach, documented in literature. The PMs are also termed as 'sustainability indicators' in various studies. Lundin and Morrison (2002) presented environmental sustainability indicators (i.e. PMs) such as water consumption, discharge of pollutant loads, and energy consumption for life cycle assessment of urban water services in Sweden. Balkema et al. (2002) developed economic, environmental, socio-cultural and technical PMs for selecting suitable wastewater treatment systems. Similar studies describing the PMs for evaluating the urban water services can be found in other literature (Bertrand-Krajewski et al., 2002; Hellström et al., 2000; Sharma et al., 2009; Valentin and Spangenberg, 2000).

The importance of selecting appropriate PMs is highlighted in the literature review conducted by Hajkowicz and Higgins (2008) with respect to Multi Criteria Decision Analysis (MCDA) problems. They argued that the MCDA problem structure (in terms of defining alternatives and PMs) is more important than the selection or the development of the MCDA method. Therefore, the challenge the planners and designers of stormwater harvesting systems face is not so much to develop a new MCDA method, but to put their effort into defining a comprehensive set of PMs and specifying the set of alternative schemes (Philp et al., 2008).

For the decision problem of the current study, a finite set of alternatives as suitable stormwater harvesting sites were obtained from the GIS based screening tool methodology described in Section 3.2. To specify the set of PMs, various indicators can be developed to describe the economic, environmental and social objectives of stormwater harvesting schemes. Thus, the set of stormwater harvesting alternative sites and the set of performance measures will form the evaluation matrix (Section 2.6), representing the decision problem for the current study. This evaluation matrix can be solved by the PROMETHEE (or any MCDA) method to rank the alternative stormwater harvesting sites (Section 2.7.5).

The chapter first explains the economic, environmental and social objectives defined for evaluation of stormwater harvesting sites in the context of current study. Then, the chapter describes the alternative stormwater harvesting sites selected for the MCDA assessment, including their site specific characteristics. The PMs used for the present study are broadly categorised under economic, environmental and social objectives. The selection of PMs is then elaborated and justified with a brief literature review. The PMs under social objective were found to be qualitative (social), while those under economic and environmental objectives were found to be quantitative. The evaluation methodology for both types of PMs is described in this chapter.

The chapter then highlights the importance of conceptual designs for sizing and costing of infrastructure components for stormwater harvesting schemes, and serves as the basis for evaluation the quantitative PMs. The chapter then describes the evaluation methodology adopted for estimation of economic and environmental PMs, which mainly consisted of development of the conceptual designs. Furthermore, PM evaluations are demonstrated for one stormwater harvesting site, using conceptual designs procedure. Finally, the system performance measures (both qualitative and quantitative) in the form of an evaluation matrix are presented in the chapter followed by the summary of the chapter.

4.2 Objectives for MCDA Evaluation

As explained in Section 2.1, the evaluation of stormwater harvesting projects is often based on economic, social, and environmental objectives with a common agreed goal of sustainability. Considering this approach, City West Water (CWW), one of the retail water authorities in Melbourne, developed an alternative water strategy (CWW, 2010) to provide a framework for the identification, design and implementation of alternative water supply projects including stormwater harvesting projects within CWW's servicing area. This alternative water strategy was developed within the framework of Victorian Government and CWW business policies including the Victorian Government White Paper - Securing Our Water Future Together (2004), the Central Region Sustainable Water Strategy (2006) and Our Water Our Future – The Next Stage of the Government Water Plan (2007).

Based on the alternative water strategy of CWW, following objectives were defined for evaluation of stormwater harvesting sites considered in the study.

1. **Economic:** The stormwater harvesting scheme should be financially viable with acceptable cost to the community.

2. **Environmental:** There should be no or minimum impact on the environment and the waterways from the stormwater harvesting schemes.

3. **Social:** The stormwater harvesting scheme should provide maximum benefit to the local community.

These objectives have an overall goal of sustainable management of stormwater harvesting systems.

4.3 Selection of Alternative Stormwater Harvesting Sites

As described in Section 4.1, a finite set of suitable stormwater harvesting sites for this study were obtained from the GIS based screening tool (Section 3.2). Although the GIS based screening tool methodology was used on two city councils i.e. City of Melbourne (CoM) and City of Brimbank (CoB) in Chapter 3, only stormwater harvesting sites from CoM area were considered in the MCDA assessment of this study. A similar procedure can be applied to CoB.

The suitable stormwater harvesting sites shortlisted for the CoM area (Section 3.4), and are shown in Table 4.1. Figure 4.1 shows the locations of these sites. Each specified site location in Figure 4.1 is documented in detail in Appendix 4A along with their associated stormwater catchments.

Table 4.1: Selected Alternative Sites for MCDA Evaluation

a) JJ Holland Park (Or simply Holland Park)	b) Clayton Reserve
c) Pleasance Garden	d) Princess Park
e) Ievers Reserve	f) Birrarung Marr Park
g) Batman Park	h) Flagstaff Park

a) Holland Park

Holland Park is located in close proximity to South Kensington Railway Station in Melbourne. The site contains three ovals, one synthetic turf and two warm season cricket pitches with a combined annual water demand of approximately 23 ML. Additionally, small areas of passive open space are located around all three playing surfaces. A number of large stormwater drains runs through or are in close proximity to the park which connect at the south west corner of the park. The total area for irrigation is approximately 2.9 ha.

b) Clayton Reserve

Clayton Reserve (area of 0.7 ha) is located in the suburb of North Melbourne. This site is also in close proximity with two other parks, namely North Melbourne Cricket Ground (area of 3.7 ha) and Gardiners Reserve Passive Turf (area of 0.8 ha). Passive areas around the sporting turf also require irrigation.

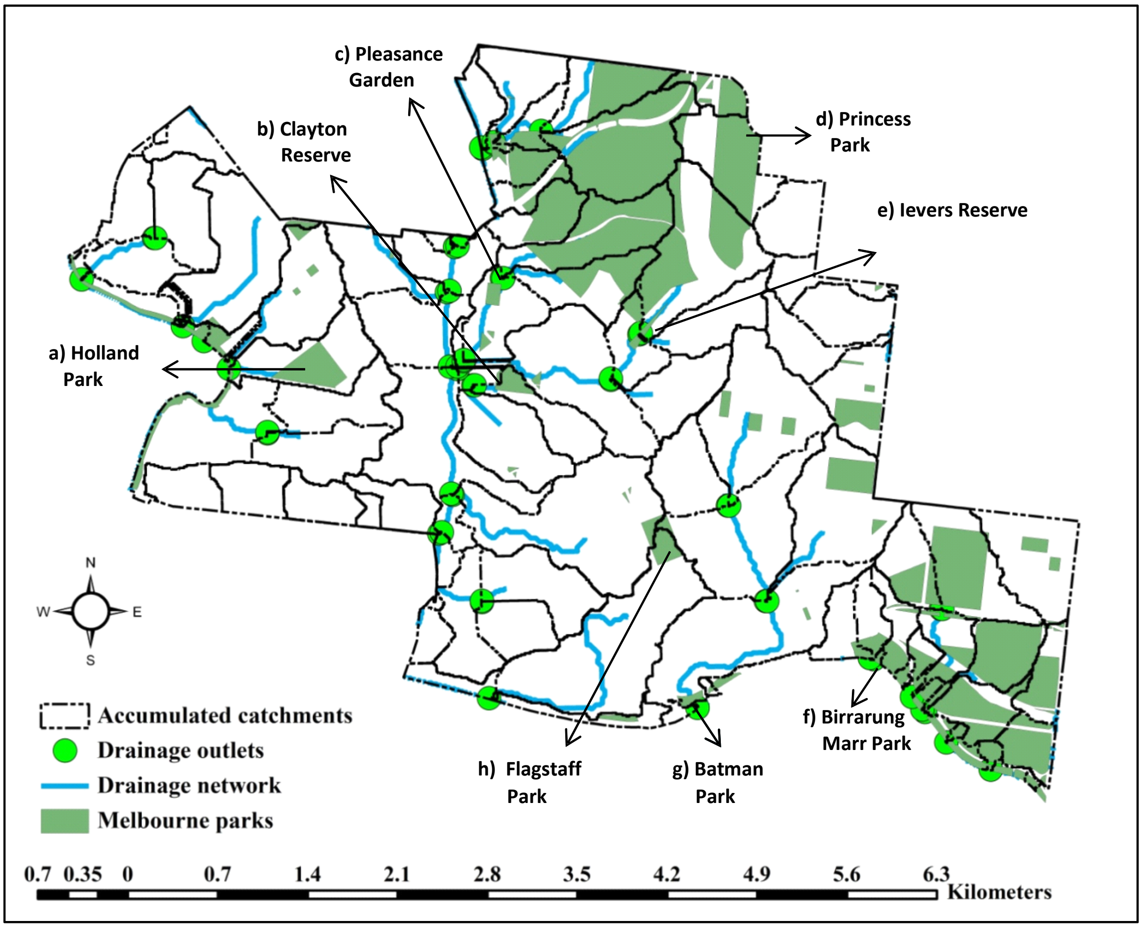

Figure 4.1: Selected Stormwater Harvesting Sites for MCDA Evaluation

The total irrigation demand for the Clayton Reserve is approximately 32 ML including all three parks (i.e. Clayton Reserve, North Melbourne Cricket Ground, and Gardiners Reserve Passive Turf). Several moderately sized drains connect into a larger drain at the southern end of North Melbourne Cricket Ground, which create an opportunity to harvest the stormwater.

c) Pleasance Garden

Pleasance Garden is located in the suburb of Carlton, and has various gardens and passive open spaces between public housing buildings. The site is also in close proximity to the several road reserves and nature strips, sprawled throughout the Carlton area providing an opportunity to supply alternative water to irrigate several amenities in the area. The estimated irrigation area is approximately 1.4 hectares with approximate irrigation demand of 8 ML.

d) Princess Park

Princes Park is located on the eastern side of CoM and consists of variety of different venues for various sporting and recreational activities including football, bowling, cricket and tennis grounds. The total area for irrigation is approximately 19.4 ha with irrigation demand of approximately 92 ML. The Lygon St main drain is in close proximity to Princess Park providing an opportunity for stormwater harvesting. The neighbouring catchment surrounding Princess Park is composed primarily of residential and commercial landuse.

e) Ievers reserve

Ievers reserve is located in the suburb of Parkville. This site consists of several grass areas that require irrigation, in addition to large oak trees and garden beds that could also utilise alternative water supply. Furthermore, several roundabouts and traffic islands are located in the local vicinity that could additionally benefit from alternative water supply. This site has an irrigation demand of approximately 7 ML for irrigation of approximately 1.4 ha turf area.

f) Birrarung Marr Park

Birrarung Marr Park is relatively new parkland located on the southern outskirts of the Melbourne Central Business District (CBD). This site has approximately 3.8 ha area with multiple recreational opportunities such as playground, barbeques, and running/bike tracks having a combined approximate demand of 18 ML. There are a number of stormwater drains in close proximity to the Birrarung Marr Park which feed into a major stormwater drain to the south west of the site.

g) Batman Park

Batman Park is located on the banks of the Yarra River in CoM. The park is primarily a passive turf with several established eucalyptus trees. This park has relatively lower irrigation demand of approximately 7.1 ML for its 1.5 ha of irrigation area. There are a number of stormwater drains in close proximity to Batman Park which discharge into a major stormwater drain running underneath ‘Kings Way’ Bridge. Additionally, within the local vicinity of Batman Park, there are several buildings that could be utilised for rainwater harvesting.

h) Flagstaff Park

Flagstaff Park is an iconic part of Melbourne's CBD streetscape. Flagstaff Park contains extensive lawns and open spaces, flowerbeds with primarily European flowers and well established trees of varying varieties. Within the close proximity to Flagstaff Park, several large stormwater drains exist, providing an opportunity for stormwater harvesting. The site has total irrigation area of 7.25 ha with an approximate irrigation demand of 70 ML.

4.4 Selection of Performance Measures (PMs)

In general, the selection of PMs for MCDA evaluation is decided by mutual deliberations of the stakeholders associated with stormwater harvesting projects who have a good knowledge of the system and understanding of the problem.

The PMs can be either quantitative or qualitative. For example, the costs of stormwater projects can be measured in numerical terms and can be categorised under quantitative PMs. However, qualitative PMs do not have such a numerical basis, and often described in terms of some graded comparative scale or rating systems to measure the impact in quantitative manner. For example, social benefits from stormwater harvesting projects can be classified under qualitative PMs and can be evaluated with a scale such as very poor (or negative), poor (or below average), average (or neutral), good (or above average), or excellent (or most beneficial) with rating vales ranging from 1 to 5.

According to Laia et al. (2008), the water industry has played a key role in advancing the science of sustainability assessment of urban water services in terms of the development of suitable PMs. For urban stormwater harvesting projects, Taylor (2006) provided guidelines to examine the economic, ecological and social dimensions concerning stormwater projects. These guidelines were based on the UK based research project 'Sustainable Water industry Asset Resource Decisions' (SWARD) which described the assessment procedures for urban water services, particularly wastewater services (Butler et al., 2003).

In the current study, PMs are described under economic, environmental and social objectives, to entail the principles of sustainability in the context of stormwater harvesting. The selection of all PMs under respective objectives was performed by conducting a literature review followed by the discussions with CWW officers.

4.4.1 Performance Measures for Economic Objectives

Cost estimation of stormwater harvesting schemes is often challenging as the schemes provide various non monetary benefits in terms of environmental flows, pollution control and other social benefits such as aesthetics and public amenity (Philp et al., 2008). Furthermore, as stormwater harvesting is an emerging area of interest, capturing reliable datasets (capital and operating costs) for various infrastructure components at different scales is essentially complex procedure (Fletcher et al., 2008).

Generally, the cost of supplying water from stormwater harvesting schemes is higher compared to cost of potable water supply in Australia (Philp et al., 2008). Such scenario put additional financial burden on community and thus affects the social acceptance of stormwater harvesting schemes. Considering these complexities, there has been lack of practical, adequate and widely accepted methodologies to objectively assess the numerous measures of costs and benefits of stormwater harvesting schemes (Hatt et al., 2004).

Life Cycle Costing (LCC) is a widely used approach in economic assessment of stormwater harvesting projects (DEC, 2006; Mitchell et al., 2006; Taylor, 2005a). Life cycle costing is defined as a "process to determine the sum of all expenses associated with a product or project, including acquisition, installation, operation, maintenance, refurbishment, discarding and disposal costs" (Australian Standards, 1999). A simplified and equivalent approach to life cycle costing is to calculate the net present value (NPV) of a project's capital and operating costs (DEC, 2006; Mitchell et al., 2006; Sharma et al., 2009; Swamee and Sharma, 2008).

NPV signifies the present value of future investments for providing and maintaining the services on an ongoing basis. If the infrastructure associated future costs are known, then with a suitable discount rate, NPV of the infrastructure can be calculated for the given analysis period. Careful consideration should be given in selecting the useful life span of different infrastructure system components of stormwater harvesting schemes over the selected analysis period.

Based on NPV estimations, Levelised Cost (LC) has been recommended as a performance measure for economic assessment of stormwater harvesting projects (DEC, 2006). LC can be defined as the net present value of the project's infrastructure costs over the analysis period divided by the net present value of total volume of water supplied over the same period. It is expressed in units of cost per kL. The current study has considered LC as the only economic performance measure as it represents LCC of stormwater harvesting schemes and associated potable water savings due to stormwater reuse. Detailed procedure for evaluating LC of selected alternative stormwater harvesting sites is described in Section 4.6.2 along with a demonstration example in Section 4.7.4.

The other economic performance measures mentioned in literature for stormwater harvesting projects are capital costs, recurring costs, financial equity between stakeholders, payback period, revenue generated (from selling stormwater) and hidden costs (Sharma et al., 2009; Taylor et al., 2006). The performance measures such as capital costs and recurring costs are integral part of LCC and hence do not need to be considered differently in economic assessment. Performance measures such as payback period and hidden costs were not considered in analysis assuming their minimal impact in the analysis.

4.4.2 Performance Measures for Environmental Objectives

This study considered Annualised Removal Costs of pollutants, Greenhouse Gas emissions, and Potable Water Savings as PMs to represent the environmental objectives. The other PMs mentioned in the literature in relation to environmental objectives were environmental impacts on the aquatic and riparian ecosystems, use of materials and energy, eutrophication and protection of waterways (Philp et al., 2008; Sharma et al., 2009; Taylor et al., 2006). These PMs were not considered in current study due to unavailability of appropriate data.

4.4.2.1 Annualised Removal Costs of Pollutants (ARC)

One of the important environmental considerations for stormwater harvesting projects is to improve quality of stormwater that goes to receiving waterways along with the protection of aqua systems. To support this consideration, stormwater harvesting projects are often assessed by comparing the pollutant loads with standard best practice targets set by the designated local/state regulators.

In Australia, the Victorian Standing Committe (1999) requires the treatment of harvested stormwater to achieve the annual pollutant load removal targets, described in the Best Practice Environmental Management Guidelines.

These pollutant load targets are:

- 45% reduction in Total Nitrogen (TN) from typical urban loads
- 45% reduction in Total Phosphorus (TP) from typical urban loads
- 80% reduction in Total Suspended Solids (TSS) from typical urban loads
- 70% reduction in Gross Pollutants (or litters)

In Victoria, stormwater harvesting projects are required to meet the above water quality targets to ensure the environmental protection of waterways. In the current study, all pollutant removal rates have been expressed in the form of Annualised Removal Costs (ARC) which also serves as a PM. The ARC for each kg of pollutant represents the cost required to remove each kg of pollutants (TSS, TN and TP) over the life cycle of stormwater harvesting schemes ($/kg/Year). Water and contaminant balance modeling has been performed to estimate the desired pollutant removal rates from all stormwater harvesting site alternatives (Section 4.6.1).

4.4.2.2 Greenhouse Gas Emissions (GHG)

In literature, Life Cycle Assessment (LCA) is considered an internationally recognized approach for assessing the environmental impacts of alternative products or services

(Grant et al., 2006). Recently, Sharma et al. (2009) analyzed the environmental impacts arising from different water service provisions. The study found that environmental impacts due to water services were largely associated with Greenhouse Gas (GHG) emissions. These GHG emissions were mainly linked with operational electrical energy for servicing. It was also found that the GHG due to embodied energy of the infrastructure were only 10-15% of the total GHG. Therefore, the present study considered GHG emission from operational energy as a performance measure for comparing the environmental impacts associated with stormwater harvesting sites. The details of GHG estimation for the current study are explained in Section 4.6.3.

4.4.2.3 Potable Water Savings

This study considered Potable Water Savings (PWS) generated from stormwater harvesting schemes as an important performance measure under the environmental objectives. It has been considered that the potable water savings are directly proportional to stormwater usage. The stormwater harvesting sites with a higher potential to replace potable water, represent improved sustainability.

4.4.3 Performance Measures for Social Objectives

In terms of the social objectives, this study considered community acceptance, construction risks (associated with stormwater harvesting), and recreational value as key PMs. These PMs are described in detail in the following sections. Some of the other social PMs mentioned in literature are spiritual values, inconvenience (caused by scheme) and institutional requirements (Taylor et al. 2006). The potential impact of these PMs was not considered in the present study, due to lack of required data.

In brief, this study evaluates all social PMs on the basis of pre-defined qualitative common scale of 1-5. The details of the evaluation for each social PM are given in this section.

4.4.3.1 Community Acceptance

Public perceptions and acceptance of water reuse are recognised as the main drivers of success for any reuse project including stormwater harvesting schemes. (DEC, 2006; Po et al., 2003). There have been several studies undertaken for assessing community acceptance for water reuse (Brown and Clarke, 2007; Brown and Davies, 2007; Marks et al., 2008). Although, majority of these studies focussed on researching the community acceptance for water recycling and reuse, the outcomes from these studies were perceived similar for stormwater harvesting (Philp et al., 2008)

In terms of analysing the social attitudes of communities towards stormwater harvesting, Mitchell et al. (2006) provided following insights regarding major Australian Cities (Perth, Melbourne and Sydney).

- Community attitudes for stormwater harvesting are a snapshot of opinions in different locations with different time and different space.
- Use of stormwater for residential gardens is preferred by the community over recycled wastewater.
- Community acceptance for stormwater harvesting is a function of the degree of human contact. The acceptance for the stormwater harvesting scheme decreases with more personal end use such as kitchen and shower.

In the current study, the end-use of stormwater is limited to meet the irrigation demand of the parks, for which community acceptance is generally very high (DEC, 2006).

For all alternative stormwater harvesting sites, the study considered basic level of assessment for quantifying the community acceptance. This assessment was done on the basis of perceived sustainability of stormwater harvesting sites in meeting larger demands, and ensuring the higher water security for community to accept the stormwater harvestings scheme. The community acceptance for each stormwater harvesting site was rated in terms of a 1 to 5 point scale (with 5 being very high and 1 being lowest) as described in Table 4.2. The City West Water officers were consulted in rating the community acceptance of stormwater harvesting sites, considering their local experience and knowledge of the case study area.

Table 4.2: Rating Scale: Community Acceptance

Category	Scale
Very High	5
High	4
Moderate	3
Low	2
Lowest	1

4.4.3.2 Construction Risks Associated with Stormwater Harvesting

Risk assessment is one of the very important factors in determining the feasibility of a stormwater harvesting scheme (Goonrey et al. 2009). Therefore, stormwater harvesting associated risks are considered as a critical PM in various studies (Taylor 2005; DEC 2006). However, Melbourne Water guidelines on TBL assessment (2007) argued that risk analysis should not be treated as a separate PM and should be covered at every stage of TBL assessment for all objectives. In the current study, such detailed risk analysis at every stage of the assessment was not conducted due to difficulties in obtaining appropriate data.

The present study considered 'construction risks' associated with stormwater harvesting as one of the key PMs under the social objective. Justification for not considering health and environmental risks is given later in this section. With CWW consultation, four factors were considered in estimating these risks: i) location of the existing drainage assets, ii) available room for suitable storage, iii) presence of heritage sites, and iv) presence of possible service disruptions such as electricity poles/transformers, tram crossings lines, etc.

The location of existing drainage assets near stormwater harvesting site can minimize the potential excavations and thus construction risks. Similarly, larger availability of storage area at a given site can also minimize the construction risks. Furthermore, the construction risks are higher near the stormwater harvesting sites in proximity of heritage sites, where construction permits are not readily granted. Similarly, major service disruptions (such as tram lines, electric poles/transformers etc.) also cause significant excavation, which in turn increase the construction risks.

The selected stormwater harvesting sites in this study were rated on a1-5 point scale separately, on above listed four factors. Furthermore, ranking obtained from the four factors was summed to derive the total combined ranking score, which was used in estimating the overall construction risks for all sites. It should be noted that this total combined score had the range of 4 to 20, which was standardised into 1-5 point scale.

As per NRMMC (2009) guidelines on stormwater harvesting and reuse projects, most roofwater schemes and small-to-medium stormwater reuse schemes involving open space irrigation can be readily managed using standard practices to minimise health and environmental risks. The health risks from stormwater harvesting are fundamentally related to the stormwater quality. This stormwater quality is directly attributed to the characteristics of stormwater catchment. Due to lack of industrial presence around the stormwater harvesting sites considered in this study, health risks associated with water quality are considered low. Additionally, the environmental risks (pollutants, GHG emissions etc.) are explicitly handled in the environmental objective and therefore they are not considered separately in the social objective.

Table 4.3 shows the scale used in rating the stormwater harvesting sites with respect to their location near existing drainage assets. The sites which are closer to drainage network are rated high (5) and vice versa. Table 4.4 shows the scale used in ranking the alternative sites with respect to available storage area. The sites with higher storage area availability are considered best and given the high score (5), and vice versa. Table 4.5 shows the scale used for rating the alternatives sites with respect to their proximity to heritage sites. The alternative sites closest to heritage sites are considered as the sites with highest potential construction risks and given score of 1 and vice versa.

Similarly, Table 4.6 is used to rate the alternative sites with respect to their proximity to potential service disruptions such as tram lines, railway crossings, electric transformers, etc. The stormwater harvesting sites with major potential service disruptions are rated worst (1) representing higher risks and vice versa.

Table 4.3: Rating Scale: Location of Drainage Assets

Category	Scale
Drainage Assets within 50m Distance from the Park	5
Drainage Assets within 50 - 300 m Distance from the Park	4
Drainage Assets within 300 - 600 m Distance from the Park	3
Drainage Assets within 600 - 1000 m Distance from the Park	2
Far Distance (> 1km)	1

Table 4.4: Rating Scale: Availability of Storage Space

Category	Scale
Very High	5
High	4
Moderate	3
Low	2
Very Low	1

Table 4.5: Rating Scale: Proximity to Heritage Sites

Category	Scale
Very Low	5
Low	4
Moderate	3
High	2
Very High	1

Table 4.6: Rating Scale: Proximity to Service Disruptions

Category	Scale
Very Low	5
Low	4
Moderate	3
High	2
Very High	1

Table 4.7 shows the categorisation of the overall construction risks on a scale of 1- 5. For any particular stormwater harvesting site (in Section 4.3), the combined score in Table 4.7 is the aggregated score of that site based on its ranking in four different factors (listed in Tables 4.3, 4.5, 4.5 and 4.6). The sites with higher construction risks were indicated by 5 and vice versa. The construction risk ranking for each site (based on Table 4.7) was further validated from the CWW officers.

Table 4.7: Qualitative Scale for Construction Risks

Construction Risks	Total Combined Score	Scale
Very High	≥ 4-7	5
High	> 7-10	4
Moderate	> 10-13	3
Low	> 13-16	2
Lowest	≥ 16	1

4.4.3.3 Recreational Value

The recreational value from stormwater harvesting schemes was also considered as a PM under the social objectives in this study. Similar equivalent PM in the literature is described as 'aesthetic benefits/value' (Philp et al., 2008; Taylor, 2005a). The recreational value of stormwater harvesting sites was estimated with respect to the amount of sports fields surrounding the sites and the popularity of these sites for recreational activities. Table 4.8 shows the 5 point scale used in evaluating the recreational value of stormwater harvesting sites. The alternative sites with large number of sport fields and recreational activities were rated high (5) and vice versa.

Table 4.8: Rating Scale: Recreational Value

Category	Scale
Very High	5
High	4
Moderate	3
Low	2
Lowest	1

4.4.4 Summary of Selected PMs

Table 4.9 provides the summary of all PMs considered in the study under economic, environmental and social objectives. It should be noted that each PM in Table 4.9 needs to be either minimized or maximized with respect to relevant objectives in the MCDA evaluation of alternative stormwater harvesting sites. Also, as seen from Table 4.9, economic and environmental objectives are quantitative PMs and social objectives are qualitative PMs.

Table 4.9: Summary of PMs Selected for the Study

Objectives	Performance measures	Unit	Max or Min
Economic	Levelised Cost	($/ kL)	Min
Environmental	Greenhouse Gas Emissions	(Kg CO_2 /kL)	Min
	Potable Water Savings	ML	Max
	Annualised Removal Cost of TSS	($/ Kg/Year)	Min
	Annualised Removal Cost of TP	($/ Kg/Year)	Min
	Annualised Removal Cost of TN	($/ Kg/Year)	Min
Social	Community Acceptance	-	Max
	Construction Risks	-	Min
	Recreational Values	-	Max

As per definition of the MCDA model explained in Section 2.6, the set of PMs listed in Table 4.9 and the set of stormwater harvesting alternative sites described in Section 4.3 forms the evaluation matrix for the current study. Using this evaluation matrix in any given MCDA model, the relative merit of each alternative stormwater harvesting site can be determined on the basis of its performance against the selected PMs.

In the current study, the estimation of the quantitative PMs (i.e. economic and environmental) is obtained through sizing the stormwater harvesting infrastructure required at each alternative site and then estimating associated costing. The evaluation procedure for conceptual designs is discussed elaborately in Section 4.5 and 4.6. Furthermore, in Section 4.7, quantification of all economic, environmental and social PMs is demonstrated for one stormwater harvesting site i.e. Flagstaff Park, including its conceptual design. The combined evaluation matrix of estimated quantitative and qualitative PMs is presented in Section 4.8.

4.5 Conceptual Designs of Stormwater Harvesting Systems

During the initial feasibility analysis phase of stormwater harvesting projects, questions such as “how much stormwater can be harvested?”, “how reliable is this supply source?” and “how large a store would be required?” are often posed, and development of conceptual designs of stormwater harvesting systems is mandatory to counter these questions. Therefore, in the current study, the conceptual designs of all eight stormwater harvesting sites were developed, and they were used to evaluate PMs of economic and environmental objectives for use in MCDA.

Melbourne Water (2005) described the conceptual designs as, a set of procedures, which involve detailed engineering calculations to size various hydraulic components of the system, connection details to accommodate site constraints and to confirm the notional size required to meet stated water quality objectives. In terms of stormwater harvesting, conceptual designs can assist in determining the various infrastructure provisions (such as storage size/treatment options, conveyance pipes, pumping and pumping mains) and associated costs. Additionally, ability of stormwater harvesting site in meeting the desired end uses and environmental water quality can be examined through system modelling approaches.

The conceptual designs have four major components of stormwater harvesting systems which consist of collection, storage, treatment, and distribution systems. The considerations in the design process for each element are discussed in the following sections.

4.5.1 Collection

Collection systems are primarily designed to capture and transport stormwater (from urban creek/stormwater drain/overland flow) into either the storage or the treatment area of the stormwater harvesting scheme. The collection systems can be categorized as traditional drainage networks (gutter/pipe/natural drainage system) or WSUD stormwater conveyance systems (such as swales/buffers/bioretention systems).

Figure 4.2 shows the percentage of different types of collection systems implemented across different stormwater projects in Australia, compiled by Hatt et al. (2004). It can be seen from Figure 4.2 that traditional drainage systems account 75% of collection systems in Australia.

The design of the collection system is heavily influenced by location of storage/treatment. For example, if storage is constructed on the existing drainage system (on-line), gravity based collection systems are often used. On the other hand, if storage is located away from the drainage system (off-line), stormwater is transported by pumping arrangements (Philp et al., 2008)

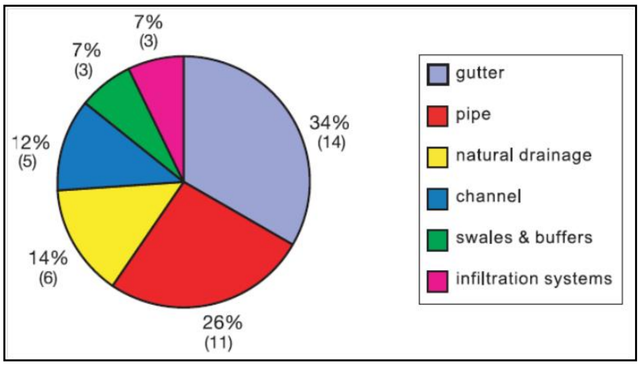

Figure 4.2: Collection Systems in Australia (Hatt et al., 2004)

Traditional drainage systems convey stormwater with minimum losses and do not provide any treatment. These losses are caused by infiltration of stormwater due to cracks in pipes/channels. These systems are designed to convey at least 1 year ARI flows (usually 2 year ARI flows and in some areas up to 10 year ARI flows), and therefore they are adequately sized for collection of harvestable stormwater (Mitchell et al., 2007).

In WSUD stormwater conveyance systems, stormwater is typically conveyed using vegetated systems such as vegetated earthen swale drains, filter drains, or bioretention (biofilters). These systems are subjected to water losses through evapotranspiration or exfiltration depending on local climatic conditions and soil type (Mitchell et al., 2006a). Additionally, Mitchell et al. (2006a) demonstrated that evapotranspiration losses are negligible compared to exfiltration losses in WSUD conveyance systems. Therefore, in designing collection systems, careful consideration should be given to exfiltration losses.

4.5.2 Storage

4.5.2.1 Different Storage Types and Associated Features

The primary function of storage systems in stormwater harvesting is to balance the variable stormwater inflows and demand to achieve a desired reliability of supply (DEC, 2006). The most common type of storage systems are:

- Open storages: These include ponds, dams, constructed wetlands, and open water bodies such as lakes, rivers, streams and creeks.

- Above ground storages (tanks): These systems include tanks or containers of different shapes, materials and sizes. Moreover, above ground storages can be also open storages.

- Underground Storages (tanks): Similar to above ground storages, underground storage tanks also come in different materials and sizes.

- Aquifer Storage Recovery (ASR): These systems include injection of water (wastewater or stormwater) into naturally occurring underground aquifers or storage systems for recovery and utilization at a later stage.

Hatt et al. (2006), in their review of stormwater harvesting schemes in Australia, found that tanks (above ground/under ground) were the most widely utilised method of storage (48% of cases) followed by ponds and basins in the form of larger dams and reservoirs (33%). Use of wetlands and aquifers for storage was infrequent (5% and 14%, respectively).

Further technical information on storage systems can be found in Goonrey (2005). Each storage system listed above has distinct advantages and disadvantages that need to be considered during planning and design phases, and they are documented in Table 4.10.

Table 4.10: Potential Advantages and Disadvantages of Storage Systems (Adopted from (DEC, 2006))

Storage Type	Potential Advantages	Potential Disadvantages
Open Storages	• Low Capital and Maintenance Cost	• Public Safety • Mosquito-Breeding Potential • Higher Potential for Eutrophication • Aesthetic Issues with Fluctuating Water Levels
Above-Ground Tanks	• Moderate Capital and Maintenance Costs • No Public Safety Issues	• Aesthetic Issues
Underground Tanks	• No Visual Issues • No Public Safety Issues	• Higher Capital Cost • Higher Maintenance Costs
Aquifer	• Little Space Required • Cost Effective • Prevents Saltwater Intrusions to Aquifer	• Requires Suitable Geological Condition • Potential to Pollute Groundwater Unless Pre-Treated

4.5.2.2 Design Considerations for Storage

In general, the design of stormwater harvesting storages varies in terms of three key aspects: function, location and capacity (DEC, 2006; Mitchell et al., 2006a; Philp et al., 2008) .

a) Function – Storages are used to provide one or more of the following functions: water supply, flood mitigation, recreational amenity, aesthetic amenity, water quality improvement, habitat provision and fire-fighting supplies. Open storages such as wetlands are most commonly designed to achieve multiple objectives. While multiple objectives may be desirable, the scheme will not be able to satisfy all objectives simultaneously, requiring some trade-offs are made between objectives.

b) Location – As described in Section 4.5.1, storages can be either inline or offline depending on topography and watercourse.

c) Capacity – The storage capacity (or sizing) will vary according to the reliability of supply required for a given end use under local climatic conditions. The estimation of storage capacity is one of the most critical aspects of conceptual designs and it is explained in detail in Section 4.6.2.4.

In addition, many of the public health and safety issues surrounding stormwater harvesting schemes are centred around on open storages (Philp et al., 2008). Various threats include: drowning, eutrophication resulting from long detention times, algal blooms, lack of nutrient removal, waterbirds, and animals depositing faecal matter containing pathogens (DEC, 2006; Mitchell et al., 2006; Philp et al., 2008). In closed storages, anaerobic conditions can develop due to the action of oxygen consuming bacteria which in turn can result in foul odour (DEC, 2006; NRMMC et al., 2009). However, anaerobic conditions in closed storages can be successfully controlled by appropriate management of storage levels, and inclusion of upstream treatment measures (such as bio-infiltration trenches, gross pollutant traps).

In terms of storage components of the conceptual designs, the present study uses underground tanks (i.e. closed storage) for meeting the irrigation demands of the parks. The underground tanks are chosen as the common storage option for all selected stormwater harvesting sites (Section 4.3), as they possess minimal risks for storage with proper maintenance.

4.5.2.3 Storage Sizing

The size of storage required for a given stormwater harvesting scheme is a function of the amount of inflow that can be directed into the storage system, the seasonality of the inflow and demand, and the degree of volumetric reliability of supply required (Mitchell et al., 2006a; Mitchell et al., 2008). It should be noted that in case of stormwater harvesting, storage sizing is often influenced by desired volumetric supply reliability (i.e. demand that can be supplied by available stormwater). For minimizing the storage system costs, the stormwater harvesting storages are often designed for a lower level of reliability of supply (e.g. 70%) in comparison to that of traditional storages such as water supply dams (e.g. 95%).

The relationship between storage capacity, supply and reliability provided by Mitchell (2006a) is described in Figure 4.3.

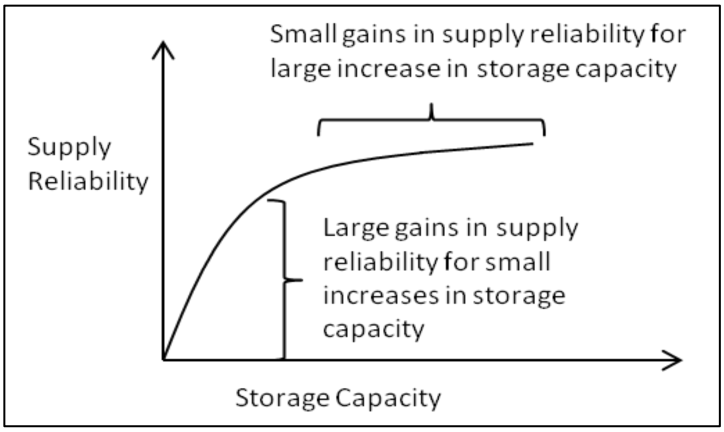

Figure 4.3: Storage Capacity vs. Supply Reliability
(Adopted from Mitchell et al. (2006a))

From Figure 4.3, it is evident that larger the storage capacity, higher the supply reliability. However, after a particular point, for increase in storage size, there are smaller gains in supply reliability. Considering this aspect, in most design situations, the selection of the storage capacity for stormwater harvesting is a trade-off between maximising supply reliability and minimising the required storage size and associated costs (Mitchell et al., 2007).

Considering the seasonal variability of runoff and demand, the storage sizing requires water balance modelling to meet the demand at desired reliability level. Computer models such as MUSIC (Model for Urban Stormwater Improvement Conceptualisation) (eWater, 2012) and UVQ (Urban Volume and Quality) (Mitchell and Diaper, 2006) can be used to determine the relationship between supply reliability and associated storage capacity.

4.5.3 Treatment

Treatment for a given stormwater harvesting project depends on the catchment properties (dictating the nature and type of pollutants) and perceived end use of stormwater. In the past, treatment technologies were designed mainly for general stormwater pollution control (Hatt et al., 2006). However, the current design practice for treatment systems is based on ‘treatment trains’ to ensure their efficiency in meeting the specified water quality targets for stormwater reuse.

The treatment train approach uses different treatment measures in series in an integrated treatment sequence to improve the overall performance of the treatment system and to improve water quality for intended end use (Wong et al., 2002). These measures generally can be categorised into primary treatment, secondary treatment, and tertiary treatment. For example, most stormwater harvesting systems depend on some primary treatment such as Gross Pollutant Traps (GPTs) to prevent the coarse materials (such as litter or plastic), which may clog the system. Secondary treatment may include WSUD technologies (such as buffers, swales, biofilters, wetlands) in order to remove the finer sediments, nutrients and other pollutants. The standard information on WSUD treatment technologies and their design aspects are not documented in this chapter, however it can be found in Melbourne Water (2005). Tertiary treatment consists of media filtration and disinfection to further refine the quality of stormwater against intended enduses.

According to DEC (2006), design of stormwater treatment systems should effectively address public health and environmental risks, which are inherently related to water quality. In Australia, the national guidelines for water recycling and stormwater reuse (NRMMC et al., 2009) provide detailed guidance on different stormwater quality criteria for managing public health risks for various end uses of stormwater including irrigation (used in this study).

The performance of the treatment train (consisting of various treatment devices) is generally associated with its ability in meeting the desired water quality targets or objectives. For this purpose, a modelling exercise is often taken to investigate the effect of various treatment measures for meeting desired water quality targets.

To date, bio-filters (or raingardens/bio-retention systems) have been the most widely adopted as treatment measure in Australia, mainly due to their excellent performance in removing nutrients and heavy metals (Bratieres et al., 2008). However, inability to remove pathogenic indicators to the desired levels together with large space requirements does not make biofilters viable as a standalone option for stormwater reuse (Bratieres et al., 2008). In order to address this problem, new treatment technologies (such as Enviss and Ecosol Sand Filter) are being developed and tested in Australia. Details of these technologies can be found on 'E-water' company website (http://listing.ewater.com.au/index.php). However, careful consideration should be given in selecting the treatment technologies, available from various private manufacturers. For this purpose, peer-reviewed published data should be referred. Specific manufacturers can also be contacted to obtain the guidance on peer-reviewed published data.

The current study uses GPT (Manufacturer: CDS) as primary treatment and Enviss infiltration media (Manufacturer: Rocla) as secondary treatment. The major reason for selecting these technologies was the demonstrated higher treatment efficiency rates of pollutants. The Enviss systems have a capacity (of treatment) seven times that of traditional biofilters (Schang et al., 2010) for a similar surface area. More importantly, these systems have demonstrated high treatment efficiencies (removing 90% TSS, 67% of TP and 79% of TN loads) to improve the stormwater quality for reuse purposes (Bratières et al., 2010). Similar high level of treatment efficiencies have been demonstrated by CDS GPTs which have 98% removal rate of gross pollutants (Rocla, 2013a). The technical description and properties of Enviss and CDS GPTs is provided in Appendix 4B.

The treatment units (CDS GPTs and Enviss technology) selected in current study should not be considered as recommendation. The study has used these technologies only for facilitating the easy comparison of different stormwater harvesting sites through MCDA. There are numerous other similar systems suitable for treating stormwater, and readers are advised to make their own judgement.

4.5.4 Distribution

The distribution component is very similar to the collection component, as both involve transportation of water. The stormwater distribution systems are required to supply water for open space irrigation, or used in non-potable water supply in residential developments through dual reticulation.

The stormwater harvesting schemes in Australia are used for open space irrigation (50%), non-potable water supply through dual reticulation (35%) and pumping (15%) (Hatt et al., 2004). The authors also found that dual reticulation systems are a viable option for large scale (neighbourhood) stormwater harvesting schemes.

The selection of distribution systems is influenced by a several issues such as spatial scale of the distribution area (e.g. open space irrigation, residential properties), the density of the single or multiple end uses, and the inclusion or exclusion of fire fighting requirements within the stormwater distribution system (Mitchell et al., 2007). According to DEC (2006), the design of the distribution system should be such that there should be no contaminant intrusion between the final treatment facility and the end use facility. Additionally, care should be taken for avoiding the cross-connection of water distribution network with the stormwater distribution system.

4.5.5 Combination of Stormwater Harvesting Components

As described in Section 4.5, conceptual designs of stormwater harvesting systems consist of determining the provisions for collection, storage, treatment, distribution systems. Figure 4.4 describes few combinations of system components that can be used in developing conceptual designs. For example, For example, storage may be located after or between collection or treatment facilities. In addition, different types of storages (on-line or off-line storages) and treatment techniques (biofilters, buffers, swales) could be considered depending on end uses and catchment water quality objectives.

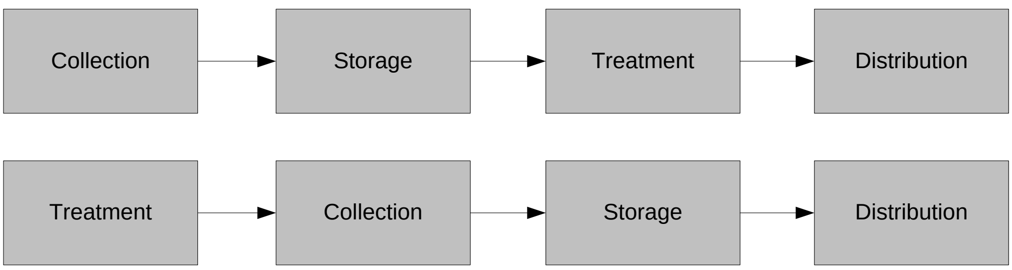

Figure 4.4: Different Combinations of Stormwater Harvesting Components

The conceptual design procedure broadly involves modelling the selected stormwater harvesting components, (especially, selected storage and treatment options) and identifying the degree to which each option meets the adopted project objectives. For example, as described in Section 4.5.2.3, water balance modelling is often employed to select the effective storage size at desired reliability level. Likewise treatment options are modelled for meeting the water quality objectives.

The perceived end-use of stormwater harvesting scheme essentially dictates the design of collection, storage and treatment components (DEC, 2006). The modelling aspect in conceptual designs could be iterative, particularly to optimise the overall project cost, which is directly influenced by the selected designs of various components (DEC, 2006). Consequently, cost estimates of stormwater harvesting sites are derived from conceptual designs. Additionally, environmental PMs such as greenhouse gas emissions and pollutant loads can be derived from the conceptual designs.

4.5.6 MUSIC Software for Conceptual Design

For developing the conceptual designs, the current study uses the modelling software named 'Model for Urban Stormwater Improvement Conceptualisation' (i.e. MUSIC), developed by the Catchment Research Centre for Catchment Hydrology (CRCCH), in Melbourne, Australia (Wong et al., 2002). MUSIC enables users to evaluate conceptual designs of stormwater management systems (or WSUD strategies) to ensure they are feasible in meeting the specified stormwater quality and quantity objectives. MUSIC is designed to simulate urban stormwater systems at spatial scale of 0.01km^2 to 100 km^2. Modelling time steps can range from 6 minutes to 24 hours to match the range of spatial scale. This study used MUSIC - version 4 during the study period. However, MUSIC version 6 (http://www.ewater.com.au/products/ewater-toolkit/urban-tools/music/) is recently launched in the market.

MUSIC simulates the performance of a group of stormwater management measures (such as rainwater tanks, detention basins, ponds, wetland and biofilters), configured as a treatment train (Section 4.6.3) and runs on an event or continuous basis, allowing rigorous analysis of the merit of proposed WSUD strategies over the short term and long term. By simulating the performance of stormwater improvement measures, MUSIC determines if proposed treatment options can meet the specified objectives, both from hydrologic and water quality perspectives. Complex stormwater management scenarios and results can be viewed using a range of graphical and tabular formats. One of the key features of MUSIC includes a life cycle costing module, which allows life cycle costing of a treatment node, or the lifecycle costing of the entire stormwater treatment train.

It is important to note that MUSIC is a basic conceptual design tool and lacks features for detailed sizing of structural stormwater quantity and/or quality facilities including the hydraulic design capabilities. Therefore, MUSIC should be seen as one of several tools used in designing WSUD strategies including stormwater harvesting. The theoretical aspects of MUSIC modelling are documented in Appendix 4C along with the model representation and relevant terminologies.

4.6 Conceptual Designs: Methodology

As explained in Section 4.5, conceptual designs were developed for eight stormwater harvesting sites in the CoM study area, selected using the GIS screening tool (Section 4.3). These conceptual designs were then used to determine the economic and environmental PMs selected (Section 4.4.1 and 4.4.2) for the MCDA.

The approach used for developing the conceptual designs for the current study is divided into three tasks and is shown in Table 4.11. This approach was common for all selected eight stormwater harvesting sites. Detailed description of each task is described in next sub-sections

Table 4.11: Approach Used for Conceptual Designs

No.	Conceptual Design Task	Derived PM	PM Category
1	Water Balance Modelling	Potable Water Savings	Environmental
2	Cost Analysis	Levelised Cost of Stormwater Harvesting Sites	Economic
		Annualised Removal Cost of TSS, TP, TN	Environmental
3	Greenhouse Gas Estimation Analysis	Greenhouse Gas Emission	Environmental

4.6.1 Water Balance Modelling using MUSIC

In the current study, water balance modelling was conducted using the MUSIC software and was divided into four steps. These steps are shown in Figure 4.5.

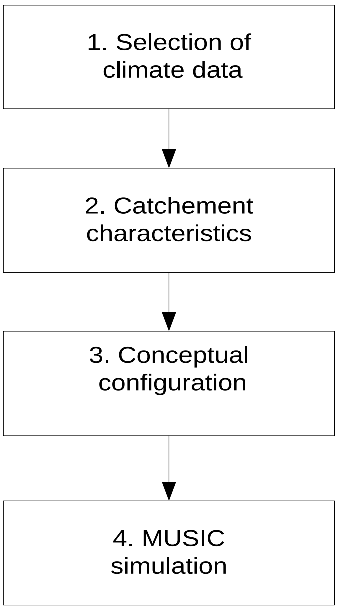

Figure 4.5: Water Balance Modelling Approach Used in the Study

4.6.1.1 Selection of Climate Data

For stormwater modelling, MUSIC requires climatic data in the form of rainfall and evapotranspiration. The present study considers rainfall period of 1997 to 2006 for MUSIC modelling. This period serves as a conservative estimate of rainfall in Victoria. Moreover, this period is consistent with the recommended stormwater modelling period specified in DSE (2006). Furthermore, the rainfall for the selected period is modelled using a recommended time step of 6 minutes (Clearwater, 2011; eWater, 2012; Melbourne Water, 2012). These climate data were obtained from in built MUSIC template for Melbourne city.

Considering the proximity to the City of Melbourne case study area, the Melbourne station was selected as base rainfall station for analysis. The average annual rainfall at this station in the selected period of 1997-2006 is 504 mm/year compared to the long term average of 650.8 mm/year.

4.6.1.2 Catchment Characteristics

After selecting the climate data, catchment properties for each selected stormwater harvesting site were defined in terms of the following parameters.

a) Catchment Type: For all stormwater harvesting sites, the catchment type was represented by an 'urban' node in the MUSIC model, representing the sub-catchments of City of Melbourne. The details of the MUSIC model terminology are provided in Appendix 4C.

b) Catchment Area/ Effective Imperviousness: The CWW officials had access to the information on the existing drainage network (provided by CoM) related to topography and land use conditions (such as impervious roofs/pavements/car parks) of at each site. With this information, the catchment area (ha) with its effective imperviousness area (in %) was estimated for each selected stormwater harvesting site.

c) Rainfall-Runoff Parameters: The MUSIC manual (eWater, 2012) and Melbourne Water (2012) provide the calibrated rainfall-runoff parameters for Melbourne City. The current study used these default parameters for modelling all stormwater harvesting sites, and they are explained in Table 4.12.

d) Pollutant load Parameters: Similar to the rainfall-runoff parameters, the study uses default pollutant load parameters available in the MUSIC manual (eWater, 2012). These parameters are shown in Table 4.13. It should be noted that water quality may vary from site to site and might significantly affect the final outcomes. However, such variation in water quality was not conducted due to data unavailability of different water quality parameters at different sites in study area.

Table 4.12: Default Rainfall-Runoff Parameters Used in MUSIC Model

Parameter	Value
Rainfall Threshold (mm)	1
Soil Capacity (mm)	30
Initial Storage (% of Capacity)	30
Field Capacity (mm)	20
Infiltration Capacity Coefficient a	200
Infiltration Capacity Coefficient b	1
Initial Depth (mm)	10
Daily Recharge Rate (%)	25
Daily Base flow Rate (%)	5
Deep Seepage Rate (%)	0

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Table 4.13: Default Pollutant Load Parameters Used in MUSIC Model

	Pollutants					
	TSS		TP		TN	
	log mg/L		log mg/L		log mg/L	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Baseflow Concentration Parameters	1.1	0.17	-0.82	0.19	0.32	0.12
Stormflow Concentration Parameters	2.2	0.32	-0.45	0.25	0.42	0.19

e) Enduse Demands: The study uses the annual demand data of selected parks (Section 4.2) available from CWW (2012). These demands were estimated on the basis of 'South Australian Water Code of Practice for the Irrigation of Open Spaces' (SA Water, 2008).

To account for the seasonal variation in demand, the current study used the monthly distribution of irrigation demand. This distribution is shown in Table 4.14, and it is based on CWW (2012).

Table 4.14: Monthly Distribution of Irrigation Demand

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Demand (%)	17	12	11	7	4	2	3	4	7	10	10	13

4.6.1.3 Conceptual Configuration

As described in Section 4.3, a typical stormwater harvesting scheme consists of combination of different options of collection, storage, treatment and distribution systems depending on the project objectives. In the current study, a common conceptual configuration was selected for all stormwater harvesting sites for maintaining the uniformity in analysis with respect to project objectives defined in Section 4.3. This configuration is shown in Figure 4.6. This configuration is modelled for each selected site separately, depending on local physical conditions and demands. The common conceptual configuration ensured easy comparison of alternative stormwater harvesting sites in terms of economic and environmental PMs.

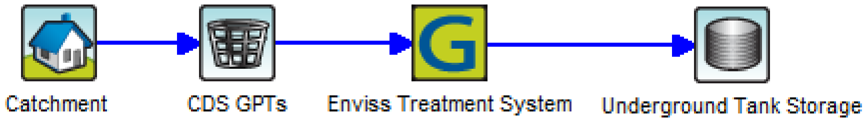


Figure 4.6: Conceptual Configuration for Stormwater Harvesting Sites

As depicted, stormwater is collected from the existing drainage network of the catchment. The provision of GPT unit (Rocla, 2013a) serves as primary treatment to remove the debris and large sediments. For this purpose, this study used GPT systems named as ‘CDS units’. Thereafter, an Enviss system (Rocla, 2013b) was used as the secondary treatment system to remove synthesized finer sediments. The treated stormwater is stored in underground storage tanks. The water from the storage tanks is then pumped and distributed for irrigation of the parks. It should be noted that representation of Enviss systems in MUSIC is as per Melbourne Water guidelines (http://www.melbournewater.com.au/Planning-and-building/Forms-guidelines-and-standard-drawings/Documents/MUSIC-tool-guidelines.pdf) for generic treatment node.

Combination of CDS GPT and Enviss system was modeled for treating stormwater for desired water quality objectives (viz. 80%, 45% and 45% reduction of TSS, TP and TN loads in Victoria). The treatment efficiencies of CDS GPTs and Enviss system are given in Table 4.15. These treatment efficiencies served as input to the MUSIC model. It should be noted that high treatment efficiencies of CDS GPTs and Enviss system should be regarded with caution until independently verified for a particular application.

Table 4.15: Treatment Efficiency of CDS GPT Units and Enviss Systems

	Pollutants	Treatment Efficiency	Source
Primary Treatment GPT (CDS Units)	Gross Pollutants	98%	(Rocla, 2013a)
	TSS	70%	
	TP	30%	
	TN	-	
Secondary Treatment (Enviss Systems)	TSS	90%	(Schang et al., 2010)
	TP	67%	
	TN	79%	

The underground concrete storage tanks were used for storing water for use of irrigation of parks, and they were modeled to determine the optimum storage capacity. The input storage properties for storage tanks in MUSIC are shown in Table 4.16.

Table 4.16: Input Data for Underground Tank Modeling

Parameter	**Value**
Low Flow Bypass* (m^3/s)	0
High Flow Bypass* (m^3/s)	100
Volume Below Overflow Pipe, kL	Determined by Trial and Error
Depth Above Overflow Pipe*, m	0.2
Depth Below Overflow Pipe*, m	1.2
Surface Area	Determined by Trial and Error
Outlet Pipe Diameter*, mm	500

**Default calibrated values of MUSIC model*

For each selected stormwater harvesting site, length and size of reticulation pipe required for distribution of stormwater were estimated. Moreover, conceptual designs also included estimation of pumping capacity and associated costing.

4.6.1.4 Simulation using MUSIC Software

Based on input data and the selected treatment train described in Section 4.6.1.2 and 4.6.1.3, the MUSIC was used for determining i) effectiveness of treatment train in achieving the water quality targets (specified in Section 4.4.2.2), ii) estimating the pollutant loads (in Kg/year) and stormwater supply, and iii) optimum storage size (as described in Section 4.5.2.3) for each selected stormwater harvesting site (Section 4.3).

On the basis of discussions with CWW, the reliability of 80% of supplied annual irrigation demand was selected for storage sizing. As explained in Section 4.5.2.3, the selected reliability value served as trade-off between supplied demand and storage capacity (and thereby cost). The optimum storage size was estimated by running model several times until model predicted stormwater yield matched the desired level of reliability (i.e. 80% of supplied demand).

The stormwater yield estimated from the MUSIC software was considered as potable water savings (environmental PM) from stormwater harvesting schemes. Additionally, MUSIC provided information on generated pollutant loads of TP, TN and TSS (in kg) from the stormwater harvesting schemes which were used in determining the annualised removal cost of pollutants, which is one of important PMs under the environmental objective.

4.6.2 Cost Analysis

As shown in Table 4.11, the cost analysis for stormwater harvesting sites was done for estimating the *Levelised Cost* (economic PM) and *Annualised Removal Cost (ARC) of Pollutants* (environmental PM) for the MCDA.

4.6.2.1 Levelised Cost

As defined in Section 4.4.1, *Levelised Cost (LC)* is defined as

$$LC = \frac{NPV\ of\ total\ stormwater\ infrastructure\ of\ site\ (\$)}{NPV\ of\ volume\ of\ water\ supplied\ by\ the\ site\ (kL)} \qquad (4.1)$$

In the current study, the Net Present Value (NPV) was estimated for all sites for the analysis period of 50 years with the discount rate of 5.1% based on discussions with CWW. Similarly, information on the useful life of various components was obtained from literature and personal communications with CWW and manufacturers and shown in Table 4.17. Additionally, based on discussions with CWW, the design and administration costs (15% of the capital costs) and construction and project management costs (30% of the capital costs) were also considered in estimating NPV.

Table 4.17: Useful Life Period of Different Components Used in the Study

Component	Useful life of Components (Years)	Source
Stormwater Diversions (Collection Systems)	80	Sharma et al. (2006)
CDS GPTs (Rocla)	50	Rocla (2013a)
Enviss Treatment Systems (Rocla)	60	Personal Communication with Rocla (2012)
Underground Storage	25	Sharma et al. (2006)
Reticulation (Distribution Systems)	100	Sharma et al. (2006)
Control System	50	Personal Communication with City West Water (2012)
Pumps	15	Sharma et al. (2006)

.

For a given stormwater harvesting site, the total NPV is the sum of all NPVs of capital and operational costs associated with stormwater harvesting components over the selected analysis period. NPV summation included following costs:

1. Capital costs associated with each component (per unit)
2. Design and administration costs (15% of capital costs),
3. Construction, project management and contingency costs (30% of capital costs)
4. Annual operation costs associated with each component

During NPV estimation, design and administration costs, and construction, project management, and contingency costs were factored (1.15 and 1.30) as part of total capital costs.

NPV Estimation for Capital Costs of Components

Some components can have useful life equal or more than the analysis period, while some components can have useful life less than the analysis period.

For the components whose useful life is equal or more than the analysis period, NPV determination of capital costs do not need to be discounted as the components are not replaced over the analysis period. However, NPV of capital costs is determined in cases where some stormwater harvesting components may have less useful life period compared to overall analysis period. For example, underground storage tanks in Table 4.17 have less useful life cycle period (such as 25 years), compared to the analysis period of the stormwater harvesting scheme (e.g. 50 years). In such case, there is one additional capital cost which accounts the replacement of underground storage tank after 25 years.

Mathematically, in cases, where useful life of a component is *n* years, over the analysis period of *3n* years, NPV of capital cost for this component can be estimated as

$$NPV_C = C + C\,(1+i)^{-n} + C\,(1+i)^{-2n} \qquad (4.2)$$

where NPV_C = NPV of capital costs
C = Capital cost of component
i = Discount rate
n = Useful life of component

The remaining useful life of the components after analysis period and salvage value of any infrastructure was not considered in the analysis.

NPV Estimation for Operational Cost of Components

The NPV of operational cost for any particular component can be estimated by calculating its equivalent annualised cost. The equivalent annualised cost is the cost of owning and maintaining the selected component over its life period. The NPV of operational cost (or equivalent annualised cost) over a given analysis period is

$$NPV_A = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad (4.3)$$

Where, A= Annual operational costs

4.6.2.2 Annualised Removal Cost

For each selected stormwater harvesting site, the *annualised removal costs (ARC)* of pollutants (TSS, TP and TN) was determined using the approach adopted in MUSIC software (eWater, 2012). Initially the annualised cost of treatment was estimated by dividing the NPV of treatment costs by analysis period of 50 years. The treatment costs for the present study consisted of cost of CDS GPTs and Enviss systems. Furthermore, for estimating the *ARC* value of pollutants, the annualised NPV value was then again divided by the pollutant loads estimated (Section 4.6.1.4) for each selected stormwater harvesting site.

Mathematically, for any given stormwater harvesting site, *ARC* of pollutants (TSS, TP and TN) can be represented by Equations 4.4 and 4.5.

$$Annualised\ Removal\ Cost\ of\ Pollutant = \frac{Annualised\ NPV\ of\ Treatment\ Cost\ (\$)}{Pollutant\ Load\ (Kg/Year)} \quad (4.4)$$

where

$$Annualised\ NPV\ of\ Site = \frac{Total\ NPV\ of\ Treatment\ Cost\ (\$)}{Analysis\ Period} \quad (4.5)$$

4.6.3 Greenhouse Gas Emissions

As described in Section 4.4.2.2, the study considered GHG emissions as one of important PM in the environmental category for assessment of stormwater harvesting sites. The GHG emissions in stormwater harvesting schemes are mostly associated with electrical energy consumption from pumps. Therefore, for each selected stormwater harvesting site (Section 4.3), the electrical energy consumption of the pumps was estimated for GHG analysis.

The GHG emissions from a given stormwater harvesting site were then estimated by taking product of electrical energy consumption and GHG Emissions factor associated with electricity consumption. This factor was obtained from Department of Climate Change, Victoria (2012), as 1.21 Kg CO_2/kWh for year 2009-10 as latest available figure during the time of study.

Mathematically, GHG emission can be represented as

The electrical consumption (kWh/kL) in Equation 4.6 was estimated by computing the annual pumping energy requirement (kWh/year) associated with annual volume of stormwater reuse.

Thus,

Energy consumption (kWh/kL) = Energy requirement of pumps ((kWh/ year) /Water Reuse Volume (kL/Year) (4.7)

To determine the energy requirement of pumps in Equation 4.7, pumping systems were sized to meet the peak daily demand for site specific stormwater reuse. The annual energy usage of the pump was a product of pump size (kW) and annual pumping hours.

*Energy requirement of pumps (kWh/year) = Pump Size *Annual Pumping hours (hr)* (4.8)

The pump size and associated costing for each site were estimated by the procedure suggested by Swamee and Sharma (2008). This procedure is documented in Appendix 4D. The annual pumping hours in Equation 4.8 were estimated with the suitable assumption based on seasonal usage of the pumps. These assumptions are based on discussion with CWW and are documented in Table 4.18. As seen from Table 4.18, the total operating hours in each season were determined by taking product of total seasonal days and per day estimated usage.

Table 4.18: Annual Pumping Hours Estimation

Season	Months	Operating Days	Usage per day	Total Hours
Summer (October-March)	6	30	8	1440
Winter (April-September)	6	30	4	720
Total				2160

4.7 Estimation of Performance Measures for Flagstaff Park

This section describes the estimation of economic, environmental and social PMs for Flagstaff Park (Table 4.11). As described earlier (Section 4.6), conceptual designs were developed to quantify the economic and environmental PMs. For quantification of social PMs for Flagstaff Park, qualitative scales as defined in Section 4.4.3 were used. The same evaluation procedure was used to quantify the PMs for the remaining sites (i.e. Holland Park, Birrarung Marr Park, Princess Park, Clayton Reserve, Batman Park, Ievers Reserve, and Pleasance Garden). The details of PM evaluations for all sites are documented in Appendix 4A.

4.7.1 General Site Description

As described in Section 4.3, Flagstaff Gardens is one of the important streetscape of Melbourne's CBD with a total irrigation area of 7.25 ha. Within the close proximity to Flagstaff Gardens, several large stormwater drains exist, providing the opportunity for stormwater harvesting. The catchment area for Flagstaff Park is shown in Figure 4.7, along with drainage network and irrigation area. As seen from Figure 4.7, there are two major stormwater catchments (A and B), divided by Elizabeth street and predominantly comprising of commercial landuse. The total area for these two catchments is shown in Table 4.19.

Table 4.19: Catchment Area: of Flagstaff Park

Catchment	Size (ha)	Impervious Area
Catchment A	36.23	70%
Catchment B	116.5	75%
Total	153.13	

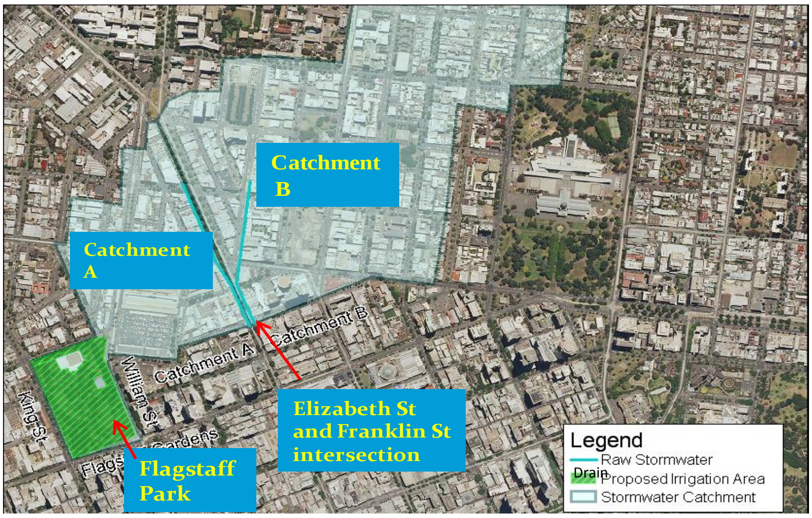


Figure 4.7: Drainage Area of Flagstaff Park

The Flagstaff Park has an annual average irrigation demand of 70 ML based on historical demands of the previous 10 years. As described in Section 4.6.1.2, this demand served as input for MUSIC software. Table 4.20 provides the monthly irrigation demand of Flagstaff Park, which is disaggregated based on its seasonal variation.

Table 4.20: Irrigation Demand Distribution for Flagstaff Park

Month	Disaggregation Factor* %	Demand per year (ML)
January	17	11.9
February	12	8.4
March	11	7.7
April	7	4.9
May	4	2.8
June	2	1.4
July	3	2.1
August	4	2.8
September	7	4.9
October	10	7
November	10	7
December	13	9.1
Total	**100**	**70**

**The disaggregation factor is obtained from CWW (2012) report*

4.7.2 Conceptual Configuration

The stormwater harvesting conceptual configuration for Flagstaff Park is shown in Figure 4.8. This configuration needs two diversion systems to collect the stormwater from the two catchments at the intersection of Elizabeth Street and Franklin Street. The diversion systems will pass raw stormwater into an in-ground CDS gross pollutant traps (GPTs). The stormwater is then diverted and pumped to Enviss systems for secondary treatment through stormwater pipes. Finally, treated stormwater will be stored in the underground storage tanks in the Flagstaff Park area and then pumped for irrigation purposes.

The sizing of GPTs essentially depends on the catchment area and associated annual flow volumes. The current study estimated the GPT volume as 55.3 m^3 for Flagstaff Park based on MUSIC modelling. MUSIC determined this GPT volume using the modelled runoff in the catchment area with the method proposed by Walker et al. (1999). Further details of GPT modelling and associated can be found in eWater (2012).

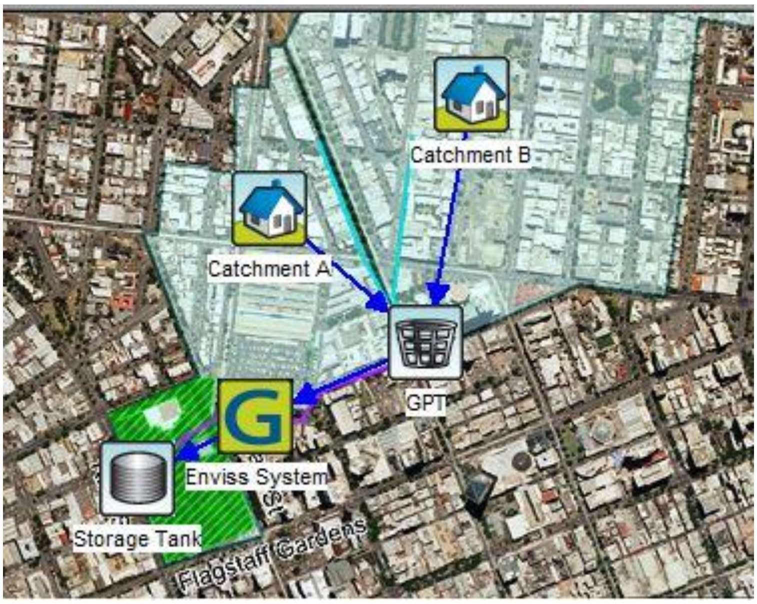


Figure 4.8: Conceptual Configuration for Flagstaff Park

The sizing of Enviss systems in the current study was conducted using software tool named as 'EnvissDT' (http://www.enviss.com.au/software). This software is developed by Enviss manufacturers in conjunction with Monash University, Melbourne. The

EnvissDT software simulates both the quantity and quality of runoff from a range of urbanised catchments and the subsequent treatment of this stormwater using a range of enviss filtration systems (EnvissDT Manual, 2012).

The EnvissDT software uses similar climate and catchment area properties of MUSIC software (Sections 4.6.1.1. and 4.6.1.2), to estimate the treatment area and number of required Enviss units for treatment. It should be noted that each treatment unit constitutes 1 m^2 surface area. The modelling algorithms of EnvissDT software are briefly explained in Appendix 4B. The EnvissDT estimated the required treatment area for Flagstaff Park as 1100 m^2 with lumped 1100 Enviss units. It should be noted that lumping of Enviss systems with 1100 m^2 area may not perform similar to 1100 separate Enviss units. Although as per EnvissDT manual, there are no restrictions on treatable area through Enviss systems, the results from EnvissDT software should be used with caution because of lumping effect.

The desired storage tank size was estimated as 3000 kL from water balance modelling using MUSIC. The details of water balance modelling are explained further in Section 4.7.3. Based on GIS mapping, the required length of stormwater pipe was calculated as 684 meters.

Furthermore, the pipe size (diameter) of 200 mm was estimated considering the daily peak discharge required for fulfilling the annual irrigation demand of 56 ML (out of desired 70 ML) at 80% supply reliability (Section 4.7.3). For this purpose, a method developed by Swamee et al. (1987) and Swamee and Sharma (2008) was used. Additionally, based on daily peak discharge, a pumping system of 4.4 kW was also designed using the procedure suggested by Swamee and Sharma (2008). The standard calculations of pipe diameter and pump sizing are documented in Appendix 4D. Two pumping systems were considered suitable for the Flagstaff Park stormwater system. One of these pumping systems was proposed before the treatment units and the other after storage tank to distribute stormwater for irrigation.

4.7.3 Water Balance Modelling Results

The proposed configuration in Section 4.7.2 was used in MUSIC modelling to estimate of storage size, potable water savings, and pollutant loads from the catchments.

Table 4.21 shows the water balance modelling results for the treatment train. As listed in Table 4.21, 375 ML of stormwater would be generated from the catchment, which was sufficient to supply 56 ML for irrigation at 80% reliability. This stormwater usage could be considered as potable water savings and was used as the environmental PM in MCDA evaluation.

Table 4.22 shows the results of contaminant balance modelling of the treatment train specified in Section 4.7.2. Additionally, Table 4.22 highlights the total incoming and outgoing annual pollutant loads of TSS, TP, and TN generated from the selected treatment train (Section 4.7.2). These pollutant loads (kg/year) were used in determining the Annualised Removal Costs ($/kg/year) of pollutants, which is an environmental PM. The method of estimation of the PM was described in Section 4.6.2.2.

Table 4.21: Results of Water Balance Modelling

Average Annual Incoming Flow, ML	Average Annual Outgoing Flow, ML	Stormwater Reuse (Potable Water Savings), ML	Irrigation Demand, ML
375	319	56	70

Table 4.22: Results of Contaminant Balance Modelling

Pollutants	Annual Average Pollutant Inflows	Annual Average Pollutant Outflows	Reduction Target* %	Reduction Achieved %
Total Suspended Solids (kg/yr)	73500	2880	80	96.1
Total Phosphorus (kg/yr)	151	42.8	45	71.7
Total Nitrogen (kg/yr)	1060	209	45	80.3
Gross Pollutants (kg/yr)	15000	0	70	100

**As described in Section 4.4.2.1*

Table 4.22 also shows the reduction of pollutants achieved from the treatment train. As seen from the last column of Table 4.22, there is load reduction of 96.1% in TSS, 71.7% in TP, 80.3% in TN and 100% in gross pollutants. With this reduced load of pollutants, water quality targets (specified in second last column of Table 4.22) were met by the treatment train, with better quality than desired. Practically, the treatment systems should be designed to get desired reduction targets as close as possible to avoid excessive costs of treatment. However, in the current study, the treatment systems with higher water quality were not changed to facilitate the easy comparison of similar stormwater harvesting site alternatives (Section 4.3).

4.7.4 Cost Analysis Results

As explained in Section 4.6.2, the cost analysis was conducted to determine *Levelised Cost (LC)* and consequently estimating the *Annualised Removal Cost (ARC) of pollutants* (TP, TN, TSS).

a) Levelised Cost

As highlighted in Section 4.6.2, *Levelised Cost (LC)* for Flagstaff Park was determined by the ratio of NPVs of stormwater infrastructure cost and supplied demand of site (stormwater reuse) over the analysis period. This study used 50 years as the analysis period with the discount rate of 5.1% to estimate the NPVs. To determine the NPV of overall stormwater infrastructure, several assumptions related capital (Table 4.23) and annual maintenance costs (Table 4.24) were made. These assumptions served as the basis for LC estimation of all selected stormwater harvesting sites including Flagstaff Park

Table 4.23 provides the listing of capital costs of different stormwater infrastructure components. Furthermore, capital cost of Enviss treatment systems was determined by taking product of estimated number of treatment units (Section 4.7.2) and per unit capital cost. Using similar procedure, capital costs of diversion systems, underground storage tanks (concrete), control systems and reticulation systems were determined on per unit basis.

The cost of diversion and control systems were estimated as per CWW (2012) report. Furthermore, costs of pumping systems were determined using the procedure suggested by Swamee and Sharma (2008). This procedure and associated computational demonstration is documented in Appendix 4D.

Table 4.24 represents the assumptions made for annual maintenance (or operational) costs. The annual maintenance costs of CDS GPTs were estimated as 7% of the capital cost as suggested in the MUSIC manual (eWater, 2012). Furthermore, the maintenance costs of Enviss systems were estimated as 2% of the capital cost after consultation with manufacturer's representative. Additionally, as seen from Table 4.24, the annual maintenance costs for other components were obtained from CWW (2012).

Table 4.23: Assumption Used for Capital Cost

Component	Capital Cost Assumptions (Per Unit)	Source
CDS GPTs	Variable[a]	MUSIC Estimate
Enviss Treatment System	$2000 per unit	Personal Communication with Rocla (http://www.rocla.com.au/Products.php?id=27)
Stormwater Diversion Systems	$75,000 per unit	CWW (2012)
Underground Storage Tanks (Concrete)	$767 per kL	Gurung et al. (2012)
Reticulation Systems (PVC Pipes)		Sharma et al. (2006)
D 225	$325 per meter	
D150	$270 per meter	
D 100	$225 per meter	
Control Systems	$30,000	CWW (2012)
Pumping Systems	Variable[b]	Swamee and Sharma (2008)

[a]*Each stormwater harvesting site had different GPT cost based on catchment characteristics used in MUSIC [Refer Taylor (2005b for details)]*
[b]*The pumping cost estimation for each site is explained in Appendix 4D*

Table 4.24: Assumptions Used for Annual Maintenance Cost

Component	Annual Maintenance Cost Assumptions	Source
CDS GPTs	7% Capital Cost	MUSIC Manual
Enviss Treatment System	2% Capital Cost	Personal Communication with Rocla (http://www.rocla.com.au/Products.php?id=27)
Stormwater Diversion Systems	$1000 per unit	CWW(2012)
Underground Storage Tanks (Concrete)	$3000	
Reticulation Systems	$650	
Control Systems	1400	
Pumping Systems	2500	
Annual Electricity Cost	0.20$ per kW	
Education and Training	$2500	

Table 4.25 shows the estimation of LC for stormwater harvesting system at Flagstaff Park. The column I indicates per unit capital cost of a given stormwater infrastructure component, based on Table 4.23. The column II indicates the total capital cost of components, based on number of units and cost per unit considered. The column III shows the annual maintenance cost of various components based on assumptions listed in Table 4.24. The column IV indicates the NPV of capital costs using Equation 4.2 and 4.3 (Section 4.6.2.1) over the selected analysis period of 50 years. Additionally, NPV values in column IV were factored to include design and administration costs (15% of total capital cost in column II), and construction, project management, and contingency costs (30% of total capital costs in column II). The NPV values of annual maintenance costs were estimated (column V) using Equation 4.3 (Section 4.6.2.1).

The addition of column IV and V provided the total NPV of each component (column VI), which was then summed to obtain total infrastructure cost of the proposed Flagstaff Park stormwater harvesting system. Using Equation 4.3, NPV of supplied demand of Flagstaff Park was estimated (column VII). It should be noted that this demand is equivalent to estimated potable water savings (or volume of water supplied) from Flagstaff Park, which was determined through MUSIC modelling (Section 4.7.3).

The LC of Flagstaff Park was then estimated as \$10.8/kL considering the ratio of NPVs of total infrastructure cost and supplied demand (columns VI and VII) as described in Equation 4.4. This estimated LC should be seen as the preliminary cost estimate for the selected conceptual configuration (Section 4.6.1).

Table 4.25: Levelised Cost Estimation of Flagstaff Park (50 Years)

Component	Life[a]	No. of Units	Capital Cost Per Unit[b]	Capital Cost	Annual Operation Cost[c]	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	**$/kL**
	Column		I	II	III	IV	V	VI	VII	**VIII**
Stormwater Diversion Structure	80	2	75,000	150,000	2,000	224,250	35,955	260,205		
CDS GPT (Size - 55 m^3)	50	1	144,675	144,675	10,127	331,634	247,370	579,004		
Enviss Treatment System (1100 m^2 Treatment Area)	60	1100	2,000	2,200,000	25,280	3,588,000	862,917	4,450,917		
Underground Concrete Storage Tank (3000kL)	25	1	767/kL	920,400	3,020	4,431,945	54,292	4,486,237		
Stormwater Pipes (684 m Long PVC Pipe with 225mm diameter)	100	-	270/Meter	47,790	650	276,097	11,685	287,782		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems (Size-4.4 kW)	15	2	96857	193,714	5,000	522,932	89,887	612,820		
Cost of Annual Electricity Consumption (19008 kWh)	50	-	0.20/kWh	-	3800	-	68,314	68,314		
Education and Training			-		2500	-	44,944	44,944		
Total Infrastructure Cost ($)						9,475,950	1,440,533	10,916,483		
Supplied Demand (56 ML)									1007	
Levelised Cost ($/kL)										**10.8**

[a]*As per Table 4.17*
[b]*As per Table 4.23*
[c]*As per Table 4.24*

b) Annualised Removal Cost of pollutants (TP, TN, TSS)

As explained in Section 4.6.2.2, the ARC estimation of pollutants with respect to Flagstaff Park is based on determining the ratio of annualised NPV of the treatment system cost ($) and pollutant loads (Kg/year) generated from the catchment.

The pollutant loads were obtained from contaminant balance results (Table 4.22) and annualised NPV as per Equation 4.4. It should be noted that NPV of treatment cost was obtained by summing the NPVs of GPT costs and Enviss treatment system costs (column VI in Table 4.25).

Table 4.26 shows the ARC of pollutants TP, TN, and TSS as $1.4/Kg/year, $929/Kg/year, and $118/Kg/year respectively.

Table 4.26: Estimation of Annualised Removal Cost of Pollutants (Flagstaff Park)

Pollutants	Pollutant loads	Total NPV of Treatment	Annualised NPV of Treatment	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
Total Suspended Solids	70120	5,029,921	100,598	1.4
Total Phosphorus /yr	108.2			929
Total Nitrogen	851			118

4.7.5 Greenhouse Gas Emission Analysis Results

As described in Section 4.6.3, the GHG emissions from a given stormwater harvesting site was considered as the product of Victorian GHG Estimation Factor (1.21) and energy consumption from electric pumps in delivering the stormwater for irrigation at a given stormwater harvesting site.

Table 4.27 shows the estimation of GHG emissions of Flagstaff Park. The GHG emissions for Flagstaff Park were determined as 0.41 Kg CO_2/kL using Equation 4.6.

Table 4.27: Energy Consumption of Flagstaff Park (kWh)

Parameters	Value	Comment
Annual Pumping Hours	2160	As per Table 4.18
Pump Size - Single Pump	4.4	As per Section 4.7.2
Annual Energy Consumption of Single Pump, kWh	9504	As per Equation 4.9
Total Annual Energy Consumption of Two Pumps, kWh	19,008	-
Water Reuse, kL (Demand)	56000	As per Section 4.7.2
Energy Consumption per kL	0.34	As per Equation 4.8
Victorian GHG Estimation Factor, Kg CO_2/kWh	1.21	As per Section 4.6.3
GHG Emission (Kg CO_2 /kL)	**0.41**	As per Equation 4.7

4.7.6 Estimation of Social PMs

Table 4.28 shows the evaluation of social PMs for Flagstaff Park, considering the qualitative scales described in Section 4.4.3. The Flagstaff Park was rated very high in community acceptance (Table 4.2), as potential stormwater harvesting scheme would substitute 56 ML of potable water demand, thereby contributing to high sustainability. Similarly, Flagstaff Park was rated high in recreational value (Table 4.8) because of number of lawns, landscapes, tennis courts and bowling facilities.

Table 4.28: Quantification of Social PMs for Flagstaff Park

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Flagstaff Park	5	4	3

Table 4.29 shows the construction risk matrix for Flagstaff Park based on qualitative scales described in Table 4.3, 4.4, 4.5 and 4.6. As seen from Table 4.29, construction risks are primarily arising from service disruptions associated with neighbouring train station and, presence of heritage sites in terms of conserved flora and fauna. Considering the aggregated score of 12 (Table 4.29), the construction risks of Flagstaff Park can be categorised as moderate (Table 4.7) in Table 4.28.

Table 4.29: Construction Risk Matrix for Flagstaff Park

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Flagstaff Park	4	4	2	2	12

4.8 Performance Measures for All Alternative Stormwater Harvesting Sites

Based on the calculation explained for Flagstaff Park (Section 4.7), the economic, environmental and social PM values calculated for each selected alternative stormwater harvesting site (Section 4.3) are listed in Table 4.30. This matrix is used as the evaluation matrix in MCDA evaluation of stormwater harvesting sites (Chapters 5 and 6). Also, as stated earlier, detailed PM estimations of rest of alternative sites are documented in Appendix 4A.

Table 4.30: Evaluation Matrix used in the Current Study

Sites	Objectives								
	Economic	Environmental					Social		
	Performance Measures								
	Levelised Cost ($/kL)	Greenhouse Gas Emissions (Kg CO_2 / kL)	Potable water Savings (ML)	Annualised removal cost ($/Kg/Year)			Community Acceptance	Recreational Value	Construction Risks
				TSS	TP	TN			
Holland Park	15.3	0.20	18.5	4	2527	327	3	5	1
Birrarung Marr Park	15.5	0.17	15.1	0.9	580	81	3	3	2
Clayton Reserve	14.0	0.17	26.2	1.4	1,021	122	4	3	2
Princess Park	12.3	0.16	73	2.8	1,832	241	5	5	3
Flagstaff Park	10.8	0.41	56	1.3	929	118	5	4	3
Batman Park	22.3	0.18	5.7	1.6	1130	140	2	3	3
Ievers Reserve	21.4	0.18	5.7	1.1	772	95	2	3	1
Pleasance Gardens	27.2	0.17	5.6	3.3	2167	266	2	2	3

Although the evaluation matrix in Table 4.30 provides the brief information on performance of alternative stormwater harvesting sites in meeting economic, environmental and social objectives, it is difficult for decision maker to select the best stormwater harvesting site by analysing this diverse information presented in different units. For example, Batman Park and Ievers Reserve have relatively similar values for different PMs in Table 4.30. Furthermore, Holland Park and Birrarung Marr Park have similar economic PM value but different environmental and social PM values. Above examples highlight the importance of MCDA analysis for bringing rationality in decision making.

The evaluation matrix described in Table 4.30 was used in deriving the preferences of various stakeholders in Section 5.4, and later served as input to D-Sight, a PROMETHEE based software (Chapter 6). Thus, this evaluation matrix was the key component of the MCDA evaluation of stormwater harvesting sites.

4.9 Summary

The decision making process for stormwater harvesting initiates with a common goal of sustainability agreed upon by the stakeholders, and represented through different categories of objectives and performance measures (PMs). The set of performance measures can describe the alternative stormwater harvesting sites from economic, environmental and social perspectives. This chapter highlighted the development of performance measures and associated estimation methodologies in the context of the current study.

The study developed nine different performance measures (PMs) describing the performance of selected stormwater harvesting sites under economic, social, and environmental objectives. A literature review of different PMs used in stormwater harvesting was conducted, along with case study descriptions of selected alternative stormwater harvesting sites. As part of Multi Criteria Decision Analysis (MCDA) evaluation, the identified PMs served as the basis for comparing the performance of eight selected alternative stormwater harvesting sites, obtained from the GIS based screening methodology.

The PMs described under economic and environmental objectives were quantitative, while the PMs under social objectives were qualitative. For estimation of quantitative PMs, the study elaborated the role of conceptual designs and associated integration of stormwater harvesting system components, namely collection, storage, treatment and distribution. To estimate the economic and environmental PM values for selected stormwater harvesting sites, the conceptual design procedure used combination of different methodologies consisting of water balance modelling, cost analysis and Greenhouse gas emission estimation. The study also developed qualitative scale for quantification of social PMs and determined social PM values accordingly. The chapter demonstrated the estimation of economic, environmental and social PMs through one stormwater harvesting site selected in the study i.e. Flagstaff Park.

Finally, the results of PM evaluations on the eight stormwater harvesting sites were presented in the form of an evaluation matrix. Although, this evaluation matrix provides the performance of stormwater harvesting sites, it is difficult to select the suitable stormwater harvesting site from this matrix, considering differences in magnitudes and units of different PMs. However, information presented with this matrix can be better analysed using a MCDA methodology and associated software. The present study uses the evaluation matrix as key input in decision analysis using the PROMETHEE methodology and associated software D-Sight (Chapter 6).

Chapter 5: Elicitation of Stakeholder Preference Parameters: Methodology and Case Study Application

5.1 Introduction

As outlined in Section 2.6, the Multi Criteria Decision Analysis (MCDA) evaluation of stormwater harvesting initiates with a set of alternative stormwater harvesting sites, and a set of performance measures (PMs) describing the performance of sites from perceived economic, environmental and social objectives. Moreover, the alternative sites and PMs together form the evaluation matrix (or decision matrix) which can be used with any MCDA method, with additional information in form of 'preferences'.

Chapter 4 described the methodology for defining and deriving the PMs to assess the sustainable stormwater harvesting systems. However, stormwater harvesting is embraced to varying degrees by different stakeholders such as State Government, the water industry, and the community, and hence preferences diverge from different stakeholders on PMs. In this context, the current chapter describes the methodology adopted for deriving representative stakeholder preference parameters on PMs and the preference elicitation results obtained from various stakeholders. The preference elicitation on PMs is conducted to use these preferences in the assessment of stormwater harvesting system options through the selected MCDA method, PROMETHEE (Section 2.7.5).

The notion of 'preferences' or 'priorities' in MCDA methods is usually associated with the Decision Maker (DM), who seeks to compare and establish the ranking between the given set of alternatives or individual Performance Measures (PMs) defining the characteristics of alternative options (Öztürké et al., 2005). Thus, the concept of preference is paramount in the field of decision making and the methods that are to derive these preferences significantly influence the selection of best alternatives (Saaty, 2003). The current chapter focuses on deriving preferences on individual PMs in terms of preference functions and weights, which are integral requirements of the PROMETHEE method (Section 2.8).

Preference elicitation in MCDA methods is always complex due to multiple sources of uncertainty (Kodikara et al., 2010). The preferences of DM are often not well shaped (i.e. subjective), lying in vague zones of uncertainty and half held beliefs and convictions (Roy, 1993). Additionally, preferences can vary with information presented to the DM and precise time of questioning. Moreover, in case of multi stakeholder environment, each DM may have his/her own set of preferences on system objectives/PMs/alternatives and there is a fair possibility of disagreements (Roy, 2005). Therefore, Brans (2002) strongly argued that the real-world decision-making should include the freedom space defined by the DM, considering his/her real world experience, hesitations and emotionality.

As pointed out in Section 2.7.2, the utility methods like Multi Attribute Utility Theory (MAUT) and Utility Theory Additive (UTA) force optimum solution on DM assuming his/her preferences as perfectly consistent. Moreover, these methods do not consider incomparability between alternatives as they provide absolute rankings for a given decision problem. Contrastingly, the outranking methods such as PROMETHEE and ELECTRE allow such incomparability between alternatives by obtaining preferences on set of PMs, which are further used in ranking of the alternatives. In this study, preferences elicitation consists of obtaining preference parameters (i.e. weights and preference functions) on each PM, as a requirement for the outranking method PROMTHEE.

This chapter first outlines the importance of stakeholder participation in urban water management in the context of stormwater management. Then, the chapter focuses on the stakeholder preference information required in analysing the decision problem of assessing and ranking the stormwater harvesting sites using PROMETHEE and associated D-Sight commercial software. The chapter then reviews the available preference elicitation methods for outranking methods (PROMETHEE) and describes the theoretical aspects of the selected methods (that are used in this study) to derive the preference functions and weights in detail. Then, the chapter highlights the selection of stakeholder participation method (i.e. workshop) and associated selection of stakeholders for the case study. Further, the chapter elaborates the detailed workshop methodology adopted for deriving preference parameters from four distinct stakeholder groups. The results obtained from preference elicitation from each stakeholder group are then explained. Finally, the chapter summary is presented.

5.2 Stakeholder Participation in Stormwater Management Decision Making

In recent years, there has been a significant growing trend in the discipline of water resources management towards policy making and planning processes, that require ongoing active engagement and collaboration between stakeholders, scientists and decision makers (Voinov and Gaddis, 2008). Many studies in the literature have highlighted the well established fact that stakeholder participation can effectively contribute to successful sustainable stormwater management (Barbosa et al., 2012; Mankad and Tapsuwan, 2011; Sharma et al., 2012). Few significant perceived benefits of stakeholder participation include; opportunity to make better decisions, better acceptance and sense of social justice to the community (Kaplowitz and Lupi, 2012; Ross and Powell, 2008).

In terms of addressing the sustainability issues, the models containing social, economic and environmental impacts as well as hydrologic analysis are widely accepted by the stakeholders (Leach et al., 2002). In such context, Water Resources Planning and Management Division of ASCE proposed 'Shared Vision Modelling' approach in 1998 (Palmer, 2000). According to Palmer (2000), shared vision models are computer models, which work on three distinct principles, i.e. i) multi-objective planning, ii) structured public participation, and iii) collaborative modelling. These models require active participation of stakeholders, water managers and water planners to evaluate the water systems considering social, economic, and environmental impacts. Similarly, the European Union (EU) developed a policy named Water Framework Directive (WFD) in 2000, which considered economic, environmental and ethical issues in water management at the river basin level considering Integrated Water Resources Management (IWRM) principles of stakeholder participation (De Stefano, 2010; Europian Comission, 2000).

In the context of stormwater harvesting, reuse and management, Alexander (2011) conducted a social survey investigating the safety, public acceptance, economics and environmental impacts of alternative options for stormwater reuse in South Australia. Alexander (2011) highlighted that any introduction of indirect potable reuse schemes should include effective communication processes with community to learn more about the benefits and risks of systems with assurance of affordable costing. The author also concluded that for better utilization of stormwater-based water supplies, it is vital to involve the stakeholders (namely water utilities, local and state governments, and the media), who would manage, use and report on water supplies.

Kaplowitz and Lupi (2012) collected stakeholder preferences through a survey, to learn about community preferred alternative best management practices (BMP) for stormwater water management, BMP combinations likely to be supported by local stakeholders, and strategies for improving public participation in watershed management decision making for Sycamore Creek in Michigan, USA. The survey results revealed that stakeholders explicitly prefer some BMPs over the others (e.g. filter strips over wetlands) and the extent of application of each BMP in the watershed plan clearly influences preference levels.

Stakeholder participation was also crucial in the study conducted by Brown and Farrelly (2008), where respondents identified the drivers and barriers for adopting the stormwater technologies. The survey conducted across 800 urban water professionals revealed that community perceptions, environmental outcomes, social amenity and public health outcomes were all perceived as encouraging factors in the adoption of stormwater technology. However, they pointed out that the institutional regulations, costs and approval delays remained major barriers in implementing the technologies. The study stressed that the credibility and the role of government institutions and regulatory frameworks were critical to the implementation of water recycling schemes.

In Australia, sustainable stormwater management is based on 'Water Sensitive Urban Design' (WSUD) principles as explained in Section 1.1. In this context, Lloyd et al. (2002) suggested that WSUD design often needs a multidisciplinary team of professional experts in urban planning, landscape architecture, engineering hydrology and hydraulics, environmental science, aquatic ecology and water resource management individually. They further claimed that successful stormwater management schemes require commitment and collaboration between WSUD designer team and key stakeholder groups (i.e. council, local water authority and the community).

5.3 Input Data Requirement for PROMETHEE/D-Sight

As described in Section 4.9, the evaluation matrix consisting of a set of 9 PMs described the overall system performance of stormwater harvesting sites under economic, environmental and social objectives. Also, as justified in the literature review (Section 2.7.5), PROMETHEE was selected as the MCDA method for ranking of stormwater harvesting sites. In terms of preference elicitation, PROMETHEE clearly specifies two sets of information (i.e. preference parameters) from the DM.

1. Preference Function - The DM is requested to specify their preferences on a given PM in terms of certain threshold values and from that information, preference functions (PFs) are derived for each PM in PROMETHEE format. The PF concept is already explained in detail in Section 2.8.

2. Weights – The DM is asked to specify the relative importance of PMs through various available weighting methods and thus weights on each PM are obtained.

As highlighted in Section 2.7.5, the D-Sight software used in the study, enables user to input these preference functions and weights through a simple graphical interface.

In the current study, to obtain the PF information, the stakeholders were directly asked to specify the preference thresholds on respective PMs. In a similar way, weights were also derived from the stakeholders with the specific format of the Analytical Hierarchy Process (AHP) method. A brief description on preference elicitation for outranking methods/PROMETHEE in general is explained in the next section.

5.4 Preference Elicitation for Outranking/PROMETHEE Methods

Preference elicitation for a given MCDA problem can be derived using direct or indirect methods depending on the properties of the MCDA method. In direct methods, the DM can directly specify information on preference parameters, while in indirect methods, the DM provides information regarding some alternatives/PMs considering his/her knowledge of the decision problem, and from this information the values of preference parameters can be inferred. Fundamentally, the type of information sought (quantitative, qualitative or conceptual/causal) dictates the selection of the direct or the indirect method, and constrains the choice of appropriate techniques in designing an elicitation procedure (Krueger et al., 2012). In this study, a combination of a direct approach for elicitation of preference functions and an indirect approach for elicitation of weights was used to derive the required information on preference parameters.

5.4.1 Preference Functions

As explained in Section 2.8.1, PFs signify the relative importance of one alternative over another with respect to the PM under consideration. Also, as explained in Section 2.8, to specify the PFs, the DM needs to define the preference threshold (p), indifference threshold (q) or Gaussian threshold (s) for the PM. In PROMETHEE, these thresholds aim at modelling the preferences of the DMs realistically which gradually increase from indifference to strict preference while comparing the alternatives on the given PM (Haralambopoulos and Polatidis, 2003). Estimation of PF threshold values requires a significant subjective input by the DMs which in turn brings the uncertainty in the MCDA model.

There is very little literature available in elicitation of preference thresholds (p, q, and s) and deriving the preference functions for outranking methods. It is also recognized in the literature that DMs may encounter difficulty in selecting the generalized criterion functions and their associated parameters (Salminen et al., 1998). In this regard, Rogers and Bruen (1998) proposed a comprehensive approach for specifying realistic limits for p and q within the context of an environmental impact assessment (noise reduction problem), where uncertainty in human opinion was taken into account. They also argued that *p* and *q* need to be chosen in a rational and defendable manner, and be explicitly estimated, rather than obtaining the arbitrary values.

Similar views were echoed by Podvezko and Podviezko (2010), who suggested that for making careful choices of preference functions and associated parameters, active participation of concerned DMs or qualified specialists is mandatory to model the preferences accurately. However, in cases where some of the DMs are general community or non specialists, the preference elicitation process needs to be designed carefully in order to model the preference parameters as accurately as possible. Such an approach of handling the preferences of non experts has been demonstrated by Kodikara et al. (2010), in assessing the performance of Melbourne water supply system in Australia.

Despite highlighting the importance of preference functions parameters and associated uncertainty, there is no formal approach mentioned in literature for elicitation in determining the preference thresholds and associated functions (Kodikara et al., 2010). Most of the studies employ the direct method of asking DM to specify the appropriate PF and associated thresholds (Mutikanga et al., 2011; Silva et al., 2010). In the current study, such direct approach was applied in elicitation of the preference function parameters from the stakeholders and it is explained in detail in Section 5.6.1.

5.4.2 Weights

The elicitation of meaningful weights is an utmost important step for any MCDA method as weights directly reflect the DMs preferences on attributes of the decision problem (Pomerol and Barba-Romero, 2000). Weights in compensatory aggregation methods (e.g. weighted sum) reflect the capacity for trade-off between the PMs, while weights in non-compensatory methods (e.g. outranking methods) describe the relative importance of PMs (Pomerol and Barba-Romero, 2000; Rowley et al., 2012).

From mathematical perspective, weights can be expressed as either ‘cardinal’ or ‘ordinal’ in nature. Weights are said to be ordinal if only their ranking is meaningful (e.g. PM is ranked as largest, second largest etc.) and ‘cardinal’ if their exact numerical value plays a role (Pomerol and Barba-Romero, 2000). In the cardinal approach, numerical weights are elicited using pre-determined scale (e.g. 0 to 1). In PROMETHEE methods, weights need to be derived on cardinal scale to reflect the importance of PMs.

There are several methods available in the literature for elicitation of weights in the MCDA context. Some of these methods are direct elicitation methods, entropy methods (Zeleny, 1982), Simple Multi Attribute Rating Techinque (SMART) / SWING (Von Winterfeldt and Edwards, 1986), Revised Simo (Figueira and Roy, 2002) and Analytical Hierarchy Process (AHP) (Saaty, 1980). Details of these methods can be found in Pomerol and Barba-Romero (2000).

In the direct elicitation methods, the decision maker directly assigns weight values intuitively. The best example of direct elicitation methods is a simple ranking method, where the decision maker specifies the order of his/her preference, and weight is derived from normalisation of the ranks. In entropy methods, weights are determined by measuring the dispersion between PM values in the evaluation matrix, without actual involvement of decision maker. The PM with higher weight has more discriminating power between the alternatives (Zeleny, 1982).

SMART and SWING are simple forms of Multi Attribute Utility Theory (MAUT) methods (Section 2.7.2), where PMs are weighted using the weighted linear averages in form of utility functions (Laia et al., 2008). There have been many improvements/variants of SMART methods as SMARTER and SMARTS (Von Winterfeldt and Edwards, 1986).

The Revised Simo Procedure consists of associating a ‘playing card’ with each PM in the decision problem. The DMs are asked to rank these cards from the least important to the most important, reflecting the order of PM importance (Figueira and Roy, 2002). The ordinal preferences (obtained from card rankings) are subsequently converted to numerical weight values to represent the relative importance of PMs. The Revised Simo procedure has been extensively applied in eliciting the weights in the studies, especially based on outranking methods (Cavallaro, 2010; Kodikara et al., 2010; Shanian et al., 2008).

Among the aforementioned various weighting methods, AHP enables weight elicitation in a systematic way, breaking the complex decision problem into a hierarchy of objectives and PMs. Weights on PMs are derived through this hierarchy so that the output result (i.e. scores on alternatives) is a multi-level weighted sum (Pomerol and Barba-Romero, 2000). The AHP method was developed by Saaty (1980), which does pair-wise comparisons of alternatives/PMs to elicit the weights. Precisely, the weights derived from the AHP are the eigenvectors obtained from the pair-wise comparison matrix of hierarchical elements (objectives/PMs).

The hierarchical property of AHP has an important advantage as it provides better overview of the decision problem, decomposing into its constituent parts (e.g. objectives/PMs), which in turn can again be subdivided into smaller parts (e.g. sub-PMs). Macharis et al. (2004) strongly recommended the combination of PROMETHEE with AHP considering the ability of AHP in the context of decision-making hierarchy and the determination of weights. The concept of PROMETHEE-AHP hybrid approach was also supported by Behzadian et al. (2010), who suggested that the approach can contribute to a more realistic and promising practical decisions than the stand-alone application of the PROMETHEE.

There have been numerous studies where AHP has been combined with PROMETHEE for weight evaluation. Such combined approach has been used in ranking of municipal solid waste treatment alternatives (Herva and Roca, 2013), manufacturing equipment selections (Dağdeviren, 2008), selecting information technology projects (Wang and Yang, 2007), forest area site selection (Kaya and Kahraman, 2011), prioritizing environmental policies for sustainable fleet vehicles (Turcksin et al., 2011), and ranking of business enterprises (Babic and Plazibat, 1998). In all these studies, the final ranking of alternatives was done by PROMETHEE and weightings of PMs were determined separately by the AHP method.

Thus, considering the aforementioned benefits of AHP and PROMETHEE combination, the current study used the AHP method for weight elicitation for deriving the weights on PMs. The theoretical aspects of the AHP methodology are discussed in detail in Appendix 5A.

5.5 Selection of Stakeholder Participation Method for the Study

Selection of the suitable stakeholder participation method for any project is always constrained by multiple factors, such as time available (to use such methods), human resources and associated costs. Moreover, perceived objectives and goals often play a critical role in selecting the appropriate stakeholder participation method (Voinov and Bousquet, 2010). Therefore, the major challenge in stormwater management is to identify the most relevant public participation method(s) to use, keeping the process simple and cost effective (Taylor, 2005).

As per detailed literature review conducted by Van Asselt Marjolein and Rijkens-Klomp (2002), the commonly applied participatory methods include: focus groups, citizens' juries, scenario workshops, consensus conferences, participatory modelling and participatory planning. The common approach for stakeholder participation methods consists of recruiting members of organized groups (stakeholders) to represent a range of interests and seek consensus among these groups for desired objectives (Larson and Lach, 2008).

Taylor (2005) provided a detailed review of stakeholder participation methods in the context of MCDA assessment of stormwater projects. Figure 5.1 provides the summary of stakeholder participation methods documented by Taylor (2005) considering basic, intermediate and high level of MCDA assessment.

According to Taylor (2005), the high level participatory methods such as Citizens' Juries and Consensus Conferences, have the ability to explore a stakeholder views on given decision problem without significant financial investment. Furthermore, Taylor argued that these methods when coupled with MCDA methods can be highly valuable tools to explore the financial, social and ecological costs and benefits in qualitative and/or qualitative terms. On a similar note, Kallis (2006) pointed out that a hybrid approach of MCDA with other participatory methods such as workshops can be highly effective for water management decision aid. However, the high level participatory methods (Figure 5.1) require significant cost and time investment and hence, were not used in the current study.

The workshop method (intermediate level) listed in Figure 5.1 is commonly designed for resolving conflicting issues or obtaining consensus from a group of invited DMs/experts/ stakeholders within short timeframe. It typically involves group discussion or brainstorming or feedback over a concerned problem. For example, in terms of stormwater harvesting, the workshop can assist in prioritizing the conflicting objectives or policies from different stakeholders such as Government, community and water authority.

A neutral facilitator needs to be present to moderate the discussions and keeping participants interested. The facilitator or organizing technical expert should explain the context of the problem through the presentations followed by supplementary documents. Depending on type of the problem, sub-groups can be formed with additional facilitators

	LEVEL OF ASSESSMENT FOR THE STORMWATER PROJECT		
	High	**Intermediate**	**Basic**
Multi Criteria Analysis (MCA) details:	Process undertaken by a group of representative citizens who are likely to act for the broader public good with input from relevant 'experts' (e.g. technical experts, representatives from traditional stakeholder groups and directly affected citizens with strong self-interests).	Process undertaken by a group of technical 'experts' with *consultation* involving community stakeholders (e.g. traditional stakeholder groups and directly affected local citizens).	Process undertaken by one stormwater manager with basic *consultation* involving technical 'experts' and other stakeholders (e.g. traditional stakeholder groups and directly affected local citizens).
RELEVANT PUBLIC PARTICIPATION METHODS	**Relevance**		
1. Consensus Conference	✓	×	×
2. Small Deliberative Panel (i.e. a scaled-down Citizens' Jury/Panel)	✓	×	×
3. Fishbowl	✓	~	×
4. Deliberative Opinion Poll	✓	×	×
5. Expert Panel	✓	✓	~
6. Delphi Study	✓	✓	✓
7. Workshop	~	✓	✓
8. Public Meeting	~	✓	✓
9. Public Conversation	~	✓	✓

Figure 5.1: Stakeholder Participation Methods for MCDA Assessment of Stormwater Projects (Source: Taylor et al. 2005)

The workshop method can serve as a simple and a quick consultation process, offering group discussions and group learning. Considering this advantage, the workshop method was selected as the stakeholder participation method for the current study. The workshop method deemed suitable as the study required stakeholder preferences on stormwater harvesting sites under limited resources in terms of cost and time. The details of the workshop methodology used for the current case study are documented in the next section.

5.6 Preference Elicitation Modelling Methodology - Case Study

As highlighted in the concluding remarks of Section 5.2, successful stormwater management schemes often need effective contribution of key stakeholder groups such as local government (City Councils), local water authority and the community. Each of these stakeholder groups may have different perspectives on stormwater harvesting objectives, and hence it is essential to account the varied stakeholder preferences on stormwater harvesting systems.

Given the context of the current study, it was difficult to define a single absolute decision maker for stormwater harvesting decision making. Moreover, in the case of the present study area, the water authority City West Water (CWW) provides the preliminary recommendations for developing stormwater harvesting schemes to the City Council of Melbourne (CoM). These recommendations are then subjected to mutual deliberations within associated water managers, council engineers, funding agency and government body.

Considering this complexity in multi-stakeholder decision making, the current study considered four key stakeholder groups namely, Water Authorities (WA), Academics (AC), Consultants (CS), and Council (CL) to reflect the diverse views on stormwater harvesting decision making. As pointed out in concluding remarks of Section 5.2, water authorities and councils constitute the key stakeholders in stormwater harvesting decision making, and therefore represented by WA and CL groups in current study. The community, one of the other important stakeholder groups (Section 5.2) was not exclusively considered in this research due to time and funding resource restrictions. However, the WA group was assumed to have a fair knowledge on community perceptions in CoM. Additionally, the AC group represented the stormwater harvesting preferences from research perspective with sound theoretical knowledge of stormwater harvesting systems. Furthermore, the CS group represented the stormwater harvesting opinions from industry perspectives. The inclusion of this group was done considering the practical fact that water authorities often consult private consultants for designing the stormwater harvesting schemes. By gathering the preference parameter information from each of these stakeholder groups, it was possible to study the decision making attitudes from each stakeholder groups on stormwater harvesting systems.

To gather the stakeholder preferences, a half day workshop was organized by inviting several experts from representative groups of WA, AC, CS and CL. The workshop was conducted in the first week of December 2012. Preference parameter information was gathered as per requirement of the PROMETHEE method (i.e. weights and preference functions) from all participated stakeholder groups.

The selection of participants for the workshop was conducted on the basis of inviting the known contacts (and their acquaintances) from the water industry, research universities, councils, and private stormwater consultancies. The water managers from different water utilities formulated the WA group. Likewise, academics, with major research focus as stomwater were shortlisted to represent the AC group. Similarly, consultants were invited from stormwater industry to form the CS group to reflect the industry perception on stormwater harvesting. Finally, the stormwater managers from different city councils were invited to represent the CL group. All invited stakeholder groups were assumed to be well conversant with the definitions of Triple Bottom Line (TBL) objectives (Section 4.2) and PMs considered in the study (Section 4.4) in relation to stormwater harvesting systems.

A personalized invitation email was sent to the thirty (30) different expert professionals selected from representative groups, describing the purpose of the workshop providing also the associated project background information. Although twenty-five (25) people confirmed their attendance, only twelve (12) people attended the workshop. Such problem of low attendance rate is well known disadvantage of the workshop method

(Taylor, 2005). However, among workshop attendees, four (4) consultants, three (3) water authority personnel, three (3) academics and one (1) council stormwater manager represented the CS, WA, AC and CL stakeholder groups respectively. It should be noted that only a single person represented the CL group. Preferences obtained from such a single representative can be subjective. However, this representative of the CL group was from City of Melbourne (CoM) and was assumed to have a reasonable knowledge on CoM policies on stormwater harvesting. The case study considered in this study evaluated and ranked stromwater harvesting sites in CoM.

During the workshop, a brief presentation was carried out describing the project background and PROMETHEE concepts of preference functions and weights. Additionally, the participants were briefly introduced to the Analytical Hierarchy Process (AHP) method for elicitation of weights. Moreover, participants were provided with additional information in the form of a separate document, describing basic concepts of preference function and weights, as required by PROMETHEE. This document is shown in Appendix 5B. Additionally, the responses of all participants were recorded on templates, designed to suit the specific format of PROMETHEE and AHP. These templates are also shown in Appendix 5B.

5.6.1 Survey Methodology- Preference Functions (PFs)

As explained earlier in Section 5.4.1, the preference level of one alternative over another for a particular PM can be expressed by a PF. At the workshop, it was aimed to obtain the PF for each considered PM (from each participant in each group). Since the stakeholder group representatives were well conversant with the definitions of PMs, it was assumed that the workshop participants had a fair knowledge about the associated feasible range of PM values within the statutory requirements needed for PF evaluation. Thus, deriving the PF was considered to be quite straightforward for all stakeholder groups.

5.6.1.1 General Approach for Assignment of PFs

As described in Section 2.8.1, there are six different types (Type I, II, III, IV, V and VI) available in PROMETHEE for describing the preferences. These preferences functions are represented through preference thresholds namely p, q and s (Section 5.4.1).

During PF elicitation, participants were requested to specify the *p* and *q* values of Type V function directly for the quantitative PMs. For qualitative PMs, participants were advised to use Type I or IV function as suggested by PROMETHEE authors. In specifying the *q* value, the workshop participants were requested to consider the maximum difference in PM value until they are indifferent between two alternative stormwater harvesting sites. Then, for obtaining the *p* value, the participants were asked to express a minimum difference in PM value beyond which they have strong preference of one alternative site over the other in terms of the considered PM.

This approach of specifying direct *p* and *q* values of Type V or IV function avoided the complexity of selecting PF from six available different PF types. Moreover, the PF Types II, III, and I are the variants of Type V function and hence can be derived from Type V function. Also, it should be noted that the Type VI function (with *s* threshold parameter) was not used in this study due to its complex nature.

The PF evaluation on nine (9) PMs (Section 4.9) was done for two separate cases, from all participants of WA, AC, CS and CL groups. These cases were:

- Case 1: Assignment of PFs given the ranges of PMs
- Case 2: Assignment of PFs given the evaluation matrix

5.6.1.2 Assignment of PFs Given Ranges of PMs (Case 1)

Under this case of PF assignment, the participants in the workshop were provided with a questionnaire table (Table 5.1) consisting of the ranges of values of PMs derived from the conceptual designs of eight shortlisted stormwater harvesting sites (obtained from GIS analysis) of the case study area. The same table additionally consisted of mean representative values of each quantitative PM derived from eight alternative stormwater harvesting sites. The participants were required to specify the appropriate *p* and *q* values (preference and indifference thresholds) for each PM considering these ranges and mean values (Table 5.1).

Table 5.1: Assignment of PFs on Ranges of PMs (Case 1)

Objectives	Performance measures	Unit	Max or Min	Range of values	Mean	q	p
Economic	Levelised Cost (LC)	($/ kL)	Min	10.8-27.2	17.4		
Environmental	Green House Gas Emissions (GHG)	(Kg CO_2 /kL)	Min	0.16-0.41	0.20		
	Potable Water Savings (PWS)	ML	Max	5.6-73	25		
	Annualised Removal Cost (ARC) of TSS	($/ Kg/Year)	Min	0.9-4	2.0		
	ARC of TP	($/ Kg/Year)	Min	580-2527	1370		
	ARC of TN	($/ Kg/Year)	Min	81-327	174		
Social	Community Acceptance (CA)	-	Max	1-5	-		
	Construction Risks (CR)	-	Min	1-5	-		
	Recreational Values (RV)	-	Max	1-5	-		

The PF values derived in Case 1 represented the preferences of WA, AC, CS, and CL sub-groups without knowing the performance of individual alternative stormwater harvesting sites in the original evaluation matrix (Section 4.8). These preferences are therefore, not exclusively limited to the present case study and thus will be based on general stormwater harvesting knowledge of participants. Moreover, as alternative site names were not considered in this case, the derived preferences in Table 5.1 avoided the introduction of bias for known alternative sites.

5.6.1.3 Assignment of PFs Given Evaluation Matrix (Case 2)

For this case, the workshop participants were provided with a questionnaire table (Table 5.2) consisting of the evaluation matrix. As explained in Section 4.8, the evaluation matrix described the performance of the eight stormwater harvesting sites in terms of different PMs. Similar to Case 1, the preference thresholds (i.e. bold p and *q* values in Table 5.2) were obtained for each PM from all participants. The only difference in Case 2 was preference thresholds were obtained considering the actual performance of PMs in known alternative decision matrix. Additionally, the names of alternative sites were given in Case 2.

The PF values obtained from Cases 1 and 2 allowed basis to check consistency of preferences threshold values with and without evaluation matrix respectively. Consequently, the preferences obtained from both cases were used in ranking of stormwater harvesting sites and robustness assessment (Section 6.3).

Table 5.2: Assignment of PFs on Evaluation Matrix (Case 2)

Sites	Objectives								
	Economic	Environmental					Social		
	Performance Measures								
	Levelised Cost ($/kL)	Greenhouse Gas Emissions (Kg CO_2 / kL)	Potable water Savings (ML)	Annualised removal cost ($/Kg/Year)			Community Acceptance	Recreational Value	Construction Risks
				TSS	TP	TN			
Holland Park	15.3	0.20	18.5	4	2527	327	3	5	1
Birrarung Marr Park	15.5	0.17	15.1	0.9	580	81	3	3	2
Clayton Reserve	14.0	0.17	26.2	1.4	1,021	122	4	3	2
Princess Park	12.3	0.16	73	2.8	1,832	241	5	5	3
Flagstaff Garden	10.8	0.41	56	1.3	929	118	5	4	3
Batman Park	22.3	0.18	5.7	1.6	1130	140	2	3	3
Ievers Reserve	21.4	0.18	5.7	1.1	772	95	2	3	1
Pleasance Gardens	27.2	0.17	5.6	3.3	2167	266	2	2	3
q									
p									

5.6.2 Survey Methodology – Weights

As described in Section 5.4.2, the Analytical Hierarchy Process (AHP) method was selected as the suitable weighting method for obtaining the weights on objectives and PMs defined for the study (Section 4.3 and 4.4). During this weight elicitation process, the participants from each representative group of WA, AC, CS, and CL were requested to provide the information on the relative importance of objectives and relative importance of PMs, on pair wise comparison scale of 1-9. This scale was suggested by the AHP author Saaty (2004) and it is shown in Table 5.3. Briefly, one (1) denotes the equal importance of PM over the other and nine (9) stands for the extreme importance of one PM over the other. The reciprocal values in Table 5.3 signify the lower importance of one PM over the other. More detail interpretation of AHP scale (Table 5.3) is described in Appendix 5A.

Table 5.3: AHP Pair-Wise Comparison Scale

Scale	Relative importance	Scale	Relative importance
1	Equal		
3	Moderately important	1/3	Moderately less important
5	Strongly important	1/5	Weakly important
7	Very Strongly important	1/7	Very weakly important
9	Extremely important	1/9	Extremely weak
2, 4, 6, 8	Intermediate values	1/2, 1/4, 1/6, 1/8	Intermediate reciprocal values

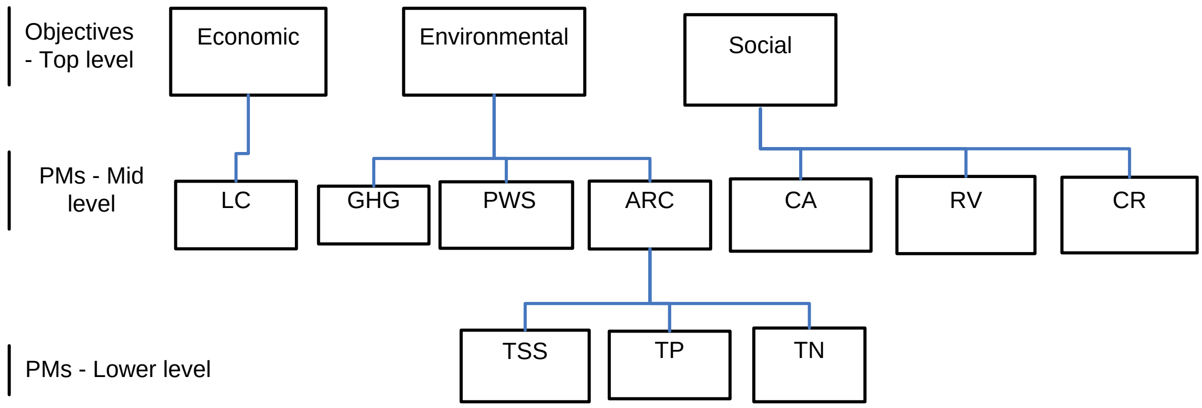
The pair wise comparison responses recorded from all participants (based on Table 5.3) were further analysed with 'EXPERT CHOICE', an AHP methodology based software, to compute the final weights. The brief details of EXPERT CHOICE are also documented in Appendix 5A.

The section below describes the step by step weight evaluation procedure used in the study.

Step (1) - Problem Structuring

As detailed earlier in Section 4.3, the study represented sustainability in terms of economic, environmental and social objectives and 9 different PMs under these objectives. The AHP provided a systematic way to organize these objectives and PMs into a hierarchy. Figure 5.2 describes the hierarchy of PMs under objectives defined for this study.

The top level in Figure 5.2 described the economic, environmental and social objectives representing the sustainability of stormwater harvesting systems. The mid level represented the PMs categorised under the top level objectives. The bottom level represented sub-PMs (TSS, TP and TN) under Annualised Removal Costs (ARC), which was one of the environmental PMs. The weights were estimated across all levels of this hierarchy in Step (3).



- *LC: Levelised Cost*
- *GHG: Green House Gas Emission*
- *PWS: Potable Water Savings*
- *ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)*
- *RV: Recreational Value*
- *CA: Community Acceptance*
- *CR: Construction Risks*
- *TSS: Total Soluble Solids,*
- *TP: Total Phosphorous*
- *TN: Total Nitrogen*

Figure 5.2: Hierarchy of Objectives, PMs and sub-PMs

The AHP method allows such pair wise comparisons to be made in any random sequence, or in a top-down or bottom-up order (Webber et al., 1997). For the present work, the workshop participants followed bottom-up order, starting with bottom level of hierarchy (Table 5.4) to the top level of objectives (Table 5.7).

Each representative stakeholder participant belonging to WA, CS, CL and AC groups was requested to perform pair wise comparison of the four tables (i.e. Table 5.4 to 5.7) using 1-9 Scale shown in Table 5.3. The pair wise comparison values specified by one participant belonging to consultant sub-group (CS-2) are shown in Table 5.4-5.7 as a demonstration.

Table 5.4: Pair Wise Comparison of Environmental Sub-PMs

	TSS	TP	TN
TSS	1	3	2
TP		1	1/2
TN			1

Table 5.5: Pair Wise Comparison of Environmental PMs

	GHG	PWS	ARC
GHG	1	1/7	1/2
PWS		1	3
ARC			1

Table 5.6: Pair Wise Comparison of Social PMs

	CA	CR	RV
CA	1	1/2	2
CR		1	3
RV			1

Table 5.7: Pair Wise Comparison of System Objectives

	Economic	Environmental	Social
Economic	1	3	2
Environmental		1	1/2
Social			1

Similar to CS-2 pair wise comparisons shown above, all participants were requested to fill only upper triangular part of the matrix for all pair wise comparisons. These responses are shown in Appendix 5C. The lower part of matrix is the reciprocal of the upper triangular part of the matrix, and hence derived automatically from the responses of participants. During this pair wise comparison, it was ensured that all participants were comfortable in understanding the concept of AHP scale.

Step (3): Estimation of Weights through EXPERT CHOICE (EC)

The pair wise comparison judgements of the participants obtained from Step (2) were served as input to EXPERT CHOICE (EC), an AHP based software to facilitate the weight analysis. As described in Appendix 5A, EC calculates the principal eigenvectors of given pair wise comparison matrix to estimate the weights for that matrix. These weights were computed at all stages of hierarchy of objectives, PMs and sub-PMs for all stakeholder participant members of WA, AC, CS and CL groups. The detailed procedure of deriving weights from pair wise comparisons is described in Appendix 5A. The hierarchical representation of weights obtained from CS-2 is shown in Figure 5.3.

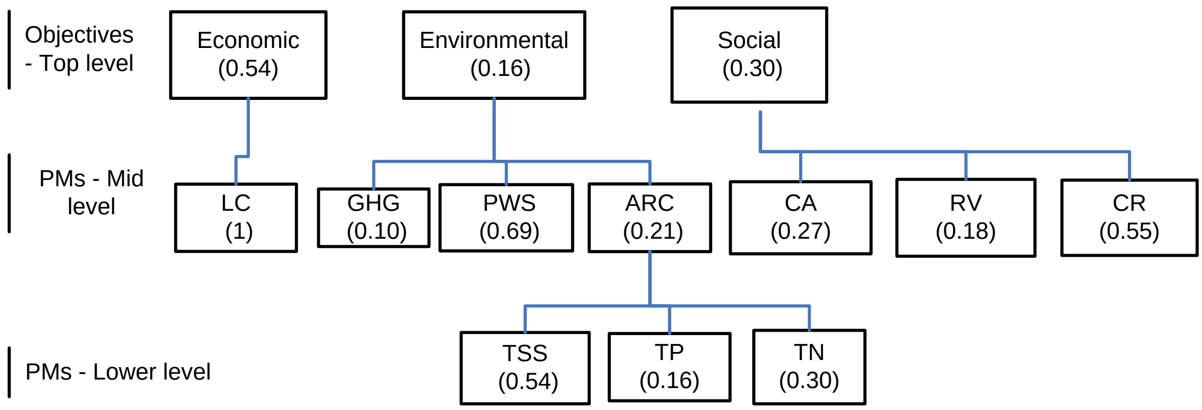


Figure 5.3: Hierarchical Representation of the Weights on PMs and Objectives Obtained from Participant CS-2

From Figure 5.3, it can be seen that the weights are established on all levels of hierarchy. It should be noted that the sum of weights at any given level of hierarchy is equal to one. Also, it can be seen that *LC* represented only PM under the economic objective and hence no pair wise comparison was done for *LC*. Consequently, *LC* had weight of 1. Moreover, the final weights on all PMs were estimated by multiplying the weights belonging to their parent PMs/ objectives at upper level hierarchy (Figure 5.3). For example, the final weight on TSS was estimated as

Final Weight of TSS = Weight on lower level of hierarchy

* Weight on mid level hierarchy (PM-ARC)

* Weight on top level hierarchy (Objective-Environmental)

= 0.54 * 0.21 * 0.16

= 0.018

Final weights (on PMs) as described above were obtained from all workshop participants of all stakeholder groups. These weights served direct input to the

PROMETHEE analysis in D-Sight software to facilitate the ranking of stormwater harvesting sites.

Step (4): Consistency Evaluation

As explained in Appendix 5A, this step did not directly contribute in estimation of weights, however, provided a logic based consistency check on responses of all participants obtained from the pair-wise comparison matrices. The EC software facilitated this consistency evaluation, providing the consistency check for every pair wise comparison made by each workshop participant belonging to WA, AC, CS and CL groups.

As described in Appendix 5A, EC measures consistency in a given pair wise comparison matrix with an index named ‘Consistency Ratio’ (C.R.). The judgement of a given DM is said to be consistent, when the pair wise comparison matrix specified by him/her has the C.R. value less than 0.1. In the current study, C.R. was estimated for all pair-wise comparisons for all participants. It should be noted that all pair wise comparisons in current study were found consistent with C.R. value less than 0.1. In case where, C.R. is greater than 0.1, the weights must be re-evaluated. For this purpose, feedback from associated stakeholders/DMs should be taken to obtain new values of consistent pair-wise comparisons.

5.7 Workshop Results: Preference Function and Weights

As described earlier, the responses obtained from the stakeholder group members were used in deriving the appropriate PFs and weights which served as input for PROMETHEE based analysis of ranking of stormwater harvesting alternative sites. The results of PFs and weights obtained from each stakeholder group of WA, AC, CS and CL are described in this section.

5.7.1 Results –Water Authority (WA)

a) Preference Functions

The PF parameters (i.e. *p, q)* derived from the responses of the WA group (both cases of preference function elicitation described in Section 5.6.1) are shown in Table 5.8. It should be noted that WA-1 and WA-2 provided identical preferences for both cases of PF evaluation after having mutual discussions. Moreover, WA-1 and WA-2 belonged to the same organization. However, WA-3 specified different values for preferences functions. Interestingly, all three WA group members had the same PF parameter values for Cases 1 and 2.

Table 5.8: Preference Function Parameters Derived from WA Group

WA	Case	PF	PM (Performance Measure)								
			Economic	Environmental					Social		
			LC	GHG	PWS	ARC			CA	CS	RV
						TSS	TP	TN			
WA-1	1	PF Type	V	V	V	V	V	V	I	I	I
		q	0	0	1	0	0	5	-	-	-
		p	0.5	0.1	5	0.1	0	0	-	-	-
	2	Same as Case 1									
WA-2	1	PF Type	V	V	V	V	V	V	I	I	I
		q	0	0	1	0	0	5	-	-	-
		p	0.5	0.1	5	0.1	0	0	-	-	-
	2	Same as Case 1									
WA-3	1	PF Type	V	V	V	V	V	V	IV	IV	IV
		q	1	0.2	5	0.2	100	30	0	1	0
		p	3	1	20	1	500	100	2	2	2
	2	Same as Case 1									

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)
- RV: Recreational Value
- CA: Community Acceptance
- CR: Construction Risks
- TSS: Total Soluble Solids,
- TP: Total Phosphorous
- TN: Total Nitrogen

b) Weight Elicitation

Pair wise judgements obtained from three members of WA group are reported in Appendix 5C. Table 5.9 provides the Consistency Ratio (C.R.) at each level of hierarchy for all three WAs. It can be seen that judgments specified by all three WAs are consistent as they are well within the acceptable limit of 0.10. Moreover, it should be noted that Cases 1 and 2 of preference function elicitation was not applicable to weight elicitation of WA group (and rest stakeholder groups) as pair wise comparison was done subjectively on basis of AHP scale.

Table 5.9: Consistency Ratio for WA Group Members

Hierarchical Level	Consistency Ratio		
	WA-1	WA-2	WA-3
Objectives	0	0	0
Environmental PMs	0	0.05	0
Environmental Sub PMs	0	0	0
Social PMs	0.05	0	0

The weights obtained from the pair wise judgements (Appendix 5C) of all three WA group members are shown in Table 5.10. This table provides detailed hierarchy of objective weights, intermediate PM and sub PM weights and final weights for all three WAs. These weights add up to 1 for given level of hierarchy.

Furthermore, Figure 5.4 provides plot of the final weights corresponding to each member of the WA group. Considering the average of final weights for three WA group members, *LC, PWS* and *RV* were emerged as top three PMs of priority.

Table 5.10: Weights on Objectives and PMs by WA Group

Objectives	PM	Sub-PM	WA - 1				WA - 2				WA - 3			
			Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight
Economic	LC		0.6	1		0.6	0.34			0.34	0.25	0.25		0.2
Environmental	GHG		0.2	0.3		0.06	0.33	0.25		0.08	0.25	0.08		0.02
	PWS			0.3		0.06		0.38		0.13		0.76		0.19
	ARC	TSS		0.4	0.78	0.06		0.37	0.43	0.05		0.16	0.77	0.03
		TP			0.11	0.01			0.14	0.02			0.11	0.01
		TN			0.11	0.01			0.43	0.05			0.11	0.01
Social	CA		0.2	0.3		0.06	0.33	0.34		0.11	0.5	0.4		0.2
	CR			0.2		0.06		0.33		0.11		0.2		0.1
	RV			0.5		0.09		0.33		0.11		0.4		0.2
Total			1			1	1			1	1			1

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)
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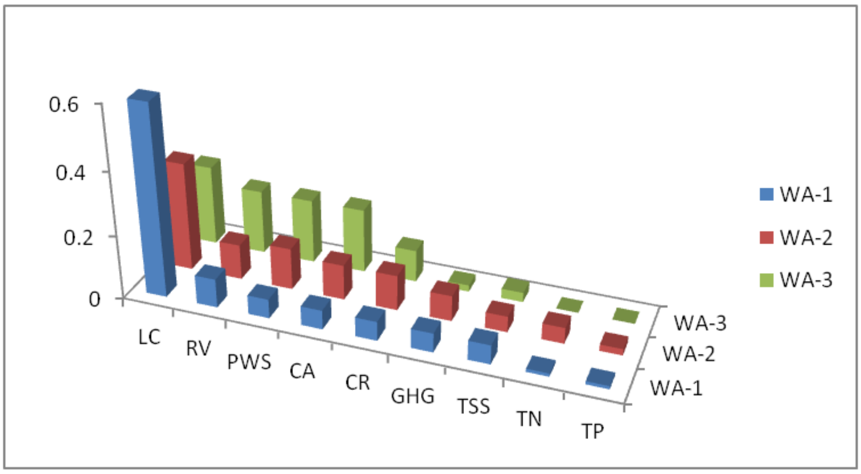

Figure 5.4: Final Weights of WA Group

5.7.2 Results - Academics (AC)

a) Preference Functions

Table 5.11 provides the information on the PF parameters (i.e. *p, q)* derived from the responses of the AC group for both cases of PF elicitation (Cases 1 and 2). Contrary to the WA group, each member in the AC group specified different sets of *q* and *p* values to the specified PMs for each case of PF elicitation. However, the member AC-2 had his/her preferences constant for both cases of PF elicitation.

Table 5.11: Preference Function Parameters Derived from AC Group

AC	Case	PF	Performance Measures								
			Economic	Environmental					Social		
			LC	GHG	PWS	ARC			CA	CS	RV
						TSS	TP	TN			
AC-1	1	PF Type	V	V	V	V	V	V	I	I	I
		q	0.2	0.1	5	0.1	25	10	0	0	0
		p	2	0.5	10	0.5	100	50	0	0	0
	2	PF Type	V	V	V	V	V	V	I	I	I
		q	2	0.4	5	0.25	100	20	0	0	0
		p	5	2	20	1	500	100	0	0	0
AC-2	1	PF Type	V	V	V	V	V	V	I	I	I
		q	0.1	0.5	1	0	0	0.1	0	0	0
		p	0.5	0.8	10	0.1	0	5	0	0	0
	2	Same as Case 1									
AC-3	1	PF Type	V	V	V	V	V	V	IV	I	I
		q	0.5	0.5	0.25	0.5	200	20	1	0	0
		p	1	2	1	1	500	50	2	0	0
	2	PF Type	V	V	V	V	V	V	IV	I	I
		q	0.8	0.4	5	0.5	200	30	1	0	0
		p	5	2	15	1	600	60	2	0	0

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)
- RV: Recreational Value
- CA: Community Acceptance
- CR: Construction Risks
- TSS: Total Soluble Solids,
- TP: Total Phosphorous
- TN: Total Nitrogen

b) Weight Elicitation

Pair wise judgements obtained from the three members of AC group are reported in Appendix 5C. The pair wise judgments provided by each academic group member were perfectly consistent (C.R. = 0) and acceptable at all levels of hierarchy (Figure 5.2), and hence a table of C.R was not produced for the AC group.

Table 5.12 shows the weights derived from these pair wise judgements. Similar to the weights obtained from the WA group members (Table 5.10), Table 5.12 provides the complete hierarchy of objective weights, intermediate PM, sub PM weights, and final weights for all PMs.

Furthermore, Figure 5.5 provides the plot of final weights corresponding to each member of the AC group. From the weight analysis of AC group members, it was found that *LC* and *PWS* were the key PMs with same average value of final weights as 0.28, for all three academics. Note that these two PMs had the highest weights also from the WA group (Section 5.7.1).

Table 5.12: Weights on Objectives and PMs by AC Group Members

Objective	PM	Sub-PM	AC-1				AC-2				AC-3			
			Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight
Economic	LC		0.2	1		0.2	0.25	1		0.25	0.4	1		0.4
Environmental	GHG		0.6	0.17		0.1	0.37	0.2		0.08	0.4	0.27		0.11
	PWS			0.67		0.4		0.6		0.23		0.55		0.21
	ARC	TSS		0.16	0.68	0.07		0.2	0.64	0.05		0.18	0.6	0.04
		TP			0.12	0.01			0.11	0.02			0.2	0.02
		TN			0.20	0.02			0.25	0.01			0.2	0.02
Social	CA		0.2	0.25		0.05	0.38	0.42		0.16	0.2	0.3		0.1
	CR			0.5		0.1		0.14		0.05		0.25		0.05
	RV			0.25		0.05		0.44		0.16		0.25		0.05
Total			1			1	1			1	1			1

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)
- RV: Recreational Value
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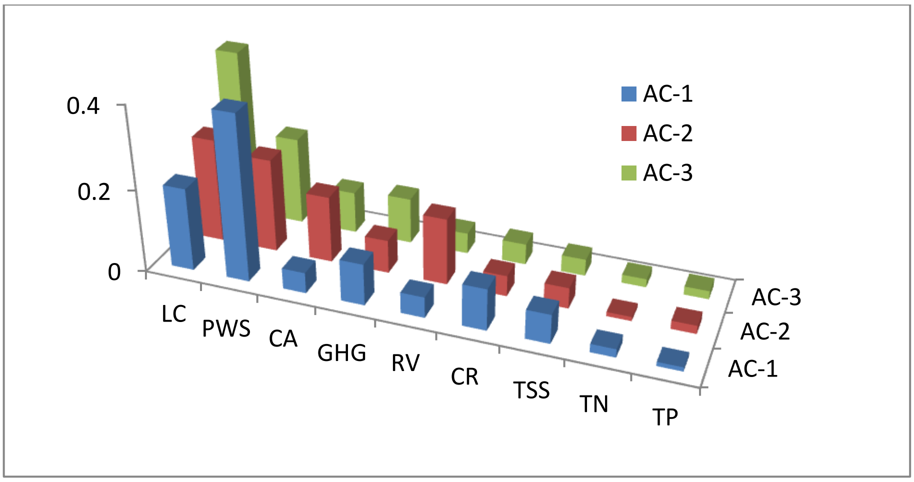


Figure 5.5: Final Weights of AC group

5.7.3 Results – Consultants (CS)

a) Preference Functions

The PF parameters (*p, q)* obtained from the consultant (CS) group members are shown in Table 5.13. Among the CS group, CS-1, CS-2, and CS-4 specified varied preferences for both cases of PF elicitation, while CS-3 had identical preference values for the two cases.

Table 5.13: Preference Function Parameters Derived from CS Group

Member	Case	PF	Performance Measures								
			Economic	Environmental					Social		
			LC	GHG	PWS	ARC			CA	CS	RV
						TSS	TP	TN			
CS-1	1	PF Type	V	V	V	V	V	V	IV	IV	IV
		q	3	0.5	5	0.5	200	30	0	0	0
		p	6	1	10	1	500	50	2	2	2
	2	PF Type	V	V	V	V	V	V	V	IV	IV
		q	2	0.5	10	0.5	250	40	0	0	0
		p	4	1	20	1	500	75	1	1	1
CS-2	1	PF Type	V	V	V	V	V	V	IV	IV	IV
		q	1	0.5	5	0.3	50	10	0	0	0
		p	3	1.5	10	1	150	50	1	1	1
	2	PF Type	V	V	V	V	V	V	IV	IV	IV
		q	0.5	0.7	5	0.5	100	30	0	0	0
		p	1.5	1	10	1.5	300	70	1	1	1
CS-3	1	PF Type	V	V	V	V	V	V	IV	IV	IV
		q	2	0.6	3	0.6	200	30	1	1	1
		p	3	1	5	1	300	50	2	2	2
	2	Same as Case 1									
CS-4	1	PF Type	V	V	V	V	V	V	I	I	I
		q	0.2	0.5	1	0.6	150	20	0	0	0
		p	1	1	5	1.2	250	35	0	0	0
	2	PF Type	V	V	V	V	V	V	I	I	I
		q	0.5	0.5	1	0.2	200	30	0	0	0
		p	2	1	5	0.5	400	60	0	0	0

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)
- RV: Recreational Value
- CA: Community Acceptance
- CR: Construction Risks
- TSS: Total Soluble Solids,
- TP: Total Phosphorous
- TN: Total Nitrogen

b) Weight Elicitation

The pair wise comparison judgements of the CS group members are shown in Appendix 5C. Table 5.14 provides the Consistency Ratio (C.R.) at each level of hierarchy for all four CS members. As these judgements are within acceptable limit (C.R. < 0.10), the judgements are nearly consistent for further evaluation of weights (as explained in Section 5.4.2.4).

Table 5.14 Consistency Ratio for CS Group Members

Hierarchical Level	Consistency Ratio			
	CS-1	CS-2	CS-3	CS-4
Objectives	0	0	0	0
Environmental PM	0.02	0.05	0	0.05
Environmental Sub PMs	0	0	0	0
Social PMs	0	0	0	0

The weights derived from the pair wise comparisons for the CS group are shown in Table 5.15. Additionally, Figure 5.6 provides the plot of final weights corresponding to each member of the CS group. From the weight analysis of CS group, it is evident that *LC* was the most important PM according to the consultants with average final weight of 0.54. Note that LC also had highest weight from the WA and AC groups. The PMs such as *PWS*, *RV* and *CR* had almost equal priority for CS group members with an average of final weight 0.11, 0.10 and 0.10 respectively.

Table 5.15: Weights on Objectives and PMs by CS Group

Objective	PM	Sub-PM	CS-1				CS-2				CS-3				CS-4			
			Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight
Economic	LC		0.5	1		0.5	0.54	1		0.54	0.55	1		0.54	0.57	1		0.57
Environmental	GHG		0.25	0.11		0.03	0.16	0.1		0.02	0.18	0.22		0.04	0.14	0.23		0.03
	PWS			0.55		0.14		0.69		0.11		0.55		0.1		0.5		0.07
	ARC	TSS		0.34	0.1	0.01		0.21	0.54	0.02		0.23	0.55	0.02		0.27	0.33	0.01
		TP			0.45	0.04			0.16	0.01			0.18	0.01			0.33	0.01
		TN			0.45	0.04			0.3	0			0.27	0.01			0.33	0.01
Social	CA		0.25	0.34		0.08	0.3	0.27		0.08	0.27	0.34		0.09	0.29	0.3		0.08
	CR			0.34		0.08		0.55		0.17		0.24		0.07		0.26		0.08
	RV			0.34		0.08		0.18		0.08		0.42		0.12		0.44		0.13
Total			1			1	1			1	1			1	1			1

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)
- RV: Recreational Value
- CA: Community Acceptance
- CR: Construction Risks
- TSS: Total Soluble Solids,
- TP: Total Phosphorous
- TN: Total Nitrogen

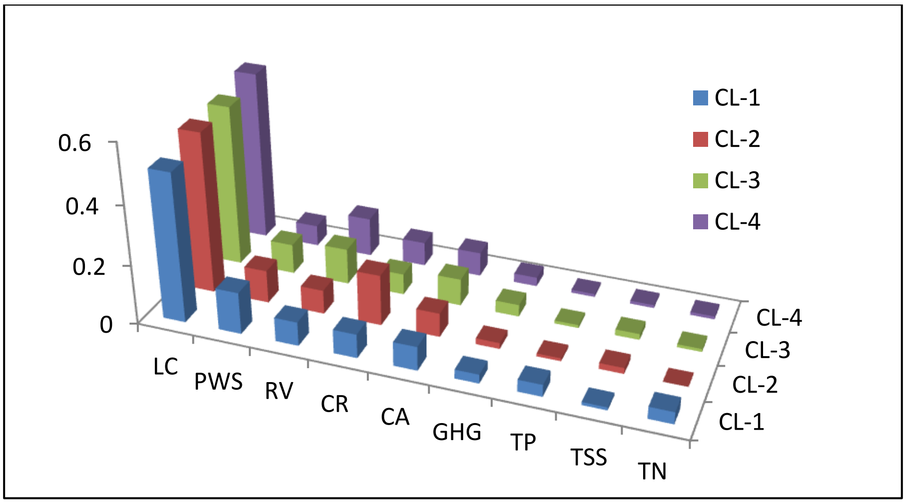


Figure 5.6: Final Weights of CS Group

5.7.4 Results – Council (CL)

a) Preference functions

Similar to all other groups, the PF values (*p*, *q)* derived from the responses of only council group member (CL-1) for two cases of PF elicitation are shown in Table 5.16. The responses of the CL member were slightly varied for the two cases of PF elicitation. This variation in *p* and *q* values was limited only to the PMs of *LC* and *PWS.*

b) Weight Elicitation

The pair wise comparison judgements were obtained from CL-1 are documented in Appendix 5C. These judgments were perfectly consistent (C.R. = 0) at all levels of the hierarchy and hence were completely acceptable for further evaluation of weights.

The weights obtained from CL-1 are shown in Table 5.17. Figure 5.7 provides the plot of final weights estimated from CL responses. From this weight analysis, it is evident that *LC* was the most important PM (same as for the WA, AC and CS groups) for the CL-1 with a weight of 0.54. The *CR* was next important PM with final weight of 0.16. Furthermore, *PWS* and *CA* were were ranked third highest (0.09) by the CL member in terms of final weights.

Table 5.16: Preference Function Parameters Derived from CL Group

CL	Case	PF	Performance Measures								
			Economic	Environmental					Social		
			LC	GHG	PWS	ARC			CA	CS	RV
						TSS	TP	TN			
CL-1	1	PF Type	V	V	V	V	V	V	I	IV	I
		q	0.3	0.2	0.5	0.2	100	20	0	1	0
		p	1	0.5	5	0.5	300	50	0	2	0
	2	PF Type	V	V	V	V	V	V	I	IV	I
		q	1	0.2	1	0.2	100	20	0	1	0
		p	2	0.5	5	0.5	300	50	0	2	0

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of
- Indicative Pollutants (TSS, TP and TN)
- RV: Recreational Value
- CA: Community Acceptance
- CR: Construction Risks
- TSS : Total Soluble Solids
- TP: Total Phosphorous
- TN: Total Nitrogen

Table 5.17: Weights on Objectives and PMs by CL Group

Objective	PM	CL-1				
		Sub-PM	Objective weight	Intermediate PM weight	Intermediate Sub PM weight	Final weight
Economic	LC		0.54	1		0.54
Environmental	GHG		0.16	0.3		0.05
	PWS			0.54		0.09
	ARC	TSS		0.16	0.54	0.02
		TP			0.16	0
		TN			0.3	0.01
Social	CA		0.3	0.3		0.09
	CR			0.54		0.16
	RV			0.17		0.05

- LC: Levelised Cost
- GHG: Green House Gas Emission
- PWS: Potable Water Savings
- ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)
- RV: Recreational Value
- CA: Community Acceptance
- CR: Construction Risks
- TSS: Total Soluble Solids,
- TP: Total Phosphorous
- TN: Total Nitrogen

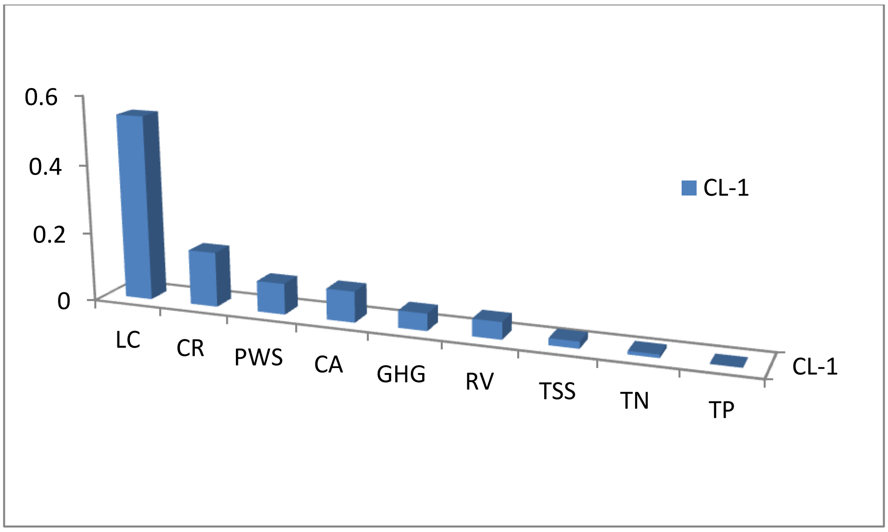


Figure 5.7: Final Weights of CL Group

5.8 Summary

Literature highlights the fact that stakeholder participation and incorporation of associated preferences are becoming integral part of planning and management of stormwater management projects. Successful stormwater management scheme requires effective collaboration from diverse range of stakeholders such as the design team, the local government, the local water authority and the concerned community. However, the preference elicitation from such stakeholders is often a complex and a tedious procedure, leading to multiple sources of uncertainty. Therefore, effort should be made to model the stakeholder preferences as accurately as possible.

The preference elicitation procedure in current study briefly comprised of deriving the preference functions and weights on the performance measures (PMs) from representatives of four broad stakeholder groups namely water authorities, academics, consultants and councils. For the purpose of preference elicitation, current study found workshop method suitable for case study, providing direct consultation with stakeholders in limited time.

A half day workshop was organised where eleven participants belonging to the four identified stakeholder groups expressed their preferences on nine PMs identified in Chapter 4. The preference function threshold values on PMs were obtained in the form of two cases, which were termed as PF assignment given the ranges of PM values (withholding evaluation matrix) and PF assignment given the evaluation matrix. These cases served as basis for investigating the robustness of preference function values and associated effect on rankings of stormwater harvesting sites (Chapter 6). Notably, it was found that preference function thresholds were similar for these two cases for all stakeholder groups, representing robustness in their preferences.

For elicitation of weights, the Analytical Hierarchy Process (AHP) method was used due to its simplicity, rational foundation and hierarchical properties. The weights on PM were elucidated for each PM through the hierarchy represented by study objectives, PMs and sub PMs. The PMs namely *Levelised Cost* and *Potable Water Savings* were given higher weights by all stakeholder groups, reflecting their higher relative importance in decision making.

The preference function thresholds and weights obtained from four stakeholder groups directly serve as data input for D-Sight, a PROMETHEE based software. By gathering the preference parameters and facilitating the associated PROMETHEE/D-Sight analysis, the stormwater harvesting sites in the City of Melbourne study area were ranked with respect to different group decision making situations. The details of this decision analysis methodology and the results are documented in the next chapter.

Chapter 6: Multi-Criteria Decision Making: Sensitivity Analysis, Robustness Evaluation and Ranking Results

6.1 Introduction

Decision making under Multi Criteria Decision Analysis (MCDA) is always associated with uncertainty at various stages starting from the initial problem formulation to the final stages of evaluation and explanation of the results. Furthermore, the MCDA problem is complicated by its uncertain input parameters and assumptions underlying in evaluation methods. Therefore, sensitivity analysis of various input parameter values is an integral part of the decision analysis process (Hyde, 2006; Pomerol and Barba-Romero, 2000).

Sensitivity analysis stimulates the thinking of decision maker (DM) and facilitates exploration of decision results by 'what if' scenarios (Pomerol and Barba-Romero, 2000). With the sensitivity analysis, it is possible to evaluate how much uncertainty in the output of a model is influenced by the uncertainty in its input parameters. The robustness analysis complements the sensitivity analysis by measuring the robustness of results under different decision making situations, and thereby, assisting DMs to make justifiable decisions with certain level of confidence. In this context, Roy (2005) argued that irrespective of the MCDA method used, it is generally indispensable to undertake a robustness analysis to elaborate a recommendation to the Decision Maker (DM). Roy described robustness analysis as a measure to check the validity of MCDA results under different scenarios (e.g. Set of data, model parameters, etc.) of a given MCDA problem.

As outlined in the Section 5.6, sub-groups of Water Authorities (WA), Academics (AC), Consultants (CS) and Councils (CL) were considered as decision making stakeholder groups in this study. Section 5.6 also described the detailed procedure followed in obtaining the preference parameters (i.e. preference functions and weights) on different Performance Measures (PMs) from the identified stakeholder groups. These preference parameters derived from each sub-group were used as input to decision analysis of stormwater harvesting sites obtained from the GIS based screening tool (Section 4.3).

The current chapter describes the decision analysis process involved in ranking of stormwater harvesting sites in the City of Melbourne (CoM) case study area. As described in Section 4.3, CoM was considered as demonstration case study and hence City of Brimbank case study was not considered for decision analysis. The decision analysis process broadly consisted of ranking of stormwater harvesting sites under various perspectives of stakeholder groups and studying the sensitivity and robustness analysis of ranking results. D-Sight (Hayez et al., 2012) was used as the decision making tool in the decision analysis process (Section 2.7.5).

The chapter first describes *D-Sight* software highlighting its various features and associated interpretations for the current study. It then focuses on the decision analysis methodology used in the current case study. The methodology consisted of ranking of stormwater harvesting sites, under two unique group decision making scenarios named as Homogenous Group Decision Making (HGDM) and Collective Group Decision Making (CGDM). The importance of sensitivity analysis and robustness analysis in the context of case study decision making is also described. The chapter then discusses the results of rankings under aforementioned two decision making scenarios and sensitivity and robustness analysis results are also presented. Finally, the summary of the chapter outcomes and recommendations are presented.

6.2 D-Sight- Features

6.2.1 General Information

As described in Section 2.7.5, among various softwares available for PROMETHEE implementation, D-Sight was selected for the present study, considering its easy commercial availability and simplicity. *D-Sight* was developed by co-founders Yves de Smet and Quantin Hayez from the University of Brussels (Université Libre de Bruxelles), Belgium. D-Sight can be purchased online through website WWW.D-Sight.Com. Free demo version can be also downloaded.

D-Sight is available in two formats namely, D-Sight Web and D-Sight Desktop. The web version runs on the standard web browser, while the desktop version runs on the windows platform. The D-Sight Web is a decision-making platform that facilitates the group decision support system (GDSS) through internet access, allowing differently located stakeholders to work in collaboration. The D-Sight Desktop is an offline version with additional analytical capabilities. The D-Sight Desktop allows decision making only by single person (i.e. single decision making). However, the GDSS in D-Sight Desktop can be facilitated through additional plug-in named as "*Multi-Users*" plug-in.

Using *Multi-Users* plug-in in D-Sight, different stakeholders are represented as different scenarios within a single template for a given decision problem. Different stakeholders can work together on the same evaluation problem with different preference parameters or they can have their own data set of the evaluation matrix and preference parameters. However, for the decision problem in this study, the latter case was not considered as the DM preferences (Section 5.6) were obtained on the same evaluation matrix generated from the conceptual designs (Section 4.8). The study uses the D-Sight Desktop version (or simply referred to as D-Sight hereafter) with additional *Multi-user* plug-in to facilitate GDSS.

D-Sight guides the user through step by step data inputs (i.e. PM evaluations, weights, and preference functions) and assists in defining scale for qualitative PMs and thresholds in the preference functions. Categories of alternatives or PMs can also be grouped separately to analyse the decision problem in efficient and compact manner. D-Sight also has several interactive tools and displays, for facilitating sensitivity analysis.

D-Sight works on the PROMETHEE algorithm which is based on pair wise comparison of alternatives. Additionally, D-Sight also supports the Geometrical Analysis for Interactive decision Aid (GAIA) methodology developed by Mareschal and Brans (1988). The GAIA plane in D-Sight complements the PROMETHEE rankings by providing visual interpretation of ranking results interactively. The GAIA plane provides the decision-maker with a synthetic visual representation of the main characteristics of the decision problem, such as the conflicts and synergies existing between the PMs or alternatives (Mareschal and De Smet, 2009). To provide this visual understanding of the problem, GAIA uses 'Principal Component Analysis', which is a popular method in multivariate data analysis for reducing the complexity of high dimensional data (Brans and Mareschal, 1994). It should be noted that GAIA is referred as Global Visual Analysis (GVA) in the D-Sight software.

6.2.2 Data Input and Result Interpretation

For a single decision maker (DM), three basic input data are required to run the software and they are given below:

- Evaluation matrix: This matrix includes *m* number of alternatives, *n* number of PMs, and (*m* x *n*) number of PM evaluations. Table 6.1 shows the evaluation matrix in the current study, which is reproduced from Section 4.8.
- Weights of PMs (Section 5.7)
- Preference functions of PMs (Section 5.7)

Table 6.1: Input Evaluation Matrix for PROMETHEE/D-Sight

Sites	Objectives								
	Economic	Environmental					Social		
	Performance Measures								
	Levelised Cost ($/kL)	Greenhouse Gas Emissions (Kg CO_2 / kL)	Potable water Savings (ML)	Annualised removal cost ($/Kg/Year)			Community Acceptance	Recreational Value	Construction Risks
				TSS[a]	TP[b]	TN[c]			
Holland Park	15.3	0.20	18.5	4	2527	327	3	5	1
Birrarung Marr Park	15.5	0.17	15.1	0.9	580	81	3	3	2
Clayton Reserve	14.0	0.17	26.2	1.4	1,021	122	4	3	2
Princess Park	12.3	0.16	73	2.8	1,832	241	5	5	3
Flagstaff Park	10.8	0.41	56	1.3	929	118	5	4	3
Batman Park	22.3	0.18	5.7	1.6	1130	140	2	3	3
Ievers Reserve	21.4	0.18	5.7	1.1	772	95	2	3	1
Pleasance Gardens	27.2	0.17	5.6	3.3	2167	266	2	2	3

[a]TP: Total Phosphorous, [b]TN: Total Nitrogen, [c]TSS: Total Suspended Solids

In case of Group Decision Making (GDM), the PROMETHEE/D-Sight requires additional information in terms of weights to be assigned to each DM representing his/her voice (default setting is the equal weights). After D-Sight is run in each case, the output results can be visualised and interpreted in different ways, as follows:

- PROMETHEE I and II rankings,
- PROMETHEE II rankings,
- GAIA plane, and
- Sensitivity analysis.

Figure 6.1 illustrates a D-Sight window showing various features; namely, data input window PROMETHEE I and II rankings, GAIA plane, walking weights and stability intervals. These software features are explained below. It should be noted that the decision problem and associated results in Figure 6.1 are in relation to a tutorial example from D-Sight which deals with a hypothetical industrial site selection.

6.2.2.1 Data Input Window

The input data in the D-Sight software can be visualised in summary format (part ***a*** in Figure 6.1), where performances of all alternatives along with their respective units, weights, preference function thresholds and max/ min objective functions is displayed.

6.2.2.2 PROMETHEE I and II rankings

As described in Section 2.8, PROMETHEE I provides partial ranking of alternatives based on the positive (Φ^+) and negative (Φ^-) preference flows of the alternatives, and highlights incomparability between alternatives. On the contrary, PROMETHEE II provides a complete ranking of alternatives from best to worst, leaving no incomparability between alternatives. This ranking is based on the net preference flow (Φ) of alternatives, which is straightforward and easier to use than partial ranking provided by PROMETHEE I.

The D-Sight software allows the simultaneous viewing of both PROMETHEE I and II rankings using a visual two dimensional tool named as 'PROMETHEE Diamond' (part ***b*** in Figure 6.1). The PROMETHEE Diamond is a recent development in PROMETHEE methodology which is proposed by Mareschal and De Smet (2009).

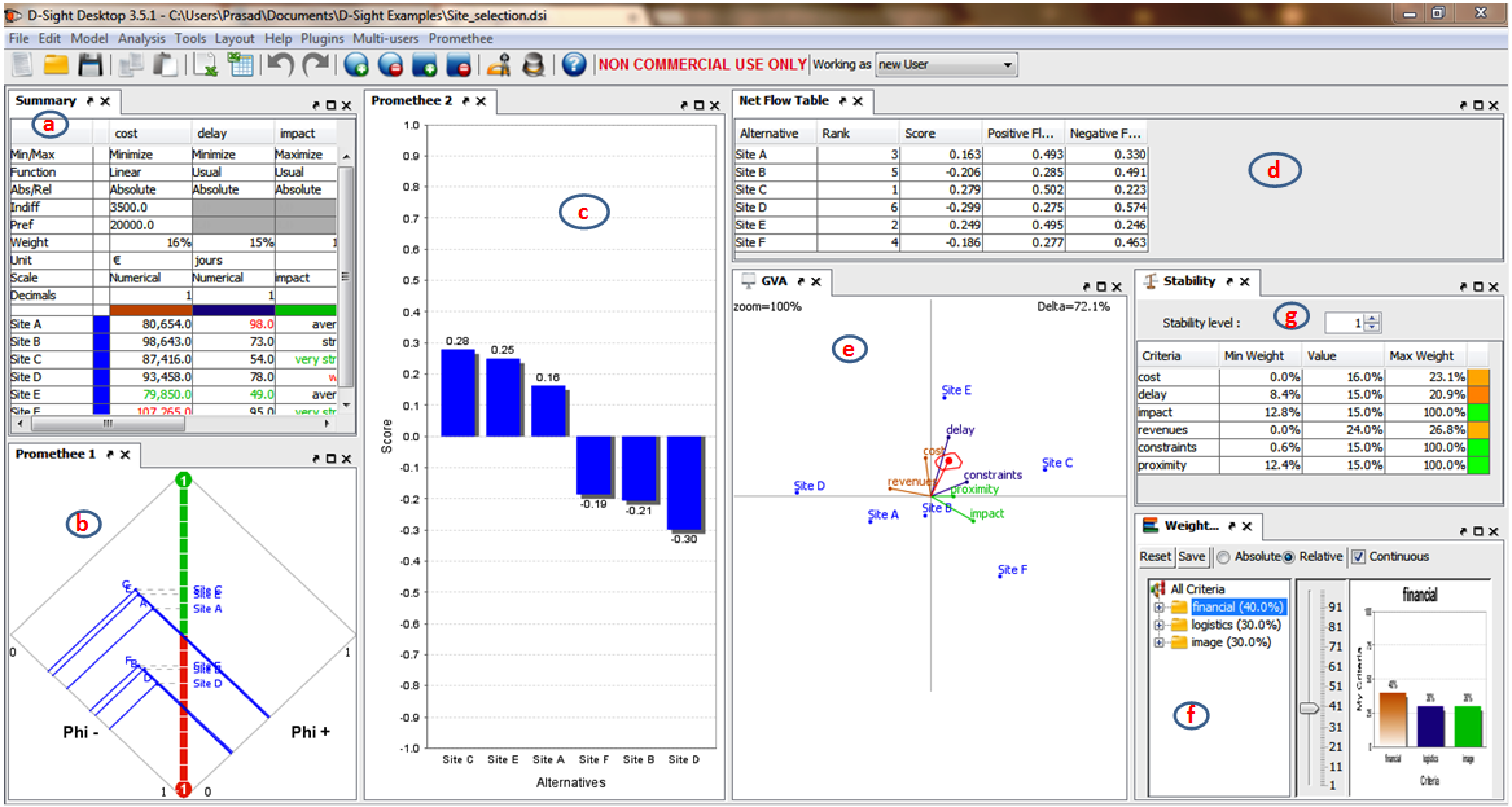


Figure 6.1: Various Features of D-Sight Software

(a) D-Sight- Data Input Window, (b) PROMETHEE I Ranking, (c) PROMETHEE II Ranking – Bar Profiles, (d) PROMETHEE II Ranking Scores, (e) GAIA plane, (f) Walking Weights, and (g) Stability Intervals

In PROMETHEE Diamond, the alternatives are represented into a plane angled 45° based on their positive (Φ^+) and negative (Φ^-) preference flows. Figure 6.2 illustrates the 'PROMETHEE Diamond' representation for the aforementioned example of ranking of industrial sites [same as part ***b*** in Figure 6.1]. In Figure 6.2, preference flows (i.e. Φ^+, Φ^-) of the alternatives are plotted in such way that vertical axis gives the net flow ($\Phi = \Phi^+ - \Phi^-$) of alternatives in ascending order.

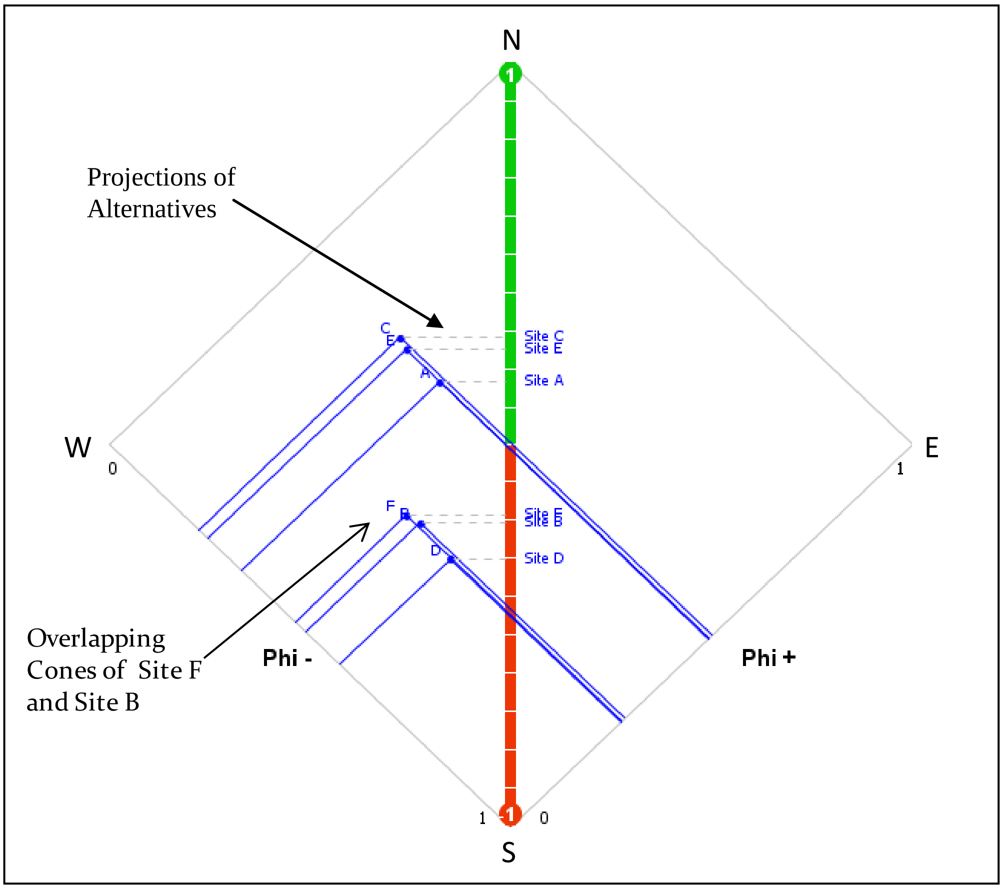


Figure 6.2: PROMETHEE Diamond Representation

For each alternative site, projection lines Φ^+ and Φ^- axes intersect with each other to form a cone in a 45° plane. When the projection lines of alternative sites (or cones) cross each other, incomparability between alternatives is observed considering rules of PROMETHEE I rankings (Section 2.8). In Figure 6.2, the cones of alternative sites F and B are overlapping and hence these alternatives sites are incomparable with each other according to PROMETHEE I rankings.

Additionally, the projections drawn from each alternative cone on a vertical (net flow) axis represents the complete ranking (i.e. PROMETHEE II ranking) of all alternatives. These projections are shown by light grey colour in Figure 6.2 and corresponding PROMETHEE II rankings of alternative sites have been represented in the same figure with site C, E, and A as the top three alternatives sites. Thus, the 'PROMETHEE Diamond' provides an integrated display of PROMETHEE I and PROMETHEE II rankings.

Apart from PROMETHEE Diamond representation, D-Sight displays PROMETHEE II rankings in traditional format of bar profiles (part ***c*** in Figure 6.1). These bar profiles are plotted according to net flow scores of alternatives (part ***d*** in Figure 6.1).

It should be noted that D-Sight does not have PROMETHEE Diamond feature for Group Decision Making (GDM) scenarios. As the present study is focussed on stormwater harvesting site decision making with different stakeholder groups, the use of PROMETHEE Diamond feature (and thereby PROMETHEE I rankings) can not be used for this study. However, the study uses PROMETHEE II rankings for evaluating stormwater harvesting sites under the GDM scenario. To display these PROMETHEE II rankings, D-Sight uses format of bar profiles as explained above (part ***c*** in Figure 6.1).

6.2.2.3 GAIA Plane

The GAIA plane in D-Sight provides a good visual representation of results obtained from PROMETHEE rankings of a given decision problem. The GAIA representation can be interpreted in two ways i.e. GAIA criteria plane (Single DM case) and GAIA-scenario plane (GDM case). However, the D-Sight software does not exclusively distinguish these interpretations and uses generic term of 'global visual analysis' for both cases.

a) GAIA Criteria Plane (Single DM Case)

To facilitate the GAIA analysis, D-Sight (PROMETHEE) uses 'single criterion net flow' (or simply unicriterion net flow) concept. A brief methodology of GAIA including unicriterion net flow concept and its relation with GAIA analysis is presented below.

According to the definitions of positive (Φ^+), negative (Φ^+) and net outranking flows (Φ) for alternative pair *a* and *i* defined in Chapter 2 (Section 2.8.3),

$$\Phi = \Phi^+ - \Phi^- \quad (6.1)$$

$$= \frac{1}{m-1}\sum_{i=1}^{m}\pi(a,i) - \frac{1}{m-1}\sum_{i=1}^{m}\pi(i,a) \quad (6.2)$$

Where, m = Number of alternatives under consideration,

$\pi(a, i)$ = Preference degree with which *a* is preferred over given alterative *i* (As explained in Section 2.8.3, Preference degree is indication of preference of one alternative over other), and

$\pi(i, a)$ = Preference degree with which *i* is preferred over *a*

$$\Phi = \frac{1}{m-1}\sum_{j=1}^{n}\{P_j[f_j(a) - f_j(i)] - P_j[f_j(i) - f_j(a)]\}W_j \quad (6.3)$$

where, n = Number of PMs under consideration,

$f_j(.)$ = Value of PM *j* under consideration,

W_j = Weight on PM *j*,

$P_j[f_j(a) - f_j(i)]$ = Preference function specified on PM $f_j(.)$, indicating preference of *a* over *i*

$P_j[f_j(i) - f_j(a)]$ = Preference function specified on PM $f_j(.)$, indicating preference of *i* over *a*

$$\Phi = \frac{1}{m-1}\sum_{i=1}^{n}\Phi_j(a)\ W_j \quad (6.4)$$

where,

$$\Phi_j(a) = \frac{1}{m-1}\sum_{j=1}^{n}\{P_j[f_j(a) - f_j(i)] - P_j[f_j(i) - f_j(a)]\} \quad (6.5)$$

For alternative *a*, Brans and Mareschal (2005) defined the single criterion net flow as Φ_j (a), which can be obtained only when one PM [i.e. $f_j(.)$] is considered (100% of total weight is allocated to that PM). The single criterion net flow signifies how an alternative '*a*' is outranks all other alternatives [$\Phi_j(a) > 0$] or is outranked by all other alternatives [$\Phi_j(a) < 0$] on particular PM $f_j(.)$. The GAIA methodology of D-Sight uses the matrix, M (m x n) of the single criterion net flows of all alternatives to analyse the decision problem visually. This matrix is represented in Table 6.2. It should be noted that single criterion net flow in Table 6.2 is estimated using Equation 6.5.

The single criterion net flow matrix in Table 6.2 provides all the information on the preference structure of the decision maker, independent of PM weights (Brans and Mareschal, 1994). This information conveys superior information than that of original evaluation matrix as $\Phi_j(a_i)$ values are expressed in dimensionless units for all PMs.

Table 6.2: Single Criterion Net Flows

Alternatives	Performance Measures						
a_1	$\Phi_1 (a_1)$	$\Phi_2 (a_1)$	….	….	$\Phi_j(a_1)$	..	$\Phi_n(a_1)$
a_2	$\Phi_1 (a_2)$	$\Phi_2 (a_2)$	….	….	$\Phi_j (a_2)$	….	$\Phi_n\ a_2.)$
….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….
a_i	$\Phi_1 (a_i)$	$\Phi_2 (a_i)$	….	….	$\Phi_j(a_i)$	….	$\Phi_n (a_i)$
….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….
a_m	$\Phi_1 (a_m)$	$\Phi_2 (a_m)$	….	….	$\Phi_j(a_m)$	….	$\Phi_m(a_n)$

[Source:(Brans and Mareschal, 2005)]

Each alternative is then represented by a point in the *n*-dimensional space defined by single criterion net flows. A 'principal components analysis' is applied to these points to obtain a two-dimensional representation of the decision problem. Unit axes for the PMs are also projected on the GAIA plane.

The GAIA plane is illustrated in Figure 6.3 (same as part ***e*** in Figure 6.1), representing the alternative sites with respect to system PMs. The delta (Δ) value in Figure 6.3 suggests the amount of information preserved after projection of single criterion net flow values, and it typically serves as an indicatior of the quality of the information provided by the GAIA plane. Brans and Mareschal (2005) considered the Δ value greater than 60% as reliable to interpret the results. The GAIA plane in Figure 6.3 has the Δ value of 72.1%, which indicates that information projected by the plane is sufficient to interpret the PROMETHEE results and there is 21.9% loss of information in the projections of alternatives and PMs.

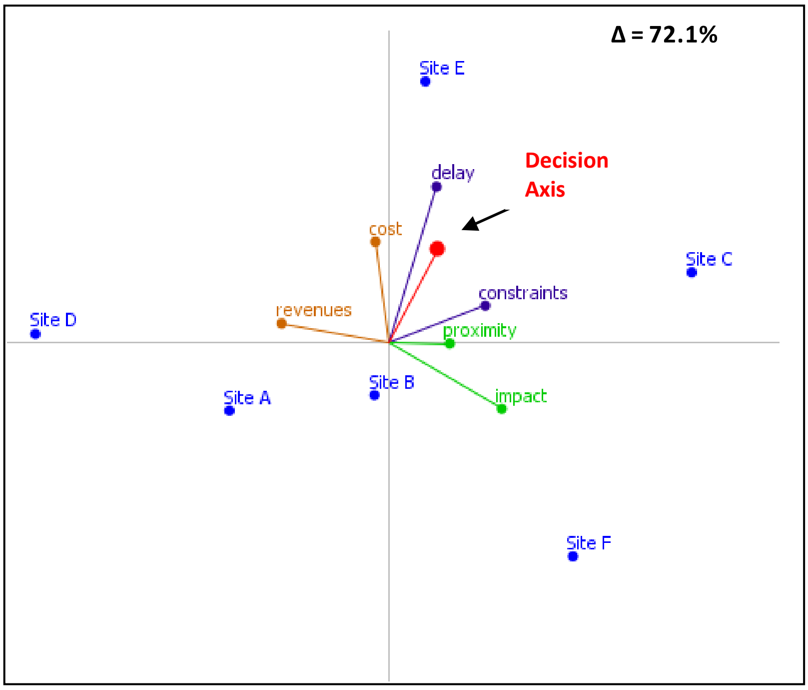


Figure 6.3: GAIA Plane
(Derived from Example in D-Sight Manual)

Provided the high Δ value, following properties (P1:P6) hold for a given decision problem (Brans and Mareschal, 2005),

- **P1:** The longer a PM axis in the GAIA plane represents the PM with more discriminating power in differentiating the alternatives. (In Figure 6.3, PM '*delay*' is showing high differentiating power among the alternatives).

- **P2:** The axes oriented in the same direction represent the PMs with similar preferences (In Figure 6.3, PMs '*proximity*' and '*impact*' are having similar preferences for DM).

- **P3:** The opposite orientation of axes represents the PMs with conflicting preferences (The PMs '*revenues'* and '*constraints'* in Figure 6.3).

- **P4:** The orthogonal axes indicate the independence of PMs in terms of preferences (The PMs '*delay*', '*constraints*', and '*impact*' in Figure 6.3)

- **P5:** Similar alternatives can be visualised in terms of the clusters (The alternative '*Site B*' and '*Site A*' can be seen as cluster in Figure 6.3).

- **P6:** The high performing alternatives on particular PM are represented by points located in the direction of the corresponding PM axis [The PMs '*delays*' (e.g. construction) for alternative '*Site E'* can be higher compared to other sites in Figure 6.3].

Figure 6.3 also shows '*PROMETHEE decision axis*' (or 'pi axis') in red colour. This axis reflects visual impact of PM weightings under the GAIA methodology. To derive decision axis, the weight vector of PMs, w: (w_1, w_2, ..,w_j,..w_n) is projected on GAIA plane. If all weights are concentrated on one PM (i.e. 100% weight on specified PM), the PROMETHEE decision axis will coincide with the axis of this PM in the GAIA plane.

The decision axis signifies the directions of best performing alternatives according to the weights given to the PMs. The orientation of the decision axis also identifies the recommended compromise alternative that corresponds to the assigned PM weights. Any variation of PM weights also updates orientation of the decision axis, reflecting the new compromised alternative. This property of decision axis is essentially used in assessing the weight sensitivity of PMs (Mareschal and De Smet, 2009). Thus, the decision axis helps the decision maker to visualise the consequences of his/her priorities. In Figure 6.3, the decision axis has been oriented towards Site E, which represents the consensus alternative considering the preferences of PMs specified by the DM.

b) GAIA scenario Plane (GDM Case)

In GDM situations, similar to the GAIA criteria plane, the GAIA scenario plane displays the properties P1 to P6 listed above for different DMs, instead of different PMs. Different DMs and their different preferences can be represented in terms of different scenarios in '*Multi-user plug-in*' of D-Sight. The voices of these DMs in the decision problem can be varied by assigning appropriate weights on them. For example, influential DMs can be assigned with higher weights and vice versa.

The GAIA scenario plane is particularly useful in identifying the compromise solutions (alternatives) considering the diverse preferences of different DMs in GDM situations. Figure 6.4 shows the GAIA scenario results for the industrial site selection example under four hypothetical DMs (DM-1, DM-2, DM-3 and DM-4), representing a group decision making situation.

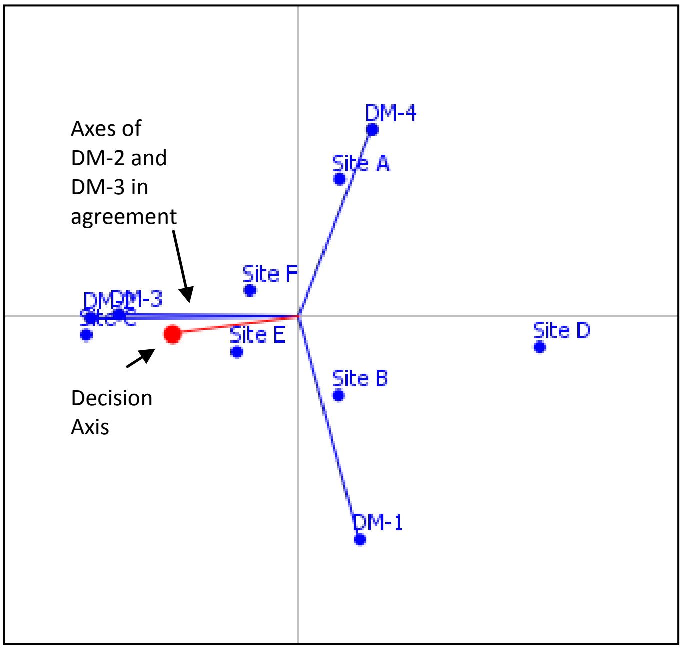


Figure 6.4: GAIA Scenario Plane

Similar to the GAIA criteria plane, the orientation of the scenario axes approximately indicate the position of group members which are in agreement (DM-2 and DM-3 in

Figure 6.4) with each other (when axes point in similar directions) and group members which are in conflict (DM-2 and DM-3 with DM-4 and DM-1 in Figure 6.4) with each other (when axes point in opposite directions). The orthogonal positions of axes indicate independent decisions of DMs (DM-4 and DM-1).

6.2.2.4 Walking Weights

The ‘Walking Weights’ feature of D-Sight allows the modifications of weights on any selected PM and the observation of resulting change of the PROMETHEE II rankings (in terms of net preference flows). Thus, the walking weight window in D-Sight provides a visual interactive way to perform the weight sensitivity analysis. The walking weight window is shown in part ***f*** in Figure 6.1. In this window, weights of *financial* PMs (highlighted in orange) can be altered with the sliding pointer and corresponding change in the ranking of alternative sites can be observed. Similarly, the weight sensitivity of other PMs (i.e. *logistics, impact*) can be analysed. In case of GDM situations, weight sensitivity is analysed on the DMs instead of PMs and the resulting variation in ranking is studied.

6.2.2.5 Stability Intervals (of weights)

For each PM, a stability interval indicates the range of the weights which can be modified without affecting the PROMETHEE II ranking (to a stated ‘stability level’), given that the relative weights of the other PMs are not modified. This feature is more comprehensive than ‘walking weights’, as it shows how PROMETHEE II rankings vary as a function of the weight of a PM and identifies the interval of stability of top ranked alternatives (Mareschal, 2013). More the stability interval on a given PM, it is less likely that corresponding PM weights have effect on rankings and thus rankings can be considered robust. Similar to walking weights, in GDM context, the weight stability is analysed in terms of weights assigned on the group members and the resulting ranking variation is studied.

Part ***g*** in Figure 6.1 shows the weight stability intervals of different PMs, indicating weight sensitivity for top alternative Site E. It should be noted that Site E corresponds to stability level ‘1’ which means that stability intervals are computed only for top alternative site E. (Similarly, if stability level is 3, stability intervals are examined for top 3 sites).

From Part ***g*** in Figure 6.1, it can be seen that, for *Cost* PM (16% weight), the weight stability interval only varies between 0% and 23% for Site E to remain as top alternative. If weight on *Cost* PM exceeds than 23%, then Site E will not be a top ranked alternative. Conversely PMs such as *impact*, *constraint* and *proximity* have weight stability interval up to 100%, indicating that their weights do not have any influence on the ranking of Site E.

6.3 Multi-Criteria Decision Analysis Methodology

In a multi-stakeholder environment (as in this study), one of the key questions to address is how to combine the preferences of various DMs in a consistent and meaningful way when differences of opinion exist about the relative importance of different strategies and objectives (Arnette et al., 2010). A robust approach can be the creation of homogeneous subgroups from within the overall set of stakeholders, and to consider the relative preferences of each of these subgroups in formulating an overall preference structure and decision making (Arnette et al., 2010).

As described in Section 6.1, the decision analysis process in the study involved the ranking of alternative stormwater harvesting sites and studying the sensitivity and robustness of the rankings obtained, utilising the capabilities of the *D-Sight* software. Figure 6.5 provides a schematic representation of the decision analysis methodology used (in this study), showing the associated stakeholders and decision making scenarios considered.

As seen from Figure 6.5, the study performed the decision analysis under two group decision making scenarios i.e. Homogeneous Group Decision Making (HGDM) scenario and Collective Group Decision Making (CGDM) scenario. Also, as reported in Section 6.1, these scenarios essentially provided the freedom to explore the decision making process (i.e. ranking of stormwater harvesting sites) under homogenous and heterogeneous groups of stakeholders respectively.

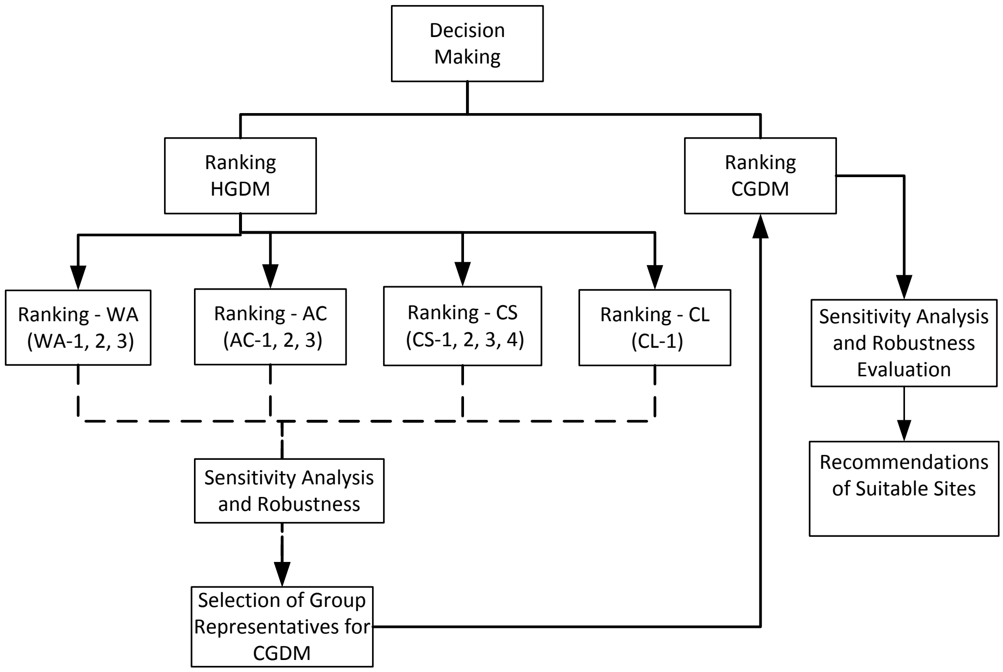


Figure 6.5 - Decision Analysis Procedure Used in Study

As described in Section 5.6, the study considered four broad stakeholder groups namely, Water Authority (WA), Academics (AC), Consultants (CS) and Councils (CL) to reflect different views on stormwater harvesting decision making.

The HGDM scenario consisted of decision analysis from each homogenous sub-group of stakeholders (WA, AC, CS and CL) and the CGDM scenario consisted of decision analysis with the collective representative stakeholders from each sub-group of HGDM scenario (Figure 6.5). The results obtained from HGDM and CGDM scenarios were studied for sensitivity and robustness before making the final recommendations of rankings of stormwater harvesting sites in the study area.

For facilitating the decision analysis process for both scenarios, the preference parameters [i.e. weights and preference functions (PFs)] obtained from each stakeholder group member (Section 5.7) were served as input data into D-Sight/PROMETHEE.

6.3.1 Homogenous Group Decision Making (HGDM) Scenario

As seen from Table 6.5, in the HGDM scenario, ranking of stormwater harvesting sites is derived from four homogenous sub-groups of considered stakeholders. However, to derive such ranking, the ranking results of all individuals (single DM cases) within each sub-group should be considered to reflect the collective opinion of the sub-group. As described in Section 5.6.1, preferences of each individual sub-group member were obtained considering two cases of Preference Functions (PFs) on PMs. Therefore, ranking of each member within each sub-group is obtained considering these two cases of preference elicitation of PMs. These two cases are:

- Case 1: Ranking using the preference values, given the ranges of PM
- Case 2: Ranking using the preference values, given the evaluation matrix

Case 1 reflected the DM preferences on ranges of PM values (without knowing the names of alternative sites and the evaluation matrix used in the study), and Case 2 reflected DM preferences on PMs knowing the evaluation matrix of the current decision problem which represented the performance of known alternative stormwater harvesting sites (including the names of sites) under various PMs. The ranking results of the stormwater harvesting sites can be compared under these two cases to investigate their effect of preference variation on ranking. Thus, robustness in the ranking results can be examined from each stakeholder group based on PF values.

6.3.2 Collective Group Decision Making (CGDM) Scenario

Decision making under the CGDM scenario can be facilitated by a group comprising of single, several or all stakeholders of WA, AC, CS and CL sub-groups. One member or few members in these sub-groups can be selected as group representatives to formulate a single heterogeneous group of stakeholders with different views on the decision problem. In present study, one member from each stakeholder sub-group was selected as representative of the sub-group, to formulate the heterogeneous group of four stakeholders, and used as CGDM scenario. Additionally, the study also considered decision making under all (11) stakeholder group members (regardless of their sub-groups) to examine the sensitivity of ranking results.

To represent the stakeholders in collective decision making, the CGDM procedure consists of identifying and selecting the representatives from each stakeholder sub-group of WA, AC, CS and CL. For this purpose, ranking of each sub-group member in all stakeholder sub-groups was evaluated separately as Single DM cases. The selection of the sub-group representative member is then done by comparing the ranking results of each sub-group member (Single DM) with HGDM ranking of the respective sub-group (Section 6.3.1). The general agreement of ranks between each individual group member and HGDM is examined, and the group member with the ranks in best agreement to the HGDM ranks is selected as the group representative. The current study uses spearman rank correlation coefficient (*R*) to test the strength of agreement between ranks of each individual sub-group member and corresponding HGDM ranks.

The spearman rank correlation coefficient *(R)* is a commonly used non-parametric statistic measure when comparing the ranks of two variables that relate in a monotonically increasing or decreasing function (Sheskin, 2003). The *R* ranges from -1 to 1 where *R* value closer to 1 indicates the good agreement between two sets of ordinal ranks and *R* value closer to -1 denotes negative correlation indicating reverse trend between considered variables. Moreover, the *R* value closer to 0 indicates poor agreement between the considered two variables.

There are many studies in the literature using *R* as the strength indicator between associated rankings for different problems. For example, Raju and Pillai (1999) used R for comparing the ranking results obtained from different MCDA methods when selecting the best river configuration policies in India. Likewise, Hajkowicz (2007) used *R* when comparing MCDA rankings with the rankings obtained from intuitive unaided decision making in the assessment of environmental projects in Queensland, Australia.

Theoretically, if U_a and V_a denote the ranks achieved by two different DMs for the same alternative a, then, *R* can be represented as follows:

$$R = 1 - \frac{6\sum_{a=1}^{n} {D_a}^2}{n(n-1)}$$

Where, n = Number of alternatives

D_a = Difference between U_a and V_a, and

$\sum$ = Summation of difference between U_a and V_a, considering all alternatives.

In current study, the R value is estimated by comparing ranks of each member (U_a) in each stakeholder sub-group (i.e. WA, AC, CS and CL) with corresponding HGDM rankings (V_a). The sub-group member with highest R value is selected for the CGDM scenario. Thus, the CGDM scenario comprises of four stakeholders representatives, representing the corresponding group views on stormwater harvesting.

From Figure 6.5, it is evident that decision analysis is done with two broad group decision making situations: HGDM scenario with four group decision making (GDM) situations (i.e. WA, AC, CS and CL) and, CGDM scenario with three GDM situations as described below.

To account for more variability of stakeholder representations, CGDM was conducted with respect to three distinct group decision making situations, namely, Group 1, Group 2, and All DM. Group 1 has an equal representation of representatives selected from stakeholder sub-groups, while Group 2 consisted of group with more weight of WA and CL (reflecting key decision makers) in decision making process (Refer Section 6.6 for details). Additionally, All DM case represented combined group decision from all stakeholder group members from all sub-groups simultaneously.

6.3.3 Sensitivity Analysis and Robustness Evaluation

The uncertainty in MCDA models typically arises either from human judgments in the evaluation procedures or unquantifiable, incomplete or non-obtainable information (in terms of PMs) about the given problem (Giannopoulos and Founti, 2010; Mareschal, 1986). In the literature, uncertainty in MCDA has also been categorised as 'internal' or 'external' (Stewart, 2005). The external uncertainty relates to uncertainty about environmental conditions that lie beyond the scope of the decision maker (such as natural calamities, or changed regulations or costs), while the internal uncertainty relates to the ambiguity of the decision maker preferences and associated problem structuring. However, the distinction boundary between external and internal uncertainties is often vague and under many circumstances, both types of uncertainties can be treated in much the same manner (Stewart, 2005).

Recently, Durbach and Stewart (2012) provided a comprehensive review of different methods to account for the uncertainties in MCDA. According to the review, probability functions, fuzzy set analysis, decision weight analysis, and scenario based analysis are some of the common approaches for evaluating uncertainty. However, the authors of the review clearly mentioned that approaches such as probability functions, or fuzzy membership functions are difficult to comprehend to the decision makers and virtually impossible to validate.

According to Roy and Vincke (1981), the inherent uncertainties and subjectivities of the input parameters to an MCDA model significantly influence the rankings of alternatives. Therefore, it is common in MCDA methods to examine the sensitivity of output for possible variations in PM weights or PM evaluations (Durbach and Stewart, 2012). However, any efforts to analyse the sensitivity due to preference threshold values, such as in PROMETHEE type outranking methods, are rarely sighted in literature (Kodikara, 2008).

Hyde et al. (2003) addressed sensitivity of input PROMETHEE parameters through a stochastic uncertainty analysis approach. This stochastic analysis involved defining the uncertainty in the input data (i.e. preference functions and weights) using probability distributions, performing reliability analysis by Monte Carlo simulation and undertaking a significance analysis using the Spearman rank correlation coefficient. Furthermore, coupling this stochastic analysis approach with distance based uncertainty analysis approach; Hyde and Maier (2006) applied PROMETHEE to address the sustainable water resource development problems in the Northern Adelaide Plains, South Australia.

Given the stormwater harvesting context of the current study, external uncertainties can arise from the systems costs, seasonally varying runoff and demand conditions, and change in regulations or policies and associated impacts on stakeholders. Similarly, internal uncertainties are subjected to varied judgements of stakeholders associated with stormwater harvesting objectives and associated PMs. The external uncertainty was beyond the scope of this case study application, and the main focus is given only to the possible variations of stakeholder preferences in different decision making situations (internal uncertainty). Therefore, the sensitivity analysis for this case study was carried out by varying stakeholder preference parameters for a single evaluation matrix (Chapter 4.9) for both HGDM and CGDM scenarios. Additionally, robustness analysis was also conducted in parallel to sensitivity analysis, by considering different stakeholder combinations.

An interesting property of the PROMETHEE methods is that the preference flows (phi values) are linear functions of the weights of the PMs which make it easier to perform sensitivity analysis (Mareschal, 2013). As stated earlier in Section 6.2.2, the sensitivity analysis in PROMETHEE can be facilitated by varying input parameters (i.e. preference functions and weights on PM values). The sensitivity of preference function values and associated rankings of each individual DM under HGDM scenario has been already discussed in Section 6.3.1.

For the single DM case, the D-Sight software has the capability to analyse the sensitivity of PM weights using comprehensive features described in Section 6.2.1.3. An example of such single DM case sensitivity analysis (for WA) is provided in Section 6.4.3. However, under GDM settings, the sensitivity evaluation on PM weights by different group members is not facilitated by D-Sight. Instead, the sensitivity analysis is done in terms of examining the stability of weights assigned on individual members of the group. As the current study focuses on two group decision making scenarios (i.e. HGDM and CGDM), the major focus of sensitivity analysis for the case study was on investigating the uncertainty associated with group composition of CGDM scenario (i.e. weights given to different group members in the CGDM).

6.4 HGDM Results -Water Authority (WA)

In this section, HGDM ranking results and associated interpretations of WA group (Single DM and GDM) are explained in detail as a demonstration example. Similar

HGDM ranking results for the other groups i.e. AC, CS and CL are explained briefly in Section 6.5.

6.4.1 PROMETHEE II Rankings

The WA stakeholder sub-group had three individual single DMs (WA-1, WA-2 and WA-3). As described in Section 5.7.1, each WA group member did not alter his/her PF values on PMs for Case 1 (PF values given ranges of PMs) and Case 2 (PF values given evaluation matrix). As these PF values were same for both cases for each WA, ranking of alternative sites for the WA sub-group was done only for Case 1 data.

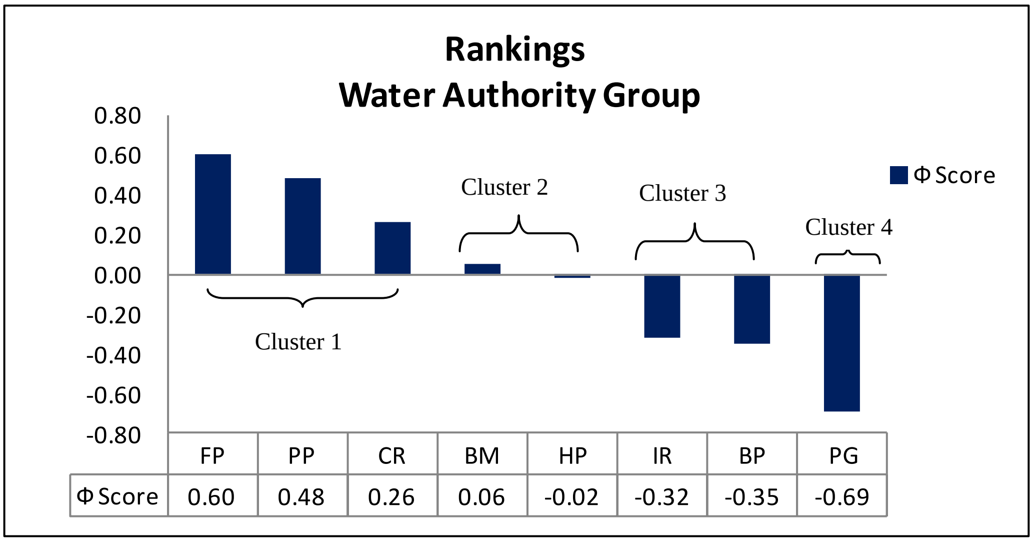
As explained in Section 6.2.2.2, the PROMETHEE II ranking results were based on net outranking scores (Φ) from each of the stormwater harvesting sites. The alternative sites with high Φ value were considered as best alternatives. Based on the preferences of individual DMs obtained in Section 5.7.1, the PROMETHEE II rankings were obtained for all three WAs. Considering the rankings of all three WAs, it was possible to observe the combined decision of all three WA together for HGDM scenario. This combined decision of WAs represented a consensus decision considering their individual preferences, and has been estimated automatically in D-Sight according to PROMETHEE GDSS methodology (Section 2.8). It should be noted that all WAs were assumed to be equally important in group decision and thereby equal weights were assigned to all three WAs.

The positive flows (Φ+), negative flows (Φ-) and net preference flows (Φ) obtained from all individual WAs are given in Table 6.3 along with the combined net preference flow of WAs as a group. In this group decision making, GDSS uses a combined net preference flow, which is a weighted average of Φ values of all DMs involved in the decision making process (as explained in Section 2.8.4).

Figure 6.6 shows the rankings of stormwater harvesting sites obtained in the HGDM situation for all three WAs.

Table 6.3: Positive Flows (Φ+), Negative Flows (Φ-) and Net Preference Flows (Φ) of WA Group Members

Alternative Sites	Single DM									Group
	WA-1			WA-2			WA-3			
	Φ+	Φ-	Φ	Φ+	Φ-	Φ	Φ+	Φ-	Φ	Φ
Flagstaff Park	0.78	0.12	0.66	0.69	0.18	0.51	0.72	0.08	0.64	0.60
Clayton Reserve	0.56	0.25	0.31	0.65	0.15	0.50	0.27	0.30	-0.03	0.26
Princess Park	0.69	0.15	0.54	0.47	0.26	0.21	0.72	0.04	0.69	0.48
Birrarung Marr Park	0.41	0.36	0.05	0.42	0.31	0.11	0.30	0.29	0.01	0.06
Holland Park	0.37	0.41	-0.03	0.34	0.41	-0.07	0.32	0.29	0.03	-0.02
Ievers Reserve	0.25	0.55	-0.30	0.21	0.48	-0.27	0.08	0.48	-0.40	-0.32
Batman Park	0.17	0.64	-0.48	0.20	0.54	-0.34	0.19	0.43	-0.24	-0.35
Pleasance Garden	0.04	0.78	-0.74	0.05	0.69	-0.64	0.01	0.69	-0.69	-0.69



- FP: Flagstaff Park
- CR: Clayton Reserve
- PP: Princess Park
- BM: Birrarung Marr Park
- HP: Holland Park
- IR: Ievers Reserve
- BP: Batman Park
- PG: Pleasance Garden

Figure 6.6: PROMETHEE II Ranking Results for WA Sub-Group

From Figure 6.6, it can be seen that alternative rankings can be categorised into four different clusters based on their Φ values. These clusters are:

- Cluster 1: Flagstaff Park, Clayton Reserve, and Princess Park (highly ranked sites)
- Cluster 2: Holland Park and Birrarung Marr Park (intermediately ranked sites)
- Cluster 3: Batman Park and Ievers Reserve (low ranked sites)

- Cluster 4: Pleasance Garden (lowest ranked site)

Table 6.4 represents the ranking of each WA member (based on the Φ value) with respect to the GDM ranking (Figure 6.6) of the WA group. The *R* value (Section 6.3.2) of each WA member with respect to the GDM ranking is also shown in Table 6.4.

As seen from Table 6.4, the Flagstaff Park and Princess Park were ranked within the top 3 positions considering ranking of each water authority individually or as a group. However, the Clayton reserve which was ranked within top two positions by WA-1 and WA-2 had significantly ranked lower by WA-3. This low ranking was the result of high weighting assigned by WA-3 on social PMs, for which Clayton Reserve had low PM values.

Table 6.4: PROMETHEE II Ranking of WA Group and Associated Group Member Selection

Alternative Sites	Single DM Rank			GDM Rank
	WA-1	WA -2	WA -3	
Flagstaff Park	2	1	2	1
Princess Park	3	3	1	2
Clayton Reserve	1	2	5	3
Birrarung Marr Park	4	4	4	4
Holland Park	5	5	3	5
Batman Park	7	6	7	6
Ievers Reserve	6	7	6	7
Pleasance Garden	8	8	8	8
R	**0.90**	**0.97**	**0.85**	**-**

Similarly, Ievers reserve and Batman Park were lowly ranked alternatives by all members of the WA group. Additionally, Pleasance Garden was rated as the lowest ranked alternative by each member of the WA group.

In order to select the WA group representative member (Section 6.3.2) for the CGDM scenario, the ranking of each WA member was compared with WA group ranking using the *R* value. From the Table 6.4, it is evident that ranking of WA-2 was in well accordance (*R*= 0.97) with the overall group ranking. Therefore, WA-2 was selected as the WA stakeholder representative member for the CGDM scenario.

6.4.2 GAIA Analysis

a) Single DM case - Water Authority (WA)

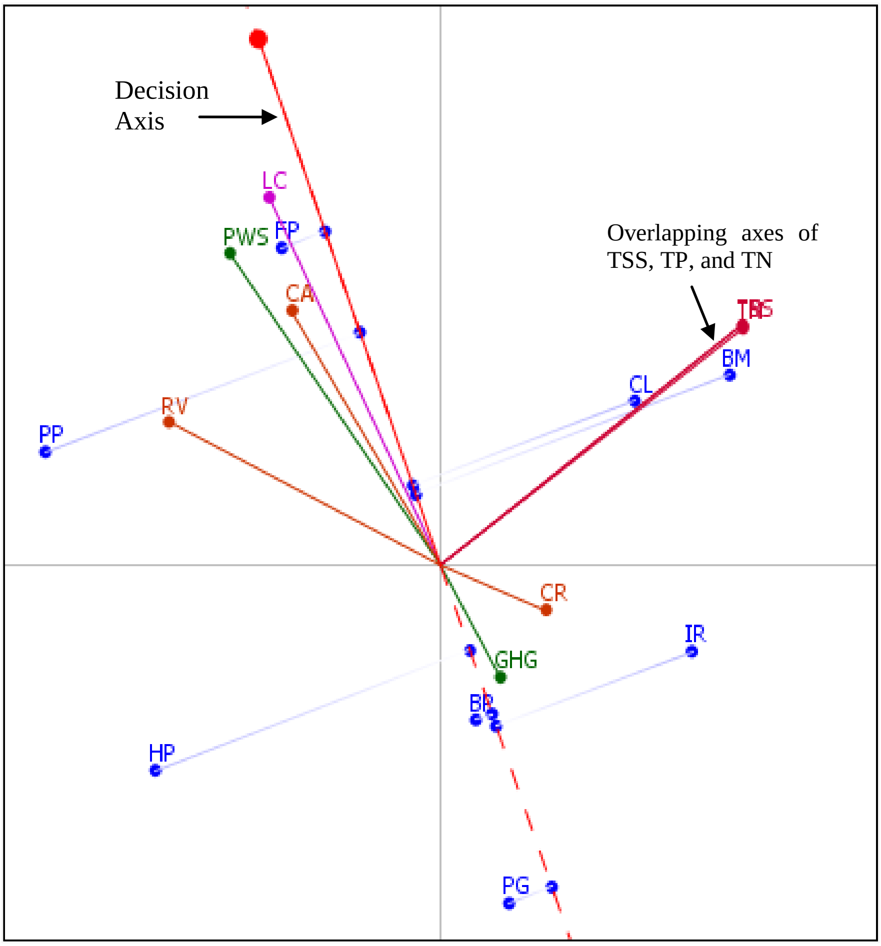
Similar to the PROMETHEE rankings, the GAIA analysis was facilitated for all single DM cases and group DM cases for each stakeholder group (i.e. WA, AC, CS and CL) in HGDM scenario. As explained in Section 6.2.2.3, GAIA provides visual interpretation of results obtained from PROMETHEE rankings of a given decision problem.

Figure 6.7 provides the interpretation of GAIA analysis for WA-2 (Single DM case) describing the relative positions of alternative sites with respect to the system PMs and resultant *pi* (or decision) axis.

In Figure 6.7, the GAIA plane had a sufficiently high value of Δ (83%) and long decision axis in red colour (marked in Figure 6.7). As this Δ value satisfied the necessary conditions reported in Section 6.2.2.3, the GAIA information obtained from WA-2 was able to derive the judgements with reasonable accuracy. Additionally, the decision axis had its projections extended in both directions (dotted red line) providing the visual aid for the directions of alternative sites with respect to the decision axis.

In Figure 6.5, the Flagstaff Park has its position closer to the direction of the decision axis. Therefore, considering properties (P1: P6) of GAIA plane in Section 6.2.2.3, Flagstaff Park is a consensus alternative site, considering the preferences of WA-2. It should be noted that Flagstaff Park is top alternative according to PROMETHEE II results of WA-2 (Table 6.4), and GAIA results assisted in validating and confirming the top ranked position of same alternative site. Similarly, the GAIA plane in Figure 6.7 also indicated the pleasance garden as a worst alternative considering its position farthest away from decision axis.

The GAIA plane in Figure 6.7 also represents the orientation of PMs with respect to the alternative stormwater harvesting sites considering preferences of WA-2. PMs such as *LC, PWS, CA, RV,* and *ARC* of *TP, TSS, and TN* had relatively long axes length indicating the major strength of differentiating the alternative stormwater harvesting sites [properties (P1:P6) in Section 6.2.2.3]. Similarly, considering the preferences of WA-2, social PMs such as *CR* and *GHG* have relatively shorter length indicating little differentiating power between alternatives.



Performance Measures

- LC : Levelised Cost
- PWS: Potable Water Savings
- GHG: Green House Gas Emission
- CA: Community Acceptance
- RV: Recreational Value
- CR: Construction Risks
- TSS, TP and TN: Annualised Removal Costs of Indicative Pollutants

Alternative Sites

- FP: Flagstaff Park
- CR: Clayton Reserve
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- HP: Holland Park
- IR: Ievers Reserve
- BP: Batman Park
- PG: Pleasance Garden

Figure 6.7: Orientation of Alternatives with Respect to Decision Axis and PMs (WA-2, $\Delta = 83\%$)

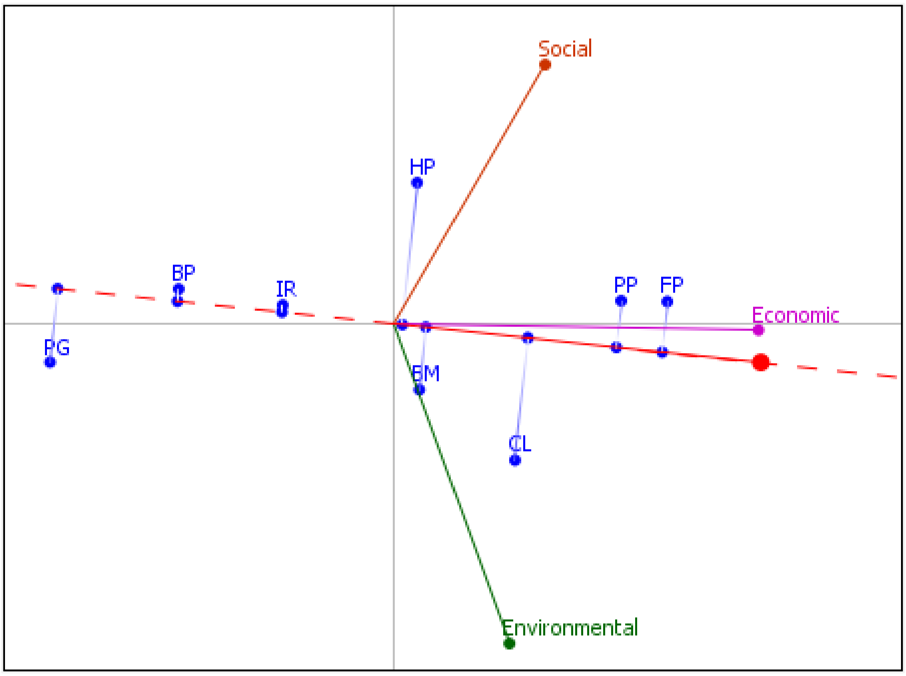
Considering the GAIA plane, it can be seen that PMs namely, *LC, PWS, CA* and *RV* are in similar direction, indicating similar preferences on PMs as per GAIA properties [properties (P1:P6) in Section 6.2.2.3]. Additionally, *CR* and *GHG* have negative correlation with *LC, PWS, CA* and *RV* as the corresponding PM axes are in opposite direction. Furthermore, the axes of *ARCs (TP, TN and TSS)* are opposite with majority of PMs (except *CR* and *GHG*).

Ideally, the negative correlation on given pair of PMs indicates conflicting preferences of decision makers on corresponding PMs. For example, in Figure 6.7, alternative sites with higher construction risks (*CR*) have lower community acceptance (*CA*) and lower recreational value (*RV*) considering the preferences of WA-2. However, such comparison of other PMs namely *CR*, *ARC* and *GHG* with each conflicting PM is impractical and it is difficult to explain in stormwater harvesting context.

Figure 6.8 represents the alternative sites in GAIA plane oriented towards the system objectives (i.e. Section 4.3) from the perspective of WA-2. Additionally, projections of alternatives drawn to decision axis are also shown. The information deduced from the GAIA plane in this case can be considered as highly reliable since the Δ value is 97.1% (Section 6.2.2.3). The decision axis in Figure 6.8 re-confirms the Flagstaff Park as topmost consensus alternative (closer in direction of decision axis) and Pleasance Garden as worst alternative (farthest in direction from decision axis).

From Figure 6.8, it was also evident that economic and environmental objective axes were longer and hence played a significant role in differentiating the alternatives with respect to the ranking [properties (P1:P6) in Section 6.2.2.3]. However, there is no apparent conflict in preferences of WA-2 as all objective axes are oriented in orthogonal position at right side of GAIA plane.

It should be noted that D-Sight allows the analysis shown in Figure 6.7 (Orientation of alternatives with respect to PMs) and Figure 6.8 (Orientation of alternatives with respect to objectives) only for Single DM case i.e. WA-2. Under GDM situations, D-Sight does not permit such analysis and only illustrates the orientation of alternative sites with respect to the DMs involved in the decision making. However, such orientation of alternative sites in GDM case would be similar to Figure 6.8 as WA-2 had similar ranking to group ranking (Table 6.4).



Performance Measures

- LC : Levelised Cost
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Alternative Sites

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- CR: Clayton Reserve
- PP: Princess Park
- BM: Birrarung Marr Park
- HP: Holland Park
- IR: Ievers Reserve
- BP: Batman Park
- PG: Pleasance Garden

Figure 6.8: Orientation of Alternative Sites with respect to Objectives (WA-2, Δ = 83%)

b) Group DM Case - WA

The GAIA plane for the WA group is illustrated in Figure 6.9. The GAIA plane in Figure 6.9 has a very high Δ value of 99.9% and a long decision axis. Therefore, the information derived from this GAIA plane can be considered highly reliable (Section 6.2.2.3). The decision axis in Figure 6.9 represents the collective consensus decision of WA-1, WA-2 and WA-3 regarding ranking of stormwater harvesting sites. The alternative Flagstaff Park located closely in the direction of decision axis is considered as the best compromising alternative [properties (P1:P6) in Section 6.2.2.3]. Additionally, the orthogonal nature of WA-1, WA-2 and WA-3 axes on the right side of plane represents the independent decisions by three DMs.

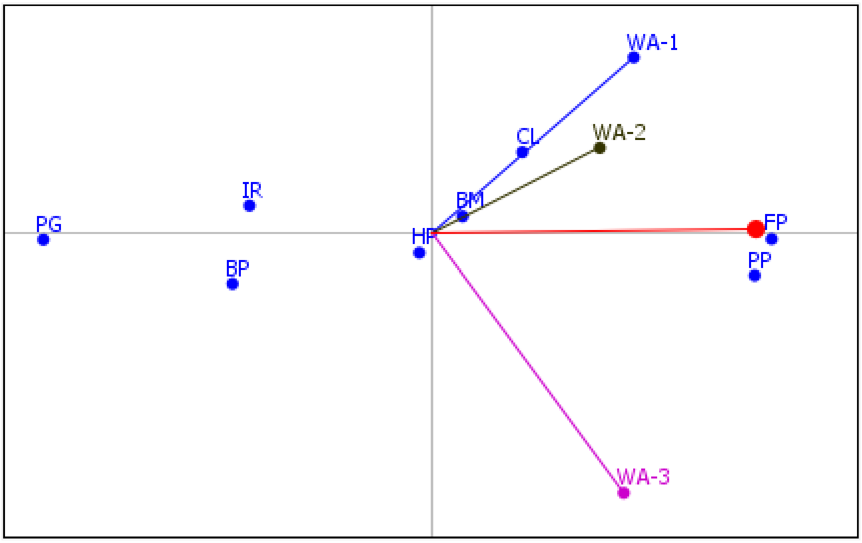


Figure 6.9: Orientation of Alternative Sites with respect to WA Group (Δ = 99.9%)

Additionally, it can be seen that axes of WA-1 and WA-2 are closer to each other compared to WA-3 which represent the similarity in ranking of WA-1 and WA-2 when compared to rankings of WA-3. Moreover, WA-2 axis is closer to the decision axis representing the consensus among WAs [properties (P1:P6) in Section 6.2.2.3]. This close nature of WA-2 axis with respect to the decision axis confirmed selection of WA-2 as WA group representative (Table 6.4) for the CGDM scenario. Figure 6.9 also clearly differentiates four distinct clusters of alternative sites (as in Figure 6.6).

6.4.3 Weight Sensitivity Analysis

For the single DM case of WA, Table 6.5 illustrates the weight sensitivity analysis in terms of weight stability intervals. As described in Section 6.2.2.5, the weight stability intervals provide the range of weights on PMs (i.e. maximum and minimum) within which the ranking of alternatives is considered stable. The ‘Weights’ column in Table 6.5 shows the weights obtained from WA-2 for all PMs considered in the study. The min/max columns in Table 6.5 indicate the range of weights which can be assigned to different PMs, so that rankings of Flagstaff Park, Princess Park and Clayton Reserve remains unchanged (at the top) among all eight stormwater harvesting sites. The weight stability interval (on a given PM) implies the stability of PM in ranking. Larger the weight stability interval of given PM, less likely is that PM will have any large effect on altering the rankings and vice versa.

In Table 6.5, the PM *Levelised cost* has the largest stability interval (69%) compared to the other PMs indicating its higher stability in rankings. The PM *GHG emissions* can be considered the most sensitive PM (in altering the rankings) as it has the smallest range of stability interval (9%). The other PMs can be also considered as sensitive given their lower ranges of stability intervals.

Table 6.5: Weight Sensitivity of WA - 2 for Top Three Alternative Sites

Performance Measures (PMs)	Weights %	Min %	Max %	Range Difference %
Levelised Cost	34	31	100	69
GHG Emissions	8	0	9	9
Potable Water Savings	13	0	16	16
TSS Removal Cost	5	4	17	13
TP Removal Cost	2	0	14	13
TN Removal Cost	5	4	17	13
Community Acceptance	11	0	20	20
Recreational Value	11	0	13	13
Construction Risks	11	0	27	27

6.5 Ranking Results - Other Stakeholders

Similar to the WA sub-group, all single DM and group DM cases within AC, CS and CL sub-groups were examined for deriving the PROMETHEE II rankings under HGDM. These rankings were further derived for two cases of PF elicitation (Assignment of PF given ranges of PMs and given evaluation matrix) as described in Section 5.6.1. Thus, the PROMETHEE II rankings obtained for each case of PF elicitation for AC, CS and CL sub-groups are described in Tables 6.6, 6.7, and 6.8 respectively.

6.5.1 Ranking Results - Academic (AC) Group

As pointed out in Section 5.7.2, the AC group consisted of three members (AC-1, AC-2, and AC-3). From Table 6.6, it is evident that ranking of AC-1 is similar for both cases of PF elicitation (i.e. C-1 and C-2). Likewise, AC-2 and GDM rankings remained unchanged for both cases.

Table 6.6: Ranking of AC Group

Alternative Sites	Single DM Rank						GDM Rank	
	AC-1		AC-2		AC-3			
	C-1[b]	C-2[b]	C-1	C-2	C-1	C-2	C-1	C-2
Princess Park	**1**[a]	1	2	2	1	1	**1**[a]	1
Flagstaff Park	**2**	2	1	1	2	2	**2**	2
Clayton Reserve	**3**	3	3	3	3	5	**3**	3
Birrarung Marr Park	**4**	4	4	4	5	4	**4**	4
Holland Park	**5**	5	5	5	4	3	**5**	5
Ievers Reserve	**6**	6	6	6	7	7	**6**	6
Batman Park	**7**	7	7	7	6	6	**7**	7
Pleasance Garden	**8**	8	8	8	8	8	**8**	8

[a]*Bold ranks indicate the selection of group representative (i.e. AC - 1)*
[b]*C-1 and C-2 represent the two cases of PF elicitation (i.e. Assignment of PFs given ranges of PMs and given evaluation matrix)*

Similar rankings of AC-1 and AC-2 indicated the robustness in PF thresholds specified by AC-1 and AC-2. However, for AC-3, there was slight difference in 3rd, 4th and 5th rank positions for two cases (highlighted in grey portion of Table 6.6), which indicated the minor inconsistency in responses of AC-3 for PF thresholds. Moreover, similar to the WA sub-group, Princess Park, Flagstaff Park, and Clayton Reserve were the best alternative sites from AC sub-group rankings. In terms of selecting the group representative for CGDM, the AC-1 was the natural choice, as his/her rankings were exactly same as the GDM rankings for the AC sub-group giving *R* value of 1.

6.5.2 Ranking Results - Consultant (CS) Group

Table 6.7 shows the rankings of the CS sub-group considering single DM and GDM cases. The individual rankings of CS-1, CS-3, and CS-4 in Table 6.7 were same for both cases of PF threshold elicitation (C-1 and C-2), reflecting the robustness in their preferences. Similar to the WA and AC sub-group rankings, the GDM ranking of the CS sub-group remained unchanged for both cases. However, the ranking of CS-2 were slightly different for 1st, 2nd and 3rd rank positions for both cases (highlighted in Table 6.7). The alternative sites Flagstaff Park, Princess Park, and Clayton Reserve were consistently ranked in top three positions among all members of the CS sub-group. In terms of CGDM representative selection, rankings of CS-1 for both cases were exactly same as GDM ranking of CS sub-group (*R*=1) and thereby making CS-1 the obvious choice as the representative CS group member for CGDM.

Table 6.7: Ranking of CS Group

Alternative Sites	Single DM case								GDM Case	
	CS-1		CS-2		CS-3		CS-4			
	C-1[b]	C-2[b]	C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2
Flagstaff Park	**1**[a]	1	2	1	2	2	1	1	**1**[a]	1
Princess Park	**2**	2	1	3	1	1	2	2	**2**	2
Clayton Reserve	**3**	3	3	2	3	3	3	3	**3**	3
Birrarung Marr Park	**4**	4	4	4	5	5	5	5	**4**	4
Holland Park	**5**	5	5	5	4	4	4	4	**5**	5
Ievers Reserve	**6**	6	6	6	7	7	7	7	**6**	6
Batman Park	**7**	7	7	7	6	6	6	6	**7**	7
Pleasance Garden	**8**	8	8	8	8	8	8	8	**8**	8

[a] *Bold ranks indicate the selection of group representative (i.e. CS - 1)*
[b] *C-1 and C-2 represent the two cases of PF elicitation*
(i.e. Assignment of PFs given ranges of PMs and given evaluation matrix)

6.5.3 Ranking Results - Council (CL) Group

As pointed out in Section 5.6, only single person represented the CL group. Table 6.8 shows the rankings of alternatives sites considering preferences of CL-1. From Table 6.8, it is evident that rankings of alternative sites for both cases were exactly the same, except the swapping top two ranks. The top three alternatives sites i.e. Flagstaff Park, Princess Park, and Clayton Reserve were in good agreements with the results of WA, AC and CS sub-group. The GDM case was not applicable for the CL sub-group as CL-1 was the only member considered for obtaining the preferences. Therefore, CL-1 was the default choice for CGDM.

Table 6.8: Ranking of CL Group

Council	CL-1	
	C-1[a]	C-2[a]
Flagstaff Park	1	2
Clayton Reserve	2	1
Princess Park	3	3
Birrarung Marr Park	4	4
Holland Park	5	5
Ievers Reserve	6	6
Batman Park	7	7
Pleasance Garden	8	8

[a]C-1 and C-2 represent the two cases of PF elicitation
(I.e. Assignment of PFs given ranges of PMs and given evaluation matrix)

6.6 CGDM Results

As described in Section 6.3.2, CGDM was conducted for three different hypothetical group decision making situations in order to study the effect of varying group composition on rankings. In the first case, four sub-group representatives (WA, AC, CS and CL) were (from the HGDM scenario) selected to form Group 1 to represent a heterogeneous group of stakeholders with equal representation. For this purpose, WA-2, AC-1, CS-1 and CL-1 were selected as the Group 1 representatives from each stakeholder sub-group (as described in Sections 6.4 and 6.5). However, as pointed out in Section 5.6, water authority and councils constitute as key stakeholders for stormwater harvesting projects. Therefore, as a second case of CGDM, Group 2 represented a decision making group with more weight on WA and CL group members. To formulate the Group 2, twice the weight of AC-1 and CS-1 was given to WA-2 and CL-1. Furthermore, All DM represented a third decision making group considering all participants in each stakeholder sub-group.

Thus, the three groups had member representation as

- Group 1: WA-2, CS-1, AC-2 and CL-1
- Group 2: 2 * WA-2, 2 * CL-1, CS-1, and AC-2
- All DM: WA-1, WA-2, WA-3, AC-1, AC-2, AC-3, CS-1, CS-2, CS-3, CS-4, and CL-1

The ranking of stormwater harvesting sites was then considered under these three group decision making situations. It should be noted that the CGDM scenario used only Case 1 data set of PF thresholds (Section 5.6.1.2) along with the weights specified by respective DMs (Section 5.6.2) to facilitate the decision making process. Case 1 data were selected as it provided decision maker preferences on PMs in more general terms compared to Case 2 data, where preferences on PMs were exclusively limited to evaluation matrix (Section 5.6.1.3) used in study. As described in Section 6.2, the D-Sight software facilitated the decision analysis process.

6.6.1 Ranking Results - CGDM Group 1

The PROMETHEE II rankings of Group 1 are shown in Figure 6.12. Similar to the HGDM scenario, four clusters of alternative sites were clearly distinguishable in Figure 6.12. Flagstaff Park, Princess Park and Clayton Reserve were the top three highly ranked alternative stormwater harvesting sites. Similarly, Pleasance Garden is rated as lowest ranked alternative considering Group 1 preferences.

The GAIA plane results for Group 1 are presented in Figure 6.13. Considering the high Δ value (99.7%) and the longer decision axis length, the properties P1:P6 described in Section 6.2.2.3 are valid to deduce judgements on the decision problem.

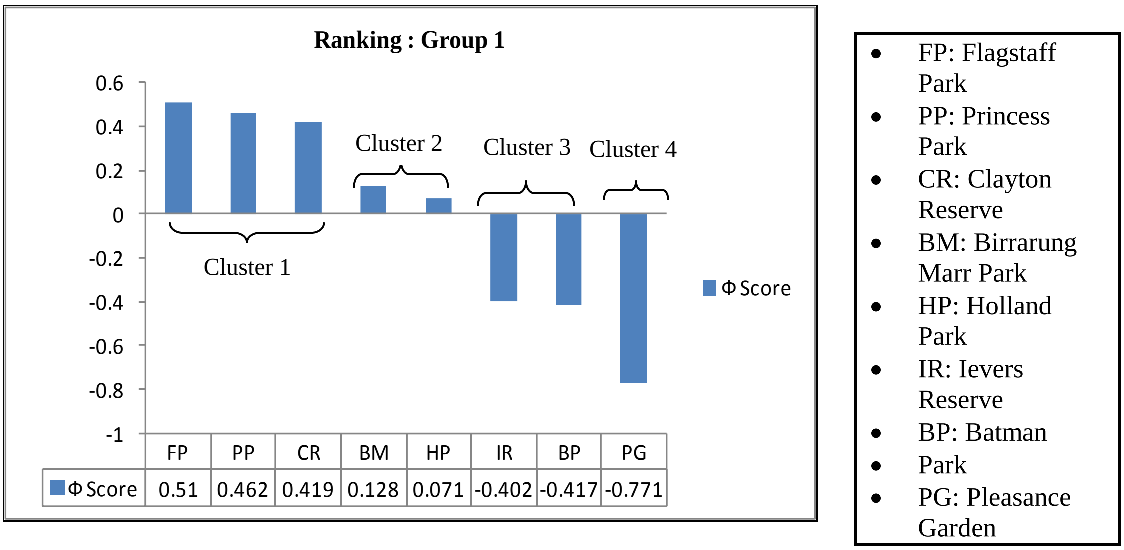
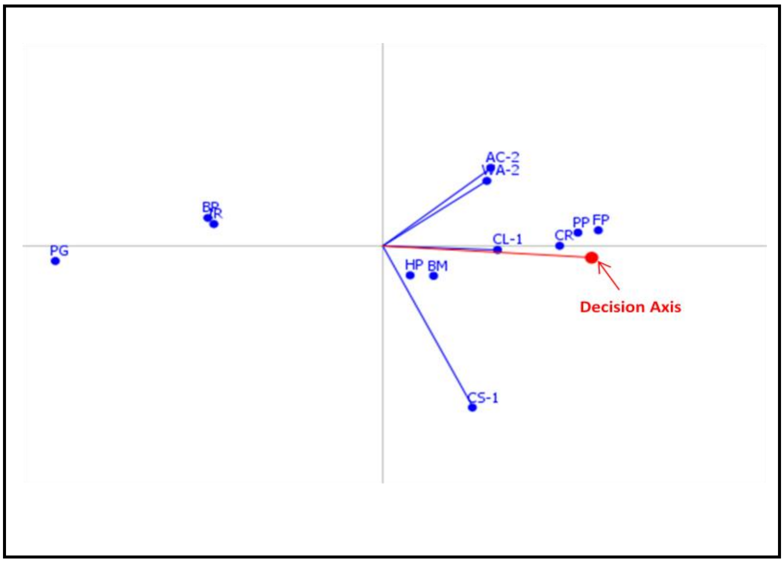


Figure 6.12: PROMETHEE II Results for Group 1



- FP: Flagstaff Park
- PP: Princess Park
- CR: Clayton Reserve
- BM: Birrarung Marr Park
- HP: Holland Park
- IR: Ievers Reserve
- BP: Batman
- Park
- PG: Pleasance Garden

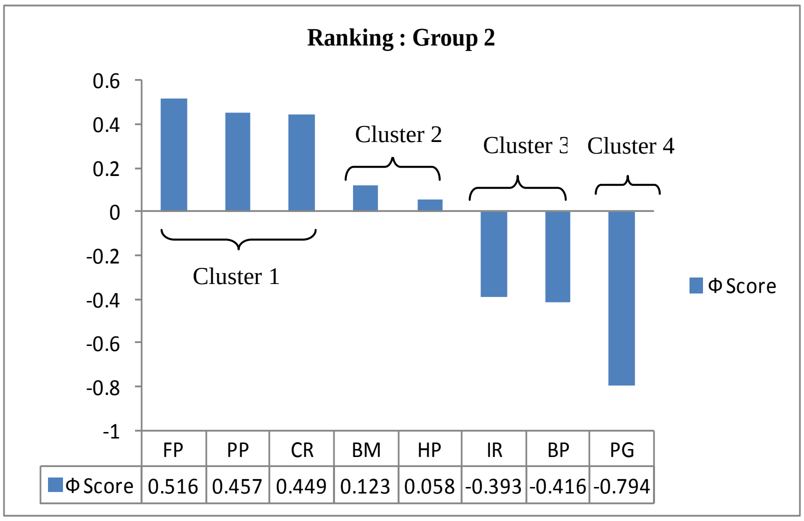
Figure 6.13: GAIA Results - Group 1

The cluster of Flagstaff Park, Princess Park and Clayton Reserve which is located closer to the direction of the decision axis represents the top alternatives. Considering the long axes length, WA-2 AC-2 and CS-1 have significant contribution in altering the ranking of Group 1 (as per properties P1:P6 described in Section 6.2.2.3) when compared to CL-1, which had shorter axes length.

The GAIA plane results are particularly useful in identifying the agreements and conflicts among the stakeholder groups. In Figure 6.13, AC-2 and WA-2 have similar preferences as their axes are oriented in the same direction (as per properties P1:P6 explained in Section 6.2.2.3). Furthermore, all DM axes (AC-2, WA-2, CL-1, and CS-1) are on right side of the plane and oriented in orthogonal direction, indicating the independent preferences with no apparent conflict in decision making (as per properties P1:P6 described in Section 6.2.2.3) . Therefore, it can be deduced that DMs in the group are in general agreement with each other.

6.6.2 Ranking Results - CGDM Group 2

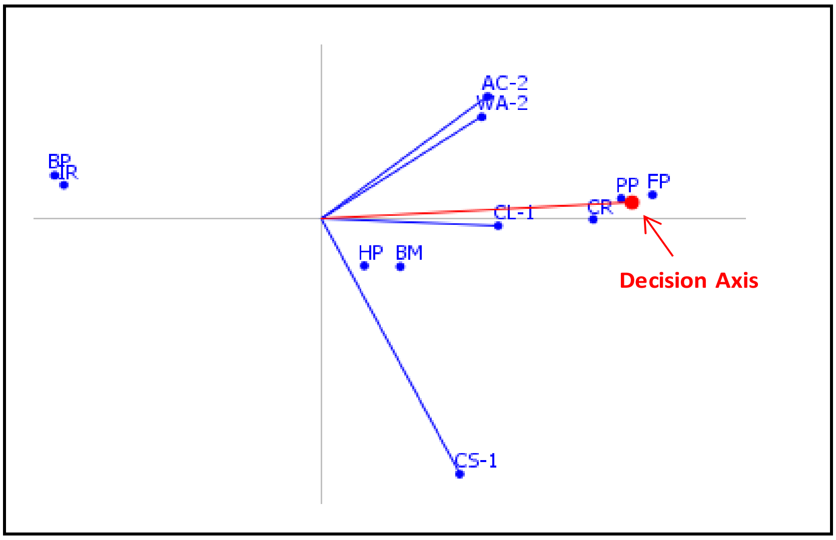
The PROMETHEE II rankings for Group 2 are shown in Figure 6.14. The rankings of Group 2 members were exactly same as ranking of Group 1 members (as discussed in Section 6.6.1). The Flagstaff Park, Princess Park and Clayton Reserve were emerged as the top alternatives again, even with the additional weightings of WA-2 and CL-1.



- FP: Flagstaff Park
- PP: Princess Park
- CR: Clayton Reserve
- BM: Birrarung Marr Park
- HP: Holland Park
- IR: Ievers Reserve
- BP: Batman Park
- PG: Pleasance Garden

Figure 6.14: PROMETHEE II Results for Group 2

The GAIA plane for Group 2 is shown in Figure 6.15. This plane has a Δ value of 99.7% and a considerably long decision axis (marked in red colour in Figure 6.15), which satisfies the necessary conditions P1: P6 of GAIA plane in Section 6.2.2.3, and hence the result interpretation from the GAIA plane can be considered reliable. Similar to Figure 6.13, four clusters of alternative stormwater harvesting sites are distinguishable in Figure 6.15. Similar to Group 1, all DM axes in Group 2 are approximately in similar directions (right side) of the GAIA plane, indicating the general agreement between DMs.



- FP: Flagstaff Park
- PP: Princess Park
- CR: Clayton Reserve
- BM: Birrarung Marr Park
- HP: Holland Park
- IR: Ievers Reserve
- BP: Batman Park
- PG: Pleasance Garden

Figure 6.15: GAIA Results - Group 2

6.6.3 Ranking Results - All DM Case for CGDM

The PROMETHEE II ranking order derived from all stakeholder group members of WA, AC, CS, and CL subgroups was exactly same as Group 1 and Group 2 rankings (Figure 6.12 and 6.14). The Flagstaff Park, Princess Park and Clayton Reserve consistently ranked as top three alternative stormwater harvesting sites (A figure with ranking of All DM case is not shown to avoid repetition).

6.6.4 Weight Sensitivity Analysis for CGDM

In the current study, the weight sensitivity analysis was done by analysing the stability of the top three alternative sites (i.e. Flagstaff Park, Princess Park and Clayton Reserve) ranked by Group 1 and 2 members (viz. Section 6.6.1 and 6.6.2). Weight sensitivity analysis was studied through the weight stability interval feature of D-Sight, similar to Section 6.4.3. The results of the weight stability intervals for weight sensitivity analysis of Group 1 and 2 are shown in Table 6.9 and 6.10 respectively.

Under the GDM situations, the weight stability interval provides a range of weights (maximum/minimum) for each group member at desired stability level of ranks (e.g. top three ranks as used in this study). For a given group member, with large weight stability intervals (i.e. larger variation in the weights), it is less likely that he/she will influence the rankings and vice versa. It should be noted that the weight sensitivity analysis is conducted considering one stakeholder at a time while the weights of other stakeholders kept at their weights.

As seen from Tables 6.9 and 6.10, the weight stability intervals specify the ranges of the weights (minimum and maximum) that can be allocated different stakeholders (or simply members) from Group 1 and 2 so that the stability (i.e. ranking positions) of top three sites will not change among the eight sites. The weight column in Table 6.9 reflects the equal representation of stakeholders, while the weight column in Table 6.10 reflects the more importance given to WA and CL sub-groups as discussed in Section 6.6.

Table 6.9: Weight Sensitivity of Group 1 for Top Three Alternative Sites (Flagstaff Park, Princess Park and Clayton Reserve)

Member	Weight	Weight %	Min %	Max %	Range Variation %
WA-2	1	25	0	55	55
CL-1	1	25	0	53	53
AC-2	1	25	11	98	87
CS-1	1	25	0	100	100

The results obtained from Table 6.9 show that both AC-2 and CS-1 provide the maximum variation in the weights (viz. 87% and 100%). This maximum variation indicates that stability for top three ranked sites (Flagstaff Park, Princess Park and Clayton Reserve), is not influenced by the weights of AC-2 and CS-1, virtually making them inconsequential in decision making. Furthermore, WA-2 and CL-1 also provide 55 and 53% variation in weights respectively, which can be considered sufficiently large to affect the stability of the top three ranks. Therefore, it can be concluded that, weights assigned to members of Group 1 have minimum influence on rankings of top three alternative sites.

Table 6.10: Weight sensitivity of Group 2 for Top Three Alternative Sites (Flagstaff Park, Princess Park and Clayton Reserve)

Member	Weight	Weight %	Min %	Max %	Range Variation %
WA-2	2	33	0	40	40
CL-1	2	33	0	39	39
AC-2	1	17	**15**	**98**	**83**
CS-1	1	17	**0**	**100**	**100**

Table 6.10 results show that Flagstaff Park, Princess Park and Clayton Reserve will remain the top alternative sites in Group 2, regardless of weight assigned to CS-1 as he/she has 100% variation in the weights. Similarly AC-2 has 83% variation in weight, indicating little influence in ranking of top three alternative sites. The WA-2 (40%) and CL-1 (39%) have relatively less weight variation compared to AC-2 and CS-1. Nonetheless, this variation in weight can be considered as marginally influential to alter the stability order of top three sites.

In summary, weight sensitivity results of both groups showed that Flagstaff Park, Princess Park and Clayton Reserve were top ranked stormwater harvesting sites, with minimum effect of weight variation on rankings.

6.6.5 Robustness Analysis for CGDM

Ranking results of Groups 1 and 2 provided insight on identifying the top three ranked alternative stormwater harvesting sites (i.e. Flagstaff Park, Princess Park and Clayton Reserve) in the case study area. Similar to the sensitivity analysis, a robustness analysis was performed for both groups through analysing weight stability intervals. However, the robustness analysis approach was different only in terms of examining the ranking and stability order of the top three ranked alternative sites with respect to different group compositions of stakeholders (i.e. by altering the Group 1 and 2 compositions).

The robustness analysis was carried out in two stages:

- Stage 1: Group compositions of Group 1 and 2 were altered and consequential ranking results were examined.
- Stage 2: Weight sensitivity analysis was again performed for each altered compositions of both groups from Stage 1. This procedure allowed studying the stability of top three ranked alternative sites.

The detailed results for robustness analysis are explained in Section 6.6.5.1 and 6.6.5.2.

6.6.5.1 Robustness Analysis by Altering Group Compositions

By varying the group compositions, it was possible to analyse the robustness of ranking results of the top three stormwater harvesting sites for Group 1 (WA-2, CL-1, AC-2 and CS-1) and Group 2 (2 x WA-2, 2 x CL-1, AC-2, and CS-1). The change in group composition for both groups was made by selecting random members from each stakeholder subgroup, while keeping the same proportion of weights as of original group member proportion (Section 6.6).

The robustness assessment in ranking for Groups 1 and 2 was done by selecting ten different random variations (or compositions) from the original group composition of both groups (Section 6.6). The rankings of stormwater harvesting sites obtained from these variations are shown are shown in Tables 6.11 and 6.12 for Groups 1 and 2 respectively.

As seen from Tables 6.11 and 6.12, Flagstaff Park (highlighted in black bold) is constantly ranked at the top for majority of different compositions of Group 1 and Group 2. However, for composition no. 4 for Table 6.11 (Group 1), Flagstaff Park and Clayton Reserve were almost equally ranked for the top position with net preference flow values of 0.525 and 0.52 respectively. A similar case was observed in Table 6.12 (Group 2), where both Flagstaff Park (0.545) and Clayton Reserve (0.544) were ranked closely. Furthermore, Princess Park was ranked at the top only for combination no. 7 in both Tables 6.11 and 6.12 considering the high net preference flow values (0.513 and 0.518).

Considering the results of Tables 6.11 and 6.12, Princess Park and Clayton Reserve (highlighted in black bold) shared second and third ranking positions consistently for ten different variations of Groups 1 and 2. Furthermore, the other stormwater harvesting sites had similar ranking positions (From 4 to 8) for both Group 1 and Group 2.

Table 6.11: Ranking of Stormwater Harvesting Sites from Group 1 and Its Compositions

No.	Group 1 and Its Compositions		Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8
1	WA -2, CL-1, AC-2, CS-1 (Group 1)	Alternative Site	**FP**	**PP**	**CR**	BM	HP	IR	BP	PG
		Φ Score	0.51	0.462	0.419	0.128	0.071	-0.402	-0.417	-0.771
2	WA-1, CL-1, AC-1, CS-2	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.524	0.502	0.467	0.141	0.09	-0.422	-0.474	-0.828
3	WA-1, CL-1, AC 3, CS-4	Alternative Site	**FP**	**CR**	**PP**	BM	HP	BP	IR	PG
		Φ Score	0.594	0.535	0.491	0.081	0.044	-0.419	-0.465	-0.861
4	WA-1, CL-1, AC-3, CS-2	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.525	0.52	0.447	0.139	0.097	-0.425	-0.463	-0.84
5	WA-3, CL-1, AC-3, CS-3	Alternative Site	**FP**	**PP**	**CR**	BM	HP	IR	BP	PG
		Φ Score	0.486	0.483	0.366	0.144	0.141	-0.417	-0.435	-0.769
6	WA-3, CL-1, AC-1, CS-4	Alternative Site	**FP**	**PP**	**CR**	BM	HP	IR	BP	PG
		Φ Score	0.544	0.508	0.418	0.105	0.095	-0.419	-0.427	-0.824
7	WA-3, CL-1, AC-3, CS-2	Alternative Site	**PP**	**FP**	**CR**	HP	BM	IR	BP	PG
		Φ Score	0.513	0.507	0.359	0.152	0.13	-0.421	-0.436	-0.804
8	WA-2, CL-1, AC-1, CS-2	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.504	0.47	0.459	0.138	0.073	-0.386	-0.456	-0.803
9	WA-2, CL-1, AC-1, CS-3	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.487	0.461	0.447	0.143	0.09	-0.399	-0.454	-0.775
10	WA-2, CL-1, AC-3, CS-4	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.556	0.505	0.481	0.092	0.051	-0.415	-0.427	-0.843

FP: Flagstaff Park	CR: Clayton Reserve	PP: Princess Park	BM: Birrarung Marr Park	HP: Holland Park	IR: Ievers Reserve	BP: Batman Park	PG: Pleasance Garden

Table 6.12: Ranking of Stormwater Harvesting Sites from Group 2 and Its Compositions

No.	Group 2 and Its Compositions		Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8
1	2WA-2, 2CL-1, AC-2, CS-1 (Group 2)	Alternative Site	**FP**	**PP**	**CR**	BM	HP	IR	BP	PG
		Φ Score	0.516	0.457	0.449	0.123	0.058	-0.393	-0.416	-0.794
2	2WA-1, 2CL-1, AC-1, CS-2	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.544	0.533	0.46	0.127	0.07	-0.432	-0.458	-0.844
3	2WA-1, 2CL -1, AC-3, CS-4	Alternative Site	**FP**	**CR**	**PP**	BM	HP	BP	IR	PG
		Φ Score	0.592	0.555	0.476	0.086	0.039	-0.421	-0.461	-0.866
4	2WA-1, 2CL -1, AC-3, CS-2	Alternative Site	**CR**	**FP**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.545	0.544	0.447	0.125	0.075	-0.434	-0.451	-0.852
5	2WA -3, 2CL-1, AC -3, CS-3	Alternative Site	**FP**	**PP**	**CR**	BM	HP	IR	BP	PG
		Φ Score	0.499	0.497	0.351	0.136	0.133	-0.412	-0.423	-0.781
6	2WA -3, 2CL -1, AC-1, CS-4	Alternative Site	**FP**	**PP**	**CR**	BM	HP	IR	BP	PG
		Φ Score	0.538	0.514	0.386	0.11	0.102	-0.413	-0.417	-0.819
7	2WA-3, 2CL -1, AC-3, CS-2	Alternative Site	**PP**	**FP**	**CR**	HP	BM	IR	BP	PG
		Φ Score	0.518	0.512	0.346	0.141	0.127	-0.415	-0.424	-0.805
8	2WA-2, 2CL-1,AC-1, CS-2	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.512	0.477	0.462	0.13	0.059	-0.382	-0.442	-0.816
9	2WA-2, 2CL-1, AC-1, CS-3	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.501	0.468	0.456	0.133	0.071	-0.39	-0.441	-0.797
10	2WA-2, 2CL-1, AC-3, CS-4	Alternative Site	**FP**	**CR**	**PP**	BM	HP	IR	BP	PG
		Φ Score	0.552	0.502	0.476	0.092	0.05	-0.407	-0.417	-0.847

FP: Flagstaff Park	CR: Clayton Reserve	PP: Princess Park	BM: Birrarung Marr Park	HP: Holland Park	IR: Ievers Reserve	BP: Batman Park	PG: Pleasance Garden

6.6.5.2 Robustness Analysis by Weight Stability Intervals

As explained in Section 6.6.4, under the GDM situations, the weight stability intervals of D-Sight provide the weight ranges (minimum and maximum) of each stakeholder (or simply member) in collective decision.

The weight stability intervals computed for 'Group 1 & its compositions' and 'Group 2 & its compositions' are shown in Tables 6.13 and 6.14 respectively. The purpose of this analysis was to examine the stability of top three ranks obtained from PROMETHEE II rankings (Table 6.11 and 6.12) under different stakeholder compositions. More importantly, for all considered compositions of Groups 1 and 2, the weight stability intervals (in terms of weight variation) specified the ability of group members to influence the ranking of top three sites. i.e. Flagstaff Park, Princess Park and Clayton Reserve.

Smaller weight variation for given group member indicate his/her higher influence on changing the stability of top three ranks. For example, WA-3 in composition no. 5 of Table 6.13 can be considered influential as his/her weight variation is very less (23%) compared to the other group members. Such influential members in each group composition are represented in bold red colour in Tables 6.13 and 6.14. Contrastingly, members with largest weight variations indicated marginal influence in group decisions and they are represented in bold red colour in Tables 6.13 and 6.14 for Groups 1 and 2 respectively.

Tables 6.15 and 6.16 provide the average weight variation for each member across different compositions in Group 1 and Group 2. Additionally, the combined average of weight variation from each stakeholder group (i.e. WA, CL, AC and CS) is also shown in these tables. From Table 6.15, it can be seen that the WA sub-group has relatively smaller weight variation (51.4%) compared to CL, AC and CS sub-groups. However, this weight variation can be considered sufficiently large to have lesser influence on the stability of the top three ranked sites (i.e. Flagstaff Park, Princess Park and Clayton Reserve). Similarly, in case of Table 6.16, all stakeholder compositions have relatively sufficiently large weight stability intervals with CL being largest (69%). Therefore, it can be concluded that, rankings of top three stormwater harvesting sites is not considerably influenced by both 'Group 1 & its compositions' and 'Group 2 & its compositions' and thus robustness in rankings is verified.

Table 6.13: Weight Stability Intervals for Group 1 and Its Compositions

Composition No.	Members	Weight %	Min %	Max %	Variation %	Composition No.	Members	Weight %	Min %	Max %	Variation %
1 (Group 1)	WA - 2	25	0	55	55	6	**WA - 3**	**25**	**8**	**48**	**40**
	CL - 1*	**25**	**0**	**53**	**53**		CL - 1	25	0	66	66
	AC - 2	25	11	98	87		**AC - 3**	**25**	**0**	**90**	**90**
	CS - 1**	**25**	**0**	**100**	**100**		CS - 4	25	0	75	75
2	WA - 1	25	12	58	47	7	WA - 3	25	18	83	65
	CL - 1	**25**	**0**	**100**	**100**		**CL - 1**	**25**	**0**	**31**	**31**
	AC - 1	**25**	**0**	**40**	**40**		AC - 3	25	0	37	37
	CS - 2	25	0	66	66		**CS - 4**	**25**	**15**	**99**	**84**
3	WA - 1	25	7	76	69	8	WA - 2	25	0	36	36
	CL - 1	**25**	**0**	**100**	**100**		**CL - 1**	**25**	**0**	**34**	**34**
	AC - 3	**25**	**0**	**48**	**48**		AC - 1	25	19	55	37
	CS - 4	25	0	72	72		**CS - 2**	**25**	**2**	**100**	**98**
4	**WA - 1**	**25**	**0**	**37**	**37**	9	WA - 2	25	0	39	39
	CL - 1	**25**	**0**	**100**	**100**		CL - 1	25	0	37	37
	AC - 3	**25**	**0**	**100**	**100**		**AC - 1**	**25**	**16**	**51**	**35**
	CS - 2	25%	4	79	75		**CS - 3**	**25**	**2**	**71**	**69**
5	**WA - 3**	**25%**	**2**	**28**	**26**	10	**WA - 2**	**25**	**18**	**100**	**82**
	CL - 1	25%	22	71	49		CL - 1	25	19	100	81
	AC - 3	**25%**	**17**	**92**	**76**		**AC - 3**	**25**	**0**	**30**	**30**
	CS - 3	25%	0	38	38		CS - 4	25	0	38	38

*bold red indicates group member with higher influence for given composition

**bold black indicates group member with lesser influence for given composition

Table 6.14: Weight Stability intervals for Group 2 & Its Compositions

Composition No.	Members	Weight %	Min %	Max %	Variation %	Composition No.	Members	Weight %	Min %	Max %	Variation %
1 (Group 2)	WA - 2	33	0	40	40	6	**WA - 3**	**33**	**10**	**48**	**39**
	CL - 1*	**33**	**0**	**39**	**39**		CL - 1	33	3	75	72
	AC - 2	17	15	98	83		**AC - 3**	**17**	**0**	**92**	**92**
	CS - 1**	**17**	**0**	**100**	**100**		CS - 4	17	0	78	78
2	WA - 1	33	2	52	50	7	WA - 3	33	29	85	56
	CL - 1	**33**	**0**	**100**	**100**		CL - 1	33	0	37	37
	AC - 1	**17**	**5**	**46**	**41**		**AC - 3**	**17**	**0**	**28**	**28**
	CS - 2	17	0	77	77		**CS - 4**	**17**	**9**	**99**	**90**
3	WA - 1	33	0	70	70	8	**WA - 2**	**33**	**13**	**100**	**88**
	CL - 1	**33**	**0**	**100**	**100**		CL - 1	33	16	100	84
	AC - 3	**17**	**0**	**53**	**53**		**AC - 1**	**17**	**0**	**25**	**25**
	CS - 4	17	0	79	79		CS - 2	17	0	38	38
4	**WA - 1**	**33**	**33**	**100**	**68**	9	**WA - 2**	**33**	**17**	**100**	**83**
	CL - 1	33	0	37	37		CL - 1	33	20	100	80
	AC - 3	**17**	**0**	**18**	**18**		**AC - 1**	**17**	**0**	**24**	**24**
	CS - 2	17	0	18	19		CS - 3	17	0	31	31
5	**WA - 3**	**33**	**5**	**35**	**30**	10	**WA - 2**	**33**	**0**	**100**	**100**
	CL - 1	33	31	77	46		**CL - 1**	**33**	**0**	**100**	**100**
	AC - 3	**17**	**12**	**93**	**81**		**AC - 3**	**17**	**0**	**36**	**36**
	CS - 3	17	0	25	25		CS - 4	17	0	58	58

*bold red indicates group member with higher influence for given composition
**bold black indicates group member with lesser influence for given composition

Table 6.15: Average and Combined Weight Variation for Group 1 & Its Compositions

Members	Average Variation By Each Member (%)	Combined Average Variation By Each Sub-group (%)
WA-1	52	51.4
WA-2	58.6	
WA-3	43.7	
CL-1	65.1	65.1
AC-1	50.5	68.5
AC-2	97	
AC-3	58.2	
CS-1	100	75
CS -2	79.6	
CS-3	53.5	
CS-4	67.2	

Table 6.16: Average and Combined Weight Variation for Group 2 & Its Compositions

Members	Average Variation By Each Member (%)	Combined Average Variation By Each Sub-group (%)
WA-1	77.25	60.4
WA-2	62.6	
WA-3	41.6	
CL-1	69.5	69.5
AC-1	45.5	57.2
AC-2	83	
AC-3	43.2	
CS-1	100	62
CS -2	44	
CS-3	28	
CS-4	76	

6.7 Recommendations for Suitable Stormwater Harvesting Alternative Sites

The results of PROMETHEE II rankings obtained from Group 1 (WA-2, CS-1, AC-2, CL-1), Group 2 (2 * WA-2, 2 * CL-1, CS-1, AC-2), and All DM case indicated the same ranks of stormwater harvesting sites (Sections 6.6.1, 6.6.2, 6.6.3 respectively). Therefore, Flagstaff Park was considered as the most preferred alternative stormwater harvesting site considering its top performance (Φ score) in both groups. Similarly, Princess Park and Clayton Reserve were emerged as the next best alternative sites for both groups. Apart from the top three alternatives, Holland Park and Birrarung Marr Park were consistently ranked in mid positions and Pleasance Garden was rated as the lowest ranked alternative for all GDM situations.

The highly ranked alternative sites Flagstaff Park, Princess Park and Clayton Reserve were examined for weight sensitivity analysis and robustness analysis for both groups. The results of the weight sensitivity analysis showed that Flagstaff Park, Princess Park and Clayton Reserve were top ranked stormwater harvesting sites, with minimum impact of assigned weights to alter the rankings.

The PROMETHEE II rankings obtained from ten different compositions of Group 1 (Table 6.11) and Group 2 (Table 6.12) conclusively confirmed that Flagstaff Park, Princess Park and Clayton Reserve were suitable sites (top three) for the City of Melbourne case study area. Similar ranking orders were observed for the other stormwater harvesting sites for the considered different compositions of Group 1 and 2. To validate the general robustness of top three sites, weight stability intervals displayed sufficiently large weight variation (average) from each stakeholder sub-group of WA, CL, AC and CS in Tables 6.15 and 6.16. Therefore, in summary, Flagstaff Park, Princess Park and Clayton Reserve are the recommended stormwater harvesting sites based on the overall MCDA assessment conducted in this Study.

6.8 Summary

The uncertainty in MCDA models can be ‘internal’, arising from human judgements in decision process or ‘external’ coming from the environment which is beyond the control of decision maker. In the present study, the ‘internal’ uncertainty is examined which is associated with the preferences of stakeholders which served input to PROMETHEE, the selected MCDA method. Additionally, the robustness analysis was considered as an integral requirement of MCDA models (including PROMETHEE) to verify the validity of results under different scenarios/inputs.

For decision analysis, the PROMETHEE MCDA methodology required data input in terms of preference functions, weights, and evaluation matrix of performance measures and alternative stormwater harvesting sites. The D-Sight software was used in MCDA analysis.

The decision analysis methodology broadly consisted of deriving PROMETHEE II rankings of eight alternative stormwater harvesting sites in the study area (i.e. City of Melbourne), examining the associated GAIA interpretations, and facilitating sensitivity and robustness analysis under selected group decision making (GDM) scenarios.

For decision analysis, the study considered two GDM scenarios, representing homogenous and heterogeneous stakeholder groups. For Homogenous Group Decision Making (HGDM) scenario, the study evaluated the rankings of stormwater harvesting sites separately, under four homogenous stakeholder sub-groups namely Water Authority (WA), Academics (AC), Consultants (CS) and Councils (CL) to reflect the different perspectives on stormwater harvesting decision making. Under the Collective Group Decision Making (CGDM) scenario, three group decision making situations were considered, which reflected the compromised ranking of stormwater harvesting sites under consensus of diverse stakeholder group.

To ascertain the validity of ranking results under these GDM situations, sensitivity analysis and robustness analysis was carried out to examine the stability of top ranking positions under different group compositions and weights. Based on the overall decision analysis, Flagstaff Park, Princess Park, and Clayton Reserve were clearly emerged as the top three highly ranked alternative stormwater harvesting sites for the case study area of CoM. Additionally, it was also found that top three ranked sites followed similar order regardless of different decision making situations and weightings.

Chapter 7: Summary, Conclusions and Recommendations

7.1 Summary

This final chapter summarises the work conducted to accomplish the aims of the research study, the conclusions inferred from the analysis and recommendations for future work.

Stormwater harvesting and reuse are emerging as a valuable alternative water resource to counter the challenges of rapid urbanisation, increasing population and climate change on the availability of fresh water sources. In this regard, identification of suitable sites for stormwater harvesting is significantly important. Furthermore, stormwater harvesting sites often need to be evaluated with respect to triple bottom line (TBL) objectives (i.e. economic, environmental and social), considering diverse views of associated stakeholders. The literature review highlighted the need for a comprehensive assessment methodology, which can support the selection of suitable stormwater harvesting sites in urban areas, and facilitate decision making under TBL objectives. The current study addressed this research gap.

The developed stormwater evaluation methodology was based on integration of two distinct methods: Geographical Information Systems (GIS) and Multi Criteria Decision Analysis (MCDA). The study formulated a GIS based screening methodology to identify the potential stormwater harvesting sites in a given urban development area, and facilitated MCDA evaluation to rank these stormwater harvesting sites under stakeholder driven TBL objectives. To develop the GIS-MCDA based evaluation framework, this study comprehensively reviewed different approaches, aspects and principles of GIS and MCDA applications. After investigating different MCDA methods, the study selected 'PROMETHEE', an outranking decision analysis method and its associated commercially available software named 'D-Sight'.

The developed GIS based screening methodology was successfully demonstrated its effectiveness in terms of site selection in case studies representing a highly urbanised area (City of Melbourne) and a semi urbanized area (City of Brimbank). These areas are serviced by the local water authority, City West Water in Melbourne, Australia.

For MCDA evaluation, this study selected a set of eight alternative stormwater harvesting sites obtained from the GIS based screening tool in the City of Melbourne area (CoM). Additionally, the study developed a set of nine performance measures (PMs) describing the performance of stormwater harvesting systems under TBL (economic, social, and environmental) objectives. Various relevant evaluation procedures were used to estimate the values of selected PMs for all the stormwater harvesting alternative sites. The PM estimates on the eight stormwater harvesting sites were presented in the form of an evaluation matrix, which served as input for the MCDA evaluation through PROMETHEE.

The decision making for the sustainable stormwater harvesting site requires effective collaboration and input from diverse range of stakeholders including designers, local government, water authority and communities. To reflect the stakeholder interests in the current study, four stakeholder participant groups were identified, namely, water authorities (WA), academics (AC), consultants (CS), and councils (CL). Eleven participants from four identified stakeholder groups expressed their preferences on the (nine) PMs. These preferences of stakeholders were further combined with the evaluation matrix and used as input for decision analysis conducted through the PROMETHEE based D-Sight software.

The decision analysis methodology broadly consisted of deriving PROMETHEE II rankings of eight alternative stormwater harvesting sites in the CoM case study area, under two distinct group decision making scenarios, namely homogenous group decision making (HGDM) and collective group decision making (CGDM). The HGDM scenario consisted of decision analysis from each homogenous sub-groups of stakeholders (WA, AC, CS and CL), and the CGDM scenario consisted of decision analysis with a selective representative stakeholder from each sub-group of HGDM scenario. Additionally, visual displays of ranking results were demonstrated to provide clear insight into the behaviour of the alternatives with respect to different stakeholders.

Furthermore, the rankings of stormwater harvesting sites were validated with sensitivity and robustness analysis procedures, which attempted to minimize the uncertainty in MCDA evaluation. The sensitivity and robustness analysis procedure demonstrated the stability of top three ranked stormwater harvesting sites under different group compositions.

In summary, the study successfully developed and demonstrated a GIS-MCDA based comprehensive methodology for evaluation of urban stormwater harvesting sites in a multi-objective and multi-stakeholder environment.

7.2 Conclusions

The major conclusions of the study are summarised below related to various aspects of the study.

7.2.1 GIS based Screening Tool Methodology

1. The GIS based screening tool methodology provided spatial assessment of runoff and demand for stormwater harvesting sites using a unique accumulated catchment concept. The accumulated catchment concept in the GIS screening tool methodology demonstrated its effectiveness in terms of the catchment specific runoff and demand assessment. Using this concept, decision makers have choice of implementing stormwater harvesting schemes in various single or accumulated catchments.

2. The GIS based screening tool methodology also demonstrated a novel approach of radius of influence to evaluate the stormwater harvesting sites from demand, supply and infrastructure perspectives. The physical distance between the stormwater harvesting site and the demand areas is critical in determining the economic

feasibility of a stormwater scheme. The radius of influence concept accounted this aspect of physical distance in the methodology.

3. The methodology demonstrated its effectiveness in evaluating the suitable sites in a highly urbanised area (City of Melbourne) and a semi urbanised area (City of Brimbank), under varying demand conditions. For both case studies, suitable stormwater harvesting sites were identified, screened and shortlisted and validated with City West Water officials. The suitable sites obtained from the study were in good agreement with the City West Water officers' judgement based on their knowledge of the potential stormwater harvesting schemes in the study area.

4. The study found JJ Holland Reserve (Holland Park), Princess Park, Batman Park, Birrarung Marr Park, Ieveres Reserve, and Clayton Reserve as suitable stormwater harvesting sites for City of Melbourne. Similarly, Green Gully Reserve, Cairnlea Reserve, and Keilor Park Recreational Reserve were found as potentially suitable locations for the City of Brimbank.

5. With basic spatial analysis knowledge and data availability, the GIS based screening tool methodology can be easily applied to assess the suitability of stormwater harvesting sites. Overall, the GIS based screening tool methodology has demonstrated a rational approach for urban stormwater harvesting site selection, and it is expected that the methodology will benefit the water professionals in preliminary level of stormwater harvesting decision making.

7.2.2 Estimation of Performance Measures

The study described and demonstrated various estimation procedures to quantify the selected nine PMs including cost analysis, water balance modelling, GHG emission analysis for quantitative PMs, and social PM estimation through qualitative scales. The results of PM evaluations related to alternative stormwater harvesting sites formulated the evaluation matrix (or decision matrix), which can be assessed with any standard MCDA method available (including PROMETHEE).

7.2.3 Stakeholder Preference Elicitation

1. The stakeholder preference elicitation methodology in this study aimed at deriving preferences parameters (i.e. preference functions and weights) as required by the selected PROMTHEE method and associated D-Sight software. For this purpose, the study found the workshop method as a simple and cost effective method. The workshop methodology consisted of deriving the preference parameters in terms of preference functions and weights on selected nine PMs, through four representative stakeholder groups namely, water authorities, academics, consultants and council.

2. For elicitation of preference functions and associated threshold values, there is no specific methodology described in the literature. Therefore, the preference function elicitation in this study was direct and straightforward, using the generalized preference function types proposed in the PROMETHEE method. The preference function values were obtained in the form of two different cases to analyse their effect on rankings of stormwater harvesting sites. It was found that rankings of sites were not affected with considered two cases of preference function values, for all selected stakeholder groups.

3. For elicitation of weights, the study found the Analytical Hierarchy Process (AHP) method suitable after reviewing different weighting methods, due to its rational foundations, ease of understanding, hierarchical properties, and the commercial software availability such as EXPERT CHOICE. In current study, the AHP method demonstrated its effectiveness in obtaining relative importance of PMs from representative stakeholder groups.

7.2.4 Decision Analysis for Stormwater Harvesting Sites

1. Based on overall decision analysis and consensus of all stakeholder subgroups, Flagstaff Park, Princess Park, and Clayton Reserve were clearly emerged as the top three best alternative stormwater harvesting sites for the case study area of CoM. The ranking of top sites also represented the best possible decision making scenario, under TBL objectives, representing sustainable stormwater harvesting systems.

2. Results of weight sensitivity analysis showed that rankings of identified top three alternatives were least affected to weight variation from different stakeholders. Also, the robustness analysis confirmed that the rankings of Flagstaff Park, Princess Park, and Clayton Reserve were very robust within different combinations of stakeholder group compositions and associated variations to the weights.

7.3 Limitations and Recommendations

The GIS-MCDA based evaluation methodology in this study has demonstrated its effectiveness in identifying and evaluating the stormwater harvesting sites in an urban area. Having demonstrated successful application to water authority in Melbourne, this methodology can be applied to any water authority in Australia. However, this methodology is constrained by few limitations, which are mostly arising from the specific approaches adopted. Therefore, the proposed methodology can be further improved in addressing these limitations and they listed below.

1. The GIS based screening tool methodology was developed to assist the water managers during initial planning process, where they can get more confidence for the proposed schemes. However, the suitability criteria i.e. runoff and demand considered in the methodology many not alone provide precise suitability for given stormwater harvesting sites. In future, it is recommended to integrate various other criteria such as technical, social, economic and environmental considerations with GIS to provide comprehensive assessment of stormwater harvesting sites.

2. Seasonal fluctuation of runoff and demand was not considered in the GIS screening tool methodology, as study used annual time step for analysis. Therefore, it is recommended to consider seasonal fluctuations of runoff and demand in future study, and investigate the suitability of stormwater harvesting sites.

3. Besides the irrigation demands considered in the study, the GIS based screening tool can also include residential demands and other non-residential demands such as commercial, industrial, or institutional demands (hospital, councils, etc.) to estimate the suitability of the stormwater harvesting sites. Such combination of different demands can be addressed in a future study.

4. The sample size used for stakeholder preference elicitation in this study was limited due to lower attendance of different professionals invited for the workshop. Therefore, it is recommended to examine the ranking results with increased sample size and with additional stakeholder groups such as government agencies and community. However, the described methodology can still be used.

5. The ranking of stormwater harvesting sites in the current study are subject to choice of the selected MCDA method, associated preference elicitation parameters and software. Therefore, ranking results can be investigated with different MCDA methods as part of the sensitivity analysis. Similarly, the PM estimates in the current study can be varied to investigate the potential effect on ranking in different decision making situations.

6. The sensitivity analysis conducted in this study did not focus on external uncertainties such as the effect of change in costs, regulations, and stochastic nature of runoff and demand. These aspects of evaluation can be considered in a future study.

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Appendix 4A

Conceptual Designs of Remaining Stormwater Harvesting Sites

Bold numbers in the tables indicate the estimated performance measure value in the evaluation matrix used in multi-criterion decision analysis of stormwater harvesting sites.

1) Holland Park

A) Site Characteristics

The Holland Park consists of three ovals, one synthetic turf and two warm season cricket pitches with a combined annual water demand of approximately 23 ML. Figure 4A-1 shows the catchment area selected for Holland Park. The catchment area is 31.2 ha with 65% imperviousness fraction. This park has flat topography.

Figure 4A-1: Holland Park and associated Catchment

B) Conceptual Designs

Table 4A-1 shows the conceptual designs of different components selected for Holland Park.

Table 4A-1: Conceptual designs of Holland Park

Component	Estimated Size/Unit
Diversion Systems	1 Unit
CDS GPTs	13.3 m^3
Enviss Treatment System	632 m^2 Treatment Area (632 Units)
Underground Concrete Storage Tank	1200 kL Storage Volume
Reticulation Systems	176 m Long PVC Pipe with 150 mm Diameter
Control Systems	1 Unit
Pumping Systems	2 Units (Size-0.70 kW Each)

C) Water Balance Modelling Results

Table 4A-2 and 4A-3 respectively show the results of water balance modelling and contaminant balance modelling for Holland Park. As seen from Figure 4A-2, there was 18.5 ML supply available for Holland Park to meet the 23 ML demand at 80% reliability. Also, from Table 4A-3, it is evident that pollutant reduction targets were successfully achieved by the designed treatment systems.

Table 4A-2: Water Balance Modelling

Average Annual Incoming Flow	Average Annual Outgoing Flow	Stormwater Reuse (Potable Water Savings)	Irrigation Demand
ML	ML	ML	ML
71.8	53.4	**18.5**	23.17

Table 4A-3: Contaminant Balance Modelling

Pollutants	Annual Average Incoming Pollutants	Annual Average Outgoing Pollutants	Reduction Target %	Reduction Achieved %
Total Suspended Solids (kg/yr)	14500	520	80	**96.4**
Total Phosphorus (kg/yr)	28.8	7.13	45	**75.3**
Total Nitrogen (kg/yr)	206	38.2	45	**81.4**
Gross Pollutants (kg/yr)	2840	0	70	**100**

D) Green House Gas Emission Analysis Results

Table 4A-4 shows the GHG emission estimation for Holland Park, which was computed as 0.16 Kg CO_2/kL.

Table 4A-4: GHG Emissions of Holland Park

Variable	**Value**
Annual Pumping Hours, (h)	2160
Pump Size - Single Pump (kW)	0.7
Annual Energy Consumption of Single Pump, (kWh)	1512
Total Annual Energy Consumption of Two Pumps, (kWh)	3024
Water Reuse, (kL)	1850
Energy Consumption (kWh/kL)	0.16
Victorian GHG Emissions Factor, (Kg CO_2/kWh)	1.21
GHG Emission, (Kg CO_2/kL)	**0.16**

E) Cost Analysis Results

Table 4A-5 shows the levelised cost of Holland Park, which was estimated as $15.3/kL.

Table 4A-5: Levelised Cost Estimation of Holland Park (50 Years)

Component	Life	No. of Units	Capital Cost Per Unit	Capital Cost	Annual Operation Cost	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	$/kL
	Column		I	II	III	IV	IV	IV	V	VI
Stormwater Diversion Structure	80	1	75,000	75,000	1,000	112,125	17,977	130,102		
CDS GPT (Size - 13.3 m^3)	50	1	144,675	144,675	10,127	216,289	182,062	398,351		
Enviss Treatment System (632 m^2 Treatment Area)	60	632	2,000	1,264,000	25,280	1,889,680	454,470	2,344,150		
Underground Concrete Storage Tank (1200KL)	25	1	767/kL	920,400	3,020	1,794,780	54,292	1,849,072		
Stormwater Pipes (176 m Long PVC Pipe with 150mm Diameter)	100	-	270/m	47,790	650	71,446	11,685	83,131		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems (Size-0.70 kW)	15	2	24,095	48,190	5,000	72,044	89,887	161,931		
Cost of Annual Electricity Consumption (3024 kWh)	50	-	0.20/ kWh	-	605	-	10,876	10,876		
Education and Training			-	-	2,500	-	44,944	44,944		
Total Infrastructure Cost						4,204,319	891,362	5,092,576		
Supplied Demand (18.5 ML)									333	
Levelised Cost, ($/kL)										**15.3**

Table 4A-6 shows the estimated annual ARC of pollutants TSS, TP and TN as $4/kg, $2527/kg and $327/kg respectively

Table 4A-6: Estimation of Annualised Removal Cost of Pollutants

Pollutants	Pollutant Loads	Total NPV of Infrastructure	Annualised NPV of Infrastructure	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
TSS	13980	2,742,501	54,850	**4**
TP	21.7			**2527**
TN	167.8			**327**

F) Estimation of Social PMs

Table 4A-7 shows the estimation of social PMs for Holland Park. The Holland Park was rated moderate in community acceptance as the scheme would substitute the 18.5 ML potable water demand. Additionally, Holland Park was rated very high in recreational value because of number of lawns, landscapes, and playgrounds.

Table 4A-7: Quantification of Social PMs for Holland Park

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Holland Park	3	5	1

Table 4A-8 shows the construction risk matrix for Holland Park. Considering the aggregated score of 19, the construction risks of Holland Park can be categorised as very low (Table 4A-7).

Table 4A-8: Construction Risk Matrix for Holland Park

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Holland Park	5	5	4	5	19

2. Clayton Reserve

A) Catchment Properties

The Clayton Reserve consists of three parks namely, North Melbourne Cricket Ground, Clayton Reserve, and Gardiners Reserve Passive Turf with combined annual water demand approximately of 32 ML. Figure 4A-2 shows catchment area selected for Clayton Reserve. The catchment area is 184.20 ha with 65% imperviousness fraction. This park has flat topography.

Figure 4A-2: Clayton Reserve and Associated Catchment

B) Conceptual Designs

Table 4A-9 shows the conceptual designs of different components selected for Clayton Reserve.

Table 4A-9: Conceptual Designs of Clayton Reserve

Component	Estimated Size/Unit
Diversion Systems	1 Unit
CDS GPT	63 m^3
Enviss Treatment System	970 m^2 Treatment Area (970 Units)
Underground Concrete Storage Tank	1000 kL
Stormwater Pipes	560 m Long PVC Pipe with 150 mm Diameter)
Control Systems	1 Unit
Pumping Systems	2 Units (Size-0.80 kW Each)

C) Water Balance Modelling Results

Table 4A-10 and 4A-11 respectively show the results of water balance modelling and contaminant balance modelling for Clayton Reserve. As seen from Table 4A-10, there was 26 ML supply available for Clayton Reserve to meet the 32 demand at 80% reliability level. Also, from Table 4A-11, it was evident that pollutant reduction targets were successfully achieved by the designed treatment systems.

Table 4A-10: Water Balance Modelling (Clayton Reserve)

Average Annual Incoming Flow, ML	Average Annual Outgoing Flow, ML	Stormwater Reuse (Potable Water Savings), ML	Irrigation Demand, ML
ML	ML	ML	ML
422	396	**26**	32.2

Table 4A-11: Contaminant Water Balance (Clayton Reserve)

Pollutants	Annual Average Pollutant Inflows	Annual Average Pollutant Outflows	Reduction Target %	Reduction Achieved %
Total Suspended Solids (kg/yr)	84000	3400	80	**96**
Total Phosphorus (kg/yr)	170	53.6	45	**68.5**
Total Nitrogen (kg/yr)	1220	249	45	**79.6**
Gross Pollutants (kg/yr)	16700	0	70	**100**

D) Green House Gas Emission Analysis Results

Table 4A-12 shows the GHG emission estimation for Clayton Reserve, which was computed as 0.17 Kg CO_2/kL.

Table 4A-12: GHG Emissions of Clayton Reserve

Variable	**Value**
Annual Pumping Hours, (h)	2160
Pump size - Single Pump, (kW)	0.7
Annual Energy Consumption of Single Pump, (kWh)	1836
Total Annual Energy Consumption of Two Pumps, (kWh)	3672
Water Reuse, (kL)	26000
Energy Consumption, (kWh/kL)	0.14
Victorian GHG Emissions Factor,(Kg CO_2/kWhr)	1.21
GHG Emission, (Kg CO_2 /kL)	**0.17**

E) Cost Analysis Results

Table 4A-13 shows the levelised cost of Clayton Reserve, which was estimated as $14/kL.

Table 4A-13: Levelised Cost Estimation of Clayton Reserve (50 Years)

Component	Life	No. of Units	Capital Cost Per Unit	Capital Cost	Annual Operation Cost	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	$/kL
	Column		I	II	III	IV	IV	IV	V	VI
Stormwater Diversion Structure	80	1	75,000	75,000	1,000	112,125	17,977	130,102		
CDS GPT (Size - 63 m^3)	50	1	271,911	271,911	19,034	406,507	342,179	748,685		
Enviss Treatment System (970 m^2 Treatment Area)	60	970	2,000	1,940,000	38,800	2,900,300	697,525	3,597,825		
Underground Concrete Storage Tank (1000KL)	25	1	767/kL Storage	767,000	3,020	1,495,650	54,292	1,549,942		
Stormwater Pipes (560 m Long PVC Pipe with 150 mm Diameter)	100	-	270/Meter	151,200	650	226,044	11,685	237,729		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems (Size - 0.80 kW)	15	2	29,102	58,204	5,000	87,015	89,887	176,902		
Cost of Annual Electricity Consumption (3672 kWh)	50	-	0.20/kWh	-	735		13,213	13,213		
Education and Training			-	-	2,500		44,944	44,944		
Total Infrastructure Cost						5,272,491	1,296,871	6,569,362		
Supplied Demand (26 ML)									468	
Levelised Cost, ($/kL)										**14.0**

Table 4A-14 shows the estimated annual ARC of pollutants TSS, TP and TN as $1.4/kg, $1020/kg and $122.4/kg respectively.

Table 4A-14: Estimation of Annualised Removal Cost of Pollutants (Clayton Reserve)

Pollutants	Pollutant Loads	Total NPV of Treatment	Annualised NPV of Treatment	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
TSS	80600	5,941,422	118,828	**1.4**
TP	116.4			**1021**
TN	971			**122.4**

F) Estimation of Social PMs

Table 4A-15 shows the estimation of social PMs for Clayton Reserve. The Clayton Reserve was rated moderate in community acceptance as the scheme would substitute the 26 ML potable water demand. Additionally, Clayton Reserve was rated moderate in recreational value.

Table 4A-15: Quantification of Social PMs for Clayton Reserve

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Clayton Reserve	3	3	2

Table 4A-16 shows the construction risk matrix for Clayton Reserve. Considering the aggregated score of 16, the construction risks of Clayton Reserve can be categorised as low (Table 4A-15).

Table 4A-16: Construction Risk Matrix for Clayton Reserve

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Clayton Reserve	4	4	4	4	16

3. Pleasance Gardens

A) Catchment Properties

The Pleasance Garden is in close proximity to the several road reserves and nature strips with annual water demand of approximately 7 ML. Figure 4A-3 shows the catchment area selected for Pleasance Garden. The catchment area is 181.2 ha with 65% imperviousness fraction.

Figure 4A-3: Pleasance Garden and Associated Catchment

B) Conceptual Designs

Table 4A-17 shows the conceptual designs of different components selected for Pleasance Gardens.

Table 4A-17: Conceptual Designs of Pleasance Gardens

Component	Estimated Size/Unit
Diversion Systems	1 Unit
CDS GPT	63 m^3
Enviss Treatment System	350 Units on 350 m^2 Treatment Area
Underground Concrete Storage Tank	250KL
Stormwater Pipes	220 m Long PVC Pipe with 100 mm Diameter
Control Systems	1 Unit
Pumping Systems	2 Units (Size - 0.18 kW Each)

C) Water Balance Modelling Results

Table 4A-18 and 4A-19 respectively show the results of water balance modelling and contaminant balance modelling for Pleasance Garden. As seen from Table 4A-18, there would be 5.6 ML supply available to meet the 7.1 ML demand at 80% reliability. Also, from Table 4A-19, it is evident that pollutant reduction targets were successfully achieved by the designed treatment systems.

Table 4A-18: Water Balance Modelling

Average Annual Incoming Flow, ML	Average Annual Outgoing Flow, ML	Stormwater Reuse ML	Irrigation Demand ML
52.2	46.6	**5.6**	7.13

Table 4A-19: Contaminant Water Balance

Pollutants	Annual Average Pollutant Inflows	Annual Average Pollutant Outflows	Reduction Target %	Reduction Achieved %
Total Suspended Solids (kg/yr)	10200	413	80	96
Total Phosphorus (kg/yr)	21.2	6.33	45	70.1
Total Nitrogen (kg/yr)	151	30.4	45	79.8
Gross Pollutants (kg/yr)	2060	0	70	100

D) Green House Gas Emission Analysis Results

Table 4A-20 shows the GHG emission estimation for Pleasance Garden, which is computed as 0.17 Kg CO_2/kL.

Table 4A-20: GHG Emissions of Pleasance Garden

Variable	**Value**
Annual Pumping Hours, (h)	2160
Pump Size - Single Pump, (kW)	0.18
Annual Energy Consumption of Single Pump, (kWh)	389
Total Annual Energy Consumption of Two Pumps, (kWh)	778
Water Reuse, (kL)	5600
Energy Consumption (kWh/kL)	0.15
Victorian GHG Emissions Factor, (Kg CO_2/kWh)	1.21
GHG Emission, (Kg CO_2 /kL)	**0.17**

E) Cost Analysis Results

Table 4A-21 shows the levelised cost of Pleasance Garden, which is estimated as $27.2/kL.

Table 4A-21: Levelised Cost Estimation of Pleasance Gardens (50 Years Analysis Period)

Component	Life	No. of Units	Capital Cost Per Unit	Capital Cost	Annual Operation Cost	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	$/kL
	Column		I	II	III	IV	IV	IV	V	VI
Stormwater Diversion Structure	80	1	75,000	75,000	1,000	112,125	17,977	130,102		
CDS GPT (Size - 63 m^3)	50	1	292,219	292,219	20,455	436,867	367,735	804,602		
Enviss Treatment System (350 m^2 Treatment Area)	60	350	2,000	700,000	14,000	1,046,500	251,684	1,298,184		
Underground Concrete Storage Tank (250KL)	25	1	767/kL	67,500	3,020	131,625	54,292	185,917		
Stormwater Pipes (220 m Long PVC Pipe with 100 mm Diameter)	100	-	225/Meter Pipe Length	49,500	650	74,003	11,685	85,688		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems (Size - 0.18 kW)	15	2	9590	19,180	5,000	28,674	89,887	118,561		
Cost of Annual Electricity Consumption (778 kWh)	50	-	0.20/kWh	-	156		2,804	2,804		
Education and Training			-	-	2,500		44,944	44,944		
Total Infrastructure Cost						1,874,644	866,177	2,740,821		
Supplied Demand (5.6 ML)									101	
Levelised Cost, ($/kL)										**27.2**

Table 4A-22 shows the estimated annual ARC of pollutants TSS, TP and TN as $3.3/kg, $2167/kg and $266/kg respectively.

Table 4A-22: Estimation of Annualised Removal Cost of Pollutants (Pleasance Gardens)

Pollutants	Pollutant Loads	Total NPV of Infrastructure	Annualised NPV of Infrastructure	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
TSS	9787	130,102.44	32,084.93	**3.3**
TP	14.87			**2167**
TN	120.6			**266.0**

F) Estimation of Social PMs

Table 4A-23 shows the estimation of social PMs for Pleasance Gardens. The Pleasance Gardens was rated low in community acceptance as the scheme would substitute the 5.6 ML potable water demand. Additionally, Pleasance Gardens was rated low in recreational value.

Table 4A-23: Quantification of Social PMs for Pleasance Gardens

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Pleasance Gardens	2	2	3

Table 4A-24 shows the construction risk matrix for Pleasance Gardens. Considering the aggregated score of 11, the construction risks of Pleasance Gardens can be categorised as moderate (Table 4A-23).

Table 4A-24: Construction Risk Matrix for Pleasance Gardens

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Pleasance Gardens	2	2	2	5	11

4. Princess Park

A) Catchment Properties

The Princess Park has various sporting ground which constitute combined annual water demand of approximately 92 ML. Figure 4A-4 shows catchment area for Princess Park. The catchment area is 107 ha with 70% imperviousness fraction. This park has flat topography.

Figure 4A-4: Princess Park and Associated Catchment

B) Conceptual Designs

Table 4A-25 shows the conceptual designs of different components selected for Princess Park.

Table 4A-25: Conceptual Designs of Princess Park

Component	Estimated Size/Unit
Diversion Systems	1 Unit
CDS GPT	35 m^3
Enviss Treatment System	1800 Units on 1800 m^2 Treatment Area
Underground Concrete Storage Tank	5000 kL
Stormwater Pipes	2081 Long PVC Pipe with 150 mm Diameter
Control Systems	1 Unit
Pumping Systems	2 Units (Size - 2.3 kW Each)

C) Water Balance Modelling Results

Table 4A-26 and 4A-27 respectively show results of the water balance modelling and contaminant balance modelling for Princess Park. As seen from 4A-26, there was 73 ML supply available for Princess Park to meet the 92 ML demand at 80% reliability level. Also, from Table 4A-27, it was evident that pollutant reduction targets were successfully achieved by the designed treatment systems.

4A-26: Water Balance Modelling

Average Annual Incoming Flow	Average Annual Outgoing Flow	Stormwater Reuse (Potable Water Savings)	Irrigation Demand
ML	ML	ML	ML
281	208	**73**	92

4A-27: Contaminant Water Balance

Pollutants	Annual Average Pollutant Inflows	Annual Average Pollutant Outflows	Reduction Target %	Reduction Achieved %
Total Suspended Solids (kg/yr)	55800	2030	80	96.4
Total Phosphorus (kg/yr)	114	27.8	45	75.7
Total Nitrogen (kg/yr)	808	152	45	81.
Gross Pollutants (kg/yr)	11300	0	70	100

D) Green House Gas Emission Analysis

Table 4A-28 shows the GHG emission estimation for Princess Park, which is computed as 0.16 Kg CO_2/kL.

Table 4A-28: GHG Emissions of Princess Park

Variable	**Value**
Annual Pumping Hours, (h)	2160
Pump Size - Single Pump, (kW)	2.3
Annual Energy Consumption of Single Pump, (kWh)	4968
Total Annual Energy Consumption of Two Pumps, (kWh)	9936
Water Reuse, (kL)	73000
Energy Consumption, (kWh/kL)	0.13
Victorian GHG Emissions Factor, (Kg CO_2/kWh)	1.21
GHG Emission, (Kg CO_2/kL)	**0.16**

D) Cost Analysis Results

Table 4A-29 shows the levelised cost of Princess Park, which is estimated as $12.2/kL.

Table 4A-29: Levelised Cost Estimation of Princess Park (50 Years)

Component	Life	No. of Units	Capital Cost Per Unit	Capital Cost	Annual Operation Cost	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	$/kL
	Column		I	II	III	IV	IV	IV	V	VI
Stormwater Diversion Structure	80	1	75,000	75,000	1,000	112,125	17,977	130,102		
CDS GPT (Size - 35 m^3)	50	1	MUSIC	173,940	12,176	260,040	218,890	478,930		
Enviss Treatment System (1800 m^2 Treatment Area)	60	1800	2,000	3,600,000	72,000	5,382,000	1,294,376	6,676,376		
Underground Concrete Storage Tank (5000 kL)	25	1	767/kL	3,835,000	3,020	7,478,250	54,292	7,532,542		
Stormwater Pipes (2081 m Long PVC Pipe with 150 mm Diameter)	100	-	270/Meter	561,870	650	839,996	11,685	851,681		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems (Size - 2.3 kW)	15	2	60,780	121,560	5,000	181,732	89,887	271,619		
Cost of Annual Electricity Consumption (19872 kWh)	50	-	0.20/kWh	-	1,988		35,739	35,739		
Education and Training			-	-	2,500		44,944	44,944		
Total Infrastructure Cost						14,298,93	1,792,959	16,091,952		
Supplied Demand (73 ML)									1312	
Levelised Cost, ($/kL)										**12.2**

Table 4A-30 shows the estimated annual ARC of pollutants TSS, TP and TN as $2.8/kg, $1831/kg and $241/kg respectively.

Table 4A-30: Estimation of Annualised Removal Cost of Pollutants (Princess Park)

Pollutants	Pollutant Loads	Total NPV of Infrastructure	Annualised NPV of Infrastructure	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
TSS	53770	$7,894,534	157,890	**2.8**
TP	86.2			**1832**
TN	656			**241**

F) Estimation of Social PMs

Table 4A-31 shows the estimation of social PMs for Princess Park. The Princess Park was rated very high in community acceptance as the scheme would substitute the 73 ML potable water demand. Additionally, Princess Park was rated very high in recreational value due to presence of playgrounds, tennis facilities and bowling courts.

Table 4A-31: Quantification of Social PMs for Princess Park

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Princess Park	5	5	3

Table 4A-32 shows the construction risk matrix for Princess Park. Considering the aggregated score of 11, the construction risks of Princess Park can be categorised as moderate (Table 4A-31).

Table 4A-32: Construction Risk Matrix for Princess Park

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Princess Park	4	3	2	2	11

5. Ievers Reserve

A) Catchment Properties

Ievers Reserve has combined demand of approximately 7 ML from several garden areas, large oak trees, and neighbouring roundabouts and traffic islands. Figure 4A-5 shows catchment area selected for Ievers Reserve. The catchment area is 55 ha with 65% imperviousness fraction. This park has flat topography.

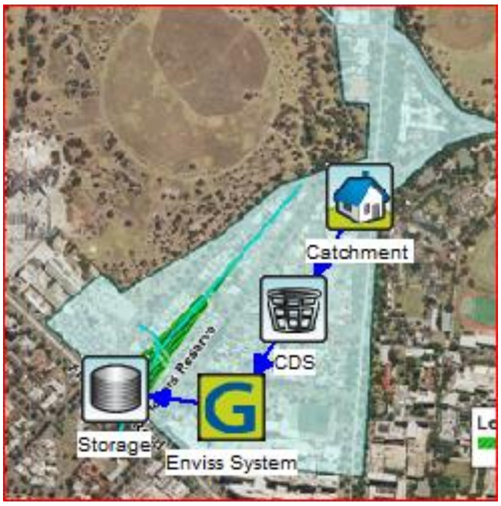

Figure 4A-5: Ievers Reserve and Associated Catchment

B) Conceptual Designs

Table 4A-33 shows the conceptual designs of different components selected for Ievers Reserve.

Table 4A-33: Conceptual Designs of Ievers Reserve

Component	Estimated Size/Unit
Diversion Systems	1 Unit
CDS GPT	22 m^3
Enviss Treatment System	280 Units on 280 m^2 Treatment Area
Underground Concrete Storage Tank	200 kL
Stormwater Pipes	93 m Long PVC Pipe with 100 mm Diameter
Control Systems	1 Unit
Pumping Systems	2 Units (Size - 0.2 kW Each)

C) Water Balance Modelling Results

Table 4A-34 and 4A-35 respectively show the results of water balance modelling and contaminant balance modelling for Ievers Reserve. As seen from Table 4A-34, there was 5.6 ML supply available to meet the 7.17 ML demand at 80% reliability level. Also, from Table 4A-35, it was evident that pollutant reduction targets were successfully achieved by the designed treatment systems.

4A-34: Water Balance Modelling

Average Annual Incoming Flow	Average Annual Outgoing Flow	Stormwater Reuse (Potable Water Savings)	Irrigation Demand
ML	ML	ML	ML
127.6	122	**5.6**	7.17

Table 4A-35: Contaminant Water Balance

Pollutants	Annual Average Pollutant Inflows	Annual Average Pollutant Outflows	Reduction Target %	Reduction Achieved %
Total Suspended Solids (kg/yr)	25100	1030	80	**96**
Total Phosphorus (kg/yr)	52.2	16.7	45	**68.1**
Total Nitrogen (kg/yr)	365	76	45	**79.2**
Gross Pollutants (kg/yr)	5050	0	70	**100**

D) Green House Gas Emission Analysis Results

Table 4A-36 shows the GHG emission estimation for Ievers Reserve, which is computed as 0.18 Kg CO_2/kL.

Table 4A-36: GHG Emissions of Ievers Reserve

Variable	**Value**
Annual Pumping Hours, (h)	2160
Pump size - Single Pump, (kW)	0.20
Annual Energy Consumption of Single Pump, (kWh)	432
Total Annual Energy Consumption of Two Pumps, (kWh)	864
Water Reuse, (kL)	5700
Energy Consumption, (kWh/kL)	0.15
Victorian GHG Emissions Factor, (Kg CO_2/kWh)	1.21
GHG Emission, (Kg CO_2 /kL)	**0.18**

E) Cost Analysis Results

Table 4A-37 shows the levelised cost of Ievers Reserve, which is estimated as $21.4/kL.

Table 4A-37: Levelised Cost Estimation of Ievers Reserve (50 Years)

Component	Life	No. of Units	Capital Cost Per Unit	Capital Cost	Annual Operation Cost	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	$/kL
	Column		I	II	III	IV	IV	IV	V	VI
Stormwater Diversion Structure	80	1	75,000	75,000	1,000	112,125	17,977	130,102		
CDS GPT (Size - 22 m^3)	50	1	120,502	120,502	8,435	180,150	151,642	331,793		
Enviss Treatment System (280 m^2 Treatment Area)	60	280	2,000	560,000	11,200	837,200	201,347	1,038,547		
Underground Concrete Storage Tank (200KL)	25	1	767/kL	153,400	3,020	299,130	54,292	353,422		
Stormwater Pipes (93 m Long PVC Pipe with 100 mm Diameter)	100	-	225/Meter	65,250	650	97,549	11,685	109,234		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems (Size - 0.2 kW)	15	2	9,714	19,428	5,000	29,045	89,887	118,932		
Cost of Annual Electricity Consumption (864 kWh)	50	-	0.20/kWh	-	173	-	3,110	3,110		
Education and Training			-	-	2,500	-	44,944	44,944		
Total Infrastructure Cost						1,600,049	600,054	2,200,103		
Supplied Demand (5.6ML)									103	
Levelised Cost, ($/kL)										**21.4**

Table 4A-38 shows the estimated annual ARC of pollutants TSS, TP and TN as $1.1/kg, $772/kg and $95/kg respectively.

Table 4A-38: Estimation of Annualised Removal Cost of Pollutants (Ievers Reserve)

Pollutants	Pollutant Loads	Total NPV of Treatment Cost	Annualised NPV of Treatment Cost	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
TSS	24070	1,370,340	27,407	**1.1**
TP	35.5			**772**
TN	289			**95**

F) Estimation of Social PMs

Table 4A-39 shows the estimation of social PMs for Ievers Reserve. The Ievers Reserve was rated moderate in community acceptance as the scheme would substitute the 5.6 ML potable water demand. Additionally, Ievers Reserve was rated moderate in recreational value.

Table 4A-39: Quantification of Social PMs for Ievers Reserve

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Ievers Reserve	3	3	1

Table 4A-40 shows the construction risk matrix for Ievers Reserve. Considering the aggregated score of 18, the construction risks of Ievers Reserve can be categorised as very low (Table 4A-39).

Table 4A-40: Construction Risk Matrix for Ievers Reserve

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Ievers Reserve	5	4	4	5	18

6. Birrarung Marr Park

A) Site Characteristics

Birrarung Marr Park has demand of approximately 18 ML from various playgrounds and grassy lands. Figure 4A-6 shows catchment area for Birrarung Marr Park. The catchment area is 31.2 ha with 65% imperviousness fraction.

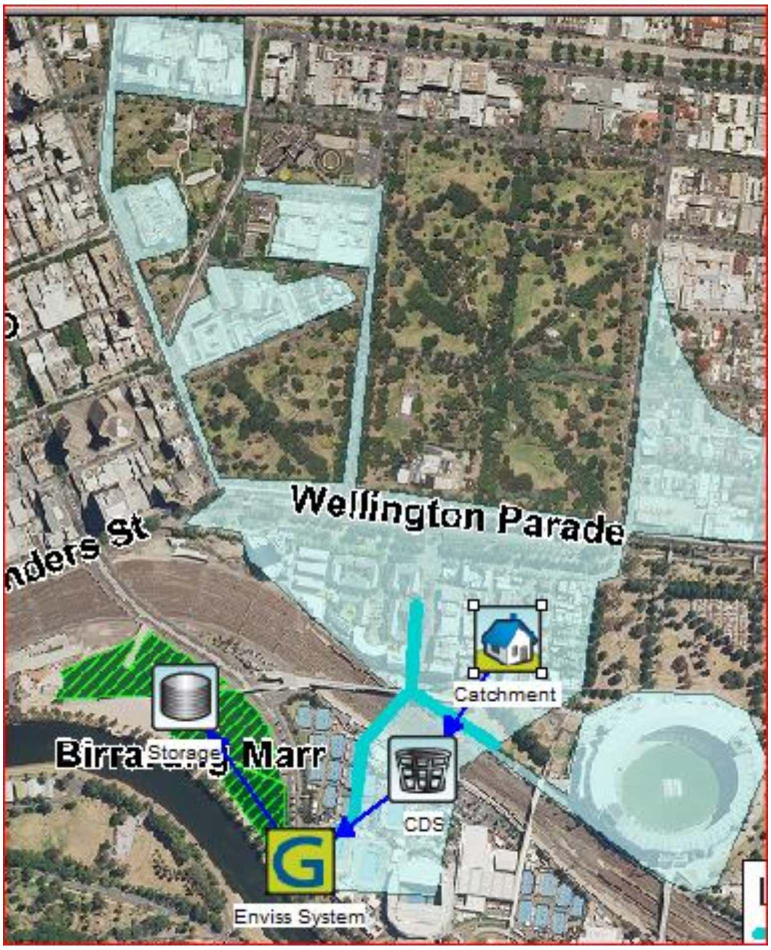

Figure 4A-6: Birrarung Marr Park and Associated Catchment

B) Conceptual Designs

Table 4A-41 shows the conceptual designs of different components selected for Birrarung Marr Park.

Table 4A-41 Conceptual Designs of Birrarung Marr Park

Component	Estimated Size/Unit
Diversion Systems	1 Unit
CDS GPT	22 m^3
Enviss Treatment System	620 Units on 620 m^2 Treatment Area
Underground Concrete Storage Tank	700 kL
Stormwater Pipes	306 m Long PVC Pipe with 150 mm Diameter
Control Systems	1 Unit
Pumping Systems	2 Units (Size - 0.5 kW Each)

C) Water Balance Modelling Results

Table 4A-42 and 4A-43 respectively show the results of water balance modelling and contaminant balance modelling for Birrarung Marr Park. As seen from Table 4A-42, there was 15.1 ML supply available to meet the 18.4 ML demand at 80% reliability level. Also, from Table 4A-43, it was evident that pollutant reduction targets were successfully achieved by the designed treatment systems.

Table 4A-42: Water Balance Modelling

Average Annual Incoming Flow	Average Annual Outgoing Flow	Stormwater Reuse (Potable Water Savings)	Irrigation Demand
ML	ML	ML	ML
144	129	**15.1**	18.40

Table 4A-43: Contaminant Water Balance

Pollutants	Annual Average Pollutant Inflows	Annual Average Pollutant Outflows	Reduction Target %	Reduction Achieved %
Total Suspended Solids (kg/yr)	55,800	1060	80	98.1
Total Phosphorus (kg/yr)	114	25	45	77.8
Total Nitrogen (kg/yr)	808	169	45	79.8
Gross Pollutants (kg/yr)	2500	0	70	100

D) Green House Gas Emission Analysis Results

Table 4A-44 shows the GHG emission estimation for Birrarung Marr Park, which was computed as 0.18 Kg CO_2/kL.

Table 4A-44: GHG Emissions of Birrarung Marr Park

Variable	Value
Annual Pumping Hours, (h)	2160
Pump size - Single Pump, (kW)	0.50
Annual Energy Consumption of Single Pump, (kWh)	1080
Total Annual Energy Consumption of Two Pumps, (kWh)	2160
Water Reuse, (kL)	15110
Energy Consumption, (kWh/kL)	0.14
Victorian GHG Emissions Factor, (Kg CO_2/kWh)	1.21
GHG Emission, (Kg CO_2 /kL)	**0.17**

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E) Cost Analysis Results

Table 4A-45 shows the levelised cost of Birrarung Marr Park, which is estimated as $15.5/kL.

Table 4A-45: Levelised Cost Estimation of Birrarung Marr Park (50 Years Analysis Period)

Component	Life	No. of Units	Capital Cost Per Unit	Capital Cost	Annual Operation Cost	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	$/kL
	Column		I	II	III	IV	IV	IV	V	VI
Stormwater Diversion Structure	80	1	75,000	75,000	1,000	112,125	17,977	130,102		
CDS GPT	50	1	101,648	101,648	7,115	151,964	127,916	279,880		
Enviss Treatment System (620 m^2 Treatment Area)	60	620	2,000	1,240,000	24,800	1,853,800	445,841	2,299,641		
Underground Concrete Storage Tank (700KL)	25	1	767/kL	536,900	3,020	1,046,955	54,292	1,101,247		
Stormwater Pipes (306 m Long PVC Pipe with 150 mm Diameter)	100	-	270/Meter	82,620	650	123,517	11,685	135,202		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems - (Size - 0.5 kW)	15	2	19,650	39,300	5,000	58,754	89,887	148,641		
Cost of Annual Electricity Consumption (2160 kWh)	50	-	0.20/kWh	-	864	-	15,533	15,533		
Education and Training			-	-	2,500	-	44,944	44,944		
Total Infrastructure Cost						3,391,964	833,243	4,225,207		
Supplied Demand (15.1 ML)									272	
Levelised Cost, ($/kL)										**15.5**

Table 4A-46 shows the estimated annual ARC of pollutants TSS, TP and TN as $0.9/kg, $580/kg and $81/kg respectively.

Table 4A-46: Estimation of Annualised Removal Cost of Pollutants

Pollutants	Pollutant Loads	Total NPV of Infrastructure	Annualised NPV of Infrastructure	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
TSS	54,740	2,579,520	51,590	**0.9**
TP	89			**580**
TN	639			**81**

F) Estimation of Social PMs

Table 4A-47 shows the estimation of social PMs for Birrarung Marr Park. The Birrarung Marr Park was rated high in community acceptance as the scheme would substitute the 15.1 ML potable water demand. Additionally, Birrarung Marr Park was rated moderate in recreational value.

Table 4A-47: Quantification of Social PMs for Birrarung Marr Park

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Birrarung Marr Park	4	3	2

Table 4A-48 shows the construction risk matrix for Birrarung Marr Park. Considering the aggregated score of 15, the construction risks of Birrarung Marr Park can be categorised as low (Table 4A-47).

Table 4A-48: Construction Risk Matrix for Birrarung Marr Park

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Birrarung Marr Park	5	4	4	2	15

7. Batman Park

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A) Catchment Properties

Batman Park has demand of approximately 7 ML primarily from passive turf with several established eucalyptus trees playgrounds. Figure 4A-7 shows the catchment area selected for Batman Park. The catchment area is 37.57 ha with 65% imperviousness fraction.

Figure 4A-7: Batman Park and Associated Catchment

B) Conceptual Designs

Table 4A-49 shows the conceptual designs of different components selected for Batman Park.

Table 4A-49: Conceptual Designs of Batman Park

Component	Estimated Size/Unit
Diversion Systems	1 Unit
CDS GPT	22 m^3
Enviss Treatment System	320Units on 320 m^2 Treatment Area
Underground Concrete Storage Tank	250 kL
Stormwater Pipes	93 m Long PVC Pipe with 100 mm Diameter
Control Systems	1 Unit
Pumping Systems	2 Units (Size - 0.2 kW Each)

C) Water Balance Modelling Results

Table 4A-50 and 4A-51 respectively show the results of water balance modelling and contaminant balance modelling for Batman Park. As seen from Table 4A-50, there was 5.7 ML supply available to meet the 18.4 ML demand of Batman Park at 80% reliability level. Also, from Table 4A-51, it was evident that pollutant reduction targets were successfully achieved by the designed treatment systems.

Table 4A-50: Water Balance Modelling (Batman Park)

Average Annual Incoming Flow	Average Annual Outgoing Flow	Reuse Supplied (Potable Water Savings)	Reuse Requested (Demands of the Park)
ML	ML	ML	ML
92.4	86.8	**5.7**	7.13

Table 4A-51: Contaminant Water Balance (Batman Park)

Pollutants	Annual Average Pollutant Inflows	Annual Average Pollutant Outflows	Reduction Target %	Reduction Achieved %
Total Suspended Solids (kg/yr)	18200	757	80	95.8
Total Phosphorus (kg/yr)	37.4	11.7	45	68.7
Total Nitrogen (kg/yr)	261	54.4	45	79.2
Gross Pollutants (kg/yr)	3700	0	70	100

D) Green House Gas Emission Analysis Results

Table 4A-52 shows the GHG emission estimation for Batman Park, which is computed as 0.18 Kg CO_2/kL

Table 4A-52: GHG Emissions of Batman Park

Variable	**Value**
Annual Pumping Hours, (h)	2160
Pump Size - Single Pump, (kW)	0.18
Annual Energy Consumption of Single Pump, (kWh)	432
Total Annual Energy Consumption of Two Pumps, (kWh)	864
Water Reuse, (kL)	5700
Energy Consumption, (kWh/kL)	0.15
Victorian GHG Emissions Factor, (Kg CO_2/kWh)	1.21
GHG Emission, (Kg CO_2 /kL)	**0.18**

E) Cost Analysis Results

Table 5A-53 shows the levelised cost of Batman Park, which was estimated as $22.4/kL.

Table 5A-53: Levelised Cost Estimation of Batman Park (50 Years)

Component	Life	No. of Units	Capital Cost Per Unit	Capital Cost	Annual Operation Cost	NPV of Capital Cost	NPV of Annual Operation Cost	NPV of Components	NPV of Supplied Demand	**Levelised Cost**
	Years	-	$	$	$	$	$	$	ML	$/kL
	Column		I	II	III	IV	IV	IV	V	VI
Stormwater Diversion Structure	80	1	75,000	75,000	1,000	112,125	17,977	130,102		
CDS GPT	50	1	96,302	96,302	6,741	143,971	121,188	265,160		
Enviss Treatment System (320 m^2 Treatment Area)	60	320	2,000	640,000	12,800	956,800	230,111	1,186,911		
Underground Concrete Storage Tank (250 kL)	25	1	767/kL	191,750	3,020	373,913	54,292	428,204		
Stormwater Pipes (93 m Long PVC Pipe with 100 mm Diameter)	100	-	225/Meter	20,925	650	31,283	11,685	42,968		
Control Systems	50	1	30,000	30,000	1,400	44,850	25,168	70,018		
Pumping Systems (Size - 0.2 kW)	15	2	9,714	19,428	5,000	29,045	89,887	118,932		
Cost of Annual Electricity Consumption (2160 kWh)	50	-	0.20/kWh	-	173	-	3,110	3,110		
Education and Training			-	-	2500	-	44,944	44,944		
Total Infrastructure Cost						1,691,987	598,364	2,290,350		
Supplied Demand (5.7ML)									103	
Levelised Cost, ($/kL)										**22.4**

Table 5A-54 shows the estimated annual ARC of pollutants TSS, TP and TN as \$1.6/kg, \$1130/kg and \$140/kg respectively.

Table 5A-54: Estimation of Annualised Removal Cost of Pollutants (Batman Park)

Pollutants	Pollutant Loads	Total NPV of Infrastructure	Annualised NPV of Infrastructure	Annualised Removal Cost
	(Kg /yr)	$	$	($/Kg /yr)
TSS	17443	1,452,071	29,042	**1.6**
TP	25.7			**1130**
TN	206.6			**140**

F) Estimation of Social PMs

Table 4A-55 shows the estimation of social PMs for Batman Park. The Batman Park was rated high in community acceptance as the scheme would substitute the 5.7 ML potable water demand. Additionally, Batman Park was rated moderate in recreational value.

Table 4A-55: Quantification of Social PMs for Batman Park

Alternative Site	Social PMs (Qualitative)		
	Community Acceptance (Max)	Recreational Value (Max.)	Construction Risks (Min.)
Batman Park	4	3	3

Table 4A-56 shows the construction risk matrix for Batman Park. Considering the aggregated score of 11, the construction risks of Batman Park can be categorised as moderate (Table 4A-56).

Table 4A-56: Construction Risk Matrix for Batman Park

Alternative Site	Location of Drainage Asset	Availability of Storage Space	Presence of Services	Presence of Heritage Sites	Total
	Max	Max	Min	Min	
Batman Park	4	4	1	2	11

Appendix 4B

Technical Description of Enviss and CDS Gross Pollutant Traps

(A) Enviss System

The Enviss filter technology is based on a specifically engineered media that removes a high proportion of particulate and dissolved pollutants found in stormwater runoff, before they enter the stormwater system.

Figure 4B-1 shows the Enviss system. As seen from Figure 4B-1, this treatment system is a complete three-stage WSUD treatment train in a single pit. The three stages consist of permeable pavers, a sediment trap and a fine filter media. The permeable pavers provide primary treatment to remove the gross pollutants. Then, the sediment trap utilises distinct filter layers to capture coarse and fine sediments. This trap also protects the filter media from frequent clogging, extending filter life and maintaining treatment efficiency between storm events. The specifically engineered Enviss filter media effectively removes pollutants such as sediment, nitrogen, phosphorus and heavy metals using a simple design.

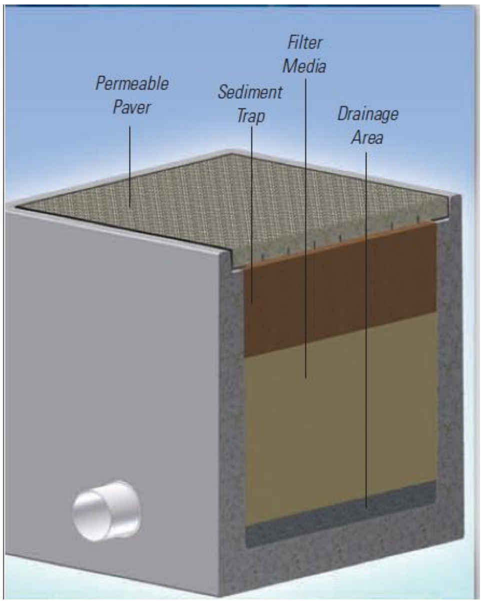

Figure 4B-1: Enviss Media Filters

(Source: Manual of Enviss system)

(http://www.enviss.com.au/h20-sentinel-pits)

Table 4B-1 shows the technical parameters associated with the Enviss system. Additionally, Table 4B-2 displays the performance of the Enviss system in removing different pollutants (Source Enviss Manual).

Table 4B-1: Technical Parameters of Enviss System

(Source: Manual of Enviss system, http://www.enviss.com.au/h20-sentinel-pits)

Technical Parameters	**Specification**
Treatable Flow Rate:	0.2 L/s
Hydraulic Conductivity:	2000 mm/ Hr
Ponding Depth (Min.):	50 mm
Treatable Area (impervious	77 m2
Maintenance Period:	2 years

Table 4B-2: Performance of Enviss System

(Source: Manual of Enviss system, http://www.enviss.com.au/h20-sentinel-pits)

Pollutants	Sentinel Pit Filter Media Performance
Total Suspended Solids	96%
Total Phosphorous	67%
Total Nitrogen	79%
Aluminium	77%
Cadmium	95%
Chromium	87%
Copper	88%
Iron	85%
Lead	81%
Zinc	94%

(B) EnvissDT Software

The EnvissDT software was developed specifically for the Enviss treatment systems. The algorithms within the EnvissDT software were developed by Monash University (Melbourne) in conjunction with Enviss Company. These algorithms are based on the study on development of novel filtration systems done by Schang et al. (2010). The main application of EnvissDT software is to design the filtration systems for a given catchment area considering local pollutant characteristics. Additionally, this software can also help to design storage systems for stormwater harvesting.

The EnvissDT software has been designed to simulate stormwater runoff from a range of spatial scales (e. any catchment size), using a constant temporal resolution of 6 minutes. The software uses a combined deterministic-stochastic modelling approach to predict flow rates and pollutant concentrations continuously over a chosen time period. However, EnvissDT should be seen as a conceptual design tool and does not provide detailed sizing of treatment systems.

A conceptual overview of different modules used in EnvissDT software is shown in Figure 4B-2.

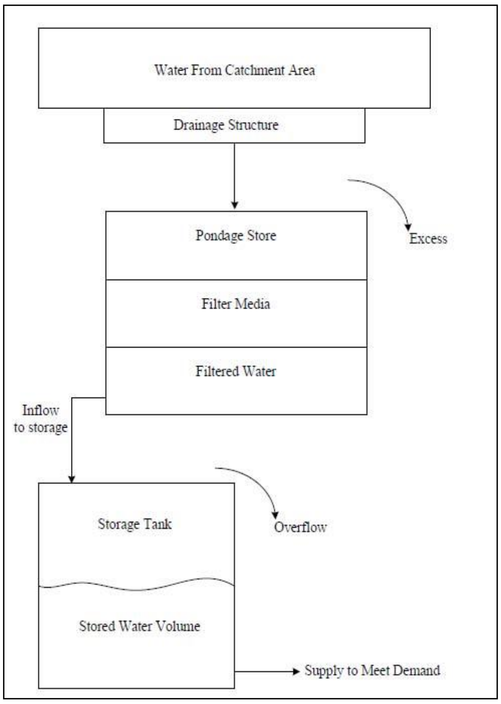

Figure 4B-2: Overview of EnvissDT Modules
(Adopted from (EnvissDT Manual, 2012))

The EnvissDT software comprises of three main modules: 1) Rainfall-Runoff Module 2) Filter Efficiency Module: and 3) Storage Behaviour Module

The EnvissDT software uses the outputs from the three main modules to determine the required filter area and storage size. Further details on EnvissDT software can be found in EnvissDT Manual (2012).

Note: The application of this stormwater treatment technology in no way should be considered as a recommended treatment technology from study. It has been simply used here for demonstrating comparison of different stormwater harvesting systems using MCDA. There may be numerous other similar systems suitable for treating stormwater and readers are advised to make their own judgement in the selection of appropriate treatment device

(C) CDS Gross Pollutant Traps (GPTs)

Figure 4B-3 shows a Continuous Deflection System (CDS) gross pollutant trap (GPT). These GPTs are designed to capture and retain gross pollutants, litter, grit, sediments and associated oils. The pollutants use the vortex force principle to separate the pollutants. As a result, the pollutants are remained in the sump, and do not block the screens of GPTs. Additionally, these GPTs provide advantage of off-line treatment and flood peak bypass from the stormwater diversions. These systems provide 95% removal of gross pollutants with size greater than 1 mm and 95% sediment removal with the size less than 200μm (Rocla, 2013).

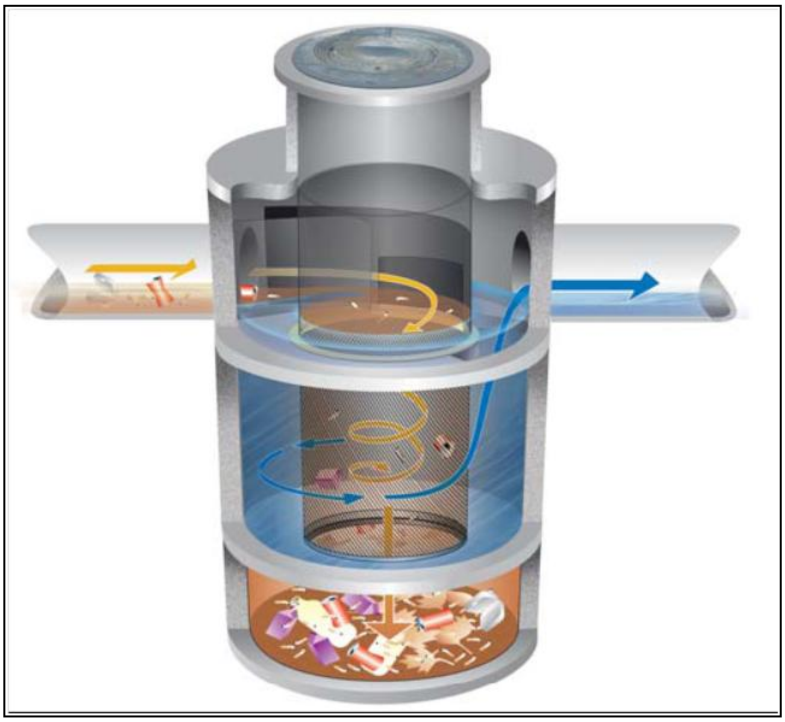

Figure 4B-3: Functional Diagram of CDS GPT

[Source: (Rocla, 2013)]

(http://www.rocla.com.au/Products.php?id=19)

It should be noted that the size and type of CDS GPT depend on the catchment area, flows, pollution loads, performance requirements, maintenance method, hydraulic limitations and site constraints. The literature review of different GPTs can be found in Neumann and Sharma (2012).

Reference:

EnvissDT Manual, 2012. EnvissDT user manual, Software Version 1.6.

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Schang, C., McCarthy, D., Deletić, A., Fletcher, T., 2010. Development of the enviss™ filtration media, NOVATECH 2010, Lyon, France

Appendix 4C
MUSIC Terminologies and Model Theory

A) Model Terminologies

The main part of any urban stormwater system is the catchment. Within the urban catchment, rainfall is converted to runoff. Consequently, pollutants are generated with runoff, and transported through the drainage system. To simulate this behaviour, MUSIC uses a combination of three nodes namely: the source node, the treatment node and the receiving nodes.

In terms of modelling, the catchment is represented as the 'source node' representing four different landuse types namely, urban, agricultural, forest and user defined. These four source nodes have their own default discharge pollutant concentrations. These source nodes are further connected to treatment nodes which represent the stormwater treatment measures within the catchment. The receiving node represents the receiving waterway (e.g. river, lake, bay).

The source node, treatment node and receiving node together form a treatment train and one such hypothetical treatment train is shown in Figure 4C-1. In Figure 4C-1, 'Urban' is the source node, and 'Gross Pollutant Trap' and 'Wetland' are the treatment nodes, while the 'Receiving Waters' is the receiving node in treatment train.

Figure 4C-1: Treatment Train Representation in MUSIC

Before setting up the treatment train, MUSIC builds the catchment file with rainfall and evapotranspiration data. The user can choose in-built meteorological data templates within the MUSIC software to build the catchment file. There are several meteorological templates available in the MUSIC software to cater for different locations, time steps and data duration periods.

B) MUSIC Theory

MUSIC simulates the performance of stormwater treatment measures in meeting the water quantity and quality objectives. The MUSIC algorithm consists of three modules. These modules are

- Rainfall Runoff Module: This module describes the hydrological cycle within the catchment that converts rainfall to runoff.
- Urban Pollutant Generation Module: This module describes the transport of water and contaminants within the drainage system.
- Universal Stormwater Treatment Module: This module describes the treatment of contaminants within selected treatment devices.

Rainfall-runoff Module

For generating urban runoff, MUSIC uses an algorithm based on the model developed by Chiew and McMahon (1999). The model is a simplified description of rainfall runoff processes in catchments involving the definition of the impervious area and soil moisture storages as shown in Figure 4C-2. This model was initially developed as a daily model, and was modified for MUSIC to enable disaggregation of the generated daily runoff into sub-daily temporal patterns. The details of modelling can be found in manual of MUSIC software (eWater, 2012).

For the behaviour analysis of stores for harvested stormwater MUSIC uses the rainfall- runoff module to estimate the inflows into the store. Furthermore, behaviour storage module in MUSIC routes the water through the store. Further details of the storage behaviour module can be found in Mitchell (2008). For MUSIC modelling, guidelines have been developed by Melbourne Water (2012) for selecting various input parameters (such as climate data, effective impervious area for different landuse, selection of time step), across different Australian cities including Melbourne.

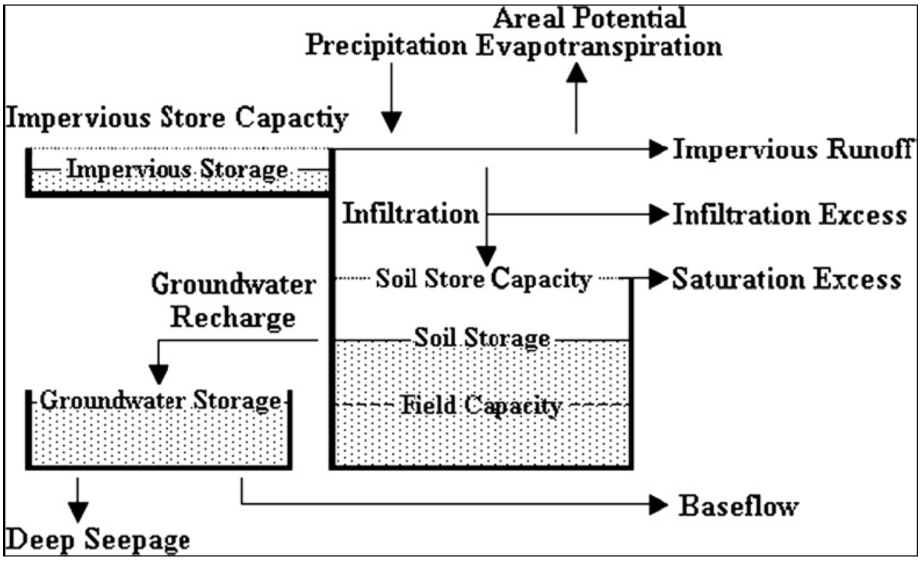

Figure 4C-2: Rainfall Runoff Model in MUSIC Software

[Source: (eWater, 2012)]

Urban Pollutant Generation Module

Within the catchment, MUSIC models the Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN) loads along with gross pollutants loads, specific to provided treatment train. For pollutant load modelling of TSS, TP and TN, the MUSIC software uses the values of event mean concentrations and Dry Weather Concentration (DWC) of TSS, TP and TN specified by Duncan (1999). The pollutant load of TP, TSS and TN is estimated stochastically by deriving pollutant concentrations from the statistical distribution described by the mean and standard deviation of each pollutant for the specified time step. Furthermore, the gross pollutant load generation is based on field monitoring data of Allison et al. (1997) for 12 storm events in inner Melbourne suburbs. Further details of Urban Pollutant Generation Module can be found in eWater (2012)

Universal Stormwater Treatment Module (USTM)

In MUSIC, stormwater treatment measures by which pollutants are first intercepted and detained are described using a unified module named Universal Stormwater Treatment Module (USTM). Two basic modelling procedures are adopted in developing the USTM – i) Hydrologic Routing, and ii) First order Kinematic Module.

- Hydrologic Routing: Hydrologic routing simulates the movement of runoff as it flows through the treatment system or catchment. This modelling provides information on storage-discharge (S-Q) relationship for a given treatment node using continuity equation.

- First order Kinematic Module: This module simulates the removal of pollutants (or contaminants) within the treatment system. The module works on the assumption that contaminant concentration in given water parcel tends to shift by an exponential decay process towards an equilibrium value at a given site. Further details on USTM model can be found in eWater (2012).

References:

Allison, R.A., McMahon, T.A., Chiew, F.H., 1997. Stormwater gross pollutants, CRC for Catchment Hydrology,1876006277.

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Duncan, H., 1999. Urban stormwater quality: A statistical overview, Cooperative Research Centre for Catchment Hydrology.

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Melbourne Water, 2012. MUSIC Guidelines-Recommended input parameters and modelling approaches for MUSIC users. <http://www.melbournewater.com.au/content/library/wsud/guidelines_for_the_use_of_music.pdf>.

Mitchell, G., McCarthy, D.T., Deletic, A., Fletcher, T.D., 2008. Urban stormwater harvesting - sensitivity of a storage behaviour model. Environmental Modelling Software. 23, 782-793.

Appendix 4D

Pipe Sizing, Pump Sizing, and Pump Costing Procedure

Part A: Theory

1. Pipe Sizing

The stormwater pipe sizing stormwater harvesting sites was based on peak daily irrigation demand, which occur in the summer season. To estimate the stormwater pipe size (or simply diameter), Swamee and Sharma (2008) used Darcy-Weisbach Equation, which can be described as

$$h_f = \frac{8fLQ^2}{\pi^2 g D^5} \qquad \text{(4D-1)}$$

where, h_f = Head loss in pipe due to friction, m

f = Friction factor

L = Pipe length, m

Q = Daily peak discharge, m^3/s

g = Accelaration due to gravity, (9.81 m/s^{2}), and

D = Pipe diameter, m

By re-arranging the Equation 4D-1, pipe diameter was estimated. In this equation, the head loss due to friction was assumed as 3 m/km as suggested by WSAA (2002), and friction factor was assumed as 0.02 as suggested by Swamee and Sharma (2008). Furthermore, the pipe length was determined using standard GIS operations. The discharge (Equation 4D-1) was determined by taking peak daily demand of a given site in summer month of January.

2. Pump Sizing

The size of pumps in the current study was estimated by determining the hydraulic energy needed for pumping systems. This energy can be computed as

$$P_H = \frac{\rho Q g H_p}{1000} \qquad (4D\text{-}2)$$

where, P_H = Hydraulic power required for pumping, kW

ρ = Density of water (kg/m^3),

Q = Daily peak discharge (m^3/s),

G = Acceleration due to gravity, (9.81 m/s^2),

H_p = Required pumping head, m

For a given stormwater harvestings site, the pumping head H_p was estimated by summing the head loss due to friction, elevation difference (between collection systems and storage point), and terminal head.

3. Pump Costing

Swamee and Sharma (2008) provided a relationship between pumping system costs associated with pumping energy. This relationship is expressed as

$$C_p = 5560 * P_H^{0.723} \qquad (4D\text{-}3)$$

where, Cp = Cost of Pumping Systems in $ (AUD)

P_H = Hydraulic Power of Pump, kW (Estimated from Equation 4D-2)

The estimated C_p was adjusted to 2% inflation rate for base year of analysis (Year 2012)

Part B: Computational Demonstration: Flagstaff Park

1. Pipe Sizing:

For Flagstaff Park, the peak daily demand for irrigation was required in summer month of January. Therefore, stormwater pipe diameter was designed to supply this peak demand. Table 4D-1 shows different steps in stormwater pipe diameter estimation with some explanation. The estimated pipe diameter is highlighted in bold.

Table 4D-1: Pipe Sizing for Flagstaff Park

No.	Parameter	Value	Comment
1	Total Demand, ML	56	As per Table 4.21
2	Demand in January, ML	9.5	As per Table 4.20 (17%)
3	Pumping Hours	8	As per Table 4.18
4	Designed Discharge, L/s	1.1	Row 4 / (Row 3 * 3600)
5	Pipe Length, m	687	Section 4.7.2
6	Head Loss, m/km	3	Part A (This Section)
7	Friction Factor	0.02	
8	Head Loss due to Friction ,m	2.3	(Row 5 * Row 6)
9	Acceleration due to gravity, m/s^2	9.81	
10	**Pipe Diameter, mm**	**225[a]**	As per Equation 4D-1

([a]Scaled to standard size of pipe)

2. Pump Size and Cost

Table 4D-2 shows the estimation of pump sizing and associated costing for Flagstaff Park. The estimated pump size and pumping cost are highlighted in bold in Table 4D-2.

Table 4D-2: Pump Sizing and Costing for Flagstaff Park

No.	Parameter	Value	Comment
1	Designed Peak Discharge, L/s	1.1	As per Table 4D-1
2	Head Loss due to Friction ,m	2.3	
3	Elevation Difference , m	10	Determined from GIS Analysis
4	Terminal Head, m	10	Part A (This Section)
5	Density of Water, Kg/m^3	1000	-
6	**Pump Size (Hydraulic Power), kW**	**4.4**	As per Equation 4D-2
7	**Pump Cost, $**	**96,857**	As per Equation 4D-3

Reference

Swamee, P.K., Sharma, A.K., 2008. Design of water supply pipe networks. Wiley. com.

WSAA, 2002. Water Supply Code of Australia, WSA 03-2002.

Appendix 5A: AHP Methodology and Software

AHP Methodology

Conceptually, the weight evaluation procedure using the AHP method consists of four broader steps i.e. 1) Problem Structuring, 2) Pair-wise comparison Matrix, 3) Elicitation of weights, and 4) Consistency Evaluation. These steps are described as follows.

Problem Structuring

In this step, the decision problem is structured and decomposed in a hierarchical way. The problem objectives are represented at the top level. The intermediate level consists of Performance Measures (PMs) and sub PMs describing the objectives at the top level.

Pair-wise comparison Matrix

After the construction of hierarchy, the pair-wise comparisons of elements (i.e. objectives /PMs) within each level of hierarchy are carried out by comparing one element to another. In this pair-wise comparison, Decision Maker (DM) needs to assess the relative importance of one element over another on the scale of 1-9 proposed by Saaty (1980). The detailed interpretation of this scale is described in Table 5A-1. The judgements of DM are recorded in the form of pair-wise comparison matrix of dimension $N \times N$, where "N" is the number of elements under consideration.

Table 5A-1: AHP pair-wise comparison scale

Scale	Relative importance	Scale	Relative importance
1	Equal		
3	Moderately important	1/3	Moderately less important
5	Strongly important	1/5	Weakly important
7	Very Strongly important	1/7	Very weakly important
9	Extremely important	1/9	Extremely weak
2, 4, 6, 8	Intermediate values	1/2, 1/4, 1/6, 1/8	Intermediate reciprocal values

The nine-point scale is considered as a standard rating system in AHP. In this scale described in Table 5A-1, one (1) denotes the equal importance of one element i over another element j and nine (9) stands for the extreme importance of element i over element j. If one element is preferred less than the other in comparison, the reciprocal values of scale (in Table 1) are used to reflect the intensity of lower importance.

The total number of pair-wise comparisons, J can be determined as

$$J = \frac{N(N-1)}{2} \qquad (5A\text{-}1)$$

where N is the number of elements under consideration.

Table 5A-2 describes an example of pair-wise comparison (using the scale in Table 5A-1) in context of the current study, but considering the objectives as elements. The economic, environmental and social objectives are compared against each other according the preferences of a hypothetical DM (using scale in Table 5A-1).

Table 5A-2: Pair wise comparison matrix in AHP

	Economic	Environmental	Social
Economic	1	3	2
Environmental	1/3	1	1/2
Social	1/2	2	1

In above example, three judgments are needed to be specified by the DM (Equation 5A-1). Thus, in Table 5A-2, the DM rated economic objective 3 times more important than the environmental objective and 2 times more important than the social objective. Similarly, for this DM, the environmental objective was 1/2 times (less) important than the social objective. The greyed cells in Table 5A-2 represent the reciprocal values of pair wise comparisons which are derived automatically from the non highlighted cells.

Estimation of weights

After obtaining the judgements from the pair-wise comparison matrices, the weight estimation task is achieved by employing matrix algebra to compute the principal eigenvector of each judgment matrix 'N' represented in a hierarchy. Mathematically, the principal eigenvector for each matrix, when normalized, becomes the vector of priorities (i.e. weights) for that matrix (Saaty 1980). These weights are estimated for every element (Objectives /PMs/sub-PMs) across all hierarchy levels. The global weights of top hierarchy elements are synthesized (aggregated) with corresponding relative weights of sub elements in lower hierarchy. As a result, the overall relative priority of each lower element (e.g. sub-PMs) is obtained with respect to corresponding top level element (Objectives /PMs) in the hierarchy.

One of the simplest procedures for estimating the approximate values of principal Eigenvectors (i.e. weights) is to divide the value of each column by the sum of that column in pair-wise comparison matrix (Table 5A-3). This step effectively normalizes the elements of that column such that their sum is unity (Table 5A-4). Then, the average of normalised row elements provides the approximate principal eigenvector value (Table 5A-4).

Table 5A-3: Normalization of Columns

	Economic	Environmental	Social
Economic	1	3	2
Environmental	1/3	1	1/2
Social	1/2	2	1
Column Sum	**1.83**	**6**	**3.5**

Table 5A-4: Estimation of weights

	Economic	Environmental	Social	Average
Economic	0.54	0.50	0.57	0.54
Environmental	0.18	0.17	0.16	0.16
Social	0.27	0.33	0.29	0.30
Column Sum	**1**	**1**	**1**	**∑= 1**

The weights elicited by the above procedure can be used only as basic estimates in case of absence of computational facilities. Although the aforementioned procedure is easily comprehendible, Saaty (1994) argues that it can lead to inconsistency in judgement. The alternate procedure recommended by Saaty (1994) for computing the eigenvector is quite complex; however, can be easily incorporated with commercial mathematical software packages. This procedure of determining the eigenvectors briefly involves iterative squaring of a pair-wise comparison matrix (e.g. Table 5A-2), then summing the rows and normalizing the elements until the difference between two successive calculations are very small i.e. remains unchanged to four decimal places (Mau-Crimmins et al., 2005; Saaty, 1994).

The weights estimated through an alternative approach are shown in the form of eigenvectors in Equation 5A-4. It can be seen that these weights are almost identical to the average weights in Table 5A-4.

$$W = \begin{Bmatrix} Economic \\ Environmental \\ Social \end{Bmatrix} = \begin{Bmatrix} 0.5396 \\ 0.1634 \\ 0.2960 \end{Bmatrix} \qquad (5A\text{-}4)$$

In the current study, such eigenvector computation was facilitated through the EXPERT CHOICE software (Ishizaka and Labib, 2009), which incorporates the holistic AHP methodology proposed by the Saaty, author of the AHP method. Brief details on Expert Choice are presented at end of this section.

Apart from the eigenvector method, there are several other methods proposed to evaluate the weights from pair-wise comparison matrix of AHP. These methods include additive normalization (AN), logarithmic least squares (LLS), weighted logarithmic least square (WLS), logarithmic goal programming (LGP), and fuzzy preference programming (FPP) (Srdjevic and Srdjevic, 2013). However, Saaty (2003) strongly recommended the eigenvector method, as this method effectively handles inconsistencies of DM during pair-wise comparisons of elements.

Consistency Evaluation

This step does not directly contribute in elicitation of weights, but, provides a logic-based consistency check on the validity of judgements (of DMs) obtained from the pair-wise comparison matrix. To understand the consistency concept, the example in Table 5A-2 can be used where DM responses are consistent. According to DM preferences, economic objectives are thrice preferred over environmental objectives and twice over social objectives. This situation naturally can be interpreted such that DM considers social objectives more important to environmental objectives (Table 5A-2).

Assume a case where DM preferences are inconsistent. Suppose the DM prefers economic objectives five times over the environmental objectives, and two times over the social objectives. This scenario naturally could be interpreted as DM prefers social objectives (5/2 times) over environmental objectives. However, in further pair-wise comparisons of social and environmental objectives, if DM prefers environmental objectives equal or more than social objectives, then his/her judgment breaks the consistency. The AHP accommodates such real world inconsistency which ensures that each pair-wise comparison matrix is within certain acceptable consistency tolerance.

The mathematical procedure for consistency evaluation and its computational demonstration with an example of Table 5A-2 is given below. It should be noted that this computational procedure is completely supported by the EXPERT CHOICE software used in the current study.

Consistency Evaluation Methodology and Demonstration

In terms of obtaining a consistent pair-wise comparison matrix, Saaty (1980) proved that the largest eigen value (λ_{Max}) associated with the principal eigenvector W (Equation 5A-4) is equal to the size of comparison matrix N.

Mathematically,

$$\lambda_{Max} = N \qquad (5A\text{-}5)$$

This property is used for consistency evaluation by estimating the value of $\lambda_{Max.}$ If Equation 5A-5 is satisfied, then judgements prescribed by the DM are said to be perfectly consistent.

The first step in the consistency evaluation is to multiply the original comparison matrix A (in Table 5A-2) by the estimated eigenvector *W* (Equation 5A-4).

$$AW = \begin{bmatrix} 1 & 3 & 2 \\ 1/3 & 1 & 1/2 \\ 1/2 & 2 & 1 \end{bmatrix} X \begin{Bmatrix} 0.5396 \\ 0.1634 \\ 0.2960 \end{Bmatrix}$$

The resulting vector is $\begin{Bmatrix} 1.6218 \\ 0.4912 \\ 0.8926 \end{Bmatrix}$

Next, the each component of the resulting vector is again divided by the values of eigenvector W (Equation 5A-4) to get a new vector, AV.

$$AV = \begin{Bmatrix} 3.005 \\ 3.006 \\ 3.015 \end{Bmatrix}$$

Then, λ_{Max} is estimated by averaging the the entries in the vector AV. The average of elements in vector AV gives maximum eigenvalue, λ_{Max} as 3.008. This λ_{Max} value is used to compute the consistency index or coefficient of inconsistency (C.I.) using Equation 5A-6. From Equation 5A-5 and 5A-6, it can be seen that C.I. equals to zero in case of consistent matrix.

$$\mathrm{C.I.} = \frac{\lambda_{\mathrm{Max}} - \mathrm{N}}{\mathrm{N} - 1} \qquad (5A\text{-}6)$$

$$\mathrm{C.I.} = \frac{3.008 - 3}{3 - 1}$$

$$= 0.004$$

The final step in the consistency evaluation is to compare the C.I. with the random consistency index (R.I.) proposed by Saaty (1980). The R.I. represents average C.I. for a huge number of randomly generated (pair-wise comparison) matrices of the given order. Table 5A- 3 shows the R.I. for different size matrices, proposed by Saaty (1980). It can be seen that R.I. for pair-wise comparison matrix for size 3 (such as Table 5A-2) is 0.58

Table 5A-3: Random Consistency Index (R.I.)

N	2	3	4	5	6	7	8	9
RI	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The ratio of C.I. to R.I. is termed as the consistency ratio (C.R.), which can be estimated as

$$\mathrm{C.R.} = \frac{\mathrm{C.I}}{\mathrm{R.I.}} \qquad (5A\text{-}.7)$$

Finally, C.R. is estimated as

$$\mathrm{CR} = \frac{0.004}{0.58}$$

$$= 0.006$$

According to Saaty (1980, 2004), the judgment formed in the pair-wise comparison matrix is acceptable, if C.R. value of less than 0.1. As C.R. for Table 5A-2 is significantly less (i.e. 0.006), the pair-wise comparisons in Table 5A-2 can be said consistent.

EXPERT CHOICE Software for AHP

EXPERT CHOICE (EC) is decision making software, based on the AHP method proposed by the T.L. Saaty. As a decision making tool, EC comes as powerful, flexible, user-friendly software (Pomerol and Barba-Romero, 2000). Furthermore, this software is well documented with sound theoretical background and intuitive graphical interface. EC principally comes in two formats: Comparion Core™ (Web Based Format) and EC Desktop™ (A windows desktop based format). For the current study, EC Desktop (Academic Version 11.5) was used. Both formats can be purchased online from the website http://expertchoice.com/.

Using the AHP methodology, the EC software assists decision makers for structuring the decision problem into hierarchy, proceeding from the objectives to performance measures, and down to the sub-performance measures or alternatives. The decision makers then make simple pair wise comparison judgments throughout the hierarchy to arrive at overall priorities for the alternatives.

The key features of the software include:

- Three different ways of pair wise comparisons: Numerical AHP Scale, Qualitative Scale, and Graphical Scale
- Interactive sensitivity analysis to changes in weights provided by the decision maker
- What-if scenarios allowing sensitivity of final results to be assessed in case of change in preferences
- Diagnostic function for detecting and evaluating the consistency of pair wise comparisons of alternatives
- Group decision making support
- Integration of data with Microsoft Excel, Microsoft Project, and Oracle Databases to visualize data in different ways.

References:

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Pomerol, J., Barba-Romero, S., 2000. Multicriterion decision in management: principles and practice. Kluwer.

Saaty, T.L., 1980. The analytic hierarchy process. McGraw-Hill, NewYork,NY, USA.

Saaty, T.L., 1994. Fundamentals of decision making. Pittsburgh: RWS Publications.

Saaty, T.L., 2003. Decision-making with the AHP: Why is the principal eigenvector necessary. European Journal of Operational Research 145, 85-91.

Saaty, T.L., 2004. Decision making — the Analytic Hierarchy and Network Processes (AHP/ANP). Journal of Systems Science and Systems Engineering 13, 1-35.

Saaty, T.L., Hu, G., 1998. Ranking by Eigenvector versus other methods in the Analytic Hierarchy Process. Applied Mathematics Letters 11, 121-125.

Srdjevic, B., Srdjevic, Z., 2013. Synthesis of individual best local priority vectors in AHP-group decision making. Applied Soft Computing 13, 2045-2056.

Appendix 5B

Information to Participants and Templates for Preference Elicitation

1. Information to Participants: Weights and Preference Functions

Information for the Participants:

Please find some background information of weights and preference functions in this document.

A popular outranking method - PROMETHEE will be used in Multi Criteria Decision Aid (MCDA) analysis. This method requires two sets of information from decision maker (DM).

1. Relative importance of Performance Measures (PMs) and objectives (represented by weights)
2. Level of preferences within each PM (represented by a 'Preference Function')

Information 1: Weights

Your expression of relative importance to each objective and PM will be obtained through a very simple weighting method, known as Analytical Hierarchy Process (AHP). The method evaluates the relative importance of PMs and objectives by comparing them one by one on 1 to 9 scale.

For example, how do you consider the importance of economic objectives over environmental objectives on a scale of 1 to 9? (In the stormwater harvesting context)

	Economic	Environmental	Social
Economic	1	3	2
Environmental	1/3	1	1/2
Social	1/2	2	1

In above example, the decision maker (DM) thinks that economic objective are 3 times more important than the environmental objective or 2 times important than the social objective. Similarly, for this DM, environmental objective are 1/2 times (less) important than the social objectives. It should be noted that the bottom triangle of the matrix indicates reciprocal importance in this pair wise comparison (e.g. 1/2 in social to economic objectives in matrix above). During elicitation of weights on PMs and objectives, you need to enter scale values in Template A, only for **non-greyed** cells.

Information 2: Preference functions

Your level of preferences for **each PM** will be obtained through a Preference Functions (PF). To facilitate the association of a PF on a given PM, the authors of PROMETHEE have proposed six different shapes. These shapes are listed in Figure 1. Most of quantitative PMs can be represented by Type V function (highlighted in green in Figure 5B-1) by defining '***q***' and '***p***' or simply '***q***' or '***p***'. Also, qualitative PMs can be represented by Type I or IV function (highlighted in blue in Figure 1). It should be noted that type VI is function is complicated to define and hence not advised to use.

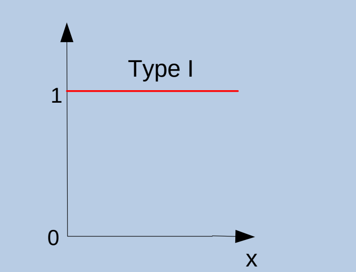
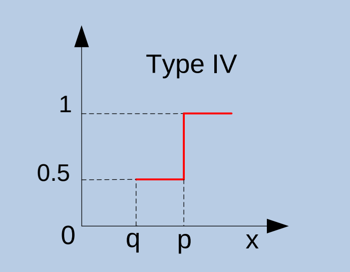
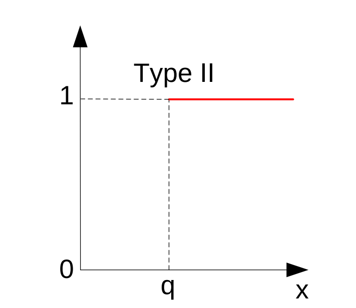
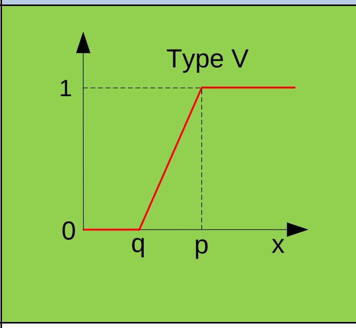
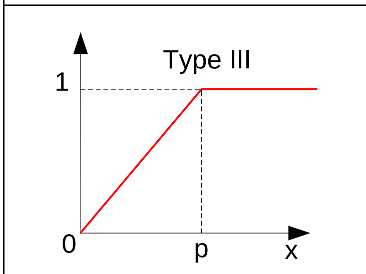
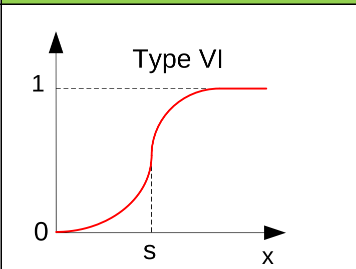
Function	Parameters to estimate	Function	Parameters to estimate
	--		p, q
	q		p, q
	p		s

Figure 1: Preference Functions Available in PROMETHE
x indicates the difference between PMs for given pair of alternatives.

What is *p* and *q*?

The parameter ***q*** represents the indifference threshold i.e. the largest difference in PM values until DM thinks the preference between alternatives *a* and *b* is negligible or indifferent. Similarly, preference threshold, ***p***, represents the smallest difference in PM values that is considered as crucial in generating strong preference of one alternative over the other (e.g. a over b).

What p and q specifies in stormwater harvesting context?

Consider two proposed stormwater harvesting schemes A and B in Table 1 for which we need information of preference (A over B or B over A). The PM considered in this case is Levelised Cost i.e. LC ($/ KL) under economic objective.

Table 1: Evaluation of ***p*** and ***q*** based on Levelised Cost

Scheme	LC ($/ KL)
A	3
B	3.2

We can specify a PF on LC by describing ***q*** and ***p*** values. Figure 2 indicates Type V function assigned as an example.

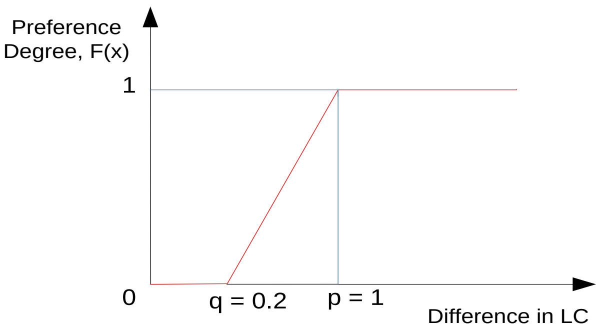


Figure 2: Preference function example

If the DM thinks the LC difference of 0.2$/KL between two alternative sites is negligible for deciding the preference (assuming similar benefits from A and B) then, ***q = 0.2***. However, if this difference between LC exceeds than 1$/KL, then the DM will strongly prefer the scheme with low LC. In this case, ***p* = 1 (*p* > *q*)**. Using the PF concept, the preference degree F(x) on LC (or any particular PM) can be expressed on scale of 0 to 1. In Figure 1, note that F(x) = 0 until ***q* = *0.2.*** During the session, we will seek **your opinion on the q and p values** appropriate for various PMs.

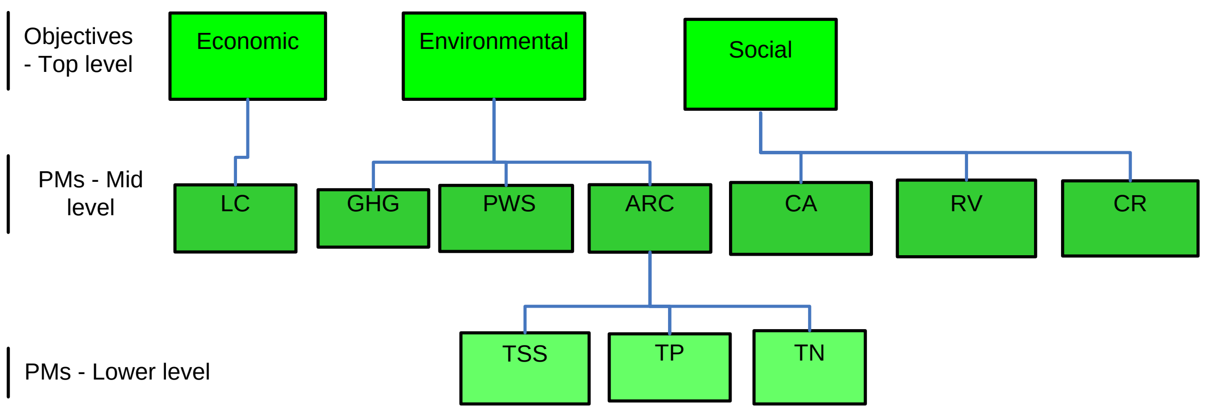
2. Templates for Preference Elicitation: Weights (AHP) and Preference Functions (PROMETHEE)

Template A: Elicitation of Weights

Information for the participants:

- The purpose of this document is to elicit the **weights** on Performance Measures and Objectives considered in this project.
- The information collected in this survey will be treated confidential.
- Some background information on weight assessment is provided in the attachment.

Weight elicitation will be done on three levels according to the hierarchy of Performance Measures (PMs) and Objectives. In the first stage, weights (or relative importance) will be obtained for the lower level of PMs. In the second stage, weight elicitation will be done for the mid level of PMs and in the final stage, weights will be obtained for objectives. Figure 1 describes the hierarchy of PMs and Objectives.



- *LC: Levelised Cost*
- *GHG: Green House Gas Emission*
- *PWS: Potable Water Savings*
- *ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)*
- *RV: Recreational Value*
- *CA: Community Acceptance*
- *CR: Construction Risks*
  - *TSS : Total Soluble Solids*
  - *TP: Total Phosphorous*
  - *TN: Total Nitrogen*

Figure 1: Hierarchy of Objectives and PMs

During elicitation of weights, you will need to rate the relative importance of PMs and relative importance of Objectives with each other on a scale of 1-9. The scale interpretation is given in Table 1. You need to fill only **non-greyed** cells in Tables 2, 3, and 4. Reciprocal of scale in Table 1 indicates importance of PMs in reverse way. Kindly refer to the supplementary attachment (Appendix 4-B) for more details on weight elicitation.

Table 1: Scale Interpretation

Scale	Relative importance	Scale	Relative importance
1	Equal		
3	Moderately important	1/3	Moderately less important
5	Strongly important	1/5	Weakly important
7	Very Strongly important	1/7	Very weakly important
9	Extremely important	1/9	Extremely weak
2, 4, 6, 8	Intermediate values	1/2, 1/4, 1/6, 1/8	Intermediate values

1. Weight assessment for the Objectives

Please rate the relative importance of objectives listed in Table 2, using the scale defined in Table 1.

Table 2: Relative importance for the objectives

	Economic	Environmental	Social
Economic	1		
Environmental		1	
Social			1

2. Weight elicitation for Environmental PMs

Please rate the relative importance of the lower level PMs listed in Table 3 and Table 4.

Table 3: Relative importance for environmental PMs

	GHG	PWS	ARC
GHG	1		
PWS		1	
ARC			1

- *GHG: Green House Gas Emission*

- *PWS: Potable Water Savings*
- *ARC: Annualised Removal Costs of Indicative Pollutants (TSS, TP and TN)*

Table 4: Relative importance for ARC (Sub PM)

	TSS	TP	TN
TSS	1		
TP		1	
TN			1

- *TSS : Total Soluble Solids*
- *TP: Total Phosphorous*
- *TN: Total Nitrogen*

3. Weight elicitation for Social PMs

Please rate the relative importance of the lower level PMs listed in Table 5.

Table 5: Relative importance of social PMs

	CA	CR	RV
CA	1		
CR		1	
RV			1

- *CA: Community Acceptance*
- *CR: Construction Risks*
- *RV: Recreational Value*

Template B: **Elicitation of Preference Functions (q and p values)**

Information for the participants:

- The purpose of this document is to elicit the information of Preference Functions (PFs) by defining the parameters *q* and *p* on Performance Measures (PMs) considered in this project.
- The information collected in this survey will be treated confidential.
- Some background information on PF is provided in the attachment.

Elicitation of Preferences:

The preference elicitation procedure will consist of assigning *q* and *p* values on listed Performance Measures (PMs) in Tables 6 and 7. Preference elicitation for the current project will be done in two stages.

- Stage 1: Assignment of PF on ranges of PMs
- Stage 2: Assignment of PF on original PM values of alternative sites

Stage (1): Assignment of PF on ranges of PMs:

Table 6 indicates a matrix of listed performance measures and their indicative ranges of values derived from the conceptual designs of alternative stormwater harvesting schemes considered in this study. Please assign appropriate *q* and *p* values on listed PMs. Kindly refer to the supplementary document for information on preference functions and associated *q* and *p* values.

Table 6: PF Assignment on Ranges of PM Values

Objectives	Performance measures	Unit	Max or Min	Range of values	Mean	q	p
Economic	Levelised Cost	($/ KL)	Min	10.8-27.2	17.4		
Environmental	Green House Gas Emissions	(Kg CO_2 /KL)	Min	0.16-0.41	0.20		
	Potable water savings	ML	Max	5.6-73	25		
	Annualised removal cost of TSS	($/ Kg/Year)	Min	0.9-4	2.0		
	Annualised removal cost of TP	($/ Kg/Year)	Min	580-2527	1370		
	Annualised removal cost of TN	($/ Kg/Year)	Min	81-327	174		
Social*	Community acceptance	-	Max	1-5	-		
	Construction Risks	-	Min	1-5	-		
	Recreational values	-	Max	1-5	-		

*Scale for qualitative PMs

Community Acceptance	Scale	Construction Risks	Scale	Recreational Value	Scale
Very High	5	Very High	1	Very High	5
High	4	High	2	High	4
Moderate	3	Moderate	3	Moderate	3
Low	2	Low	4	Low	2
Lowest	1	Lowest	5	Lowest	1

Stage (2): Assignment of PF on PMs considering actual evaluation matrix

Table 7 represents the real stormwater harvesting sites considered in the analysis along with their performance in different PMs. Kindly indicate your preferences on PMs with appropriate *p* and *q* values. If you wish to keep the same preferences as in Table 6, do not fill this table

Table 7: PF Assignment on Original PM Values of Alternative Sites

Sites	Objectives								
	Economic	Environmental					Social		
	Performance Measures								
	Levelised Cost ($/KL)	Greenhouse Gas Emissions (Kg CO_2 / KL)	Potable water Savings (ML)	Annualised removal cost ($/Kg/Year)			Community Acceptance	Recreational Value	Construction Risks
				TSS	TP	TN			
Holland Park	15.3	0.20	18.5	4	2527	327	3	5	1
Birrarung Marr Park	15.5	0.17	15.1	0.9	580	81	3	3	2
Clayton Reserve	14.0	0.17	26.2	1.4	1,021	122	4	3	2
Princess Park	12.3	0.16	73	2.8	1,832	241	5	5	3
Flagstaff Garden	10.8	0.41	56	1.3	929	118	5	4	3
Batman Park	22.3	0.18	5.7	1.6	1130	140	2	3	3
Ievers Reserve	21.4	0.18	5.7	1.1	772	95	2	3	1
Pleasance Gardens	27.2	0.17	5.6	3.3	2167	266	2	2	3
q									
p									

Appendix 5C: Pair Wise Comparison (AHP): Reponses of Workshop Participants

Based on AHP scale, Table 5C-1 shows the pair-wise comparisons of workshop participants

Table 5C-1: Pair-wise comparisons of Workshop Participants

		Eco	Env	Soc		GHG	PWS	ARC		TSS	TP	TN		CA	CR	RV
WA-1	Eco	1	3	3	GHG	1	1	3/4	TSS	1	2	1	CA	1	2	1/2
	Env		1	1	PWS		1	3/4	TP		1	2	CR		1	1/2
	Soc			1	ARC			1	TN			1	RV			1
WA-2	Eco	1	3	3	GHG	1	2	1	TSS	1	2	1	CA	1	2	1
	Env		1	1	PWS		1	1/2	TP		1	1/2	CR		1	1/2
	Soc			1	ARC			1	TN			1	RV			1
WA-3	Eco	1	1	1/2	GHG	1	1/9	1/2	TSS	1	7	7	CA	1	2	1
	Env		1	1/2	PWS		1	5	TP		1	1	CR		1	1/2
	Soc			1	ARC			1	TN			1	RV			1
AC-1	Eco	1	2	2	GHG	1	7	5	TSS	1	1/2	1/5	CA	1	7	9
	Env		1	1	PWS		1	1/5	TP		1	1/2	CR		1	9
	Soc			1	ARC	1		1	TN			1	RV			1
AC-2	Eco	1	1/3	1	GHG	1	4	1	TSS	1	5	4	CA	1	2	1
	Env		1	3	PWS		1	1/4	TP		1	1/2	CR		1	2
	Soc			1	ARC	1		1	TN			1	RV			1
AC-3	Eco	1	2	2	GHG	1	3	1/3	TSS	1	5	3	CA	1	1/3	1
	Env		1	1	PWS		1	1/3	TP		1	3	CR		1	1/3
	Soc			1	ARC			1	TN			1	RV			1
CS-1	Eco	1	2	2	GHG	1	1/2	1/4	TSS	1	1/4	1/4	CA	1	1	1
	Env		1	1	PWS		1	2	TP		1	1	CR		1	1
	Soc			1	ARC			1	TN			1	RV			1
CS-2	Eco	1	3	2	GHG	1	1/7	1/2	TSS	1	3	2	CA	1	1/2	3/2
	Env		1	1/2	PWS		1	3	TP		1	1/2	CR		1	3
	Soc			1	ARC			1	TN			1	RV			1
CS-3	Eco	1	3	2	GHG	1	2/5	1	TSS	1	3	2	CA	1	5/4	3/4
	Env		1	2/3	PWS		1	5/2	TP		1	2/3	CR		1	3/5
	Soc			1	ARC			1	TN			1	RV			1
CS-4	Eco	1	4	2	GHG	1	1/2	4/5	TSS	1	1	1	CA	1	3/2	1/2
	Env		1	1/2	PWS		1	2	TP		1	1	CR		1	4/5
	Soc			1	ARC			1	TN			1	RV			1
CL-1	Eco	1	3	2	GHG	1	1/2	2	TSS	1	3	2	CA	1	1/2	2
	Env		1	1/2	PWS		1	3	TP		1	1/2	CR		1	3
	Soc			1	ARC			1	TN			1	RV			1