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Developing micro-level urban ecosystem indicators for sustainability assessment

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ABSTRACT

Sustainability assessment is increasingly being viewed as an important tool to aid in the shift towards sustainable urban ecosystems. An urban ecosystem is a dynamic system and requires regular monitoring and assessment through a set of relevant indicators. An indicator is a parameter which provides information about the state of the environment by producing a quantitative value. Indicator-based sustainability assessment needs to be considered on all spatial scales to provide efficient information of urban ecosystem sustainability. The detailed data is necessary to assess environmental change in urban ecosystems at local scale and easily transfer this information to the national and global scales. This paper proposes a set of key micro-level urban ecosystem indicators for monitoring the sustainability of residential developments. The proposed indicator framework measures the sustainability performance of urban ecosystem in 3 main categories including: natural environment, built environment, and socio-economic environment which are made up of 9 sub-categories, consisting of 23 indicators. This paper also describes theoretical foundations for the selection of each indicator with reference to the literature.

1. Introduction

According to Guidotti (2010), urban ecosystems are basically complicated blends of artificial and natural ecological systems, where people built their settlements on the remnants of natural ecosystems and form a complex structure that mimics their functions. A sustainable urban ecosystem is defined by Newman and Jennings (2008, p. 108) as "*ecosystems which are ethical*, *effective* (*healthy and equitable*), *zero-waste*, *self-regulating*, *resilient*, *self-renewing*, *flexible*, *psychologically-fulfilling and cooperative*". The sustainability of urban ecosystem depends on balanced interaction between human activities and natural resources by applying sustainable development principles, which can be summarized as follows:

- Sustainable land use and urban design through: (1) improving the quality of life by providing social interactions and easier access to a wide range of services; (2) minimizing energy consumption via green building design technologies; (3) reducing greenhouse gas emissions by providing less auto-dependent development, and; (4) creating environmentally sensitive areas to restore park and greenway systems (Williams et al., 2000; Coplak and Raksanyi, 2003; Wheeler, 2004; Jabareen, 2006).
- Sustainable transportation through promoting energy-efficient and environmentally friendly transport options, via: (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 via 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 through protecting the existing species, habitats and ecosystems in the city by creating ecologically valuable green spaces: (1) gardens; (2) parks; (3) green alleys; (4) green roofs, and; (5) *green buffer zones*, such as green belts, green wedges, green ways, green fingers (Coplak and Raksanyi, 2003; Jabareen, 2006; Convery et al., 2008).
- Renewable energy and waste management is essential for developing sustainable urban ecosystems. Renewable energy technologies can be summarized as: (1) hydropower; (2) biomass energy; (3) geothermal energy; (4) wind power; (5) solar energy, and; (6) photovoltaic technologies (Strong, 1999). Another approach is waste management practices: (1) landfill; (2) incineration; (3) biological treatment; (4) zero waste; (5) recycling-orientated eco-industrial parks, and; (6) environmental taxes, law and policies (Davidson, 2011).
- Creating a sustainable economy promotes: (1) clean technologies (i.e., Silicon Valley in California); (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).
- Environmental justice and social equity through protecting public health and welfare by managing natural resources in an equitable manner. The strategies for creating well-balanced, integrated and *socially*

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equal communities are: (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).

In recent years, cities have been working to create sustainable urban ecosystems through new initiatives such as Adelaide 'Christie Walk Eco-Village' Project; Kawasaki 'Eco Town' Program; Johannesburg 'Green-House People's Environmental Centre' Project; 'Melbourne Principles' for Sustainable Cities by the United Nations Environment Program; Freiburg Green City; the 'Hannover Principles' by William McDonough and Michael Braungart; 'One Planet Living Framework' by BioRegional Development Group and World Wildlife Fund. By looking at these practices, it is necessary to regulate the natural processes and control the scale of human activities; therefore, sustainability assessment needs to be integrated into the planning process. This integration is important in terms of understanding the physical characteristics of urban settlements as well as recognising their potential, limitations and risks in the planning process (Lein, 2003). In this context, sustainability assessment provides a fundamental approach to the efficient use of natural resources while adapting human activities in a less harmful way to the environment (Clini et al., 2008).

There is *a wide variety of sustainability assessment tools*, *among them*; *composite indicators have a role in the reporting of progress towards sustainable development by* providing information about the environmental performance, efforts to influence that performance, or the condition of the environment (Warhurst, 2002). As the impacts of environmental problems have multi-scale characteristics, assessment needs to be considered on all scales to provide efficient information of urban ecosystem sustainability. The detailed micro-level data is necessary to assess local environmental change in urban ecosystems by identifying the hotspots of unsustainability and to provide insights into the national and global scales. The main objective of this paper is to recommend key micro-level urban ecosystem indicators for monitoring the sustainability of urban development. The paper is structured as follows. Section 1 provides an introduction to the concept of urban ecosystems by establishing principles for the management of their sustainability. Section 2 discusses sustainability assessment by underlining the role of indicators to assess environmental change in urban ecosystems. Section 3 describes urban ecosystem indicators by introducing a review of international sustainability indicator initiatives. Section 4 proposes a new indicator framework for micro-level sustainability assessment by describing theoretical foundations for the selection of each indicator with reference to the literature. The proposed set of indicators, excluding socio-economic category due to limited budget and time schedule, was used in the calculation of the Micro-level Urban-ecosystem Sustainability IndeX (MUSIX) by applying in a case study investigation in the Gold Coast City, Queensland, Australia (please refer to Dizdaroglu and Yigitcanlar, 2014 for more information). Finally, Section 5 summarizes and concludes the paper.

2. Sustainability assessment using indicators

Sustainability assessment is: "*a generic term for a methodology that aims to assist decision making by identifying*, *measuring and comparing the social*, *economic and environmental implications of a project*, *program*, *or policy option*" (DSE, 2007, p.1). According to Guijt and Moiseev (2001), the main uses of sustainability assessment are providing: (1) an input to strategic planning and decision-making for governments, international and non-governmental organisations; (2) information for monitoring, evaluation and impact analysis; (3) a source for reporting on international conventions, state of the environment reporting and on specific themes, and; (4) a process to raise awareness about sustainable development issues. There are three general categorization of sustainability assessment including indicators/indices, integrated assessment and product-related assessment tools (Ness et al., 2007). These tools are arranged on a time continuum based on if they are retrospective (indicators/indices), prospective (integrated assessment) or both (product-related assessment). The first category consists of *indicators/indices*. An indicator is a variable which describes one characteristic of the state of a system through observed or estimated data. An index is a quantitative aggregation of many indicators which provides a simplified, coherent, multidimensional view of a system (Mayer, 2008). Indicators/indices are used to monitor the long-term sustainability trends from a retrospective point of view. The information they provide helps in making short-term projections and relevant decisions for the future. The second category consists of *integrated assessment tools* which investigate policy change or project implementation through developing scenarios. Examples of this category are: (1) *Multi-Criteria Analysis* is used in the comparison of policy options, by identifying the effects of these options, their relative performance and the trade-offs to be made (Hirst et al., 2012); (2) *Cost Benefit Analysis* is used for evaluating public or private investment proposals by weighing the costs of the project against the expected benefits, and; (3) *Impact assessment* is a group of forecasting tools used for improving the basis for policymaking and project approval process. 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). The third category consists of *product-related assessment tools* focusing on the material and energy flows of a product or service from a life cycle perspective. These tools allow both retrospective and prospective assessments that support decision-making. 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. *Product Material Flow Analysis* and *Product Energy Analysis* are other examples of this category.

As one of them, indicator-based sustainability assessment is increasingly recognized as a useful tool which contributes to the planning process by: (1) indicating the state of local sustainability; (2) making sustainability measurable and therefore manageable; (3) providing feedback on the progress during the implementation stage of sustainable development, and; (3) representing the advantages and disadvantages of different development alternatives to help finding win–win situations (Ciegis et al., 2009). Urban ecosystem indicators play an important role in successfully achieving urban sustainability. In this context, selecting relevant indicators is necessary to monitor the implementation of sustainability policies and provide feedbacks needed to accomplish the desirable state of sustainable urban development (Shen et al., 2011). According to Kellaway and Lukacs (2000), a good indicator is a measure of one or more ecological factors that reflects the overall health and sustainability of an ecosystem. Key urban ecosystem indicators should be able to (NZOSA, 2014):

- *Be valid and meaningful*: It should reflect the phenomenon it is intended to measure and is appropriate to the needs of the user,
- *Be sensitive and specific to the underlying phenomenon*: It should respond relatively quickly and noticeably to changes,
- *Be statistically sound*: Indicator measurement needs to be methodologically sound and fit for the purpose to which it is being applied,
- *Be intelligible*: It should be sufficiently simple to be interpreted in practice,
- *Allow international comparison*: It needs to reflect local policy goals/objectives, but also needs to be consistent with other international indicator programs to allow comparisons across countries,
- *Be consistent over time*: The usefulness of indicators is related directly to the ability to track trends over time,

- *Be timely*: Data needs to be collected and reported regularly and frequently, relative to the phenomena being monitored, and;
- *Be linked with policy or emerging issues*: It should be selected to reflect the important and emerging issues as closely as possible.

In sum, sustainability assessment is an important part of the planning process in terms of visualising and measuring progress in our efforts to move towards urban sustainability. In order to provide quantitative results there is a need for specific measures for sustainability assessment. Indicator frameworks provide a comprehensive understanding of what the concept of sustainability encompasses how to measure it through incorporating the key dimensions, potential indicator sets, and their linkages (Wu and Wu, 2012).

3. Urban ecosystem indicators

As defined by Newton et al. (1998, p. 8), "*urban ecosystem 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, social and economic issues. Urban ecosystem indicators are categorized in several different ways. The World Resources Institute divided indicators into four categories based on the human and environment interactions (Hammond et al., 1995; Alberti, 1996): (1) *Source indicators*, for measuring the depletion of resources and the degradation of biological systems (i.e. agriculture, forest, marine resources); (2) *Sink indicators*, for evaluating the capacity of resources to absorb emissions and waste (i.e., climate change, acidification, toxification); (3) *Life Support indicators*, for monitoring the change in the state of the Earth's ecosystems and biodiversity (i.e., threatened species, special lands, oceans), and; (4) *Human impact indicators*, for measuring 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), 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 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).

In recent years, an increasing number of urban ecosystem indicator initiatives have been developed by international organisations. A widely used framework *the* "*Driving force-Pressure-State-Impact-Response* (DPSIR)" developed by the Organisation for Economic Cooperation and Development has provided a basis for other initiatives, including United Nations Commission on Sustainable Development Theme Indicator Framework, United Nations Centre for Human Settlements Indicators, Millennium Development Goal Indicators, European Environment Agency list of core indicators, World Health Organisation Healthy Cities Indicators, and, Rio to Johannesburg Dashboard of Sustainability. Furthermore, several countries have developed indicator initiatives to achieve sustainable cities (e.g., Sustainable Calgary, Victoria Community Indicators Project, London Quality of Life Indicators, Sustainable Seattle, Sustainable Chattanooga, and Sustainable Community Roundtable of South Puget Sound). In *addition*, there are number of initiatives working on developing sustainability indices which is basically an aggregation of different indicators under a well-developed and pre-determined methodology (e.g., Human Development Index, *City Development Index*, Environmental Sustainability Index, Environmental Performance Index, Environmental Vulnerability Index, Well-being Index, Living Planet Index, Ecological Footprint, and Index of Sustainable Economic Welfare).

As can be seen from the aforementioned examples, they are concerned only with larger geographical units. They evaluate environmental impacts at the macro-levels from national to regional and international scales. Although they are promising, these studies report multiple barriers in terms of data availability during the indicator development process, which raised the issue of missing data treatments. For instance, in the Environmental Sustainability Index, a number of indicators including wetland protection, the quality of solid and hazardous waste management, exposure to heavy metals and toxics, and ecosystem functionality are excluded due to a lack of adequate data to measure them across in a number of countries (Emerson et al., 2010). Due to lack of comparable data, countries including Marshall Islands, Monaco, Nauru, Korea, San Marino, Somalia, South Sudan and Tuvalu have been omitted in the calculation of Human Development Index (UNDP, 2005). The lack of reliable data for some environmental policy areas including waste management, recycling and removal; impacts of toxic chemicals and heavy metals; SO_2 emissions and acid rain; soil erosion and soil productivity, and; ecosystem problems (e.g. loss of wetlands and fragmented human settlements) has put constraints on the calculation of the Environmental Performance Index (Kraemer and Peichert, 2007). The conclusion can be drawn from this discussion that the major problem in sustainability assessment lies in the gathering of reliable and accessible data. This implies availability of micro-level data as a key criterion for providing useful information in the comparison of different countries (Kulig et al., 2010). Further research is required to develop more effective approaches and solutions supporting the measurable and accessible data for the indicator development as well as capable of performing a comparative assessment via indicators at micro-level so as to aggregate these assessment findings to national and international levels.

4. A micro-level indicator framework for sustainable urban ecosystem assessment

To develop scientifically sound urban ecosystem indicators it is necessary to formulate a theoretical framework that serves as a starting point for the selection of relevant indicators and data sets. The theoretical framework of the proposed parcel-scale indicator set is based on the definition of sustainable city. As defined by Hoornweg and Freire (2013), sustainable cities are urban communities that are committed to improving the well-being of current and future residents; they integrate economic, environmental, and social considerations. Cities which are considered to be sustainable are those which have strong economic growth, are socially inclusive in their growth, and are environmentally responsible (i.e. have a positive or at least minimal adverse impact on the environment). The inter-linkages among the three pillars of sustainable development are evident in cities, which function as integrated systems (Hirst et al., 2012).

The city as a place "where nature and artifice meet" (Levi-Strauss, 1961), is a dynamic organism composed of people, built-up environment and infrastructure which are highly dependent on nature. To examine the interaction between urban development and environmental change we need to consider cities as heterogeneous ecosystems with their natural and built environments whose interactions are characterized by socio-economic settings within urban areas. In this sense, an urban ecosystem comprises: (1) natural environment (i.e., topographical features, flora/fauna, soil, water); (2) built environment (i.e., buildings, roads, bridges and other infrastructure), and (3) socio-economic environment (i.e., demographic structure

Table 1
Theoretical framework for the indicator selection.

Aims	Goals	Categories	Indicators	Contribution to sustainability
Ecological resilience of natural environment	Hydrological conservation	Hydrology	Impervious surface ratio Surface runoff	Impervious surfaces play an important role on urban hydrology and stormwater management. 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. The high volume and velocity caused by stormwater runoff increases the risk of flooding and erosion by destroying aquatic and riparian habitats.
	Urban heat island mitigation	Microclimate	Green area ratio Surface albedo	Alteration of vegetated surfaces to impervious surfaces results in increased land surface temperatures that affects absorption of solar radiation, storage of heat and causes temperature difference between urban and rural areas which is called the urban heat island effect.
	Environmental quality	Pollution	Air pollution Stormwater pollution Noise pollution	Land cover change results in the form of air pollutant emissions from transport activity and noise pollution emitted by transportation systems. Noise pollution affects human health by causing psychological symptoms. 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.
Sustainable development of built environment	Sustainable mobility & accessibility	Location	Proximity to land use destinations Access to public transport stops Sidewalk design	As a consequence of rapid urbanisation, distances between housing, jobs and other land use destinations have increased. Dispersed land use patterns are usually designed for motor vehicle transport, which causes increased consumption of non-renewable resources and traffic congestion. Auto-oriented development 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.
	Sustainable urban design	Design	Lot design Landscape design	Buildings have significant environmental impacts on natural resources through their construction, operation and demolition phases. Also, there are many significant effects of buildings on the microclimatic conditions through building location, orientation, design, material form, types and colors. These effects can be summarized as: higher level of temperatures, humidity, rainfall, air pressure, wind speeds and energy usage.
	Use of renewable resources	Efficiency	Energy conservation Renewable energy	Private households make significant contributions to 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, cooling of the buildings and water consumption.
Socially & economically sustainable community	Environmental awareness	Demographic characteristics	Household type Age Immigration status	A number of studies (Lenzen et al., 2004; Ferrer-i-Carbonell and Van Den Bergh, 2004; Barr and Gilg, 2006; Jensen, 2008; Kerkhof et al., 2009; Caeiro et al., 2012) have discussed the connection between socio-economic characteristics of households and their consumption patterns. Additionally, Luck et al. (2009) found that immigrants are generally less familiar with the local environment and land management practices than native residents. Troy et al. (2007) found a positive relationship between education level and the level of knowledge of land management and environmentally sensitive behaviors. Researchers have found that lifestyle behavior is an important predictor of consumption patterns. The Baltimore Ecosystem Study proposed the term "ecology of prestige" refers to the phenomenon in which 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. This theory suggests that a households' land management decisions are influenced by its desire to uphold the prestige of its community and outwardly express its membership in a given lifestyle group (Grove et al, 2006).
	Social equity	Social stratification	Equivalized household income Employment status Level of education	
	Sustainable households	Lifestyle	Car ownership Home ownership Dwelling type	

of the users within the area, economic activities, employment structure, regulations and policies). Thereby, they constitute a basis for the selection of indicator categories and indicators (Table 1).

The indicator set was developed by 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). Indicators need to be chosen carefully so that they reflect the environmental issues and measure the sustainability performance of the area effectively. As a result of the subjective nature of indicator selection, expert survey allows experts from various backgrounds – that are familiar with local conditions, environmental needs and policy priorities – to agree on a consensus view of the relative importance of the indicators based on their experience and judgment. 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., 2005), Urban Sustainability Index (Zhang, 2002), and Index of Environmental Friendliness (Puolamaa et al., 1996). In this study, a total of 21 experts comprising academics, planners, engineers and architects were chosen for survey, through purposive sampling of the project's industry partners. In order to allow comparison, it is desirable to standardize the data for all the indicators by conducting numerous methodologies such as: standardisation (or z-scores), min-max, distance to a reference, indicators above or below the mean (OECD, 2008). According to the theoretical framework and the data properties, benchmarking normalisation was employed to remove the scale effects of different indicator units. By reviewing various studies in the literature, benchmark values for each indicator were assigned according to their minimum and maximum impacts on urban sustainability. Each indicator is expressed with a score ranging between 1 and 5 indicating (Carraro et al., 2009): (1) Low (extremely unsustainable situation); (2) Medium-Low (not sustainable but not as severely as in the previous level); (3) Medium (a discrete level of sustainability); (4) Medium-High (satisfactory level of sustainability but not on target), and; (5) High (target level of sustainability). It has to be mentioned that this normalisation method is only implemented for the natural and built environment categories of indicators. Data on the indicators related to socio-economic structure of the urban ecosystem *were generated by household surveys.* The data was collected using a questionnaire survey with the households living in the area. Telephone or face to face interviews were conducted with the participant by special trained interviewers. In case of privacy concerns, alternative methods might be selected. The proposed micro-level indicator framework measures the sustainability performance of urban ecosystem in 3 main categories which are made up of 9 sub-categories, consisting of 23 indicators, presented in Appendix A.

5. Concluding remarks

As defined by Olalla-Tarraga (2006), a city is an ecological black hole which is depleting natural resources and productivity beyond its boundaries and an urban sustainability appraisal is necessary for the assessment of these implications. Urban ecosystem indicators can be considered as a powerful tool for evaluating the impacts of urban development on the environment and society and making political decisions for achieving sustainability. When selected carefully and used appropriately, they simplify and summarize enormous flows of information by providing quantitative data, and; develop useful feedback mechanisms by highlighting urban hotspots (Ciegis et al., 2009). Indicator selection is often subjective and there is no silver bullet solution that helps to choose the best indicator, therefore, the choice of an indicator depends on factors such as whether they are cost-effective, easy to understand, scientifically reliable and internationally comparable (Agol et al., 2014). According to the North West Regional Assembly (2003), an effective indicator framework needs to take into account the following basic criteria: (1) policy relevance and utility for users, (2) analytical soundness, and; (3) measurability. However, *because of data unavailability*, it is difficult to produce indicators which meet all these requirements. *In recent years*, *n*umerous organisations have developed sustainable development indicator frameworks at a wide range of geographical units including neighborhood, city, region, and country. However, most of them raise important challenges in terms of measurement due to *poor data availability at different scales.* Scale of data collection is considered as a critical step *in developing an indicator framework. The interpretability power of the assessment depends on the quality of detailed data.* From the above arguments, it is obvious that an indicator framework has to capture critical issues at the micro-level to provide a comprehensive picture of sustainable development at the meso- and macrolevels.

The proposed indicator set can be used for benchmarking sustainability performance at the micro-level and that it also serves as a tool for different stakeholders in establishing sustainable development policies in many ways: (1) It 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; (2) It 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, and; (3) It increases the awareness of individual residents on the environmental issues and the findings can be used to encourage them to make sustainable improvements in their own parcels. Finally, the *proposed indicator set* focuses on sustainability assessment of the residential developments by collecting data in a micro-level spatial unit and provides a conceptual basis for the policy recommendations and strategies for achieving sustainable cities. The studies in the literature show that there is a lack of consistent data sources within and between communities (Kraemer and Peichert, 2007; Mayer, 2008; Singh et al., 2009; Mori and Christodoulou 2011; Emerson et al., 2010). Therefore, the *development of sustainability indicators* requires further investigation and more micro-level indicators are needed to be developed to work with more detailed data in sustainability assessments.

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Appendix A. Supplementary data

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Didem Dizdaroglu is an Assistant Professor at the School of Urban Design and Landscape Architecture, Bilkent University, Ankara, Turkey. She received her Ph.D. degree from Queensland University of Technology, Brisbane, Australia. The Ph.D. thesis focused on developing a new parcel-level sustainability assessment tool with the use of ArcGIS and SPSS software to assist in the decision-making for policy-officers and planners to investigate the impacts of urban development on ecosystems and come up with effective environmental policies for sustainable urban development. Her Ph.D. study received the QUT Outstanding Doctoral Thesis Award 2013. Her research interests include sustainable urban ecosystems, urban sustainability assessment using geospatial analysis, sustainability indicators, ecological planning, climate responsive design, green roofs and vertical gardens.

1st Category: Natural environment

Indicator 1 | Impervious Surface Ratio | Unit: %

Calculation

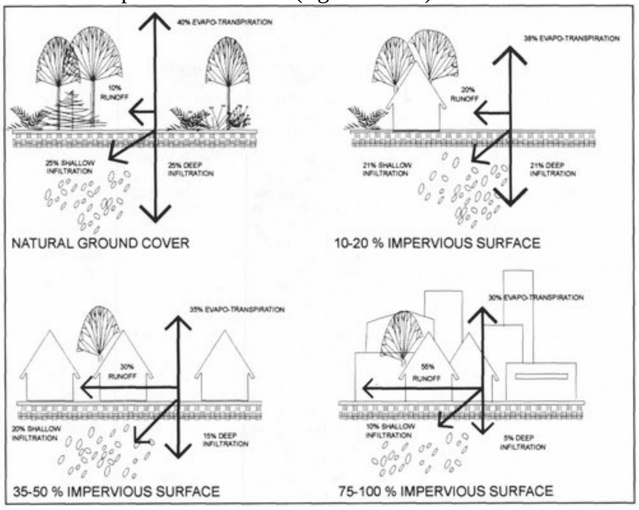
This indicator investigates changes in evapotranspiration resulting from impervious surfaces. Evapotranspiration is a collective term which comprises transpiration from urban vegetation and evaporation from wet pervious and impervious surfaces. The impervious surface ratio is calculated by dividing the 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 Scores

The parameters of this indicator are derived from the U.S. Environmental Protection Agency (1993, p.46) study, which investigates the changes of evapotranspiration rates resulting from increased impervious surfaces (figure below).



Benchmark values are assigned as shown below.

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

Limitation: 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 are not contiguous. Therefore, five reference levels are assigned by taking the arithmetic mean of these evapotranspiration rates and impervious surface ratios.

Indicator 2 | Surface Runoff | Unit: %

Calculation

Surface runoff rate for each parcel is 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 is 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.

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 Scores

Benchmark scores derived from Markart *et al.* (2006) are assigned as shown below.

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

Appendix 1. Description of indicators

Appendix 1. Cont'd

1st Category: Natural environment

Indicator 3	**Green Area Ratio**	**Unit: %**

Calculation

The green area ratio is based on the calculation of the crown area of existing trees and shrubs as well as low lying vegetation. Green area ratio for each parcel is 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 Scores

Benchmark values derived from Japanese green rating tool CASBEE (2007) are assigned as shown below.

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

Indicator 4	**Surface Albedo**	**Unit: %**

Calculation

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. The albedo of different surfaces for each parcel is calculated based on the 'effective albedo' formula derived from the study conducted by Taha *et al.* (1988). The effective albedo is 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.

The albedo values for each surface type are:

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)
Deciduous Forest	0.10-0.20	0.15	Akbari *et al.* (1992)
Coniferous Forest	0.05-0.15	0.10	Akbari *et al.* (1992)
Grass	0.25-0.30	0.28	Akbari *et al.* (1992)
Walkway (concrete)	0.25-0.40	0.33	Akbari *et al.* (2009)

Benchmark Scores

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

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

Indicator 5	**Air Pollution**	**Unit: µg/m³**

Calculation

This indicator is calculated based on transport related lead concentrations in the air. Among the various transport related pollutants, Lead (Pb) is chosen as the cursor pollutant. However, another air pollutant can be used according to the air quality targets of the other case study areas.

Benchmark Scores

Benchmark values are assigned in accordance with the classification and standards of air toxics from the Department of Sustainability, Environment, Water, Population and Communities as shown below (DSEWPC, 2001).

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

Appendix 1. Cont'd

1st Category: Natural environment

Indicator 6	**Stormwater Pollution**	**Unit: mg/L**

Calculation

This indicator is calculated based on transport related pollutants in the stormwater runoff.

Benchmark Scores

Benchmark values are derived from water quality standards for drinking, recreational and irrigation advised by National Health and Medical Research Council and the Natural Resource Management Ministerial Council (NHMRC & NRMMC, 2004).

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

Limitation: The indicator may need to be changed or modified in the implementation of other case studies according to the available data sources.

Indicator 7	**Noise Pollution**	**Unit: dBA**

Calculation

This indicator is calculated based on the road traffic noise in the study area. The method of calculation is adapted from the CORTN (calculation of road traffic noise) developed by the UK Department of Transport (DOT/Welsh Office, 1988). The CORTN model estimates the basic noise level L_{10} (This is the noise level exceeded for 10 % of the time of the measurement period) both on 1h and 18h reference time. This level is obtained at a reference distance of 10 m from the nearest carriageway edge of a highway. First, virtual receptors are located to the site through ArcGIS software. Additionally, all the relevant road and traffic data (such as traffic volumes, compositions and speeds) need to be provided from local council or the relevant Authority. By using this data, the noise level for each receptor is calculated by using ArcGIS software.

Benchmark Scores

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

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

Limitation: The topography of the area needs to be excluded from the analysis as well as traffic speeds needs to be taken as constant, and the receptor points are need to be considered as same height.

2nd Category: Built environment

Indicator 8	**Proximity to Land Use Destinations**	**Unit: NDAI score**

Calculation

This indicator is 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 is taken as the maximum threshold that residents in the neighbourhood will walk.

Benchmark Scores

Benchmark values are 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 are assigned to each domain based on their relative importance as a catalyst to physical activity (See Appendix 2). The weighted domain scores are then summed to produce a total neighbourhood destination index score (Mavoa et al., 2009, p.16).

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

Appendix 1. Cont'd

2nd Category: Built environment

Indicator 9	**Access to Public Transport Stops**	**Unit: Meter**
Calculation		Benchmark Scores

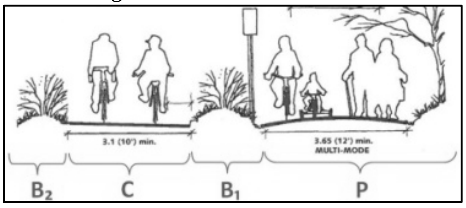
The distance to the nearest public transport stop is calculated for each parcel by using the ArcGIS Network Analysis tool.

Benchmark values are, adapted from the Land Use and Public Transport Accessibility Model (LUPTAI) developed by Yigitcanlar *et al.* (2007), assigned as shown below.

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

Indicator 10	**Sidewalk Design**	**Unit: Points**
Calculation		Benchmark Scores

This indicator investigates site's accessibility for cyclists and pedestrians by looking at the design of sidewalks. Points are assigned based upon achieved criteria for sidewalk design advised by Time-Saver Standards for Urban Design, as shown:



Abbreviations: P (pedestrian way), B_1 (vegetative buffer zone), C (Cycleway), B_2 (buffer zone) (Watson *et al.*, 2003, p. 541)

Benchmark values are assigned as shown below.

Sidewalk Design	Benchmark Value
$P + B_1 + C + B_2$	HIGH
$P + B_1 + C$	MEDIUM-HIGH
$P + B_1$	MEDIUM
P	MEDIUM-LOW
None	LOW

Indicator 11:	**Lot Design**	**Unit: Points**
Calculation		Benchmark Scores

With this indicator, passive design of the existing lot is investigated. Points are assigned based upon the principles of passive design met by the existing lot plan (derived from King *et al.*, 1996; DEWHA, 2008). The table below presents the efforts (one point per each effort on the list) that are evaluated for this indicator.

Efforts to be evaluated	Benefits	Points
Lot shape	To get best solar access and most suitable for maximising lot yield	1
Building orientation	To maximise the best use of solar energy	1
Solar access to living areas or outdoor spaces	To improve energy efficiency by providing access to winter sun	1
Setbacks/zero lot lines	To reduce lot size, maximise solar access and outdoor living space	1
Dwelling type (detached, semi-detached or attached house)	To save energy and reduce greenhouse gas emissions	1
Location of other buildings such as carports or sheds	To maximise the use living areas	1

Benchmark values are assigned as shown below.

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

Limitation: The assessment criteria for this indicator may need to be modified to suit local conditions for different climates.

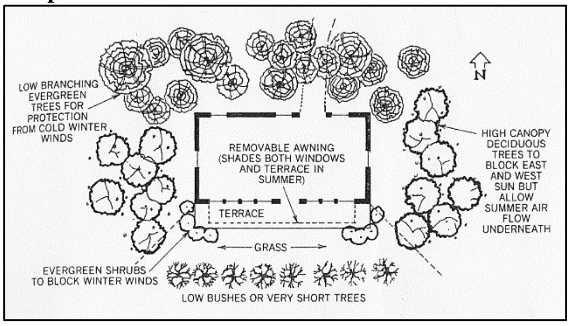
Appendix 1. Cont'd

2nd Category: Built environment

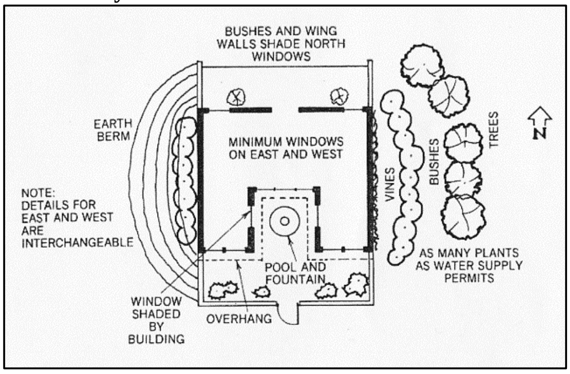
Indicator 12:	**Landscape Design**	**Unit: Points**
Calculation		Benchmark Scores

Points are assigned based upon the principles of climate responsive landscape design met by the existing lot plan. There are different landscaping techniques appropriate for four main climates. Points are given for the efforts taken for planting design of each side around the building below (Lechner, 2009).

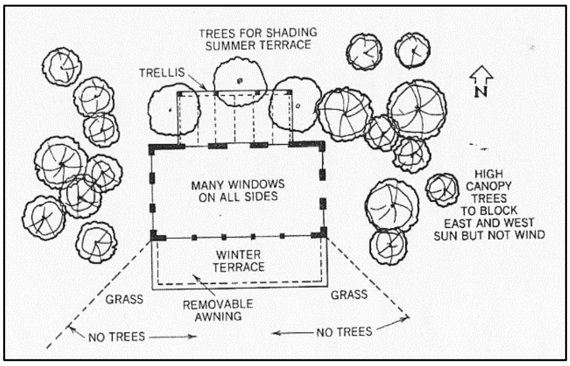
Temperate climate:



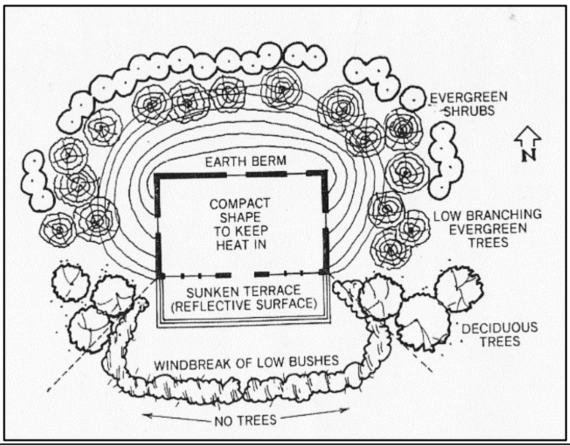
Hot and dry climate:



Hot and humid climate:



Cold climate:



Benchmark values are assigned as shown below.

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

Limitation: The assessment criteria for this indicator may need to be modified to suit local conditions for different climates.

Appendix 1. Cont'd

<table>
<tr><th colspan="3">2nd Category: Built environment</th></tr>
<tr><td>Indicator 13:</td><td>Energy Conservation</td><td>Unit: Points</td></tr>
<tr><td colspan="2">Calculation</td><td>Benchmark Scores</td></tr>
<tr><td colspan="2" rowspan="2">With this indicator, annual energy consumption is investigated. Points are assigned based upon the level of annual energy consumption of the household expressed as "kWh/m²/year" which is calculated by dividing the annual electricity use by m² space of the house.</td><td>In France, 5 levels of regulatory requirements for the energy performance of buildings are defined. The BBC (Bâtiment Basse Consommation)-Effinergie label is created jointly with the French Ministry of Housing and the Effinergie association (EFFINERGIE, 2008). Benchmark values are assigned as shown below.
<table><tr><th>Energy consumption (kWh/m²/year)</th><th>Benchmark Value</th></tr><tr><td>< 50</td><td>HIGH</td></tr><tr><td>51-150</td><td>MEDIUM-HIGH</td></tr><tr><td>151-330</td><td>MEDIUM</td></tr><tr><td>331-450</td><td>MEDIUM-LOW</td></tr><tr><td>> 450</td><td>LOW</td></tr></table></td></tr>
<tr><td>Limitation: Household energy usage data is one of the essential parameters required for defining energy efficiency. However, under some conditions, this data may not be provided due to privacy issues.</td></tr>
<tr><td>Indicator 14:</td><td>Renewable Energy</td><td>Unit: Points</td></tr>
<tr><td colspan="2">Calculation</td><td>Benchmark Scores</td></tr>
<tr><td colspan="2">With this indicator, use of renewable energy systems are investigated. Points are assigned based upon the renewable energy systems implemented in the existing parcel plan. Points are given for the efforts taken for the installation of renewable energy systems below.
<table><tr><th>Efforts to be evaluated</th><th>Points</th></tr><tr><td>Solar panels</td><td>1</td></tr><tr><td>Rainwater tank</td><td>1</td></tr><tr><td>Roof-mounted wind turbine</td><td>1</td></tr><tr><td>Green roof</td><td>1</td></tr></table></td><td>Benchmark values are assigned as shown below.
<table><tr><th>Renewable energy</th><th>Benchmark Value</th></tr><tr><td>4 points</td><td>HIGH</td></tr><tr><td>3 points</td><td>MEDIUM-HIGH</td></tr><tr><td>2 points</td><td>MEDIUM</td></tr><tr><td>1 point</td><td>MEDIUM-LOW</td></tr><tr><td>0 point</td><td>LOW</td></tr></table></td></tr>
</table>

Appendix 1. Cont'd

3rd Category: Socio-Economic environment	
Indicator 15	**Household Type**
Description	Categories
This indicator refers to the types of grouping of persons and living arrangements found in a household.	A. One family households • Couple family with children • Couple family without children • Lone-parent family 1. Female lone-parent 2. Male lone parent B. Two or more family households C. Non-family households • One person households • Two person households • Three or more person households
Indicator 16	**Age**
Description	Categories
This indicator refers to the age distribution of the household members.	Age group (years) • 0-14 • 15-24 • 25-44 • 45-64 • 65+
Indicator 17	**Immigration status**
Description	Categories
This indicator refers to the immigration status of the persons in the household.	This indicator is represented by two variables derived from a study conducted by Luck *et al* (2009): • Persons, in the household, not born in the country • Persons, in the household, arriving in the country in the last 10 years
Indicator 18	**Equivalised household income**
Description	Categories
This indicator refers to the total income (per week) of a household divided by the number of households converted into equalised adults.	Households are equalised by weighting each according to their age, using the OECD equivalence scale: • 1 to the first adult; • 0.5 to the second and each subsequent person aged 14 and over; • 0.3 to each child aged under 14.
Indicator 19	**Employment Status**
Description	Categories
This indicator refers to the employment status of the households.	• Self-employed • Employed (Full time/Part time) • Not employed • Homemaker • Student • Retired • Unable to work
Indicator 20	**Level of Education**
Description	Categories
This indicator refers to the educational level of households.	• Less than high school • High school • University/College • Master's degree and higher • Did not go to school

Appendix 1. Cont'd

3rd Category: Socio-Economic environment	
Indicator 21	**Car Ownership**
Description	Categories
This indicator refers to the number of cars in the households.	• Having a single car • Having more than one car • Not having a car
Indicator 22	**Home Ownership**
Description	Categories
This indicator refers to the households living in their own home.	• Owned by someone in the household • Rented
Indicator 23	**Dwelling Type**
Description	Categories
This indicator refers to the physical configuration of the dwelling.	• Single-detached house • Semi-detached house • Row house

Appendix 2. 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

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