ASSESSING THE SUSTAINABILITY OF URBAN ECOSYSTEMS: AN INNOVATIVE APPROACH

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ABSTRACT

At the turn of the millennium, the Earth's human population has reached unprecedented levels and its natural resources are being pushed to the limit. Thus, cities are focused on sustainable development and they have begun to develop new strategies for improving the built environment. Sustainable development provides the best outcomes for the human and natural environments by improving the quality of life that protects and balances the ecological, social and economic values. This brings us to the main point: to build a sustainable built environment, cities need to redesign many of their technologies and planning policies within the context of ecological principles. As an environmental sustainability index model, ASSURE is developed to investigate the present environmental situation of an urban area by assessing the impacts of development pressure on natural resources. It is an innovative approach to provide the resilience and function of urban ecosystems secure against the environmental degradation for now and the future. This paper aims to underline the importance of the model (ASSURE) in preserving biodiversity and natural ecosystems in the built environment and investigate its role in delivering long-term urban planning policies.

Keywords: *Sustainable Urban Ecosystem, Environmental Sustainability, Indicator-based Sustainability Assessment, Environmental Sustainability Index.*

INTRODUCTION

Cities are complex human-dominated ecosystems and human activities make them different from natural ecosystems in several aspects (Alberti, 2008). Rapid population growth affects the quality of city services such as housing, public infrastructure, social facilities and causes a crisis in living conditions. Unplanned urbanisation provides a threat to the health and safety of human beings, as well as urban productivity, and combined with inadequate infrastructures, it accelerates environmental degradation (Ichimura, 2003). To ameliorate these problems, various environmental impact assessment tools were introduced. Various studies and practices still are carried on to find out more environmental solutions to these problems. The main purpose of all of these efforts is creating an 'ecologically sustainable city' that has an effective use of its resources while reducing ecological impacts and sustaining their ecological functioning on the other hand providing higher living standards and a healthier urban environment for its citizens.

This paper introduces a new index model to figure a template of a sustainable assessment tool which will enable to identify the interaction between urban ecosystems and human activities in the context of environmental sustainability and evaluate the possible environmental impacts in an existing and future urban context by using sustainability indicators. While the model is only in its preliminary stages and has yet to be piloted in the case study of Gold Coast Australia, the paper will present the structure and the methodology of this model. Finally, the paper will highlight the key findings of this study and emphasise the role of the proposed model in conserving and managing urban ecosystems.

HUMAN INFLUENCE ON ECOSYSTEMS

An ecosystem is a dynamic ecological system 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 benefits to people including: the stuff of their life such as food, water, timber etc., air quality maintenance, climate regulation, erosion control, regulation of human diseases, water purification and cultural services (recreational and aesthetic experiences) (MEA, 2005). Over the centuries, as an integral part of ecosystem, humans have made unprecedented changes to the ecosystems. As their lifestyle, needs and expectations changed, their activities began to alter the earth's environment, and therefore, they came up against the problem of environmental pollution (Randolph, 2004).

Even though cities are the 'engines' for economic development, the impacts of rapid urbanisation provides a threat to the health of human beings, as well as ecosystem quality and productivity. The sprawl of settlements, development of transportation networks and industrial activities causes destructive and irreversible effects on the soil source and its quality (Pauleit et al., 2005; Dorsey, 2003). The evolution of technological change, the introduction of motorised vehicles and the increase in energy consumption due to population growth contribute to the growing air pollution problem (Mage et al., 1996). In addition, air pollution creates climate change which is directly linked to ozone depletion, increased greenhouse gases and has long-term environmental effects such as desertification, rising sea levels and global warming.

Urban development and population pressure create water pollution through daily activities. Urbanisation affects the quantity of water bodies with its impervious surfaces by preventing the infiltration of stormwater into the ground and increasing the amount of runoff. Furthermore, these surfaces cause significant threats to the quality of aquatic and terrestrial habitats (Randolph, 2004; Barnes et al., 2001). Unfortunately, the area of urban settlements is growing faster than the amount of people living in these areas. Such rapid urbanisation is intertwined with changing lifestyle patterns and both these developments influence significantly on natural urban habitats and species (Yli-Pelkonen et al., 2005; Petersen et al., 2007).

As nations develop technologically, their level of consumption and waste increase, their ecological footprints expand due to their advanced economies. Economy is a self-regulating mechanism which produces energy consumption and material flow of ecological services. These services are called natural capital and they are generated by human-made capital which refers to factories, buildings, roads and other physical artefacts. Each of them demands an environment of space for shelter, reproduction and waste assimilation. However, the degradation of environment and its services are irreversible and no type of human-made capital can substitute for them. In this sense, there is a need to balance the increasing human demands on the natural systems (Rees, 1992; Cleveland, 2003).

SUSTAINABLE URBAN ECOSYSTEMS

Urban ecosystem, as called by Alberti (1996, p. 382) ‘urban ecological space’, encompasses the total natural capital and flows on which a city depends to meet the long-term needs of its inhabitant. A sustainable urban ecosystem manages its natural resources in a “closed loop” by minimizing the risk of environmental damage while controlling flows of resources and reduces its energy, materials and information losses. It ensures environmental justice in the shared use of urban ecosystems while balancing environmental quality against resource use (Moura & Cuchi, 2007). Providing long term sustainable vision for urban ecosystems is based on the following principles (Newman & Jennings, 2008):

- *Protect and restore biodiversity and natural ecosystems:* Cities maintain biodiversity through the creation of protected areas like gardens, parks, greenways, wilderness areas, and biosphere reserves. Ecological design of architecture and infrastructure can also support and enhance biodiversity through zero energy buildings, green roofs, stormwater management, and water sensitive urban design.
- *Minimise the ecological footprints of cities:* Ecological footprint is useful as a tool for monitoring the global impacts of resource consumption. Ecological footprints need to be managed through ecosystem assessments that determine the biocapacity of rivers, groundwater, soils and airsheds. In the light of the assessments, regulations can be developed to minimise the flow of nutrients or wastes into the ecosystem.
- *Provide sustainable production and consumption:* Sustainable production and consumption refers to the use of services and related products which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life-cycle so as not to jeopardize the needs of future generations (Norwegian Ministry of the Environment, 1994).
- *Enable cooperative networks towards a sustainable future:* An effective partnership between government, business and the community is necessary for cities to find innovative solutions to the issues of sustainability. Building cooperative networks is essential for creating resilient cities and making people more able to respond to feedback and take appropriate action.

Examining the city as an ecosystem enables to investigate the flows of energy and material in the ecological systems along with the interactions between human and non-human parts of the system. Because change is an inevitable result of human activities, the capacity of urban ecosystems to respond and adapt these changes is an important factor to take into consideration in transforming cities into sustainable ecosystems that is healthy, zero-waste, self-regulating, resilient, flexible and self-renewing (Alberti, 2008).

URBAN ECOSYSTEM SUSTAINABILITY ASSESSMENT

Sustainability assessment is performed by applying different approaches and tools ranging from indicators to comprehensive models. World Resources Institute (1995) divided sustainability indicators into four categories: (1) *Source Indicators* measure how much people depletes the resources and degrades the biological systems which their sustainability depend; (2) *Sink Indicators* evaluate the capacity of resources in order to absorb emissions and waste; (3) *Life Support Indicators* monitor the change in the state of earth's ecosystems and biodiversity, and; (4) *Human Impact and Welfare Indicators* measure the impacts of environmental problems on public health and the quality of life. They are all fundamental process of information collection to calibrate the impacts of environmental problems and develop sustainable planning polices towards these problems (Alberti, 1996: RCEP, 2002).

Recent years, an increasing number of assessment tools have been developed to track and measure the sustainability of urban environment. Although they are derived from different indicator datasets, 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. The most widely used international approach for developing indicators is the "Pressure-State-Response" framework developed by the Organization for Economic Cooperation and Development. 'Pressure' variable describes the problems caused by human activities. 'State' variable refers to indicators that monitor the physical, chemical and biological quality of the environment. 'Response' variable indicates how the society responds to environmental changes (Segnestam, 2002). This PSR model was further enhanced by the European Environment Agency as 'Driving force–Pressure–State–Impact–Response' (Figure 1). \`Driving force\` variable is added as the underlying causes which lead to environmental pressures. \`Impact\` variable expresses the level of environmental harm on human health, ecosystems, biodiversity and so on. (Kristensen, 2004).

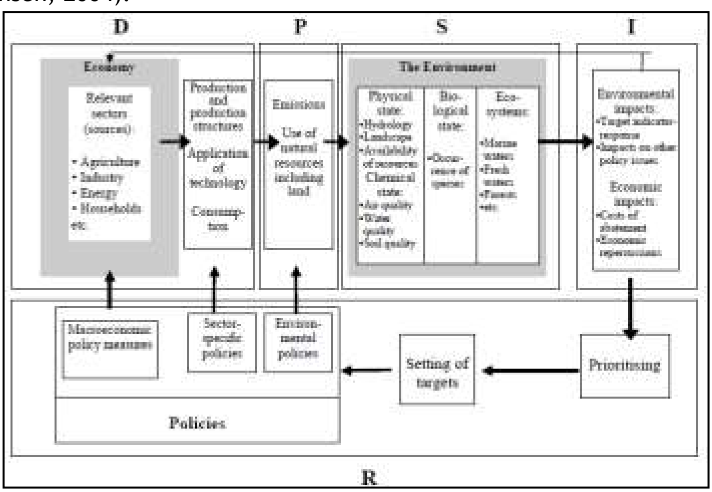


Figure 1. The DPSIR Framework (Kristensen, 2004)

In the literature, 426 indicators of environmental sustainability has been proposed from the following six indices: 2006 Environmental Performance Index, 2005 Environmental Sustainability Index, 2004 Environmental Vulnerability Index, Rio to Johannesburg Dashboard of Sustainability, The Wellbeing of Nations and 2006 National Footprint Accounts (SEDAC, 2007). The indicators of these indices have been used at international and national levels in state of the measurement of environmental progress and performance, planning, clarifying policy objectives and setting priorities (OECD, 2003). These trends in the quality of urban ecosystems and their impacts on natural resources help us to analyse the interactions between urban systems and the environment. In order to understand this interaction, we need to examine how cities spatial dynamics, organisational structure and lifestyle affect their environmental quality and performance. Thus, sustainability assessment provides a basis to assess status and trends in ecological systems and diagnose the causes of the problems across a wide range of spatial scales. It also helps to assist local and national policymakers to improve their action towards sustainability. Briefly, the city considered as an urban ecosystem requires a holistic sustainability assessment tool to monitor the urban metabolism and help the decision-making authorities and actors to control it (Alberti, 1996; Dakhia & Berezowska-Azzag, 2010).

MICRO-SCALE ENVIRONMENTAL SUSTAINABILITY INDEX MODEL

An environmental sustainability index is constructed from several indicators weighed together to describe total impact on certain aspects within the broader state-of-the-environment. It defines the current environmental situation of an urban area by assessing the impacts of development pressure on natural resources. It provides environmental data to explore the areas which have particular ecological characteristics that render them unsuitable for urban development and need to be protected. Furthermore, it assesses the probable effects of proposed plans or projects on the environment and makes comparisons with the effects of alternative options (RCEP, 2002).

Human behaviours are the major determinant on the ecosystem dynamics. They irreversibly influence the biodiversity of land and the consumption of resources. The most important human impact on the physical environment is land cover change by increasing impervious surface areas. Since the rapid urbanisation of populations has increased, forests and agricultural lands have been transformed into built-up areas by creating impervious surfaces (Arnold & Gibbons, 1996). Imperviousness represents the imprint of land development on natural landscapes. In this context, impervious surface is a key environmental indicator for monitoring the sustainability of urban ecosystems (Schueler, 1994; Brabec et. al., 2002). The focus of this study is to evaluate the relationship between the impervious surfaces and natural environment by measuring the carrying capacity of resources. In this context, the study aims to investigate the impacts of land cover change on urban ecosystems by developing a micro-scale index model to assess their indirect or consequential effects for environmental sustainability.

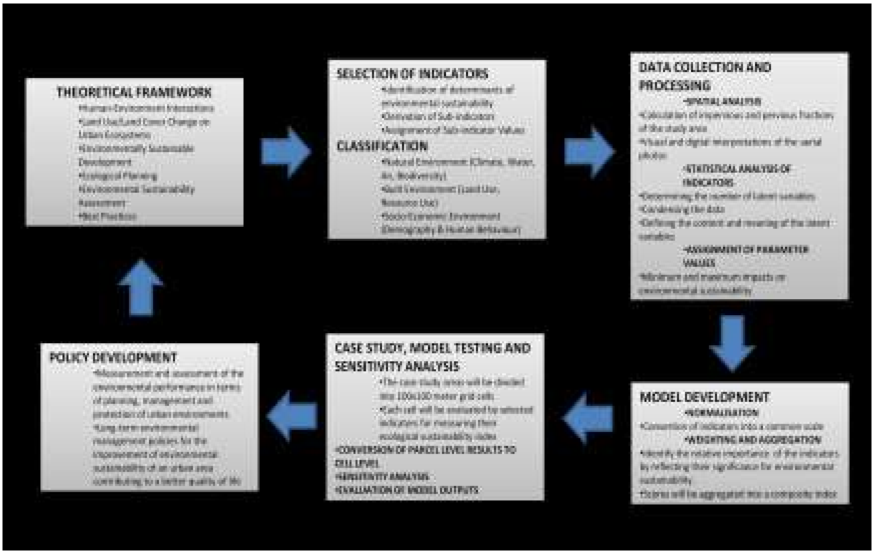


Figure 2. Structure of the ASSURE Model

Proposed model is entitled 'ASsessing the Sustainability of URban Ecosystems (ASSURE)'. It is an innovative approach to provide the resilience and function of urban natural systems secure against the environmental changes or degradation for now and the future. The structure of the ASSURE model is illustrated in Figure 2 above. The model is developed by following four steps: theoretical framework of the model; indicator selection of the model; development of the model; model testing and policy development. These parts of the model will be explored in more detail below.

Theoretical Framework of the Model

Humans affect urban ecosystems at extraordinary rates through alteration of land and resource consumption. These effects are both obvious (e.g. Pavement) and subtle (e.g. Conversion of forest to agriculture and then to suburbs, acid rain), both immediate (e.g. Dams drown river valleys) and long term (e.g. New intercity highways promote city growth on 20 to 100 year scales) (Alberti et al. 2003). Therefore, environmental sustainable development becomes an essential vehicle in order to protect and enhance the environmental conditions of urban ecosystems. The concept of environmentally sustainable development (ESD) which is defined as 'the integration of human activities into natural systems with ensuring the long-term sustainability of these systems' constitutes the theoretical framework of the model. As a subset of sustainable development, ESD ensures environmental justice in the shared use of urban ecosystems while balancing environmental quality against resource use (Weiland, 2000). The objectives of ESD are; (1) to enhance the economic development by safeguarding the welfare of future generations, (2) to provide the equity within and between generations and (3) to protect biological diversity by preserving essential ecological processes and life support systems (Commonwealth of Australia, 1992). As the dependent variable of the model, ESD will be used to evaluate environmental performance at a given area based on some indicator sets. Furthermore, it will provide decision-making support for establishing sustainable development strategies.

Indicator Selection of the Model

As shown in Table 1, the indicator base of the model has been divided into three main categories regarding human, built and natural components of the urban ecosystems. These three categories are separated into 9 indicator sets and 26 indicators.

Table 1. Selected Indicators of the ASSURE Model

CATEGORIES	INDICATOR SET	INDICATORS
NATURAL ENVIRONMENT	CLIMATE	TEMPERATURE
		EVAPOTRANSPIRATION
		PRECIPITATION
	WATER	STORMWATER RUNOFF
		INFILTRATION
		WATER POLLUTION
	AIR	AIR POLLUTANT EMISSIONS
		NOISE POLLUTION
	BIODIVERSITY	THREATENED FLORA
		THREATENED FAUNA
BUILT ENVIRONMENT	RESOURCE USE	ENERGY CONSUMPTION
		WATER CONSUMPTION
		WASTE GENERATION
	LAND USE & TRANSPORT	STREET CONNECTIVITY
		VEHICLE KILOMETRES TRAVELLED
		MODE OF TRANSPORT
		FREQUENCY OF TRIPS
		PROXIMITY TO PUBLIC TRANSPORT
		CAR OWNERSHIP
SOCIO-ECONOMIC ENVIRONMENT	DEMOGRAPHY	POPULATION DENSITY
		AGE
		IMMIGRATION STATUS
	SOCIAL STRATIFICATION	DISPOSABLE INCOME
		EDUCATION
	LIFESTYLE BEHAVIOR	FAMILY SIZE
		MARRIAGE STATUS

In terms of natural environment, impervious surfaces have negative impacts on human comfort and health in terms of decreased precipitation and evapotranspiration rates as well as increased surface temperatures. Built and paved surfaces impede rainwater infiltration and groundwater recharge that leads to increased stormwater runoff and pollutant load carried by stormwater into the waterways. Land cover change results in the form of air pollutant emissions from transport activity and noise pollution emitted by transportation systems. Furthermore, built environment directly affects habitats and ecosystems through consumption, fragmentation, and replacement of natural cover with impervious surfaces. The extent of land development, the type of development and the location of infrastructure have direct and long-lasting implications for ecosystems.

In terms of built environment, private households make significant contributions to environmental sustainability in terms of resource consumption. As impervious surfaces collect solar heat in their dense mass, they raise air temperatures which lead to increased energy consumption resulting from the lighting, heating, and cooling of the buildings, water consumption and domestic wastes. Increased consumption of resources leads to increased demand for human needs and more intensive use of land. New dwellings bring about the development of large commercial and industrial areas as well as roads, utilities and other infrastructure. As development becomes more dispersed with increasing numbers of families living on large lots at the urban fringes and as jobs and housing become increasingly segregated from one another distances between destinations have increased. People are forced to make more trips by car which creates environmental problems including: greenhouse gas emissions, increased traffic noise and upstream impacts from activities associated with vehicle use.

In terms of socio-economic environment, accelerating rates of land cover change is associated with increased population densities within the region. This development has a negative effect on vegetation cover as land is cleared to support more people and infrastructure. The urban vegetation is associated with the social stratification among urban neighborhoods in terms of disposable income and education levels. High income and higher education level have a positive relationship with vegetation cover due to a number of reasons such as ability to maintain elaborate gardens, migrate to desirable green areas, contribute to community green-space projects and reflect the level of knowledge of the environment and environmental problems. Lastly, researchers have found that lifestyle behavior is an important predictor of land cover change indicating that household patterns of consumption and expenditure on environmentally relevant goods and services are motivated by group identity and perceptions of social status associated with different lifestyles.

The indicator sets of the index model need to be flexible enough to respond to the different needs of urban environment and trends of development at the different levels and scales of the urban system (Li et al., 2009). The validity, interpretability, and explanatory power of the index model depend on the availability and quality of the environmental data. Environmental data are difficult to come by compared to data for economic and social indicators. As environmental issues are complex and problems are multifaceted, it is virtually impossible to monitor and measure every aspect of the environment. Assessment and evaluation of environmental data is the combination and comparison of information that is often subjective and not able to be measured. For this study, data collection can be a major problem due to unavailability of data at parcel level. It should be emphasised that, for some indicators, the data will be provided by Census Collection District (CCD) level and then will be transferred into parcel level by a disaggregated method.

Development of the Model

Monitoring of ecosystem or resource management requires a comprehensive data about the characteristics of a specific urban environment. Many of the existing environmental indices measure the sustainability of environment on macro-scales (national, regional, international). They may lead to an understanding of the general situation but may not be representative of a smaller area. Thus, the proposed environmental index model will give an opportunity to investigate the situation by doing observations on a micro-scale (parcel level) which brings out the general picture of the environmental problems.

The spatial analysis is the first phase of the proposed model. The main purpose of this phase is to estimate impervious and pervious fractions of the study area based on surface measurement that will be carried out through remote sensing data. At this stage, different type of land surfaces (such as paved, vegetated, water) will be evaluated by using satellite imagery. From visual and digital interpretations of the aerial photos, the total area of each land cover type within parcel house will be measured. Then, all measured surfaces in the parcel blocks and surrounded roads will be summed up in order to give the total surface area in the border of a grid cell (Figure 3).

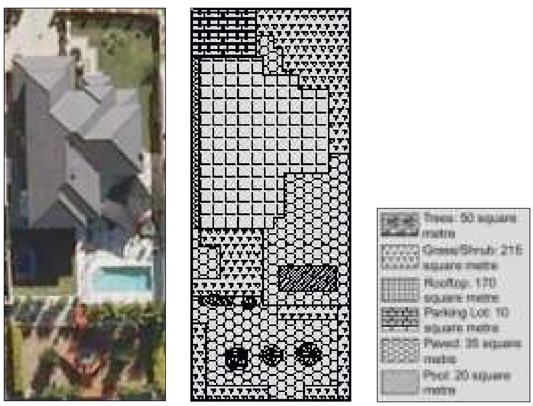


Figure 3. An Example of a Surface Measurement in a Parcel House

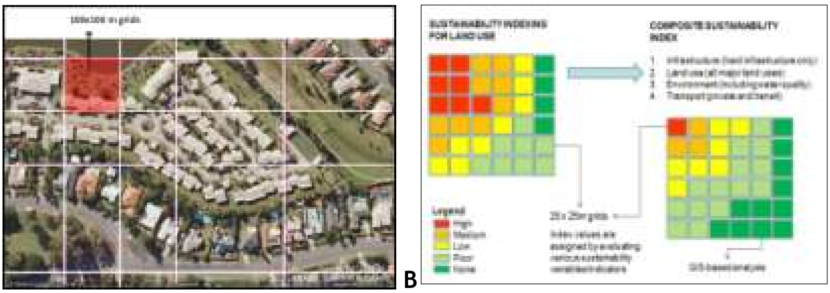
In order to clarify the relationship between indicators, at the next step statistical analysis will be used for data reduction and correlation analysis. This step will assess the accuracy of the data set and provide an understanding of the implications of the methodological processes (e.g. weighting and aggregation) during the construction phase of the model. It designates whether the nested structure of the composite indicator is well defined and the set of available individual indicators is sufficient or appropriate to describe the phenomenon. At the next stage, parameter values of indicators will be allocated in terms of their minimum and maximum impacts on environmental sustainability. Parameter values will be assigned by reviewing various studies in the literature. However, for some indicators, it is inevitably hard to define parameters related to literature review. Therefore, expert survey will be conducted for the parametric classification of these indicators. Expert survey is a widely used method for gathering data from respondents within their domain of expertise in order to gain judgments on complex matters where precise information is unavailable. Expert survey will provide a rating for each indicator regarding its 'environmental sustainability value' on different land cover types using a scale from 1 to 10. Respondents will be asked to designate a score between 1 and 10 which a value of 0 refers to the poorest level and 10 refer to the highest level.

Indicators are expressed in a variety of statistical units, ranges or scales. Normalisation is necessary to remove the scale effects of different units of measurement which cannot be integrated equally into the indicator framework in their original mode. There are a number of normalisation methods available such as ranking, standardisation, re-scaling, categorical scales, indicators above or below the mean and so on. The normalisation method should take into account the data properties and the objectives of the composite indicator. The issues that could guide the selection of the normalisation method include whether: (1) hard or soft data are available, (2) exceptional behaviour needs to be rewarded/penalised, (3) information on absolute levels matters, (4) benchmarking against a reference country is requested, and (5) the variance in the indicators needs to be accounted for (Nardo et al., 2005). Before weighting and aggregation procedures, the values of each indicator will be normalised to render them comparable. Then, different weights will be assigned to indicators in order to identify their relative importance in the model by reflecting their significance for environmental sustainability. After weighting scores have been assigned to each indicator, these scores will be aggregated into a composite index. Lastly, a sensitivity analysis should be undertaken to assess the robustness of the index in terms of the mechanism for including or excluding single indicators, the normalisation scheme, the imputation of missing data, the choice of weights and the aggregation method (OECD, 2008).

Model Testing and Policy Development

In order to test the performance of the model, Gold Coast City in Australia has been selected as the case study for this research. GCC is located in south-east Queensland, about 78 kilometres south of Brisbane. The topography of the Gold Coast consists of a coastal plain that includes beaches and dunes, river deltas, bays, estuaries and wetlands, rolling foothills and low mountain ranges. The beaches and dunes are a primary asset to the area. They are important to the quality of life of many residents and form the basis of the tourism, recreation and leisure industries that exist in the city. Environmentally, Gold Coast is one of the most bio-diverse cities in Australia. A wide range of natural landforms and vegetation types, ranging from sand flats and coastal heath to mountain eucalypt and rainforests, create diverse habitats for flora and fauna (GCCC, 2005).

As a major tourist attraction and a vibrant economic hub, Gold Coast confronts major environmental problems depending on its high growth rate, growing water demand and climate change. Rapid population growth, combined with development pressure, has significant impacts on quality and quantity of natural water systems and the degradation of waterways and beaches of the city. Beach erosion and high waves from tropical cyclones is an another environmental issue that affects Gold Coast by threatening infrastructure. Clearing and habitat destruction is the primary threat to biodiversity as a result of the growth of the city. For instance, up to 300-500 hectares per year of bushland is being cleared mainly for urban development. Furthermore, road traffic and inappropriate fire regimes are examples of a number of factors associated with land management practices that threaten biodiversity (GCCC, 2005).



A B

Figure 4. (A) An Example of 100x100 meter grid cell (B) An Example of Composite Sustainability Index

The model will be piloted within a particular area in order to test the capabilities and accuracy of the model. After piloting, the model will be recalibrated and applied in a number of suburbs of the Gold Coast. The case study areas will be divided into 100x100 meter grid cells. Each surface type in the parcel will be evaluated by selected weighted indicators for measuring their environmental sustainability. Then, these values of all indicators will be transferred into grid cells in a Likert scale from 0 (low) to 5 (high) that is indicating the sustainability level of each grid cell. A composite sustainability map will be prepared for all indicators produced by the GIS-based model. Figure 10 illustrates an example composite sustainability index structure of the GIS-based model. The findings of the testing and analysis process will be used to develop long-term environmental management policies for the improvement of environmental sustainability of an urban area contributing to a better quality of life. The proposed model will be a valuable tool to assist municipal authorities to measure and report on their environmental performance in terms of planning, management and protection of urban environments.

CONCLUSION

Recent years, an increasing number of environmental indices have been developed to track and measure the sustainability of ecosystems. They investigate the environmental problems at macro-scales from local to regional and international levels. While they have been developed to measure progress towards sustainability in a macro level, there is a particular gap in the availability of national data for many countries due to lack of local data. In this regard, there is a need to develop a micro-scale environmental index that provides sufficient local data for assessing the sustainability of a country. In an attempt to advance research in this area, this study proposes a parcel-scale environmental index that will give an opportunity to investigate the environmental problems by collecting data in a local context. Furthermore, it will give directions about the problem in a national context.

The proposed model will be an useful guidance to evaluate the urban development and its environmental impacts to achieve a sustainable urban future. It will offer long-term environmental, economic and social benefits for cities. *Environmentally,* implementation of the model will create ecologically effective green areas, reduce ecological risks, and improve the quality of water, air and soil. *Economically,* it will prevent urban sprawl and traffic congestion by providing better utilisation of existing infrastructure. *Socially,* it will reduce health risks; improve the quality of urban life and city services (e.g. health, education, transportation, and recreation). With all these benefits, this research will provide further opportunities in turning unhealthy urban areas into potential sustainable urban ecosystems. Finally, the model will contribute in developing integrated solutions to environmental challenges in the city of Gold Coast. Furthermore, the model will support the future urban development projects of Gold Coast from the perspective of environmental sustainability and propose policies and strategies for both current and future needs.

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