A MICRO-LEVEL INDEXING MODEL FOR THE ASSESSMENT OF SUSTAINABLE URBAN ECOSYSTEMS

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Abstract

During the last several decades, the quality of natural resources and their services have been exposed to significant degradation from increased urban populations combined with the sprawl of settlements, development of transportation networks and industrial activities (Dorsey, 2003; Pauleit *et al.*, 2005). As a result of this environmental degradation, a sustainable framework for urban development is required to provide the resilience of natural resources and ecosystems. Sustainable urban development refers to the management of cities with adequate infrastructure to support the needs of its population for the present and future generations as well as maintain the sustainability of its ecosystems (UNEP/IETC, 2002; Yigitcanlar, 2010). One of the important strategic approaches for planning sustainable cities is ‘ecological planning’. Ecological planning is a multi-dimensional concept that aims to preserve biodiversity richness and ecosystem productivity through the sustainable management of natural resources (Barnes *et al.*, 2005). As stated by Baldwin (1985, p.4), ecological planning is the initiation and operation of activities to direct and control the acquisition, transformation, disruption and disposal of resources in a manner capable of sustaining human activities with a minimum disruption of ecosystem processes. Therefore, ecological planning is a powerful method for creating sustainable urban ecosystems.

In order to explore the city as an ecosystem and investigate the interaction between the urban ecosystem and human activities, a holistic urban ecosystem sustainability assessment approach is required. Urban ecosystem sustainability assessment serves as a tool that helps policy and decision-makers in improving their actions towards sustainable urban development. There are several methods used in urban ecosystem sustainability assessment among which sustainability indicators and composite indices are the most commonly used tools for assessing the progress towards sustainable land use and urban management. Currently, a variety of composite indices are available to measure the sustainability at the local, national and international levels. However, the main conclusion drawn from the literature review is that they are too broad to be applied to assess local and micro level sustainability and no benchmark value for most of the indicators exists due to limited data availability and non-comparable data across countries. Mayer (2008, p. 280)

advocates that by stating "as different as the indices may seem, many of them incorporate the same underlying data because of the small number of available sustainability datasets". Mori and Christodoulou (2011) also argue that this relative evaluation and comparison brings along biased assessments, as data only exists for some entities, which also means excluding many nations from evaluation and comparison.

Thus, there is a need for developing an accurate and comprehensive micro-level urban ecosystem sustainability assessment method. In order to develop such a model, it is practical to adopt an approach that uses a method to utilise indicators for collecting data, designate certain threshold values or ranges, perform a comparative sustainability assessment via indices at the micro-level, and aggregate these assessment findings to the local level. Hereby, through this approach and model, it is possible to produce sufficient and reliable data to enable comparison at the local level, and provide useful results to inform the local planning, conservation and development decision-making process to secure sustainable ecosystems and urban futures. To advance research in this area, this study investigated the environmental impacts of an existing urban context by using a composite index with an aim to identify the interaction between urban ecosystems and human activities in the context of environmental sustainability. In this respect, this study developed a new comprehensive urban ecosystem sustainability assessment tool entitled the 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX). The MUSIX model is an indicator-based indexing model that investigates the factors affecting urban sustainability in a local context. The model outputs provide local and micro-level sustainability reporting guidance to help policy-making concerning environmental issues.

A multi-method research approach, which is based on both quantitative analysis and qualitative analysis, was employed in the construction of the MUSIX model. First, a qualitative research was conducted through an interpretive and critical literature review in developing a theoretical framework and indicator selection. Afterwards, a quantitative research was conducted through statistical and spatial analyses in data collection, processing and model application. The MUSIX model was tested in four pilot study sites selected from the Gold Coast City, Queensland, Australia. The model results detected the sustainability performance of current urban settings referring to six main issues of urban development: (1) hydrology, (2) ecology, (3) pollution, (4) location, (5) design, and; (6) efficiency. For each category, a set of core indicators was assigned which are intended to: (1) benchmark the current situation, strengths and weaknesses, (2) evaluate the efficiency of implemented plans, and; (3) measure the progress towards sustainable development. While the indicator set of the model provided specific information about the environmental impacts in the area at the parcel scale, the composite index score provided general information about the sustainability of the area at the neighbourhood scale. Finally, in light of the model findings, integrated ecological planning strategies were developed to guide the preparation and assessment of development and local area plans in conjunction with the Gold Coast Planning Scheme, which establishes regulatory provisions to achieve ecological sustainability through the formulation of place codes, development codes, constraint codes and other assessment criteria that provide guidance for best practice development solutions. These relevant strategies can be summarised as follows:

- Establishing hydrological conservation through sustainable stormwater management in order to preserve the Earth’s water cycle and aquatic ecosystems;
- Providing ecological conservation through sustainable ecosystem management in order to protect biological diversity and maintain the integrity of natural ecosystems;
- Improving environmental quality through developing pollution prevention regulations and policies in order to promote high quality water resources, clean air and enhanced ecosystem health;
- Creating sustainable mobility and accessibility through designing better local services and walkable neighbourhoods in order to promote safe environments and healthy communities;
- Sustainable design of urban environment through climate responsive design in order to increase the efficient use of solar energy to provide thermal comfort, and;
- Use of renewable resources through creating efficient communities in order to provide long-term management of natural resources for the sustainability of future generations.

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List of Abbreviations

ARC - Australian Research Council

CBD - City Business District

DPSIR - Driving force-Pressure-State-Impact-Response

ESUD - Environmentally Sustainable Urban Development

FEEM - Fondazione Eni Enrico Mattei

GCC - Gold Coast City

GIS - Geographical Information System

MUSIX - Micro-level Urban-ecosystem Sustainability Index

QUT - Queensland University of Technology

List of Publications

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Dizdaroglu D., Yigitcanlar T. & Dawes, L. (2012). A Micro-Level Indexing Model for Assessing Urban Ecosystem Sustainability, *the Smart and Sustainable Built Environment (SASBE) Journal*, *1*(3), p. 291-315.

Book Chapter

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Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: 05/01/2013

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Chapter 1: Introduction

This chapter provides an outline of the background and research problem of this study. The research questions, aims, objectives and significance of the study are defined by addressing the research scope and limitations. Finally, this chapter concludes with an outline of the thesis.

1.1 BACKGROUND AND RESEARCH PROBLEM

Over the past century, the quality of natural resources and their services have been exposed to significant threats from increasing urban populations combined with the sprawl of settlements, development of transportation networks and industrial activities (Dorsey, 2003; Pauleit *et al.*, 2005). The ecological consequences of these changes can be briefly summarised as global warming, degradation of air, water and soil quality, changes in terrestrial and aquatic habitats as well as species' richness and composition which results in loss of biodiversity (McKinney, 2002). In this regard, a sustainable framework for urban development is needed to provide the resilience of natural resources in urban environments.

As a sustainable framework for urban development, cities need to be well-managed with a balance of meeting the needs of the present while ensuring their availability for future generations (WCED, 1987). Sustainable cities require adequate infrastructure and flexibility to support the needs of its population for the present and future generations as well as maintain the sustainability of its ecosystems (UNEP/IETC, 2002). Cities are dynamic and complex ecosystems shaped by human activities. To understand the interrelation of human activities and urban ecosystems, the impact of urban spatial structures, legislative actions and lifestyles on environmental quality and sustainability performance needs to be examined.

Sustainability assessment of the urban ecosystem provides an analysis of the current state of ecological urban systems by identifying the causes of the impact at different spatial scales. These assessment strategies serve as a tool for helping the decision-making and policy-making process in order to support actions for creating more liveable and sustainable cities. In recent years, various instruments have been developed for sustainability assessment of the urban ecosystem. They mainly focus on two perspectives of assessment. The first is the evaluation of existing local government initiatives towards sustainable development. The second is the evaluation of proposed policies and plans to assess their compliance with sustainability goals (Devuyst *et al.*, 2001).

There are several different methods used in the sustainability assessment of urban ecosystems and among them sustainability indicators and composite indices are the most commonly used instruments for assessing the progress towards sustainable management of the environment and natural resources (Li *et al.*, 2009). Currently a variety of indices are available to measure the sustainability at macro-scales from national to regional and international levels. However, they come along with many challenges due to data availability and collection, indicator selection, spatial and temporal coverage issues (Hacking *et al.*, 2008; Singh *et al.*, 2009). As stated by Mayer (2008, p.287) "*all indices are problematic, if data are unavailable for the majority of the aggregated indicators, which at present is a common weakness to all sustainability efforts regardless of scale or publicity*".

The aforementioned challenges and issues demonstrate that there is a need for developing more effective approaches and models, particularly at the local and micro levels, in the sustainability assessment of urban ecosystems (Devuyst *et al.*, 2001). To advance research in this area, this study investigates the environmental impacts of an existing urban setting by using a sustainability index with an aim to identify the interaction between urban ecosystems and human activities in the context of environmental sustainability. In this respect, this study develops a new comprehensive sustainability assessment indexing model entitled 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX). The MUSIX model is an indicator-based sustainability-indexing model that aims to monitor the interaction between human activities and urban ecosystems in a local context. The model is an innovative approach designed to assess the resilience of ecosystems towards the impacts of current development plans and the model results are targeted to serve as a guide for the policy-making process to take actions towards achieving sustainable urban development.

1.2 RESEARCH AIM, OBJECTIVES AND QUESTIONS

The aim of this research is to investigate the impacts of urban development on the natural environment by developing a micro-level indexing model to assess the indirect or consequential effects by using environmental sustainability indicators. This research aim is supported by the following research objectives:

- To identify the environmental impacts of impervious surfaces on the urban ecosystem;
- To develop a set of indicators in order to define the environmental issues within urban areas at a micro-level spatial unit, and;
- To establish an urban ecosystem sustainability assessment tool that assesses the sustainability of urban development policies.

In light of the research aim and objectives, this study explores the following research questions, which constitute the literature review and methodology of the study:

- What are the major environmental impacts arising from globalisation and population growth?
- How can long-term sustainable management of urban ecosystems be achieved through an ecological planning approach?
- What are the existing assessment methodologies and their sustainable outcomes?
- How can a new sustainability assessment approach be developed to monitor the parcel-scale environmental impacts of human activities?
- How can this approach be integrated into planning policies and practices for present and future settlements?

1.3 RESEARCH SIGNIFICANCE

In accordance with the aims and objectives mentioned above, theoretical underpinning of this research is based on developing 'sustainable urban ecosystems' that have an effective use of their resources while reducing the impacts and sustaining their ecological functioning as well as providing higher living standards and a healthier urban environment for their citizens. Examining urban areas as ecosystems and understanding the relationship and linkages between these ecosystems and human well-being is the key to sustainable urban development. Urban ecosystems are dynamic complex systems; hence, their interaction with human activities needs to be monitored regularly. Sustainability assessment is increasingly being viewed as an important tool to monitor this interaction through a set of indicators that provide comprehensive information about the state of the environment over different temporal and spatial scales.

This research contributes to the knowledge theoretically by proposing an environmental sustainability-indexing model that provides reporting guidance for indicator-based sustainability assessment theory. The proposed sustainability-indexing model contributes in a number of ways to indicator-based sustainability assessment theory by:

- *Defining environmental issues via selecting the relevant indicators;*

In the MUSIX model, a set of relevant indicators is developed through a comprehensive review of existing indicator initiatives (e.g., UNCSD, 2001; OECD, 2003; EEA, 2005; Japan Sustainable Building Consortium, 2007; SEDAC, 2007; U.S. Green Building Council, 2008, 2009). The model is also highly benefited from the expert opinions, both academic and professional, and their local knowledge concerning the study area during the selection of indicators. Additionally, indicators are selected through consideration of the local environmental issues and data availability for the study area. In this way, the MUSIX model identifies a set of relevant indicators that can be used for monitoring the impacts of existing development planning on urban ecosystems.

- *Monitoring current sustainability performance through the appropriate method;*

Several methods are used in sustainability assessment and among them sustainability indicators and composite indices are the most commonly used tools for assessing the progress towards sustainable land use and urban management. Currently, a variety of composite indices are available to measure the sustainability at different levels. However, in most of them, there is a particular gap due to the challenges in data collection difficulties and availability of local data, thereby; there is no effective micro-level assessment tool that measures urban ecosystem sustainability accurately. In this context, the MUSIX model is developed as a micro-level sustainability-indexing model for policy-making that monitors the sustainability performance of an existing urban ecosystem by using relevant indicators.

- *Assessing the effectiveness of the existing development policies through the proper data analysis and interpretation of results;*

It is important to develop an accurate and proper method in sustainability assessment. In order to develop such a method, it is necessary to adopt an approach that utilises indicators for collecting data, designates certain threshold values or ranges, performs a comparative sustainability assessment via indices at the micro-level, and aggregates these assessment findings to a local-level. In this regard, the MUSIX model provides specific information about the environmental impacts in an urban area at the parcel scale, furthermore; the composite index score provides general information about the sustainability of an urban area at the neighbourhood scale.

This research contributes to the knowledge practically by developing and testing an assessment tool that assists local government authorities to measure their environmental performance in terms of planning, management and protection of urban ecosystems. The MUSIX model provides fundamental information and guidance that assists developers, planners and policy-makers to investigate the multidimensional nature of sustainability at the local level by capturing the environmental pressures and their driving forces in highly developed urban areas. The outcomes of the model helps in finding solutions for the environmental impacts in the urban area through proposing efficient policy recommendations which can be incorporated into local planning scheme, such as:

- Sustainable stormwater management;
- Ecological conservation;
- Enhancement of environmental quality;
- Development of walkable neighbourhoods;
- Sustainable design of urban environment, and;
- Efficient use of resources.

In summary, the contributions of this research provide opportunities in transforming unsustainable urban areas into potential sustainable urban futures.

1.4 RESEARCH SCOPE AND LIMITATIONS

This study focuses on developing a new approach for sustainability assessment based on a set of indicators that can be used to guide policy-makers and planners in promoting sustainable urban environments. In the scope of the study, both qualitative and quantitative data collection were employed. First of all, in order to provide an overview of sustainability assessment methodologies, practices and policies, literature including a large number of books, publications, reports, journals as well as best practices were reviewed. This qualitative research was also used in theoretical framework development, indicator selection and the parameter assignment stages of the MUSIX model. Afterwards, quantitative research was employed in Geographical Information System (GIS)-based spatial analysis and statistical methods in data collection, processing and model implementation. This study is a part of the joint Australian Research Council (ARC) Linkage project that aims to develop recommendations for the adaptation of current water sensitive urban design (WSUD) practices to climate change, changing transport patterns and urban form and Gold Coast City is chosen as the test bed for this project. In order to ensure the data and content integrity within the ARC project, two suburbs, Upper Coomera and Helensvale, in the Gold Coast City were selected for the implementation of the model. In this regard, the Gold Coast City Council and Queensland Transport and Main Roads provided aerial remote sensing data, previous planning studies and future investment plans of the study area.

An indexing model for measuring environmental sustainability embodies the pressures, impacts and challenges of an urban area and describes the present condition as well as forecast the future progress of the urban environment. The indicator sets of the model need to be flexible enough to respond to the different needs of the urban environment and trends of development at the different levels and scales of the urban system (Li *et al.,* 2009). The interpretability and explanatory power of the model depend on the availability and quality of the environmental data. The main limitation of this research was the lack of reliable data during the indicator selection of the MUSIX model. Even though the ARC Linkage Project industry partners supported this PhD study with expert views and data provision, data collection was still a major issue due to the unavailability of information at the parcel-level, limited budget and time schedule. At the beginning of the study, a comprehensive list of indicators was presented to the representatives of industry partners at workshops; however, indicators were selected based on the availability of data. For instance, some indicators of the earlier versions of the model, which were related to socio-economic structure of the urban ecosystem, had to be excluded due to problems with individual or household level data collection and privacy issues. In addition to this, for some of the selected indicators, transportation, noise, air and stormwater pollution data were provided from the other studies of the ARC Linkage Project at different scales and were then disaggregated into parcel scale. This is explained in detail in the methodology chapter.

1.5 THESIS OUTLINE

This thesis is organised into six chapters as outlined below.

Chapter 1 starts with a background to the research problem, aim and objectives. The research questions, significance of the study as well as research scope and limitations are also introduced in this chapter.

Chapter 2 presents a review of the current literature within the scope of the research. The review describes the interaction between the natural environment and human activities. The review provides an introduction to the concept of sustainable development by underlining the important role of ecological planning in achieving sustainable cities. The review describes urban ecosystem sustainability assessment by introducing current assessment methods as well as provides an outline of indexing urban environmental sustainability. Briefly, this chapter provides a conceptual framework for the research as well as outlines approaches for the research methodology.

Chapter 3 introduces the research methodology of the study. This chapter includes the following sections involved in the construction of the MUSIX model: (1) theoretical framework of the model, (2) selection of indicators and their contribution to environmental sustainability evaluation, (3) data collection and the analysis of the collected data, (4) development and application of the model, and; (5)

policy development of the model. Briefly, the methodological approaches undertaken in the model are identified and interpretation of their results is presented.

Chapter 4 presents the model results of the four pilot study sites. The parcel-level sustainability scores of each indicator as well as the grid-based composite index scores are discussed for each pilot study site. This chapter also provides a general description of Gold Coast City including its physical, natural and socio-economic characteristics, environmental challenges, existing planning strategies and the characteristics of the four pilot study sites selected from Upper Coomera and Helensvale suburbs.

Chapter 5 provides a discussion of the sustainability performance of the study area with reference to the MUSIX model outputs. In light of the model findings, this chapter also consists of recommendations about the integration of the model outputs with sustainable urban development policies in Gold Coast City.

Chapter 6 provides a conclusion to the thesis by discussing whether the research questions are answered and the research aim and objectives are met. This chapter also summarises major research findings in relation to these research questions, aim and objectives. Furthermore, this chapter presents research implications, limitations and recommendations for further research.

Chapter 2: Literature Review

This chapter presents the review of relevant literature for the study and comprises six sections. The first section describes the interaction between the natural environment and human activities by identifying environmental effects resulting from this interaction. The second section provides an introduction to the concept of sustainable development by underlining the important role of ecological planning in achieving sustainable cities. The third section introduces the notion of 'urban ecosystems' by establishing principles for the management of their sustainability. The fourth section describes urban ecosystem sustainability assessment by introducing a review of current assessment methods. The fifth section provides an outline of indexing urban environmental sustainability, and, finally, the sixth section concludes with a summary of the chapter.

2.1 HUMAN ENVIRONMENT INTERACTIONS

> *"It is clear that we control much of Earth, and our activities affect the rest. In a very real sense, the world is in our hands and how we handle it will determine its composition and dynamics, and our fate"* (Vitousek *et al.*, 2008, p. 11).

Since the mid twentieth century, globalisation and the growth of human population have been threatening the sustainability of resources by changing the structure and functioning of the environment. Human beings have exceeded the carrying capacity of the Earth by consuming natural resources, damaging the climate and generating more waste. As a result of population growth, the changes in land use patterns and changing needs and lifestyle expectations of people living in these patterns have altered the natural environment. Moreover, globalisation, rapid urbanisation, development of industrialisation and modern transportation systems, increased consumerism and overproduction has affected the natural environment in several ways (Figure 2.1).

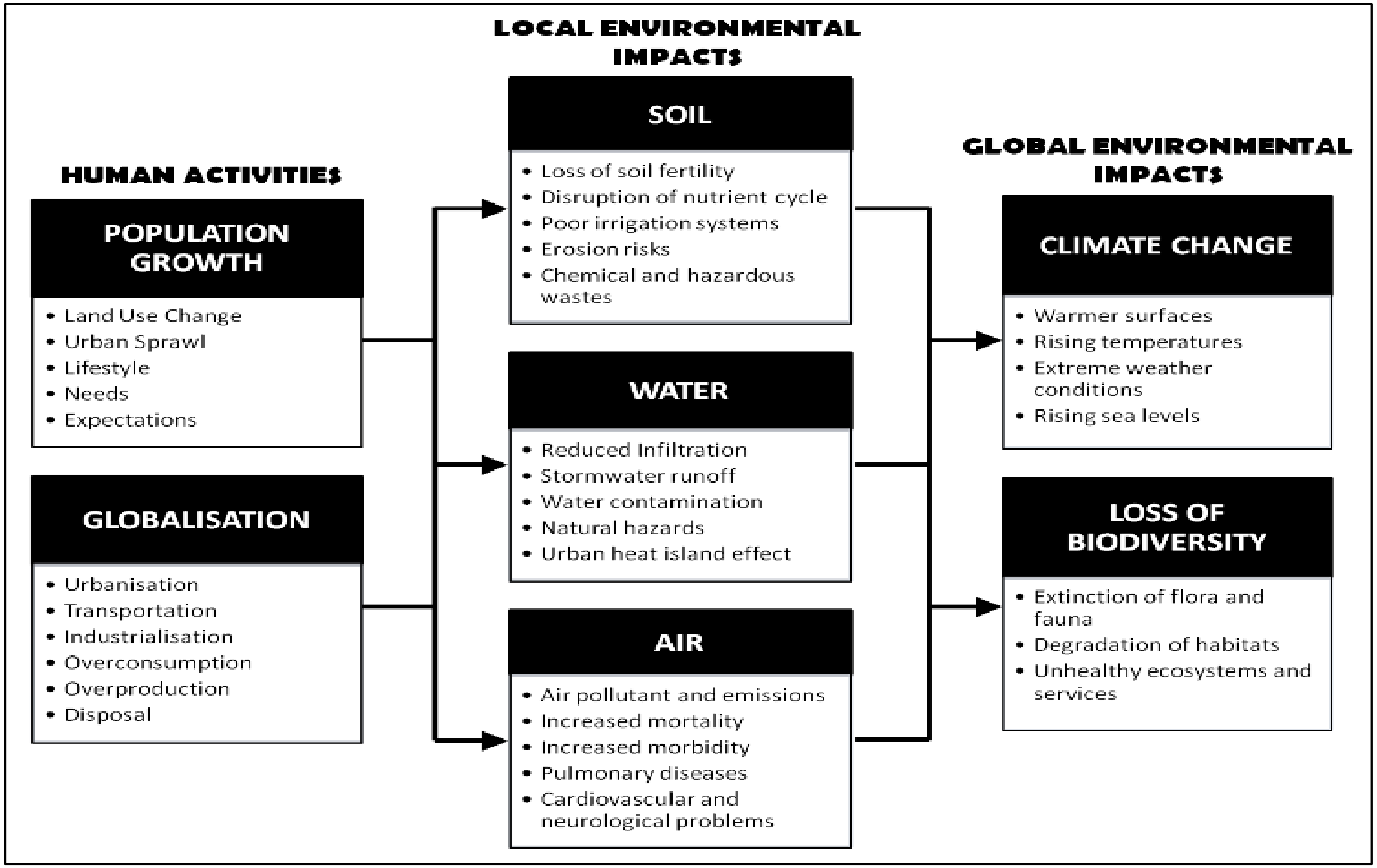


Figure 2.1 Impacts of human activities on natural systems

Human activities have complex and destructive impacts on soil quality and productivity. Population pressure increases the demand for land use by encouraging deforestation. Destruction of vegetation cover through urbanisation and agricultural activities results in the loss of soil fertility and fragmentation of landscape. These activities also disrupt the natural gas and nutrient cycling in ecosystems. Altered soil structure causes poor irrigation and drainage systems. Soil erosion is another critical environmental issue resulting from soil compaction. Furthermore, the use of chemicals in agriculture, and hazardous waste generated by construction and industrial activities threaten human health and the environment (Cropper and Griffiths, 1994; Ojima *et al.,* 1994; Dorsey, 2003, Pauleit *et al.,* 2005).

Urban development and population pressure are associated with degraded water quality and aquatic systems. The domestic, industrial and commercial discharges from heavily populated urban areas to natural water bodies cause the main type of pollution. Increased impervious surfaces resulting from urbanisation alters the water cycle by decreasing the infiltration of stormwater and increasing surface runoff. Even more dramatically, these surfaces contribute to increased urban flood events. Furthermore, the urban heat island effect, which is a result of impervious surfaces, leads to increased temperatures that are linked to impaired water quality (Barnes *et al.,* 2001; Randolph, 2004; EPA, 2012).

Air pollution is another serious environmental problem caused by mainly energy production and use, vehicular traffic and industrial activities. Nitrogen oxides, sulphur oxides, carbon oxides, volatile organic compounds (VOCs) and suspended particulate matter (SPM) are the main air pollutants that affect human health by causing pulmonary diseases, heart disorders, lung cancer, headache, fatigue, increased mortality and neurobehavioral problems (Mage *et al.,* 1996; Schwela *et al.,* 1997). Furthermore, allergies, asthma, respiratory infections, skin, nose or throat irritations are associated with indoor air pollution in residential and other non-industrial environments (Berglund *et al.,* 1991).

These local environmental impacts mentioned above contribute to two environmental issues, which have global significance: climate change and loss of biodiversity. Due to the increase of impervious surfaces and solar radiation, emissions of greenhouse gases and aerosols alter the energy balance of the Earth's climate system by causing a phenomenon known as global warming (IPCC, 2007). The main impacts of climate change are: (1) warmer surfaces that lead to higher water temperatures, droughts, food shortages, increased water loss and irrigation demand; (2) intense precipitation rates that lead to natural disasters such as floods, soil erosion or landslides; (3) rising sea levels due to melting polar ice and glaciers, and; (4) human exposure to extreme temperatures and devastating weather events such as storms or hurricanes (Pittock, 2003).

Climate change also has a major impact on biodiversity. Cities are frequently located on rivers, hilltops and along the coastlines, and, hence, a large percentage of Earth's biodiversity exist in urban areas (Convery *et al.*, 2008). Unfortunately, the area of urban settlements is growing faster than the amount of people living in these areas. Such rapid urbanisation is intertwined with climate change and both significantly modify the characteristics of biodiversity by altering the quality and quantity of habitats available to flora and fauna. Furthermore, due to climate change, soil and wind erosion are other issues that have a direct effect on species by damaging soil fertility, soil depth and water storage capacity (Pittock, 2003).

In recent years, cities all over the world have started to struggle with the aforementioned local and global environmental issues. Scholars and practitioners from different disciplines have begun to seek sustainable planning and design solutions to overcome these problems. As stated by Birkeland (2008, p. 3), the goal is the positive development of built environments which refers to *"design of cities, buildings, landscapes and infrastructure that generates healthy ecological conditions, increase the life-support services, reverse the impacts of currents systems of development and improve life quality for everyone"*. This brings us to the main point: the integration of sustainable development into the current urban development policies and practices is fundamental towards achieving sustainable cities.

2.2 PLANNING FOR SUSTAINABLE CITIES

The concept of 'sustainability' emerged in the early 1970s in response to growing concerns about the impact of development practices on the state of the environment. As stated by Paul Hawken in his book 'The Ecology of Commerce: A Declaration of Sustainability' (1993, p. 139), sustainability is a manifesto for the destructive human activities: *"Leave the world better than you found it, take no more than you need, try not to harm life or the environment, make amends if you do".* The core objectives of sustainability as defined by the Commonwealth of Australia (1992, p.2) are: "*[1] enhance individual and community welfare by following a path of economic development that safeguards the welfare of future generations; [2] provide equity within and between generations, and; [3] protect biological diversity and maintain ecological processes and life support systems"*.

The debate on sustainability started with the United Nations Stockholm Conference on the Human Environment in 1972. In this conference, a declaration was produced emphasising the international concern about environmental protection. The declaration proclaimed that environmental problems have become a growing global concern, and, thus international cooperation among nations, governments and non-governmental organizations is required. In 1980, the International Union for the Conservation of Nature and Natural Resources prepared the World Conservation Strategy, which was the first attempt to promote the principles of the sustainable use of natural resources. In 1983, the United Nations established the World Commission on Environment and Development, which was charged with developing a global agenda for the conservation of natural resources. The commission published a report known as the Brundtland Report in 1987 and the term 'sustainable development' was first introduced in this report. The report proposed sustainable development as a global goal to achieve a harmonious balance of the three components of urban development: social welfare, economic development and environmental protection (Smith, 1995; Sum and Hills, 1998).

In 1992, the United Nations Conference on Environment and Development, also known as the Rio Earth Summit, was organised. The Rio Conference produced Agenda 21, which provides a comprehensive plan of action for sustainable development. Furthermore, the conference concluded with four major agreements including: (1) the Rio Declaration on Environment and Development which refers to 27 principles of sustainable development; (2) the convention for the prevention of climate change; (3) the convention for the conservation of biological diversity, and; (4) the statement of principles for the sustainable management of forests. In 1996, the United Nations HABITAT II conference was held in Istanbul. This conference produced a Habitat Agenda, which was signed by 171 countries to show their commitment towards ensuring a better living environment for their citizens. In 1997, the Kyoto Protocol was agreed in the United Nations Framework Convention on Climate Change. The Kyoto Protocol is an environmental agreement that contains legally binding emission targets for industrialised countries to be achieved (Böhringer, 2004). In 2002, the World Summit on Sustainable Development was held in Johannesburg. The summit discussed the global challenges in respect of conservation of natural resources, sustainable consumption and production, eradication of poverty and development of a healthy and productive life. Since then, sustainable development in the urban context has gained more importance as a fundamental objective for global sustainability (Smith, 1995; Sum and Hills, 1998).

2.2.1 SUSTAINABLE DEVELOPMENT IN THE URBAN CONTEXT

Sustainable development is a self-contradictory term, or paradox, consisting of two words, that have completely different meanings. *Sustainability* refers to maintaining the existence of the ecosystem and its services while also providing for human needs, while, in contrast, *development* refers to any activity that improves the quality of life by depleting natural resources and devastating natural areas. As Baker (2006) stated, sustainability is used to describe how an ecosystem can sustain itself over time. The addition of development to sustainability needs to focus on forming a balance between human beings and the natural environment by using resources carefully and transferring them to the next generations.

In the literature, there are many definitions of sustainable development. The most widely definition of sustainable development was developed by the World Commission on Environment and Development (WCED, 1987, p.43) in its report Our Common Future: "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". The World Conservation Union (IUCN/UNEP/WWF, 1991, p.10) provides another definition of sustainable development: "*improving the quality of human life while living within the carrying capacity of supporting ecosystems*". A more comprehensive definition was developed by Jacobs *et al.* (1987, p.20): *"sustainable development seeks to respond to five broad requirements: [1] integration of conservation and development; [2] satisfaction of basic human needs; [3] achievement of equity and social justice; [4]*

provision of social self-determination and cultural diversity, and; [5] maintenance of ecological integrity".

Environmental quality, economic prosperity and social equity are the three pillars of sustainable development and their interaction can be explained as follows; environmental quality is the necessary basis for sustainable development by using economic prosperity as a tool towards achieving the target of providing a sufficient life for present and future generations (EEA and NFM, 2006; Dijken *et al.*, 2008). As a necessary basis for sustainable development, the *environmental dimension* refers to securing the living and physical environment through the sustainable use of natural resources. As a tool in achieving sustainable development, the *economic dimension* refers to the effective distribution of limited resources, goods and services in order to satisfy the needs of all people living now as well as all people of future generations. As the target of sustainable development, the *social dimension* refers to improving the quality of life by achieving social equity which targets allocating resources equitably and allowing all members of the society to take advantage of public services such as education, health and transport (Torjman and Minns, 2001; EEA and NFM, 2006; Tweed and Sutherland, 2007). To sum up, it becomes necessary to provide the sustainable balance of human activities in the natural environment by applying sustainable development principles, which can be summarised as follows:

- *Sustainable land use and urban design*

Sustainable city refers to a vision of an ideal urban structure formed by sustainable land use and urban design principles. Compact urban design with mixed land use: (1) improve the quality of life by providing social interactions and easier access to a wide range of services; (2) minimise energy consumption through green building design technologies; (3) reduce greenhouse gas emissions by providing less auto-dependent development, and; (4) ease the pressure on environmentally sensitive areas by preventing urban sprawl as well as restoring park and greenway systems (Williams *et al.*, 2000; Coplak and Raksanyi, 2003; Wheeler, 2004; Jabareen, 2006).

- *Sustainable transportation*

The form of current cities indicates that transportation systems are the determinant of the development of city form. Sustainable Transportation refers to transportation services that respect the carrying capacity of the Earth's systems by promoting energy-efficient and environmentally friendly transport options, such as: (1) providing and maintaining bike paths and bicycle lanes; (2) improving pedestrian ways and their connectivity; (3) promoting accessibility of public transport, and; (4) reducing traffic road usage demand through implementing congestion pricing, road use or parking charges, vehicle taxes (Drumheller *et al.,* 2001; Coplak and Raksanyi, 2003; Wheeler, 2004; Jabareen, 2006; AASHTO, 2010).

- *Environmental protection and restoration*

Urban biodiversity is an important component of the city. One of the principles of sustainable development is to protect and restore the existing species, habitats and ecosystems in the city by creating ecologically valuable green spaces, such as public or private green spaces (i.e., gardens, parks, green alleys and streets, green roofs) and green buffer zones (i.e., green belts, green wedges, green ways, green fingers). These green spaces: (1) bring nature into city life; (2) make urban places more attractive and pleasant; (3) ameliorate the negative impacts of urban development; (4) offer recreational opportunities, and; (5) provide a habitat for wildlife and aquatic life (Coplak and Raksanyi, 2003; Jabareen, 2006; Convery *et al.,* 2008).

- *Renewable energy and waste management*

As a result of growing demand for non-renewable resources, a renewable approach to resource use is essential for developing sustainable communities. As stated by Wheeler (2004, p. 78) "reduction, reuse, and recycling" are the 3R strategies for sustainable resource use. Renewable energy technologies can be summarised as: hydropower, biomass energy, geothermal energy, wind power, solar energy, and photovoltaic technologies (Strong, 1999). Additionally, another approach is waste management practices, such as landfill, incineration, biological treatment, zero waste, recycling-orientated eco-industrial parks and environmental taxes, law and policies (Davidson, 2011).

- *Environmental justice and social equity*

Existing urban development policies reflect the inequities and discrimination between the lifestyles of the rich and poor at both national and global levels. One of the principles of sustainable development is to protect public health and welfare by managing the Earth's natural resources in an equitable manner. The strategies for creating well-balanced and sustainable communities can be summarised as: (1)

increasing affordable housing; (2) providing efficient transportation and easier access to public amenities; (3) promoting local economic growth through increased job opportunities; (4) providing environmental quality and protection, and; (5) improving community participation into decision-making processes (Agyeman and Evans, 2003; Wheeler, 2004).

- *Economic development*

As stated by Pearce and Barbier (2004, p.160), the sources of environmental problems lie in the failure of the economic system while providing valuable environmental services and functions. Creating a sustainable economy promotes: (1) clean technologies (i.e., Silicon Valley in California, USA); (2) renewable energy sources; (3) green business and job initiatives; (4) green tax policies; (5) green infrastructure, and; (6) walkable, mixed-use and transit-oriented real estate developments (Nixon, 2009).

In recent years, cities are adopting sustainable development policies into their urban plans. Table 2.1 provides a brief summary of best practices of urban sustainability at different spatial scales.

Table 2.1 Summary of reviewed best practices of urban sustainability **(**derived from McDonough and Partners, 1992; Newman and Jennings, 2008; Danish Architecture Centre, 2012; BioRegional and WWF, 2012; City of Freiburg, 2012)

Scale	Project	Background	Targeted Sustainability Goals
Building	*Germany: Commerzbank Headquarters*	An ecological skyscraper	• Provide natural day lighting and ventilation through the sky gardens and operable windows • Maximise energy efficiency through double skin facades and the use of water-filled chilled ceilings for cooling • Maximise water efficiency through grey water recycling
District	*England: Cleveleys 'the New Wave' Project*	A flood and coastal defence strategy plan	• Break flood waters by building a wave of concrete stairs • Waste management by reusing the materials from the old sea wall • Provide a pedestrian promenade with a diverse variety of leisure and recreational activities

Table 2.1 (Cont'd)

Scale	Project	Background	Targeted Sustainability Goals
District	*Australia: Adelaide 'Christie Walk Eco-Village' Project*	An environmentally friendly neighbourhood	• Reduce energy consumption through passive design, use of heat-efficient materials and vegetation • Proximity to services and public transport • Waste reduction and recycling • Improve water consumption through sustainable stormwater management • Provide on-site food production with creation of communal gardens
City	*Germany: Model City Mannheim (MoMa)*	A smart city that promotes energy efficiency by using solar energy and smart control technologies (i.e. Energy Butler system)	• Connect every household with a smart-energy network • Raise the awareness of households about their energy habits and general energy prices • Help households to cut their energy bills by using energy efficient technologies • Reduce the energy prices
City	*Canada: Calgary's C-Train 'Ride the Wind' Program*	A wind-powered light rail transit system	• Provide sustainable modes of transportation • Provide a better air quality by reducing greenhouse gas emissions • Reduce car dependency
City	*Japan: Kawasaki 'Eco Town' Program*	Zero waste industrial ecosystem	• Reduce greenhouse gas emissions • Energy conservation • Waste management by turning one's waste into another's raw material
City	*South Africa: Johannesburg 'GreenHouse People's Environmental Centre' Project*	Community involvement and education with urban gardening and green building principles	• Provide an environmental demonstration and training centre for the citizens through small community gardens • Enhance the quality of community's life by providing them a sustainable living such as organic farming, medicinal herb gardening
City	*Germany: Freiburg Green City*	The green and solar capital of Germany	• Sustainable economy (environmental industry and research, eco-industrial tourism) • Sustainable mobility (environmentally compatible modes of transport) • The city's resource capital: nature (parks and nature conservation areas, emission control, soil protection, premium quality water) • Sustainable urban development (far-sighted planning and citizen participation) • Citizen commitment (environment education)

Table 2.1 (Cont'd)

Scale	Project	Background	Targeted Sustainability Goals
Global	*The 'Melbourne Principles' for Sustainable Cities by the United Nations Environment Programme*	Creating environmentally healthy, vibrant and sustainable cities	• A long-term sustainability vision • Economic and social security • Biodiversity and ecosystem conservation • Minimise the ecological footprint of cities • Model cities as ecosystems • Provide a sense of place • Empower people and foster participation • Cooperative networks towards sustainability • Sustainable production and consumption • Provide a good urban governance
Global	*The 'Hannover Principles' by William McDonough and Michael Braungart*	Designing for sustainability	• Rights of humanity and nature to co-exist • Interdependence between humans and nature • Respect relationships between spirit and matter • Responsibility for the consequences of design • Safe objects of long-term value • Eliminate the concept of waste • Rely on natural energy flow • Understand the limitations of design • Share knowledge for constant improvement
Global	*The 'One Planet Living Framework' by BioRegional Development Group and World Wildlife Fund*	A vision for sustainable world	• Zero carbon • Zero waste • Sustainable transport • Sustainable materials • Local and sustainable food • Sustainable water • Land use and wildlife • Culture and heritage • Equity and local economy • Health and happiness

For a sustainable built environment, it is necessary to regulate the natural processes and control the scale of human activities; therefore, environmental processes need to be integrated into the planning process. This integration is important in terms of understanding the physical characteristics of the developed areas as well as recognising the mechanism of the environment, its potential, limitations and risks in the planning process (Lein, 2003). In this respect, ecological planning is a fundamental approach to the sparing and efficient use of natural resources while adopting human activities in a less harmful way to the environment (Clini *et al.*, 2008).

2.2.2 AN ECOLOGICAL APPROACH TO PLANNING FOR SUSTAINABLE CITIES

> *"The eco-city, or eco-polis, is the next, and perhaps most important step in the evolution of our urban environments: built to fit its place, in co-operation with nature rather than in conflict; designed for people to live whilst keeping the cycles of atmosphere, water, nutrients and biology in healthy balance; empowering the powerless, getting food to the hungry and shelter to the homeless"* (Downton, 2009, p. 21).

Ever since the beginning of urban settlements, planners, architects, landscape architects, urban theorists and historians have sought ways of integrating nature into the built environment. The evolution of ecological planning can be traced back to the early works of Frederick Law Olmsted, Ebenezer Howard, Frank Lloyd Wright, Patrick Geddes, Lewis Mumford and Ian McHarg. Frederick Law Olmsted, the founder of landscape architecture, exhibited a concern for the preservation of the natural beauty and ecological function in the city. This concern resulted in the development of several successful national park systems. Afterwards, Ebenezer Howard expanded this idea further. His 'garden city' theory provided an inspiration to introduce an ecological approach to urban planning. He proposed to bring nature back to cities by outlining a self-sustaining city model surrounded by greenbelts (Wong and Yuen, 2011).

Frank Lloyd Wright, in his philosophy of 'organic architecture', developed the idea of using nature as a basis for the architectural approach. In his designs, he used the built environment in harmony with its natural surroundings. Patrick Geddes, in his 'Bioregionalism' theory, proposed the idea of integrating people, commerce, and land into a regional context based on an ecological balance (Bonan, 2008). Afterwards, Lewis Mumford expanded Geddes's idea further by introducing the idea of a 'greenbelt community'. The greenbelt communities were seen as providing a limit on the growth of population and on the physical breadth of a city. Ian McHarg proposed the methodology of 'ecological land use planning' that links ecological thinking to the planning problems and design practices. In his theory of ecological land use planning, he developed a model called the 'layer-cake' which overlays suitability maps of different land use patterns in order to identify ecologically sensitive places and provide strategies based on the analysis. This model also provides a theoretical basis for the geographic information systems (GIS) (Steiner, 2000).

In the 1980s, the environmental movement emerged into a broader context. Great technical advances were made in the harnessing of solar and wind energies as renewable sources of power, and many environmentally friendly projects were undertaken. These ideas were extended in the 1990s and resulted in the emergence of the 'eco-city' concept, which aims to create liveable and walkable communities. By the beginning of the twenty-first century, ecological planning emerged as an expression of a sustainability world-view, which seeks to integrate the human and natural ecosystems. All of the above-mentioned theories laid the foundation of the ecological planning theory and they additionally contributed to shaping many other important planning concepts (Shu-Yang *et al.*, 2004; Wu, 2004).

As stated by Steiner (2000, p. 9), *planning* is *"a process that uses scientific and technical information to build consensus among a group of choices"*. *Ecology* is the study of interaction between living organisms and their environments. *Ecological planning* then is defined as the use of biophysical and socio-cultural information derived from this interaction as decision- making opportunities and constraints in the management of ecological systems. Ecological planning is a broad concept based on strategies and methods to create green, safe, vibrant and healthy urban environments (Roseland, 1997). It is an important planning tool in the establishment of sustainable cities. As stated by Ndubisi (2002, p. 5), "*ecological planning is more than a tool: it is a way of mediating the dialogue between human actions and natural processes based on the knowledge of the reciprocal relationship between people and the land. It is a view of the world, a process and a domain of professional practice and research within the profession of planning".* According to Shu-Yang *et al.* (2004, p. 102), the key characteristics of ecological planning can be summarised as below:

- *Meeting the inherent needs of human beings:* Ecological planning is an essential tool for enhancing the sustainability of human enterprise through finding environmentally friendly ways of manufacturing goods, constructing buildings and planning recycling-orientated enterprises to reduce ecological damage as much as possible.

- *Moving towards resource sustainability:* Ecological planning promotes the urban form that requires minimum energy and resource input as well as minimises waste generation and ecological damage through efficient use, re-use and recycling.
- *Maintaining ecological integrity:* Ecological planning integrates human activities with the dynamics of natural flows and cycles of materials and energy by developing solutions to particular planning issues. This can be achieved through defining the carrying capacity of ecosystems for the proposed human activities.
- *Emulating natural ecosystems:* Another goal of ecological planning is to emulate natural ecosystems when planning for anthropogenic activities, so that the resulting effects will be relatively 'natural'. For instance, this can be achieved through developing a symbiotic industrial system that refers to an integrated process in which the waste of one process becomes a resource for another.

In many parts of the world, new or existing developments move towards a more ecological direction. As presented in Table 2.2, many cities develop integrated solutions to the major environmental challenges of today and transform into sustainable and self-sufficient communities.

Table 2.2 Summary of reviewed best practices of ecological planning

Project	Ecological Planning Approaches	What has been achieved?	References
Germany: Stuttgart's climate planning strategy	The use of green infrastructure such as: • ventilation lanes (tree-flanked arteries) • climate-relevant open spaces such as public parks • roof greening • facade greening	Turning an industrial city into a cool and green city: • manage urban heat island with natural wind patterns and vegetation • protect biological diversity • improve air quality • reduce traffic related noise pollution • provide large and connected green spaces for cooling and shading	Danish Architecture Centre (2012)

Table 2.2 (Cont'd)

Project	Ecological Planning Approaches	What has been achieved?	References
South Korea: the Cheonggye River Restoration Project	• Stream design (water supply and Management) • Environmentally friendly waterfront by landscape design • Environmentally friendly transport system • High-quality modern residences • Restoration of historical relics	Transforming a freeway into a river and public park: • reduce the heavy vehicular traffic • provide a natural drainage system • prevent flooding risk due to impermeability • improve water quality and nourish wildlife by landscape planning • provide a recreational waterfront for inhabitants	Hwang (2007) Danish Architecture Centre (2012)
UK: the BedZED (Beddington Zero Energy Development) Eco-Village	• Energy efficient buildings • Water saving appliances • Use of renewable energy sources • Waste recycling • Biodiversity plan for the urban natural environment • Green transport plan (public transport, rental car clubs, cycle routes and storage facilities)	An eco-friendly housing development: • zero emission neighbourhood • resource-efficient way of life • enhanced the biodiversity and natural amenity value • less car dependent lifestyle	BioRegional Development Group (2002)
Sweden: Malmo Bo01 Ecological District	• Energy efficient buildings • Wind parks that supplies the electricity of the area • Recycling of food waste as biogas for electricity and heat generation • Rainwater management through green roofs, ponds, wetlands and rain water channels • Green spaces such as parks, woodlands, flower gardens and green roofs • Built-in nesting boxes for birds • High priority of designing pedestrian and cycle tracks	An eco-friendly housing development: • increase the biological diversity • stormwater management • use of renewable sources • green transport • waste management • energy conservation • green architecture • ecologically aesthetic urban environment • open urban spaces for recreational activities	Hancock (2001) Jamison (2008) Danish Architecture Centre (2012)

Table 2.2 (Cont'd)

Project	Ecological Planning Approaches	What has been achieved?	References
Germany: Emscher Park Brownfield Redevelopment	• The use of green infrastructure such as greenbelts, public gardens • Thematic tourist driving and biking route called 'route of industrial culture' • Multi-use urban waterfront including energy-efficient offices • Adaptive reuse of industrial buildings • Recycle and reuse of industrial wastes in the park design • Walls used for rock climbing	Turning a degraded industrial region into a regional network of open spaces: • enhance the ecological health of Emscher river and its tributaries • regenerate the degraded landscape • provide social and cultural activities • preserve the historic industrial heritage • provide local employment	Labelle (2001) Danish Architecture Centre (2012)
USA: New York High Line Park	• Native and low-maintenance landscape design • Green roof and technologies for water drainage • public open spaces for people • Energy-efficient lighting design • benches and other structures made of wood from certified sustainable forests	Turning an old elevated railway into a green corridor: • better microclimate and environmental conditions • an urban habitat for wildlife and people • urban regeneration and adaptive reuse • an economically productive neighbourhood	David (2002) Danish Architecture Centre (2012)
USA: Seattle Green Factor *Germany: Berlin Biotope Area Factor*	A scoring system which calculates ecologically effective urban area by assigning an ecological value to the each type of existing landscape element such as: • groundcovers, shrubs, trees • porous pavements • green roofs • green walls • water features, rain gardens • drought tolerant plants	A parcel scale landscape management strategy for ecological city vision: • promote urban green spaces • improve the ecological function and richness of the urban environment • urban heat island management • stormwater management • soil protection	SenStadtUm (2012) Seattle DPD (2012)

2.3 TOWARDS SUSTAINABLE URBAN ECOSYSTEMS

The main purpose of all the aforementioned efforts is modelling cities as "*sustainable ecosystems, which are ethical, effective (healthy and equitable), zero-waste, self-regulating, resilient, self-renewing, flexible, psychologically-fulfilling and cooperative*" (Newman and Jennings, 2008, p. 108). In this regard, cities need to be considered as ecosystems in order to develop sustainable development policies and programmes.

2.3.1 THE CITY AS AN ECOSYSTEM

An ecosystem is a dynamic ecological system that consists of a community of plants, animals and microorganisms living in a particular environment that interacts as a functional unit with their non-living environment and anthropogenic components. They provide a variety of services to people including: (1) provisioning services (i.e., food, fibre, fresh water and fuel); (2) regulating services (i.e., air quality maintenance; climate regulation, water purification and flood control); (3) cultural services (i.e., educational, recreational and aesthetic experiences), and; (4) supporting services (i.e., nutrient cycling, soil formation, primary production) (Rebele, 1994; Millennium Ecosystem Assessment, 2005; Zhang *et al.*, 2006; ICSU/UNESCO/UNU, 2008).

As presented in Figure 2.2, ecosystems are strongly influenced by the human social system, which is shaped by peoples' population, psychology and social organisation. Values and knowledge influence how individuals interpret and process the information while translating it into action. Social organisations and institutions specify acceptable behaviours and norms; furthermore, technology defines the possible actions. As a closed loop system, the ecosystem provides services to the human social system by moving energy, materials and information to meet their needs. In contrast, energy, materials and information resulting from human activities move from the social system to the ecosystem by damaging the ability of the ecosystem to continue providing services for the people (Marten, 2001).

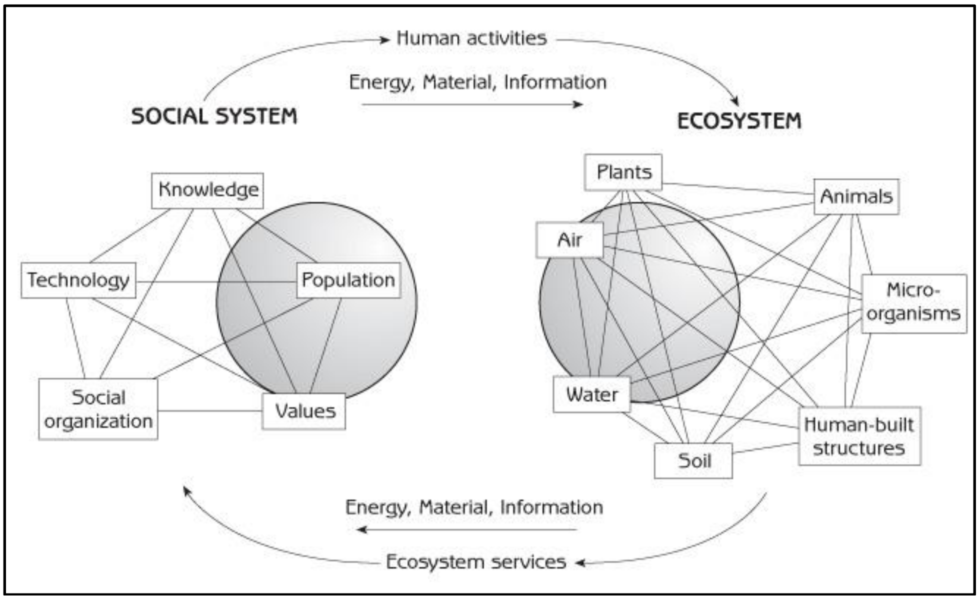


Figure 2.2 Interaction between the ecosystem and human social system (Marten, 2001, p. 2)

Briefly, the city as a place where 'nature and artifice meet' (Levi-Strauss, 1961), is a dynamic biological organism that consists of a human population and built-up environment that are highly dependent on nature. In other words, a city is the most dramatic manifestation of human activities on the environment (Ridd, 1995). As stated by Alberti (2005), this human-dominated organism degrades natural habitats, simplifies species composition, disrupts hydrological systems, and modifies energy flow and nutrient cycling. To examine this interaction, we need to consider cities as 'urban ecosystems', in other words, as defined by Alberti (1996, p. 382) "urban ecological spaces", with their biological and physical complexities that interact with each other.

2.3.2 PLANNING FOR SUSTAINABLE URBAN ECOSYSTEMS

> *"To build a sustainable society for our children and future generations - the great challenge of our time - we need to fundamentally redesign many of our technologies and social institutions so as to bridge the wide gap between human design and the ecologically sustainable systems of nature"* (Capra, 2002, p. 99).

A sustainable urban ecosystem can be characterised as an ecosystem that exists in and around an urban settlement that manages the natural environment by: (1) using natural resources effectively; (2) producing zero waste through recycling and reusing; (3) maintaining the ecological functions and processes through self-regulation; (4) providing resilience against environmental disturbances, and; (5) flexibility in response to these disturbances (Bolund and Hunhammar, 1999;

Berkowitz *et al.*, 2002). As human existence depends on the biological diversity of ecosystems, ecosystem goods and services is required to be managed in a more sustainable way. Sustainable management of the urban ecosystem is centrally based on a number of principles (Meier, 1984; Mcmanus and Haughton, 2006; Newman and Jennings, 2008; United Nations, 2011; Kowarik, 2011):

- *Providing a long-term city vision:* The development of a long-term city vision emerges as a key element in providing a basis for setting sustainability goals and action plans by defining the ecological, social and economic characteristics of the community and their constraints. Furthermore, a vision serves as a guiding framework for future decision-making and gives communities a chance to rebuild their cities in a sustainable direction.

- *Achieving long-term economic and social security:* Cities need to integrate their social values and economies into a sustainable framework. To achieve economic and social security, human communities and institutions need to become more equitable, resilient, flexible and ecologically minded by transforming their economies to serve bioregional and local community priorities.

- *Protecting and restoring biodiversity and natural ecosystems:* Cities need to be managed to provide opportunities for biodiversity conservation through the creation of protected areas like gardens, parks, greenways, wildlife corridors and biosphere reserves. Furthermore, ecological architecture and infrastructure, such as zero energy buildings, green roofs, stormwater management and water sensitive urban design also enhance biodiversity and natural ecosystems.

- *Minimising the ecological footprint of cities:* As an indicator towards sustainability, the ecological footprint represents the carrying capacity of an urban area exposed to resource consumption and waste disposal. Cities need to reduce their ecological footprints through ecosystem assessments, managing population growth and city sprawl, reducing their consumption patterns.

- *Building a sense of place that reflects the distinctive characteristics of cities:* The way of designing our cities and our lifestyles, social and political processes, and institutions within need to match the distinctive patterns of the places we live in. Therefore, cities need to build a sense of place by protecting cultural, historic and natural heritage, designing with natural processes, connecting the urban form with its bioregion and using cultural practices and the arts to deepen the sense of place.

- *Providing sustainable production and consumption:* Cities need to minimise their resource use, toxic materials, waste emissions and pollutants for bringing a better quality of life. Therefore, they need to increase the carrying capacity of ecosystems through the use of environmentally sound technologies and effective demand management of resources.

- *Enabling cooperative networks towards a sustainable future:* An effective partnership between government, business and the community is necessary for finding innovative solutions to the issues of sustainability. Furthermore, building cooperative networks is essential for creating resilient cities and making people more able to respond to feedback and take appropriate action.

In summary, examining the city as an ecosystem and understanding the interaction between urban ecosystem and human activities is an important factor to take into consideration while transforming cities into sustainable communities. Thus, a holistic sustainability assessment approach is required in order to monitor this interaction over time and geographic scales.

2.4 URBAN ECOSYSTEM SUSTAINABILITY ASSESSMENT

Urban ecosystem sustainability assessment plays an important role in the decision-making and urban planning processes at the national, regional or local levels. The main purposes of urban ecosystem sustainability assessment are to: (1) define sustainable development targets and assess progress made in meeting those targets; (2) revise the effectiveness of current planning policies and help in making the necessary corrections in response to changing realities, and; (3) make comparisons over time and across space by performance evaluation as well as provide a basis for planning future actions. In other words, urban ecosystem sustainability assessment is a powerful tool to connect past and present activities to future development goals (Hardi *et al.*, 1997).

Urban ecosystem sustainability assessment is performed via applying different approaches and tools ranging from indicators to comprehensive models. The selection of the appropriate assessment method depends on the subject of the assessment, the nature and complexity of the environmental impacts as well as time and scale aspects (ARE, 2004). Urban ecosystem sustainability assessment methods are categorised in three groups by Srinivasan *et al.,* (2011), as follows:

- First category - includes *assessment frameworks,* which are basically integrated and structured procedures that assist in the comparison of proposed project and policy alternatives based on their environmental impacts (i.e., Environmental Impact Assessment-EIA and Strategic Environmental Assessment-SEA).

- Second category - includes *analytical evaluation tools,* which are used to conduct analysis in order to support decision-making by finding potential solutions to specific problems within the framework. These tools are divided into two sub-categories:
    1. *Reductionist tools* use a single measureable indicator or dimension or objective or scale of analysis or time horizon for evaluation (i.e., economic tools such as Cost Benefit Analysis-CBA and Whole Life Costing-WLC, biophysical models such as Material Flow Analysis, Ecological Footprint and Energy Accounting, indicators/composite indices), and;
    2. *Non-reductionist tools* follow a series of methodological choices, which are subjective and influenced by the analyst (i.e., Multi-Criteria Analysis-MCA).

- Third category - includes *sustainability metrics,* which are divided into three sub-categories:
    1. *Ecosystem-scale,* such as Ecological Footprint Analysis, Environmental Sustainability Index-ESI and Wellbeing Index-WI,

2. *Building-environment scale,* such as green building rating systems, and;
3. *Building scale,* such as Net Energy, Zero Energy, and Renewable Energy Balance-REB.

As another categorisation shown in Figure 2.3, made by Ness *et al.* (2007), urban ecosystem sustainability assessment methods are divided into three categories, as follows:

- First category - includes *product-related assessment tools,* which investigate the flows related to production and consumption of goods and services. The most established example is the 'Life Cycle Assessment', which evaluates resource use, and resulting environmental impacts of a product throughout its lifecycle and the outputs influence environmental policies and regulations.

- Second category - includes *integrated assessment tools,* which investigate policy change or project implementation through developing scenarios. For instance, 'Environmental Impact Assessment' and 'Strategic Environmental Assessment' are commonly used examples for assessing the environmental impacts of development projects or strategic decisions in order to reduce their potential externalities (Partidario, 1999; Sadler, 1999).

- Third category - includes *sustainability indicators and composite indices*, which are increasingly recognised as useful assessment tools. They provide guidance in the urban planning process by detecting the current sustainability performance of an urban setting by assessing the impacts of development pressure on natural resources. Examples of this category are explained in detail in the next section.

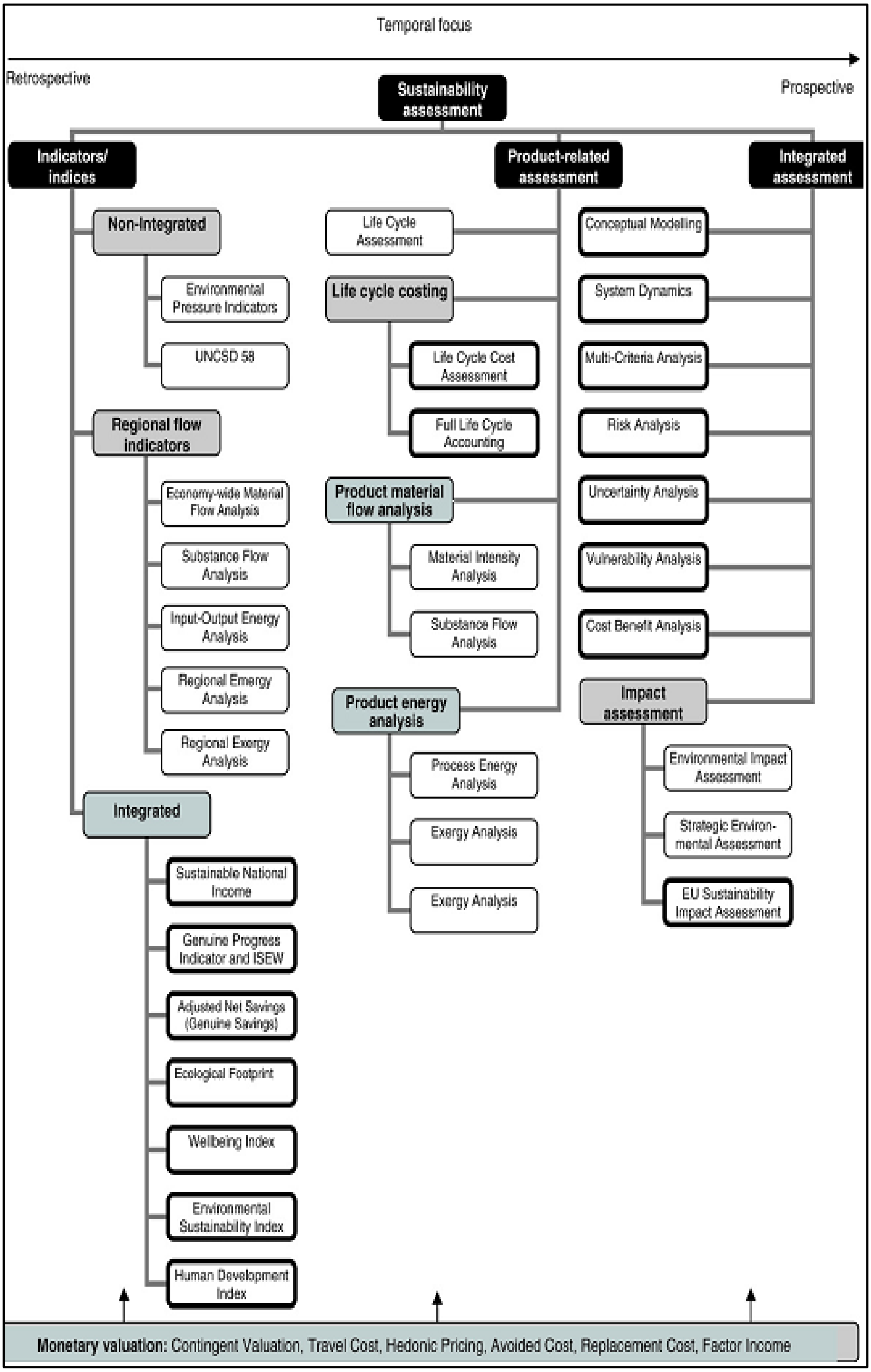


Figure 2.3 Framework for urban ecosystem sustainability assessment tools (Ness *et al.*, 2007, p. 500)

As can be seen from the aforementioned categorisation of the assessment methods, the spatial scale is an important aspect of assessment in detecting urbanisation impacts on natural resources and ecosystems. Scale is linked to variation and predictability of the assessment. The amount of detail determines the accuracy of the assessment. Furthermore, the scale of the assessment influences both the definition of the environmental issue and the range of possible actions and policy responses (Weins 1989; Levin 1992; Millennium Ecosystem Assessment, 2003). While conducting sustainability assessment at larger-scales, there are usually limitations in collecting reliable and accurate information. For this reason, the micro-scale is the ideal scale to detect the environmental stress in an urban ecosystem by providing more detailed data and preventing loss of detail in collecting coarser spatial data.

The impacts and complexity of environmental issues have different temporal and spatial characteristics. Many problems, which emerged at the local level several years ago, have become national and global problems today. Therefore, sustainability assessment needs to be carried out at different scales in order to evaluate environmental problems. For instance, as seen in Figure 2.4, climate change is a global environmental issue; however the policy responses and strategies are developed at the national levels and applied at the local level. In a similar manner, it is difficult to analyse the state of the environment and natural resources at regional scale, hence, regions needs to be classified on a broader scale. Additionally, ecosystems are the local units where the causes and outcomes of implemented policies can be assessed (Winograd, 1997).

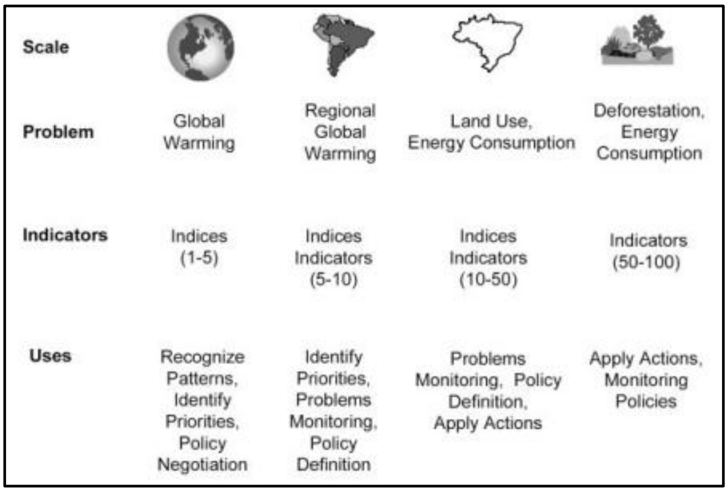


Figure 2.4 Scales and uses of sustainability assessment (Winograd, 1997, p. 17)

It is clear from the above example that, urban ecosystems are affected by various spatial scales of human activities. As stated by Alberti (2008, p. 102), the smallest spatial unit in the urban ecosystem allows for producing socioeconomic and biophysical information that varies from household and building levels to street and parcel levels. These parcels then combine to create new functional units as suburbs and neighbourhoods that interact with regional and national scales. In this context, as a result of the multi-scale characteristics of environmental problems, detailed and up-to-date micro-scale data is crucial in order to assess national and global environmental change in urban ecosystems.

2.4.1 REVIEW OF EXISTING URBAN ECOSYSTEM SUSTAINABILITY ASSESSMENT TOOLS

As presented in Table 2.3, there are many countries that are making progress on the development of urban ecosystem sustainability assessment tools at different spatial scales.

Table 2.3 Summary of reviewed urban ecosystem sustainability assessment tools

Assessment Tool	Context	Themes	References
Australia: VicUrban Sustainability Charter	A decision-making and monitoring tool used at three stages of development: project vision and goal setting, project design, project delivery and final reviews	• Commercial success • Community well-being • Environmental leadership • Urban design excellence • Housing affordability	VicUrban (2006)
USA: The Leadership in Energy and Environmental Design (LEED)-Neighbourhood Developments	A green certification tool aims to develop a national set of standards for neighbourhood design based on the combined principles of smart growth, urbanism and green building	• Smart Location and Linkage • Neighbourhood Pattern and Design • Green Infrastructure and Buildings • Innovation and Design Process • Regional Priority Credit	U.S. Green Building Council (2005)

Table 2.3 (Cont'd)

Assessment Tool	Context	Themes	References
Australia: The Australian Housing and Urban Research Institute (AHURI)	A performance assessment framework for the existing developments	• Housing Affordability • Neighbourhood and Community safety and satisfaction • Transportation • Environment - Biodiversity • Environment - Energy • Environment - Other resources • Environment - Wastewater and stormwater control	Blair *et al.* (2004)
Japan: The Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)	A tool for evaluating urban development and buildings in terms of their environmental performance	• Natural Environment (microclimates and ecosystems) • Service functions for the designated area • Contribution to the local community • Environmental impact on microclimates • Social infrastructure • Management of the local environment	CASBEE (2007)
UK: The Building Research Environmental Assessment Method (BREEAM)	An environmental assessment rating system for buildings including: offices, homes, industrial units, retail units and schools	• Energy • Transport • Pollution • Materials • Water • Land Use and Ecology • Health and Wellbeing • Management	BREEAM (2006)
Australia: The Green Star of the Green Building Council of Australia (GBCA)	A green star rating tool for assessing environmental impacts related to building design	• Management • Indoor Environmental Quality • Energy Consumption • Transport • Water • Materials • Land use & Ecology • Emissions • Innovation	Tan (2006)

Table 2.3 (Cont'd)

Assessment Tool	Context	Themes	References
Australia: The National Australian Building Environmental Rating System (NABERS)	A performance-based rating system for existing buildings	• Energy • Water • Waste • Indoor environment	Seo (2002)
Hong Kong: The Building Environmental Assessment Method (HK-BEAM)	A rating tool that provides a guidance to developers, designers on green development practices	• Site aspects • Materials aspects • Energy use • Water use • Indoor environmental quality • Innovations	HK-BEAM (2004)
The European Commission: Building Environmental Quality for Sustainability through Time (BEQUEST) international framework	A tool for sustainable urban development, helps decision-makers to examine the strengths, weaknesses and gaps in development projects	• Development activity • Environmental and societal issues • Spatial level • Time scale	Hurley and Horne (2006)
The European Commission: System for Planning and Research in Towns and Cities for Urban Sustainability (SPARTACUS)	An integrated land use/transport model for analysing urban sustainability	• Air pollution • Resource consumption • Health • Equity • Opportunities	European Commission (1998)
The European Commission: Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability (PROPOLIS)	A model system for defining sustainable long-term urban strategies and demonstrating their effects	• Global climate change • Air pollution • Consumption of natural resources • Environmental quality • Health • Equity • Opportunities • Accessibility and traffic • Total net benefit from transport	Spiekermann and Wegener (2007)

Table 2.3 (Cont'd)

Assessment Tool	Context	Themes	References
UK: Environmental Impact Estimating Design Software (ENVEST)	A software tool that estimates the life cycle environmental impacts of a building from the early design stage	• Resource (Fossil fuel depletion/extraction, minerals extraction, water extraction) • Environmental loadings (Climate change, acid deposition, ozone depletion, human toxicity, low level ozone depletion, eco-toxicity, eutrophication, waste disposal)	Seo (2002)
Canada: The ATHENA Environmental Impact Estimator	A Life cycle assessment-based environmental decision support tool for buildings	• Embodied primary energy use • Global warming potential • Solid waste emissions • Pollutants to air • Pollutants to water • Natural resource us	Seo (2002)
UK: The South East England Development Agency (SEEDA) checklist	A sustainability checklist for developments in order to highlight best practice & regionally specific sustainability & planning issues	• Climate change & energy, transport & movement, ecology, energy & water efficient building • Resources protection • Community support, sensitive place making • Support for business	Karol and Brunner (2009)
The Netherlands: Eco-Quantum	A tool calculating the environmental performance of a building over its total life span	• Resources • Emissions • Energy • Waste	Bruno and Katrien (2005)
Norway: Eco-Profile	An environmental assessment tool for buildings	• External Environment • Resources • Indoor climate	Pettersen (2000)

Over the past several years, there has been a significant increase in the development of urban ecosystem sustainability assessment tools in order to provide guidance for the evaluation of the environmental impacts of existing and new urban developments. As stated by Karol and Brunner (2009, p. 625), even though they use different assessment themes and sub-themes, they outline the common sustainability principles, such as conservation of native vegetation, reduction of non-renewable energy use, waste reduction, water efficiency, high quality public transport and social safety. Therefore, they need to be integrated into the policy and decision-making to build sustainable urban environments.

2.4.2 INTEGRATING URBAN ECOSYSTEM SUSTAINABILITY ASSESSMENT INTO POLICY AND DECISION-MAKING

Urban ecosystem sustainability assessment provides a systematic approach to policy and decision-making during the different stages of sustainable development. The purpose of assessment is to assist the planning authorities in the evaluation of economic, social and environmental impacts of the projects. Urban ecosystem sustainability assessment can be used in policy and decision-making at three stages: (1) *Ex ante* assessments carried out at the beginning of the project in order to analyse the potential negative and positive impacts of proposed project options and help in choosing the best-fit option; (2) *Concurrent* assessments carried out during the process of developing the project in order to monitor the progress towards meeting sustainability goals, and; (3) *Ex post* assessments provide an evaluation of the consequences of the selected project and policies after a particular period of time in order to mitigate their negative impacts through revisions (Abaza, 2003; LUDA, 2012).

In order to assess environmental performance, examine ecological limits as well as provide the long-term protection of environmental quality, urban ecosystem sustainability assessment is a potential planning tool for policy and decision-making. As outlined by the UNEP (2004), integration of urban ecosystem sustainability assessment into policy and decision-making process provides the following benefits:

- *Supporting sustainable development*: The assessment results: (1) highlight the economic, social, environmental opportunities and constraints; (2) organise the policy and decision-making process by reducing the complexity of each stage, and; (3) help governments to reach proposed sustainability targets.

- *Facilitating good governance and institution-building:* The integrated assessment: (1) promotes the transparency of the policy and decision-making process; (2) helps build social consensus about its acceptability, and; (3) enhances coordination and collaboration between different government ministries and bodies.

- *Saving time and money:* The integrated assessment: (1) strengthens the intersectoral policy coherence; (2) provides early warning of the potential problems, and; (3) minimises environmental, social and health impacts thereby reducing the costs required to remedy them.

- *Enhancing participatory planning for sustainable communities:* The integrated assessment: (1) increases the awareness of governments and citizens on the significance of ecosystem functioning, and; (2) strengthens national commitment to sustainable development.

Nevertheless, the research on employing different tools and methodologies to help policy and decision-making is still in progress. As stated by Schepelmann *et al.* (2008), although the guideline documents in the literature often identify the required procedural steps and checklists, they provide insufficient information about the methodological and analytical guidance. As another critical issue, many urban ecosystem sustainability assessment approaches evaluate the social, economic and ecological impacts of policy and decision-making process separately; hence, they struggle to integrate their separate findings into a single framework.

An example of the methodology for urban ecosystem sustainability assessment, which measures the interaction between human and ecosystem wellbeing, as developed by the International Union for Conservation of Nature and Natural Resources consists of seven stages as follows (Guijt and Moiseev, 2001):

1) *Determine the purpose of the sustainability assessment:* In this step, the purpose and objectives of the assessment are clarified. The intended users and participants, its intended uses and methods are defined.

2) *Define the system and goals:* In this step, the geographic area for the assessment is defined. A vision and goals for sustainable development are developed and then recorded. Finally, base maps for the assessment are prepared.

3) *Clarify dimensions, identify elements and objectives:* In this step, the dimensions, which will be used for measuring performance towards sustainable development are developed. The elements for all dimensions and the objectives for each element are identified. Data collection and storage are also carried out.

4) *Choose indicators and performance criteria:* In this step, all selected indicators are explained in detail and the performance criteria for each indicator are justified.

5) *Gather data and map indicators:* In this step, the indicator scores are calculated and the scores are mapped.

6) *Combine indicators and map the indices:* In this step, the indicator scores are aggregated into an index through some methodological steps and the scores are mapped in order to explain the findings easily.

7) *Review results and assess implications:* This step involves the analysis of the results, causes and implications as well as identification of the priorities for improvement. The results of the assessment give a snapshot of the current situation and the findings help to determine the policies and actions.

Briefly, urban ecosystem sustainability assessment is a powerful tool for tracking environmental progress as well as the environmental effects of policies and actions taken for sustainable development. They provide valuable information for effective decision-making and policy formulation (Nguyen, 2004). As Devuyst *et al.* (2001, p. 419) summarise *"urban ecosystem sustainability assessment aims to steer societies in a more sustainable direction by providing tools that can be used either to predict impacts of various initiatives on the sustainable development of society or to measure progress toward a more sustainable state*". It is an essential process in the development of sustainable polices in terms of collecting information for the planners and decision makers concerning the severity of environmental problems and their impacts on natural environment (RCEP, 2002).

2.5 INDEXING URBAN ECOSYSTEM SUSTAINABILITY

After reviewing the existing urban ecosystem sustainability assessment tools, a micro-scale indicator-based sustainability-indexing model, which measures the environmental sustainability performance of the built environment, was developed as an assessment tool for policy-making in this study. In this section, the role of indicator-based composite indexing in the urban ecosystem sustainability assessment, the methodology of index-construction, the meaning of environmental indicators and their role in sustainable development by presenting international indicator initiatives are discussed.

2.5.1 ENVIRONMENTAL INDICATORS

As defined by Newton *et al.* (1998, p. 8), *"environmental indicators are physical, chemical, biological or socio-economic measures that best represent the key elements of a complex ecosystem or environmental issue"*. They reflect environmental changes over a period of time and provide information about the interrelationship between environment and human activities by underlining emerging environmental issues. Environmental indicators are categorised in several different ways. The World Resources Institute divided environmental indicators into four categories based on the human and environment interactions (Hammond *et al.*, 1995; Alberti, 1996): (1) *Source indicators,* which measure the depletion of resources and the degradation of biological systems (i.e. agriculture, forest, marine resources); (2) *Sink indicators,* which evaluate the capacity of resources to absorb emissions and waste (i.e., climate change, acidification, toxification); (3) *Life Support indicators,* which monitor the change in the state of the Earth's ecosystems and biodiversity (i.e., threatened species, special lands, oceans), and; (4) *Human impact indicators,* which measure the impacts of environmental problems on public health and the quality of life (i.e., housing, waste, health, natural disaster).

According to Bakkes *et al.* (1994), environmental indicators are classified in three ways: (1) *classification by use* assists to investigate the same environmental problem with different indicator sets depending on the environmental policy or scientific development; (2) *classification by subject or theme* (i.e., climate change and energy consumption) assist to investigate particular political issues, and; (3) *classification by position in causality chains* such as environmental pressures, environmental status and societal responses. The World Bank (1997) also identified three major types of environmental indicators: (1) *Individual indicator sets,* which include large lists of indicators covering a wide range of issues to improve the integration of environmental concerns into policies (i.e., the OECD indicators); (2) *Thematic indicators,* which include a small set of indicators to evaluate environmental policy for each of the issues (i.e., World Development indicators), and; (3) *Systemic indicators,* which include one indicator to identify a complex problem (i.e., the wealth and genuine savings indicators).

The choice of appropriate environmental indicators depends on clear selection criteria. The indicator should (Newton *et al.,* 1998):

- Reflect a fundamental aspect of the environmental condition and problems;
- Be applicable to all scales of environmental issues;
- Be cost-effective as well as monitored regularly and interpreted easily;
- Be internationally comparable with other indicators;
- Provide statistically verifiable and reproducible data showing changes over time;
- Provide information that meets the policy and management needs, and;
- Track progress towards implemented significant environmental policies.

Indicators are one of the key pieces of the sustainability puzzle that helps to draw a picture of the current situation of development and reveal whether sustainability targets are being met. As stated by Gabrielsen and Bosch (2003, p. 5), environmental indicators are used for four major purposes: (1) providing information on environmental problems to assist planners and policy-makers in evaluating their severity; (2) supporting policy formulation by identifying pressure factors on the environment; (3) monitoring the effects and effectiveness of policy implementation, and; (4) raising public awareness on environmental issues by providing information on the driving forces of environmental impacts and their policy responses. In recent years, an increasing number of environmental indicator initiatives have been developed by international organisations. Although they are derived from different indicator datasets and developed at different scales, their common framework is based on addressing these questions: (1) What is happening to the state of natural resources; (2) Why is it happening, and; (3) What is being done about it (Hammond *et al.,* 1995). A brief description of major environmental indicator initiatives is identified below.

2.5.2 INTERNATIONAL INITIATIVES

The most internationally known indicator initiative is the ‘Pressure-State-Response Framework’ (PSR) developed by the Organisation for Economic Cooperation and Development (OECD), which is based on `Pressure’ indicators that describe the problems caused by human activities; `State’ indicators that monitor the physical, chemical and biological quality of the environment, and; `Response’ indicators that indicate how the society responds to environmental changes and concerns (Segnestam, 2002). This framework was further extended by the European Environment Agency (EEA) as `Driving force-Pressure-State-Impact-Response’ (DPSIR), which can be widely adapted from regional to global levels to provide a more comprehensive approach in analysing environmental problems (Figure 2.5). `Driving force’ indicators underlie the causes, which lead to environmental pressures and `Impact’ indicators express the level of environmental harm on the state of natural resources (Gabrielsen and Bosch, 2003). Furthermore, several international organisations have developed indicator initiatives, such as Indicators of Sustainable Development of United Nations Commission on Sustainable Development (UNCSD), Healthy Cities Core Indicators of World Health Organization (WHO), and Urban Indicators of United Nations Centre for Human Settlements (UNCHS), Local Sustainability Indicators of European Union (EU), and EUROSTAT Sustainable Development Indicators.

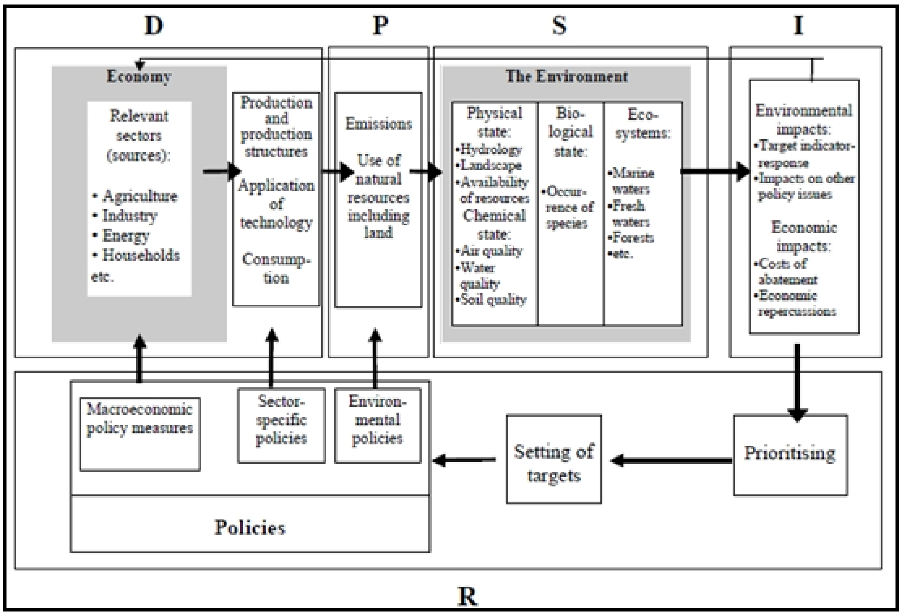


Figure 2.5 The DPSIR framework (Kristensen, 2004, p. 3)

Moreover, as shown Table 2.4, several communities have developed indicator initiatives to design their local plans to achieve sustainable urban development.

Table 2.4 Overview of international sustainability indicator initiatives (derived from Leicestershire County Council, 2008; Vancouver City Council, 2009; London Sustainable Development Commission, 2009; Mahoney *et al.*, 2010; Sustainable Measures 2012)

Country	**Sustainability Indicator Initiative**	**Project Detail**
Australia	*City of Sydney*	A city program to develop a vision, goals and strategies in the areas of environment, transport, economy, city design, culture, community and governance
	Victoria Community Indicators Project	Well being indicators for all the local governments in the state of Victoria
	City of Melbourne	A number of environmental indicators in the areas of air quality, biodiversity, buildings, litter and transport
	City of Gosnells Sustainable Development Initiative	Environmental Management Plan 2006-2009 has objectives with measurable indicators
Canada	*Sustainable Calgary*	Inspired by Sustainable Seattle, this group has published several "State of Our City" reports with sustainability indicators
	Sustainable Vancouver Plan	The plan sets out nine major goal areas: climate change; environment and public health; resource conservation; transportation; economic development; land use; the built environment; social equity; and civic engagement
	City of Atlanta Sustainability Plan	A plan that encourages the community dedicated to environmental sustainability through innovative leadership
Europe	*Fife Regional Council, Fife House*	Sustainability Indicators for Fife lists a number of indicators including economy, environment, housing, and quality of life
	London Quality of Life Indicators	The Commission has identified 23 headline Quality of Life Indicators to monitor London's progress towards becoming a sustainable city
	Leicester Community Sustainability Indicators	A Sustainable Community Strategy sets out our priorities for improvement in Leicestershire

Table 2.4 (Cont'd)

Country	Sustainability Indicator Initiative	Project Detail
United States	*Sustainable Seattle*	Sustainable Seattle was one of the first organizations to produce sustainable community indicators grouped into four broad areas: environment, population and resources, economy, culture and society
	Sustainable Chattanooga	A Sustainability Plan focuses on environment, energy, transportation, economic development, neighbourhoods, crime and safety
	Portland Comprehensive Plan	The city has a vision and a strategic plan with sustainable development goals and indicators
	Sustainable Community Roundtable of South Puget Sound	The Sustainable Community Roundtable was one of the nation's first grassroots organizations promoting the vision and principles of sustainability
	Austin Sustainable Community Initiative	The city of Austin has compiled information and resources on 11 categories of actions to promote sustainability
	Santa Monica Sustainable City Program	The plan covers goals including resource conservation, environmental and public health, transportation, economic development, open space and land use, housing
	Minneapolis Sustainability Initiative	Sustainability Initiative is reporting on progress towards specific goals relating to housing, health and safety, equity, learning, connected communities, arts and culture, environment, and economy

Apart from these initiatives, in recent years, there has been an increasing amount of initiatives on environmental sustainability indices. For instance, the Compendium of Environmental Sustainability Indicator Collections include 426 indicators of environmental sustainability derived from the following six indices: Environmental Sustainability Index (ESI), Environmental Performance Index (EPI), Environmental Vulnerability Index (EVI), and Rio to Johannesburg Dashboard of Sustainability, The Wellbeing of Nations and National Footprint Accounts (Ecological Footprint and Bio-capacity) (SEDAC, 2007).

Yale and Columbia Universities developed the Environmental Sustainability Index (ESI) in collaboration with the World Economic Forum and the Joint Research Centre of the European Commission. ESI assesses the sustainable use of natural resources by benchmarking the environmental performance at the national level. The index evaluates a nation's potential to avoid major environmental deterioration in terms of natural resource endowments, past and present pollution levels, environmental management efforts, contributions to protection of the global commons and a society's capacity to improve its environmental performance over time (Esty *et al.*, 2005). Complementary to ESI, the Environmental Performance Index (EPI) measures the effectiveness of the efforts undertaken for national environmental protection in 163 countries. EPI ranks countries in two broad policy categories: (1) environmental health, which measures environmental stresses to human health, and; (2) ecosystem vitality, which measures ecosystem health and natural resource management (Emerson *et al.*, 2010). The Environmental Vulnerability Index (EVI) is another example based on predicting the vulnerability of the environment of a country to cope with future hazardous events (Kaly *et al.*, 2004).

The Dashboard of Sustainability is a tool, which was developed by the European Commission-Joint Research Centre (Ispra, Italy), designed to present complex relationships between economic, social and environmental issues for decision-making (Joint Research Centre, 2004). Furthermore, the Wellbeing of Nations, which was developed by the World Conservation Union (IUCN) and the International Development Research Centre, surveys 180 countries in terms of wellbeing assessment. Wellbeing assessment includes the indicators of health, population, wealth, education, communication, freedom, peace, crime, and equity, which constitute a Human Wellbeing Index (HWI), and the indicators of land diversity, protected areas, land quality, water quality, water supply, global atmosphere, air quality, species diversity, genetic diversity, energy use, and resource pressures, which constitute an Ecosystem Wellbeing Index (EWI). The two indices are then combined into a composite Wellbeing Index that measures the amount of stress each country's development places on the environment (Prescott-Allen, 2001). Lastly, the National Footprint Accounts calculate the ecological footprint and bio-capacity of individual countries and of the world (Global Footprint Network, 2006).

2.5.3 DEVELOPING AN INDICATOR-BASED COMPOSITE INDEX

As defined by Gasparatos (2010, p. 1616), *"a composite index is an aggregation of different indicators under a well developed and pre-determined methodology"* (Figure 2.6). An indicator-based composite index serves many purposes, including to: (1) identify the analysis of relevant issues, current states and future trends; (2) provide a necessary information base for the definition of objectives, goals and the actions required; (3) direct decision making and urban planning processes in terms of monitoring, assessing performance and controlling, and; (4) serve for communication between administrative bodies and the public, for the initiation of discussions and increasing awareness (Weiland, 2006).

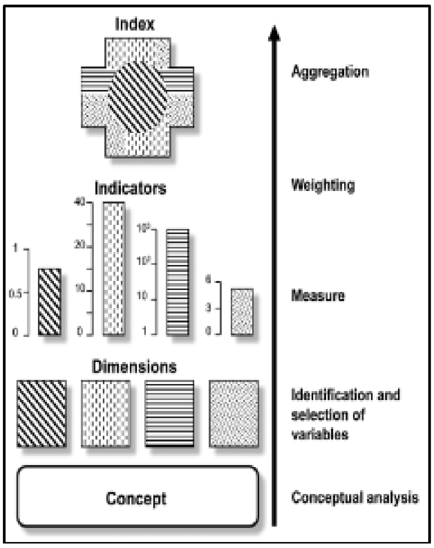


Figure 2.6 Construction of index (Boulanger, 2008, p. 47)

Although composite indices are useful in focusing on simplifying the problem by evaluating its various aspects, which can then be incorporated into a single comparable index, composite indices have some disadvantages that are summarised in Table 2.5.

Table 2.5 Advantages and disadvantages of composite index (from Saisana and Tarantola, 2002, p. 13)

Advantages	Disadvantages
Summarise complex or multi-dimensional issues, in view of supporting decision-makers	May send misleading policy messages, if poorly constructed or misinterpreted
Are easier to interpret than trying to find a trend in many separate indicators	May invite drawing simplistic policy conclusions, if not used in combination with the indicators
Facilitate the task of ranking countries on complex issues in a benchmarking exercise	May be misused (i.e. to support the desired policy), if the construction process is not transparent and lacks sound statistical or conceptual principles
Assess progress of countries over time on complex issues	The selection of indicators and weights could be the target of political challenge

Table 2.5 (Cont'd)

Advantages	Disadvantages
Reduce the size of a set of indicators or include more information within the existing size limit	May disguise serious failings in some dimensions of the phenomenon, and thus increase the difficulty in identifying the proper remedial action
Place issues of countries performance and progress at the centre of the policy arena	May lead wrong policies, if dimensions of performance that are difficult to measure are ignored
Facilitate communication with ordinary citizens and promote accountability	

Based on the *Composite Indicators Methodology and User Guide* proposed by the OECD (2008), the construction of indicator-based sustainability composite index involves the following steps:

1. *Developing a theoretical framework:* This step refers to the definition of the environmental phenomenon to be measured and its sub-components. The theoretical framework of the index is based on an in-depth review of the literature. A theoretical framework also provides a basis for determining the relevant indicators that describes the measured phenomenon. This step also involves expert and stakeholder consultations in order to provide multiple viewpoints to increase the robustness of the index.

2. *Selecting indicators and data collection:* This step involves selection of the indicators that are linked to the theoretical framework. An indicator is a statistical measure of relevant phenomena that pictures current conditions or changes in order to set goals, strategies and solutions (Heink and Kowarik, 2010). As the most important part of index construction, indicator selection needs to be based on the following dimensions of measurement, as summarised by Singh *et al.* (2009, p. 195):
    - *What aspect of the sustainability does the indicator measure?*
    - *What are the techniques and methods employed for the construction of index (i.e., quantitative or qualitative, subjective or objective, cardinal or ordinal, one-dimensional or multidimensional?*
    - *Does the indicator compare the sustainability measure (a) across space or time and (b) in an absolute or relative manner?*

- *Does the indicator measure sustainability in terms of input (means) or output (ends)?*
- *Clarity and simplicity in its content, purpose, method, comparative application and focus.*
- *Data availability for the various indicators across time and space.*
- *Flexibility in the indicator for allowing change, purpose, method and comparative application.*

This step also includes data collection process for the selected indicators. There are two kinds of environmental data in the composition of the index: (1) objective data, which are based on observations extracted from the monitoring stations, and; (2) subjective data, which are based on people's perceptions of contamination that are extracted from census data (Montero *et al.*, 2008).

3. *Imputation of missing data:* In order to provide a complete dataset, this step is applied to address the issue where the data is missing. There are two general methods for dealing with missing data. First method is case deletion which is based on omitting the missing data from the analysis. The other method is based on providing a value for each missing data. In this method, the missing data values are generated through single imputation (*e.g.*, mean/median/mode substitution), regression imputation, expectation-maximisation imputation, or multiple imputation (*e.g*., Markov Chain Monte Carlo algorithm).

4. *Multivariate analysis:* Multivariate analysis is used to investigate the overall quality of the data set and the soundness of the procedures applied in the construction of the index. This step includes the statistical analysis of the indicators in order to investigate the degree of correlation to each other. Different statistical methods can be used including: Principal Components Analysis, Factor Analysis, Cronbach's Coefficient Alpha, Cluster analysis, Pearson's correlation coefficient and Spearman's rank correlation coefficient. The result shows whether there are any indicators that measure the same or similar aspects that need to be excluded or replaced with some other suitable indicator measures.

5. *Normalisation of data:* In this step, a normalisation procedure is applied to the indicator set so as to convert the different indicator units into a common

scale. The commonly used normalisation methods are: (1) ranking which allows the performance of indicators to be followed over time in terms of relative positions, (2) standardisation which converts indicators to a common scale with a mean of zero and standard deviation of one, (3) Min-Max which allows indicators to have an identical range by subtracting the minimum value and dividing by the range of the indicator values, and; (4) categorical scale which assigns a score for each indicator.

6. *Weighting and aggregation:* Weighting procedure reflects the importance given to the indicators comprising the index or the substitution rates between them. Different weighting methods can be used including: statistical models (i.e., factor analysis, data envelopment analysis, unobserved components models), and participatory methods (i.e., budget allocation, analytic hierarchy processes). Furthermore, weights can be determined based on expert opinion that is familiar with policy priorities and theoretical backgrounds. Aggregation procedure refers to the grouping of all the indicator scores into a composite index score. Different aggregation methods are possible: summing up (linear aggregation), multiplying (geometric aggregation) or aggregated using non-linear techniques (multi-criteria analysis).

7. *Robustness and sensitivity:* A sensitivity analysis is needed to assess the robustness of the composite index in terms of the choice of normalisation, weighting, and aggregation methods.

8. *Visualisation of the results:* This step involves the interpretation of the findings in order to provide a clear and accurate presentation of index results. Many visualisation techniques exist such as tabular format, bar or line charts, ranking or dashboards.

2.6 SUMMARY OF THE CHAPTER

During the last several decades, the quality of natural resources and their services have been exposed to significant degradation from increased urban populations combined with the sprawl of settlements, development of transportation networks and industrial activities (Dorsey, 2003; Pauleit *et al.,* 2005). As a result of this environmental degradation, a sustainable framework for urban development is required to provide the resilience of natural resources and ecosystems. Sustainable urban development refers to the management of cities with adequate infrastructure to support the needs of its population for the present and future generations as well as maintain the sustainability of its ecosystems (UNEP/IETC, 2002; Yigitcanlar, 2010). One of the important strategic approaches for planning sustainable cities is 'ecological planning'. Ecological planning is a multi-dimensional concept that aims to preserve biodiversity richness and ecosystem productivity through sustainable management of natural resources (Barnes *et al.*, 2005). As stated by Baldwin (1985, p.4), ecological planning is the initiation and operation of activities to direct and control the acquisition, transformation, disruption and disposal of resources in a manner capable of sustaining human activities with a minimum disruption of ecosystem processes. Therefore, ecological planning is a powerful method for creating sustainable urban ecosystems.

In order to explore the city as an ecosystem and investigate the interaction between urban ecosystem and human activities, a holistic urban ecosystem sustainability assessment approach is required. Urban ecosystem sustainability assessment serves as a tool that helps policy and decision-makers in improving their actions towards sustainable urban development. Several methods are used in urban ecosystem sustainability assessment and among them sustainability indicators and composite indices are the most commonly used tools for assessing the progress towards sustainable land use and urban management. Currently, a variety of composite indices are available to measure the sustainability at the local, national and international levels. However, the main conclusion drawn from the literature review is that they are too broad to be applied to assess local and micro level sustainability and no benchmark value for most of the indicators exists due to limited data availability and non-comparable data across countries. Mayer (2008, p. 280) advocates that by stating "as different as the indices may seem, many of them incorporate the same underlying data because of the small number of available sustainability datasets". Mori and Christodoulou (2011) also argue that this relative evaluation and comparison brings along biased assessments, as data only exists for some entities, which also means excluding many nations from evaluation and comparison.

Thus, there is a need for developing an accurate and comprehensive micro-level urban ecosystem sustainability assessment method. In order to develop such a model, it is practical to adopt an approach that uses a method to utilise indicators for collecting data, designate certain threshold values or ranges, perform a comparative sustainability assessment via indices at the micro-level, and aggregate these assessment findings to the local level. Hereby, through this approach and model, it is possible to produce sufficient and reliable data to enable comparison at the local level, and provide useful results to inform the local planning, conservation and development decision-making process to secure sustainable ecosystems and urban futures. To advance research in this area, this study investigates the environmental impacts of an existing urban context by using a composite index with an aim to identify the interaction between urban ecosystems and human activities in the context of environmental sustainability. With this regard, this study develops a new comprehensive urban ecosystem sustainability assessment tool entitled the 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX). The next chapter presents the methodology of the MUSIX model.

Chapter 3: Research Methodology

This chapter introduces the research design of the study in order to develop an indexing model for the evaluation of environmental sustainability performance. The research design of the study comprises the following sections in the construction of the 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX) model. The first section presents the theoretical framework of the model. The second section explains the selection of indicators and their contribution to environmental sustainability evaluation. The third section outlines the data collection and the analysis of the collected data. The fourth section describes the development and application of the model. Lastly, the final section defines the policy development of the model and concludes with a summary of the chapter.

3.1 RESEARCH DESIGN OF THE STUDY

The purpose of this study, as discussed in the introduction chapter, is to investigate the interaction between human activities and the natural environment by evaluating the environmental sustainability performance of an existing urban setting. Previous sections of the literature review have shown that human behaviour affects the ecosystem function and dynamics irreversibly through population growth and rapid urbanisation. The increasing demand of productivity and consumption depletes and degrades the natural resources. Rapid urbanisation of populations is associated with the transformation of agricultural and forestland uses into built-up areas and this conversion has created large portions of impervious surfaces. Impervious surfaces are regarded as the imprint of human activities on the natural environment. Therefore, imperviousness is a key environmental impact indicator for urban sustainability assessment (Schueler, 1994).

Remote sensing is a useful tool in order to detect the impact of impervious cover on the natural environment. Change detection on the natural land cover using remote sensing helps sustainability assessment by: (1) discovering the changes that have occurred, (2) establishing the nature of the change, (3) measuring the extension of the change, and; (4) assessing the spatial pattern of the change (MacLeod and

Congalton, 1998). To analyse the land cover change in sustainability assessment, remote sensing data can be used in several ways, such as spatial analysis by the sustainability-indexing model. A sustainability-indexing model is composed of several indicators, which, together, report the state of the environment covering a wide variety of geographic scales (USEPA, 2010). Indicators are helpful tools in benchmarking sustainability performance, monitoring problems and reviewing the effectiveness of current policies (Giannetti *et al.*, 2009).

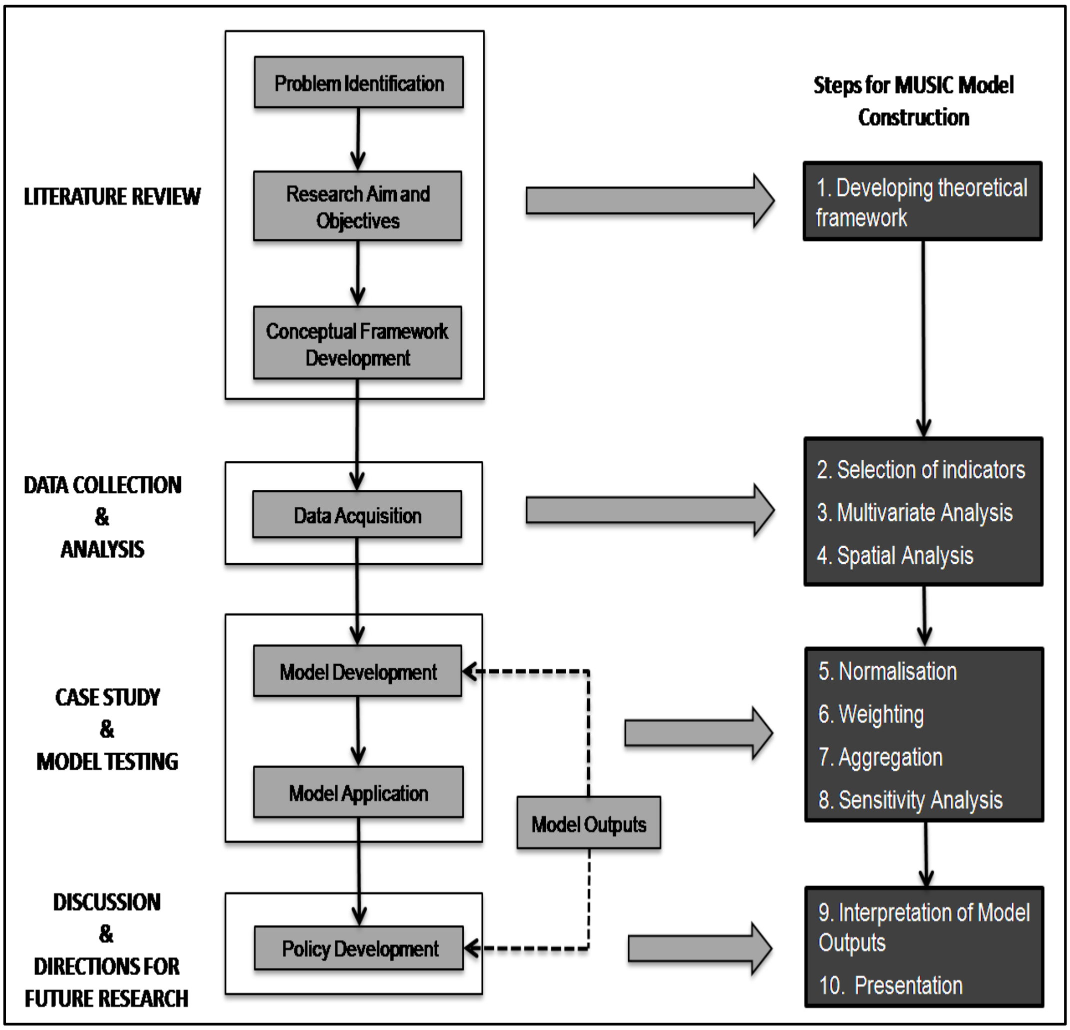


Figure 3.1 Research design of the study

In this study, a new sustainability-indexing model is developed to monitor the environmental impact of human activities on the urban ecosystem. The model entitled the ‘Micro-level Urban-ecosystem Sustainability IndeX’ (MUSIX) is an indicator-based indexing model, which investigates the factors affecting urban sustainability in a local context. The model outputs evaluate current development plans; moreover, they provide local and micro-level sustainability reporting guidance to help policy-making concerning environmental issues. Gold Coast City, which is located in South East Queensland, Australia, was selected as the case study. Figure 2.7 outlines the methodology adopted for this research project, starting with problem definition, research aim and objectives development, data collection and analysis. In addition, the following steps in the construction of the model, model implementation, interpreting and reporting the findings are also included.

As shown in Figure 3.1, in the first step of the MUSIX model, the answer to the question of what is being measured was defined referring to the theoretical framework based on the literature review. As the second step in the data collection and analysis, the theoretical framework was linked with various sub-groups and the underlying indicators answering the question of how it is being measured. As stated by the OECD (2003), indicators were selected on the basis of their policy relevance, analytical soundness, measurability, and country coverage. In order to investigate the correlation between selected indicators, the third step includes the statistical analysis of the indicators. Spearman's rank correlation was used to analyse the structure of the indicator set by looking at the correlation coefficients. Afterwards, spatial analysis was carried out through remote sensing data in order to calculate impervious and pervious fractions of the study area. In the fifth step, a normalisation procedure was applied to the indicator set so as to convert the different indicator units into a common scale. As for the next step, to reflect the relative importance of each indicator, weightings were assigned by using expert opinion via the Budget Allocation Method. After the weighting process, the indicator's parcel-level scores were aggregated into grid cells to give the final score of the model. Following this, sensitivity analysis was undertaken to assess the robustness of the index. Lastly, the results of the model were analysed and discussed. The comprehensive structure of the MUSIX model is summarised in Figure 3.2. All the steps are explained in detail in this chapter.

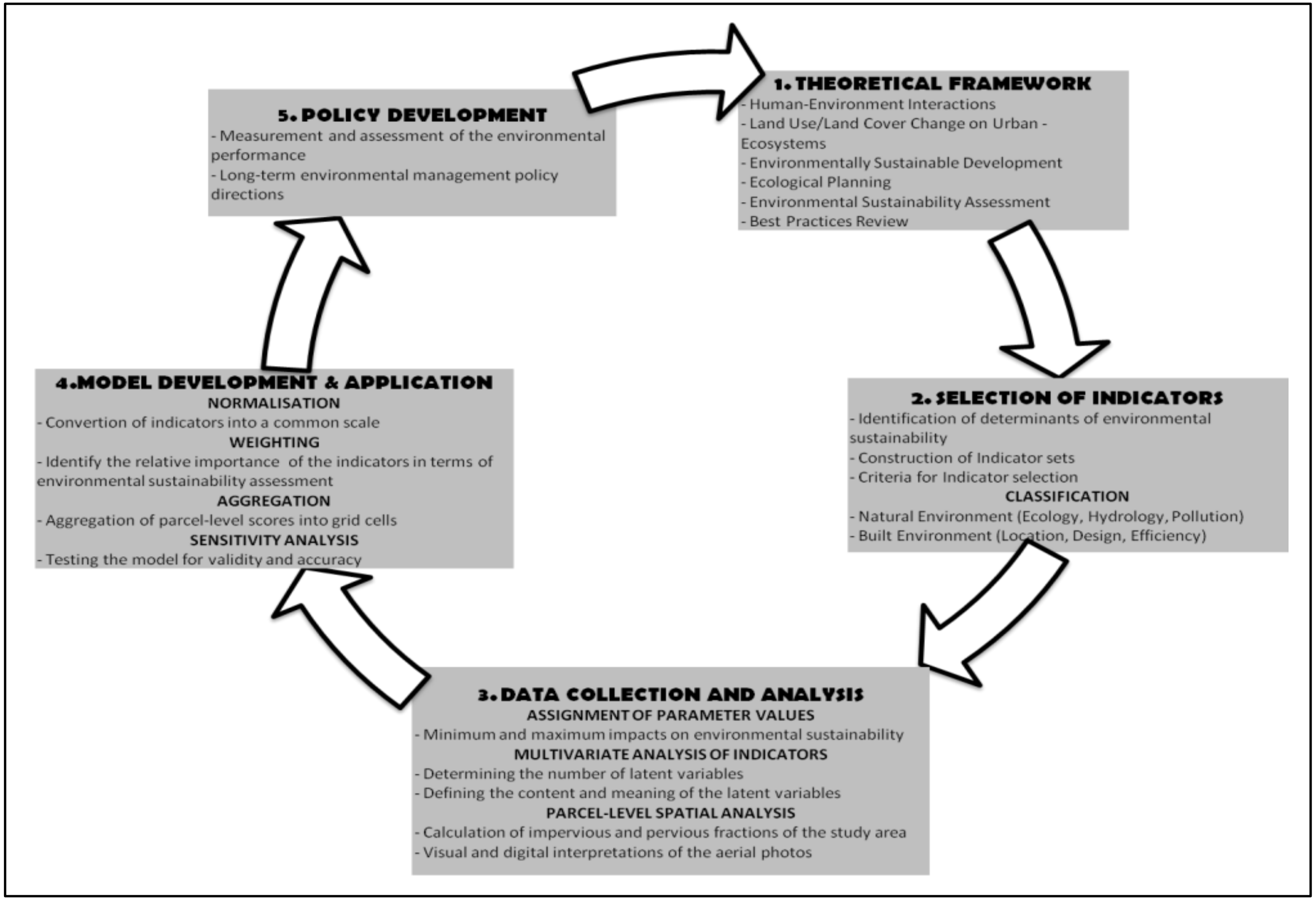


Figure 3.2 Structure of the MUSIX model

3.2 THEORETICAL FRAMEWORK OF THE MUSIX MODEL

Sinclair (2007) describes a theoretical framework as a map or travel plan. When people plan their journey to a foreign country, they seek as much information as possible for the best way to travel. This information helps them to have a safe and successful journey with good outcomes. In the initial stages of a research study, a theoretical framework helps to pin down the aim and purpose of the research by looking at different references. It helps to explain the problem and specify the questions to be used to guide the research. Moreover, it gives direction to identify the variables required to analyse the research questions. In this case, developing a theoretical framework for an indexing model is necessary for the success of the study. It identifies the main objectives of the model that underpin the methodological approach to be applied. Accordingly, it clarifies the relevant indicators and data sets that are related to the desirable outcomes followed by the development of policies.

As sustainable development of natural resources is a broad and multi-dimensional concept, a theoretical framework is necessary in order to address what is meant by sustainability, what is the sustainable use of resources and what kind of planning tools need to be developed for the assessment of their sustainability (Carraro *et al.,* 2009). In this context, the theoretical framework of the MUSIX model is based on environmental sustainable urban development, which aims to integrate human activities into natural systems by carrying out environmental development policies in order to ensure their long-term sustainability. As a dimension of sustainable development, environmental sustainable urban development promotes ecologically diverse and dynamic cities with balanced use of their resources for the welfare of future generations. Environmental sustainable urban development (ESUD) consists of two main principles: (1) *ecological resilience of the natural environment* by preserving the ecosystem's stability while improving its resistance to tolerate the damage and renew itself (Walker *et al.,* 2002), and; (2) *sustainable development of the built environment* towards eco-friendly architectural design and urban planning so as to achieve high environmental quality of housing and neighbourhoods (Newman and Jennings, 2008). In light of these guiding principles, the MUSIX model incorporates six main targets that aim to achieve environmental sustainable urban development (Figure 3.3):

- *Establishing hydrological conservation* through sustainable stormwater management in order to preserve the Earth's water cycle and aquatic ecosystems;
- *Providing ecological conservation* through sustainable ecosystem management in order to protect biological diversity and maintain the integrity of natural ecosystems;
- *Improving environmental quality* through developing pollution prevention regulations and policies in order to promote high quality water resources, clean air and enhanced ecosystem health;
- *Creating sustainable mobility and accessibility* through designing better public services and walkable neighbourhoods in order to promote healthy life style and provide alternative modes of transportation;
- *Sustainable design of urban environment* through environmentally sustainable site design in order to increase the efficient use of solar energy to provide thermal comfort, and;
- *Use of renewable resources* through creating efficient communities in order to provide a long-term management of natural resources for the sustainability of future generations.

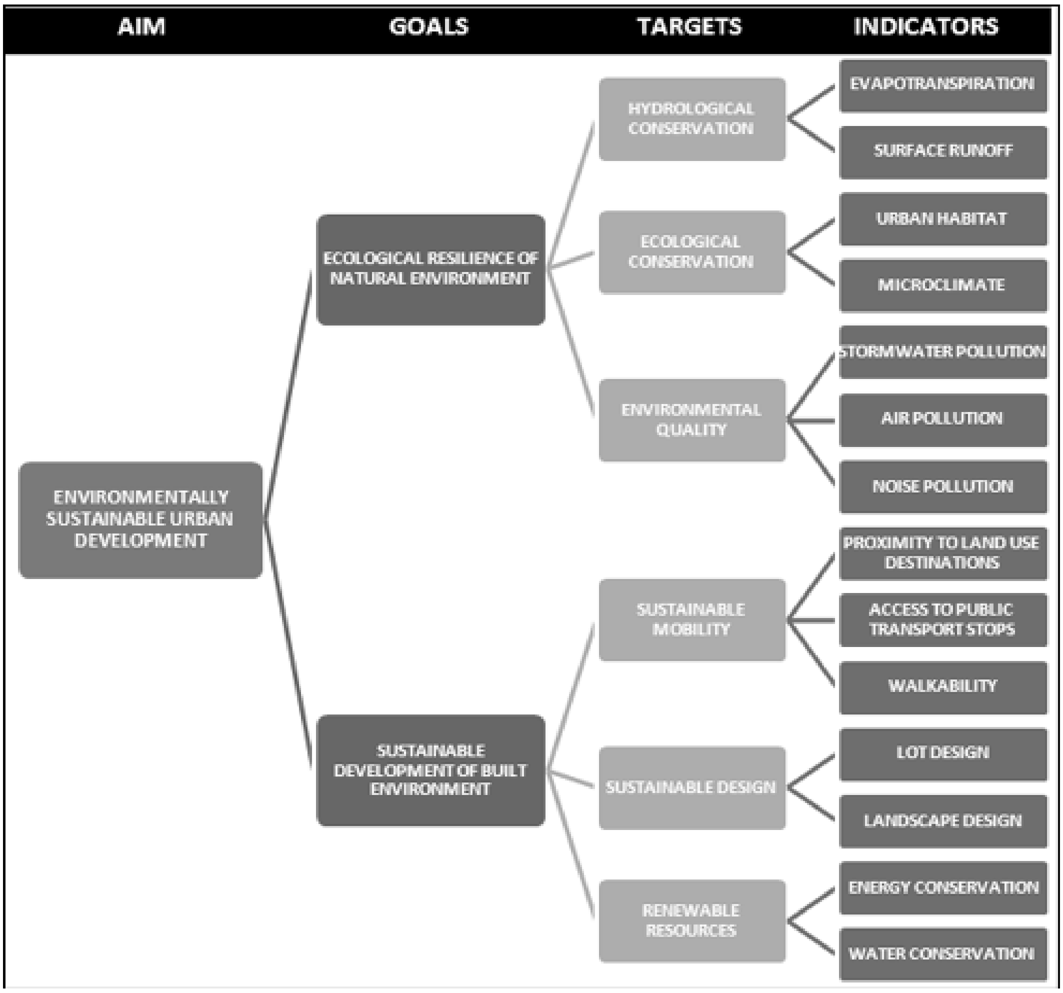


Figure 3.3 the Theoretical foundation for indicator development and selection

Additionally, Figure 3.4 provides a conceptual framework for the environmental assessment and reporting structure of the MUSIX model which is adapted from the Driving force-Pressure-State-Impact-Response (DPSIR) framework developed by the Organization for Economic Cooperation and Development (OECD):

- *Driving forces* are the underlying causes that lead to environmental pressures on the urban ecosystem;
- *Pressures* are the environmental problems caused by driving forces;
- *State* variable refers to the selected indicators of the model that monitor the pressures and problems;
- *Impacts* correspond to the indicator sub-category sets of the model that express the level of impact on the urban ecosystem, and;
- *Responses* are the actions that are taken in order to achieve a sustainable urban future.

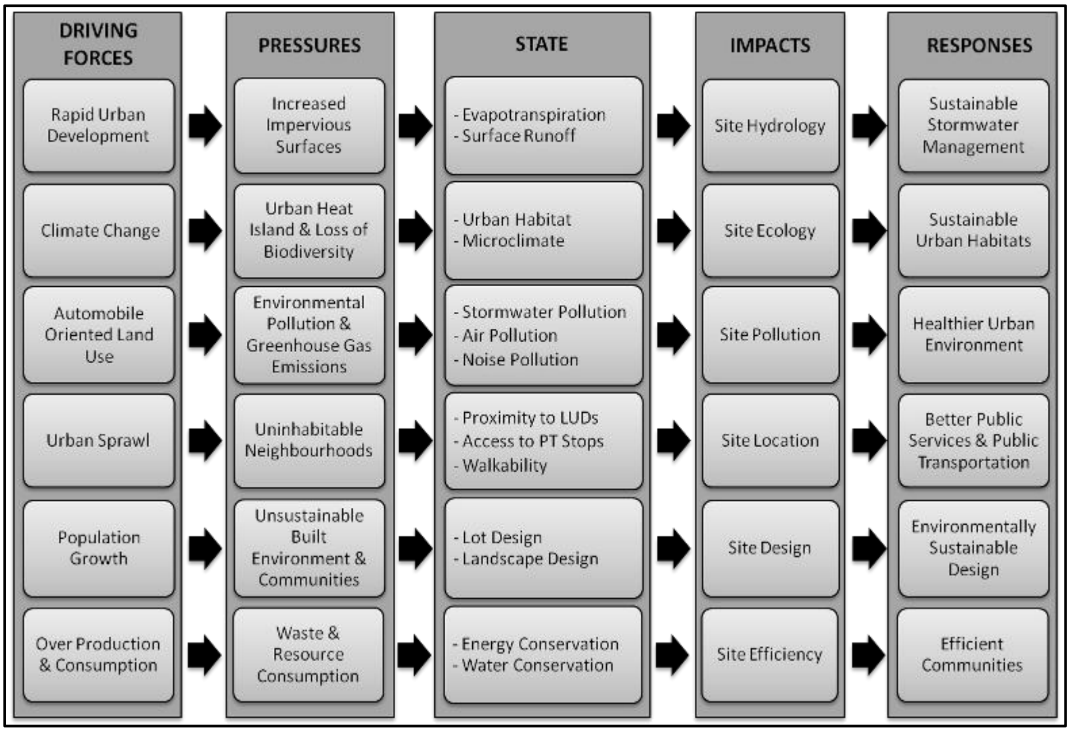


Figure 3.4 DPSIR framework of the MUSIX model

Briefly, as stated by Birkmann (2006), a theoretical framework clearly depicts what is being assessed by defining the influencing factors. In this research, ESUD and its above-mentioned key principles constitute a basis for the determination of indicator categories and indicators. Moreover, a DPSIR approach helps to conceptualise a wide range of issues that address the problem by presenting the reasons and the degree of harm caused in the ecosystem (Pearson *et al.*, 2011). The DPSIR framework of the model examines the linkages between human activities and ecosystems by clarifying the complex relationship between them. It is a useful tool for reporting this relationship as well as helping to develop potential solutions. It leads to a better understanding of the selection of indicators that are relevant to environmental sustainability assessment and also provides a conceptual basis for the policy needs. The next section identifies the selection of indicators and the construction of indicator sets for measuring environmental sustainability.

3.3 INDICATOR SELECTION

Environmental indicators represent the physical, chemical, biological or socio-economic measurements of a complex ecosystem or environmental issue (Newton *et al.*, 1998). They are able to reflect the changes over a period of time depending on the problem by providing information about its severity and draw attention to the effectiveness of current policies (Hammond *et al.*, 1995). Gabrielsen and Bosch (2003, p.5) describe the main purposes of environmental indicators as follows:

- Detecting environmental problems to enable policy-makers to evaluate their impact;
- Providing guidance for policy development to mitigate the pressure on the environment;
- Monitoring the effectiveness of policy responses, and;
- Raising the public awareness about environmental issues to strengthen public support on sustainable environmental management.

In order to measure environmental sustainability performance, a reliable set of indicators is required. A set of relevant indicators was developed through a comprehensive review of existing indicator initiatives (e.g., UNCSD, 2001; OECD, 2003; EEA, 2005; Japan Sustainable Building Consortium, 2007; SEDAC, 2007; U.S. Green Building Council, 2008, 2009). Additionally, an expert panel, consisting of the Gold Coast City Council, Queensland Transport and Main Roads and Queensland University of Technology, reached a consensus on the desired indicators through a series of workshops. The indexing model highly benefited from the expert opinions of panel members, both academic and professional, and their local knowledge concerning the study area during the selection of indicators. These workshops provided useful insights into the selection of relevant indicators for the policy formulation process. As it was difficult collecting and implementing data at the local level, indicators were also selected through consideration of the local context and data availability for Gold Coast City.

Based on the theoretical background (Figure 2.9) provided in the previous section, the MUSIX model measures the interaction between impervious surfaces and ecosystems in two categories which both constitute the main components of an urban ecosystem: (1) *natural environment,* which comprises the physical surroundings that have not been significantly modified by human activity including topographical features, flora/fauna, soil, water, climatic features, and; (2) *built environment,* which comprises the physical surroundings created by human activity (e.g., roads, houses, buildings, bridges, etc.) and related infrastructure services.

There is also another component called the socio-economic environment, which is the part of the environment that is linked to social, economic, cultural and political human activities, such as demographic structure of the users within the area, economic activities, employment structure, regulations and policies. As a consequence of data availability and scale issues, the indicators belonging to this component were not included in the model.

The model measures the state of the environment for each category with three indicator sets using 14 indicators rating from 1 to 5 according to their environmental performance:

- As a result of rapid urban development, increased built and paved surfaces leads to less evapotranspiration as well as infiltration and increased runoff from urban areas and affects the catchment hydrology and water quality (Barnes, 2001). In this context, it consists of two performance indicators: (1) Evapotranspiration; and (2) surface runoff.
- Increased built and paved surfaces are directly linked to global warming and cause climate change that results in the urban heat island effect and loss of biodiversity (UNFCCC, 2007). In this context, the second indicator set includes two performance indicators: (3) urban habitat; and (4) microclimate.
- The evolution of technological change, the introduction of motorised vehicles and the increase in energy consumption creates a distinctive impact on environmental quality (Mage *et al.*, 1996). In this context, the third indicator set accommodates three performance indicators: (5) stormwater pollution, (6) air pollution; and (7) noise pollution.
- Increased demand for human needs resource consumption lead to more intense and complex patterns of land use. These dispersed, automobile-oriented land use patterns degrade the environment by creating unliveable neighbourhoods (Litman, 2007). In this context, the fourth indicator set consists of three performance indicators: (8) proximity to land use destinations, (9) access to public transport stops; and (10) walkability.

- As a result of urban sprawl, the layout of new developments alters the natural environment and creates unsustainable living conditions. Therefore, climate responsive design is necessary for creating ecologically sustainable site design (Hyde, 2000). In this context, the fifth indicator set contains two performance indicators (11) lot design; and (12) landscape design.
- Private households make significant contributions to environmental sustainability in terms of resource consumption (Lorek and Spangenberg, 2001). In this context, the sixth indicator set accommodates two performance indicators: (13) energy conservation; and (14) water conservation.

Table 3.1 shows the list of indicators including their descriptions, unit of measurements and data sources. As mentioned previously, for this study, data collection was a major problem due to the unavailability of data at the parcel scale. Therefore, it should be emphasised that, for some indicators - transportation, noise, air and stormwater pollution - data were derived from the other studies of the ARC Linkage Project in different scales and were then disaggregated into parcel scale. This is explained in detail in the next section.

Table 3.1 Indicator set of the MUSIX model

MAIN CATEGORIES	SUB-CATEGORIES	INDICATORS	DESCRIPTIONS	UNITS	DATA SOURCES
NATURAL ENVIRONMENT	HYDROLOGY	Evapotranspiration	Changes in evapotranspiration rates resulting from impervious surface ratio	%	• Literature review • Aerial imagery data derived from GCCC • ArcGIS software
		Surface Runoff	Runoff based on the % of different types of surfaces	%	
	ECOLOGY	Urban Habitat	Green area ratio	%	
		Microclimate	Albedo of surfaces by their area percentages	%	
	POLLUTION	Stormwater Pollution	Transport related lead concentrations in stormwater runoff	mg/L	• Literature review • Aerial imagery data derived from GCCC • ArcGIS software • ARC Linkage Project
		Air Pollution	Transport related lead concentrations in air	$\mu g/m^3$	
		Noise Pollution	Calculation of road traffic noise	dBA	
BUILT ENVIRONMENT	LOCATION	Proximity to Land Use Destinations	Access to public services within 800 m walking distance	NDAI score	• Literature review • Aerial imagery data derived from GCCC • ArcGIS software • ARC Linkage Project
		Access to Public Transport Stops	Public transport stops proximity to lots	m	
		Walkability	Design of pedestrian and bikeways	points	
	DESIGN	Lot Design	Existing lot plan meets the principles of passive solar design	points	• Literature review • Aerial imagery data derived from GCCC • ArcGIS software
		Landscape Design	Existing landscape plan meets the principles of subtropical landscape design	points	
	EFFICIENCY	Energy Conservation	Existing plan meets the principles of energy efficient design	points	
		Water Conservation	Existing plan meets the principles of water efficient design	points	

3.3.1 SPECIFICATION OF NATURAL ENVIRONMENT INDICATORS

Box 3.1 Indicator 1

Indicator 1: Evapotranspiration
Description: Evapotranspiration, defined by Wang *et al.* (2001), is a collective term for the transfer of water into the atmosphere from both vegetated and non-vegetated land surfaces. This indicator investigates the changes in evapotranspiration rates resulting from impervious surfaces.
Environmental impacts: As a component of the hydrologic cycle, evapotranspiration protects and restores natural hydrology through vegetated surfaces.
Contribution to environmental sustainability: Vegetated surfaces increase the rate of evapotranspiration which contributes to cooling the air temperature by absorbing radiation and releasing water vapour. Forests help to promote the infiltration of water and reduce surface runoff. The roots and the fauna above the soil maintain the porosity and permeability of the forest ground, thereby, keeping the soil unsaturated through evapotranspiration. Furthermore, vegetation reduces the rainfall intensity by intercepting water temporarily on their canopy surfaces.
References: Kittredge, 1973; Stewart, 1977; Mcpherson and Rowntree, 1993; Van Dijk and Bruijnzeel, 2001 Keim *et al.*, 2006; Wilder and Kiviat, 2009.

Box 3.2 Indicator 2

Indicator 2: Surface Runoff
Description: This indicator investigates the surface runoff rates of different land cover types.
Environmental impacts: The high volume and velocity caused by stormwater runoff increases the risk of flooding and erosion by destroying aquatic and riparian habitats.
Contribution to environmental sustainability: Vegetated surfaces protect and preserve the water quality in streams. They provide numerous valuable environmental benefits including moderating stream flow, controlling volume, duration and intensity of runoff, buffering against pollutants, preventing flooding

and erosion. Urban vegetation helps to slow down stormwater runoff and soil erosion through canopy interception. Moreover, water sensitive urban design provides an integrated approach to surface runoff management, within this context; there are many implemented vegetative practices such as vegetation swales, bioretention basins and constructed wetlands.
References: Schueler, 1994; Arnold and Gibbons, 1996; Brabec *et al.*, 2002; Gold Coast City Council, 2007; Day and Dickinson, 2008; Wilder and Kiviat, 2009.

Box 3.3 Indicator 3

Indicator 3: Urban Habitat
Description: This indicator investigates the environmental quality in the urban development by measuring the green area ratio (calculation of the crown area of existing trees, shrubs except low lying vegetation such as perennials, grass).
Environmental impacts: Urbanisation affects natural ecosystems through habitat fragmentation by altering migration, nesting and breeding success which results in the extinction of species.
Contribution to environmental sustainability: Urban green spaces contributes to local habitat conservation by performing a variety of important ecosystem functions such as: (1) enhancing vegetation composition and diversity as well as providing a habitat for wildlife in metropolitan settings, (2) providing amelioration of urban microclimates by reducing albedo and radiation loads, (3) preventing nonpoint water pollution and providing filtering of the air by trapping particulate pollutants, and; (4) stabilisation of stream banks.
References: Sukopp and Werner, 1982; Oke, 1990; Nowak, 1994; Breuste *et al.*, 1998; Fahrig, 2003; Randolph, 2004; Grove *et al.*, 2006a.

Box 3.4 Indicator 4

Indicator 4: Microclimate
Description: Albedo, defined by Akbari *et al.* (1992), is the ability of a surface to reflect incoming solar radiation. Surfaces with low albedo absorb most of the solar energy whereas surfaces with high albedo reflect most of the solar energy. This

indicator investigates the urban heat island effect of impervious surfaces on the microclimate by measuring the albedo of surfaces.
Environmental impacts: Impervious surfaces causes increased land surface temperatures, which results in an air temperature difference between urban and rural areas called the urban heat island effect.
Contribution to environmental sustainability: Urban vegetation moderates the heat island effect in urban areas by controlling the specific heat capacities and thermal conductivities of surfaces and ameliorates urban microclimate. Vegetation reduces surface temperatures by releasing moisture to the air through evapotranspiration and providing shade to buildings and dark surfaces as well as reducing energy use.
References: Saito *et al.*, 1990-91; Akbari *et al.*, 1992; Shashua-Bar and Hoffman, 2000; Dimoudi and Nikolopoulou, 2003; Alessandri *et al.*, 2007; Hamada and Ohta, 2010; EPA, 2012.

Box 3.5 Indicator 5

Indicator 5: Stormwater Pollution
Description: This indicator investigates transport related stormwater runoff pollution.
Environmental impacts: Urban stormwater is a major contributor to the pollution of water bodies. Pollutants produced by transportation activities are carried into waterways by stormwater, and this increased amount of pollutants leads to the physical degradation of urban streams.
Contribution to environmental sustainability: The most effective way to control stormwater pollution is to protect the native vegetation, which plays an important role in stormwater quality by removing pollutants from surface runoff. Furthermore, vegetation prevents sedimentation and eutrophication of waterways, preserves drinking water quality in catchments and prevents the loss and fragmentation of aquatic habitats.
References: Leopold, 1968; Goonetilleke *et al.*, 2005; Carle *et al.*, 2005; Duncan, 2006; Kloss and Calarusse, 2006.

Box 3.6 Indicator 6

Indicator 6: Air Pollution
Description: This indicator investigates transport related air pollution.
Environmental impacts: Transportation activities contribute to air pollution through the emission of greenhouse gases, particulates and toxic gases. Transportation affects the environment through acidification and eutrophication of the water bodies, and ozone depletion, which causes the damage of forests, wetlands and agricultural lands.
Contribution to environmental sustainability: Urban vegetation improves the air quality by removing air pollutants via their leaves. They control the greenhouse effect and prevent increased ultraviolet radiation. They lower the emissions of Volatile Organic Compounds, thereby, contributing to the formation of ozone in urban areas.
References: Schwela *et al.*, 1997; Gorham, 2002; EPA, 2006; IGES, 2007; Nowak, 2012.

Box 3.7 Indicator 7

Indicator 7: Noise Pollution
Description: This indicator investigates transport related noise pollution.
Environmental impacts: Noise pollution reaches harmful levels in cities. For instance, people who live close to industrial or commercial suburbs along traffic corridors are exposed to a high level of noise pollution. Noise pollution affects human health by causing psychological symptoms, such as hypertension, hearing loss, high stress levels and sleep disturbances. Noise pollution also affects wildlife by disrupting their breeding, feeding and migration patterns.
Contribution to environmental sustainability: Urban vegetation helps reduce noise pollution through blocking and absorbing sound waves, thereby, protecting the physiological and psychological health of humans. Furthermore, urban vegetation maintains wildlife habitats and territory by preventing the loss of their food supply and behavioural changes in mating, predation and migration.
References: Anderson *et al.*, 1984; Dwyer *et al.*, 1992; Ragnar, 1997; Singh and

Davar, 2004; Gidlöf-Gunnarsson and Öhrström, 2007.

3.3.2 SPECIFICATION OF BUILT ENVIRONMENT INDICATORS

Box 3.8 Indicator 8

Indicator 8: Proximity to Land Use Destinations
Description: This indicator investigates the accessibility of the site to the land use destinations within walking distance (800 m).
Environmental impacts: As a consequence of rapid urban development, distances between housing, jobs, schools and other land use destinations have increased, accordingly, vehicle miles travelled and vehicle trips have increased. Increased vehicle travel creates environmental problems including: degraded air quality and stream hydrology, greenhouse gas emissions, noise pollution and chronic health problems.
Contribution to environmental sustainability: Close proximity to land use destinations reduces the volume of traffic by minimising automobile oriented transportation as well as their associated environmental impacts. Land use patterns with a high mixture of land uses encourage walking, biking or public transit by providing easier access to community support services.
References: Griffin, 1998; Frank, 2000; U.S. EPA, 2001; Cerin *et al.*, 2007; Litman, 2007; McCormack *et al.*, 2008.

Box 3.9 Indicator 9

Indicator 9: Access to Public Transport Stops
Description: This indicator investigates the accessibility of the site by public transport.
Environmental impacts: Dispersed land use patterns are usually designed for motor vehicle transport, which causes increased consumption of non-renewable resources, traffic congestion, pollution and noise.
Contribution to environmental sustainability: Better public transport accessibility tends to provide easier access and shorter times to the destinations by increasing the use of alternative modes. Moreover, better public transport reduces the need for

vehicle travel as well as encourages people to walk or cycle.
References: Murray *et al.*, 1998; Murray, 2001; Steg and Gifford, 2005; Litman, 2007; Glaeser *et al.*, 2008; Zavitsas *et al.*, 2010.

Box 3.10 Indicator 10

Indicator 10: Walkability
Description: This indicator investigates the site accessibility by looking at the design of streets and pedestrian ways.
Environmental impacts: Automobile-oriented planning faces a number of challenges such as heavy and high vehicle traffic, poor pathways blocked by parked cars, disconnected street systems and unsecure street environments.
Contribution to environmental sustainability: Walkable streets promote sustainable neighbourhoods and districts by ensuring safe, appealing and comfortable pedestrian environments. They encourage healthy communities by increasing physical activity, reducing traffic injuries and human exposure to air pollution.
References: Tolley, 2003; Southworth, 2005; City of Ottawa, 2009; Cutts *et al.*, 2009; Tomalty and Haider, 2009.

Box 3.11 Indicator 11

Indicator 11: Lot Design
Description: This indicator investigates the implementation of passive solar design principles within the existing lot plan.
Environmental impacts: Buildings have significant environmental impacts on natural resources through their construction, operation and demolition phases. These impacts can be summarised as: increased energy use, water consumption and pollution, greenhouse gas emissions, indoor air quality problems and waste generation.
Contribution to environmental sustainability: Passive design is a design approach that encourages energy efficiency by using solar energy for the heating and cooling of living spaces. Passive design improves thermal comfort of the site by

creating optimum conditions for the use of solar design strategies such as orientation, building shape, shading, glazing, landscaping, thermal mass and insulation.
References: King *et al.*, 1995; Scott *et al.*, 2006; Boyano and Wolf, 2010; Suagee, 2011; ATA, 2012.

Box 3.12 Indicator 12

Indicator 12: Landscape Design
Description: This indicator investigates the implementation of subtropical landscape design principles within the existing parcel plan.
Environmental impacts: There are many significant effects of buildings on the microclimatic conditions through building location, orientation, design, material form, types and colours. These effects can be summarised as: higher level of temperatures, humidity, rainfall, air pressure, wind speeds and energy usage.
Contribution to environmental sustainability: Landscape design provides many opportunities for environmental sustainability by: (1) reducing heating and cooling energy needs, (2) controlling microclimate, (3) improving comfort level of outdoor spaces by shading and wind protection, and; (4) providing a better visual effect on built environment.
References: Hyde, 2000; Ahmed, 2003; Axarli, 2005; Chen, 2007; Drogemuller *et al.*, 2009; ATA, 2012.

Box 3.13 Indicator 13

Indicator 13: Energy Conservation
Description: This indicator investigates the implementation of energy efficient design principles within the existing parcel plan.
Environmental impacts: Households contribute to energy consumption through residential energy demand for cooling, heating, lighting and home appliances. Increased energy consumption is associated with environmental problems, such as global warming, climate change, ozone depletion, acid precipitation, limited non-renewable sources and environmental degradation.

Contribution to environmental sustainability: Climate responsive design contributes to energy conservation by: (1) encouraging the use of renewable energy, such as photovoltaic panels and solar water heating, (2) creating outdoor living spaces to improve thermal comfort, and; (3) reducing effects of urban heat island by using lighter colour paving and roofing materials.
References: Dincer, 1999; Dincer and Rosen, 1999; Hyde, 2000; Perez-Lombard *et al.*, 2008; OECD, 2008; Omer, 2008.

Box 3.14 Indicator 14

Indicator 14: Water Conservation
Description: This indicator investigates the implementation of water efficient design principles within the existing parcel plan.
Environmental impacts: Households contribute to water consumption through indoor water use (showers, flushing toilets, washing and cleaning) and outdoor water use (watering lawn and gardens, car washing and pool maintenance) activities. Environmental issues related to water deficiency can be summarised as warmer and drier microclimates, desertification, and loss and alteration of aquatic and riparian habitats.
Contribution to environmental sustainability: Climate responsive design contributes to water conservation by: (1) installing rainwater tank and grey water systems, (2) using efficient irrigation systems, (3) choosing water saver plants, and permeable paving materials, (4) designing rain gardens or green roofs, and; (5) efficient use of pool and other water features.
References: Hazell *et al.*, 2006; Oberndorfer *et al.*, 2007; Bates *et al.*, 2008; OECD, 2008; GCCC, 2012.

3.3.3 OMITTED INDICATORS

Even though the ARC Linkage Project industry partners supported this PhD study with expert views and data provision, data collection was still a major issue due to the unavailability of information at the parcel-level, limited budget and time schedule. Therefore, some of the indicators of the earlier versions of the model, which were related to socio-economic structure of the urban ecosystem, had to be excluded due to individual or household level data collection problems and privacy issues. This section gives a brief description of these omitted indicators.

Box 3.15 1st Sub-Category

1st Sub-Category: Demography **Indicators: (1) Population density, (2) Age, (3) Immigration status**
A number of studies (Martin *et al.,* 2004; Grove *et al.,* 2006; Luck, 2007; Troy *et al.,* 2007; Jenerette *et al.,* 2007) have shown that there is a relationship between vegetation cover change and neighbourhood demographic characteristics, such as population density, age, ethnicity, cultural background and immigration status. Perry and Nawaz (2008) investigated the impact of demographic statistics on the increasing trend in garden paving in an area of Leeds, United Kingdom. The results indicate that the presence of a large number of retired people, who are generally older, prefer to pave their gardens. Because of mobility problems they need to park their car very near to the house and also they are unable to walk or cycle to public transport and other services. In another study, conducted by Luck *et al.* (2009), it was found that vegetation cover is related to immigration status as immigrants are generally less familiar with the local environment and land management practices than native residents. Kirkpatrick *et al.* (2011) analysed the influence of cultural background on urban vegetation by documenting the temporal and spatial variation of urban trees in six eastern Australian cities. The results indicated that tree density is inversely related to the proportion of Australian-born residents. This was explained by their negative attitude to urban trees because of their family links to the rural landscape where trees are considered as an obstacle to production and a danger to property. In contrast, Lohr *et al.* (2004) found that Americans, who have lived on a farm during their early childhood, consider trees more important to the quality of life than those who have spent their entire lives in city.

Box 3.16 2nd Sub-Category

2nd Sub-Category: Social Stratification **Indicators: (1) Income, (2) Education Level**
Troy *et al.* (2007) examined the relationship between social stratification and

vegetation based on income and education levels in Baltimore, Maryland, and found that higher income neighbourhoods have more spaces for planting. A strong relationship between income and plant diversity have been found in other studies (Grove and Burch 1997; Iverson and Cook 2000; Kinzig *et al.*, 2005) stating that wealthy neighbourhoods exhibit high plant diversity because of the land use of the residents in the neighbourhood. Hope *et al.* (2003) reported that there is a significant relationship between plant diversity and family income indicating that wealthier households have much greater plant diversity than lower income households. This was explained by the financial opportunity of higher income households to migrate to more desirable and healthy places, such as near parks, furthermore, provide the maintenance of their elaborate gardens or support community green-space projects (Luck *et al.,* 2009). In their study Luck *et al.* (2009) also found a positive relationship between education level and vegetation cover that reflects the level of knowledge of land management and environmentally sensitive behaviours. Heynen (2006) investigated the relationship between changes in household income and urban forest canopy cover in Indianapolis. The results showed that increased household income brings about the gentrification of existing housing structures and amenities by leaving less space for trees, which results in the removal of trees. In contrast, lower income residents are likely to live in older neighbourhoods characterized by smaller houses with higher densities and low income areas are more likely to be located in or near to polluted areas (Pauleit *et al.,* 2005; Landry and Chakraborty, 2009).

Box 3.17 3rd Sub-Category

3rd Sub-Category: Lifestyle Behaviour

Indicators: (1) Family size, (2) Marriage Status

Grove *et al.* (2006) conducted a study in Baltimore, Maryland, which examined the impacts of household characteristics on the vegetation of urban ecosystems. They found that lifestyle behaviours, such as average family size, marriage status and percentage of single-family detached homes are important predictors of land cover change. They promoted a new term - ‘ecology of prestige’. Ecology of prestige refers to the phenomenon in which household environmental behaviours, consumption and expenditure are influenced by group identity and perceptions of

social status associated with different lifestyles. For instance, married households prefer living on the outskirts of the city and occupy more open spaces because of needing more space than single households. In addition, average household size and marriage rates are positively associated with tree cover. Married households with more children tend to plant and maintain more trees or chose to move to a neighbourhood with more trees (Pickett and Cadensasso, 2006; Troy *et al.*, 2007; Zhou *et al.*, 2009)

3.4 DATA COLLECTION AND ANALYSIS

This section introduces data collection and analysis of the MUSIX model, which is presented by three sub-headings: (1) normalisation and calculation of indicators, (2) multivariate analysis of indicators, and; (3) parcel-level spatial analysis.

3.4.1 NORMALISATION AND CALCULATION OF INDICATORS

In this study, each indicator has different measurement units which cannot be integrated equally in their original mode to generate a composite index. Therefore, the benchmarking normalisation method was employed to remove the scale effects of these different units by standardising the original indicator units to normalised units (Ebert and Welsch, 2004; Nardo *et al.*, 2005a). By reviewing various studies in the literature, benchmark values for each indicator were assigned according to their minimum and maximum impacts on environmental sustainability. Each indicator is expressed as a value between 1 and 5 indicating different levels of sustainability. Similar to the normalisation method chosen for the FEEM Sustainability Index (Carraro *et al.*, 2009), Figure 3.5 represents the definitions of these five reference levels.

5	**HIGH** (target level of sustainability)
4	**MEDIUM-HIGH** (satisfactory level of sustainability but not on target)
3	**MEDIUM** (a discrete level of sustainability)
2	**MEDIUM-LOW** (not sustainable but not as severely as in the previous level)
1	**LOW** (extremely unsustainable situation)

Figure 3.5 Benchmark based normalisation levels

Box 3.18 Indicator 1

Indicator 1: Evapotranspiration

Unit of measurement: %

Calculation: The evapotranspiration rate for each parcel was assigned based on the impervious surface ratio within the parcel. The impervious surface ratio was calculated by dividing the total impervious surfaces in a parcel by the total parcel area, as shown below:

$$ISR = \frac{IA_{total} * 100}{A_{Total\ area}}$$

Where: IA_{total} is the total impervious area within parcel, $A_{Total\ area}$ is the total parcel area.

Benchmark Values: The parameters of this indicator were derived from the U.S. Environmental Protection Agency (1993) study, which investigates the changes of evapotranspiration rates resulting from increased impervious surfaces (Figure 3.6).

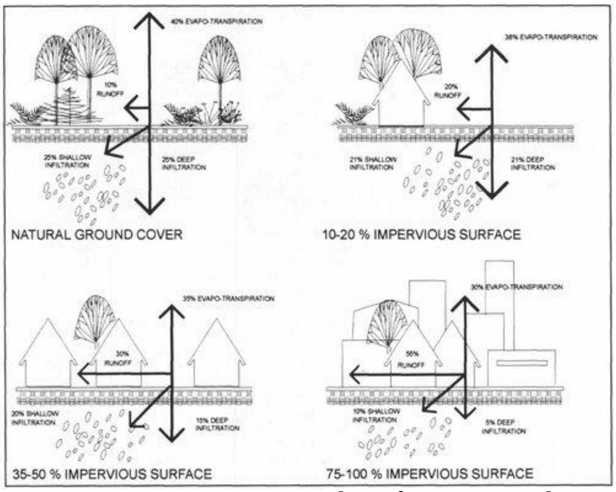


Figure 1 Changes in evapotranspiration rates resulting from increased impervious area (U.S. Environmental Protection Agency, 1993, p.46)

Benchmark values were assigned as shown below (Table 3.2):

Table 3.2 Normalisation values for evapotranspiration indicator

Evapotranspiration Rate (%)	Impervious Surface Ratio (%)	Benchmark Value
40	0 (Natural Ground cover)	HIGH
39	1-15	MEDIUM-HIGH
37	16-43	MEDIUM
33	44-88	MEDIUM-LOW
30	89-100	LOW

Limitations: In their study, the U.S. Environmental Protection Agency calculated evapotranspiration rates under four categories - natural ground cover, 10-20% impervious surface, 35-50% impervious surface and 75-100% impervious surface. However, impervious surface ratios were not contiguous. Therefore, five reference levels were assigned by taking the arithmetic mean of these evapotranspiration rates and impervious surface ratios.

Box 3.19 Indicator 2

Indicator 2: Surface Runoff

Unit of measurement: %

Calculation: Surface runoff rate for each parcel was calculated based on the 'composite runoff coefficient' formula, which has been used in a number of studies in the literature (Caltrans, 2001; ODOT, 2005; Nicklow *et al.*, 2006; City of Springfield, 2007). The runoff coefficient (C) is defined as the % of rainfall that becomes runoff. Composite runoff coefficient was generated by multiplying each surface type by its coefficient and then dividing the sum of these results by the total parcel area, as shown below:

$$C_{com} = \frac{\sum(C_{individual\ \ area})(A_{individual\ \ area})}{A_{total\ \ area}}$$

Where: $C_{individual\ \ area}$ is the runoff coefficient of each surface type, $A_{individual\ \ area}$ is the area of each surface type within parcel, and $A_{total\ \ area}$ is the total parcel area.

The runoff coefficient for each surface type was obtained from Table 3.3.

Table 3.3 Runoff coefficients

Type of Surfaces	**Ranges**	**Runoff Coefficients**	**References**
Tree cover	0.06-0.20	0.13	Lindeburg (1994)
Grass	0.05-0.35	0.20	ASCE/WEF (1992)
Barren soil	0.35-0.45	0.40	ASCE/WEF (1992)
Driveway/walkway/cycleway	0.75-0.85	0.80	Lindeburg (1994)
Pavement(asphalt, concrete, brick)	0.70-0.95	0.83	ASCE/WEF (1992)
Roof	0.75-0.95	0.85	ASCE/WEF (1992)

Benchmark Values: Benchmark values derived from Markart *et al.* (2006) were assigned as shown below (Table 3.4):

Table 3.4 Normalisation values for surface runoff indicator

Surface Runoff Ratio (%)	Benchmark Value
<10	HIGH
11-30	MEDIUM-HIGH
31-50	MEDIUM
51-75	MEDIUM-LOW
75<	LOW

Box 3.20 Indicator 3

Indicator 3: Urban Habitat

Unit of measurement: %

Calculation: The green area ratio is based on the calculation of the crown area of existing trees and shrubs. Low lying vegetation, such as perennials and grass, was not included. Green area ratio for each parcel was calculated by dividing the total green area in a parcel by the total parcel area, as shown below:

$$GAR = \frac{GA_{Total\ area}}{A_{total\ area}}$$

Where: $GA_{Total\ area}$ is the total green area within parcel, $A_{total\ area}$ is the total parcel area.

Benchmark Values: Benchmark values derived from Japanese green rating tool CASBEE (2007) were assigned as shown below (Table 3.5):

Table 3.5 Normalisation values for urban habitat indicator

Green Area Ratio (%)	Benchmark Value
50<	HIGH
41-50	MEDIUM-HIGH
31-40	MEDIUM
21-30	MEDIUM-LOW
<20	LOW

Box 3.21 Indicator 4

Indicator 4: Microclimate
Unit of measurement: %

Calculation: The albedo of different surfaces for each parcel was calculated based on the 'effective albedo' formula, which was derived from the study conducted by Taha *et al.* (1988). The effective albedo was generated by multiplying each surface type by its albedo value and then dividing the sum of these results by their total area as shown below:

$$EA = \frac{\sum(A_i * \propto_i)}{\sum A_i}$$

Where: A_i is the area of each surface type within parcel, $\propto_i$ is the albedo value of each surface type.

Trees and other plants provide a natural microclimate control through their cooling effects on higher urban temperatures. Therefore, they were excluded from the calculation due to their positive contribution to environmental sustainability. The albedo values for each surface type were obtained from Table 3.6.

Table 6 Albedo values

Type of Surfaces	**Ranges**	**Averages**	**References**
Roads (driveway/cycleway) (asphalt)	0.05-020	0.13	Oke (1978), Akbari *et al.* (1992)
Water surface (solar altitude between >10°C and >45°C)	0.05-0.22	0.14	German Solar Energy Society (2008)
Barren soil	0.17	0.17	German Solar Energy Society (2008)
Pavement	0.15-0.25	0.20	Akbari *et al.* (2009)
Building/roof	0.10-0.35	0.23	Taha *et al.* (1988)
Grass	0.25-0.30	0.28	Akbari *et al.* (1992)
Walkway (concrete)	0.25-0.40	0.33	Akbari *et al.* (2009)

Benchmark Values: As stated by Oke (1978, p. 247), the albedo value of urban surfaces are in the 10-27 range. Therefore, five reference levels were equally assigned in this range, as shown below (Table 3.7):

Table 7 Normalisation values for microclimate indicator

Effective Albedo (%)	Benchmark Value
27 <	HIGH
21.4-27	MEDIUM-HIGH
15.7-21.4	MEDIUM
10-15.7	MEDIUM-LOW
<10	LOW

Box 3.22 Indicator 5

Indicator 5: Stormwater Pollution

Unit of measurement: mg/L

Calculation: This indicator was calculated based on transport related to lead concentrations in the stormwater runoff. As mentioned previously, this PhD study is part of an ARC Linkage project, which investigates the transport related pollutants build-up and wash-off from road surfaces that are collected from 11 sites in the study area. In the scope of this project, for this indicator, stormwater pollution data were derived from the study conducted by Mahbub (2011). Among the various transport related pollutants, Lead (Pb) was chosen as being one of the prominent dangerous environmental heavy metal pollutants. Statistical and spatial analyses of grid cell level data for this indicator were performed by Dur (2012). This data were then disaggregated into parcel-level scale for this study using ArcGIS software.

Benchmark Values: Benchmark values were derived from water quality standards for drinking, recreational and irrigation developed by the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ 2000) and Australian Drinking Water Guidelines (NHMRC and NRMMC, 2004). Values were assigned as shown below (Table 3.8):

Table 8 Normalisation values for stormwater pollution indicator

Pb concentration (mg/L)	Benchmark Value
0.00-0.02	HIGH
0.03-0.10	MEDIUM-HIGH
0.11-0.20	MEDIUM
0.21-0.50	MEDIUM-LOW
0.51-1.00	LOW

Box 3.23 Indicator 6

Indicator 6: Air Pollution
Unit of measurement: μg/m³
Calculation: This indicator was calculated based on transport related lead concentrations in the air. In the scope of this project, for this indicator, air pollution data were derived from the study conducted by Gunawardena (2011). As in the previous indicator, the same statistical and spatial analyses and disaggregation procedure were applied for this indicator.

Benchmark Values: Benchmark values were assigned as shown below (Table 3.9):

Table 9 Normalisation values for air pollution indicator

Pb concentration (μg/m³)	Benchmark Value
0.000-0.050	HIGH
0.050-0.125	MEDIUM-HIGH
0.125-0.250	MEDIUM
0.250-0.375	MEDIUM-LOW
0.375-0.5	LOW

Table 3.24 Indicator 7

Indicator 7: Noise Pollution
Unit of measurement: dBA
Calculation: This indicator was calculated based on the road traffic noise in the study area. The method of calculation was adapted from the CORTN (calculation of road traffic noise) developed by the UK Department of Transport (DOT/Welsh Office, 1988). Calculation of this indicator at the grid cell level was performed by Dur (2012) and this data were disaggregated into the parcel-level scale by using ArcGIS software.

Benchmark Values: Benchmark values derived from Kloth *et al.* (2008) were assigned as shown below (Table 3.10):

Table 10 Normalisation values for noise pollution indicator

Traffic noise pollution (dBA)	Descriptions	Benchmark Value
<45	Excellent sound level (The threshold for sleep interference is 45 dBA)	HIGH
46-55	Good sound level (55 dBA is the level of a quiet suburban street)	MEDIUM-HIGH
56-65	Acceptable sound level (65 dBA is the level of normal conservation)	MEDIUM
66-75	Mediocre sound level (75 dBA is the level of a passenger car)	MEDIUM-LOW
76-90	Harmful sound level (90 dBA is the level of a heavy truck)	LOW

Box 3.25 Indicator 8

Indicator 8: Proximity to Land Use Destinations

Unit of measurement: NDAI score

Calculation: This indicator was calculated based on the accessibility of each parcel to land use destinations, which is located within 800 m walking distance by using the ArcGIS Network Analysis tool. Land use destinations are defined as the local services provided for the residents to visit regularly for their needs, such as shopping, education, recreation and health facilities. As recommended by similar studies (Austin *et al.*, 2005; Algert *et al.*, 2006; Witten *et al.*, 2011), an 800-metre distance was taken as the maximum threshold that residents in the neighbourhood will walk. For this indicator, the grid cell level data was obtained from another study, which was conducted by Dur (2012) as a part of the same ARC Linkage Project. This data were then disaggregated into the parcel-level scale.

Benchmark Values: Benchmark values were adapted from the Neighbourhood Destination Accessibility Index (NDAI) developed by Mavoa *et al.* (2009). The NDAI is a GIS tool that measures the pedestrian access to eight domains of neighbourhood destinations (education, transport, recreation, social and cultural, food retail, financial, health, other retail) within given boundaries (Witten *et al.*, 2011, p. 205). Weightings ranging from 2 to 5 were assigned to each domain based on their relative importance as a catalyst to physical activity (See Appendix 3.1). The weighted domain scores were then summed to produce a total neighbourhood destination index score (Mavoa *et al.*, 2009, p.16). The NDAI scores (varying between 0 and 135), which were modified by Dur (2012), were assigned as benchmark values for this indicator (Table 3.11).

Table 3.11 Normalisation values for proximity to land use destinations indicator

Access to local services (NDAI score)	**Benchmark Value**
103-135	HIGH
69-102	MEDIUM-HIGH
35-68	MEDIUM
15-34	MEDIUM-LOW
0-14	LOW

Box 3.26 Indicator 9

Indicator 9: Access to Public Transport Stops

Unit of measurement: meter

Calculation: The distance to the nearest public transport stop was calculated for each parcel by using the ArcGIS Network Analysis tool. As in the previous indicator, the same disaggregation procedure was applied for this indicator.

Benchmark Values: Benchmark values were adapted from the Land Use and Public Transport Accessibility Model (LUPTAI) developed by Yigitcanlar *et al.* (2007) and assigned as shown below (Table 3.12):

Table 3.12 Normalisation values for access to public transport stops indicator

Access to public transport (meter)	**Benchmark Value**
<200	HIGH
201-400	MEDIUM-HIGH
401-600	MEDIUM
601-800	MEDIUM-LOW
801<	LOW

Box 3.27 Indicator 10

Indicator 10: Walkability

Unit of measurement: points

Calculation: With this indicator, site walkability was investigated by looking at the design of streets, cycle and pedestrian ways. Points were assigned based upon achieved criteria for walkable street design, as shown in Figure 3.7.

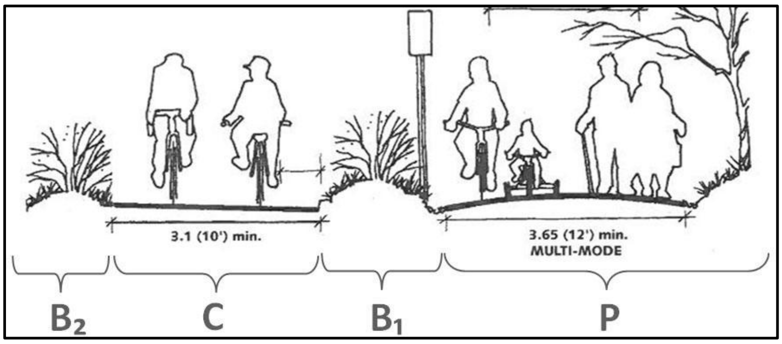


Figure 2 Walkable street design - Abbreviations: P (pedestrian way), B_1 (vegetative buffer zone), C (Cycleway), B_2 (buffer zone) (Watson *et al.*, 2003, p. 541)

Benchmark Values: Benchmark values were assigned as shown below (Table 3.13):

Table 3.13 Normalisation values for walkability indicator

Walkability	Benchmark Value
P + B_1 + C + B_2	HIGH
P + B_1 + C	MEDIUM-HIGH
P + B_1	MEDIUM
P	MEDIUM-LOW
None	LOW

Box 3.28 Indicator 11

Indicator 11: Lot Design

Unit of measurement: points

Calculation: With this indicator, passive solar design principles within the existing lot plan were investigated. Points were assigned based upon the principles of passive solar design met by the existing lot plan. Table 3.14 presents the efforts (one point per each effort on the list) that are evaluated for passive solar design in the climate of Australia. Figure 3.8 illustrates the appropriate lot designs to maximise solar access.

Table 3.14 Passive solar design principles (derived from King *et al.*, 1996; DEWHA, 2008)

Efforts to be evaluated	Benefits	Points
Lot shape: Rectangular	To get best solar access and most suitable for maximising lot yield	1
Building orientation: Long side E-W orientated	To maximise the best use of solar energy	1
Solar access: North facing living areas or outdoor spaces	To improve energy efficiency by providing access to winter sun	1
Zero lot line: houses set to south of lots	To reduce lot size, maximise solar access and outdoor living space	1
Attached housing: sharing walls with neighbours particularly on the E or W boundaries	To save energy and reduce greenhouse gas emissions	1
Location of other buildings: Avoid other buildings carports, sheds) on the northern side of the lot	To maximise the use of north facing living areas	1

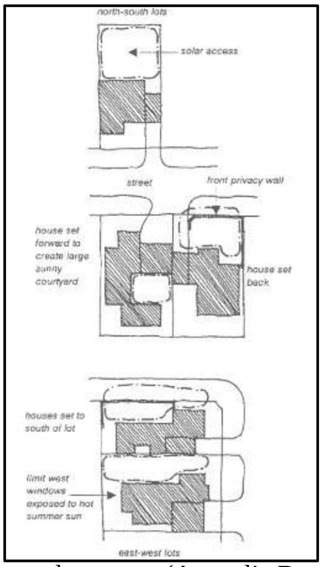


Figure 3.8 Lot designs to maximise solar access (Australia Department of Health & Community Services, 1995, p. 342)

Benchmark Values: Benchmark values were assigned as shown below (Table 3.15):

Table 3.15 Normalisation values for lot design indicator

Lot design	Benchmark Value
6 points	HIGH
4-5 points	MEDIUM-HIGH
3 points	MEDIUM
1-2 points	MEDIUM-LOW
0 point	LOW

Limitations: Natural green spaces were not included in the benchmarking of this indicator. Accordingly, the highest benchmark value was assigned as their sustainability score.

Box 3.29 Indicator 12

Indicator 12: Landscape Design

Unit of measurement: points

Calculation: With this indicator, subtropical landscape design principles within the existing parcel plan were investigated. Points were assigned based upon the principles of subtropical landscape design met by the existing parcel plan. Table 3.16 presents the efforts (one point per each effort on the list) that are evaluated for subtropical landscape design. Figure 3.9 illustrates the appropriate landscape design for subtropical climate.

Table 3.16 Subtropical landscape design principles (derived from Kennedy, 2010)

Efforts to be evaluated	Points
Southern side: No trees.	1
Northern side: Trees shading the north of buildings can reduce energy needs in summer by providing cooling. Depending on their height and distance from the building, such trees may need to be deciduous.	1
Eastern side: Trees shading the eastern sides of buildings cast shadows in the cooler morning hours.	1
Western and South-western sides: Trees shading the west and south-west of buildings reduce summertime energy demand for cooling by blocking the hot afternoon sun.	1

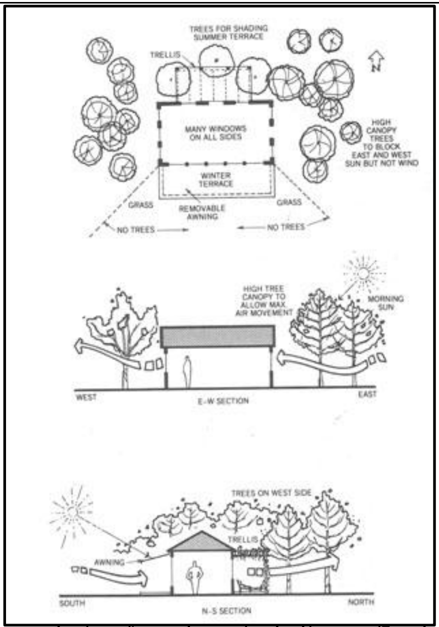


Figure 3.9 Landscape design for subtropical climate (Lechner, 2009, p. 336)

Benchmark Values: Benchmark values were assigned as shown below (Table 3.17):

Table 3.17 Normalisation values for landscape design indicator

Landscape design	**Benchmark Value**
4 points	HIGH
3 points	MEDIUM-HIGH
2 points	MEDIUM
1 point	MEDIUM-LOW
0 point	LOW

Limitations: Natural green spaces were not included in the benchmarking of this indicator. Accordingly, the highest benchmark value was assigned as their sustainability score.

Box 3.30 Indicator 13

Indicator 13: Energy Conservation

Unit of measurement: points

Calculation: With this indicator, energy efficient principles within the existing parcel plan have been investigated. Points were assigned based upon the principles of energy efficient design met by existing parcel plan. Table 3.18 presents the efforts (one point per each effort on the list) that are evaluated for energy efficient design.

Table 3.18 Energy efficient design principles (derived from Olgyay, 1963; Hyde, 2000)

Efforts to be evaluated	Points
Create an outdoor living space such as courtyard, verandas, balconies	1
Use of renewable energy such as photovoltaic panels, solar water heating	1
Use of light-coloured roof	1
Use of light-coloured paving	1

Benchmark Values: Benchmark values were assigned as shown below (Table 3.19):

Table 3.19 Normalisation values for energy conservation indicator

Energy conservation	Benchmark Value
4 points	HIGH
3 points	MEDIUM-HIGH
2 points	MEDIUM
1 point	MEDIUM-LOW
0 point	LOW

Limitations: Natural green spaces were not included in the benchmarking of this indicator. Accordingly, the highest benchmark value was assigned as their sustainability score. Moreover, it has to be mentioned that household energy usage data is one of the essential parameters required for defining the energy efficiency of the parcel. However, this data could not be provided due to privacy issues.

Box 3.31 Indicator 14

Indicator 14: Water Conservation

Unit of measurement: points

Calculation: With this indicator, water efficient principles within the existing parcel plan have been investigated. Points were assigned based upon the principles of water efficient design met by existing parcel plan. Table 3.20 presents the efforts (one point per each effort on the list) that are evaluated for water efficient design.

Table 3.20 Water efficient design principles (derived from Olgyay, 1963; Hyde, 2000)

Efforts to be evaluated	Points
Use of green roof	1
Reuse of water (rainwater tank)	1
No pool or other water features	1
Estimated Irrigation water use does not exceed the residential water consumption target implemented by the Queensland Water Commission	1

Benchmark Values: Benchmark values were assigned as shown below (Table 3.21):

Table 3.21 Normalisation values for water conservation indicator

Water conservation	Benchmark Value
4 points	HIGH
3 points	MEDIUM-HIGH
2 points	MEDIUM
1 point	MEDIUM-LOW
0 point	LOW

Limitations: Natural green spaces were not included in the benchmarking of this indicator. Accordingly, the highest benchmark value was assigned as their sustainability score. Moreover, it has to be noted that indoor and outdoor household water usage data is one of the essential parameters required for defining the water efficiency of the parcel. However, this data could not be provided due to privacy issues. Instead of this data, estimated irrigation water use was added as a parameter in order to predict outdoor water demand. Irrigation water use for each parcel was calculated based on forecasting the amount of water required for the irrigation of total garden area. As stated in Queensland Water Commission's efficient irrigation for water conservation guideline (2011, p.6), a well-designed garden requires around 10 mm of water each week to sustain growth. In this context, 10 mm was chosen for

the calculation of water demand. Each parcel gets one point if their estimated irrigation water use (litres/week) does not exceed the residential water consumption target implemented by the Queensland Water Commission.

3.4.2 MULTIVARIATE ANALYSIS OF INDICATORS

As stated by Nardo *et al.* (2005b), if the indicators are chosen arbitrarily without investigating the interrelationships between them, the index result can lead to overwhelming, confusing and misleading decisions by policy-makers. This situation can be characterised as ‘indicator rich but information poor’. Therefore, the underlying structure of the data needs to be examined before the construction of composite index. For the next step, a statistical analysis was employed. This step designates whether the theoretical framework of the index is well defined and the selected indicators are appropriate to describe the measured phenomenon (Nardo *et al.*, 2005a).

Firstly, a Kolmogorov-Smirnov test was performed by using PASW Statistics 18 in order to investigate the distribution of the indicator data set (See Appendix 3.2). As a result of the non-normal distribution of data set, the Spearman’s rank correlation method was chosen. Spearman’s rank correlation analysis was conducted to examine the relationship between the indicators with reference to a number of similar studies (e.g. Pinho and Manso Orgaz, 2000; Srinivasa Raju *et al.,* 2000; Saltelli *et al.,* 2004; Dramstad *et al.,* 2006; Schulman and Peters, 2008; Can *et al.,* 2011; Rinner and Hussain, 2011). As stated by Rubin (2010, p.131), the *p* value indicates a sufficiently low probability that the results were produced by sampling error. Due to the large data set, the level of significance was set at 0.05 indicating a 5% chance that the results may have occurred due to random error or chance. Furthermore, a two-tailed test was chosen to identify the level of significant differences between the indicator data set in either direction.

The correlation between the indicator data set is presented in Table 3.22. The highly correlated indicators are highlighted in bold. The correlation coefficient (r) is a measure of linear association between variables that indicates the direction and strength of the relationship varying between -1 and +1 values (Mac an Bhaird, 2010, p.50). A number of studies (Katz, 1999; Lehman *et al.*, 2005; Morien, 2006;

Christmann and Badgett, 2009) state that below 0.8 is a moderate value of correlation. Specifically, a very high correlation was found between (‘evapotranspiration’ and ‘surface runoff’, r=0,734), (‘stormwater pollution’ and ‘air pollution’, r=0,648) and (‘proximity to land use destinations’ and ‘access to public transport stops’, r=0,731) indicators which may lead to a risk of double counting. Despite these correlated indicator couples are in the same indicator sub-category, they measured different variables by using different calculation methods. Furthermore, the correlation analysis was conducted based on the normalised indicator values; hence, it was expected to see a high correlation between the scores. Additionally, based on the literature, these correlations can be interpreted as follows:

- Large amounts of impervious surfaces *(ISR)* are associated with increased surface runoff *(SR)*,
- Stormwater pollution *(SW)* is associated with air pollution *(AIR)*, which means transport related pollutants become washed off during a rainfall from paved surfaces by causing stormwater pollution.
- Proximity to land use destinations *(LUD)* is related with access to public transport *(PT),* which means sustainable mobility encourages public transport by providing easier access and shorter times to get to the destination.

Table 3.22 Spearman correlation coefficients of the indicator data set

	ISR	SR	SW	AIR	NOISE	GAR	EA	LUD	PT	WLK	LOTDSG	LNDDSG	ENERGY	WATER
ISR	1.000													
SR	**,734****	1.000												
SW	,005	,062**	1.000											
AIR	,075**	,120**	**,648****	1.000										
NOISE	-,034	-,040**	,290**	,304**	1.000									
GAR	,271**	,327**	,036	,023	-,132**	1.000								
EA	,070**	,044**	-,018	,013	,066**	-,109**	1.000							
LUD	-,099**	-,041**	,137**	,109**	-,169**	-,012	-,035	1.000						
PT	-,079**	,009	,244**	,089**	-,105**	,064**	-,051**	**,731****	1.000					
WLK	-,075**	-,062**	,086**	,014	-,059**	,058**	-,021	,177**	,188**	1.000				
LOTDSG	,301**	,256**	-,117**	-,053**	-,093**	,014	,070**	-,114**	-,161**	,032	1.000			
LNDDSG	,460**	,445**	-,137**	-,036	-,190**	,427**	,000	-,157**	-,113**	-,014	,340**	1.000		
ENERGY	,282**	,250**	,022	,110**	,060**	,016	,068**	-,065**	-,053**	-,011	,306**	,271**	1.000	
WATER	,241**	,234**	,212**	,216**	,127**	-,249**	,114**	,150**	,062**	,010	,261**	,044**	,216**	1.000

**. Correlation is significant at the 0.05 level (2-tailed) , n=2843

Abbreviations: Impervious surface ratio (ISR), surface runoff (SR), stormwater pollution (SW), air pollution (AIR), noise pollution (NOISE), green area ratio (GAR), albedo (EA), land use destinations (LUD), public transport (PT), walkability (WLK), lot design (LOTDSG), landscape design (LNDDSG), energy consumption (ENERGY), and water consumption (WATER).

3.4.3 PARCEL-LEVEL SPATIAL ANALYSIS

As a result of urbanisation, natural ecosystems have been significantly modified and covered with impervious surfaces due to vegetation removal, soil compaction, ditching, draining and filling of wetlands (Hill *et al.,* 2003). Higher levels of impervious surfaces result in increased runoff with higher peak discharge, poor water quality, depleted vegetation, transformation of the global carbon and hydrologic cycle and climate change (Barnes, 2001). Therefore, the percentage of impervious surface emerges as an important environmental indicator to monitor the degree of urbanisation severity on natural ecosystems (Arnold and Gibbons, 1996). Remote sensing is an important source of mapping the percentage of impervious surface area.

As stated by Oluseyi *et al.* (2009), in recent years, remote sensing and geographic information systems have become effective tools in the transformation of multi-spectral, multi-resolution and multi-temporal data into valuable information for monitoring environmental processes and impacts. Remote sensing provides information concerning the changes on the Earth's surface over a wide range of spatial (local to global) and temporal (years to decades) scales (Baumgartner and Apfl, 1996). With an effectively integrated geographic information system, remotely sensed data offers resource managers and decision-makers storage and manipulation of information in spatial and non-spatial domains as well as assists in the measuring, mapping and modelling activities (Estes, 1992).

Spatial analysis of the study area was carried out through aerial remote sensing data with the use of ArcGIS software. From visual and digital interpretations of the aerial photo imagery derived from Google Maps™, the total area of each land cover type within parcels were measured by using the ArcGIS Analysis tool. The land cover classficiation was based on nine main types: (1) roof-building; (2) pavement; (3) driveway; (4) cycleway; (5) walkway; (6) tree-shrub; (7) water; (8) turf-grass, and; (9) barren soil. Figure 3.10 demonstrates an example of a land cover measurement in a parcel taken from the study area. As seen from the example, the total area of each land cover type was calculated seperately.

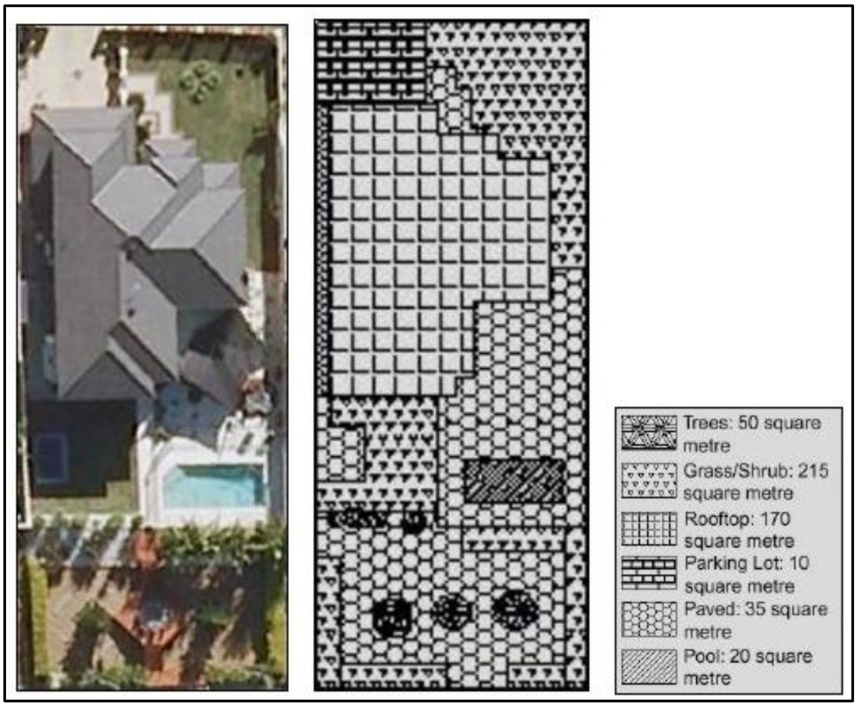


Figure 3.10 Example of a land cover measurement in a residential parcel (Dizdaroglu *et al.*, 2010)

Data limitations: As the measurement was done through aerial photography, some challenges have occurred during land cover detection. For some residential areas, the images were not detectable due to poor spatial accuracy, poor weather conditions, and shadowing issues. Cost and time-efficient solutions were implemented for the success of the study:

- The land cover measurement was based on the uppermost surface area, which is visible in the aerial photo.
- Because of the overlapping problem, trees and shrubs were measured under one category as ‘tree-shrub’.
- Because of poor data resolution, different pavement types could not be detected in the study area; therefore, they were measured under one category as ‘pavement’.
- Driveways were divided into two equal parts and each part was included in the measurement of parcel area, which is located along the side of the road.
- Because of the residential character of the area, water surface category included man-made water bodies, such as swimming pools and garden ponds.
- Natural water bodies (i.e., creeks, streams) and large artificial water bodies (i.e., canals, reservoirs, recreational lakes) were not included in the measurement.

3.5 MODEL DEVELOPMENT AND APPLICATION

This section provides an outline of the MUSIX model development and application stages, which is presented by three sub-headings: (1) indicator weights based on expert opinion, (2) parcel-level calculation of the indicators, and; (3) aggregation of parcel-level scores into a composite index score.

3.5.1 INDICATOR WEIGHTS BASED ON EXPERT OPINION

In composite indices, indicator weighting reflects the importance given to the variables forming the index. During the calibration process, pilot studies were conducted with equal weightings in order to test the capabilities and accuracy of the model. Moreover, a series of workshops were organised with the team of ARC Linkage project experts, researchers and local government policy-makers to provide their professional opinion about selected indicators. In these workshops, participants were asked to provide their professional opinion about the relevance of selected indicators. They were asked to comment on whether the indicators were: (1) too specific and needed to be merged as new indicators or with another indicators in the list; (2) too general and needed to be defined more specifically; or (3) irrelevant and needed to be removed from the list.

The construction of composite indicators consists of different stages (i.e., analytical approach, weighting criteria, aggregating technique, and sensitivity analysis). Each stage is subjective, which requires selecting an appropriate methodological approach (Maggino and Ruviglioni, 2009). One of the key tasks is to select appropriate weighting criteria. Indicators need to be chosen carefully so that they reflect the environmental issues and measure the environmental performance of the study area effectively. As a result of the subjective nature of indicator selection, expert survey allows experts from various backgrounds to agree on a consensus view of the relative importance of the indicators based on their experience and subjective judgment. For this study, expert opinion weighting was selected due to the spatial scale and scope of the research. First of all, the MUSIX model is developed to measure the local-level environmental performance of an urban area. In this sense, consultation of local expert’s opinion helps to reflect the implications of the current planning policies, local environmental issues and needs of the study area. Secondly, the MUSIX model is developed as an assessment tool to serve in policy and decision-making processes. In this sense, the model results are highly benefited from the input from developers, planners and policy makers that consist of the expert survey participants. Expert judgment has been used in a number of studies, including Environmental Performance Index (Esty *et al.*, 2006), Environmental Sustainability Index (ESI, 2005), Eco-indicator 99 (Pre Consultants, 2004), E-Business Readiness Index (Pennoni *et al.*, 2006), Urban Sustainability Index (Zhang, 2002), and Index of Environmental Friendliness (Puolamaa *et al.*, 1996).

In the next step, weightings for the indicators were assigned via expert survey. A total number of 21 experts participated in the survey. The participants comprised academics, planners, engineers and architects who are familiar with policy priorities and theoretical background. Participants were chosen from the industry partners of the ARC Linkage project: Queensland Transport and Main Roads (n=7) and Gold Coast City Council (n=7) and Queensland University of Technology (n=7). Purposive sampling was used to select the experts for this study, which means that industry partner representatives were asked to suggest appropriate contact persons. The invitation letters were sent by email (See Appendix 3.3). The interview times and locations were arranged that were most convenient for participants.

The survey comprised of two stages. The first stage consisted of a demonstration survey showing snapshots from various parcels (with their equally weighted indicator scores) in the selected case study areas (See Appendix 3.4). Each participant was asked to assign a sustainability level for each parcel using a five-point Likert scale (1=low, 5=high), by analysing the aerial photos and indicator scores. This survey was designed to make participants more familiar with the calculation and interpretation of the indicators. Therefore, the results were not included in the study.

For the second stage, a ranking survey sheet (which consists of two steps) was prepared (See Appendix 3.5). In the first step, each participant was asked to rate the importance of each indicator in terms of its contribution to environmental sustainability assessment using a five-point Likert scale as follows:

1. *Not important:* Does not affect the assessment of environmental sustainability.

2. *Slightly important:* Affects the assessment of environmental sustainability in a minor way.
3. *Moderately important:* Affects the assessment of environmental sustainability in a moderately way.
4. *Important:* Essential and affects the assessment of environmental sustainability in a significant way.
5. *Very important:* Very essential and affect the assessment of environmental sustainability in an extremely significant way.

In the second step, each participant was asked to assign a weight using the budget allocation method by allocating a total of 100 points to each sub-category in terms of their importance in the model and for each indicator in terms of their importance in the sub-category. First, weightings for sub-categories were calculated by dividing the sum scores of each sub-category by the total sum score of all sub-categories and then the result was multiplied by 100 to provide a percentage weighted score. Second, weightings for indicators were calculated by dividing the sum scores of each indicator by the total sum score of all indicators in the same sub-category and then the result was multiplied by the sub-category's weighted score. Lastly, these scores were rescaled between 0 and 1, as illustrated by a chart in Figure 3.11.

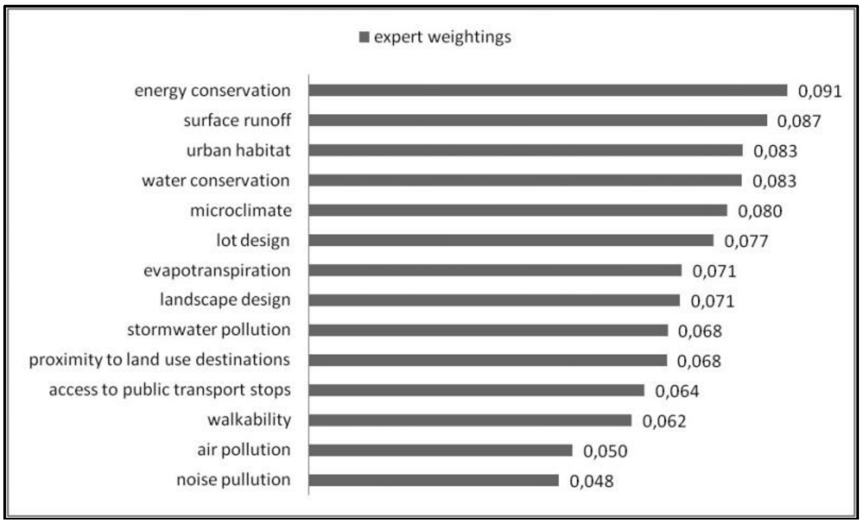


Figure 3.11 Rescaled expert weightings

Afterwards, statistical analysis of the participant's responses was computed using PASW Statistics 18. A descriptive analysis and Cronbach's alpha reliability test were conducted to identify the central tendencies of data (See Appendix 3.6). The

Cronbach's alpha reliability test is used to measure the internal consistency of the data. The Cronbach's alpha result (α = 0.824) was over the acceptable reliability threshold stated by George and Mallery (2003). The descriptive analysis showed the average of all participants' level of agreement per indicator (mean, median, and mode) and the distribution of the respondents` score that fell within the scale (frequency distribution). Furthermore, the standard deviation showed the average amount that respondent's ratings varied from the mean and indicated the varied view between respondents.

Table 3.23 Mean relevance rate, rescaled weightings and ranking of indicators

Indicators	Relative importance	Expert weightings	Ranking
Energy conservation	4,38	0,091	1
Surface runoff	4,24	0,087	2
Urban habitat	4,14	0,083	3
Water conservation	4,14	0,083	3
Microclimate	4,10	0,080	5
Lot design	3,95	0,077	6
Evapotranspiration	3,81	0,071	7
Landscape design	3,81	0,071	7
Stormwater pollution	3,76	0,068	9
Proximity to land use destinations	3,76	0,068	9
Access to public transport stops	3,67	0,064	11
Walkability	3,62	0,062	12
Air pollution	3,52	0,050	13
Noise pollution	3,48	0,048	14

Tables 3.23 present the mean relevance rating, rescaled weightings and ranking of indicators based on their relative importance. The results shown in Table 3.2 indicate that experts assigned 'energy conservation' as the most important indicator and they assigned 'noise pollution' as the least important indicator. Moreover, the results show that all indicators met the minimum required relevance rate of 3 and above so that they were confirmed by experts as key components in environmental sustainability assessment.

3.5.2 PARCEL-LEVEL CALCULATION OF THE INDICATORS

Increased population, resource consumption and environmental pressures draw great attention to effective management of land by developing environmental policies. To ensure the best use of land as well as meet the demands of future developments, up to date and more detailed information about land characteristics needs to be collected and processed (Derby, 2007). Parcel-based data provide comprehensive land related information, which helps to: (1) provide a detailed analysis of environmental impacts, (2) improve the quality of infrastructure and utilities, (3) manage the sustainable use of resources, and; (4) implement efficient land use policies (Tuladhar, 2004).

The spatial data unit for this study is the land parcel, which is defined by WG-CPI (2006, p.1) as *a single area of land or more particularly a volume of space, under homogeneous real property rights and unique ownership.* Parcel-based spatial analysis collects reliable and accurate land use information for planners and policy-makers. It provides a spatial link between different geographic land use information through an efficient infrastructure network environment. It identifies detailed information regarding the pattern and extent of urban development in the neighbourhood, such as location, topographical description, land ownership, land use and resources, and economic value (Tuladhar, 1996).

In this step, an indicator score for each parcel was calculated by their formula using Microsoft Office Excel 2007 and ArcGIS software. Each parcel was scored using a five-point Likert scale, which represents its environmental sustainability performance regarding each indicator. As an example of the parcel-level calculation, the sustainability performance of case study site 2 is presented in Figure 3.12. Afterwards, expert weightings were applied to these raw indicator scores. These parcel-level indicator scores were then aggregated linearly into 100 x 100 metre grid cells to give the final composite index score, as explained in the next section.

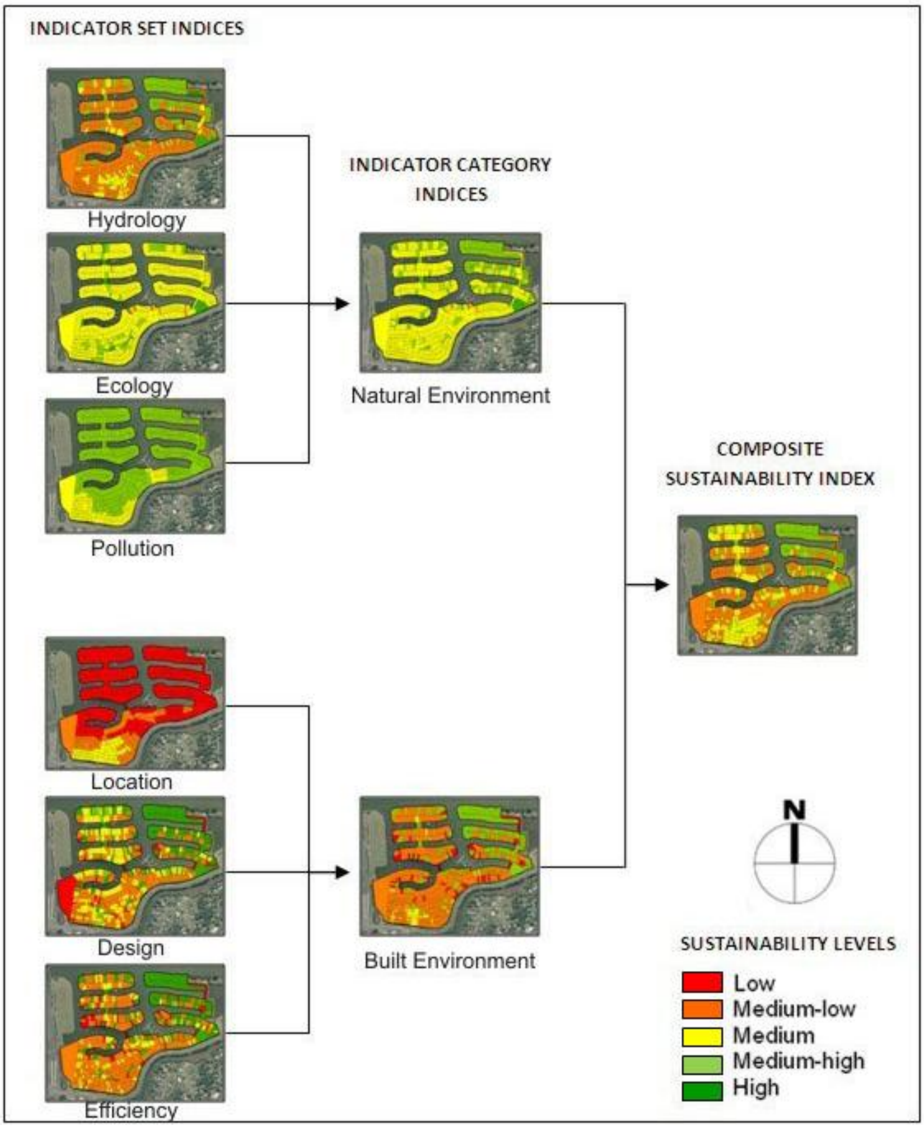


Figure 3.12 Parcel-level sustainability performance of case study site 2

3.5.3 AGGREGATION OF PARCEL-LEVEL SCORES INTO A COMPOSITE INDEX SCORE

- *Arithmetic Aggregation*

As the next step, aggregation was necessary in order to combine multi-dimensional indicator scores to form a single meaningful composite index. Many aggregation methods are available, such as additive aggregation, geometric aggregation or non-linear techniques (e.g., multi-criteria analysis). Each technique involves different assumptions and has specific outcomes. The choice of an appropriate method depends on the underlying theoretical framework of the composite index and data properties. (Nardo *et al.*, 2005b; ESI, 2005). The additive aggregation was used in a number of studies, including the Ecological Footprint

(Wackernagel and Rees, 1996), Human Development Index (UNDP, 2005), Environmental Sustainability Index (ESI, 2005), Environmental Performance Index (Esty *et al.,* 2006), Environmental Vulnerability Index (SOPAC, 2005), Index of Sustainable Economic Welfare (Cobb, 1989), Genuine Savings Index (Pearce and Atkinson, 1993), Composite Leading Indicators (OECD, 2002).

The additive aggregation method is useful when all indicators have normalised measurement unit. Furthermore, additive aggregation has the ability to compensate the low performance of some indicators by higher values of other indicators by using weights as relative trade-offs between them (Ebert and Welsch, 2004; Nardo *et al.,* 2005a). In the MUSIX model, the relationship between indicators is compensatory. The state of environment is expressed in a variety of indicators by measuring different aspects of environmental changes. Therefore, additive aggregation is more appropriate for assessing their composite environmental impacts by combining their weighted standardised scores.

Additive aggregation is basically the arithmetic average of the weighted and normalised indicator scores. The composite index score was calculated by the following formula:

$$MUSIX\ model\ score = \sum_{i=1}^{n} w_i \, . \, x_i$$

Where *n* is the number of indicators, w_i is the weight for indicator i, and x_i is the normalised indicator value.

Finally, the composite index score was presented in five comparative sustainability levels: low (0.00-1.00), medium-low (1.01-2.00), medium (2.01-3.00), medium-high (3.01-4.00), and high (4.01-5.00).

- *Spatial Aggregation*

As defined by Rao (2012), spatial aggregation is the process of grouping spatial data at a level of detail or resolution that is coarser than the level at which the data were collected. A spatial aggregation was needed for the data integration with the ARC Linkage Project. After arithmetic aggregation, the study area was divided into 100 x 100 metre grid cells and ArcGIS software was used to transfer this parcel-level aggregated composite index score into grid cell score. Figure 3.13 demonstrates an example of spatial aggregation for a grid cell from a case study site. As seen from the example, each parcel's composite index score was multiplied by its % area within the grid cell and then summed into a single composite score for each grid cell. As a limitation of this aggregation process, some of the edge grid cells were not fully calculated because of the case study's site boundaries. For this reason, spatial aggregation for these grid cells was conducted by considering the parcels within the site boundary, as shown in the example in Figure 3.14.

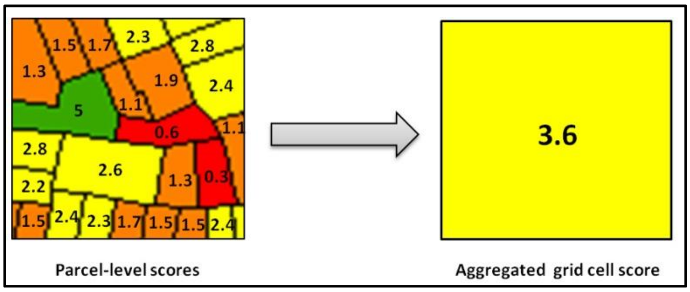


Figure 3.13 Example of spatial aggregation for a grid cell

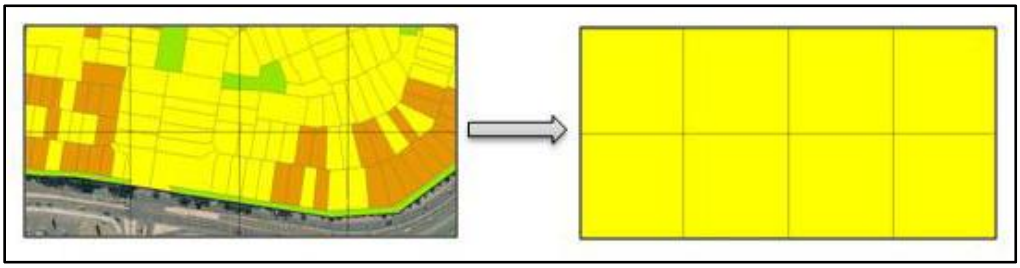


Figure 3.14 Example of spatial aggregation for edge grid cells

The aggregation of geographical data is widely used in the analysis of urban systems. However, there are many challenges, such as the Modifiable Areal Unit Problem (MAUP), which is a widely recognised spatial analytical issue that affects the results of such analyses due to the scale or zoning of the space (Paez and Scott, 2004). For instance, if the areal units are too small the results might not be meaningful, in contrast, if they are too big the results might not be accurate. Therefore, an interim scale is necessary in order to avoid detection issues.

In this study, the MUSIX model investigated the environmental impacts at a micro-level in which parcels were used as spatial units. However, in addition to parcel-level information, the outcomes of this study were also presented at the grid cell level. The advantage of providing information at grid cell level was to easily integrate the parcel-level model outputs with the different scale assessment tools in the local planning process. A grid cell size of 100 metres was chosen. In order to investigate the sensitivity of the changes that occurred from different spatial scales, a study was conducted by one of the PhD researchers of the ARC Linkage project. Descriptive statistics of aggregated data were performed for 50, 100 and 150 metre grid cell sizes. The details of this analysis can be found in Dur (2012). Eventually, a 100 metre grid cell was selected as the spatial unit based on the acceptable results from the analysis.

3.6 POLICY DEVELOPMENT

The MUSIX model serves as an environmental performance assessment tool for local governments and planning agencies, moreover, the outcomes of the model can be a useful guide in the development of relevant policies and strategies for both current and future developments. The MUSIX model combines the information derived from the six theoretical pillars of environmental sustainability (hydrological conservation, ecological protection, environmental quality, sustainable mobility, environmental design and renewable resources) into a single measure. The results provide useful information that can be used in sustainability assessment and benchmarking of urban settings as well as guide the development of sustainable urban policies. As a future direction of this study, the model can also be used for alternative future scenarios for the decision-making process.

In this step, the results of the MUSIX model and policy applications were presented. The model results detected the sustainability performance of current urban settings referring to six main issues of urban development: (1) hydrology, (2) ecology, (3) pollution, (4) location, (5) design, and; (6) efficiency. For each category, a set of core indicators were assigned which are intended to: (1) benchmark the current situation, strengths and weaknesses; (2) evaluate the efficiency of implemented plans, and; (3) measure the progress towards sustainable development. Finally, in light of the model findings, integrated ecological planning strategies were developed for the local government planning scheme. These strategies include: sustainable stormwater management, healthier urban environment, sustainable urban habitats, better public services and transportation, environmentally sustainable design and efficient communities.

3.7 SUMMARY OF THE CHAPTER

In this chapter, the research design for this study is discussed. The methodologies and strategies undertaken within the scope of the research are identified and interpretation of their results is presented. Furthermore, this chapter introduces an indicator-based indexing model entitled 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX). The MUSIX model consists of a set of micro-level environmental sustainability indicators that is aimed to be used in the evaluation and monitoring of the impact of existing development plans on urban ecosystems. The model is designed to assess the resilience of urban ecosystems towards human activities and the results serve as a guide for policy-makers to take actions in achieving sustainable development. A multi-method research approach, which is based on both quantitative analysis and qualitative analysis, is employed in the construction of the MUSIX model. First, a qualitative research was conducted through interpretive and critical literature review in developing the theoretical framework and indicator selection. Afterwards, a quantitative research was conducted through statistical and spatial analyses in data collection, processing and model application.

The model includes 14 indicators which are organized into six sub-categories and finally combined into two main categories. These indicators that were chosen from a variety of sustainability indicator databases monitor the major environmental issues in the study area. As indicators were expressed in a variety of units, the benchmarking normalisation method was employed to remove the scale effects. Afterwards, Spearman's rank correlation analysis was conducted to investigate the relationship between the indicators. Then, different weights were assigned to the indicators through expert judgment in order to identify their relative importance in the model. After the weighting process, each parcel was scored using a five-point Likert scale, which represents its environmental sustainability performance regarding each indicator and these scores were then arithmetically aggregated into an overall composite index. Lastly, sensitivity analysis was undertaken to assess the robustness of the model. The model was tested in four pilot study sites selected from the Gold Coast City, Queensland, Australia. The next chapter presents the findings of the model implementation.

Chapter 4: Implementation of the MUSIX Model

This chapter presents the results of the 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX) model implementation to the Gold Coast City study area. The chapter comprises four main sections. The first section provides a general description of the Gold Coast City including its physical, natural and socio-economic characteristics, environmental challenges, existing planning strategies and the characteristics of the four pilot study sites selected from Upper Coomera and Helensvale suburbs. The second section discusses the parcel-level sustainability scores for each indicator from the pilot study sites. The third section provides an outline of the current situation by discussing the grid-based composite index scores. The fourth section presents the analysis for the sensitivity of the model, and, finally, the fifth section concludes with a summary of the chapter.

4.1 GENERAL DESCRIPTION OF THE GOLD COAST CITY

In order to test the performance of the MUSIX model, Gold Coast City has been selected as the study area. As mentioned previously in the introduction chapter, the main reason for choosing this particular location is that this study is a part of an Australian Research Council Linkage (ARC) Project - *Adaptation of Water Sensitive Urban Design to Climate Change, Changing Transport Patterns and Urban Form* - and Gold Coast City was chosen as the test bed for this project. This section provides a general description of the Gold Coast City and four pilot study sites.

4.1.1 PHYSICAL AND NATURAL CHARACTERISTICS

Gold Coast City (GCC) is located in the South East of the state of Queensland, Australia. The city is the sixth largest city in Australia and covers an area of 1,378 square kilometres with its rapidly growing population and urban settlements. The GCC is a linearly developed city running parallel to the ocean, which consists of a beach strip connected with high rise residential areas, highways, canal estates, suburbs and semi-rural hinterland (Griffin, 2002). The existing land use pattern of the city includes a coastline with a high density residential and tourism accommodation surrounded with low-density housing developments, industrial areas, commercial activity centres and developing knowledge precincts (GCC Council, 2008a).

The topography of the GCC is a coastal plain that includes beaches, dunes, river deltas, bays, estuaries and wetlands, rolling foothills and low mountain ranges. The city has a subtropical climate with an average of 287 days sunshine annually. The average summer temperatures are 19 to 29 °C and the average winter temperature is 9 to 21 °C. A wide range of landscapes and habitats, ranging from mangroves to eucalyptus woodlands and rainforests, create diverse habitats for flora and fauna. Over 1,550 species of native plant have been identified, as well as, more than 323 species of bird, over 105 species of reptile and amphibian and over 72 species of mammal. Furthermore, 1,600 different marine species have been identified in the Gold Coast waters. The city has also many important natural parks, conservation areas (i.e., South Stradbroke Island) and world heritage sites that are protected from development pressures (GCC Council, 2006, 2012a). The GCC has a diverse soil type and terrain that provides many subtropical ecosystem units which are summarised in Table 4.1.

Table 4.1 The GCC ecosystems (derived from GCC Council, 2012b)

Ecosystem Units	**Habitats**
Estuaries and inlets	• Vegetated habitats (mangroves, sea grass and salt marshes) • Hard surfaces (reefs, rocky shores, rocky outcrops, sea walls, pontoons and jetties) • Non-vegetated soft sediment habitats (sub-tidal soft sediment, coastal beaches and mud flats) • Open water (pelagic)
Islands	• Mangroves • Salt marshes • Mudflats • Sandbanks • Open waters • Coastal woodland • Open forest • Rainforest • Sand dunes and beach ridges
Hinterlands	• Mountains and hills • Bushlands • Eucalypt woodland and forest • Rainforest • Melaleuca woodland and forest

4.1.2 SOCIO-ECONOMIC CHARACTERISTICS

As noted by Stimson and Minnery (1998, p. 196), the GCC can be presented with four images; "*a city of leisure; a city of enterprise; a city of tourism; and a city in its own right within the South East Queensland 'sun-belt' growth metropolis"*. The city is an attractive immigration destination for business and trades people moving from other parts of Australia. The estimated resident population (as at 30 June 2011) was 527.828 and the population density is 395.7 persons / km² (Australian Bureau of Statistics, 2006). The community profile of the GCC based on the 2006 Census of Population and Housing published by the Australian Bureau of Statistics can be summarised as follows (GCC Council, 2009a):

- 22% of the population was aged between 0 and 17, and 20.9% were aged 60 years and over,
- 24.7% of the population was born overseas, and 9.4% were from a non-English speaking background,
- 15.3% of the population earned a high weekly individual income, and 38.2% earned a low weekly individual income,
- 19.7% of the households earned a high weekly income, and 17.5% were low income households,
- 37.2% of the population held educational qualifications, and 46.7% had no qualifications,
- 94.8% of the labour force was employed, and 5.2% was unemployed,
- The three most popular industry sectors were: retail trade (16.8%), construction (11.6%), and property and business services (11.4%),
- 2.9% used public transport, while 72.9% used a private vehicle,
- 81.7% of the households owned at least one car, while 7.3% did not,
- 40.4% of total families were couple families with child(ren), and 16.6% were one-parent families,
- There were 23.1% of lone person households, and 22.6% of larger households,
- 50.4 % occupied a separate house; 21.3 % occupied a medium density dwelling; while 14.9 % occupied high density dwellings.

4.1.3 ENVIRONMENTAL STATE, PRESSURES AND RESPONSES

As a tourist attraction and vibrant economic hub, the GCC confronts major environmental problems depending on its high population growth rate, expanding urban development and transport infrastructure. These environmental pressures have significant impacts on coastal environments and water resources. According to the Commonwealth Scientific and Industrial Research Organisation (CSIRO, 2007) studies, in the coming years, the number of dry days in the GCC is expected to be extended and precipitation events are expected to be more intense, which will bring extreme drought and flood events. Furthermore, as most of the population live on reclaimed dunes, coastal areas and constructed canal estates, the residential pressures is expected to be even heavier than today's (Baum *et al.*, 2009). Beach erosion and high waves from tropical cyclones are already an environmental issue that threatens the infrastructure along the Gold Coast (Voice *et al.*, 2006).

The Gold Coast City council works to preserve and protect the natural environment through a range of strategies, programmes and regulations. The city council recently published 'Our Living City Report' that presents the state of the environment in its three basic dimensions: economic, social, and ecological. The report is based on a 'Pressure-State-Response' framework, which is adapted from the approach of the Organization for Economic Cooperation and Development (OECD). The report outlines the pressures on the state of the environment as well as introduces the federal, state and regional actions taken towards these problems. The ecological dimension of this framework is briefly presented in Table 4.2. The rest is presented in the next section in the Gold Coast Planning Scheme.

Table 4.2 Environmental state, pressures and responses (derived from GCC Council, 2006)

State	Pressures	Responses
Atmosphere	• Local air pollution emissions from growing economic activity and vehicle use • Low vehicle occupancy rates due to inadequate public transport • Diesel vehicles emitting high levels of NOx and SO_2 emissions and petrol vehicles which is the dominant fuel type consumed emitting high levels of CO, VOCs and NOx	• National Pollutant Inventory by Federal Government • Environmental Protection (Air) Policy by State Government • Regional responses: ✓ SEQ Regional Air Quality Strategy ✓ Transport Management Plan ✓ Planning Scheme ✓ Cities for Climate Protection Program

Table 4.2 Cont'd

State	Pressures	Responses
Biodiversity	• Clearing and habitat destruction • Road traffic • Inappropriate fire regimes	• Environment Protection and Biodiversity Conservation Act by Federal Government • The Queensland Nature Conservation Act (1992) by State Government • Council responses: ✓ Bushfire Management Strategy ✓ Nature Conservation Strategy ✓ Beaches to Bushland programs ✓ Coastal Dune Restoration programs ✓ Private Land Conservation Programs
Land	• Beach erosion due to foreshore development and unnecessary use for recreational purposes • Acid sulphate soil runoff and groundwater flow on the coastal lowlands • Contaminated sites from defence force former training grounds	• The Coastal Acid Sulphate Soils Program as part of the Federal Government's Oceans Policy (1998) • The Northern Gold Coast Beach Protection Strategy
Waterways and Groundwater	• Increased urban development as well as growing number of tourists, visitors and day-trippers • Land modification, particularly canal constructions • The demand for clean and safe drinking water	• Environmental Protection (Water) Policy 1997 by State Government • Council responses: ✓ Gold Coast Catchment Management Strategy ✓ Waterwatch ✓ Stormwater Runoff Studies (i.e. WSUD Guidelines) ✓ Northern Wastewater Treatment Strategy ✓ Community and Industry Awareness Program ✓ Acid Sulphate Soil Management Plan
Solid Waste and Wastewater	• Increased population and visitor numbers	• Waste Management Strategic Plan • The Northern Wastewater Strategy • Energy Management Scheme • Wastewater Spillage Abatement Strategy • Trade Waste Policy • Biosolids Reuse Policies • Pimpama-Coomera Water Futures
Natural Resources	• Population growth and demand per-capita increases drinking water and energy consumption	• Cities for Climate Protection Program • Water Quality Management System • Water pricing system • Hinze and Little Nerang Dams Recreation Management Policy

4.1.4 OVERVIEW OF CURRENT PLANNING STRATEGIES

The GCC council developed environmental planning strategies and projects for the protection of its ecosystems and sustainable management of its resources, which can be summarised as:

- *Climate Change Strategy (2009-2014):* The strategy document presents the city council's existing activities and targeted actions to avoid future impacts of climate change. The strategic outcomes and key actions presented in the report are shown in Table 4.3.

Table 4.3 Strategic outcomes and key actions for climate change (derived from GCC Council, 2009b)

Outcomes	Actions
Governance and leadership	• Promote carbon footprint reduction initiatives • Review relevant council climate change decisions and policies • Undertake council staff training on climate change considerations as part of risk assessment • Investigate options for renewable resource use
Research	• Provide a budget dedicated to Gold Coast specific climate change research initiatives • Develop a detailed Gold Coast existing information for decision making purposes • Identify and map the Gold Coast environments most at risk from the impacts of climate change
Advocacy and awareness	• Decrease the city's carbon footprint • Develop an integrated community-wide education and awareness campaign on climate change mitigation • Develop a training and awareness campaign for council staff to increase understanding of climate change mitigation
Infrastructure	• Review the maintenance requirements for city's recreational facilities, public spaces and infrastructure to prevent climate change risk and impacts • Construct all new council buildings based on the Australian 5 star Greenhouse Building Standards • Develop and implement management plans for efficient energy consumption of council buildings and assets
Planning and regulation	• Provide better public transport services for the Gold Coast community • Improve local food production and purchase on the Gold Coast • Promote council's strategies, plans and policies that meet climate change requirements and responsibilities

- *Corporate Plan (2009-14):* The plan identifies the city council's six key actions towards sustainable development, as shown in Table 4.4.

Table 4.4 Six key focus priorities (derived from GCC Council, 2009c)

Aim	Actions
A city leading by example	• Support Gold Coast businesses and residents to adopt sustainable living practices • Increase community engagement in planning towards responding to the city challenges • Develop a strong partnerships across government, business and the community
A city loved for its green, gold and blue	• Establish a green network of greenways and parklands across the city that serves people of all different ages and abilities • Ensure the conservation of the city's biodiversity, wildlife and vegetation • Protect ecological systems in coastal, estuarine and marine environments • Resource conservation and sustainable waste management practices
A city connecting people and places	• Prepare local plans for transit-orientated developments based on high quality pedestrian and open space environments • Encourage environmentally friendly modes of travel • Improve cultural facilities, festivals, events for building socially diverse community
A safe city where everyone belongs	• Implement crime prevention environmental urban design principles • Promote public health by identifying, protecting and remedying health-related hazards and risks • Plan adequate social infrastructure including human services, sport and recreational facilities that meets all needs of the community
A city with a thriving economy	• Encourage the development of knowledge-based centres • Support local economy to attract new business and investments to the city • Promote a green energy industry hub to develop sustainable industries • Promote the city as a nationally and internationally ideal place for public/private investment
A city shaped by clever design	• Promote affordable and accessible housing for sustainable communities • Develop and implement long-term infrastructure plans that meets the growing needs of the community • Implement high quality urban design principles and guidelines for the new developments and infrastructure projects

- *Gold Coast Planning Scheme:* The Planning Scheme has been prepared as an instrument under the provisions of the Integrated Planning Act 1997 (IPA). The Planning Scheme establishes regulatory provisions to achieve ecological sustainability through the formulation of place codes, development codes, constraint codes and other assessment criteria that provide guidance for best practice development solutions (GCC Council, 2008a). The Planning Scheme also includes a list of *Environmental Performance Indicators* that aims to measure the effectiveness of the Planning Scheme as well as guide the review process of the Planning Scheme (Table 4.5).

Table 4.5 Environmental performance indicators (derived from GCC Council, 2012d)

	Desired Environmental Outcomes	**Performance Indicators**
ECOLOGICAL	*Biodiversity and Landscape Values* The conservation of native vegetation and other natural ecosystems, biodiversity and natural landscape values	• Total area of all ecologically significant areas and of all regional ecosystem types that are conserved as part of an approval for impact or code assessment • Number and percentage of approved development applications that successfully incorporate any relevant visual amenity considerations of the Planning Scheme, including those within the Planning Strategies and Local Area Plans (LAPs)
	Water Quality The protection of natural drainage catchments, river systems and other water bodies to maintain the ecological values and functions of the ecosystems	• Change in water quality statistics, expressed in terms of pollutant loads for each major catchment • Number and nature of stormwater treatment devices provided as part of approved developments
	Air Quality The maintenance of high standards of air quality, including minimising and reducing of greenhouse gas emissions	• Change in corporate and community greenhouse gas emissions • Number and proportion of new dwellings/lots approved within 500m of an activity centre or cluster or major transport interchange • Number of new dwellings approved in accordance with Planning Scheme provisions for energy efficient design
	Waste Management The minimisation of waste products and the provision of efficient systems to ensure their effective reuse, treatment or disposal	• Per-capita waste management costs • Number of approved developments that incorporate waste reuse initiatives

Table 4.5 Cont'd

	Desired Environmental Outcomes	Performance Indicators
ECONOMIC	<u>*Economic Growth and Diversification*</u> The provision of an efficient land use pattern that is conducive to business activity, and attractive for new business opportunities	• Number of jobs in the City as a whole and within its component parts • Number of jobs in various industry sectors
	<u>*Improved Integration of Residential and Business Activities*</u> Enhanced employment and investment opportunities through better integration of residential and business activity	• Number of jobs within each local area • Number of dwellings approved in non-residential domains
	<u>*Activity Centres and Clusters*</u> The provision of a viable system of activity centres and clusters to ensure that the community have access to a wide range of suitably planned and located goods and services	• Number of approved developments within major activity centres and clusters • Number of jobs within major activity centres and clusters
	<u>*Tourism*</u> The enhancement of the tourism industry, including the protection of existing attractions, the protection and ecologically sustainable use of the significant natural assets	• Number of visitor nights spent within the city • Number of approved developments for tourist facilities or accommodation • Results of industry surveys
	<u>*Natural Resources*</u> The prudent use of renewable and non-renewable natural resources	• Value of primary industries to the local economy • Number and type of development approvals within the Rural or Conservation Domains
	<u>*Infrastructure Provision*</u> The use and safe operation of existing and committed infrastructure is maximised and future infrastructure is provided efficiently	• Number and proportion of development applications approved within the Priority Infrastructure Plan • Proportion of relevant capital works financed from development contributions

Table 4.5 Cont'd

	Desired Environmental Outcomes	Performance Indicators
SOCIAL	*Local Character and Identity* The establishment, conservation and enhancement of local character and the promotion of a distinctive local identity	• Number and percentage of approved developments that successfully incorporate any relevant visual amenity or nature conservation considerations of the Planning Scheme, including those within the Planning Strategies and LAPs
	Access to Community Facilities and Employment The location and design of residential areas and support facilities to maximise accessibility to community facilities and places of employment	• Percentage of new developments that achieve the planned residential density • Length of new pedestrian/bicycle paths required through development applications
	Housing Choice The provision of a range of housing choice that is responsive to the changing demographic structure of the City's population and promotes equity in access to goods and services	• Proportion of dwelling types approved within each locality of the City
	Cultural Heritage The identification and protection of places and objects of recognised historic, indigenous and cultural heritage significance	• Number of development applications approved that require the preservation or enhancement of local cultural heritage values • Number of development applications approved that integrate and protect places and sites with cultural heritage values
	Residential Amenity The maintenance of residential amenity, through the minimisation of any environmental harm or adverse social impacts occurring from the construction and operation activities	• Number of development related complaints per 1,000 head of population received in respect of approved developments
	Transport Services The provision of a safe, clean, accessible and affordable transport system that efficiently connects the various parts of the city	• Kilometres travelled by mode of transport
	Hazard Mitigation The location and design of development to minimise the potential risk to life and property from known natural hazards	• Proportion of all buildings below the design flood level • Number of buildings approved in High Potential Bushfire Hazard Areas or High Risk Soil Stability areas • Number of developments designed and managed to minimise potential bushfire hazard

- *Nature Conservation Strategy (2009-2019):* The plan identifies strategic outcomes and key actions for the conservation of the city's biodiversity and natural assets, as shown in Table 4.6.

Table 4.6 Strategic outcomes and key actions for nature conservation (derived from GCC Council, 2009d)

Outcomes	Actions
Nature conservation is integrated as core business for Council and recognised as an essential foundation for a sustainable city	• Corporate Governance Framework • Corporate information management • Open Space Preservation Levy funding
The Gold Coast community has an appreciation, awareness and involvement with the natural environment	• Conservation partnerships program • Urban biodiversity program • Integrated volunteer program • Education, communication and marketing • Flora and Fauna Database • Ecosystem services assessment
The city's terrestrial, aquatic and marine biodiversity, ecosystems and their ecological processes are conserved within a connected network of natural areas	• Ecological offset policy, administrative framework and mapping • A framework for vegetation protection • Planning of ecological corridors • Catchment management • Coastal management • Threatened species research and management • Bushfire management • Pest management • Ecological restoration • Roadside conservation
The city has a comprehensive, adequate and representative natural area reserve system	• Open Space Preservation Levy Land Acquisition Program
Adaptive management that responds to risks, such as climate change, is applied in administering Council's natural area reserve system	• Natural area reserve classification system • Natural area reserve management • Nature-based recreation plan for natural area reserves
Nature conservation is achieved through partnerships that promote, research, invest in, and coordinate the management of the city's biodiversity	• Community environmental grants program • Cooperative partnerships with natural resource management and planning bodies, other levels of government, and research institutes • Ecotourism

- *Natural Area Management Plans:* These plans include sustainability principles and goals, such as protection of native vegetation and fauna, habitat and wildlife corridors, bushfire management, pest and weed control, and development of recreational opportunities (GCC Council, 2012e).

- *East Coomera Koala Conservation Project:* The City Council undertakes a conservation project for monitoring koalas. Each koala undergoes a health check up and also micro-chipped, ear-tagged and fitted with a radio collar for tracking. This project helps to protect the koala population from development pressures by relocating them from risk areas (GCC Council, 2012f).

- *Solid Waste Management Strategy - 2020 Vision on Waste:* The plan includes strategies for the sustainable management of the solid waste, such as educational training and programmes, green waste management practices, development of resource recovery facilities, waste audit services for businesses, public place recycling, white goods, electronic goods and waste collection services (GCC Council, 2002).

- *The Pimpama Coomera Waterfuture Master Plan:* The plan is an integrated urban water management strategy that guides the sustainable management of water resources in the Pimpama Coomera region. The international award winning plan includes strategies such as the introduction of alternate water sources, such as recycled water and rainwater tanks, water sensitive urban design, water efficient garden design, irrigation and cost saving tips (GCC Council, 2008b).

4.1.5 CHARACTERISTICS OF PILOT STUDY SITES

Two suburbs, Upper Coomera and Helensvale, in the GCC are selected for the implementation of the MUSIX model. In addition, study sites have different urban spatial patterns that provide diverse information for the model implementation. In the early stages of the study, the model was tested within a particular area for its capability and accuracy. After testing, the model was recalibrated and implemented in the selected pilot study sites. The model was piloted within four residential areas, as shown in Figure 4.1.

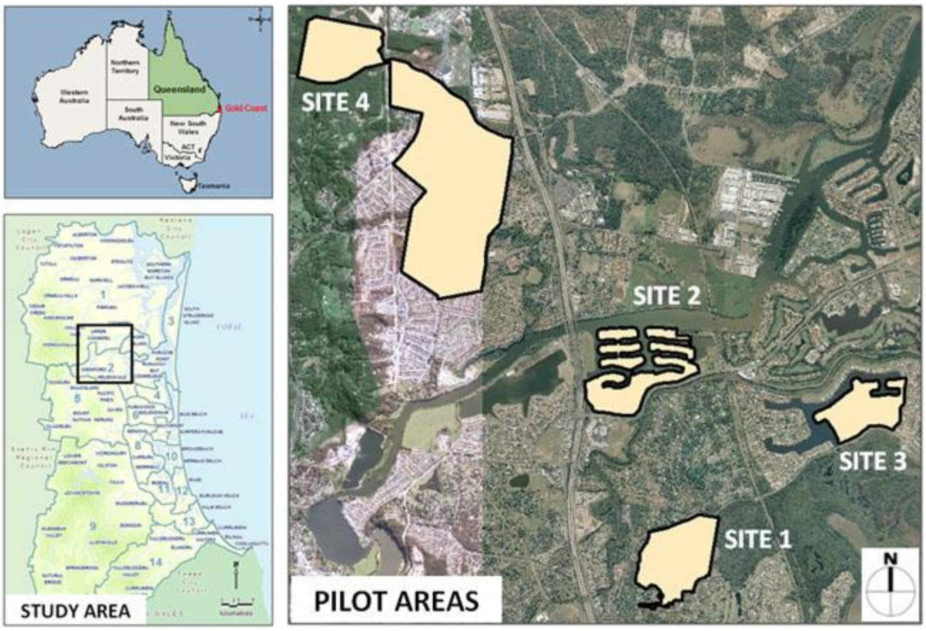


Figure 4.1 Location maps of the study and pilot areas (GCC Council, 2012c)

Upper Coomera is one of the rapid growing suburbs located at the northern end of the GCC with a population of 18,549 including mostly low-income groups (Australian Bureau of Statistics, 2006). Wetlands and sugar cane lands are located on the eastern boundary. On the west, the suburb is bounded by Brygon Creek which flows into the Coomera River and Hotham Creek. The suburb has an undulated topography that forms a steep valley to the west. This steeper land is a vegetated land that is threatened by potential future residential development. The suburb includes a popular theme park, Dreamworld, a major shopping centre and a university campus as well as close to the Gold Coast railway line and the Pacific Motorway (GCC Council, 2012d).

Helensvale is a newly developed suburb with a population of 14,767 including mostly medium-high income groups (Australian Bureau of Statistics, 2006). Low wooded ridges border the suburb from the Pacific Motorway on the west side. The Coombabah wetlands are located on the east side, which is an important nature reserve of the city. Helensvale is an important transport hub, which includes a railway station, and, bus and taxi set downs. Due to its proximity to the Gold Coast CBD, the suburb also includes retail, commercial and educational uses such as state high school, golf club, major shopping centre and parklands, and it is also very close to two popular theme parks Movieworld and Wet ‘n’ Wild (GCC Council, 2012d).

The detailed characteristics of the four pilot sites are as follows:

Box 4.1 Characteristics of pilot sites

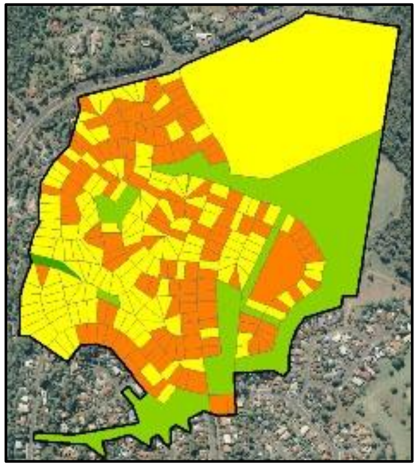
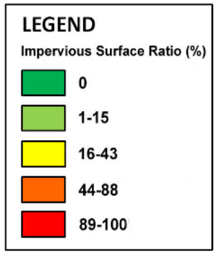
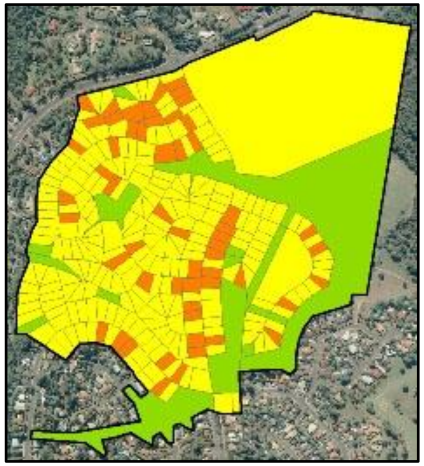
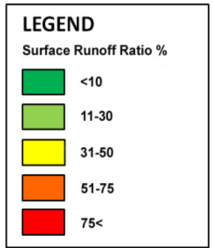
Site 1: Discovery Dr, Helensvale
The pilot area is a residential development located on Discovery Drive in the suburb of Helensvale. The area consists of detached single and two storeys large lot dwellings. The houses are in good condition, and, predominantly, have large backyard gardens. The total size of the pilot area is approximately 59 hectares and the total number of parcels is 292. There is also a secondary school, rugby club and aquatic centre located in the area. The area has a cul-de-sac street pattern that is highly dependent on motor vehicle use.
Site 2: Hope Island Rd, Helensvale
The pilot area is located on Hope Island Road close to the Pacific Motorway, which connects the Gold Coast to the state capital Brisbane. It is a residential canal-estate development in the suburb of Helensvale. The area consists of detached single and two storey narrow lot dwellings. The total size of the pilot area is approximately 62 hectares and the total number of parcels is 712. The area is highly dependent on motor vehicle use. The site is in an ongoing development, where most of the land is already developed and some of the canal parcels are empty or currently under construction.
Site 3: Dalley Park Dr, Helensvale
The pilot area is a residential canal-estate development located on Dalley Park Drive in the suburb of Helensvale. The area consists of detached single and two storeys lot dwellings. There is parkland located in the area. The total size of the pilot area is approximately 40 hectares and the total number of parcels is 324. The area is highly dependent on motor vehicle use with poor walkability.
Site 4: Peanba Park Rd, Billinghurst Crest, Abraham Rd, Reserve Rd, Upper Coomera
The pilot area is a high density residential development located on Peanba Park Road, Billinghurst Crest, Abraham Road and Reserve Road in the suburb of Upper Coomera. The area consists of detached single and two storeys lot dwellings with small backyard gardens. The total size of the pilot area is approximately 272 hectare and the total number of parcels is 1,515. There is also a state college, Catholic college and an Anglican college located in the area. The area is highly dependent on motor vehicle use with poor walkability.

4.2. PARCEL-LEVEL SCORES OF EACH INDICATOR

Each area was evaluated via selected indicators for measuring their urban ecosystem sustainability index scores. The model outputs are presented and discussed below and the sustainability performance of the sites are illustrated in Tables 4.7, 4.8, 4.9 and 4.10.

4.2.1 CASE STUDY SITE 1

Table 4.7 Model outputs of Site 1

<table>
<tr><td></td><td colspan="4">NATURAL ENVIRONMENT</td></tr>
<tr><td rowspan="4">HYDROLOGY</td><td colspan="2">Evapotranspiration</td><td colspan="2">Surface Runoff</td></tr>
<tr><td rowspan="2"></td><td>
</td><td rowspan="2"></td><td>
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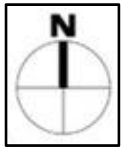
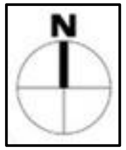
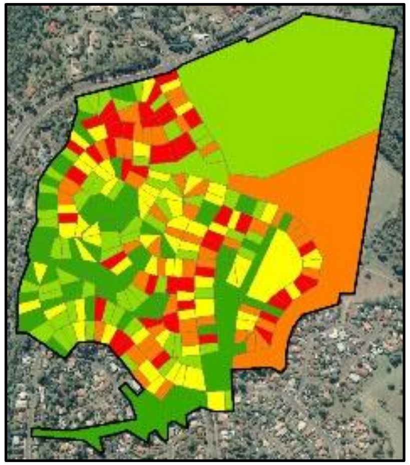
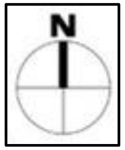
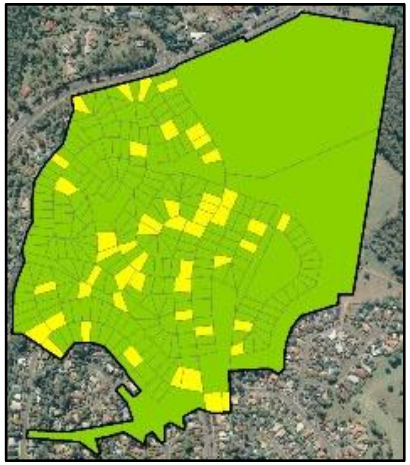
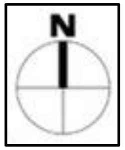
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="4">In terms of hydrology, the sustainability performance score of the area is predominantly in the medium to medium-low ranges. The results confirm that a large percentage of impervious surfaces cause low evapotranspiration rates. Moreover, as the area has an auto-dependent pattern of development, the results show increased rates of surface runoff in the area.</td></tr>
</table>

Table 4.7 Cont’d

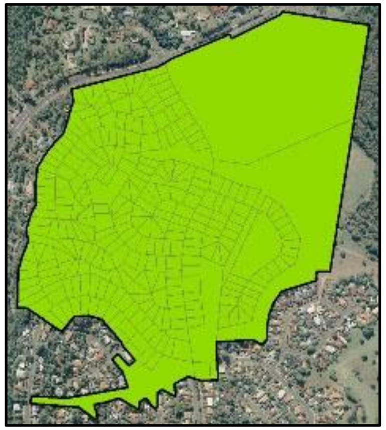
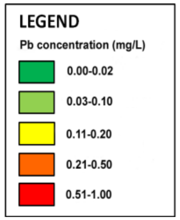
ECOLOGY

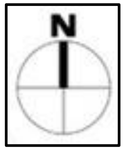
NATURAL ENVIRONMENT

Urban Habitat		*Microclimate*	
	**LEGEND** Green Area Ratio % 50< 41-50 31-40 21-30 <20  		**LEGEND** Effective Albedo % 27< 21.4-27 15.7-21.4 10-15.7 <10 

In terms of ecology, the sustainability performance score of the area is predominantly in the medium to medium-high ranges. As most of the parcels have large backyard gardens, the results demonstrate a high green area ratio in the area. In addition, the microclimate and thermal effect of the site is generally favourable except for a few parcels with a large percentage of impervious surfaces.

Table 4.7 Cont'd

<table>
<tr><td rowspan="4">POLLUTION</td><td colspan="6">NATURAL ENVIRONMENT</td></tr>
<tr><td colspan="2">Stormwater Pollution</td><td colspan="2">Air Pollution</td><td colspan="2">Noise Pollution</td></tr>
<tr>
<td></td>
<td>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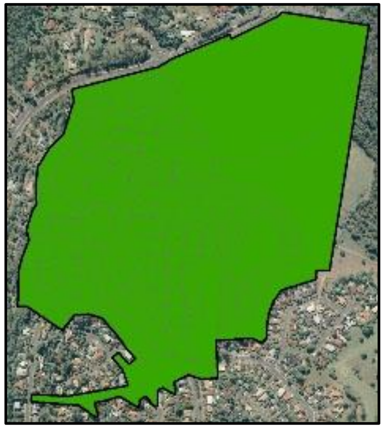
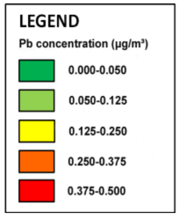
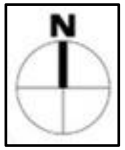
<td></td>
<td>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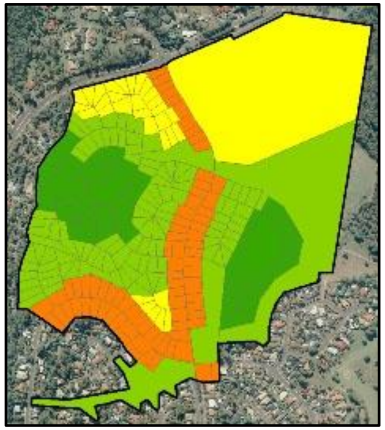
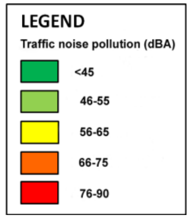
<td></td>
<td>


</td>
</tr>
<tr><td colspan="6">In terms of pollution, the sustainability performance score of the area is high (on average). The results represent a good picture of stormwater and air quality in the area. Exclusively, parcels, which are close to a main arterial road, are exposed to high levels of noise.</td></tr>
</table>

Table 4.7 Cont’d

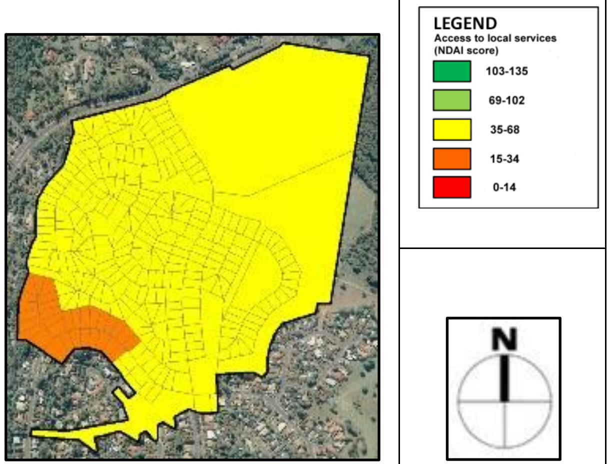
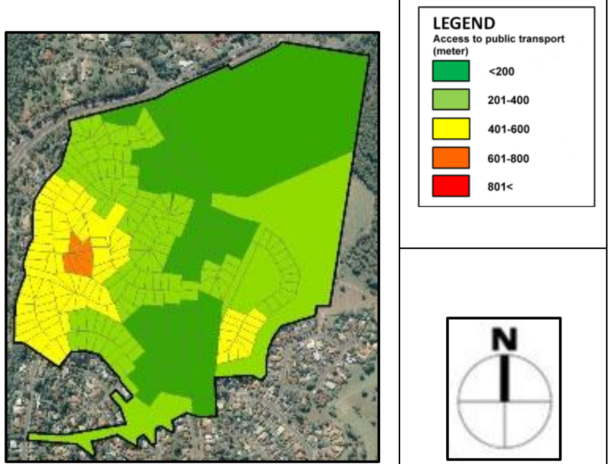
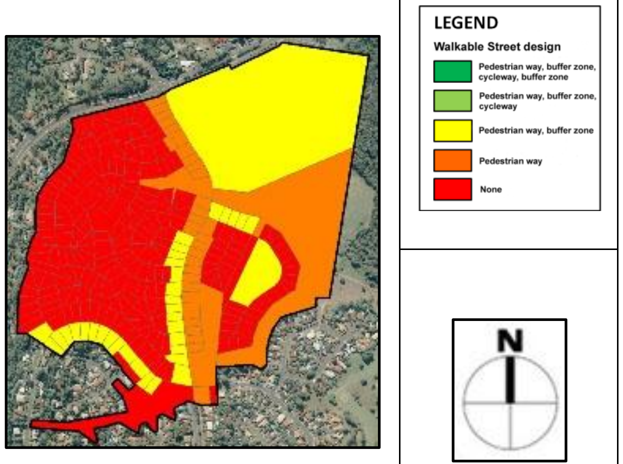
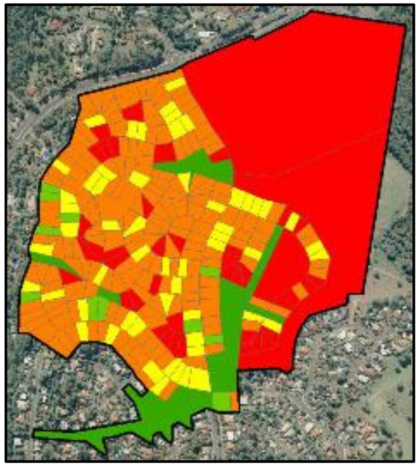
LOCATION	**BUILT ENVIRONMENT**		
	Proximity to Land Use Destinations	*Access to Public Transport Stops*	*Walkability*
			
	In terms of location, the sustainability performance score of the area is medium (on average). The results indicate that the area has limited accessibility to land use destinations by walking. The area has a good public transport access in general, however, the frequency of services are not enough. Lastly, as the area is highly dependent on motor vehicle use, the results clarify that the neighbourhood is not walkable.		

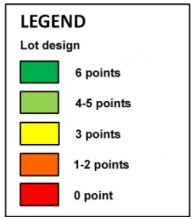
Table 4.7 Cont’d

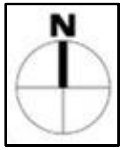
DESIGN

BUILT ENVIRONMENT

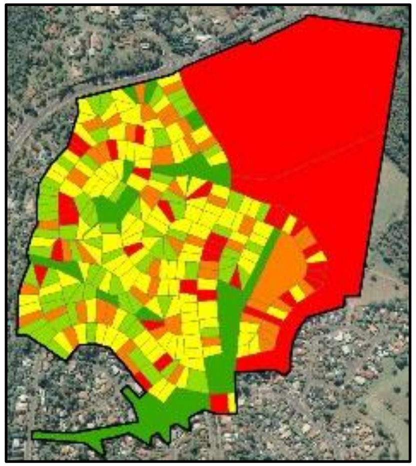
Lot Design

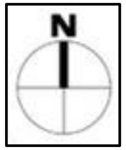






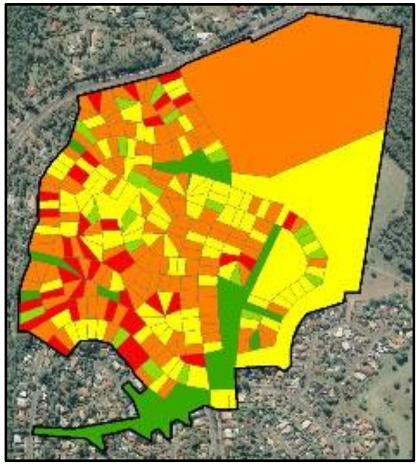
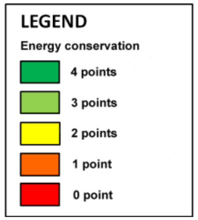
Landscape Design

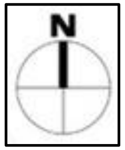
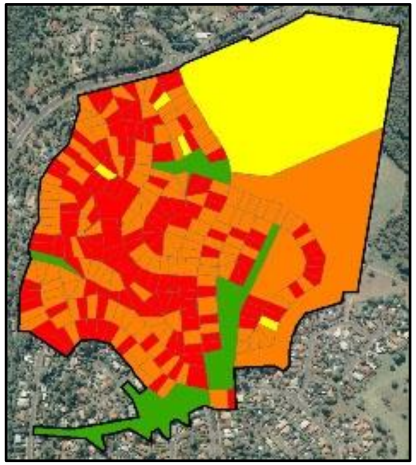
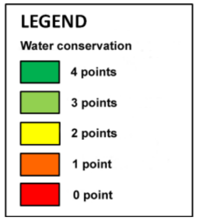


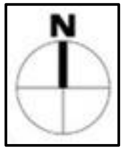


In terms of design, the sustainability performance score of the area is low (on average). The results reveal that existing parcel layouts in the area do not meet the principles of passive solar design in terms of lot shape, building orientation, solar access and so on. Furthermore, even though they have large backyards, their gardens do not meet the principles of subtropical climate responsive design.

Table 4.7 Cont'd

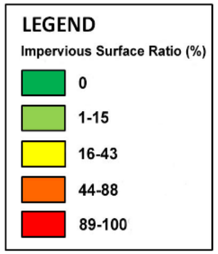
<table>
<tr><td rowspan="4">EFFICIENCY</td><td colspan="4">BUILT ENVIRONMENT</td></tr>
<tr><td colspan="2">Energy Conservation</td><td colspan="2">Water Conservation</td></tr>
<tr><td></td><td>

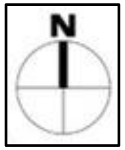
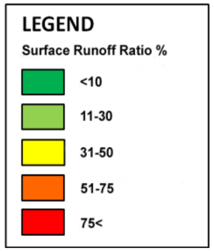

</td><td></td><td>


</td></tr>
<tr><td colspan="4">In terms of efficiency, the sustainability performance score of the area is medium-low (on average). The results show that existing parcel layouts in the area do not meet the principles of energy and water efficient designs. Especially, most of the parcels do not use sustainable energy sources such as rainwater tanks or solar panels. Furthermore, they have large amounts of grass in their garden area that lead to increased water use.</td></tr>
</table>

4.2.2 CASE STUDY SITE 2

Table 4.8 Model outputs of Site 2

<table>
<tr><td rowspan="4">HYDROLOGY</td><td colspan="4">NATURAL ENVIRONMENT</td></tr>
<tr><td colspan="2">Evapotranspiration</td><td colspan="2">Surface Runoff</td></tr>
<tr><td></td><td>


</td><td></td><td>

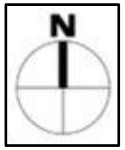
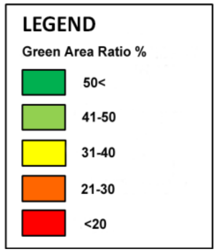
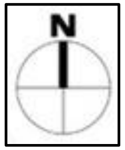

</td></tr>
<tr><td colspan="4">In terms of hydrology, the sustainability performance score of the area is medium-low (on average). The poor evapotranspiration results clarify that there are large amounts of impervious surfaces as a result of canal-estate development in the area. Moreover, the results indicate that the parcels located on the canal side have higher surface runoff rates compared to other parcels located inland.</td></tr>
</table>

Table 4.8 Cont’d

<table>
<tr><td rowspan="4">ECOLOGY</td><td colspan="4">NATURAL ENVIRONMENT</td></tr>
<tr><td colspan="2">Urban Habitat</td><td colspan="2">Microclimate</td></tr>
<tr><td></td><td>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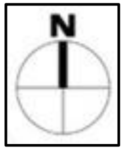
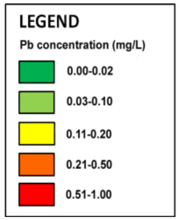

</td></tr>
<tr><td colspan="4">In terms of ecology, the sustainability performance score of the area is medium (on average). As most of the parcels have a large amount of impervious surfaces, the results demonstrate a low green area ratio in the area. However, the thermal effect of the site is generally favourable as parcels mostly have light-coloured roofs and surfaces related to the climatic conditions.</td></tr>
</table>

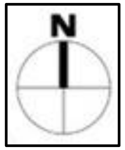
Table 4.8 Cont'd

POLLUTION

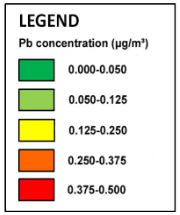
NATURAL ENVIRONMENT

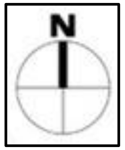
Stormwater Pollution



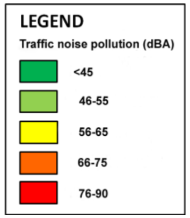


Air Pollution





Noise Pollution



In terms of pollution, the sustainability performance score of the area is medium-high (on average). The results represent a moderate picture of stormwater quality due to the large amount of impervious surfaces. The parcels located on the canal side have good air quality as they are not exposed to traffic. However, the parcels that are close to a main arterial road are exposed to high levels of noise pollution.

Table 4.8 Cont'd

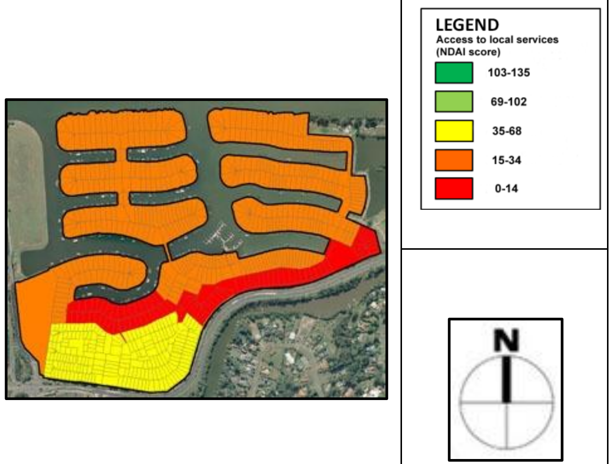
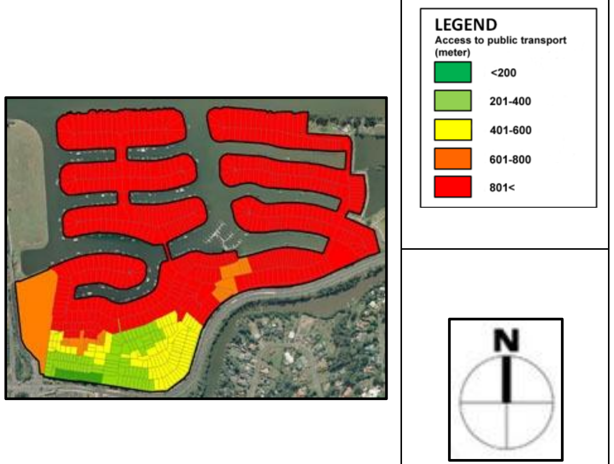
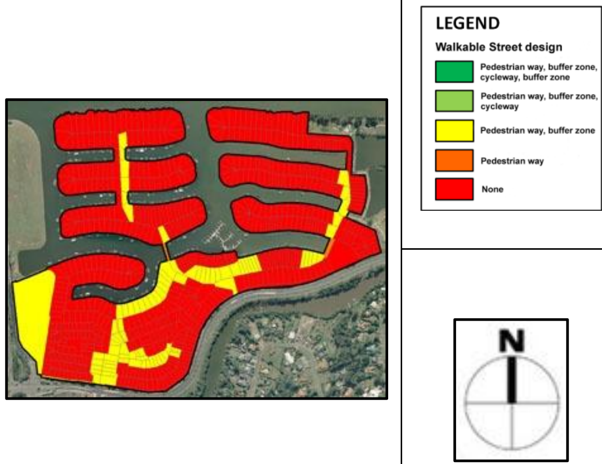
LOCATION	BUILT ENVIRONMENT		
	Proximity to Land Use Destinations	*Access to Public Transport Stops*	*Walkability*
			
	In terms of location, the sustainability performance score of the area is predominantly in the medium-low to low ranges. The results indicate that the area has limited accessibility to land use destinations by walking. The area that is close to the Pacific Motorway on the site has good public transport access. However, the canal estates do not have any public transport access and do not have walkable street patterns.		

Table 4.8 Cont'd

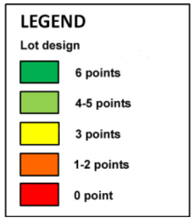
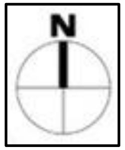
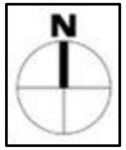
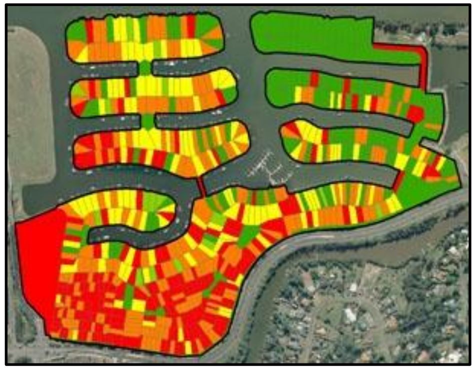
DESIGN	**BUILT ENVIRONMENT**			
	Lot Design		*Landscape Design*	
		 		 
	In terms of design, the sustainability performance score of the area is medium-low (on average). The results reveal that the existing parcel layouts in the area do not meet the principles of passive solar design in terms of lot shape, building orientation, solar access and so on. Furthermore, most parcels lack green space as well as climate responsive landscape design.			

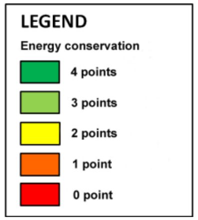
Table 4.8 Cont'd

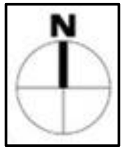
EFFICIENCY

BUILT ENVIRONMENT

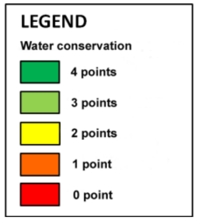
Energy Conservation

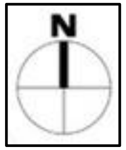






Water Conservation

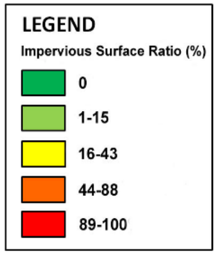


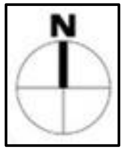
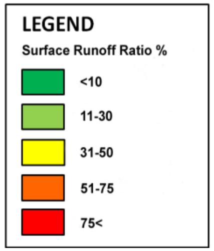


In terms of efficiency, the sustainability performance score of the area is medium-low (on average). The results show that existing parcel layouts in the area do not meet the principles of energy and water efficient designs. As the area consists of old dwellings, the results demonstrate that they do not use sustainable energy sources, such as rainwater tanks or solar panels. Furthermore, they have a large amount of grass in their garden area that leads to increased water use.

4.2.3 CASE STUDY SITE 3

Table 4.9 Model outputs of Site 3

<table>
<tr><td rowspan="4">HYDROLOGY</td><td colspan="4">NATURAL ENVIRONMENT</td></tr>
<tr><td colspan="2">Evapotranspiration</td><td colspan="2">Surface Runoff</td></tr>
<tr><td></td><td>


</td><td></td><td>

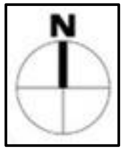
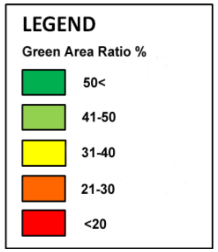
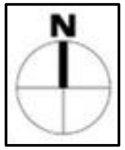

</td></tr>
<tr><td colspan="4">In terms of hydrology, the sustainability performance score of the area is predominantly medium-low. The poor evapotranspiration results clarify that there are large amounts of impervious surfaces as a result of canal-estate development in the area. Moreover, as the area has auto-dependent pattern of development, the results show increased rates of surface runoff in the area.</td></tr>
</table>

Table 4.9 Cont’d

<table>
<tr><td rowspan="4">ECOLOGY</td><td colspan="4">NATURAL ENVIRONMENT</td></tr>
<tr><td colspan="2">Urban Habitat</td><td colspan="2">Microclimate</td></tr>
<tr><td></td><td>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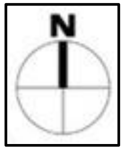
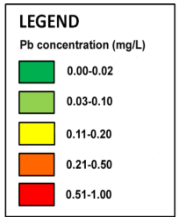
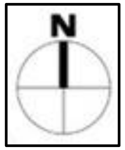

</td></tr>
<tr><td colspan="4">In terms of ecology, the sustainability performance score of the area is medium (on average). As most of the parcels have large amounts of impervious surfaces, the results demonstrate a low green area ratio in the area. However, the thermal effect of the site is generally favourable as parcels mostly have light-coloured roofs and surfaces related to climatic conditions.</td></tr>
</table>

Table 4.9 Cont’d

<table>
<tr><td rowspan="4">POLLUTION</td><td colspan="6">NATURAL ENVIRONMENT</td></tr>
<tr><td colspan="2">Stormwater Pollution</td><td colspan="2">Air Pollution</td><td colspan="2">Noise Pollution</td></tr>
<tr>
<td></td>
<td>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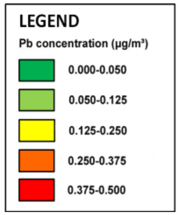
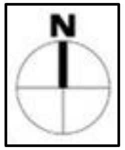
<td>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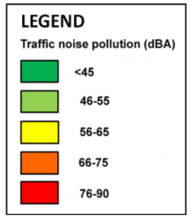
<td>


</td>
</tr>
<tr><td colspan="6">In terms of pollution, the sustainability performance score of the area is predominantly medium-high. The results represent a good picture of stormwater quality. The parcels located on the canal side have good air quality as they are not exposed to traffic. However, parcels that are close to main arterial roads are exposed to noise pollution.</td></tr>
</table>

Table 4.9 Cont'd

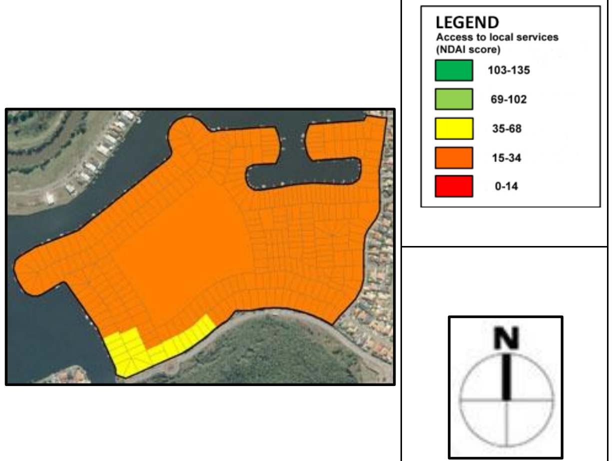
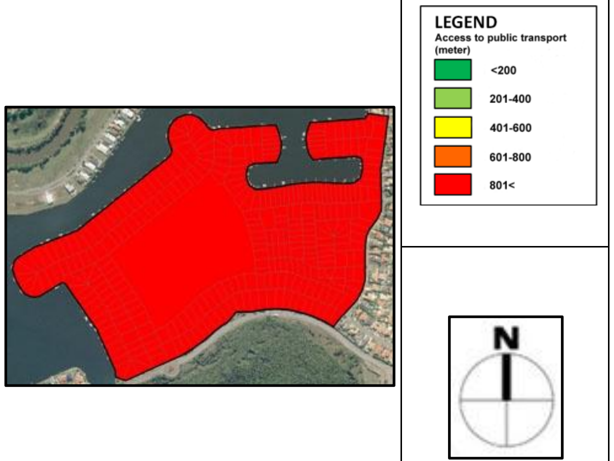
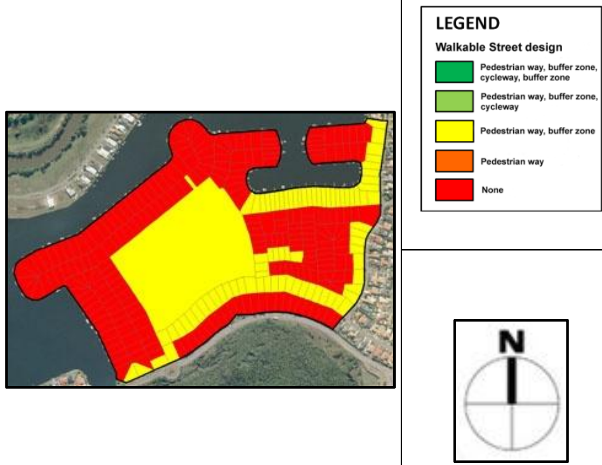
LOCATION	**BUILT ENVIRONMENT**		
	Proximity to Land Use Destinations	*Access to Public Transport Stops*	*Walkability*
			
	In terms of location, the sustainability performance score of the area is predominantly low. The results show that the area has poor accessibility to land use destinations by walking. The area does not have public transport access. Furthermore, as the area is highly dependent on motor vehicle use, the results clarify that the neighbourhood is not walkable.		

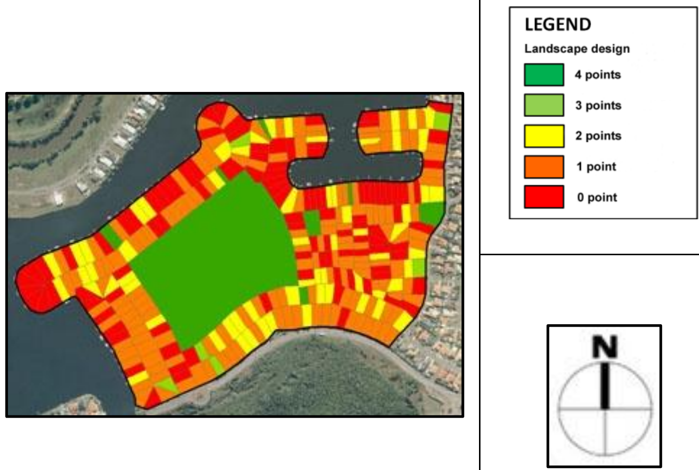
Table 4.9 Cont’d

DESIGN

BUILT ENVIRONMENT

Lot Design

Landscape Design



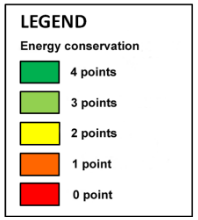
In terms of design, the sustainability performance score of the area is medium-low (on average). The results reveal that existing parcel layouts in the area do not meet the principles of passive solar design in terms of lot shape, building orientation, solar access and so on. Furthermore, most parcels lack green space as well as climate responsive landscape design.

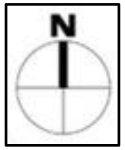
Table 4.9 Cont’d

EFFICIENCY

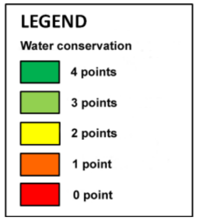
BUILT ENVIRONMENT

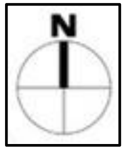
Energy Conservation





Water Conservation





In terms of efficiency, the sustainability performance score of the area is predominantly in the medium to medium-low ranges. The results show that existing parcel layouts in the area do not meet the principles of energy and water efficient designs. Additionally, the results demonstrate that they do not use sustainable energy sources, such as solar panels. However, the water conservation of the site is generally favourable as the results indicate a high rate of rainwater tank usage.

4.2.4 CASE STUDY SITE 4

Table 4.10 Model outputs of Site 4

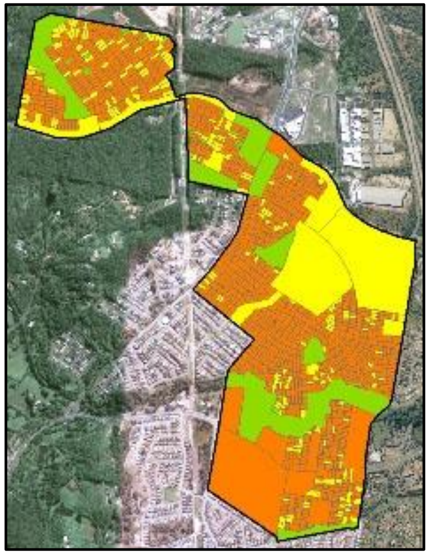
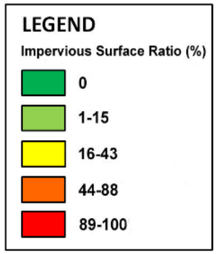
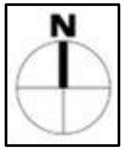
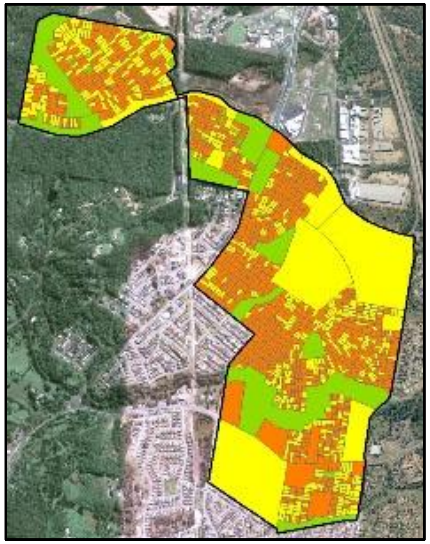
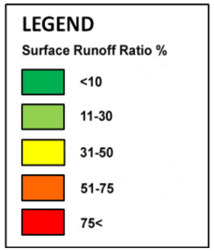
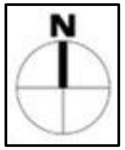
HYDROLOGY	NATURAL ENVIRONMENT			
	Evapotranspiration		*Surface Runoff*	
		 		 
	In terms of hydrology, the sustainability performance score of the area is medium (on average). The poor evapotranspiration results clarify that there are large amounts of impervious surfaces due to the lack of green space as well as high-density development. Moreover, as the area has an auto-dependent pattern of development, the results show increased rates of surface runoff in the area.			

Table 4.10 Cont'd

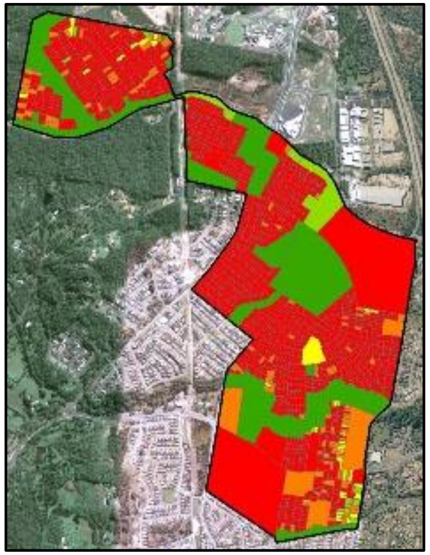
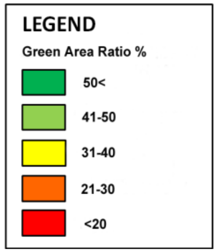
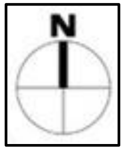
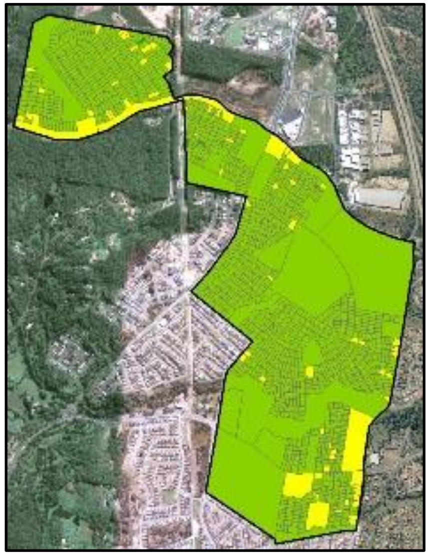
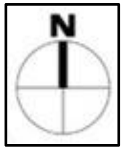
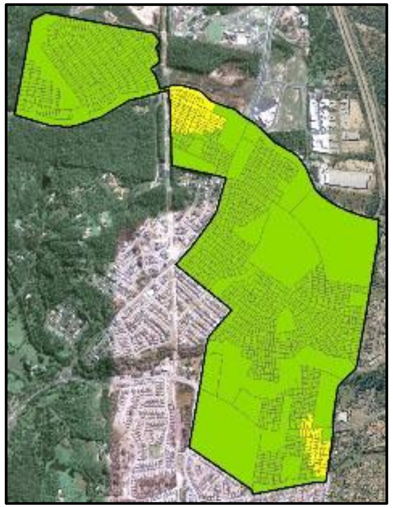
<table>
<tr><td rowspan="4">ECOLOGY</td><td colspan="4">NATURAL ENVIRONMENT</td></tr>
<tr><td colspan="2">Urban Habitat</td><td colspan="2">Microclimate</td></tr>
<tr><td></td><td>
</td><td></td><td>
</td></tr>
<tr><td colspan="4">In terms of ecology, the sustainability performance score of the area is medium (on average). As most of the parcels have large amounts of impervious surfaces, the results demonstrate a low green area ratio in the area. However, the thermal effect of the site is generally favourable as parcels mostly have light-coloured roofs and surfaces related to the climatic conditions.</td></tr>
</table>

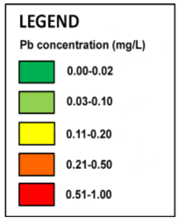
Table 4.10 Cont'd

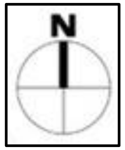
POLLUTION

NATURAL ENVIRONMENT

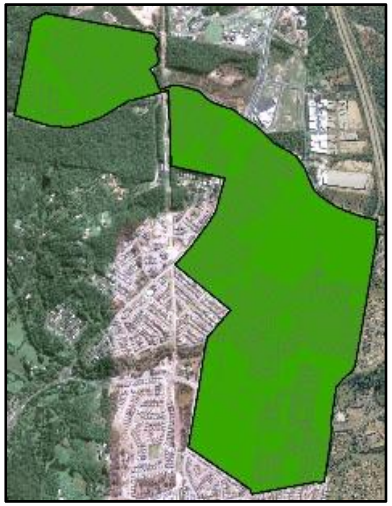
Stormwater Pollution

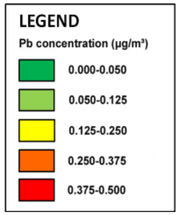


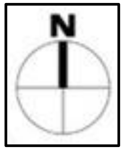




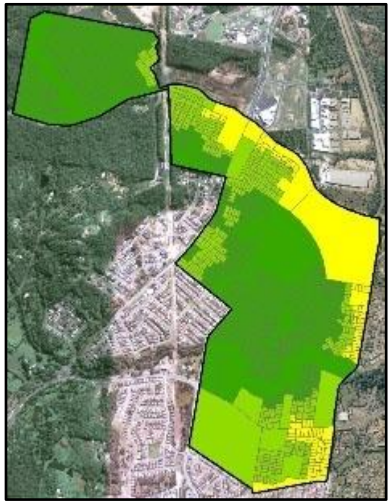
Air Pollution

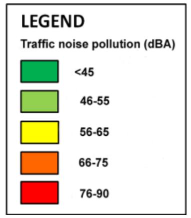






Noise Pollution





In terms of pollution, the sustainability performance score of the area is predominantly medium-high. The results represent a good picture of stormwater and air quality in the area. Moreover, the area does not have a serious noise pollution, except, parcels that are close to a main arterial road.

Table 4.10 Cont'd

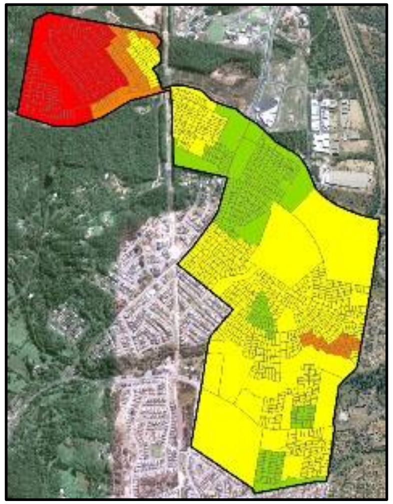
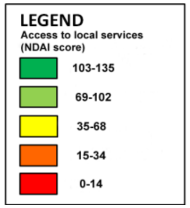
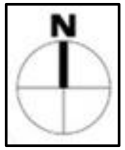
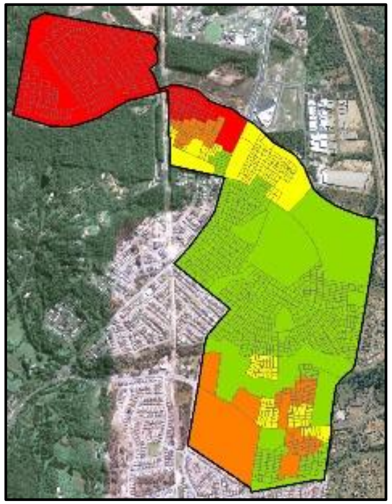
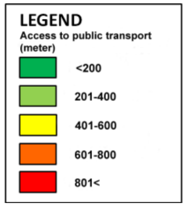
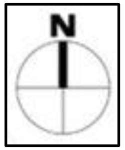
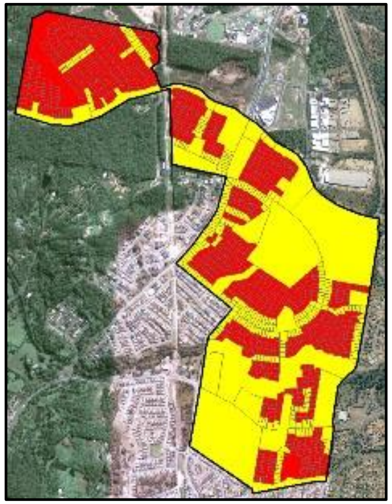
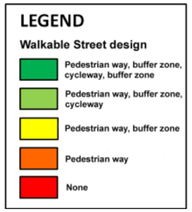
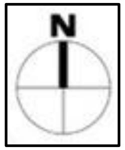
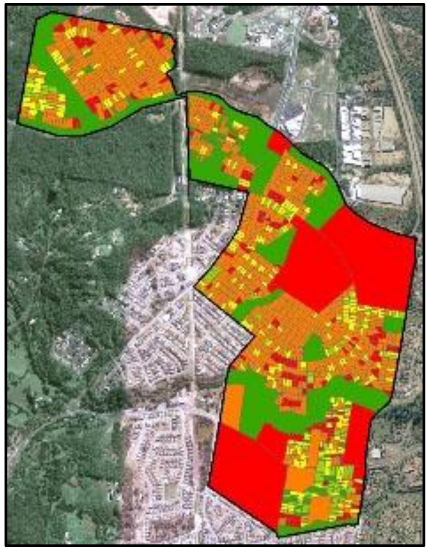
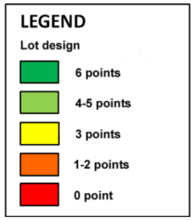
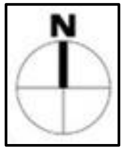
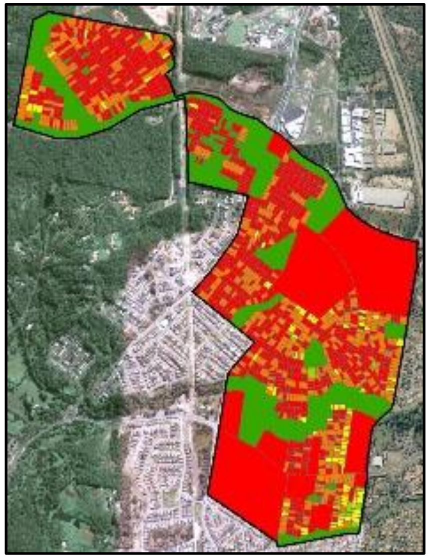
<table>
<tr><td rowspan="4">LOCATION</td><td colspan="6">BUILT ENVIRONMENT</td></tr>
<tr><td colspan="2">Proximity to Land Use Destinations</td><td colspan="2">Access to Public Transport Stops</td><td colspan="2">Walkability</td></tr>
<tr><td></td><td>
</td><td></td><td>
</td><td></td><td>
</td></tr>
<tr><td colspan="6">In terms of location, the sustainability performance score of the area is medium (on average). The results indicate that the area has limited accessibility to land use destinations by walking for the northern part. The rest of the area has favourable accessibility. The area, except the northern part, has good public transport access in general; however, the frequency of services is inadequate. Lastly, as the area has a high-density car-dependent community, the results clarify that the neighbourhood is not walkable.</td></tr>
</table>

Table 4.10 Cont’d

<table>
<tr><td rowspan="4">DESIGN</td><td colspan="4">BUILT ENVIRONMENT</td></tr>
<tr><td colspan="2">Lot Design</td><td colspan="2">Landscape Design</td></tr>
<tr><td></td><td>


</td><td></td><td>

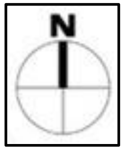
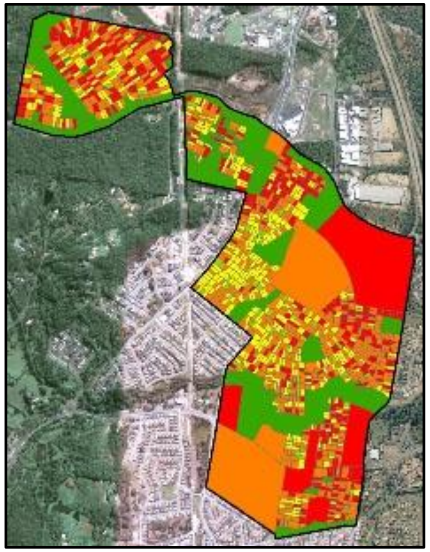
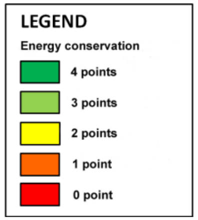
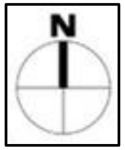
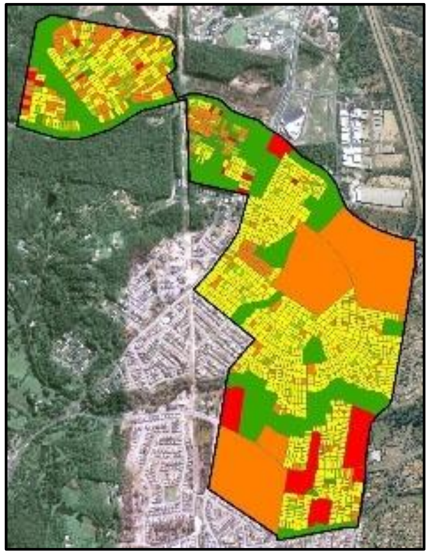
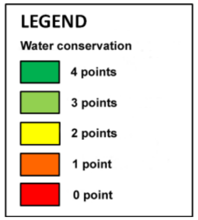
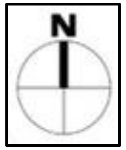

</td></tr>
<tr><td colspan="4">In terms of design, the sustainability performance score of the area is low (on average). The results reveal that existing parcel layouts in the area do not meet the principles of passive solar design in terms of lot shape, building orientation, solar access and so on. Furthermore, the area lacks green spaces due to high-density development.</td></tr>
</table>

Table 4.10 Cont’d

<table>
<tr><td rowspan="4">EFFICIENCY</td><td colspan="4">BUILT ENVIRONMENT</td></tr>
<tr><td colspan="2">Energy Conservation</td><td colspan="2">Water Conservation</td></tr>
<tr><td></td><td>
</td><td></td><td>
</td></tr>
<tr><td colspan="4">In terms of efficiency, the sustainability performance score of the area is predominantly in the medium to medium-low ranges. The results show that existing parcel layouts in the area do not meet the principles of energy and water efficient designs. Additionally, the results demonstrate that they do not use sustainable energy sources such as solar panels. However, the water conservation of the site is generally favourable as the results indicate a high rate of rainwater tank usage.</td></tr>
</table>

4.3 GRID-BASED COMPOSITE INDEX SCORES

As mentioned previously in the methodology section, the MUSIX model investigates environmental impacts at a micro-level in which parcels are used as spatial units. However, in addition to parcel-level information, the outcomes of this study are also presented in grid cell level. The study area is divided into 100 x 100 metre grid cells. ArcGIS software was used to transfer parcel-level aggregated composite index scores into grid cell scores. This section presents grid-based composite index scores. Composite index maps of the case study sites are illustrated in Table 4.11.

Table 4.11 Composite index maps of the case study sites

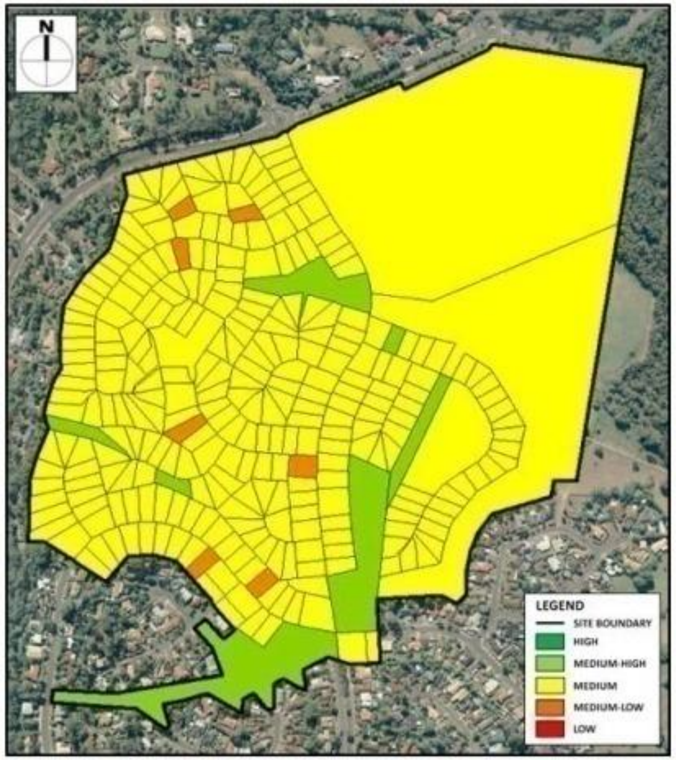
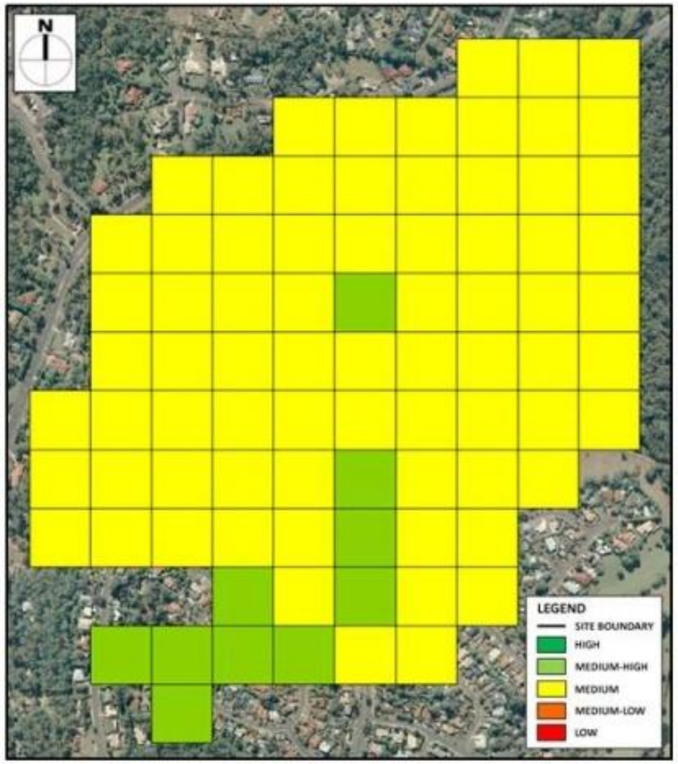
	Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
SITE 1		

Table 4.11 Cont'd

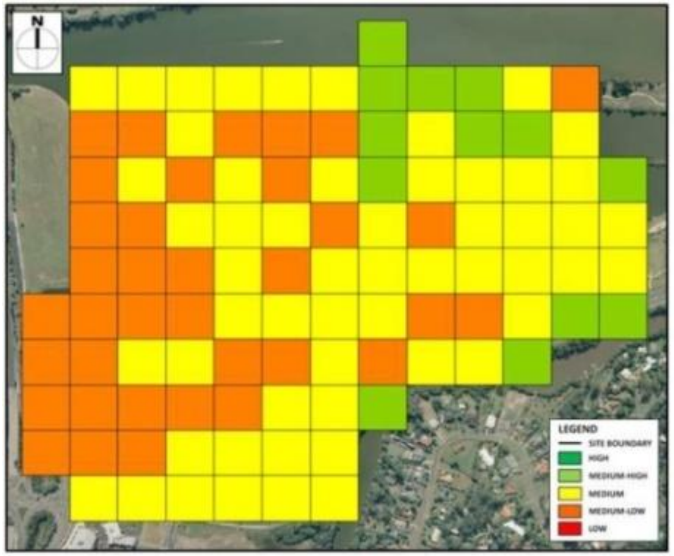
	Parcel-Level Composite Index Score	Grid-Based Composite Index Score
SITE 2		

Table 4.11 Cont'd

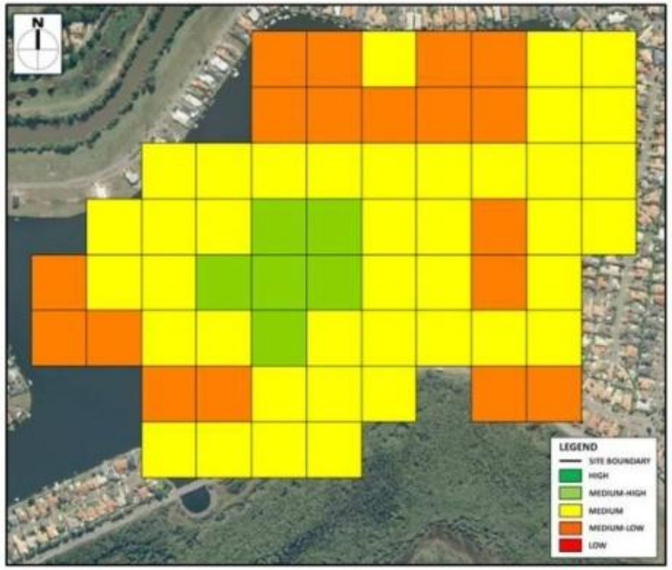
<table>
<tr><th></th><th>Parcel-Level
Composite Index Score</th><th>Grid-Based
Composite Index Score</th></tr>
<tr><td>SITE 3</td><td>
</td><td>
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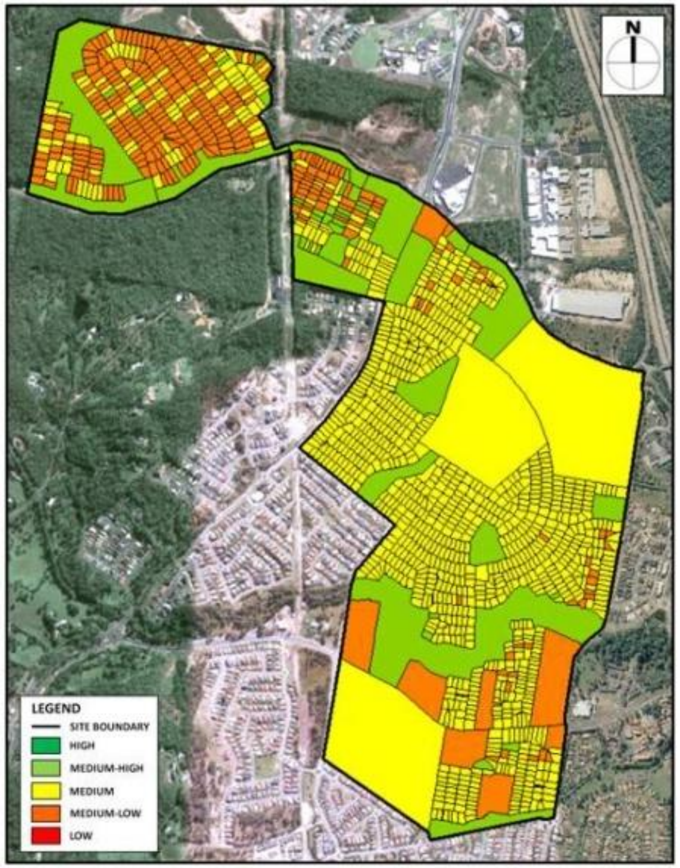
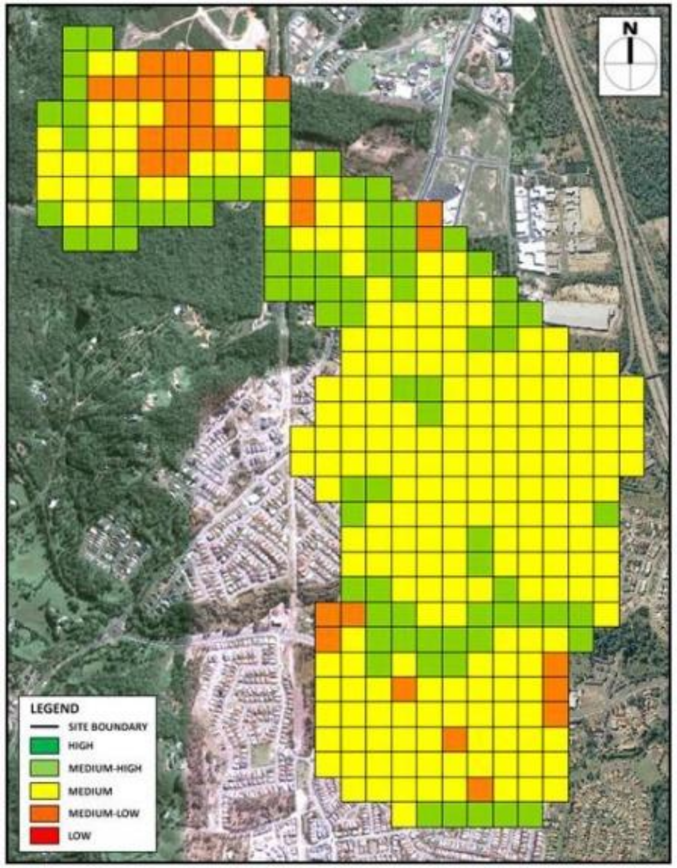
Table 4.11 Cont'd

	Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
SITE 4		

As can be seen from the figures above, the overall sustainability performance scores for Site 1 and Site 4 are predominantly medium. Particularly:

- *In terms of natural environment:* The percentage of green spaces is considerably high in Site 1. The dwellings located in the site have gardens with large trees and shrubs. This vegetation provides outdoor living spaces by sheltering the buildings. They improve the microclimate of the site by cooling air temperature as well as absorbing radiation. In contrast, Site 4 lacks green spaces. There are only a few large urban green spaces in the site; which unfortunately, are threatened by development pressure. Both sites provide a good picture of environmental quality in terms of stormwater, air and noise pollution. Exclusively, Site 1 has a cul-de-sac street pattern, which provides less traffic noise for the adjacent and surrounding parcels, whereas, parcels which are close to the main arterial road are exposed to high levels of noise. Furthermore, both sites have an auto-dependent pattern of development that results in increased rates of surface runoff in the area.

- *In terms of the built environment:* Both sites are close to local amenities and services; hence, they provide good public transport access; however, the service frequency is not enough. Exclusively, the northern periphery of Site 4, which is a newly developing area, represents low performance due to its long distance from the urban centre. The streets in both sites mainly serve motor vehicle mobility; hence the neighbourhoods are not designed to be pedestrian friendly. Before discussing the sites in terms of their sustainable design and efficiency, it needs to be noted that the MUSIX model does not provide information about the architectural design of the buildings within the parcels. There might be architecturally designed passive solar homes in the study area. It is the same with landscape design. There is no detailed information about the plant species or the type of irrigation systems used. Therefore, the MUSIX model examines the implementation of climate responsive design, energy and water efficiency principles by a rating system based on aerial photos. Site 1 yields better performance than Site 4 regarding the lot and landscape design. Site 4 lacks green spaces, which is due to high-density development. The area consists of narrow parcels with small backyards. The use of rainwater tanks and solar energy is not common in either site. Furthermore, most of the houses have swimming pools, which have a major impact on water usage.

Overall, the sustainability performance scores of Site 2 and Site 3 are lower than Site 1 and Site 4. Particularly:

- *In terms of natural environment:* Both sites are residential canal-estate developments and some of the canal parcels are currently under construction. The results show that this type of development leads to increased runoff quality and quantity. Especially, the parcels located on the canal side have more surface runoff rates. The canal estate parcels are almost completely covered with impervious surfaces; therefore, these sites are assigned the lowest scores in terms of green area ratio. This result also affects the stormwater quality of the sites. Apart from this, both sites provide a good picture of environmental quality in terms of air and noise pollution. Exclusively, parcels that are located adjacent to the arterial road are exposed to high levels of noise.

- *In terms of the built environment:* Both sites are far from local amenities and services; hence, they have an auto-dependent pattern of development. There is no easy access to public services within walking distance and the service frequency is also not enough. As the streets mainly serve motor vehicle mobility, neither site is designed as pedestrian friendly. Both sites present poor performance regarding lot and landscape design. They lack green spaces due to the loss of native vegetation cover from canal construction. In the summer, particularly, all houses are exposed to direct sunlight, which is not healthy for the thermal comfort and microclimate of the sites. The use of rainwater tanks and solar energy is not common in either site. Furthermore, most of the houses have only grass and swimming pools in their backyards, which lead to increased water use in the area.

4.4 SENSITIVITY ANALYSIS OF THE MODEL

Each composite index is constructed by several subjective steps, which include the calculation method, selection of indicators, choice of aggregation and weighting procedures that are associated with some uncertainties in the methodology. Therefore, it is necessary to analyse the sensitivity of the index by using alternative methodological assumptions (Manca *et al.*, 2010). A sensitivity analysis helps to assess the robustness of the index, and investigate the potential changes and their impact on the results derived from the index. As stated by Pannell (1997, p. 140), a sensitivity analysis is helpful in model development in order to: (1) test the model for validity or accuracy; (2) search for errors in the model; (3) calibrate the model; (4) cope with poor or missing data, and; (5) prioritise acquisition of information. In this context, a sensitivity analysis was performed to show the impact of the alternative methodological approaches on the overall results of the MUSIX model.

As the first part of the sensitivity analysis of the model, alternative techniques were applied in the weighting and aggregation procedures as follows: (1) *Equal Weighting,* which provides the measurement of each indicator with the same degree of importance, (2) *Factor Analysis (FA),* which allows investigating a statistical relationship to determine the importance of each indicator (the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy (above 0.8 is acceptable) and the Bartlett's Test of Sphericity (below 0.05 is acceptable) are used to examine the appropriateness of FA (Hanafizadeh *et al.*, 2009), see Appendix 4.1), and; (3) *Geometric aggregation* (in which indicators are multiplied and weights appear as exponents), which allows investigating the correlation among the performance of the indicators (Nardo *et al.*, 2005b; Saisana, 2008). The composite index scores were calculated by different combinations of alternative methodological techniques, as illustrated in Appendix 4.2.

As seen from the maps in Appendix 4.2, for all sites, the calculation based on 'Expert Opinion Weighting & Geometric Aggregation', 'FA Weighting & Geometric Aggregation' and 'Expert Opinion Weighting & Geometric Aggregation' yield lower sustainability results compared to the MUSIX model results. Specifically, FA weighting with geometric aggregation performed negative differences in a couple of grid cells compared to other scenarios. The underlying reason for this difference depends on the fact that geometric aggregation uses multiplication to summarise data; hence, it performs lower scores than arithmetic aggregation. Additionally, the FA revealed a slightly different categorisation of the indicator set, which is grouped under four factors. As shown in Table 4.12, the first factor includes indicators referring to *Hydrology, Design* and *Efficiency* categories. This correlation can be interpreted as being due to the large amounts of impervious surfaces, which are associated with increased surface runoff, unsustainable design of built environment and higher resource consumption. The second factor includes indicators referring to the *Pollution* category. The third factor includes indicators referring to the *Location* category and the fourth factor includes indicators referring to the *Ecology* category. These factors show the same structure as the MUSIX model categorisation.

Table 4.12 Factor analysis weightings of the indicator set

CATEGORY	**INDICATORS**	**Weighted Factor Loadings**			
		1	**2**	**3**	**4**
HYDROLOGY	Impervious surface ratio (ISR)	0,101	0,000	0,001	0,001
	Surface runoff (SR)	0,092	0,001	0,000	0,003
DESIGN	Lot design (LOTDSG)	0,073	0,003	0,000	0,005
	Landscape design (LNDDSG)	0,092	0,002	0,001	0,004
EFFICIENCY	Energy consumption (ENERGY)	0,070	0,000	0,000	0,004
	Water consumption (WATER)	0,051	0,005	0,003	0,020
POLLUTION	Air pollution (AIR)	0,001	0,096	0,001	0,000
	Stormwater pollution (SW)	0,000	0,094	0,004	0,001
	Noise pollution (NOISE)	0,001	0,047	0,014	0,006
LOCATION	Land use destinations (LUD)	0,001	0,000	0,096	0,000
	Public transport (PT)	0,001	0,002	0,091	0,002
	Walkability (WLK)	0,000	0,000	0,021	0,000
ECOLOGY	Green area ratio (GAR)	0,014	0,000	0,000	0,056
	Albedo (EA)	0,002	0,000	0,000	0,018

In order to assess the overall impact of these different methodological assumptions on the MUSIX model results, Spearman's rank correlation analysis was performed with reference to a number of similar studies (Groh *et al.*, 2008; Groh and Wich, 2009; Saisana, 2010). Due to the large data set, the level of significance was set at 0.05 and a two-tailed test was chosen to identify the level of significant differences between the indicator data set in either direction. The correlation analysis revealed that the impact of any of these assumptions is negligible overall as the correlations between the MUSIX model results and the others is greater than 0.9 (Table 4.13). All correlations are positive, which indicates that they point in the same direction. 'FA Weighting & Geometric Aggregation' method has the lowest correlation while 'Equal Weighting & Linear Aggregation' method has the highest correlation with the implemented method.

Table 4.13 Correlation between the MUSIX model results and different methodological assumptions

Alternative calculation methods	Correlation with the implemented method (Expert opinion weighting, Linear aggregation)
Equal Weighting, Linear Aggregation	**,995****
FA Weighting, Linear Aggregation	,988**
Equal Weighting, Geometric Aggregation	,985**
FA Weighting, Geometric Aggregation	**,975****
Expert Opinion Weighting, Geometric Aggregation	,990**

**. Correlation is significant at the 0.05 level (2-tailed)

Complementary to the correlation analysis, the impact of an underlying indicator on overall outcome of the model was assessed by performing 'exclusion of one indicator at a time'. The analysis was conducted by removing one indicator at a time and then recalculating a reduced model score (Table 4.14). A low correlation between the MUSIX model score and reduced model score implies that the model is highly sensitive to the exclusion of that indicator. The analysis revealed that the removal of the noise pollution indicator had the highest effect while removal of air pollution and walkability indicators have the lowest effect on the overall model score. In general, the correlation between the MUSIX model score and the reduced model scores are greater than 0.5, which is considered to be acceptable (Katz, 1999; Lehman *et al.*, 2005; Morien, 2006; Christmann and Badgett, 2009). This means that the removal of indicators does not significantly change the overall MUSIX model score.

Table 4.14 Correlation between the MUSIX model score and reduced model scores

Reduced Model	Spearman's Correlation
Evapotranspiration removed	,727**
Surface Runoff removed	,657**
Urban Habitat removed	,607**
Microclimate removed	,630**
Stormwater Pollution removed	,674**
Air Pollution removed	**,808****
Noise Pollution removed	**,563****
Proximity to Land Use Destinations removed	,696**
Access to Public Transport Stops removed	,709**
Walkability removed	**,861****
Lot Design removed	,699**

Landscape Design removed	,759**
Energy Conservation removed	,661**
Water Conservation removed	,641**
The MUSIX model	1,000

**. Correlation is significant at the 0.05 level (2-tailed)

4.5 SUMMARY OF THE CHAPTER

In this chapter, the findings of the MUSIX model from the case study sites were presented at both parcel and grid-based levels. While the indicator set of the model provided specific information about the environmental impacts in the area at the parcel scale, the composite index score provided general information about the sustainability of the area at the neighbourhood scale. Following model implementation, sensitivity analysis was undertaken to assess the robustness of the model. The results of the sensitivity analysis showed that the MUSIX model scores are reliable and not highly sensitive to changes in the weighting or aggregation methods. Furthermore, none of the indicators have a dominant effect on the overall result. According to the model findings, the sites located in the canal development performed lower sustainable behaviour than the other case study sites. Environmental impacts associated with canal-estate development include: increased stormwater and runoff, loss of natural vegetation, inadequate public transportation, automobile dependency, and irregular shaped lots covered by large impervious surfaces and lack of energy efficient design (e.g., lot shape, siting of the house, building orientation, use of rain water tanks or solar panels). Furthermore, the sites that are close to the local amenities and services performed better than canal-estate developments. The parcels located in the sites provide a high percentage of green spaces, which also promotes microclimate and outdoor thermal comfort. Additionally, the sites provide a good picture of environmental quality in terms of air and noise pollution. However, these sites also confront the same environmental impacts, such as increased surface runoff, auto-dependent pattern of development as well as dependence on non-renewable resources. Briefly, analysis of the findings clearly shows that there are major environmental impacts in the study area arising from increased impervious surfaces due to urban development and population growth. In light of the model findings, the following chapter provides a more in-depth discussion of the environmental impacts arising from development pressure on urban ecosystems in the case of GCC by highlighting the recommended environmental policy actions.

Chapter 5: Discussion

This chapter provides a discussion of the sustainability performance of the Gold Coast study area from the lens of urban ecosystems. The chapter comprises three main sections. The first section evaluates the current environmental situation of the study area with reference to the 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX) model outputs. The second section consists of recommendations about the integration of the model outputs into sustainable urban development policies. Finally, the third section concludes with a summary of the chapter.

5.1 SUSTAINABILITY PERFORMANCE EVALUATION OF THE GOLD COAST CITY STUDY AREA

Before presenting the general sustainability performance assessment, some conclusions can be drawn based on the six main issues of urban development that the MUSIX model detected in the study area:

1. *Hydrology:* The model results show that land cover change has negative impacts on the hydrologic cycle of the study area. As a feature of urban development, Gold Coast City is made up of a series of human-made canals and waterfront dwellings. However, this residential canal development has resulted in increased runoff rates in the area. For instance, the parcels located on the canal side are covered by large amounts of impervious surfaces. Thus, they yield lower performance in terms of surface runoff rates. Moreover, the results indicate that a large amount of impervious surfaces due to high-density development lower the rate of evapotranspiration in the area.

2. *Ecology:* The model results show that conversion of vegetated surfaces to impervious surfaces alters microclimate and thermal effect of the study area. The canal-estate developments have adverse impacts on urban habitat and ecosystems through the clearing of natural vegetation. New dwellings located on the canals are designed as narrow lots that mostly consist of large amounts of impervious surfaces and less green spaces. Furthermore, old dwellings

have large grassy yards, which are generally unused and neglected. The results indicate that canal parcels have the lowest levels of green area ratio due to the loss of their native vegetation cover from canal construction. This finding indicates that the type of development has a direct and adverse impact on the urban habitat and ecosystems.

3. *Pollution:* The model results of transport related lead (a heavy metal) concentrations in stormwater runoff and in the air indicate that there is a growing stormwater pollution problem due to a high level of car dependency in the study area. Moreover, traffic-related pollution is also associated with the street pattern. For instance, the cul-de-sac street pattern in the study area provides less traffic noise for the adjacent and surrounding parcels, whereas, parcels that are close to a major arterial road are exposed to high levels of noise pollution. In addition to car dependency, canal construction contributes to the stormwater pollution problem in the area. In this respect, the results confirm that Gold Coast City has environmental pollution associated with increased pollutant loads, poor air quality and degraded human welfare.

4. *Location:* The model results show that the study area is highly dependent on car-based transport. There is no easy access to public services within walking distance or enough use of alternative modes of transportation, such as bicycles or buses. This finding shows us that public transport service frequencies and operating hours are not enough to meet the demand. Additionally, the public transport service and frequency in the study area were investigated by Dur (2012) as a part of the same ARC Linkage Project. According to the results of his study, the area yields lower performance in terms of public transport services. Furthermore, the results demonstrate that the design of pedestrian ways and bikeways for the area need to be improved in order to improve the walkability of the streets.

5. *Design:* Existing parcel layouts in the study area are analysed to determine whether or not they meet the principles of passive solar design in terms of lot shape, siting of the house, building orientation, solar access and location of the other buildings. The model results reveal that new dwelling designs respond to the climatic conditions compared to old dwellings. In the summer,

especially, all houses are exposed to direct sunlight, which is not healthy for the thermal comfort of the sites. In addition to this, the landscape design of these parcels is analysed to determine whether or not they meet the principles of South East Queensland (the region that the Gold Coast City is located in) subtropical design. The model results present that high-income dwellings have large and well maintained gardens compared to low income dwellings. However, in general, there is lack of green space as well as climate responsive landscape design in the study area.

6. *Efficiency:* Existing parcels are analysed to determine whether or not they meet the principles of energy and water efficient designs. The researched principles are summarised as: (i) use of appropriate building and pavement materials; (ii) use of open living spaces such as balconies, courtyards and verandas; (iii) use of green roofs; (iv) use of sustainable energy sources such as rain water tanks and solar panels, and; (v) meeting water consumption targets implemented by the Queensland Water Commission. The results indicate that most of the dwellings lack climate responsive design strategies in terms of energy and water efficiency aspects. For instance, the use of rainwater tanks and solar energy is not common in the area. Furthermore, most of the houses have only grass and swimming pools in their backyards, which have a major impact on water usage.

In light of the above-mentioned six key aspects of environmental issues, the MUSIX model provides a holistic sustainability assessment by monitoring the impacts of impervious surfaces on the urban ecosystem of Gold Coast City. According to the findings of the model, the growing residential pressure and canal-estate developments in the study area result in increased impervious surfaces, which have significant impacts on the site hydrology through increased surface runoff. In addition to this, the car-dependent pattern of development in the area contributes to surface runoff by creating more impervious surfaces and increases the risk of the transport of pollutants to the waterways. An increase in the impervious surfaces also affects the ecology of the study area by clearing natural vegetation. Furthermore, their high thermal conductivity and heat storage capacity causes increased land surface temperatures. However, there is a large use of light-coloured roofing material and surface design related to climatic conditions in the area that mitigates the negative impacts of impervious surfaces.

The conventional suburban development patterns in some parts of the study area provide a hierarchy of streets beginning with cul-de-sacs and result in large intersections at major junctions, greater congestion along major streets and an environment that discourages pedestrian and bicycle travel. The intense transportation activities in the study area contribute to air pollution through the emission of greenhouse gases, particulates and toxic gases. Furthermore, stormwater and noise pollution are the other problems of car dependency. Parcels with large impervious surfaces contribute to environmental pollution by carrying pollutants from roads and parking lots into waterways via stormwater and reflecting high-frequency road traffic noise. These environmental impacts caused by impervious surfaces also affect human health by causing psychological symptoms and affect wildlife habitats in the city by disrupting their breeding, feeding and migration patterns.

As the study area is highly dependent on motor vehicle use, there is limited accessibility by walking (800 m) to land use destinations such as convenience stores, shopping malls, banks, ATMs, cafes and restaurants. According to the findings of the model, the type of development affects local amenity accessibility. For instance, canal-estate developments are far from local amenities and services and do not have any public transport access. The rest of the study area has favourable accessibility. When we look at the lot and landscape design in the study area, as a result of high-density development, the area consists of narrow parcels with small backyards or large parcels with no vegetation cover. These parcels usually have large amounts of impervious surfaces and swimming pools in their backyards. Passive solar design is an important part of lot design through the encouragement of energy efficiency in subtropical regions like the study area. Unfortunately, most of the parcel layouts do not meet the principles of passive solar design in terms of lot shape, building orientation or solar access. Additionally, there is a lack of interest about climate responsive landscape design in the study area which may cause significant effects on the microclimate, such as higher levels of temperature, humidity, air pressure, wind speed and energy usage. Another important aspect of climate responsive design, the implementation of energy and water saving strategies is not common in the study area. For instance, most of the houses have swimming pools, which have a major impact on water usage. Furthermore, waterfront development is also not suitable for water conservation methods, such as underground rainwater tanks.

In conclusion, the outcomes of the model show that there are major environmental impacts caused by increased impervious surfaces from rapid urban development in Gold Coast City. According to the results, increased impervious surfaces are linked to higher surface temperatures, increased surface runoff, car dependency, transport related pollution, poor public transport accessibility, unsustainable urban design approaches as well as water and energy use. The results also indicate that there is a growing gap between the depletion of natural resources in the urban ecosystem and their capacity to meet the human demands. Thus, there is a need to revise the current planning and development practices in order to provide more effective land use policies to protect natural resources in the urban ecosystem. The next section discusses how the model outputs can be used to formulate and implement sustainable urban development policies.

5.2 INTEGRATION OF THE MODEL OUTPUTS WITH SUSTAINABLE URBAN DEVELOPMENT POLICIES

As mentioned previously in the methodology chapter, a conceptual framework for the environmental assessment and reporting structure of the MUSIX model, which is adapted from the Driving force-Pressure-State-Impact-Response (DPSIR) framework was developed in order to examine the linkages between human activities and ecosystems by clarifying the complex relationship between them. The aim of this framework was to serve as a useful tool for reporting this relationship as well as helping to develop potential solutions for addressing the impacts. In this context, this framework provided a better understanding of the selection of indicators that are relevant to the environmental sustainability assessment of the study area and also provided a conceptual basis for the policy recommendations for sustainable urban development.

As shown in Figure 5.1, each component of this framework represents the following aspects of the model:

- *Driving forces* are the underlying causes that lead to environmental pressures on the urban ecosystem;
- *Pressures* are the environmental problems caused by driving forces;
- *State* variable refers to the selected indicators of the model that monitor the pressures and problems;
- *Impacts* correspond to the indicator sub-category sets of the model that express the level of impacts on urban ecosystem, and;
- *Responses* are the actions that are taken in order to achieve a sustainable urban future.

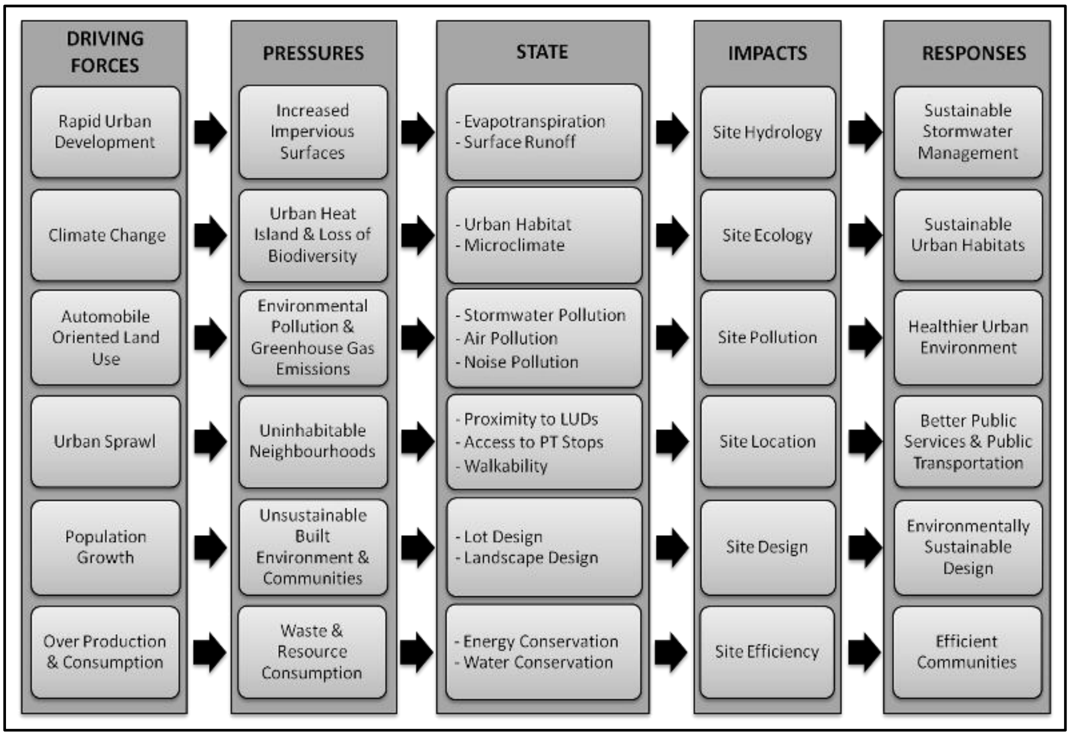


Figure 5.1 DPSIR framework of the MUSIX model

The results have shown that the MUSIX model can serve as a useful tool to address the environmental impacts arising from development pressure on the urban ecosystem in the case of Gold Coast City. The model also provides fundamental information and guidance that can be incorporated into the planning scheme in order to guide the development of sustainable policies. In light of the model findings, the issues, related policy objectives and proposed ecological planning strategies can be categorised based on the DPSIR framework under the following headings:

Box 5.1 Policy objective 1

Policy objective: Establishing hydrological conservation through sustainable stormwater management in order to preserve the Earth's water cycle and aquatic ecosystems.
Driving Force: The model detected that there is growing environmental pressure in the study area due to rapid urban development.
Pressure: As a result of rapid urban development, increased built and paved surfaces lead to less evapotranspiration as well as infiltration and increased runoff from urban areas, which affect the catchment hydrology.
State: The selected indicators for monitoring the pressures and problems in the area are: (1) evapotranspiration, and; (2) surface runoff.
Impacts: The selected indicators measure the sustainability performance of site hydrology.
Responses: The following ecological planning strategies need to be taken into consideration: • The sustainable stormwater management and flood prevention needs to be provided through improving green infrastructure. Specifically, the results show that the type of development, such as canal estates has adverse impacts on stormwater quantity. In this context, green infrastructure can mitigate these impacts. • The natural hydrological balance of the study area needs to be protected by water sensitive urban design i.e., the Pimpama Coomera Waterfuture Project. Water sensitive urban design practices, such as swales, bioretention trenches and rain gardens provide an integrated approach to surface runoff management. • The results show that transport-related activities in the study area cause stormwater pollution. Therefore, pollutants from stormwater runoff need to be removed by using infiltration basins, pollutant traps, constructed wetlands and vegetated buffers. • The runoff and peak flows needs to be reduced by using highly water-retaining roofing systems, vegetated rooftops, rain barrels and permeable paving. • The evapotranspiration balance of the study area needs to be improved through increased vegetated surfaces, which contribute cooling air temperature by absorbing radiation from impervious surfaces.

Box 5.2 Policy objective 2

Policy objective: Providing ecological conservation through sustainable ecosystem management in order to protect biological diversity and maintain the integrity of natural ecosystems.
Driving Force: The model detected that there is a growing environmental pressure in the study area due to climate change.
Pressure: Increased built and paved surfaces are linked to global warming and cause climate change that results in the urban heat island effect and loss of biodiversity.
State: The selected indicators for monitoring the pressures and problems in the area are: (1) urban habitat, and; (2) microclimate.
Impacts: The selected indicators measure the sustainability performance of site ecology.
Responses: The following ecological planning strategies need to be taken into consideration: • The results show that canal-estate development has adverse impacts on urban habitat through the clearing of natural vegetation. Therefore, the maintenance of the existing native biodiversity and natural ecosystems needs to be provided through improving urban green spaces. • There is growing land clearing and urban development in the study area. Therefore, the rehabilitation of endangered and threatened species needs to be provided. A wildlife habitat also needs to be provided in order to continue their migration, nesting and breeding maintenances. • The community awareness of environmental issues in the area as well as the need for protection of ecosystems and biodiversity needs to be promoted. Additionally, the new developments need to be focused on previously developed, degraded or Brownfield sites that have no ecological value. • The results show that the study area is losing its native vegetation cover from increased impervious surfaces and canal construction. Therefore, the city's green space network needs to be improved through creating public parks, greenways, community gardens, green roofs or green walls. • As a result of increased paved surfaces, the heat island effect needs to be mitigated by using highly reflective materials, light-coloured surfaces and green or shaded surfaces.

Box 5.3 Policy objective 3

Policy objective: Improving environmental quality through developing pollution prevention regulations and policies in order to promote high quality water resources, clean air and enhanced ecosystem health.
Driving Force: The model detected that there is a growing environmental pressure in the study area due to automobile oriented land-use patterns.
Pressure: The evolution of technological change, the introduction of motorised vehicles and the automobile oriented land-use patterns have a distinctive impact on environmental quality including air, water and noise pollution.
State: The selected indicators for monitoring the pressures and problems in the area are: (1) stormwater pollution, (2) air pollution, and; (3) noise pollution.
Impacts: The selected indicators measure the sustainability performance of environmental quality of the site.
Responses: The following ecological planning strategies need to be taken into consideration: • As a feature of urban development, the study area is made up of a series of human-made canals and waterfront dwellings that affect the water quality. In this context, the natural hydrology of the water systems needs to be protected by reducing the construction of man-made water bodies, such as reservoirs, canals and ponds. • The results show that people who live close to major arterial roads are exposed to high levels of noise pollution. The impact of noise pollution needs to be reduced through appropriate planting, sound insulation or other construction techniques. • The results show that there is a growing stormwater pollution problem due to the high level of car dependency in the study area. Therefore, transport-related air pollution and emissions need to be reduced by promoting green transportation. • In addition to providing outdoor environmental quality, the indoor environmental quality and health in the study area also needs to be improved through green building design strategies. • To improve environmental quality within the study area, greenbelt development also needs to be encouraged. Moreover, greenbelt development improves the aesthetic quality of the study area.

Box 5.4 Policy objective 4

Policy objective: Creating sustainable mobility and accessibility through designing better local services and walkable neighbourhoods in order to promote safe environments and healthy communities.
Driving Force: The model detected that there is growing environmental pressure in the study area due to urban sprawl.
Pressure: Increased demand for human needs resource consumption lead to more intense and complex patterns of land use. These dispersed, automobile oriented land-use patterns degrade environment by creating unliveable neighbourhoods.
State: The selected indicators for monitoring the pressures and problems in the area are: (1) proximity to land use destinations, (2) access to public transport stops, and; (3) walkability.
Impacts: The selected indicators measure the sustainability performance of site location.
Responses: The following ecological planning strategies need to be taken into consideration: • As a result of automobile oriented land-use patterns in the study area, the automobile dependency needs to be reduced by providing different transport modes and mixed-use neighbourhood centres. Moreover, walking and cycling activities needs to be encouraged through designing safe and well-connected walking and cycling pathways. • The results show that there is no easy access to public services within walking distance and that the alternative modes of transportation, such as bicycles and buses, are inadequate. In this context, public transport needs to be encouraged in the area by providing efficient PT routes and times. • To reduce automobile dependency, new residential and commercial developments need to be located close to local services and amenities. Furthermore, an easy access to open spaces needs to be provided to encourage physical recreational activities. • The study area needs to be designed a people-orientated city through walkable, appealing and comfortable streets. Furthermore, a safe and convenient environment also needs to be provided with crime prevention through environmental design.

Box 5.5 Policy objective 5

Policy objective: Sustainable design of urban environment through climate responsive design in order to increase the efficient use of solar energy to provide thermal comfort.
Driving Force: The model detected that there is a growing environmental pressure in the study area due to population growth.
Pressure: As a result of urban sprawl, the layout of new developments alters the natural environment and creates a built environment and communities that are unsustainable.
State: The selected indicators for monitoring the pressures and problems in the area are: (1) lot design, and; (2) landscape design.
Impacts: The selected indicators measure the sustainability performance of site design.
Responses: The following ecological planning strategies need to be taken into consideration: • The results show that conversion of vegetated surfaces to impervious surfaces alters the microclimate and thermal effect of the study area. In this context, the microclimate needs to be improved by controlling solar radiation, humidity and wind and air temperature. • To improve thermal comfort, energy conservation needs to be encouraged through passive design strategies, such as solar orientation, passive heating and cooling, natural ventilation and thermal mass. • Energy conservation also needs to be encouraged through climate responsive landscape design. Climate responsive landscape design reduces heating and cooling energy needs as well as improves the comfort level of outdoor spaces by shading in subtropical regions like the study area. • There are many significant effects of buildings on the thermal comfort through design, material form, types and colours. Therefore, thermal comfort needs to be improved by using climate responsive building and pavement materials as well as creating outdoor living spaces, such as courtyards, verandas or green roofs. • The results show that the study area lacks green spaces. Therefore, eco-friendly landscape design needs to be integrated into the built environment in order to support local biodiversity by using endemic vegetation.

Box 5.6 Policy objective 6

Policy objective: Use of renewable resources through creating efficient communities in order to provide a long-term management of natural resources for the sustainability of future generations.
Driving Force: The model detected that there is growing environmental pressure in the study area due to over production and consumption.
Pressure: Private households make significant contributions to environmental sustainability in terms of resource consumption.
State: The selected indicators for monitoring the pressures and problems in the area are: (1) energy conservation, and; (2) water conservation.
Impacts: The selected indicators measure the sustainability performance of site efficiency.
Responses: The following ecological planning strategies need to be taken into consideration: The results show that implementation of energy and water saving strategies is not common in the study area. In this context, more efficient use of resources needs to be provided by: • Encouraging alternative sources such as photovoltaic panels and solar water heating; • Using sustainable and renewable materials in building and pavement construction; • Encouraging reuse of vegetative debris for landscaping or composting purposes; • Improving water use efficiency through water-saving systems such as rainwater harvesting, recycled water reticulation and grey water reuse; • Minimising outdoor water use through water efficient landscaping and irrigation systems; • Encouraging swimming pool efficiency through use of pool covers, rainwater tanks, energy-efficient pump and filtration systems, and; • Sustainable waste management though recycling, reusing and reducing waste.

5.3 SUMMARY OF THE CHAPTER

In this chapter, the significant findings of the MUSIX model in the case of Gold Coast City are presented. According to the model results, some key ecological planning strategies are recommended to guide the preparation and assessment of development and local area plans in conjunction with the Gold Coast Planning Scheme, which establishes regulatory provisions to achieve ecological sustainability through the formulation of place codes, development codes, constraint codes and other assessment criteria that provide guidance for best practice development solutions. These recommended strategies contribute in so many ways to environmental sustainability which can be summarised as follows:

- *Sustainable approaches need to be adapted to urban stormwater management in order to:*
    - Reduce the impact of urban development;
    - Manage surface runoff;
    - Reduce pollution, flooding and erosion risks;
    - Improve the green infrastructure, and;
    - Protect water and air quality.
- *Sustainable ecosystem management needs to be provided in order to:*
    - Preserve the existing native biodiversity and natural ecosystems;
    - Protect endangered and threatened species;
    - Promote urban green space network, and;
    - Reduce the urban heat island effect from impervious surfaces.
- *Pollution prevention regulations and policies need to be developed in order to:*
    - Provide environmental quality;
    - Reduce air emissions and stormwater discharges;
    - Prevent transport-related noise pollution, and;
    - Provide a healthy environment.
- *Sustainable mobility and accessibility need to be provided in order to:*
    - Minimise automobile dependency;
    - Promote walking, cycling as well as public transport;
    - Provide mixed-use neighbourhoods that are easily accessible, and;

    - Provide a safe and convenient environment for pedestrians.
- *Sustainable design of urban environment needs to be achieved in order to:*
    - Ameliorate the microclimate and improve thermal comfort;
    - Reduce the environmental impact of buildings and paved surfaces;
    - Encourage energy efficiency, and;
    - Provide a better visual effect on built environment.
- *The use of renewable resources needs to be encouraged in order to:*
    - Provide energy conservation;
    - Improve water use efficiency;
    - Provide sustainable waste management, and;
    - Achieve the long-term management of natural resources.

The findings have shown that the MUSIX model has the potential to be used for measuring and benchmarking sustainability performances, particularly at the local and micro-levels through the development of sustainability indicators and composite indices. The research has also demonstrated what type of environmental policies can be generated to promote sustainable urban development by implementing the MUSIX model. The following chapter provides conclusions, discusses the research implications and outlines the strengths and weaknesses of the model. Furthermore, future research recommendations are presented.

Chapter 6: Conclusion

This chapter provides a conclusion to the study by summarising the major research findings in relation to these research questions, aim and objectives. Furthermore, this chapter presents research implications, limitations and recommendations for further research.

6.1 RESEARCH FINDINGS

The main purpose of this study was to investigate the impacts of urban development on the natural environment by developing a micro-level indexing model to assess their indirect or consequential effects by using environmental sustainability indicators. In order to meet this aim, three major research objectives were developed. The first objective was to identify the environmental impacts of impervious surfaces on urban ecosystem. The second objective was to develop a set of indicators in order to define the environmental issues within urban areas at a micro-level spatial unit. The third objective was to establish an urban ecosystem sustainability assessment tool that assesses the sustainability of urban development policies. In light of the research aim and objectives, the following research questions were addressed in this study:

What are the major environmental impacts arising from globalisation and population growth?

The literature review has shown that globalisation and population growth have been threatening the sustainability of resources by changing the structure and functioning of the environment. Human beings have exceeded the carrying capacity of the Earth by consuming natural resources, damaging the climate and generating more waste. As a result of population growth, the changes in land use patterns and changing needs and lifestyle expectations of people living in these patterns have altered the natural environment. Moreover, globalisation, rapid urbanisation, development of industrialisation and modern transportation systems, increased consumerism and overproduction has affected the natural environment in several ways:

- Loss of soil fertility and fragmentation of landscape, disruption of nutrient cycle, poor irrigation and drainage systems, erosion risks, chemical and hazardous wastes;
- Reduced infiltration, increased surface runoff, increased urban flood events, water contamination and urban heat island effect;
- Air pollutants and emissions, pulmonary diseases, heart disorders, lung cancer, headache, fatigue, increased mortality and neurobehavioral problems;
- Climate change (warmer temperatures, intense precipitation rates, rising sea levels and devastating weather events such as storms or hurricanes), and;
- Loss of biodiversity (altered quality and quantity of habitats available to flora and fauna).

How can long-term sustainable management of urban ecosystems be achieved through an ecological planning approach?

For a sustainable built environment, it is necessary to regulate the natural processes and control the scale of human activities; therefore, environmental processes need to be integrated into the planning process. This integration is important in terms of understanding the physical characteristics of the developed areas as well as recognising the mechanism of environment, its potential, limitations and risks in the planning process. In this respect, ecological planning is a fundamental approach to the sparing and efficient use of natural resources while adopting human activities in a less harmful way to the environment. It is an important planning tool in the establishment of sustainable urban ecosystems. Long-term sustainable management of urban ecosystems can be achieved through ecological planning approach, such as:

- The use of green infrastructure (i.e., ventilation lanes, climate-relevant green spaces, roof greening, facade greening);
- The use of green transport through high priority of designing pedestrian and cycle tracks);
- Stormwater management for improved stream quality;

- Biodiversity plan for the ecological function and richness of urban environment;
- The use of renewable sources and waste management.

<u>What are the existing assessment methodologies and their sustainable outcomes?</u>

Urban ecosystem sustainability assessment is a powerful tool for tracking environmental progress as well as the environmental effects of policies and actions taken for sustainable development. It is an essential process in the development of sustainable polices in terms of collecting information to the planners and decision makers about the severity of environmental problems and their impacts on natural environment. Urban ecosystem sustainability assessment is performed via applying different approaches and tools ranging from indicators to comprehensive models, which were presented in the second chapter. Even though they use different assessment themes and sub-themes, they outline the common sustainability principles, such as conservation of native vegetation, reduction of non-renewable energy use, waste reduction, water efficiency, high quality public transport and social safety. Therefore, they provide valuable information for effective decision-making and policy formulation by (UNEP, 2004):

- *Supporting sustainable development*: The assessment results: (1) highlight the economic, social, environmental opportunities and constraints; (2) organise the policy and decision-making process by reducing the complexity of each stage, and; (3) help governments to reach proposed sustainability targets.
- *Facilitating good governance and institution-building:* The integrated assessment: (1) promotes the transparency of policy and decision-making process; (2) helps build social consensus about its acceptability, and; (3) enhances coordination and collaboration between different government ministries and bodies.
- *Saving time and money:* The integrated assessment: (1) strengthens the intersectoral policy coherence; (2) provides early warning of the potential problems, and; (3) minimises environmental, social and health impacts thereby reducing the costs required to remedy them.

- *Enhancing participatory planning for sustainable communities:* The integrated assessment: (1) increases the awareness of governments and citizens on the significance of ecosystem functioning, and; (2) strengthens national commitment to sustainable development.

How can a new sustainability assessment approach be developed to monitor the parcel-scale environmental impacts of human activities? How can this approach be integrated into planning policies and practices for present and future settlements?

Several methods are used in urban ecosystem sustainability assessment and among them sustainability indicators and composite indices are the most commonly used tools for assessing the progress towards sustainable land use and urban management. Currently, a variety of composite indices are available to measure the sustainability at the local, national and international levels. However, the main conclusion drawn from the literature review is that they are too broad to be applied to assess local and micro level sustainability and no benchmark value for most of the indicators exists due to the limited data availability and non-comparable data across countries. In this context, there is a need for developing an accurate and comprehensive micro-level sustainability assessment method. To advance research in this area, this study developed a new sustainability assessment tool entitled 'Micro-level Urban-ecosystem Sustainability IndeX' (MUSIX).

Through a case study of Gold Coast City, the MUSIX model investigated the environmental impacts of an existing urban residential area by using a set of indicators with the aim to identify the interaction between urban ecosystems and human activities in the context of environmental sustainability. A set of relevant indicators were developed through a comprehensive review of existing indicator initiatives. Additionally, an expert panel, consisting of practitioners and academics from the Gold Coast City Council, Queensland Transport and Main Roads and Queensland University of Technology, reached a consensus on the desired indicators through a series of workshops. The indicators of the model provided information referring to the six main environmental impacts arising from rapid urban development and population growth: (1) increased built and paved surfaces; (2) urban heat island effect and loss of biodiversity; (3) environmental pollution; (4) inaccessible neighbourhoods; (5) unsustainable built environment and communities, and; (6) resource consumption. Related to that, the model results set out the following urban design principles which can be incorporated into the planning scheme in order to achieve environmentally sustainable cities:

Sustainable urban form: As characterized by Williams *et al.* (2000), sustainable urban form refers to a compact urban design with mixed land-use, interconnected street patterns that are well integrated with public transport networks, high-quality environment and efficient use of urban land. This study has shown that the current form of urban development dramatically degrades natural ecosystems and their ecological services through land cover change. For instance, human-made canals and waterfront dwellings in the study area result in increased impervious surfaces, which cause many environmental impacts, such as increased stormwater and runoff, loss of natural vegetation, inadequate public transportation and automobile dependency. In this context, development patterns have to be designed to support natural land cover by implementing eco-friendly policies, such as sustainable stormwater management, green transportation, green infrastructure and building design.

Environmental protection and restoration: Urban green spaces play an important role in urban sustainability. They bring nature into city life and make urban places more attractive and pleasant. Furthermore, they ameliorate the negative impacts of urban development and provide a habitat for wildlife and aquatic life (Coplak and Raksanyi, 2003; Jabareen, 2006; Convery *et al.*, 2008). This study has indicated that the form of urban development is important for environmental protection and restoration. The results have shown that the study area loses its native vegetation cover from canal-estate developments. Therefore, the existing native biodiversity and natural ecosystems have to be protected and restored by improving ecologically rich open spaces, such as public or private green spaces (i.e., gardens, parks, green alleys and streets, green roofs) and green buffer zones (i.e., green belts, green wedges, green ways, green fingers).

Efficient use of land with high quality local services and amenities: Reducing the need for vehicle travel is one of the essential goals in achieving sustainable cities. Therefore, mixed land-use planning has an important role to achieve this goal. Mixed land-use provides many services within a walking distance, and, thus encourages walking, cycling and public transport use (Thorne and Filmer-Sankey, 2003). One of the important findings from this study was that the efficient use of land with high quality local services and amenities contributes to environmental sustainability. According to the model results, due to its long distance from the urban centre, edge developments in the study area have limited accessibility to local services and amenities as well as public transportation. In this context, mixed land-use development that is easily accessible to public transportation has to be encouraged in order to reduce car dependency and its associated environmental impacts.

Sustainable mobility and accessibility: The form of current cities indicates that transportation systems are the determinant of the development of urban form, thus there is a need for sustainable transportation that refers to transportation services that respect the carrying capacity of the Earth's systems by promoting energy-efficient and environmentally friendly transport options (Jabareen, 2006). This study has shown that auto-dependent communities are one of the most important environmental issues relating to the development of city form. For instance, the automobile oriented land-use patterns of the study area create a distinctive impact on environmental quality including air, stormwater and noise pollution. The results also show that there is no easy access to public services within walking distance in the area. In this context, sustainable mobility and accessibility have to be encouraged by creating pedestrian-friendly cities. Moreover, accessibility to public transport has to be promoted through efficient routes and times.

Climate responsive design: Another important finding from this study was that the built environment alters microclimate through building location, orientation, design, material form, types and colours. In this context, urban form, buildings and the landscape design have to respond to the climate of the area. Passive design is a design approach that encourages energy efficiency by using solar energy for the heating and cooling of living spaces. Passive design improves the urban microclimate by creating optimum conditions for the use of solar design strategies, such as orientation, building shape, shading, glazing, thermal mass and insulation. Additionally, climate responsive landscape design reduces heating and cooling energy needs as well as improves the comfort level of outdoor spaces by controlling the microclimate (Hyde, 2000; Suagee, 2011; ATA, 2012).

Resource efficiency: Unsustainable patterns of consumption are the major cause of global environmental degradation today. As defined by the Ministry of the Environment, Norway (1995), sustainable consumption and production minimizes the use of natural resources and toxic materials as well as the emissions of waste and pollutants so as to protect resources for future generations. This study has illustrated that a renewable approach to resource use is essential for developing sustainable communities. According to the model results, as another important aspect of climate responsive design, the implementation of energy and water saving strategies is not common in the study area. For instance, most of the houses have swimming pools without rainwater tanks which have a major impact on water usage. Waterfront development is also not suitable for water conservation methods, such as underground rainwater tanks. Therefore, a more efficient use of resources has to be provided in order to provide long-term management of natural resources.

6.2 IMPLICATIONS OF THE RESEARCH

This research makes a contribution to the body of knowledge and practice of sustainable urban development in a number of ways:

First, this research develops a micro-level environmental sustainability index that aims to provide reporting guidance to planners and policy-makers for sustainability assessment. In recent years, an increasing number of sustainability indices have been developed to measure progress towards sustainable urban development. They evaluate environmental impacts at the macro-levels from national to regional and international levels. However, in most of them, there is a particular gap in data availability for many countries due to the lack of local data. As a result of challenges in data collection difficulties and availability of local data, there is no effective micro-level assessment tool that measures urban ecosystem sustainability accurately. In this context, the MUSIX model fills this gap by focusing on the measurement of sustainability performance at micro-level.

Second, this research monitors environmental issues associated with land cover change by developing relevant parcel-scale indicators. For this study, data collection was a major problem due to the unavailability of data at the parcel-scale. As most of these indicators had never been used before because of data unavailability, some assumptions have been made for the normalisation and calculation of the indicators, which were presented in the methodology section. According to the literature, the impacts of environmental issues have different temporal and spatial characteristics. Many problems that emerged at the local level several years ago have become national and global problems today. Therefore, indicators need to be developed at the local-level in order to provide information about the impact on a national and global scale. In this context, the MUSIX model fills this gap by identifying a set of parcel-scale indicators that can be used for monitoring the impacts of existing development planning on urban ecosystems.

Third, this research assesses the sustainability of the residential developments through providing data analysis and interpretation of results in a new spatial data unit. From the literature, increased population, resource consumption and environmental pressures draw great attention to effective management of land by developing environmental policies. To ensure the best use of land as well as meet the demands of future developments, more detailed information about land characteristics need to be collected and processed. By developing and testing the MUSIX model, this research validates that parcel-based spatial analysis collects reliable and accurate land use information for planners and policy-makers. The results confirm that the model can be used for benchmarking sustainability performance at the micro-level and that it also serves as a tool for different stakeholders in order to discuss and develop sustainability policies as followings:

- The model helps master planned communities and developers to rate the sustainability of their development which can also be linked to other sustainability rating systems, such as BREEAM, LEED, Green Star, and CASBEE;
- The model assists local governments to detect environmentally problematic areas in the existing settlements, thereby; this information can be used to improve the future development of infrastructure and services;
- The model increases the awareness of individual residents on the environmental issues and the model findings can be used to make sustainable improvements in the residential parcels.

6.3 LIMITATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The results of this study have shown that the MUSIX model provides fundamental information and guidance that assists developers, planners and policy-makers to investigate the multidimensional nature of sustainability at the local level by capturing the environmental pressures and their driving forces in highly developed urban areas. However, like other indices, the MUSIX model has both strengths and limitations. The strengths of the model include:

- The model is based on a theoretical framework that investigates all aspects of environmental sustainability including hydrology, ecology, pollution, location, design and efficiency with a relevant indicator set.
- The model serves as a rating tool for assessing the environmental performance of the current development by highlighting environmental opportunities and constraints in the area.
- The model also serves as a design support tool for assisting the environmental quality of future urban areas by setting standards for energy-efficient and climate-responsive residential parcel design.
- The model provides a snapshot of the current local environmental situation, which the outputs can be used for setting environmental policies, objectives and targets. Thus, it provides a useful assessment tool for the local government planning scheme in order to guide the development of sustainable policies.
- The model assists governments and planning institutions at the local level to monitor and evaluate urban ecosystems by providing quantitative information for key environmental impacts.

The limitations of the model include:

- Data availability and quality is an essential prerequisite for an accurate measurement of sustainability performance. For many of the indicators in the model, data were not available at the parcel scale. Therefore, some indicators had to be omitted and a number of assumptions, which are based on the best available information, were made for the parameter assignment and calculation of remaining indicators, which are subject to limitations.

- As measuring environmental sustainability encompasses a wide range of issues, the indicator set of the model was selected by considering sustainability characteristics of the local area, environmental concerns and data availability. However, they can be adapted and applied to different land uses by excluding or including new indicators.
- The spatial scale of the model, parcel-level, was selected particularly based on the sustainability assessment of residential dwellings. However, for some large parcels, such as schools or shopping centres, it needs to be taken into consideration that the parcel-level scale might cause loss of detail.
- The cost of implementing sustainable design practices becomes an important issue in the use of sustainability assessment tools. Therefore, it is necessary to use the assessment tool early in the design and development process in order to reduce the cost and time required to remedy the environmental problems that occurred after development.
- As sustainability is measured by different indicators, there might be compensability issues among the indicators while aggregating the indicator scores (i.e., one or more indicators receive good scores while others get poor scores). In this case, in order to avoid this issue, non-compensatory multi-criteria aggregation approach needs to be used (Nardo *et al.*, 2005b).
- While doing the land cover measurement through aerial remote sensing data, challenges occurred during land cover detection. For some residential areas, the images were not detectable due to poor data resolution, weather conditions or shadowing issues. Hence, some practical and time-efficient solutions were implemented for the success of the study.
- As a future research direction, it is planned to restructure the model by updating the dataset with more detailed and recent information, which will enable it to be used to measure the changing performance of the urban development over time.

Finally, this study has shown that the outcomes of the MUSIX model are very promising and worth further development with more comprehensive methodology and recent data. As the purpose of this study is to identify the process of developing a micro-level sustainability assessment tool, the model currently can be implemented only for Gold Coast City. However, as an extension of this study, further research can be carried out to adapt and apply the model to different land use patterns as well as cities. In this way, the results can be compared with each other in order to give information about evaluating the sustainability performance of different land uses and cities. It is important to mention again that the indicator set needs to be further developed in order to include all the aspects of environmental indicators that were excluded from the model because of data unavailability.

There are many stakeholders with different priorities and objectives involved in the urban planning decision-making process, thereby; a Multiple Criteria Decision Making (MCDM) evaluation is required to select the best decision alternatives from the perspectives of different authorities. As a future direction of this study, the MUSIX model can be improved and used for alternative future scenarios in the decision-making process. The model results detect the sustainability performance of current urban settings referring to six complex issues of urban development, which are: (1) hydrology, (2) ecology, (3) pollution, (4) location, (5) design, and; (6) efficiency. The key role of the model in decision-making process can be to provide information to compare the level of sustainability associated with these issues during the evaluation of proposed projects and plans. Therefore, the model helps practitioners to choose the most appropriate plan that best accomplishes sustainability goals in the area. Moreover, the model can be further developed in order to facilitate interdisciplinary coordination in decision-making. The model findings can promote coordination and collaboration between different government ministries and bodies work together towards ensuring environmental sustainability of neighbourhoods.

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Appendices

APPENDIX 3.1: NEIGHBOURHOOD DESTINATION ACCESSIBILITY INDEX (NDAI) DOMAIN WEIGHTINGS

Domain/sub-domain	Data type	Maximum sub-domain score	Weighting score
1. Education			
Kindy/daycare/playcentres	Binary	1	
Primary schools	Binary	1	
Intermediate/full primary schools	Binary	1	
Secondary schools	Binary	1	
Total		4	4
2. Transport			
Bus stops & train stations	Tertile	3	5
3. Recreation			
Accessible green space	Tertile	3	
Sports facilities	Tertile	3	
Beaches	Tertile	3	
Total		9	5
4. Social & Cultural			
Museums/art galleries	Binary	1	
Public libraries	Binary	1	
Churches	Binary	1	
Cinemas	Binary	1	
Community halls/centres	Binary	1	
Marae	Binary	1	
Cafes and restaurants	Binary	1	
Alcohol outlets (hotels, taverns, clubs, bottle stores)	Binary	1	
Total		8	3
5. Food retail			
Supermarkets	Binary	1	
Convenience stores/dairies	Binary	1	
Petrol Stations	Binary	1	
Fast food outlets	Binary	1	
Butchers & Fishmongers	Binary	1	
Bakeries	Binary	1	
Greengrocers	Binary	1	
Total		7	5
6. Financial			
Banks, Credit Unions & ATMs	Binary	1	
Post offices	Binary	1	
Total		2	3
7. Health			
General practitioners	Binary	1	
Pharmacies	Binary	1	
Plunket	Binary	1	
Total		3	2
8. Other Retail			
Shopping centres/malls	Binary	1	
Video shop	Binary	1	
Retail - Op Shop	Binary	1	
Total		3	4

APPENDIX 3.2 KOLMOGOROV–SMIRNOV TEST

One-Sample Kolmogorov-Smirnov Test

		ISR	SR	SW	AIR	NOISE	GAR	EA	LUD	PT	WLK	LOTDSG	LNDDSG	ENERGY	WATER
N		2843	2843	2843	2843	2843	2843	2843	2843	2843	2843	2843	2843	2843	2843
Normal Parameters[a],b	Mean	2,296166	2,461133	3,765389	4,864931	4,266268	1,481182	3,949349	2,594091	2,521632	1,404854	2,515301	2,057334	2,335209	2,670067
	Std. Deviation	,6131988	,6367955	,4238302	,3418569	,8647924	,9861360	,3063406	,8278196	1,4205959	,7960611	1,0782353	1,2182137	1,1541233	1,0394273
Most Extreme Differences	Absolute	,464	,379	,475	,519	,301	,432	,493	,275	,282	,486	,327	,269	,248	,244
	Positive	,464	,379	,290	,346	,198	,432	,412	,198	,282	,486	,327	,269	,248	,244
	Negative	-,313	-,233	-,475	-,519	-,301	-,313	-,493	-,275	-,243	-,306	-,215	-,193	-,138	-,208
Kolmogorov-Smirnov Z		24,751	20,224	25,351	27,649	16,051	23,026	26,279	14,687	15,025	25,908	17,416	14,364	13,210	13,024
Asymp. Sig. (2-tailed)		,001	,001	,001	,001	,001	,001	,001	,001	,001	,001	,001	,001	,001	,001

APPENDIX 3.3 INVITATION LETTER

Queensland University of Technology

SURVEY ON ASSESSMENT FOR SUSTAINABLE URBAN ECOSYSTEMS: AN INDEX FOR GOLD COAST

Dear Sir/Madam

I am Ms. Didem Dizdaroglu, a current PhD student at the School of Urban Development. This research is a part of an Australian Research Council (ARC) Linkage project conducted in conjunction with the Gold Coast City Council (GCCC) and Queensland Department of Transport and Main Roads (DTMR), which investigates the interrelationship between landuse, transport and land cover with pollutants and stormwater quality. The research team invites you to participate in our survey. We would like to obtain your assessment about sustainability performance of the selected areas regarding individual indicator values via an expert survey.

The survey consists of two stages. Firstly, we prepared a survey showing various snapshots of lots in the selected case study areas. We will ask you to give a sustainability score for each lot from high to low (on a Likert scale) according to the indicator scores. Secondly, we prepared a general ranking survey sheet which consists of three steps. Firstly, you will rank the importance of the indicators in terms of their contribution to environmental sustainability assessment. Secondly, you will assign a weight to each sub-category in terms of their importance in the index. Lastly, you will assign a weight for each indicator in terms of their importance in the sub-category. The scoring of the scales will be as follows:

1. **Not important:** Does not affect the assessment of environmental sustainability.
2. **Slightly important:** Affects the assessment of environmental sustainability in a minor way.
3. **Moderately important:** Affects the assessment of environmental sustainability in a moderately way.
4. **Important:** Essential and affects the assessment of environmental sustainability in a significant way.
5. **Very important:** Very essential and affect the assessment of environmental sustainability in an extremely significant way.

The survey will take place in your work place or any other designated location which could be advised by you and will take approximately 40-50 minutes. It will consist of an introduction part, where I will explain the calculation of indicators if necessary, and the survey part.

In accordance with the National Statement on Ethical Conduct in Human Research and QUT's Research Ethics policies and procedures, all information, opinions and comments provided by the participants will be kept confidential and shall not be shared with third parties without participant's consent. In the dissertation, all personal details and opinions are anonymous, unless otherwise stated. If you do agree to participate, you can withdraw from participation during the project without comment or penalty. As stated before, neither the information provided by the participants nor the details of participation process will be disclosed to any other parties.

Please note that this study has been approved by the QUT Human Research Ethics Committee (approval number 1100001263).

Many thanks for your consideration of this request.

Didem Dizdaroglu - PhD Student
School of Urban Development
Queensland University of Technology
2 George Street, GPO BOX 2434
Brisbane, QLD 4001, Australia
Mobile: +61 (0)4 1183 4590
e-mail: d.dizdaroglu@qut.edu.au

APPENDIX 3.4 PARCEL SNAPSHOTS RANKING SURVEY

Sub-Category 1 HYDROLOGY

SITE 1

INDICATOR 1. EVAPOTRANSPIRATION	Impervious Surface Ratio=65%
INDICATOR 2. SURFACE RUNOFF	% of rainfall that becomes runoff=60%

SITE 2

INDICATOR 1. EVAPOTRANSPIRATION	Impervious Surface Ratio=90%
INDICATOR 2. SURFACE RUNOFF	% of rainfall that becomes runoff=79%

SITE 3

INDICATOR 1. EVAPOTRANSPIRATION	Impervious Surface Ratio=47%
INDICATOR 2. SURFACE RUNOFF	% of rainfall that becomes runoff=49%

SITE 4

INDICATOR 1. EVAPOTRANSPIRATION	Impervious Surface Ratio=48%
INDICATOR 2. SURFACE RUNOFF	% of rainfall that becomes runoff=49%

Sub-Category 2 POLLUTION

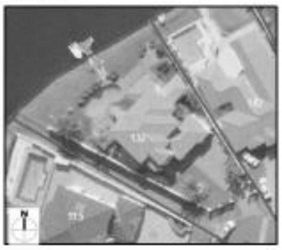
SITE 1

INDICATOR 3. STORMWATER POLLUTION	Transport related Pb concentration in stormwater runoff=0.09mg/L
INDICATOR 4. AIR POLLUTION	Transport related Pb concentration in air=0.010μg/m³
INDICATOR 5. NOISE POLLUTION	Calculation of road traffic noise= 66dBA

SITE 2

INDICATOR 3. STORMWATER POLLUTION	Transport related Pb concentration in stormwater runoff=0.12mg/L
INDICATOR 4. AIR POLLUTION	Transport related Pb concentration in air=0.065μg/m³
INDICATOR 5. NOISE POLLUTION	Calculation of road traffic noise= 63dBA

SITE 3



INDICATOR 3. STORMWATER POLLUTION	Transport related Pb concentration in stormwater runoff=0.08mg/L
INDICATOR 4. AIR POLLUTION	Transport related Pb concentration in air=0.001μg/m³
INDICATOR 5. NOISE POLLUTION	Calculation of road traffic noise= 36dBA

SITE 4

INDICATOR 3. STORMWATER POLLUTION	Transport related Pb concentration in stormwater runoff=0.10mg/L
INDICATOR 4. AIR POLLUTION	Transport related Pb concentration in air=0.010μg/m³
INDICATOR 5. NOISE POLLUTION	Calculation of road traffic noise= 45dBA

Sub-Category 3 ECOLOGY

SITE 1

INDICATOR 6. URBAN HABITAT	Green Area Ratio=66%
INDICATOR 7. MICROCLIMATE	Effective albedo=22%

SITE 2

INDICATOR 6. URBAN HABITAT	Green Area Ratio=17%
INDICATOR 7. MICROCLIMATE	Effective albedo=23%

SITE 3

INDICATOR 6. URBAN HABITAT	Green Area Ratio=40%
INDICATOR 7. MICROCLIMATE	Effective albedo=22%

SITE 4

INDICATOR 6. URBAN HABITAT	Green Area Ratio=12%
INDICATOR 7. MICROCLIMATE	Effective albedo=22%

Sub-Category 4 LOCATION

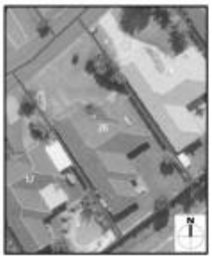
SITE 1

INDICATOR 8. PROXIMITY TO LAND USE DESTINATIONS	NDAI score=53
INDICATOR 9. ACCESS TO PUBLIC TRANSPORT STOPS	158m
INDICATOR 10. WALKABILITY	The lot has; • pedestrian walkway • green buffer

SITE 2

INDICATOR 8. PROXIMITY TO LAND USE DESTINATIONS	NDAI score=15
INDICATOR 9. ACCESS TO PUBLIC TRANSPORT STOPS	928m
INDICATOR 10. WALKABILITY	The lot has; • pedestrian walkway • green buffer

SITE 3



INDICATOR 8. PROXIMITY TO LAND USE DESTINATIONS	NDAI score=44
INDICATOR 9. ACCESS TO PUBLIC TRANSPORT STOPS	1063m
INDICATOR 10. WALKABILITY	The lot has no pedestrian or bikeway design

SITE 4

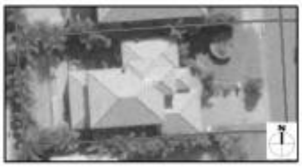
INDICATOR 8. PROXIMITY TO LAND USE DESTINATIONS	NDAI score=78
INDICATOR 9. ACCESS TO PUBLIC TRANSPORT STOPS	495m
INDICATOR 10. WALKABILITY	The lot has; • pedestrian walkway • green buffer

Sub-Category 5 DESIGN

SITE 1

SITE 2

SITE 3



SITE 4

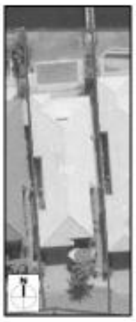
INDICATOR 11. LOT DESIGN	Existing lot plan meets the principles of passive solar design: • **Lot shape:** Rectangular • **Building orientation:** Long side E-W orientated • **Solar access:** North facing living areas or outdoor spaces • **Zero lot line:** houses set to south of lots • **Attached housing:** sharing walls with neighbours particularly on the E or W boundaries • **Location of other buildings:** Avoid other buildings(carports, sheds) on the northern side of the lot
INDICATOR 12. LANDSCAPE DESIGN	Existing landscape plan meets the principles of SEQ subtropical design: • **S:** No trees. Trees on the south may increase electricity use, particularly in winter months, if their shade causes people to use artificial lighting during the day. • **N:** Trees shading the north of buildings can reduce energy needs in summer by providing cooling. Depending on their height and distance from the building, such trees may need to be deciduous • **E:** Trees shading the eastern sides of buildings cast shadows in the cooler morning hours • **W and SW:** Trees shading the west and south-west of buildings reduce summertime energy demand for cooling by blocking the hot afternoon sun

Sub-Category 6 **EFFICIENCY**

SITE 1

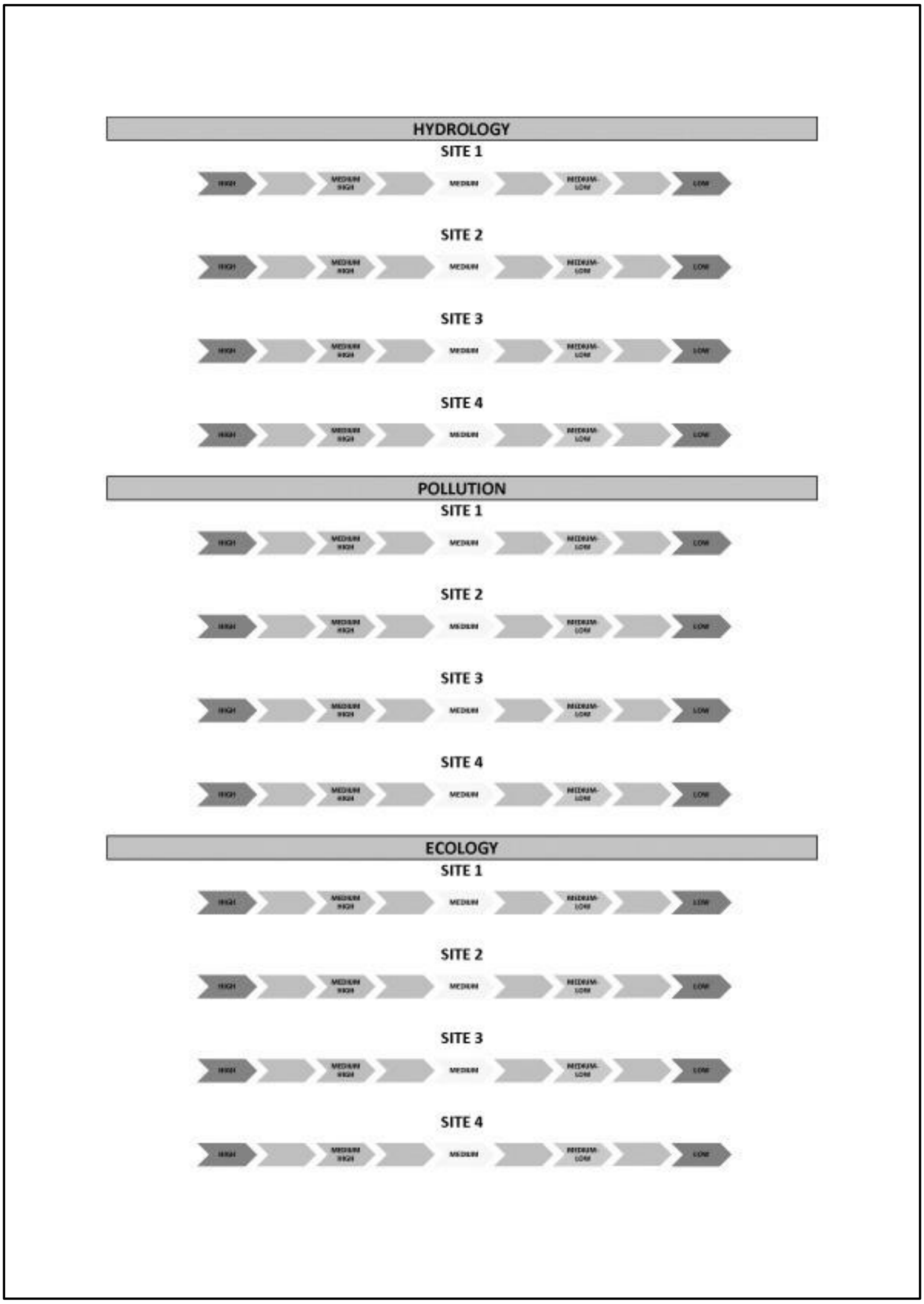
SITE 2

SITE 3

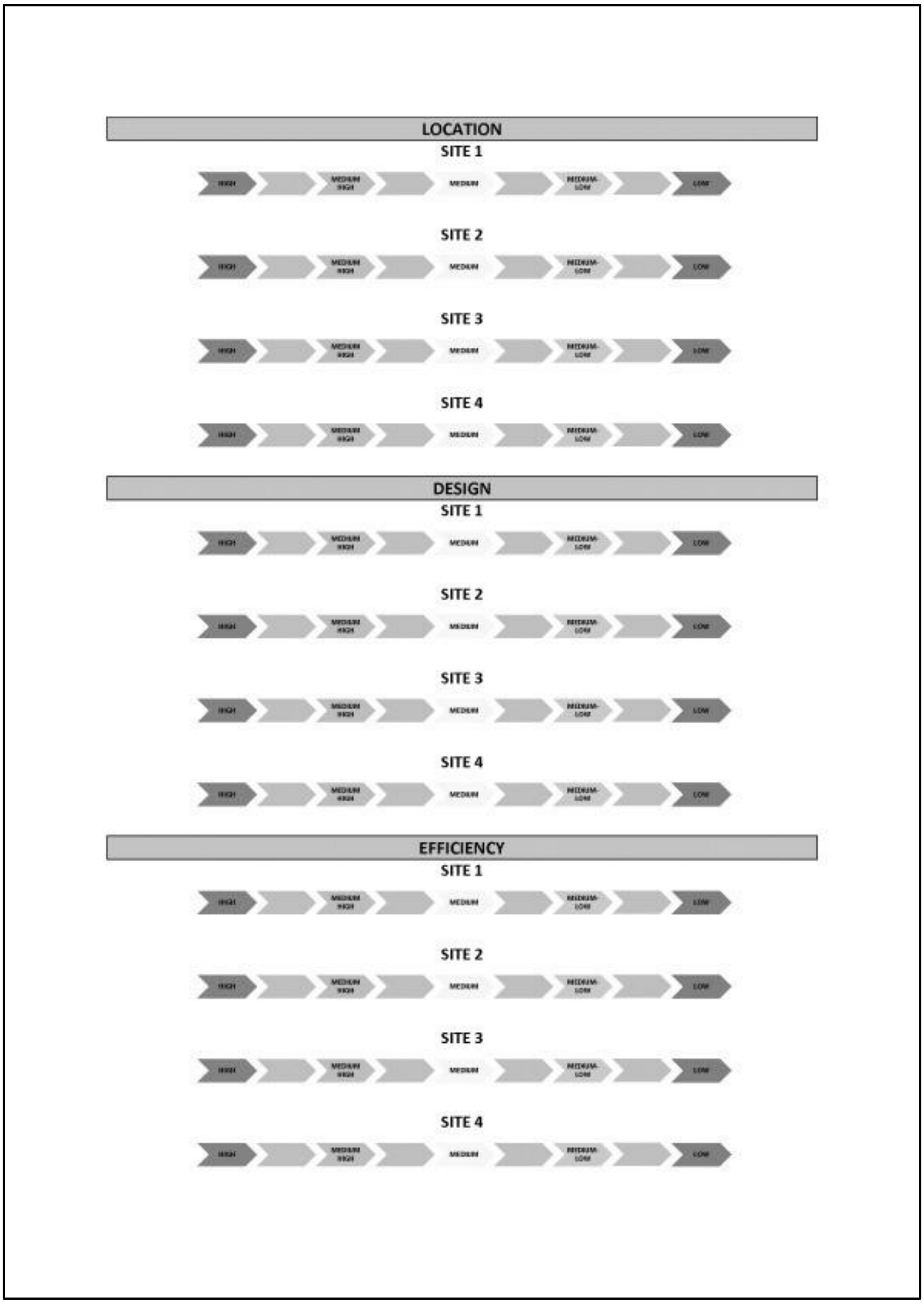


SITE 4

INDICATOR 13. ENERGY CONSERVATION	Existing plan meets the principles of climate responsive design. Efforts to be evaluated: • create an outdoor living space such as courtyard, verandah, balconies • use of renewable energy such as photovoltaic panels, solar water heating • use of light-colored roof • use of light-colored paving
INDICATOR 14. WATER CONSERVATION	Existing plan meets the principles of climate responsive design. Efforts to be evaluated: • use of green roof • reuse of water(rainwater tank) • no pool or other water features • Irrigation water use not exceeds the residential water consumption target (8400 litres/week) implemented by Queensland Water Commission ➢ Lot's estimated irrigation water use is ❖ Site 1 snapshot: 5504 litres/week ❖ Site 2 snapshot: 981 litres/week ❖ Site 3 snapshot: 1615 litres/week ❖ Site 4 snapshot: 4142 litres/week



HYDROLOGY
SITE 1
SITE 2
SITE 3
SITE 4
POLLUTION
SITE 1
SITE 2
SITE 3
SITE 4
ECOLOGY
SITE 1
SITE 2
SITE 3
SITE 4


LOCATION
SITE 1
SITE 2
SITE 3
SITE 4
DESIGN
SITE 1
SITE 2
SITE 3
SITE 4
EFFICIENCY
SITE 1
SITE 2
SITE 3
SITE 4

APPENDIX 3.5 INDICATOR RANKING SURVEY

Respondent's Name:		Date:	
Organisation Name:		Profession:	

1. ***Please rank the importance of the following indicators in terms of their contribution to environmental sustainability assessment.***
2. ***Please assign a weight to each sub-category in terms of their importance in the index (sum of all weights should be 100).***
3. ***Please assign a weight for each indicator in terms of their importance in the sub-category (sum of all weights should be equal to sub-category weighting).***

MAIN CATEGORIES	SUB-CATEGORIES	INDICATORS
Natural Environment	**Hydrology**	Evapotranspiration Surface Runoff
	Pollution	Stormwater Pollution Air Pollution Noise Pollution
	Ecology	Urban Habitat Microclimate
Built Environment	**Location**	Proximity to Land Use Destinations(LUDs) Access to Public Transport(PT) Stops Walkability
	Design	Lot Design Landscape Design
	Efficiency	Energy Conservation Water Conservation

The scoring of the scales is as follows:

1- **Not important:** Does not affect the assessment of environmental sustainability.
2- **Slightly important:** Affects the assessment of environmental sustainability in a minor way.
3- **Moderately important:** Affects the assessment of environmental sustainability in a moderately way.
4- **Important:** Essential and affects the assessment of environmental sustainability in a significant way.
5- **Very important:** Very essential and affect the assessment of environmental sustainability in an extremely significant way.

1

NATURAL ENVIRONMENT INDICATORS	1 Not important	2 Slightly important	3 Moderately important	4 Important	5 Very important	WEIGHT OF THE SUB-CATEGORY (100)		WEIGHT OF INDICATOR IN THE SUB-CATEGORY
Evapotranspiration To promote infiltration of water To reduce surface runoff To reduce the absorption of solar radiation To maintain porosity and permeability of soil fauna						HYDROLOGY		
Surface Runoff To control volume, duration and intensity of runoff To protect rainwater infiltration and groundwater recharge To prevent increase of pollutant loads To prevent flooding and erosion								
Stormwater Pollution To preserve drinking water quality in catchments To prevent sedimentation and eutrophication of waterways To prevent the loss and fragmentation of aquatic habitat						POLLUTION		
Air Pollution To control greenhouse effect To prevent increased UV radiation To protect human health								
Noise Pollution To protect physiological and psychological human health To prevent loss of wildlife habitat and territory; loss of food supply; behavioural changes in mating, predation and migration								
Urban Habitat To provide amelioration of urban microclimates To reduce albedo and radiation loads To enhance vegetation composition and diversity To provide habitat for wildlife in metropolitan settings						ECOLOGY		
Microclimate To enhance urban albedo to reduce energy needs and diminish urban heat island effect To control the specific heat capacities and thermal conductivities of surfaces and prevent global warming								

2

BUILT ENVIRONMENT INDICATORS	1 Not important	2 Slightly important	3 Moderately important	4 Important	5 Very important	WEIGHT OF THE SUB-CATEGORY (100)		WEIGHT OF INDICATOR IN THE SUB-CATEGORY
➢ **Proximity to Land Use Destinations** ○ To provide access to community support services ○ To reduce the volume of traffic ○ To encourage walking, biking or public transit						LOCATION		
➢ **Access to Public Transport Stops** ○ To increase use of alternative modes ○ To provide an easier access and shorter times to get the destination ○ To minimise dependency on automobiles								
➢ **Walkability** ○ To provide safe, appealing and comfortable street environments ○ To support public health by reducing pedestrian injuries ○ To encourage daily physical activity								
➢ **Lot Design** ○ To encourage energy efficiency by creating optimum conditions for the use of passive solar strategies						DESIGN		
➢ **Landscape Design** ○ To reduce costs of winter heating and summer cooling ○ To maximise outdoor comfort in summer and winter ○ To provide solar access, wind control and a better visual environment								
➢ **Energy Conservation** ○ To create an outdoor living space as a thermal refuge from the building ○ To encourage the use of renewable energy ○ To reduce effects of urban heat island by selecting lighter colour paving and roofing materials						EFFICIENCY		
➢ **Water Conservation** ○ To reduce effects on natural water resources ○ To reduce water consumption such as pool filling ○ To limit the use of water on site for landscape irrigation								

3

APPENDIX 3.6 DESCRIPTIVE STATISTICS, FREQUENCY TABLE, CRONBACH'S ALPHA RELIABILITY

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
evapotranspiration	21	2,00	5,00	3,8095	,87287
surface_runoff	21	3,00	5,00	4,2381	,70034
stormwater_pollution	21	2,00	5,00	3,7619	,83095
air_pollution	21	2,00	5,00	3,5238	1,03049
noise_pullution	21	2,00	5,00	3,4762	,98077
urban_habitat	21	2,00	5,00	4,1429	,91026
microclimate	21	3,00	5,00	4,0952	,76842
proximity_to_LUDs	21	2,00	5,00	3,7619	,83095
access_to_PT_stops	21	2,00	5,00	3,6667	,79582
walkability	21	2,00	5,00	3,6190	,80475
lot_design	21	3,00	5,00	3,9524	,80475
landscape_design	21	2,00	5,00	3,8095	,81358
energy_conservation	21	3,00	5,00	4,3810	,74001
water_conservation	21	3,00	5,00	4,1429	,72703
Valid N (listwise)	21				

		evapotranspiration	surface_runoff	stormwater_pollution	air_pollution	noise_pullution	urban_habitat	microclimate	proximity_to_LUDs	access_to_PT_stops	walkability	lot_design	landscape_design	energy_conservation	water_conservation
N	Valid	21	21	21	21	21	21	21	21	21	21	21	21	21	21
	Missing	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mean		3,8095	4,2381	3,7619	3,5238	3,4762	4,1429	4,0952	3,7619	3,6667	3,6190	3,9524	3,8095	4,3810	4,1429
Median		4,0000	4,0000	4,0000	4,0000	3,0000	4,0000	4,0000	4,0000	4,0000	4,0000	4,0000	4,0000	5,0000	4,0000
Mode		4,00	4,00	4,00	4,00	3,00	5,00	4,00	4,00	4,00	3,00	4,00	4,00	5,00	4,00

Frequency Table

evapotranspiration

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	1	4,8	4,8	4,8
	moderately important	7	33,3	33,3	38,1
	important	8	38,1	38,1	76,2
	very important	5	23,8	23,8	100,0
	Total	21	100,0	100,0	

surface_runoff

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	moderately important	3	14,3	14,3	14,3
	important	10	47,6	47,6	61,9
	very important	8	38,1	38,1	100,0
	Total	21	100,0	100,0	

stormwater_pollution

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	1	4,8	4,8	4,8
	moderately important	7	33,3	33,3	38,1
	important	9	42,9	42,9	81,0
	very important	4	19,0	19,0	100,0
	Total	21	100,0	100,0	

air_pollution

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	4	19,0	19,0	19,0
	moderately important	6	28,6	28,6	47,6
	important	7	33,3	33,3	81,0
	very important	4	19,0	19,0	100,0
	Total	21	100,0	100,0	

noise_pullution

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	3	14,3	14,3	14,3
	moderately important	9	42,9	42,9	57,1
	important	5	23,8	23,8	81,0
	very important	4	19,0	19,0	100,0
	Total	21	100,0	100,0	

urban_habitat

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	1	4,8	4,8	4,8
	moderately important	4	19,0	19,0	23,8
	important	7	33,3	33,3	57,1
	very important	9	42,9	42,9	100,0
	Total	21	100,0	100,0	

microclimate

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	moderately important	5	23,8	23,8	23,8
	important	9	42,9	42,9	66,7
	very important	7	33,3	33,3	100,0
	Total	21	100,0	100,0	

proximity_to_LUDs

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	2	9,5	9,5	9,5
	moderately important	4	19,0	19,0	28,6
	important	12	57,1	57,1	85,7
	very important	3	14,3	14,3	100,0
	Total	21	100,0	100,0	

access_to_PT_stops

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	1	4,8	4,8	4,8
	moderately important	8	38,1	38,1	42,9
	important	9	42,9	42,9	85,7
	very important	3	14,3	14,3	100,0
	Total	21	100,0	100,0	

walkability

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	1	4,8	4,8	4,8
	moderately important	9	42,9	42,9	47,6
	important	8	38,1	38,1	85,7
	very important	3	14,3	14,3	100,0
	Total	21	100,0	100,0	

lot_design

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	moderately important	7	33,3	33,3	33,3
	important	8	38,1	38,1	71,4
	very important	6	28,6	28,6	100,0
	Total	21	100,0	100,0	

landscape_design

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	slightly important	1	4,8	4,8	4,8
	moderately important	6	28,6	28,6	33,3
	important	10	47,6	47,6	81,0
	very important	4	19,0	19,0	100,0
	Total	21	100,0	100,0	

energy_conservation

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	moderately important	3	14,3	14,3	14,3
	important	7	33,3	33,3	47,6
	very important	11	52,4	52,4	100,0
	Total	21	100,0	100,0	

water_conservation

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	moderately important	4	19,0	19,0	19,0
	important	10	47,6	47,6	66,7
	very important	7	33,3	33,3	100,0
	Total	21	100,0	100,0	

Case Processing Summary

		N	%
Cases	Valid	21	100,0
	Excluded[a]	0	,0
	Total	21	100,0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
,824	14

APPENDIX 4.1 FACTOR ANALYSIS WEIGHTINGS

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,736
Bartlett's Test of Sphericity	Approx. Chi-Square	15378,026
	df	91
	Sig.	,000

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3,813	27,237	27,237	3,813	27,237	27,237	3,768	26,917	26,917
2	2,095	14,966	42,203	2,095	14,966	42,203	1,935	13,824	40,741
3	1,807	12,909	55,112	1,807	12,909	55,112	1,895	13,536	54,277
4	1,311	9,363	64,475	1,311	9,363	64,475	1,428	10,198	64,475
5	,951	6,792	71,268						
6	,912	6,517	77,784						
7	,659	4,707	82,491						
8	,563	4,019	86,511						
9	,443	3,168	89,679						
10	,393	2,806	92,484						
11	,371	2,648	95,132						
12	,277	1,980	97,112						
13	,220	1,569	98,681						
14	,185	1,319	100,000						

Extraction Method: Principal Component Analysis.

Rotated Component Matrix[a]

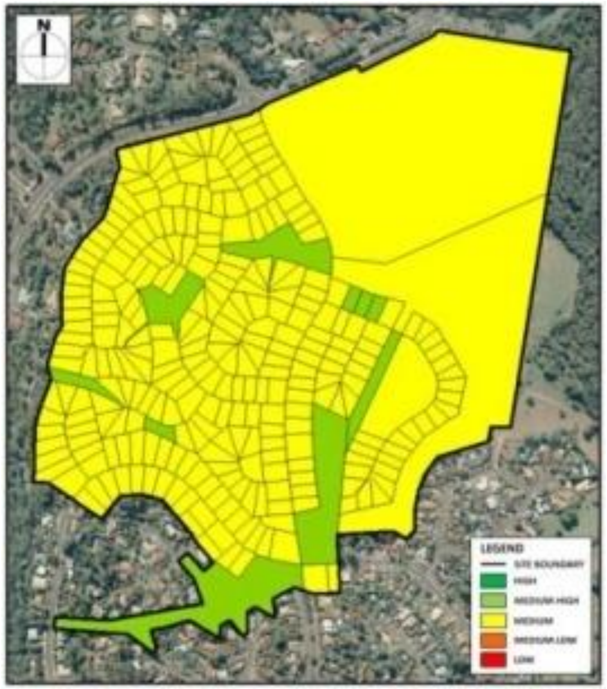
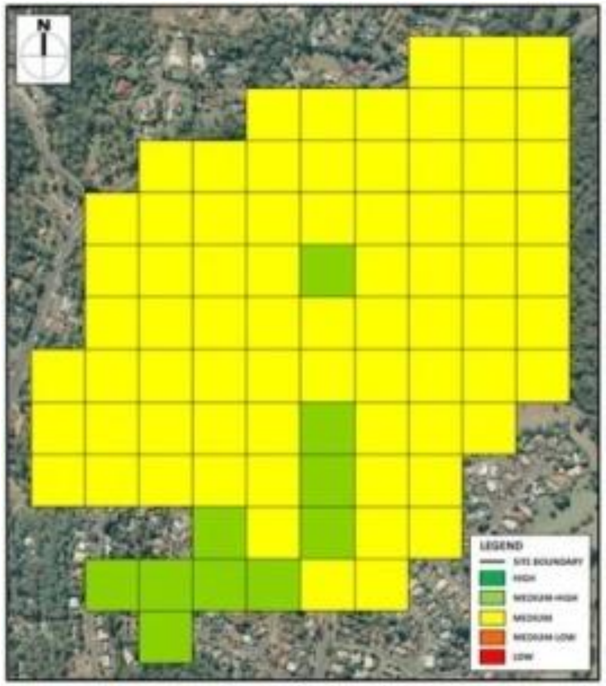
	Component			
	1	2	3	4
ISR	,873	,037	-,101	-,098
LNDDSG	,832	-,132	-,097	-,223
SR	,832	,091	-,035	-,194
LOTDSG	,744	-,152	-,051	,253
ENERGY	,729	,043	-,050	,206
WATER	,623	,205	,144	,489
AIR	,080	,861	,070	-,038
SW	-,028	,848	,189	-,077
NOISE	-,080	,604	-,334	,273
LUD	-,062	,059	,883	,010
PT	-,103	,111	,861	-,157
WLK	-,020	-,030	,417	,049
GAR	,323	,010	,052	-,816
EA	,132	-,001	-,011	,459

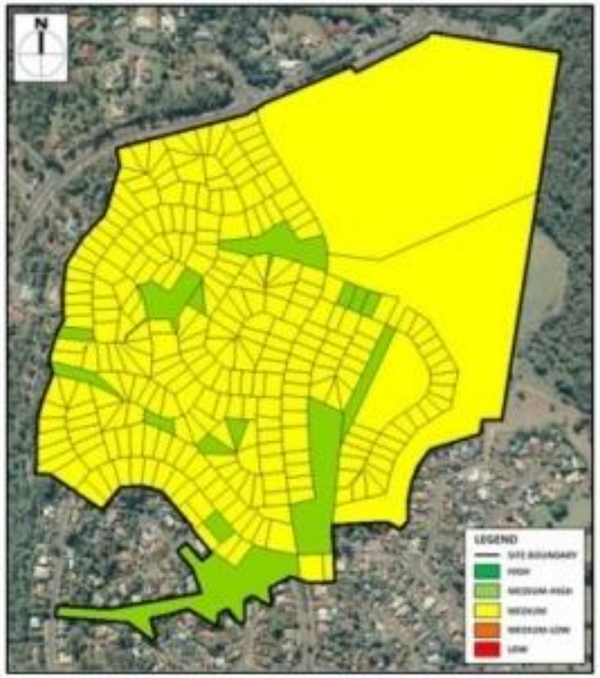
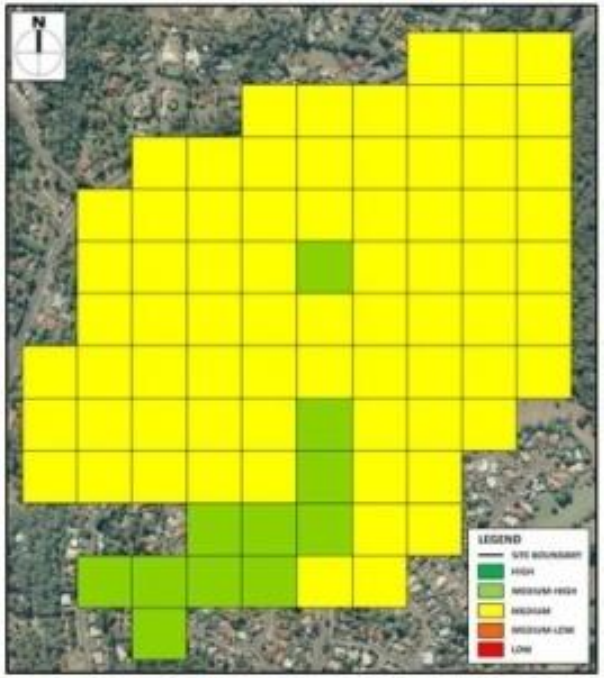
Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

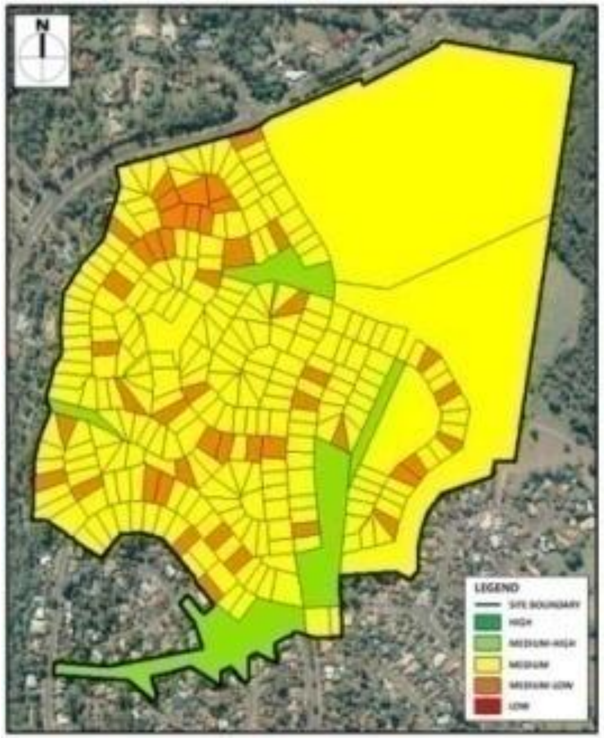
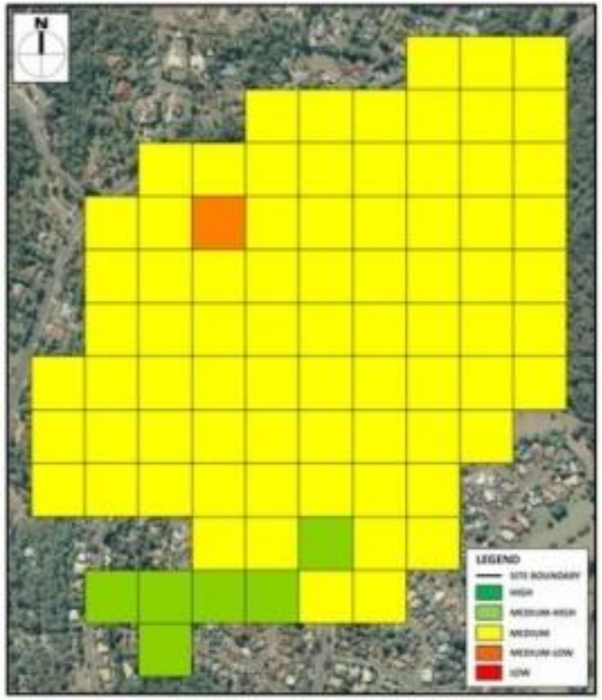
a. Rotation converged in 5 iterations.

Abbreviations: Impervious surface ratio (ISR), surface runoff (SR), stormwater pollution (SW), air pollution (AIR), noise pollution (NOISE), green area ratio (GAR), albedo (EA), land use destinations (LUD), public transport (PT), walkability (WLK), lot design (LOTDSG), landscape design (LNDDSG), energy consumption (ENERGY), and water consumption (WATER).

APPENDIX 4.2 COMPOSITE INDEX MAPS CALCULATED BY ALTERNATIVE METHODOLOGICAL TECHNIQUES

SITE 1: Equal Weighting & Linear Aggregation	
Parcel-Level **Composite Index Score**	**Grid-Based** **Composite Index Score**
	

SITE 1: FA Weighting & Linear Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

SITE 1: Equal Weighting & Geometric Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
 	

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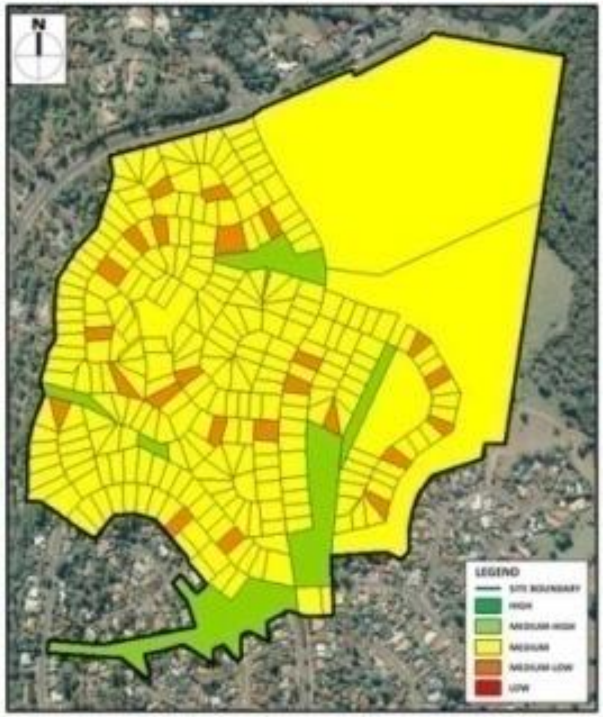
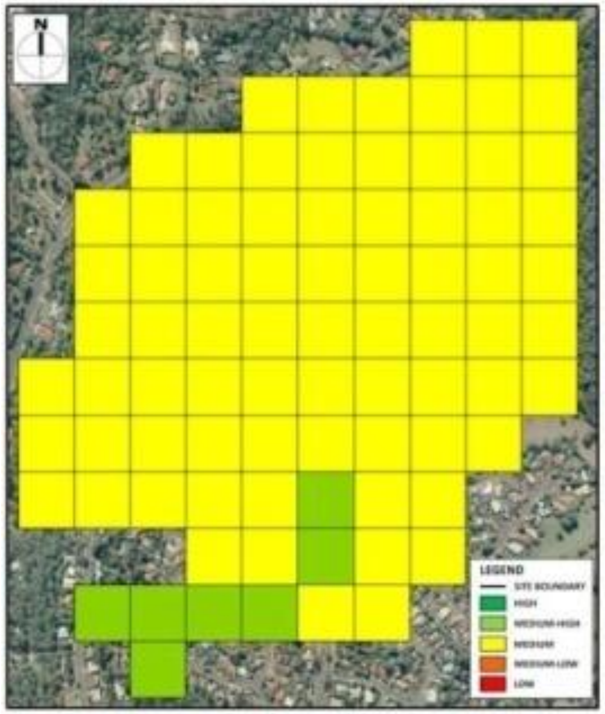
Composite Index Score</th><th>Grid-Based
Composite Index Score</th></tr>
<tr><td>
</td><td>
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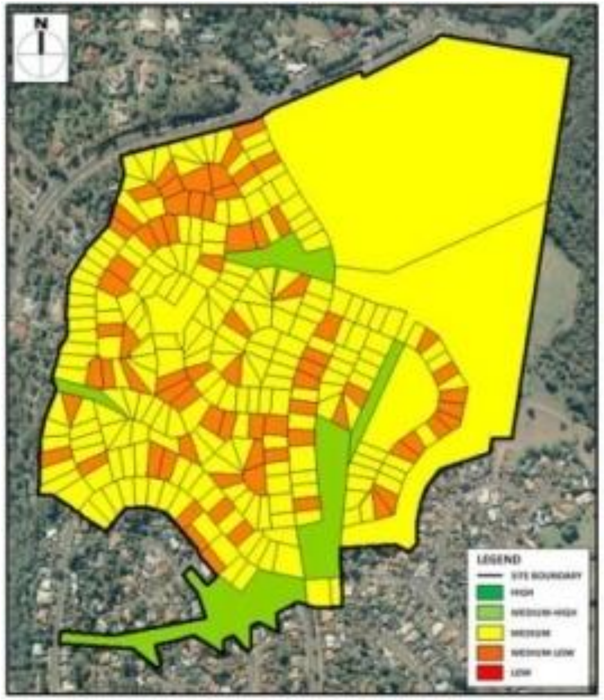
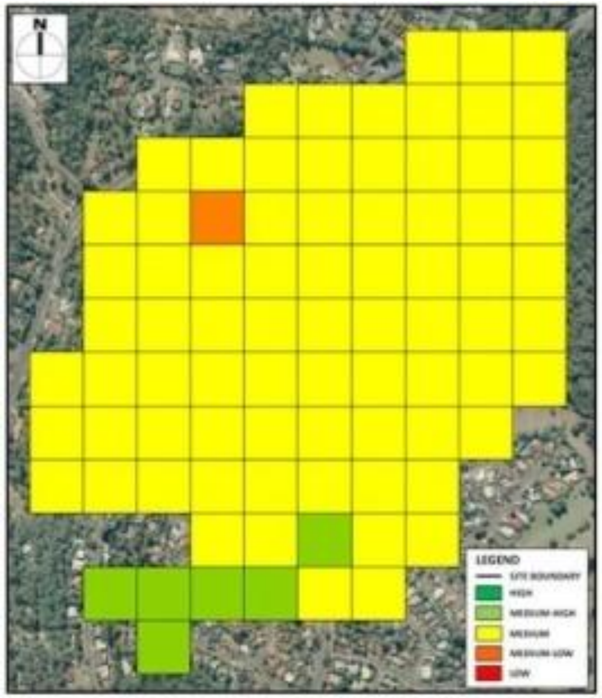
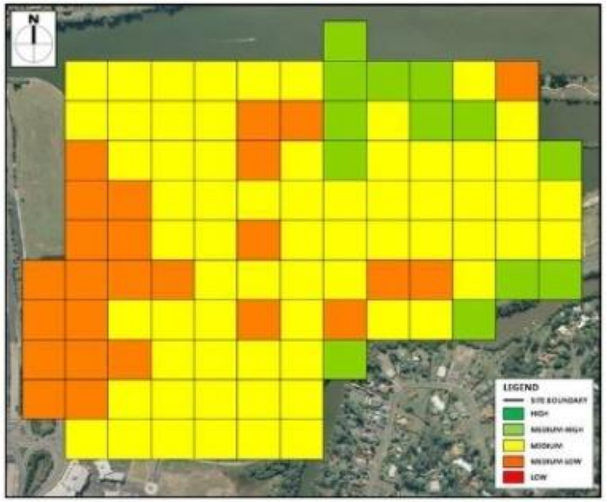
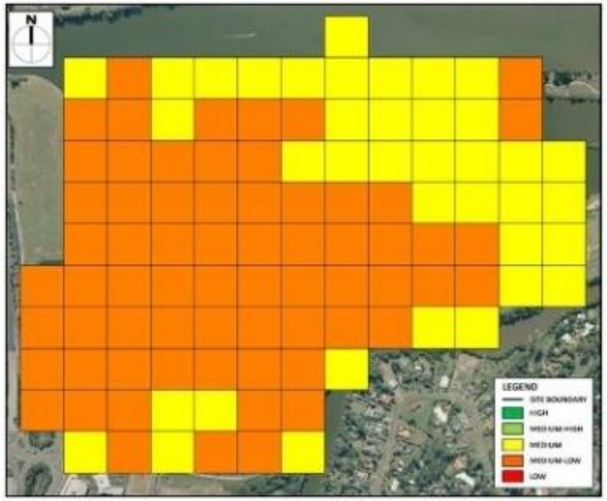
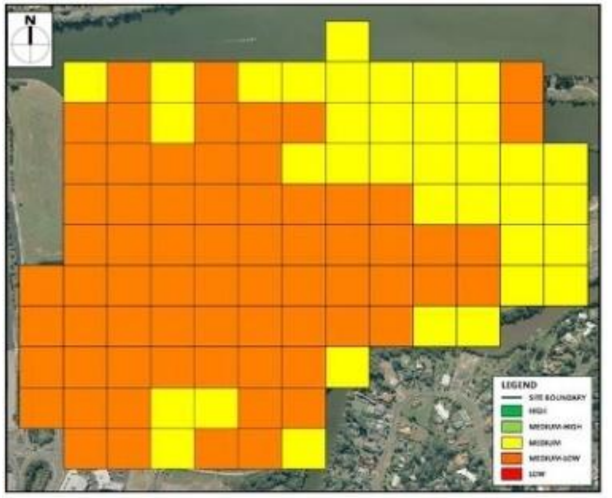
SITE 1: Expert Opinion Weighting & Geometric Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

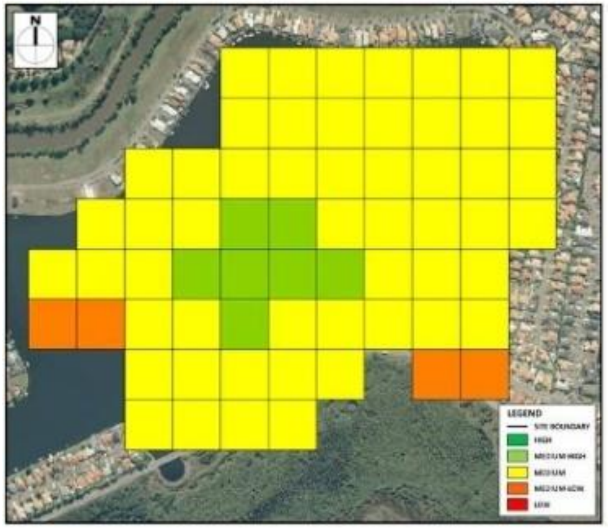
SITE 2: Equal Weighting & Linear Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

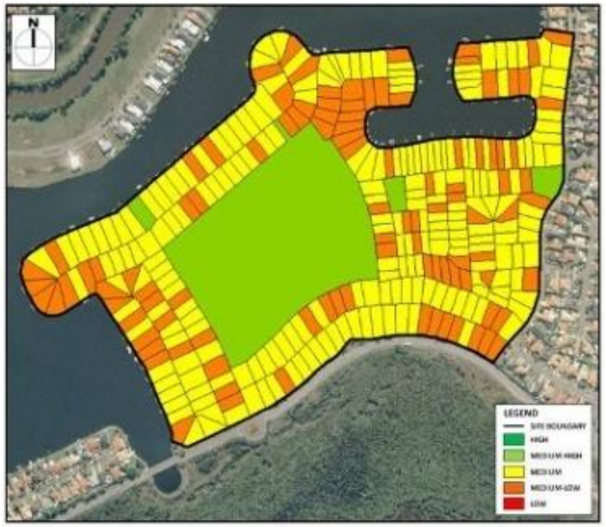
SITE 2: FA Weighting & Linear Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

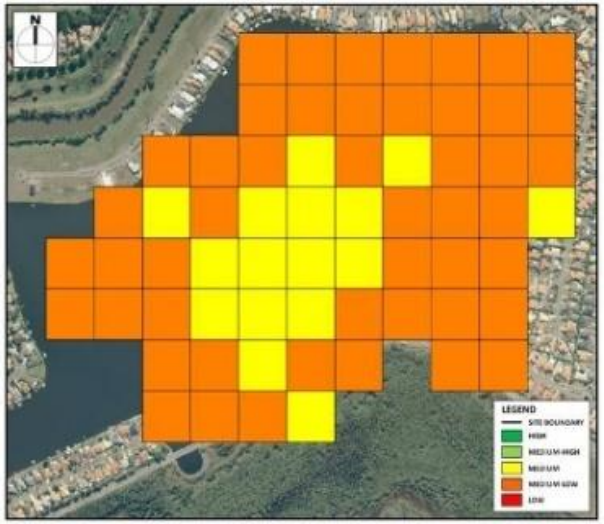
SITE 2: Equal Weighting & Geometric Aggregation	
Parcel-Level **Composite Index Score**	**Grid-Based** **Composite Index Score**
 	

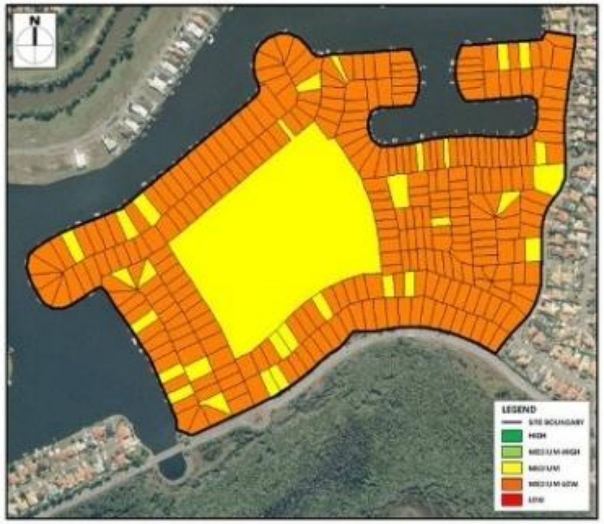
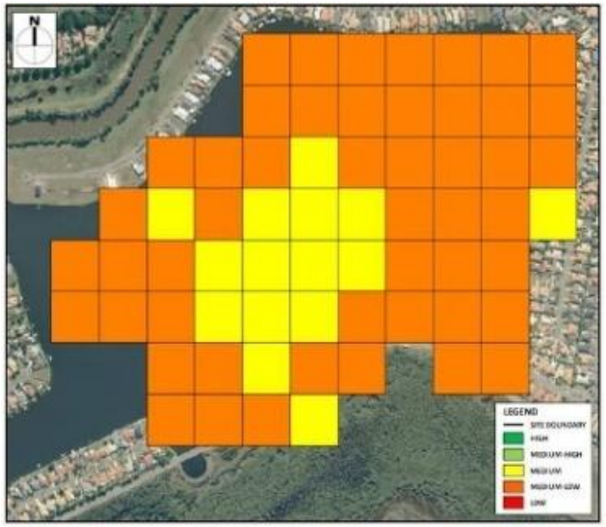
SITE 2: FA Weighting & Geometric Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

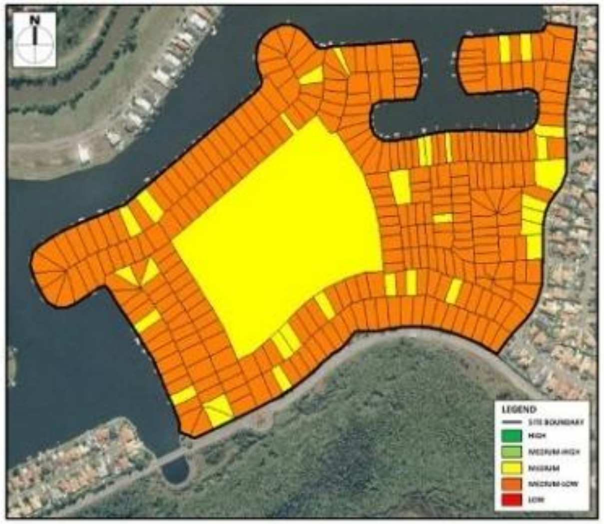
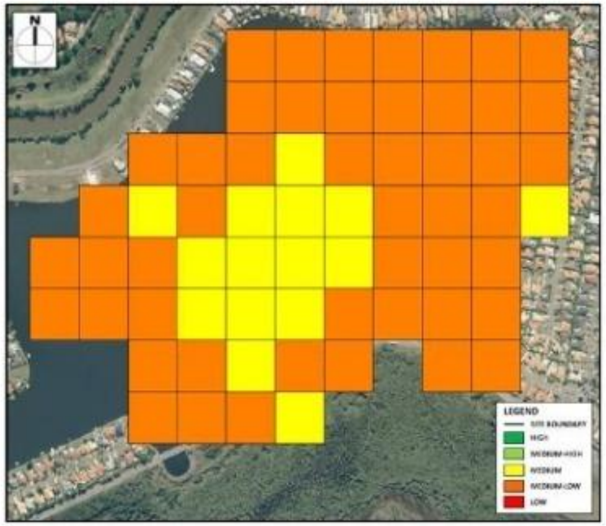
SITE 2: Expert Opinion Weighting & Geometric Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

SITE 3: Equal Weighting & Linear Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

SITE 3: FA Weighting & Linear Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
 	

SITE 3: Equal Weighting & Geometric Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

SITE 3: FA Weighting & Geometric Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

SITE 3: Expert Opinion Weighting & Geometric Aggregation	
Parcel-Level Composite Index Score	**Grid-Based Composite Index Score**
	

SITE 4: Equal Weighting & Linear Aggregation	
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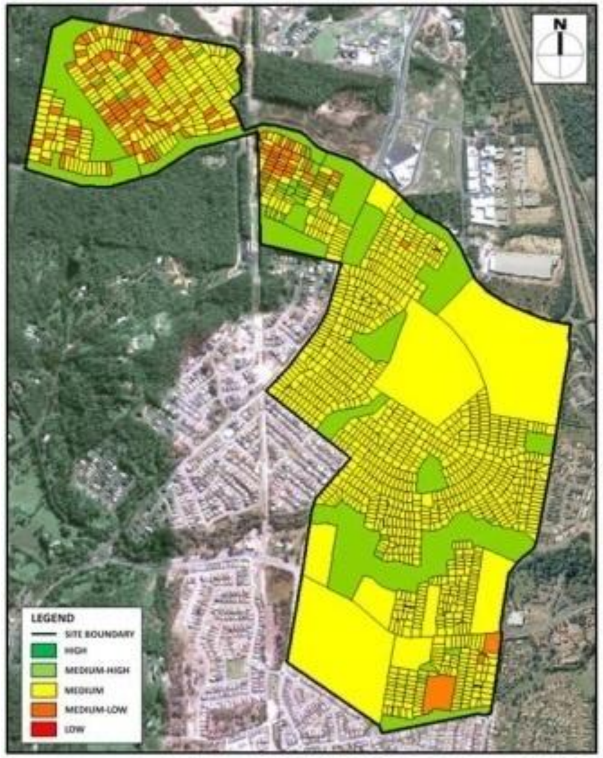
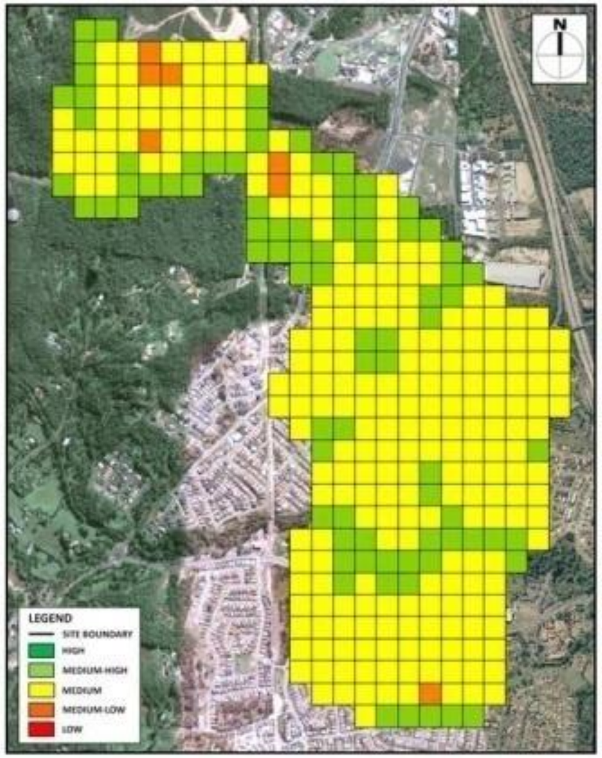
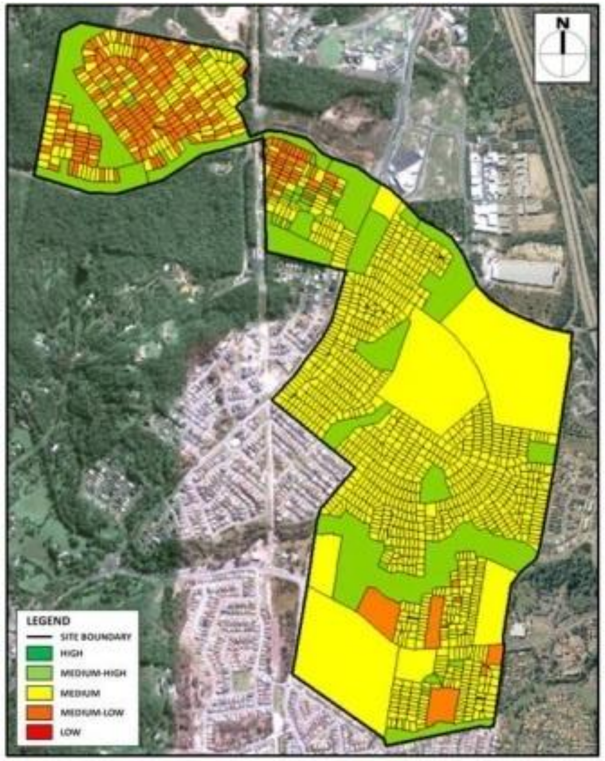
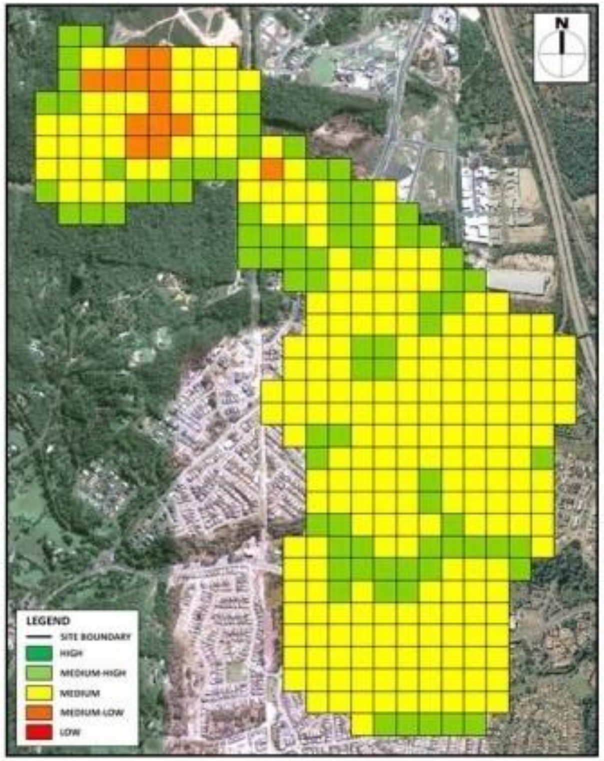
	

SITE 4: FA Weighting & Linear Aggregation

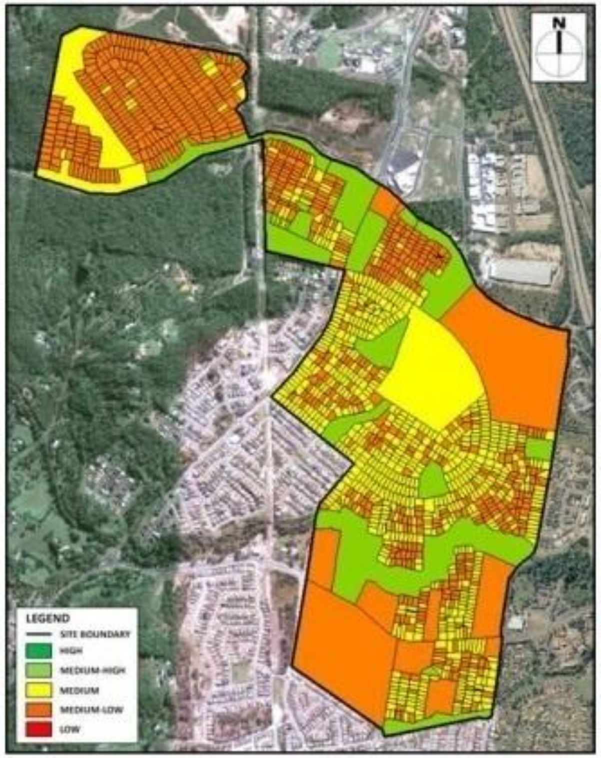
Parcel-Level
Composite Index Score

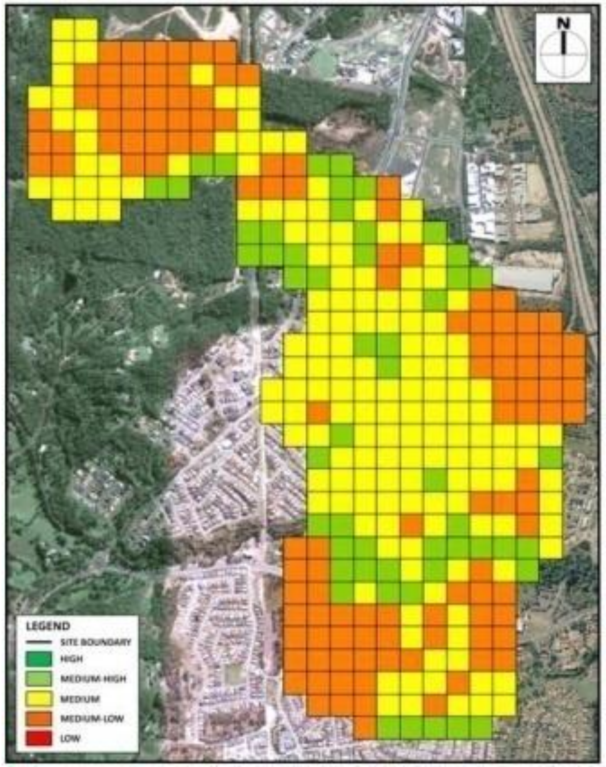


Grid-Based
Composite Index Score



SITE 4: Equal Weighting & Geometric Aggregation	
Parcel-Level **Composite Index Score**	**Grid-Based** **Composite Index Score**





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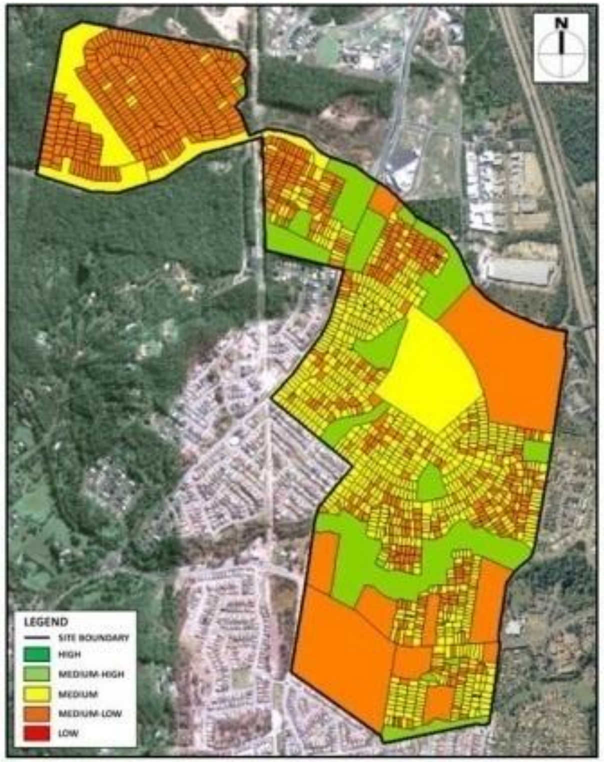	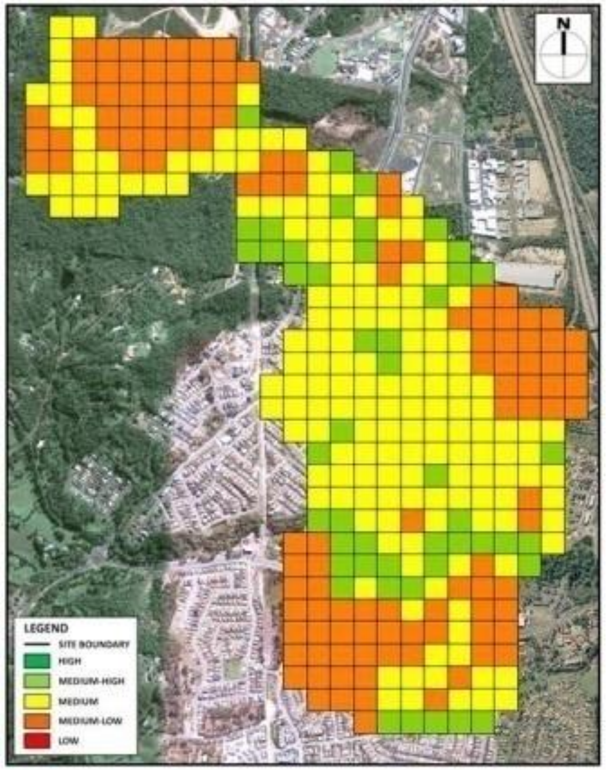

SITE 4: Expert Opinion Weighting & Geometric Aggregation

Parcel-Level Composite Index Score	Grid-Based Composite Index Score
see below	see below