Monitoring urban sustainability based on an integrated indicator model using geospatial technique and multiple data sources: a case study in the city of Saskatoon, Saskatchewan, Canada

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By

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ABSTRACT

A comprehensive understanding of urban development is critical for moving towards the goal of sustainability. Despite a collection of urban sustainability indicator (USI) conceptual frameworks proposed and explored in practical urban sustainability assessment, establishing an integrated, well-quantified, spatially characterized USI model is still a challenging task. Therefore, based on a manuscript-style format this thesis develops a subjectively weighted integrated USI model and then applies it to the city of Saskatoon, SK, Canada, as a case study, based on quantifying a hierarchical index system. In addition, urban environmental sustainability is spatiotemporally investigated for an improved understanding of Urban Heat Island (UHI) effect.

Results show that the proposed integrated USI model improved urban sustainability measurement by overcoming the shortages in existing USI models. Geospatial statistics demonstrated disparity in urban sustainability across residential neighbourhoods for Saskatoon in 2006 based on the significant clusters and outliers. It also found that population increases can possibly improve intellectual and economic well-being and promote urbanization, but may cause environmental degradation and lead to a decline in overall urban sustainability. This research also demonstrates that satellite imagery can be used to study environmental sustainability at different spatiotemporal scales. This research reveals that both urban water and green spaces had significant cooling effects on the surrounding urban LST within specific ranges. Urban surface temperature can be estimated based on a multiple linear regression model with sustainable traveling mode index and land use information as input variables.

The overall significance of this research has three folds. First, it lays a preliminary theoretical foundation for a comprehensive understanding of urban sustainability based on a well-quantified integrated USI model. Second, it is relatively original with respect to improving urban sustainability measurements through the incorporation of subjective information into objective data. Third, this research has explored spatiotemporal analysis to detect urban sustainability patterns based on compiling multiple data sources using geospatial techniques. The proposed USI model is highly suitable for comparison analysis at different spatial scales as well as continuously tracking the dynamic changes. Therefore, this research can be a good practice of applying the spatiotemporal philosophy to urban geographical problems.

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CHAPTER 1
INTRODUCTION

According to the United Nations Population Fund (UNFP) report in 2012, approximately 50% of the world's populations now live in urban areas and this number will increase to 60% by the year 2025 and 70% by 2050 (UN, 2006; UNFP, 2012). Urban area, as a complex system highly interacted with other broader systems for resource input and waste output, will definitely experience further dramatic population growth and become the primary human habitat (McGranahan, 2005; Bettencourt et al., 2007). Global urbanization partly contributed by rural-urban migration has turned out to be a critical issue associated with long-term human survival (Birch & Wachter, 2011). Since the concept of *sustainable development* was put forward in the well-known report *Our Common Future in 1987* by the UN World Commission on Environment and Development (the Brundtland Commission) (Bruntland, 1987), urban sustainability gained increasing popularity amongst governments, administrators, urban planners, and scientific communities in North America, Europe, and the Asian Pacific Region (Nijkamp and Perrels, 2009; Sanders, 2010; Slavin, 2011; Huang et al., 2009; Tamagawa, 2006; Tsenkova, 2005). However, increasing urbanization problems, including urban land use change, disparity of income, unemployment, increasing crime rate, *Urban Heat Island (UHI)* effect, and environmental degradation, have markedly impacted urban residents' quality of life and the overall urban sustainability (Holden, 2008; Keivani, 2009; Pearsall & Pierce, 2010; Birch, 2011). Focusing on the process of urban development towards a sustainable goal is of great significance with respect to improving both the objective status of urban system as well as urban residents' well-being.

1.1 CURRENT STATE OF RESEARCH ON URBAN SUSTAINABILITY

Although over 200 definitions concerning different circumstances can be found from diverse disciplines, the debate on precise conceptualisations of sustainable development in cities and towns has still not generated considerable consensus (Parkin, 2000; Shen et al., 2011; Mori & Christodoulou, 2011). A number of international organizations such as UN habitat, European Commission, Organization for Economic Co-operation and Development (OECD), President's Council on Sustainable Development (PCSD) have been dedicated to propose definitions of urban sustainability and launch urban sustainability initiatives (Shen et al., 2011). Based on some areas of agreement, both previous and current literature demonstrates that the widely accepted interpretation of "urban sustainability" always emphasizes a state with mixed achievements in three primary domains including economic prosperity, societal equity, and environmental health (Maclaren, 1996; Mebratu, 1998; Newman, 2007; Esquer-Peralta 2007; Wu and Wu, 2012; Samuel et al., 2013). A review by Keivani (2009) not only highlighted the concurrent concerns of the three domains and their two-way interactions either towards a positive or vicious cycle, but also pointed out the primary challenges of urban sustainably including social inequities within cities (e.g., income gaps, crime, social exclusion, authoritarian administration, disease, mortality, etc.), economic restructuring, institutional weakness, the release of greenhouse gases (GHG), climate change, and access to infrastructure and services. In addition, governance has been more and more involved in the concept of urban sustainability with the feedbacks from policy implementation as an effective instrument to track the sustainability progress (Werna et al., 2009; Huang et al., 2009; Shen et al., 2011). For urban sustainability at a local level it is more dependent upon its specific context and development goals (Scipioni et al., 2009).

To effectively monitor urban sustainability, “parameters or values derived from parameters” are developed to form different urban sustainability indicator (USI) models for quantitatively measuring and evaluating urban sustainability from both the holistic and narrow perspectives (Hardoy et al., 1992; Alberti, 1996; Haughton, 1998; Næss, 2001; Keirstead and Leach, 2008). To systematically monitor and assess urban development progress towards sustainability, a time series of previous studies have described step by step procedures for developing USI models (Li and Huang, 2007; Mori and Christodoulou, 2011; Wu and Wu, 2012). First of all, an unambiguous interpretation of urban sustainability is required to provide the overall direction of the USI system. Establishing a suitable framework and defining a set of selection criteria are deemed two essential steps in this whole process (Huang et al., 2009; Tanguay et al., 2010). Such knowledge has been summarized in Chapter 2 Section 2.5.3. USIs under those standards are supposed to characterize the relevant phenomena or aspects of urban development very well and be informative to the public in a spatiotemporal dynamic pattern (Shen et al., 2013). They should also be easily quantified with available measurement data in an acceptable expense.

According to the identified selection criteria, a preliminary list of possible urban sustainability indicators are supposed to be proposed based on specialized knowledge as well as the suggestions from other stakeholders (general public or policy makers). Then both equal and unequal weighting of the importance of identified selection criteria can be used to evaluate each proposed initial indicator. This indicator evaluation process can be based on the one-step procedure, a sequential procedure, or a hybrid procedure summarized by Maclaren (1996). The specific goal for local development and adopted methodologies may also contribute to adding to or reducing from the original indicator set. Finally, after the selection of final indicators for the

USI system, the effectiveness of this system should be tested in real case studies for evaluating urban sustainability (Carruthers, 1994). Various types of USI models (comprising conceptual frameworks and indicator measurements) have been proposed to provide both quantitative and qualitative assessments of the progress of urban development either towards or away from sustainability goals (Haughton and Hunter, 2003; Keirstead and Leach, 2008, Mascarenhas et al., 2010; Mori and Chirstodoulou, 2011). Those USI framework model mainly refer to "domain-based frameworks", "goal-based frameworks", "sectoral frameworks", "issue-based frameworks", "causal frameworks", and "combination framework" (Maclaren, 1996; Wu and Wu, 2012). USI models established in existing global urban sustainability initiatives include *"Sustainable Seattle indicators"* (Sustainable Seattle, 1993), *"British Columbia State of Sustainability Indicators"* (British Columbia Round Table, 1994), *"Hamilton-Wentworth Indicators"*(Regional Municipatiliy of Hamilton-Wentworth, 1995), "*Iserlohn, Germany, sustainability indicators*" (Valentin and Spangenberg, 2000), *"Taipei's sustainability index"* (Lee and Huang, 2007), "*Algarve, Portugal sustainability indicators*" (Mascarenhas et al., 2010), *"The sustainability of the N. Aegean island"* (Kondyli, 2010), *"London's urban sustainability indicators"* (LSDC, 2012), and so on.

1.2 RESEARCH PROBLEMS AND OPPORTUNITIES

Although progresses have been achieved to quantitatively measure urban sustainability, challenges and limitations can still be found in the existing urban sustainability monitoring.

First, existing USI models has shown a weak integration of possible indicators from different domains to provide a comprehensive understanding of urban sustainability (Walton et al., 2005).

Both monitoring urban sustainability and investigating its influential factors, requires an integrated USI model which is well quantified at different aggregated levels (Kondyli, 2010; Wu and Wu, 2012). A “synthetic value” and multiple “specific indices” derived from a set of indicators are needed to monitor the whole picture and also the specific status of an urban system (Gosselin et al., 1991; Mori and Christodoulou, 2011). Maclaren argued that multiple indicators are required to measure the multiple dimensions of urban sustainability because indicators devoted to any single domain fail to draw the whole picture (Maclaren, 1996). However, more indicators included for a wider coverage of urban development results in more complexity caused by measurement and quantification. Therefore, minimizing the amount of indicators without sacrificing the information content is another requirement for maximizing the efficiency of urban sustainability evaluation. To solve this problem, constructing composite USI can be a possible way by conjoining multiple specific indicators into a more integrated one (Cobb, 2000; Freudenberg, 2003). For example, QOL is a typical composite indicator which is constructed by incorporating multiple dimensions of urban life (economic, social, educational, and environmental) (Liu, 2001; Small, 2004; Jensen et al., 2004; Li and Weng, 2007; Gatrell and Jensen, 2008). Similarly, urban sustainability can also be evaluated by such composite indicator indices at different integrated levels for planning and policy-making purposes.

Second, in most USI models, the census data collected for quantifying USIs are commonly objective data merely indicative of the physical status or socioeconomic conditions of urban development. Subjective data (e.g., people’s perceptions, feeling, and sense) is almost ignored (Weng et al., 2007). This is likely due to the increased difficulty in acquiring such data which involves face-to-face interviews, detailed questionnaire design, collaborations with multiple agencies, and ethics approvals. However, as principle participants in urban activities, urban residents' living experience and perspectives impact and in turn are impacted by urban development in an interactive manner. Most current USI models highly dependent on census data generally lack the consideration of subjective (peoples' feelings and sense) perspectives to provide a more inclusive and comprehensive measurement of urban sustainability (Ojala, 2013). This can degrade the accuracy of urban sustainability monitoring and also hamper the investigation of linkages between indicators in different domains. To avoid the risk imposed by particular interests or the bias from elite governance, public participation is required in the process of urban sustainability evaluation to promote democracy (Béal, 2011). Only through the involvement of multiple stakeholders, especially the grassroots actors and groups, in the priority identification, goal setting, and policy-making, can urban sustainability measurement and evaluation maximize social equity (Béal, 2011).

In addition, existing USIs normally measured based on traditional tabular data (e.g., census information, surveyed results, etc.) cannot easily provide the spatial processes and temporal dynamics of urban sustainability changes (Jeroen et al., 1999; Devuyst, 2000; Xing et al., 2009; Putzhuber and Hasenauer, 2010; Graymore et al., 2010; Munier, 2011). For instance, based on a pressure-state-response framework, the sustainability indicators developed for Taiwan municipality by Huang et al. (2009) can analyze the influence from public policies on urban development and the interactions between different dimensions. At the same time, the authors admitted that their model fails to provide the spatial characteristics of urban development for each geographic unit. Moreover, a temporal trend of the dynamic urban sustainability changes also has possibility in providing sound feedbacks to facilitate public policy making. To this point, lacking spatial and temporal analysis can be identified as one of the dominant limitations of current urban sustainability indicator development. Also, Wu and Wu (2012) pointed out that spatiotemporal comparison analysis are found difficult to be conducted due to the poor measurements obtained from limited data sources. Since advanced geomatic approaches - remote sensing (RS) and Geographic Information Systems (GIS) have become powerful tools and data sources for revealing the spatiotemporal dynamic processes and patterns of multiple urban conditions and their interrelationships (Sutton, 2003; Shen et al., 2013), it is in need to explore those approaches and multiple data sources to improve urban sustainability investigation.

Therefore, the main purpose of this study is to address the aforementioned problems based on comprehensively investigating urban sustainability from both theoretical and empirical perspectives. The core work conducted in this thesis includes: (1) establishing an integrated USI framework model with a hierarchical index system; (2) testing the proposed USI model by incorporating both subjective and objective information in Saskatoon as a case study; (3) spatiotemporally characterizing urban temperatures and relevant influential factors for environmental consideration. This research will not only provide a theoretical basis for a comprehensive understanding of urban sustainability, but also exploit a combination of different techniques and data sources for quantitative and comparative analysis, particularly from a spatiotemporal perspective.

1.3 RESEARCH OBJECTIVES

The overall objective of this research is to advance the current understanding and practice of urban sustainability assessment based on an integrated and subjectively weighted indicator model using multiple data sources. The city of Saskatoon (SK, Canada) will serve as a context and case study for the research.

The proposed research will achieve following objectives:

1) To develop an integrated theoretical USI framework model based on a hierarchical index system;
2) To apply the proposed USI model in a case study for index quantification and pattern identification; and
3) To spatiotemporally investigate urban environmental sustainability for an improved understanding of *UHI* effect.

1.2 THESIS STRUCTURE

This thesis follows a manuscript format and is composed of six chapters (Figure1.1). Chapter 1 presents a brief introduction of the research background, hypothesis, objectives, and a general flowchart of the thesis structure. Chapter 2 gives a critical literature review of the pertinent theories and identifies how to define effective indicators and indices for applicable urban sustainability assessment. Chapter 3 achieved research objective 1 that an integrated conceptual USI framework model was established to address the problems found in existing USI models, providing a theoretical foundation for the applicable practice of urban sustainability measurement in Chapter 4. Chapter 4 fulfilled the second research objective by testing the proposed USI model in the city of Saskatoon as a real case study. Subjective weighted information was incorporated in multiple objective datasets and spatial pattern analysis was conducted based on geomatic techniques. To address research objective 3, Chapter 5 spatiotemporally investigated urban temperatures and the relevant influential factors based on geomatic and statistical approaches for an improved understanding of urban heat island effect.

Chapter 6 is the summary and conclusions for this thesis, which focuses on the overall contributions, current limitations, and potential opportunities in future research development.

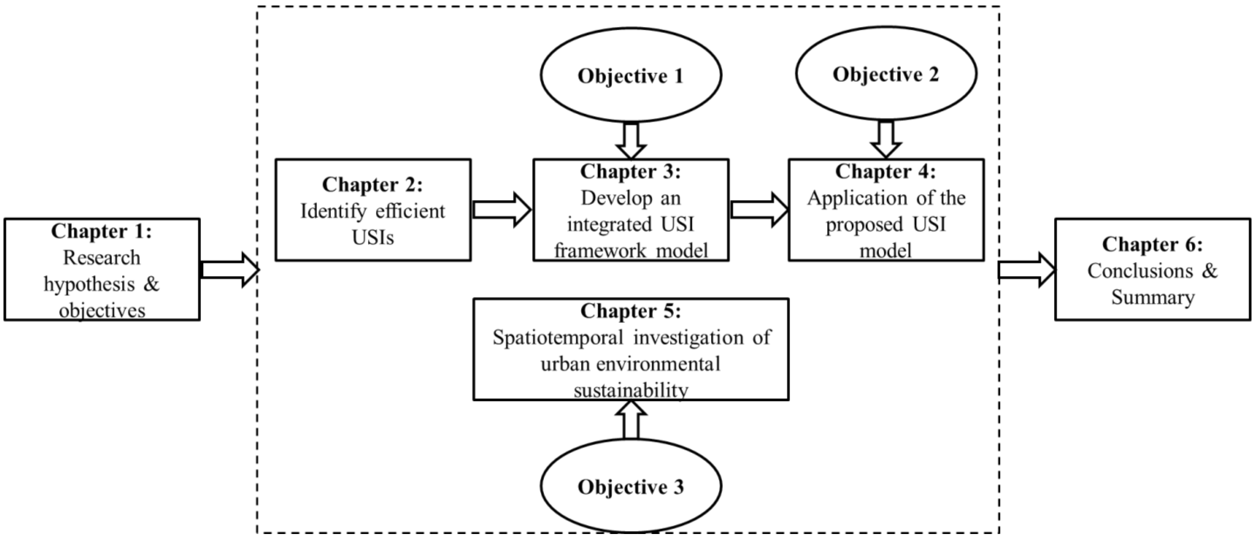


Figure 1.1 Methodology framework of the thesis.

CHAPTER 2

HOW TO IDENTIFY EFFECTIVE INDICATORS AND INDICES FOR APPLICABLE URBAN SUSTAINABILITY ASSESSMENT?

2.1 ABSTRACT

Previous literature indicates that it is difficult to successfully select effective indicators or indices for urban sustainability evaluation. This chapter is attempted to discuss on how to effectively identify indicators and indices for applicable urban sustainability assessment. Based on a discussion of the interpretation of sustainability, sustainability indicators and indices, and conceptual models, it is concluded that good urban sustainability indicators should meet three requirements including being reflective of appropriate interpretations of sustainability, being developed within an integrated conceptual framework, and being consistent with commonly accepted indicator selection criteria.

2.2 INTRODUCTION

Since the industrial revolution in 1760, increasing anthropogenic activities have dramatically disturbed our natural ecosystem. Unprecedented population growth, overconsumption of resources, environmental degradation, climate change, poverty, inequity, and wars have imposed great threats to our future development (Hopwood et al., 2005). Therefore, sustainability and sustainable development were proposed as a promising path to address such issues (Kidd, 1992).

Existing literature shows no essential distinction between those two terms and they are frequently replaced by each other. However, sustainable development is more of a long-term process through which the expected goal can be achieved while sustainability indicates the ultimate status of such processes (Maclaren, 1996; Mori and Christodoulou, 2011). *Our Common Future* (or *the Bruntland Report*) (UN, 1987), presented at the UN World Commission on Environment and Development Conference in 1987, proposed a definition of sustainable development as "*developments that meet the needs of present without compromising the ability of future generations to meet their own needs*", which has since attracted global attention in both academia and public discourse. Another international sustainability wave was promoted by the Earth Summit in Rio de Janeiro in 1992, with the action plan *Agenda 21* approved by over 70 countries for devotion to sustainable development (UNCED, 1992).

With the broad popularity of sustainability, a key issue has arisen - how can we transform the theoretical concept or philosophy into real measurements (Briassoulis, 2001; Shen et al., 2011)? More and more researchers and practitioners recognized and recommended quantitative sustainability indicators and indices as possible instruments in sustainability evaluation to improve target setting, promote effective communication, and provide easily understood feedbacks (Weng and Yang, 2003; Keirstead, 2008). However, another critical concern has emerged - how to identify effective indicators and indices in applicable urban sustainability assessment?

Effective sustainability indicators and indices cannot be identified successfully without an explicit interpretation of sustainability, an integrated USI conceptual framework, and an accepted set of selection criteria (Alberti, 1996; Weng and Yang, 2003; Roseland, 2010; Munier, 2011; Wu and Wu, 2012). Those three elements can be used as the fundamental considerations for defining the characteristics of 'good' or 'useful' sustainability indicators and indices to provide both quantitative and qualitative assessment of the progress towards or away from the goal of sustainability, particularly for the comparison analysis (Haughton and Hunter, 2003; Keirstead and Leach, 2008). This chapter attempts to address the challenge of how to identify useful indicators and indices following the aforementioned three bases. Section 2.3 and 2.4 provide a critical review of some major philosophies and methodologies related to the core issue, serving as a background for the discussion of problem solution in Section 2. 5.

2.3 INTERPRETATION OF SUSTAINABILITY

2.3.1 Definitions of sustainability

Identifying an adequate definition of urban sustainability is recognized as the foremost step for the further development and implementation of practical urban sustainability (Wu and Wu, 2012). So far, a universally accepted interpretation of urban sustainability has not yet been formed due to the intrinsic interdependence of development processes and socioeconomic structures (Brandon and Lombardi, 2005; Shen et al., 2011). A variety of definitions have been proposed based on diverse specific environmental and socioeconomic contexts. Some regard it as a desirable goal while others take it as a process (Newman, 2007). However, the vagueness and generality of defining sustainability cannot be avoided because of the complexity, multifacet, and priority of components for different development contexts and goals (Weng and Yang, 2003).

2.3.2 Three key components of sustainability

The fundamental components described by the triple bottom line (TBL/3BL) "social, ecological (environmental), and economic" or the basic domains of the three pillars "people, planet, and profit", *environmental quality*, *social equity*, and *economic development* are universally adopted in most existing literature and considered by most governments (Wu and Yang, 2003; Esquer-Peralta, 2007; Holdren, 2008; Wu and Wu, 2012; Samuel et al., 2013). The concept of TBL can abstractly simplify the complex relationship between the aforementioned three significant aspects of sustainability (Mori and Christodoulou, 2011). The environmental aspect is highly related to ecosystem integrity; the economic goal should achieve maximized well-being in monetary measurements; the social one should emphasize individuals' justice (Weng and Yang, 2003).

2.3.3 Two paradigms: weak and strong sustainability

When it comes to the issue "whether the natural capital (exhaustible capital) can be substituted by human-made capital (produced or manufactured capital)", the concept of sustainability falls into two distinct paradigms namely "weak sustainability" and "strong sustainability" (Nourry, 2008; Mori and Christodoulou, 2011). Typically strong sustainability is espoused by most ecologists and natural scientists but rebuked by neo-classical economists whose standpoints favour weak sustainability (Kuhlman and Farrington, 2010).

Weak sustainability emphasizes that natural resources can be alternated or compensated by certain manufactured capital whereas strong sustainability accentuates no substitution of natural capital by any produced capital owing to the limitations in growths and techniques (Daly, 1997; Ekins et al., 2003). In other words, in perspective of weak sustainability, as long as the total stock of man-made and natural capitals is constant over time, then the system can be regarded as sustainable with unrestricted replacement and transformation between different forms of capital. A representative example of weak sustainability is the philosophy of ecological modernization which is recognized as a symptomatic and reform-oriented approach primarily dependent upon technologies, financial regulations, and economic growth (Connelly and Roseland 2010). This philosophy is more applicable to specific projects or issues instead of integrated strategies.

In contrast, strong sustainability pays more attention to the unavoidable limitations of technical advancement rather than economic growth (Connelly and Roseland, 2010). Strong sustainability insists that the process of depleting natural resources is irreversible and extinct species are unable to recover. Some ecologists have argued that no manufactured capital can serve as a substitute for some necessary life-supporting resources (Alberti, 1996). However, Breheny (1990) holds that substitution of some natural resources with human-made capitals (e.g., buildings, roads) is necessary for better living places. This means urban sustainability somewhere in-between strong and weak sustainability instead of the absolute strong sustainability view. Local sustainability requires improvements of both physical environments and socioeconomic conditions in communities simultaneously (Haughton and Hunter, 1994).

2.4 SUSTAINABILITY INDICATORS AND INDICES

2.4.1 Definition of sustainability indicators and indices

Sustainability indicators are generally defined as a set of parameters or integrated associated parameters to quantify the attributes (e.g., dynamics, status, performance) of a target system (Gallpoin, 1997). Numeric values extracted from surveys or objective measurements are used to assess development towards, maintain, or away from the direction of sustainability. Also, quantified indicators can be used to investigate the interaction of human-environmental systems, taking urban quality, flows, and patterns together into measurements. Indicator development is highly dependent upon the specified circumstances, policy focus, geographical scale, time, and limiting factors. Sustainability indices are aggregated indicators based on mathematical combination in most cases. The essential difference between indicators and indices lies in the level of aggregation. Wu and Wu (2012) emphasized that there is little significance in distinguishing indictors and indices because indices can be interpreted as indicators.

2.4.2 Criteria for sustainability indicator (or indices) selection

Potential sustainability indicators can be selected directly from relevant literature, which has similar research backgrounds or evaluation goals. Also, they can be developed according to the widely acknowledged methodologies established for previous studies (Patrick, 2002). Indicators can also be identified based on top-down approaches and bottom-up approaches (Singh et al., 2009). The former approaches are more suitable for comparison analysis between different urban cases by gathering professional experts to develop indicators and conceptual frameworks (Mascarenhas et al., 2010). In contrast, the later approaches are designed for more specific practices at smaller scales (local and regional) by promoting public participation of multiple stakeholders (Reed et al., 2006). USI selection should follow a series of standard criteria.

One commonly used set of indicator selection criteria is the "Bellagio Principles," which was approved by a worldwide team of scholars and practitioners at the Bellagio international conference in 1996 (Handy and Zdan, 1997). The ten Bellagio principles can be summarized into eight key points namely explicit definition, integrity and inclusiveness, spatial-temporal dynamics, simplicity, accessibility, engagement, continuity, and adaption. In addition, Alberti (1996) generalized four fundamental guidelines of USI selection as "policy-relevant, scientifically-founded, readily-implementable, and usable for planning". A more detailed set of standards was recommended by Maclaren (1996), who listed twelve principles based on a wide range of previous studies and practices. In particular, Maclaren (1996) emphasized that an effective set of indicators should be of a relatively small size for efficient management. Other similar principles can be found in Keirstead and Leach (2008), who underlined some basic characteristics of USIs such as "clearly defined", "data availability and measurability", "compartmentalization", "consensual and participatory processes", and so on. Those aforementioned sets of indicator selection criteria are consistent with each other.

2.4.3 Sustainability indicator framework models

Sustainability indicator frameworks, also known as conceptual models, can provide a comprehensive understanding of the sustainability goals to measure and evaluate it through incorporating the key dimensions, potential indicator sets, and the linkages between indicators into a synthetic system (Wu and Wu, 2012).

A number of conceptual frameworks can be found in existing studies and practices. Early in a report of Canadian experience in developing urban sustainability indicators, Maclaren (1996) summarized six primary types of USI models including "domain-based frameworks", "goal-based frameworks", "sectoral frameworks", "issue-based frameworks", "causal frameworks", and "combination framework". In the same document she also pointed out the characteristics of each framework type. The domain-based framework has the capability to encompass most dimensions of sustainable development (socioeconomy, environment, and well-being) which is more readily for providing an integrated interpretation of urban sustainability. The goal-based framework that is more specific to certain emphasized topics related to urban sustainability allows for development process monitoring. The sectoral framework can best serve as a tool for the formulation of public regulations due to its explicit identification of policy-associated issues.

On the other hand, sectoral frameworks compromise to some extent the integration of different aspects in urban sustainability. The same limitations also exist in issue-based framework. Although the causal framework is able to demonstrate the linkages between different dimensions or indicators, still it is considered the most complex and difficult type in identifying the explicit stressors and conditions. Further discussion on sustainability indicator models can also be found in Wu and Wu (2012) who listed another five types of commonly used sustainability indicator models including “Pressure-state-response (PSR) frameworks”, “Theme-based frameworks”, “capital-based frameworks”, “integrated accounting frameworks” and “Bossel’s orientor frameworks” highly similar to Maclaren’s work. Sustainability indicator frameworks play an indispensible role in helping select indicators within a conceptualized structure for an overall consideration of urban sustainability evaluation.

2.5 CHARACTERISTICS OF GOOD SUSTAINABILITY INDICATORS OR INDICES

Based on the literature review of existing research theories and practices, three general characteristics of ‘good’ sustainability indicators can be extracted: 1) reflective of an integrated definition of sustainability; 2) developed within an integrated conceptual framework; 3) satisfying the commonly accepted indicator selection criteria. Each of these is discussed below.

2.5.1 Reflective of appropriate interpretations of sustainability

Good sustainability indicators should first reflect the coexistence of weak and strong sustainability by making use of their respective advantages. This means that those indicators are supposed to cover all the relevant dimensions of sustainability and guarantee the ecological priority at the same time. However, the adoption of which of the philosophies to define urban sustainability is quite dependent upon the specific urban contexts and their priority goals. There is not always a conceptualized urban sustainability adapted to all case studies.

There is no absolute right or wrong for “weak” versus “strong” sustainability because both philosophies are applicable in respect to different circumstances. Their distinction either in theoretical definition or in practical application is ambiguous due to the vague identification of natural capital (Mori and Christodoulou, 2011). On one hand, strong sustainability emphasizes ecological priorities and weak sustainability underlines the substitutes of different capitals. With the growing consumption of natural resources and stresses caused by dramatic population growth, it does make sense to adopt philology of strong sustainability. This is especially so for some fundamental ecosystem functions, which are prerequisites for the regular maintenance of human survival and socioeconomic activities in terms of delivering raw materials, assimilating waste output, and providing operational environments. Most environmental resources or services cannot be substituted by manufactured products or facilities. On the other hand, for practical urban sustainability evaluation, a balanced and harmonious development between multiple dimensions (economy, environment, society, etc.) is more accepted (Elkington, 1997; Wu and Wu, 2012; Samuel et al., 2013). However, when it comes to avoidable conflicts between domains or major indicators for achieving the overall sustainability, those trade-offs should be eliminated or minimized by involving more public participation processes of clear identification of the disagreement, replacement with better alternatives or incorporation of offsets, and even resetting of the priority goals for the whole sustainability initiative (Gibson, 2013).

Sustainability indicator model developed based on this definition is the typical application of the concept of TBL. Several reasons accounts for this inclusion. First, as a complex system formed by the natural power and anthropogenic transformation, urban development is highly influenced by multiple socioeconomic interactions such as commercial activities, manufacturing production, cultural communication, public administration, and political involvement. If socioeconomic dimensions are not encompassed, the potential indicator model will not be a comprehensive one to reflect the overall sustainable status. Second, the urban or community ecological system is not purely the natural environment and in fact it is impacting and being impacted by the disturbances from socioeconomic activities. Thus, the definition of sustainability should be used to guarantee a comprehensive set of sustainability indicators. Three pillars should be connected and integrated dimensions instead of separated aspects towards a sustainable goal. Environmental quality needs to be ensured by making appropriate economic regulations. Social equality should be implemented from both intra-generation and inter-generation perspectives. Economic development should be advanced on both qualitative and quantitative improvement. However, the conflicts are found to inevitably exist among different aspects of the overall urban sustainability, particularly for the environmental dimension and the other ones. Also, trade-offs are obvious between simplification of indicator set and presenting sufficient information (Bell and Morse, 2008). Fischer et al. (2007) improved the TBL by proposing a hierarchical nested structure of sustainability instead of the parallel relationships of the three dimensions. In addition, Mori and Christodoulou (2011) further argued that absolute thresholds are necessary to be set for determining the levels that sustainability must meet based on independent evaluation of urban sustainability without any offset.

2.5.2 Developed within an integrated conceptual framework

Helpful sustainability indicators should also be developed within an integrated conceptual framework. Only by establishing an integrated indicator model, can full coverage of relevant dimensions be accomplished by identifying potential indicators within such a conceptual framework. Even for the same type of framework, there are diverse practical models in various ways of categorizing and calculating indicators based on different sustainability interpretations under specific circumstances and goals. Therefore, the combined framework is strongly recommended by Maclaren (1996) to minimize the disadvantages of each single framework and to incorporate multiple advantages into one integrated system.

A practical example in existing literature can be found in Shen et al. (2013), who proposed a domain-based conceptual framework of integrated multiple sustainability indicators. This USI framework encompasses three fundamental domains (environmental, socioeconomic, and well-being) based on an appropriate concept of urban sustainability. Hierarchical themes ranging from broad to specific levels were further developed with reference from substantial literature. Figure 2.1 shows the adopted definition for interpreting urban sustainability definition. Figure 2.2 is the indicator conceptual framework. Figure 2.3 illustrates the hierarchical system of indicators or indices at different aggregated levels. The quantification of this indicator model can be conducted based on both spatial data (satellite imagery, vector data) and census data by incorporating subjective weights collected from social surveys. The specific measurements for each indicator are provided in Figure 2.4. Compared to the previously established urban sustainability indicator models, this newly developed one is more suitable for quantitatively assessing the urban development from a balanced and comprehensive perspective.

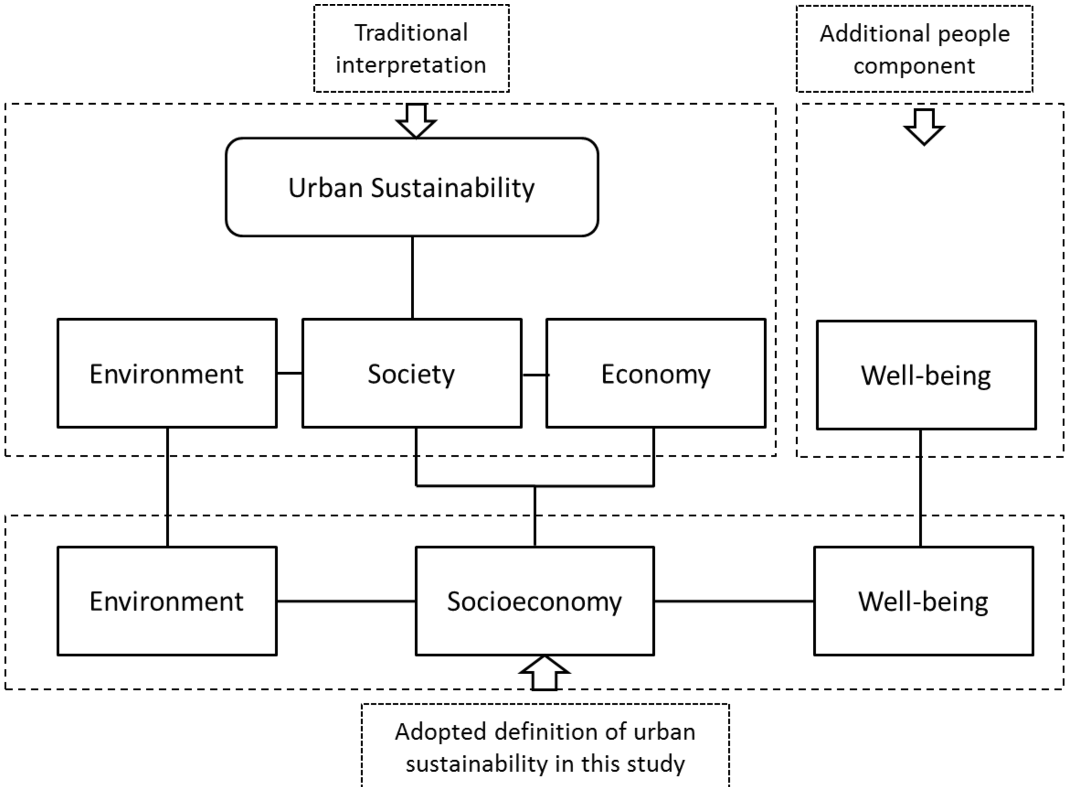


Figure 2.1 The adopted interpretation of urban sustainability (Shen et al., 2013).

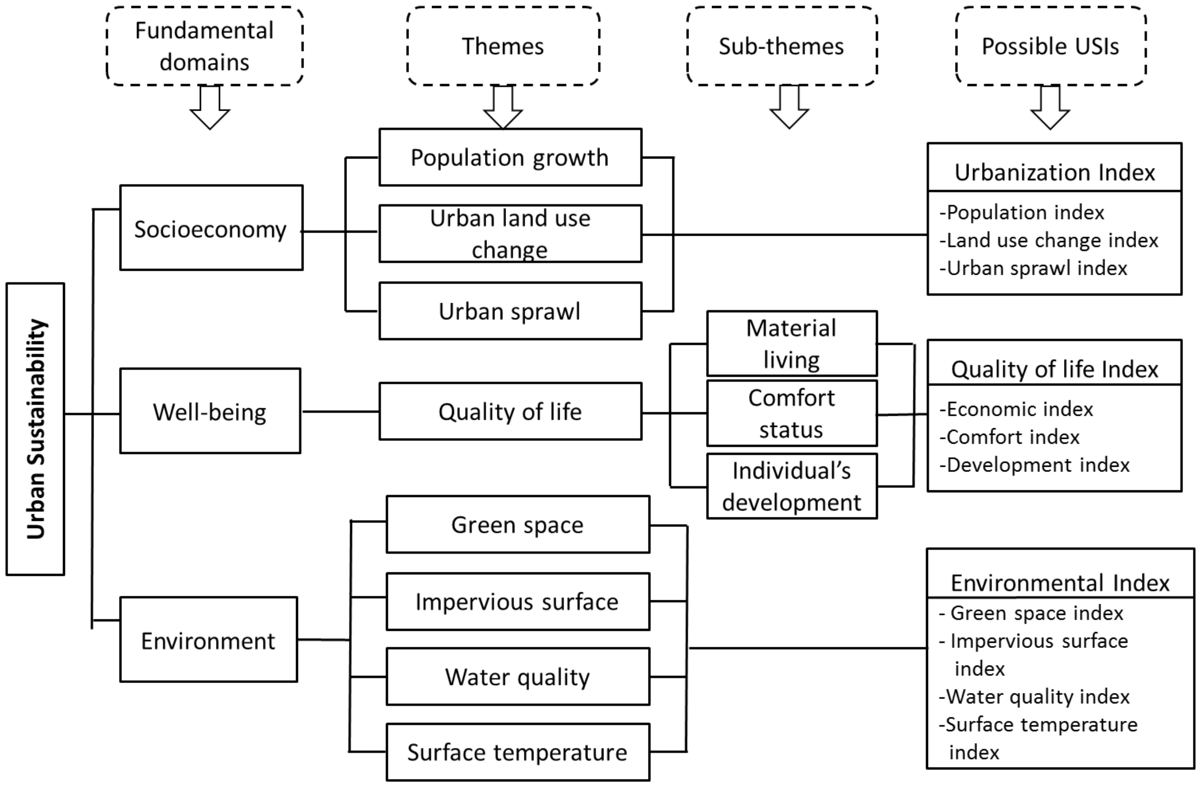


Figure 2.2 The integrated USI conceptual framework model (Shen et al., 2013).

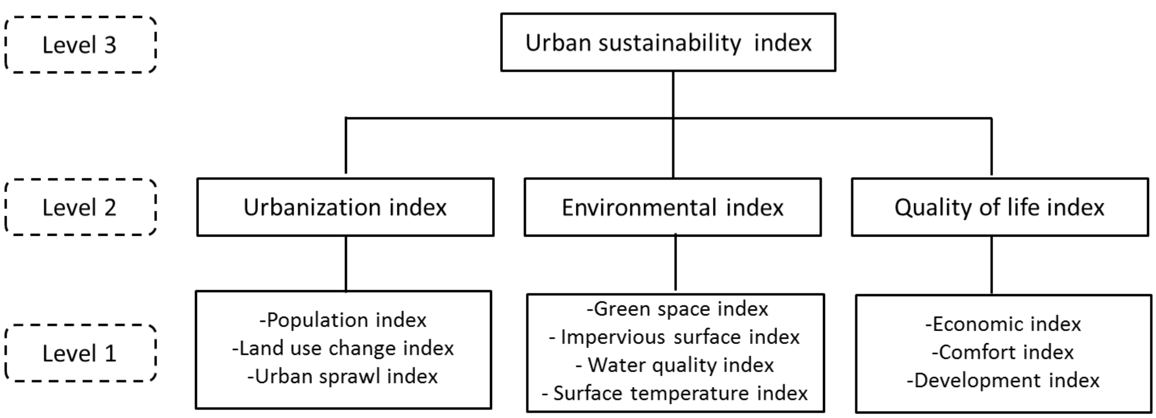


Figure 2.3 A hierarchical index system for USI model quantification at three aggregated levels (Shen et al., 2013).

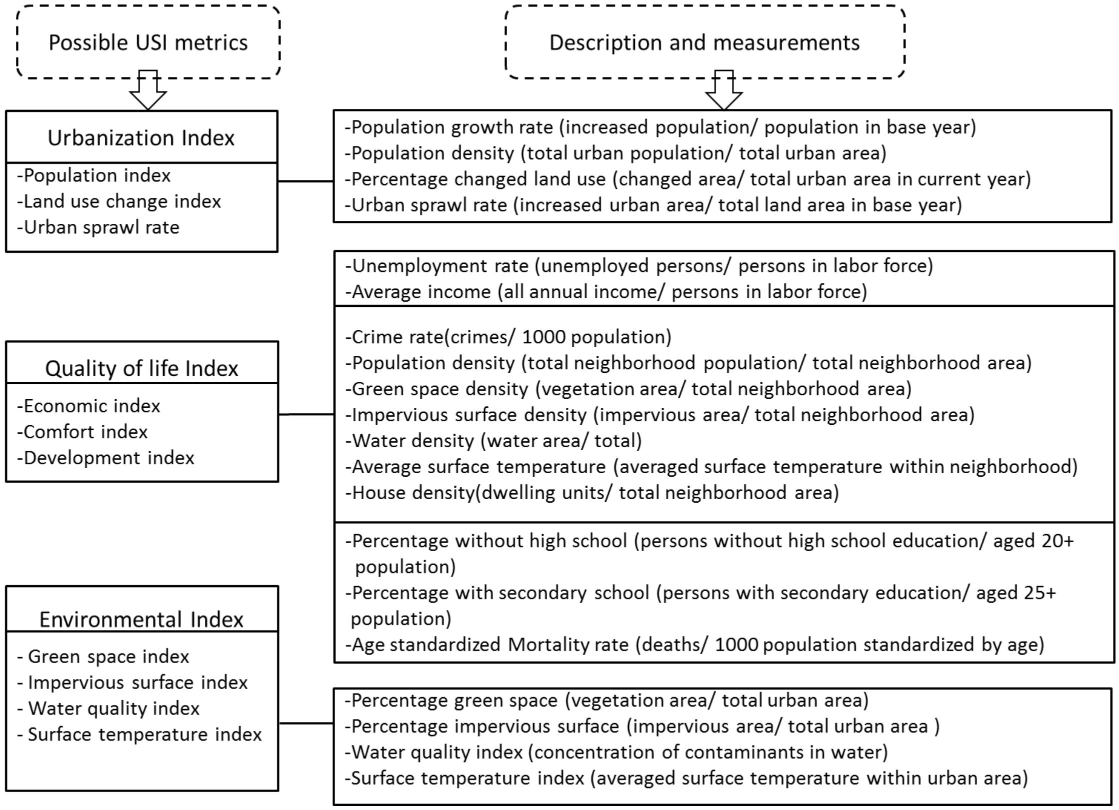


Figure 2.4 Description and measurements for potential urban sustainability indicators (Shen et al., 2013).

2.5. 3 Consistent with commonly accepted indicator selection criteria

Last but not least, a set of quality sustainability indicators should be well gauged by commonly accepted indicator selection criteria. This helps to build trust and reliability of the proposed sustainability indicators. Before the application of indicator selection criteria, the preliminary sustainability indicators should be selected based on specialized knowledge as well as the suggestions from different stakeholders (general public, researchers, or policy makers). Then the initial indicator set can be evaluated based on the selection criteria of different weights. It is also dependent upon the local priorities to add, reduce, or modify the initial indicators (Parris and Kates, 2003). The last step is to test the indicator set in real studies for practical urban sustainability evolution (Carruthers, 1994). Based on existing literature, a more general set of USI selection criteria is provided in Table 2.1.

Table 2.1 A more general set of criteria for USI selection (Shen et al., 2013)

Selection criteria for urban sustainability indicators
Clearly defined and scientifically representable
Responsive to target goals and audience
Data available
numerically measurable
spatially and temporally comparable
cost-effective

In particular, the spatiotemporal characteristic of sustainability indicators should be satisfied for better decision making within politically-based boundaries (Jeroen et al., 1999; Devuyst, 2000; Xing et al., 2009; Putzhuber and Hasenauer, 2010). In fact, this criterion is difficult to be applied in most of previous practices due to the ambiguity of identifying spatial units for governance or for resource management (Graymore et al., 2010). Similar emphasis of the spatiotemporal characteristics of sustainability indicators was also pointed out by other researchers. In 1980s, Rossi and Gilmartin (1980) stressed that repeatable measures during a long temporal period should be an indispensable feature of USIs for detecting the dynamic changes of specific urban phenomena. Likewise, the expert group at the 1996 Bellagio Conference also agreed that USIs should be characterized by the capability of indicating the dynamic spatial-temporal pattern of the targeted sustainable variables. Li and Huang (2007) pointed out the importance of studying urban system from a spatial perspective. Furthermore, Munier (2011) highlighted that developing urban sustainability indicators is highly dependent upon different spatial scales for application.

2.6 CONCLUSIONS

This chapter addressed bout how to identify the characteristics of useful indicators for applicable urban sustainability assessment. It critically reviewed the well-acknowledged definition of sustainability from the perspective of TBL and two popular paradigms – weak sustainability and strong sustainability. Also, the importance of sustainability indicators and their selection criteria were discussed. The findings in this chapter suggest that good sustainability indicators should be reflective of appropriate interpretations of sustainability, responsive to the community capital approach, developed within an integrated conceptual framework, and consistent with commonly accepted indicator selection criteria. For practical urban sustainability evaluation, sustainability based on a balanced and harmonious development strategy between multiple dimensions is more suitable to provide an overall understanding of the urban status due to the equal contributions of socioeconomic activities and natural environment. Beside, the combined indicator framework, especially for the domain-based and goal-based ones, is strongly recommended to maximize the advantages of different models within one integrated system especially for the domain-based and goal-based types. Furthermore, spatiotemporal concerns of sustainability indicators need to be taken into account for better decision making at different scales.

CHAPTER 3

AN INTEGRATED INDICATOR MODEL BASED ON A HIERARCHICAL INDICES SYSTEM FOR MONITORING URBAN SUSTAINABILITY

3.1 ABSTRACT

In recent decades, global urbanization has increased unprecedentedly and caused a series of problems including population growth, urban sprawl, land use change, unemployment, and environmental degradation. Urban sustainability and its measurement have gained increasing attention from administrators, urban planners, and scientific communities throughout the world with respect to improving urban development and human well-being. The widely accepted definition of urban sustainability emphasizes the balancing of three primary domains (urban economy, society, and environment). This chapter attempts to improve the aforementioned definition of urban sustainability by incorporating a human well-being dimension. Major problems identified in existing urban sustainability indicator (USI) models include a weak integration of potential indicators, poor measurement and quantification, and insufficient spatial-temporal analysis. To address these challenges an improved integrated USI model based on a hierarchical indices system was established for monitoring and evaluating urban sustainability. This model can be applied by quantifying indicators using both traditional statistical approaches and advanced geomatic techniques based on satellite imagery and census data, which aims to provide a theoretical basis for a comprehensive assessment of urban sustainability from a spatial-temporal perspective.

3.2 CURRENT CHALLENGES AND OPPORTUNITIES IN THE DEVELOPMENT OF USI MODELS

3.2.1. Development of urban sustainability indicator (USI) models

Urban sustainability can be considered as both a desirable goal and an ongoing process (Newman, 2007). Although over 200 definitions concerning different circumstances can be found in related literature from diverse disciplines, the widely accepted interpretation of urban sustainability always emphasizes balancing development in three primary domains: urban economy, society, and environment (Parkin, 2000; Holden, 2008; Keivani, 2009; Pearsall and Pierce, 2010). Overall, the definition of urban sustainability can be divided into two categories, holistic and narrow. The former highlights the general status of urban development with an offset view of different domains while the latter focuses more on one or two relevant domains concerning different circumstances. Accordingly, USIs as "parameters or values derived from parameters" are developed to form different USI models for quantitatively measuring and evaluating urban sustainability from both the holistic and narrow perspectives (Hardoy et al., 1992; Alberti, 1996; Haughton, 1998; Næss, 2001; Keirstead and Leach, 2008).

To systematically monitor and assess urban development progress towards sustainability, a time series of previous studies have described step by step procedures for developing USI models (Li and Huang, 2007; Mori and Christodoulou, 2011; Wu and Wu, 2012). First of all, an unambiguous interpretation of urban sustainability is required to provide the overall direction of the USI system. Establishing a suitable framework and defining a set of selection criteria are deemed two essential steps in this whole process (Huang et al., 2009; Tanguay et al., 2010). Such knowledge has been summarized in Chapter 2 Section 2.5.3. USIs under those standards are supposed to characterize the relevant phenomena or aspects of urban development very well and be informative to the public in a spatiotemporal dynamic pattern (Shen et al., 2013). They should also be easily quantified with available measurement data in an acceptable expense.

According to the identified selection criteria, a preliminary list of possible urban sustainability indicators are supposed to be proposed based on specialized knowledge as well as the suggestions from other stakeholders (general public or policy makers). Then both equal and unequal weighting of the importance of identified selection criteria can be used to evaluate each proposed initial indicator. This indicator evaluation process can be based on the one-step procedure, a sequential procedure, or a hybrid procedure summarized by Maclaren (1996). The specific goal for local development and adopted methodologies may also contribute to adding to or reducing from the original indicator set. Finally, after the selection of final indicators for the USI system, the effectiveness of this system should be tested in real case studies for evaluating urban sustainability (Carruthers, 1994).

3.2.2 Problems and opportunities in current USI models

USI models established in existing global urban sustainability initiatives mainly include *"Sustainable Seattle indicators"* (Sustainable Seattle, 1993), *"British Columbia State of Sustainability Indicators"* (British Columbia Round Table, 1994), *"Hamilton-Wentworth Indicators"*(Regional Municipatiliy of Hamilton-Wentworth, 1995), "*Iserlohn, Germany, sustainability indicators*" (Valentin and Spangenberg, 2000), *"Taipei's sustainability index"* (Lee and Huang, 2007), "*Algarve, Portugal sustainability indicators*" (Mascarenhas et al., 2010), *"The sustainability of the N. Aegean island"* (Kondyli, 2010), and *"London's urban* *sustainability indicators"* (LSDC, 2012). However, several limitations can be found in these USI models.

Firstly, effective USI models are supposed to reflect inter-generational equity (future generation and current generation), intra-generational equity (social equity and geographical equity), ecological equity (species conservation, minimizing environmental impact, and efficient resources use), and human well-being (Maclaren, 1996; Haughton, 1999; Tanguay et al., 2010; Wu and Wu, 2012). Assessing inter-generational equity requires tracking the same indicator or index over time based on the same evaluation standard, while monitoring intra-generational equity needs spatial comparison among geographical areas at different levels (international, national, regional, urban, neighborhood). However, the current USIs normally measured by traditional tabular data (e.g., census information, surveyed results, etc.) cannot easily provide such spatial processes and temporal dynamics of urban sustainability changes (Jeroen et al., 1999; Devuyst, 2000; Xing et al., 2009; Putzhuber and Hasenauer, 2010; Graymore et al., 2010; Munier, 2011). For instance, based on a pressure-state-response framework, the sustainability indicators developed for Taiwan municipality by Huang et al. (2009) can analyze the influence from public policies on urban development and the interactions between different dimensions. However, the authors admitted that their model fails to provide the spatial characteristics of urban development for each geographic unit. Moreover, a temporal trend of the dynamic urban sustainability changes over multiple-year periods has more possibility in providing sound feedbacks on the efficiency of public policies. To this point, lacking spatial and temporal analysis can be identified as one of the dominant limitations of current urban sustainability indicator development.

For the measurement and quantification of USIs, it is difficult to collect the expected census data by conducting social surveys which are time-consuming, expensive, and labor-intensive. In most USI models, the census data collected for quantifying USIs are commonly objective data merely indicative of the physical status or socioeconomic conditions of urban development. Subjective data (e.g., people's perceptions, feeling, and sense) is almost ignored (Weng et al., 2007). This is likely due to the increased difficulty in acquiring such data which involves face-to-face interviews, detailed questionnaire design, collaborations with multiple agencies, and ethics approvals. However, as principle participants in urban activities, urban residents' living experience and perspectives impact and in turn are impacted by urban development in an interactive manner. Most current USI models highly dependent on census data lack such encompassing measurement and quantification from both objective and subjective aspects, which can degrade the accuracy of urban sustainability monitoring and also hamper the investigation of linkages between indicators in different domains.

Another shortage in existing USIs lies in the weak integration of possible indicators from different domains to provide a comprehensive understanding of urban development (Kondyli, 2010). Maclaren argued that multiple indicators are required to measure the multiple dimensions of urban sustainability because indicators devoted to any single domain fail to draw the whole picture (Maclaren, 1996). However, more indicators included for a wider coverage of urban development results in more complexity caused by measurement and quantification. Therefore, minimizing the amount of indicators without sacrificing the information content is another requirement for maximizing the efficiency of urban sustainability evaluation. To solve this problem, constructing composite USI can be a possible way by conjoining multiple specific indicators into a more integrated one (Cobb, 2000; Freudenberg, 2003). For example, QOL is a typical composite indicator which is constructed by incorporating multiple dimensions of urban life (economic, social, educational, and environmental) (Liu, 2001; Small, 2004; Jensen et al., 2004; Li and Weng, 2007; Gatrell and Jensen, 2008). Similarly, urban sustainability can also be evaluated by such composite indicator indices at different integrated levels for planning and policy-making purposes.

It is therefore important to establish an integrated USI model based on a hierarchical indices system. This model should incorporate both objective and subjective information to provide a more accurate evaluation of urban sustainability. Additionally, geospatial data (satellite imagery and maps) and traditional census data are both needed to guarantee an effective spatial-temporal pattern analysis of urban sustainability distribution which is indispensable for decision makers in formulating and implementing adaptive strategies for each geographic unit according to its own sustainability status fed back from the spatial measurement. For example, further economic growth may need to be promoted in some areas while intensive environmental protection is possibly required in other places.

3.3 IMPORTANT DOMAINS OF URBAN SUSTAINABILITY EVALUATION

3.3.1 Urbanization

Urbanization can be simultaneously considered both a condition and a process that links different physical and social systems to a higher concern of sustainability with regards to environmental problems, public infrastructures, service development, and policy making (Jensen and Gatrell, 2004). Global economic growth has driven urbanization to experience an unprecedented period.

An increasing number of unsustainable problems arising from urbanization process include urban sprawl, and harmful land cover/land use change (e.g., a loss of wetlands, intensified urban heat island caused by increased impervious area), which has drawn great concern from a variety of stakeholders such as policymakers, urban planners, social scientists, geographers, economists, environmentalists, entrepreneurs, and urban residents (Keivani, 2009; Book et al., 2010). Particularly, such urbanization issues have negatively affected sustainable spatial planning of environmental and socioeconomic development (Næss, 2001). For example, the increase loss of pervious surface to impervious surface for development of buildings or parking lots give rise to a series of environmental problems such as floods and sandstorm. Key elements of urban spatial sustainability include balancing population growth with the city's carrying capacity, , guaranteeing sufficient green space, and minimizing urban sprawl, natural area change, use of environmentally-damaging materials (e.g., impervious surface), and reducing emissions (Tanguay et al., 2010; Mascarenhas et al., 2010).

3.3.1.1 Home ownership and non-family households

Home ownership rate is an important factor to urban sustainability in respect to property investment, homeless dynamics, and land use planning (Carter et al., 2009). House ownership has been widely selected as indicators for urbanization analysis (CRDF, 2013). In addition, the percentage of family households in an urban area is another influential factor of sustainable residential development because it delivers information associated with household size and income status. Low density and low house ownership as a result of rising housing cost severely damage neighbourhood's overall well-being (Kearns et al., 1991). Also, poor accessibility to affordable housing can also degrade individual well-being and accentuate social inequity and division of the low-income residents known as the marginal population (Mak, et al., 2007).

3.3.1.2 Land cover /land use change, mixed land use

Urban dynamic spatiotemporal patterns (e.g., structure, forms, and organization) play a critical role in explaining the interdependence of urban systems and broader systems such as regional system, national system, and even the global system. Monitoring urban patterns is considered an important procedure for urban planners and administrators towards urban sustainability (Alberti, 1996; Tewolde and Pedro, 2011). In addition, the impacts of urban patterns on urban environmental conditions also belong to the urban sustainability domain. Variations of urban sprawl, and land use/land cover (LULC) over different time periods are regarded as indicators that can demonstrate the urban dynamic spatial-temporal patterns. Those indicators are widely accepted by different communities and are used in diverse urban sustainability evaluation frameworks, such as "rate of expansion of urban development lands" in Taipei sustainability index (Li and Huang et al., 2007), "percent of land modified" in Sustaining Human Carrying Capacity (SHCC) framework (Graymore et al., 2010), and "land use" in Algarve region sustainability evaluation system (Mascarenhas et al., 2010)

Land cover refers to natural or man-made materials present on the earth surface such as vegetation, soil, water, and impervious surfaces while **land use** is about what is caused by anthropogenic activities including residential, commercial, industrial, and agricultural areas, etc. (Jensen, 2007). Land cover and land use change can impact both local and regional environmental conditions, and is further associated with global change process for its interaction with climate, ecosystem, biochemical cycles and anthropogenic actives (Weng, 2001). Also, urban land use pattern is highly linked with energy consumption and air pollution patterns as well as transportation trends. Urbanization has facilitated the transformation of natural land covers (e.g., soil, vegetation) to urban land uses such as industry, commerce, and residence covered by impervious surfaces, which strongly impact the whole earth ecosystem (Xiao et al., 2006).

Land use conversion and destruction in the urban development process can cause huge damage to both the environmental and human beings as illustrated in examples of ecological balance, species extinction, flood, drought, sandstorms, global warming and pollution (Zhang et al., 2011). Studying the spatial distribution of urban LCLU change across time can help monitor urban dynamic process for an improved understanding of urban sprawl, which supports making better strategies of land planning and management for future sustainable development (Yeh and Li, 2001). Therefore, urban land cover (e.g., total area, total built-up area, open area, transportation network, etc.) and land use have been selected as source sustainable indicators in a number of USI systems including the United Nations Center for Human Settlements (UNCHS), the Europe Environment Agency (EEA), and the Leicester Core Set of Sustainable Development Indicators. Since urban sprawl and land cover/land use change is of great significance for achieving urban sustainability, it is an urgent need to monitor and evaluate the magnitude and spatial-temporal pattern of urban dynamic process**.**

3.3.2 Urban environment

An urban environmental system is a necessary component of the whole urban ecosystem, which is of primary importance to urban sustainability. With respect to urban environmental policies which emphasize either ‘ecology within the city’ or ‘city in ecology’, environmental quality always to a high extent determines urban residents' overall well-being (e.g., health, recreation, etc.) (Graymore, 2010; Ojala, 2013). Urban environmental issues generally involve energy use, biodiversity conservation, landscape amenity, and natural resource protection. Specific urban environmental concerns comprise aspects of green vegetation space (GVS), impervious surface area (ISA), water quality, and urban air condition (temperature and components). All of these elements are associated closely with the overall quality of the physical environment as well as residential QOL (Alberti, 1996). It is important to assess urban environmental conditions by investigating such features for further examining the urban QOL (QOL) from a sustainability perspective.

3.3.2.1 Green space (GS)

Green space or vegetated area is, in an absolute sense, an indispensable component of urban sustainability. A number of advantages of green space can be found in urban sustainable development. Firstly, vegetation plays a critical role in cooling the air and saving energy, which is consistent with the sustainable goal of a low-energy future highlighted by Bruntland (1987). Secondly, green vegetation can absorb the pollutant emissions (e.g., carbon dioxide, sulfur dioxide, etc.) released by consumption of fossil fuels and in doing so help mitigate the greenhouse effect as well as reduce urban noise improving the health of inhabitants. Increasing green space is also a helpful strategy for reducing habitat loss, preventing species extinction, and protecting biodiversity. In addition to environmental amelioration, adequate urban vegetation also provides opportunities of outdoor recreations, which can improve QOL and contribute to the ultimate urban sustainability.

Indicators developed based on vegetation characteristics can reflect the quality of the urban environment as well as the health of the ecosystem, providing feedback information for sustainability assessment. Huang et al. (1998) pointed out that decreased green space caused by economic development is one influential factor contributing to Taipei city's unsustainable status, so he suggested using one green coverage ratio to indicate the life-support capability in urban areas for sustainability evaluation. Different vegetation-related indicators (e.g. green space area per capita, green space area per income, green space diversion, public access to green space, etc.) can be found in a number of USI systems designated into different categories for sustainability evaluation. For example, percent green area has been selected as an urban land cover indicator in EEA indicator systems while both green space surface area and public access to green space have been chosen as environmental indicators in the WHO's healthy cities indicator system. In addition, measure of public green space was also selected as a common local indicator for the municipal sustainability assessment in the Algarve region (Mascarenhas et al., 2010). Tanguay et al., (2010) identified green space as a frequently used indicator to represent the environmental conditions based on 17 urban sustainability studies in developed countries, Accessibility of green space is also considered as a health-related indicator in the Sustainable Urban Revitalization system proposed by Vehbi and Hoskara (2009).

3.3.2.2 Water quantity and quality

As one of the essential resources used for drinking, agriculture, industry and recreational purposes, water is a vital component to maintain human life and urban development. Both water quantity and quality are closely linked with residents' health and safety. Water quantity and water quality in an urban area can greatly affect residents' daily domestic water supply for drinking, washing, and other usage. In addition, water contributes significantly to improving the urban environment in terms of cooling temperature, purifying air, beautifying landscape, and preventing dryness (Lundin and Morrison, 2002). Therefore, urban water quality and quantity have significant implications for sustainability. However, urbanization problems along with other anthropogenic activities can degrade both water quantity and quality by reclamation and contamination. Holdren (2008) in his well-known paper published in the journal of *Science* pointed out that unsustainable anthropogenic processes (l) have caused severe water scarcity and pollution owing to the alternation of drainage patterns, the disturbance of natural hydrological cycle, the contamination from industrial production, and the intensifying completion of resources. Diverse water-related indicators can be found in most frameworks of urban sustainability, such as *the concentration of contaminants in water* responsive to the ecosystem indicators domain proposed by the National Round Table on Environment and Economy (1993), the *quantity of available water resources per resident* and *pressure-based assessment index of drinking quality* as environmental indicators adopted in the North Aegean region sustainability evaluation system (Kondyli, 2010), and *quality of water for human consumption* as a common local indicator in Algarve region sustainability assessment (Mascarenhas et al., 2010).

3.3.2.3 Impervious surface area (ISA)

Impervious surface commonly refers to water-resistant materials including asphalt, concrete, and other construction substances used for building roofs, roads, sidewalks, and parking lots. Urban land uses of impervious surface mainly contain transportation, commercial areas, industrial zones as well as parts of residential spaces (e.g., buildings roofs, sidewalks, etc.) (Li and Weng, 2007). As a predominant element of the built environment, impervious surfaces can characterize the composition of urban morphology, which is a major concern in assessing urban sustainability (Maclaren, 1996). Because impervious surfaces used for buildings and infrastructures are mostly produced from non-renewable resources by high energy-cost processing and transportation, expanding impervious surfaces severely violate the sustainable goal of reducing energy use. In addition, such non-porous urban materials can alter the surface albedo and runoff regimes resulting in reduced evaporation and increasing storm disasters (Lo and Quattrochi, 2003; Schreier and Marsalek, 2008). Moreover, the increasing impervious surface is considered a key driving factor of the rising urban heat island (UHI) effect attributing to its high heat absorption, thermal capacity, and conductivity (Weng, 2001). Therefore, the amount of impervious surface area (ISA) acts as a critical indicator of urban environmental quality as well as areal pollution of watersheds or runoff (Slonecker et al., 2001). Schreier and Marsalek (2008) emphasized that it is necessary to replace impervious surfaces with permeable materials to help infiltrate and reduce urban runoff. Extracting ISA variation allows detecting LCLU change for developing urban growth models to monitor dynamic urbanization processes (Yang et al., 2003). Mapping impervious surface can also play an indispensable role in providing input information for many land-atmosphere energy and exchange models, leading to a better understanding and preservation of the whole urban ecological system (Phinn et al., 2002). Associated USIs can be found in the Leicester Core Set of Sustainable Development Indicators which were intended to measure the quality of the built environment, the sustainable use of materials and land, and the accessibility impacted by land use change.

3.3.2.4 Urban surface temperature

Urban surfaces characterized by non-porous materials have much higher thermal absorption and capacity in comparison to other land covers such as vegetation or water. A huge amount of solar heat can be stored by impervious surfaces in the day time and subsequently released at night, which causes urban areas experience a higher temperature compared to their rural counterparts. This phenomenon is referred to as urban heat island (UHI) effect and is exacerbated by rapid urbanization processes (Weng, 2001; Lo and Quattrochi, 2003; Chen et al., 2006; Liu and Zhang, 2011). Particularly, increased amount of impervious surfaces as well as decreased vegetated areas has noticeably intensified this phenomenon. Moreover, the rising urban surface temperature is also contributed to by the release of urban waste heat including house heating, transportation, industry, and other disruptive anthropogenic activities. The UHI effect has posed considerably adverse impacts to urban sustainability by threatening both environmental quality and human health. The rising temperature can facilitate some harmful chemical reactions releasing poisonous gases and particles (e.g., photochemical smog) which severely degrade air and water quality and some can even lead to species extinction. Also, the UHI, a public health hazard, has given rise to high levels of human diseases and mortality because of either the associated pollutants or the extreme heat stress itself (Changnon, et al., 2004). Therefore, sustainability indicators with temperature concern can be found in previous literature. For example, the National Round Table on Environment and Economy (1993) adopted *temperature* (*daily and trends over time*) as one of the preliminary USI in the ecosystem domain. Temperature changes were also included as state indicators of environment quality in the OECD Pressure-State Response approach (Rennings and Hubert, 1997). Li and Weng (2007) also incorporated remote sensing derived land surface temperature as an environmental variable into the QOL model to assess the QOL in Indianapolis, US.

3.3.3 Quality of life (QOL)

3.3.3.1 Definition of QOL

QOL is a composite indicator for measuring the personal satisfaction of living status (Schwab, 1992). Previous literature (Graymore et al., 2008; Xing et al., 2009; Somarriba and Pena, 2009) has demonstrated that there are diverse definitions of QOL by either emphasizing the individual subjective sense in terms of "active, happy, or high self-esteem" or highlighting the objective linkages existing between the personal conditions and the external environments.

Consequently, there are two primary types of variables used for developing QOL indicators, and these variables can be taken as sub-indicators that compromise QOL. One type is called objective indicators (or proxies), which focus on the measurements of objective urban circumstances including physical and built environment, and socioeconomic development (e.g., population density, housing density, green vegetation, impervious surface, unemployment rate, etc.) (Cobb, 2000). The other type is subjective indicators, which highlight the personal perception of their experienced urban conditions. Those indicators are mainly comprised of individual values, attitudes, and senses. For example, the green space area in a neighbourhood belongs to the objective category while the residents' satisfaction with their green space area in the same neighbourhood is a subjective indicator. Objective indicators are usually measured using data from indirect data sources (e.g., census data, biophysical field data, photographs, maps, or satellite imagery). Subjective indicators are mainly obtained directly from attitudinal data based on interviews, surveys or questionnaires by adopting various forms (e.g., face-to-face, telephone, online, etc.) (Environment Canada, 1994). For QOL evaluation both objective and subjective indicators are needed to complement each other for a more comprehensive and accurate understanding of QOL (Duun et al., 1998).

There are advantages and limitations in both types of QOL indicators. First, subjective indicators are advantageous in that they are first-hand information which can indicate a residents' well-being more accurately. However, it is difficult to conduct psychological data collection due to the time-consuming and expensive measurements needed, ethical issues, as well as interviewees' accessibility, so the use of subjective indicators are quite limited for establishing a comprehensive QOL for sustainability evaluation. In addition, the validity and reliability of subjective indicators are questioned by researchers because of the difficulty in quantifying and comparing QOL interpersonally. Also, since the flexibility exists in residents' psychological evaluations towards their actual living standards, the honesty and accuracy of the interviews' feedback is viewed with skepticism. Objective indicators can be obtained from accessible data sources such as census, field work, or imagery acquisition. In addition, they are capable of being quantified and compared based on standardized values. The disadvantages of objective indicators lie in the measurement errors during data recording (e.g., underreporting mortality) and subjective judgment inevitably introduced by indicators selection. Take the evaluation of an indicator such as building density towards sustainability for example. High building density can be interpreted as "negative" because this urban pattern destroys the natural urban landscape from an environmental aspect while it can be explained as "positive" from an economic development perspective. Therefore, a universally accepted indicator assessment criteria within most communities is needed to avoid the weakness shown by the objective indicators.

A well-developed QOL model should be based on the incorporation of both physical and psychological variables (Cutter, 1985; Myers, 1987). Nonetheless, it is difficult to incorporate subjective information into objective data for quantifying QOL model due to the extensive work required for data collection based on conducting surveys for each geographic unit (Li and Weng , 2007). Some researchers (Kuz, 1978; Miles, 1985; Oswald and Wu, 2010) believe that objective indicators can represent the subjective ones based on the assumption that there is a high correlation existing between the two. However, Narvaez et al., (2008) argued that objective information cannot exclusively explain the concept of individual's QOL owing to the complexity of psychological processes. QOL studies conducted by Somarriba and Pena (2009) have demonstrated that subjective well-being is a necessary component of a synthetic QOL indicator by depicting a panoramic picture of interactions between individual's perceptions and the external conditions.

3.3.3.2 Sustainability implications of QOL

QOL has significant sustainability implications because of the close connections between individual well-being and corresponding urban conditions. As a composite index, QOL is capable of representing socioeconomic and environmental conditions associated with local people's life (Somarriba and Pena, 2009). QOL has been identified as an essential dimension of sustainability QOL with consensus from a wide range of studies (Board, 1994; Alberti, 1996; Graymore et al., 2008; Mascarenhas et al., 2010). QOL is also a widely adopted goal or indicator for national, regional, or local sustainability assessment (DEFRA, 2004; Jozsa and Brown, 2005; Mascarenhas et al., 2010). Singh et al., (2009) overviewed a number of sustainability indictors from previous initiatives and summarized various QOL related indices including gender empowerment measure, physical quality of life index, well-being index, and so on.

Despite the popularity of developing various USIs frameworks, previous literature and planning reports demonstrated that there is a weak integration of potential USIs in existing urban sustainability evaluation systems. A “synthetic value” derived from an integrated system of multiple indicators is required to measure and evaluate the whole picture of an urban situation (Gosselin et al., 1991). In addition, there is a lack of linkages among the different dimensions of an explicit interpretation of urban sustainability from both objective and subjective perspectives. Also, the USIs developed for previous frameworks cannot be completely compared or quantified due to their poor measurements and quantification.

Furthermore, little attention has been paid to the spatial and temporal patterns of urban development. The strengths of geomatic approaches, including GIS and remote sensing has not been fully explored for the urban dynamic analysis. Most remote sensing and GIS based research separately investigated economic, social, or environmental aspects of urban development either on urban sprawl, land use, or urban environmental problems (GV, ISA, UHI) while other studies applied such spatial methods merely for assessing QOL. However, urbanization issues (urban sprawl and land use, urban environmental problems) and QOL are of great association with spatial sustainability. The detachment of assessing each dimension of urban sustainability without a spatial-temporal perspective is a common disadvantage of much contemporary urban sustainable studies.

3.4 AVAILABILITY OF POTENTIAL APPROACHES

A lot of research has shown that statistical approaches and RS & GIS are effective tools in addressing most any environmental problems (Jensen, 2004). In particular, the incorporation of both methodologies can significantly enhance the ability of researchers in characterizing urban morphology (Yeh and Li, 2001; Weng, 2002; Seto and Kaufmann, 2003; Mohan, 2010), monitoring the urban dynamic process (Weng, 2001; Wilson et al., 2006; Xiao et al., 2006; Tewolde and Cabral, 2011), investigating urban environmental problems (Ridd, 1995; Weng, 2001; Phinn et al., 2002), and assessing urban QOL (Lo and Faber, 1997; Randall and Morton, 2003; Jensen et al., 2004; Li and Weng, 2007). Statistical approaches mainly include correlation-regression analysis, the expansion method, factor analysis, principalal component analysis (PCA), and analysis of variance (Li and Weng, 2007; Randall and Morton, 2003).

Advanced geospatial techniques have excellent capabilities to integrate multiple data sources (e.g., census data, satellite imagery, and maps) into one platform and extract diverse spatial-temporal information from the complex urban system. First, remote sensing can provide huge amounts of data (e.g., aerial photography, satellite imagery) with different spatial and temporal resolutions, which enable large-scale and continuous coverage of the study area. In addition, remote sensing data processing techniques and Geomatic Information Systems have powerful spatial analysis functions for incorporating tabular or attribute data with spatial data to facilitate investigation of biophysical and socioeconomic information at different scales (Jensen et al., 2004). Compared to traditional non-spatial methods, RS and GIS hold great possibility for characterizing urban LULC change information, urban dynamic growth, and environmental conditions due to their advantages in mapping and handling massive datasets in a time-labor efficient way (Xian et al., 2008). Moreover, developing a dynamic prediction model from spatial-temporal perspective can contribute significantly to the understanding of future urban expansion, which allows for an effective evaluation of the proposed planning policies before being put into action (Liu et al., 2001). However, the combination of aforementioned statistical and geospatial approaches has until recently been limited to a relatively narrow range of application. Most urbanization studies such as urban sprawl or urban heat island issues (Chen et al., 2006; Jiang and Tian, 2010; Taubenböck, et al., 2012) derived from land use land over information were conducted based on remote sensing classification and change detection methods but paid relatively little attention to the influence of socioeconomic factors. Even though the urbanization problems can be effectively observed or monitored from a physical perspective, the linkages between the phenomenal problems and its profound socioeconomic influence or other anthropogenic factors seem to be unrevealed. However, formulation of the goal of urban sustainability and implementation of further sustainable urban development requires a better understanding of the cause-condition information which is possibly obtained by using other analytical approaches such as statistical modeling or correlation investigation (Ma and Xu, 2010).

3.4.1 Urban expansion and land use change

Urban sprawl is commonly quantified by deriving the built-up area difference between different periods from physical field survey, historical maps, or remotely sensed imagery (Mohan, 2010). LULC change can be conducted by combining remote sensing change detection techniques and GIS spatial analysis functions (Weng, 2001). Weng (2002) detected the trend and spatial pattern of land use change in the Zhujiang Delta of South China based on geospatial analysis and stochastic modeling. He also found a large loss of cropland in the past decade resulting from an abnormal urban growth, which demonstrated the impacts of urban sprawl on land use dynamic conversion. Mohan (2010) studied the same region by applying an econometric model with inputs of Landsat Thematic Mapper (TM) imagery of 30 m spatial resolution and economic-demographic data, which indicated that the external investment in industry is the paramount driver of local land use change. Similarly, the spatial-temporal dynamics of urban sprawl in the city of Shijiazhuang (China) was explored by Xiao et al. (2006) who integrated socioeconomic census data, historical maps, and satellite imagery to the GIS spatial analysis platform. LULC change detection was also carried out in this study and was found to be greatly driven by this urban expansion phenomenon as well as other influencing factors. In addition, urban sprawl and LULC studies are also conducted in Africa. Tewolde and Cabral (2011) employed remote sensing object-oriented classification and a multi-layer perception neural network to develop an urban growth model, which can predict land use change and urban expansion in the next decade. In this study high spatial resolution imagery (IKONOS-2 of 1 m and Quickbird of 0.6 m), DEM data, and land cover maps were used simultaneously as ancillary data to assist classification and accuracy assessment.

3.4.2 Urban environment detection

3.4.2.1 Mapping vegetation

Remote sensing provides an effective tool for accurately mapping and monitoring vegetation abundance. Compared to natural vegetation measuring, urban vegetation requires imagery with higher spatial resolution due to its heterogeneity and comparatively smaller geographical scales (Price, 1987). Phinn et al. (2002) demonstrated that 10 to 20 m is the most appropriate spatial scale to identify urban structures. In fact, Landsat TM imagery of 30 m spatial resolution is not appropriate for characterizing urban features due to the image pixels of mixed spectral features. Multispectral Satellite Pour l'Observation de la Terre (SPOT) 4 and 5 imagery of 20 m spatial resolution can be used to extract urban land cover distribution as well as vegetation abundance. As a ratio-based index, Normalized Difference Vegetation Index (NDVI) calculated from red and near-infrared reflectance can be used to indirectly estimate the amount of green biomass (Jensen, 2007). Nicole and Lee (2005) pointed out that NDVI is sensor dependent because of the different definitions of spectral regions of different instruments. Small (2001) suggested that Chlorophyll Index (green red ratio) derived from high spatial resolution IKONOS satellite imagery better estimate urban vegetation compared to NDVI owing to its sensitivity to multiple canopy layers particularly in dry seasons. Another popular approach to estimate urban vegetation is named spectral mix analysis (SMA) which is capable of characterizing spectral heterogeneity of the urban mosaic (Song, 2005). SMA is developed based on a linear mixture model with different proportions of "end members" (fundamental components of the urban landscape) reflectance within one image pixel, which shows great advantages in analyzing Landsat TM and SPOT imagery for urban classification (Small, 2004; Lo, 1997; Jackson, 1975). With the development of remote sensors for obtaining high spatial resolution (<10 m) imagery, texture analysis and object-oriented techniques can also make accurate urban land cover information extraction possible (Price, 1987).

3.4.2.2 Mapping impervious area

Early studies used remote sensing approaches to identify ISA based on the simple classification of roads, parking lots, rooftops, and buildings (Plunk et al., 1990; Morgan et al., 1993; Ji and Jensen, 1999). More recent research computed ISA by considering it as a basic category of urban land cover and land use (LCLU) classification systems (Yang et al., 2003; Lu et al., 2011; Weng, 2012;). However, similar to urban vegetation mapping, it is difficult to guarantee a high accuracy of SIA extraction from heterogeneous urban areas using traditional pixel-based classification methods. It is possible that moderate satellite imagery with a spatial resolution between 10 m to 100 m (e.g., Landsat TM or SPOT) suffer from the scale problems owing to the impure pixels of mixed land covers when applied to extract information from the urban mosaic. Remote sensing classification confusion can be frequently caused by the spectral mixture within the instantaneous field of view. Therefore, both SAM methodologies and high spatial resolution imagery are needed for accurately extracting impervious surface features (e.g., area, percentage or pattern) from the urban landscape (Phinn et al., 2002; Lo and Faber, 1997; Lu and Weng, 2004; Xian, 2007). Setiawan et al. (2006) investigated the urban spatial and temporal patterns of both Las Vegas and Tampa by developing a subpixel imperviousness assessment model (SIAM). A Vegetation-Impervious surface-soil (VIS) model developed by Small (2004) has proved successful in quantifying different physical compositions of the urban environment based on parameter standardization (Lo and Faber, 1997; Xian, 2007; Gao, 1996).

3.4.2.3 Urban water quality and quantity

Urban Water quantity can be obtained by land cover analysis based on remote sensing classification. In particular, it is possible to improve the accuracy of water extraction from satellite imagery by adopting some advanced classification techniques such as SMA or object oriented approaches (Weng, 2012). Band ratio indices are another way to quantitatively distinguish water information with a certain threshold from the imagery of the urban landscape such as Normalized Difference Water Index (NDWI) (Xu, 2006; Imhoff et al., 2010). Water quality parameters such as dissolved oxygen (DO), chemical oxygen demand (COD) index, nitrogen as ammonia, total phosphorous (TP) can be measured using experimental instruments at monitoring stations (Yin et al., 2005).

3.4.2.4 Urban surface temperature

Since 1972, remotely sensed thermal radiation ranging from 8 to 13 μm of the electromagnetic spectrum has been utilized to retrieve land surface temperature based on the physical theories of the Stefan-Boltzmann law, Wien's displacement law and Planck's law (Streutker, 2003). Both day and night land surface temperature can be derived from the thermal energy obtained by satellite sensors. Digital brightness of the thermal imagery can record the radiant energy as an expression of the thermal emissivity of distinct objects (Price, 1987). Previous research has shown that diverse satellite imagery of different spatial, temporal and spectral resolutions have been exploited to extract the land surface temperature for interpretation of the urban heat island phenomenon. Low spatial resolution imagery such as the Advanced Very High Resolution Radiometer (AVHRR) within an Instantaneous Field of View (IFOV) of 1 km allows for spatial-temporal analysis of surface temperature in Houston, Texas at a regional scale (Gallo and Owen, 1998). Similar applications can also be found in the research by (Nicole and Lee, 2005; Chen et al., 2005). Compared to low spatial resolution imagery, thermal infrared imagery of moderate spatial resolution, such as TM (120 m) and Enhanced Thematic Mapper Plus (ETM+) (60 m), are more popular for small-scale (e.g., local, neighborhood) urban studies. For example, Liu (1975) applied multi-temporal TM and ETM+ data to retrieve the spatial variation of brightness temperature in Shenzhen (China) from 1990 to 2000, showing that obvious heat island effects can be identified in the most urbanized regions. In addition, existing literature has also demonstrated that surface temperature has a negative relationship with water and vegetation percentages but a positive linkage with impervious surface area. These aforementioned impacts of land cover and land use pattern can be obtained by spatial statistical analysis of classification results and the surface temperature distribution.

3.4.3 QOL assessment

Previous literature shows great potential and availability for geomatic techniques and statistical approaches in assessing QOL from a spatial perspective. Randall and Morton (2003) estimated QOL in Athens-Clarke County (Georgia, US) by incorporating TM imagery-derived environmental information (e.g., land use land cover percentage, NDVI, and surface temperature) and socioeconomic census data (e.g., population density, per capita income, median home value, and percentage of college graduates). The intercorrelation of different variables was also investigated by this study, which presented a comprehensive explanation of the multiple contributors to the overall QOL. The methodologies proposed by this study can well match the essential characteristics of QOL (subjectivity and objectivity) interpreted in early studies (Diener and Suh, 1997; Lo, 1997) by conducting both the subjective and objective QOL assessments respectively based on PCA and GIS overlay approaches. Likewise, Lo and Quattrochi (2003) adopted the same idea in the QOL study of Indianapolis city (US) and they expanded the original variable set to encompass more input information such as the impervious surface area extracted from satellite imagery, poverty, employment rate and house characteristics for the quantitative QOL model. In addition, they used ETM+ imagery instead of TM for surface temperature retrieval, which improved the spatial resolution of the thermal band from 120 m to 60 m. Moreover, they conducted Pearson’s correlation and factor analysis to reduce the redundant information of the dataset to derive combined information representing different aspects of QOL. Similar QOL studies can also be found in (Xian et al., 2008; Gatrell and Jensen, 2008; City of Saskatoon, 2010).

3.4.4 Opportunities in available methodologies

These aforementioned approaches are nothing new since they have been widely applied in a number of studies including environmental studies, urban planning, and some social sciences. However, most of these techniques have been used separately to investigate one or two aspects of urban development. Some focused on urban sprawl or land use (Setiawan, 2006; Mohan, 2010; Tewolde and Cabral, 2011) while others concentrated on impervious surface extraction (Xian, 2007; Lu et al., 2011; Weng, 2013), urban heat island study (Streutker, 2003; Fabrizi et al., 2010; Rinner and Hussain, 2011), or urban vegetation mapping (Small, 2001; Phinn et al., 2002; Nicole and Lee, 2005) as well as quality of life modeling (Jensen et al.,2004; Li and Weng, 2007). Such issues are highly associated with urban sustainability; but they have rarely been studied together based on integrated geomatic approaches for comprehensive urban sustainability evaluation. Remote sensing and GIS techniques have still not been fully explored to develop a whole picture of urban sustainability due to their detached applications. Some statistical data can further illustrate this point. For example, in the database *Web of Science* users can access 3043 articles on urban sustainability if *'urban sustainability'* has been selected for as the defined key words. However, if the key words are set to *'urban sustainability'* and *'remote sensing'* at the same time, the search result is only 47 records. Similarly, only 120 articles can be found if the key words are set to *'urban sustainability'* and *'GIS'*. If it is set to *'urban sustainability'*, *'remote sensing'*, and *'GIS'* simultaneously, only 20 articles are returned. This indicates that approximately 1.5% ~ 3.9% of urban sustainability studies have used advanced geospatial techniques. Accordingly the spatial-temporal comparability of these USIs is somehow challenged. It is necessary to explore the potential of advanced geomatic approaches in such aspects for improving the evaluation of urban sustainability.

3.5. A POTENTIAL INTEGRATED MODEL FOR MONITORING URBAN SUSTAINAIBLITY

To lay the conceptual framework for effectively monitoring and evaluating urban sustainability, it is of importance and priority to establish an integrated USI model based on an appropriate understanding of urban sustainability. Then, candidate urban sustainability indicators need to be determined according to the different domains and themes identified within the framework model.

3.5.1 Define a suitable interpretation of urban sustainability

A holistic interpretation of urban sustainability is adopted in this urban sustainability study, which can be explained as: A sustainable city is one undergoing simultaneous development of environment, economy, and society to satisfy the residents' quality of life. Although this definition has been rejected by the United Kingdom's Local Government Management Board (1994) in their description of urban sustainability owing to a lack of innovation, this traditional way is still suggested in comprehensively explaining the complexity of urban systems (Nijkamp and Vreeker, 2000; Kondyli, 2010). So far, this triple bottom line based interpretation is still regarded as a relatively integrated one with encompassing coverage of multiple aspects relevant to urban sustainability (Gasparatos et al., 2008; Mori and Christodoulou, 2011). The USI model established based on this interpretation of urban sustainability has more possibility for application in different urban contexts due to its generality and comprehensiveness. In addition, people's well-being can demonstrate more subjective information of urban sustainability status while the other three basic domains (environment, society, and economy) provide more objective evidence. People as an essential and active component of urban activities are supposed to be taken into consideration to give evidence of urban sustainability. Since urban quality of life consists of social, economic, environmental, and subjective well-being, a simply defined definition of urban sustainability with two broad aspects (urbanization and QOL) is adopted for urban sustainability measurement (Figure 3.1). In comparison to the interpretation of urban sustainability proposed by Shen et al. (2013), this is more concise and explicit because QOL is an inclusive concept which also considers urban environmental impacts. The other broad category of indicators within the whole urban sustainability framework for this study is referred to as Urbanization. Urbanization focuses more on the land use related conditions of the whole city's development while QOL puts close attention to the individual's overall well-being. Both QOL and Urbanization constitute the fundamental domains of a hierarchical multiple-indicator system for the proposed USI framework model.

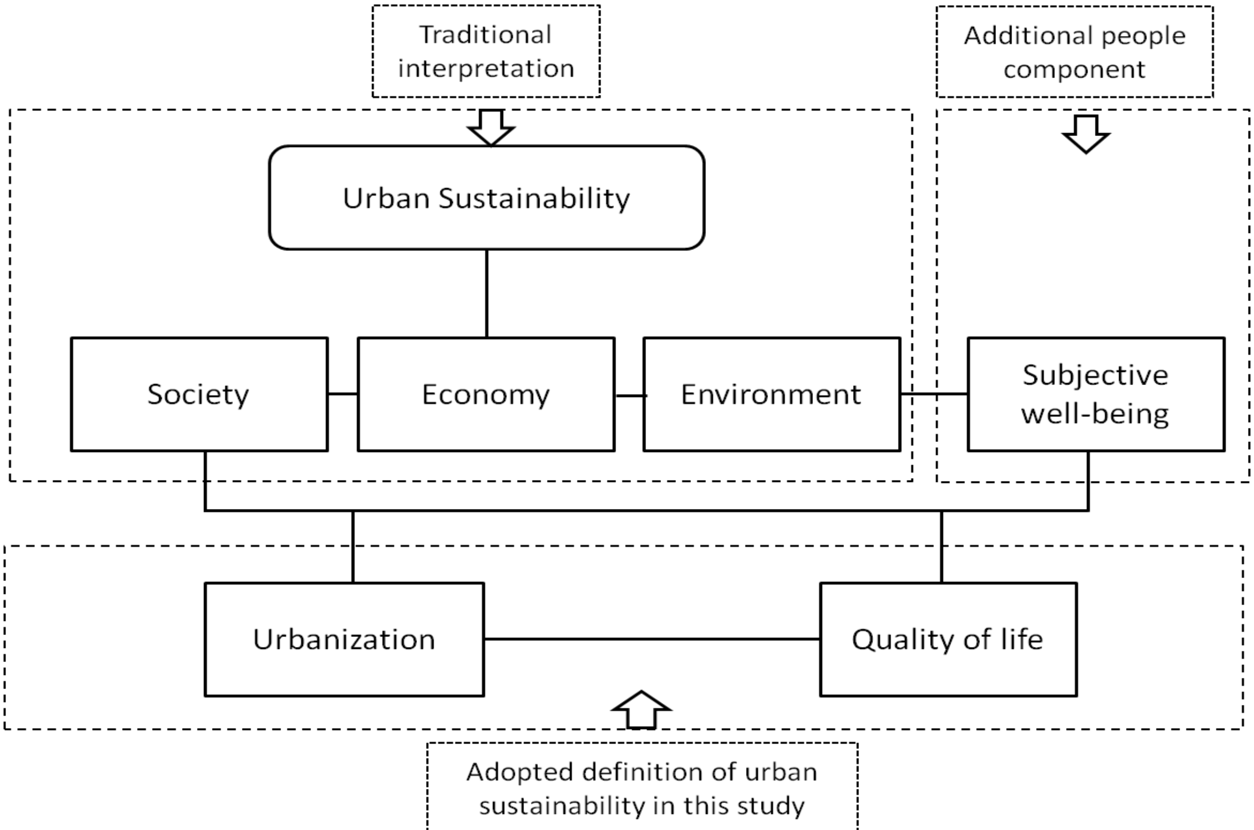


Figure 3.1 The adopted definition of urban sustainability for the improved USI model

3.5.2 Establish the framework of the integrated USI model

First, this integrated USI model will be a domain-based framework. As Keirstead and Leach (2008) suggested, USIs should be presented within clearly allocated categories, themes, and sub-themes focusing on policy goals. In response to the adopted definition of urban sustainability aforementioned in Section 3.5.1, the proposed USI model also encompasses two basic categories (urbanization and QOL) (Figure 3.2). The specific themes and sub-themes within the two broad domains are determined based on the key influential elements extracted from the literature. The urbanization domain contains the themes of house, household and mixed land use. QOL domain comprises four key aspects, which are economic, socio-political, intellectual, and environmental well-beings. This USI model can also be regarded as a process-outcome framework in that the urbanization domain acts as a stressor agent while the environment and well-being domains represent the condition agents. Also, the environment domain can play the stressor role in the outcome of intellectual well-being or the economic domain contributes to the sociopolitical well-being.

This USI model is an improved version of the previous conceptual framework developed by Shen et al. (2013). This improved USI model has incorporated more smart growth relevant indicators such as mixed land use, supermarket access (reflective of food desert), and sustainable traveling index (promoting non-automobile lifestyle) as relevant indicators. On the other hand, the improved USI model at the same time excludes measures of *population growth rate*, *population density, percentage changed land use, urban sprawl rate, unemployment rate, average income, house density, and water quality*. Several reasons can explain such modifications. First, the improved USI model is adapted to be more easily quantified with a smaller and equal-sized indicator set for each domain as much as possible. There indicators were selected for each domain with four for the environmental one because the urban environmental condition is more vulnerable and complex as a foremost aspect of most USI models. Second, although demographic information (e.g., *population growth*, *population density*) is widely regarded as good indicators for evaluating urbanization, concerns still exist for accepting them in the USI model. It is difficult to identify the quantitative thresholds of demographic changes for defining sustainability or unsustainability which is highly dependent upon the particular urban circumstances. For populated metropolitan areas increasing residents is undeniably a disaster whereas for sparsely populated cities population growth can promote urban sustainability.

Therefore, to avoid confusion and complexity, household and house related indicators are adopted instead of direct population growth or density in this USI model, but the impacts of demographic change on other USIs will be discussed based on statistical analysis. *House density* is replaced by *house ownership percentage* because the latter one can represent tenure status which is more adopted in existing USI models (Winston and Eastaway, 2008). Third, *average family income* has some overlap with *unemployment rate* and the former one is more inclusive to reflect the economic status of the neighborhood residents. Some laid-off residents can still make a living with the financial support from government or other organizations. Fourth, *percentage changed land use* is substituted by the *mixed land use index* due to the difficulty in accurately quantifying the positive or negative land use changes. Fifth, *urban sprawl rate* is an indicator more aimed at a whole city as the evaluation target and it may be not appropriate to measure each neighbourhood with a relatively stable areal size over a period of time. Finally, data availability is the constraint that caused the indicator *water quality* to be removed. Admittedly, *water quality* and other commonly used indicators such as *air quality*, *energy consumption*, *noise level, and waste recycled* also play an important role in determining the overall urban environmental sustainability status. The inclusion of those indicators will possibly affect the evaluation results. However, for urban sustainability studies based on neighbourhood as the fundamental unit, it may be very difficult to collect the indicator measurements under the same standards. It is not the case for urban sustainability monitoring with the whole city as the study target. Therefore, it seems that data availability is a primary limiting factor for including certain relevant indicators to spatially measure urban sustainability at smaller geographical scales.

Figure 3.3 illustrates the model quantification philology based on a hierarchical index system at two aggregated levels. Figure 3.4 is the specific measurements, which will be extracted from both spatial data (satellite imagery) and censuses data by incorporation of subjective weights obtained from social surveys. Compared to the previously established USI model in Shen et al., (2013), this newly developed framework is more suitable for quantitatively assessing urban development due to the ideas of smart growth as guidance. Details about this model will be illustrated in the following sections.

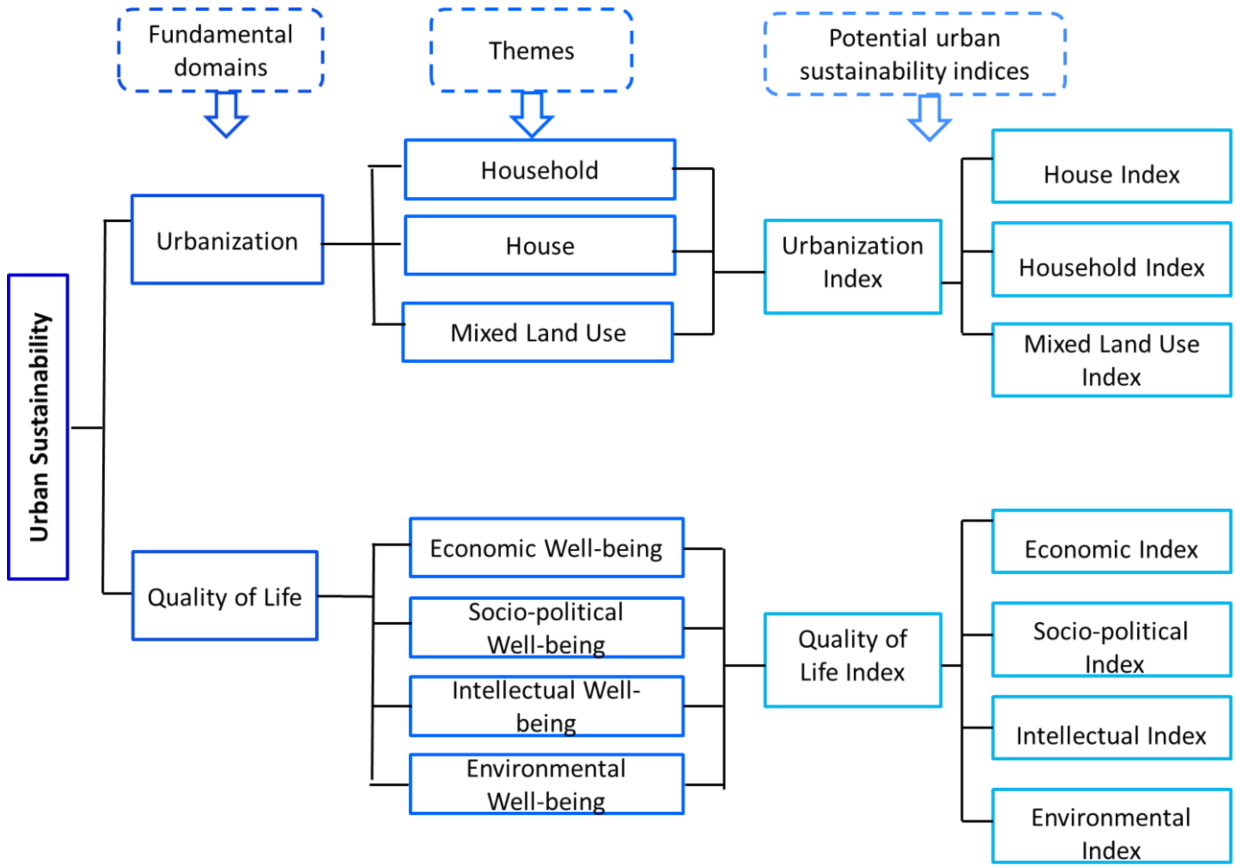


Figure 3.2 An improved integrated USI model for monitoring urban sustainability.

3.5.3 Identify preliminary indicators and measurements for the USI model

Different interpretations of urban sustainability can lead to different selections of indicator sets, so both academic and practical literature were studied to identify suitable USIs capable to evaluate the fundamental domains within the USI model. This step is critical to determine whether accurately monitoring of urban sustainability can be achieved using a synthesized framework. Existing USI models including *OECD indicators (OECD, 1993), WHO Health Cities indicators (WHO, 1993), Saskatoon Quality of Life Indicators by CUISR (Sun, 2004), QOL for the City of Indianapolis (Lu and Weng, 2007), Sustainability Index for Taipei (Li and Huang, 2007), International Urban Sustainability Indicator List (Shen et al., 2011), and Sustainability Indicators for North Aegean Region* (Kondyli, 2010) were examined to draw appropriate indicators for the proposed USI model in this study. The advantages and disadvantages of each possible indicator should be assessed according to the identified indicator selection criteria. The validity, accessibility, and measurement of the potential indicators should be considered and evaluated as well.

To effectively measure and quantify this proposed USI model, a hierarchical index system is developed at three aggregated levels (Figure 3.3). In this system, there are ten indices in total from Level 1 to Level 3, which was aimed to achieve urban sustainability measurements from detailed to more synthetic perspectives. Level 1 category includes seven USI indices namely *House Index, Household Index, Mixed Land Use Index, Economic Index, Socio-political Index, Intellectual Index, and Environmental Index* as subsets of two Level 2 indices (*Urbanization Index and Quality of Life Index*). All Level 1 and Level 2 indices perform as subsets of the most integrated Level 3 Index (*Urban sustainability Index).* Each Level 1 USI index can describe one specific dimension of its corresponsive Level 2 indices. Similarly, each Level 2 USI index depicts a specific picture of the overall *Urban Sustainability Index*.

For the further application of this USI framework in Chapter 4, all urban sustainability indicators will be quantified in the format of index; this allows standardized calculation of different indicators as well as easy comparability among indicators to overcome the weakness pointed out in Section 3.2.2. The hierarchical relationships exist based on the degree of integrity or synthesis for different indicators. Level 1 indices represent the least aggregated USIs which can be directly measured or simply calculated using the census data or imagery information. As Level 2 indices *QOL Index* and *Urbanization Index* are more aggregated and calculated based on a function of mixed practice with Level 1 indices as input parameters. The overall Level 3 index *Urban sustainability Index* is the most integrated one. It will be derived based on all Level 2 indices. The formulas for all calculation are weighted linear equations. All objective variables in equations are obtained from available census data or imagery information. The weights for QOL Index are output data collected through conducting social surveys while the component indicators for *Urbanization Index* and *Urban Sustainability Index* are equally weighted in the linear equation.

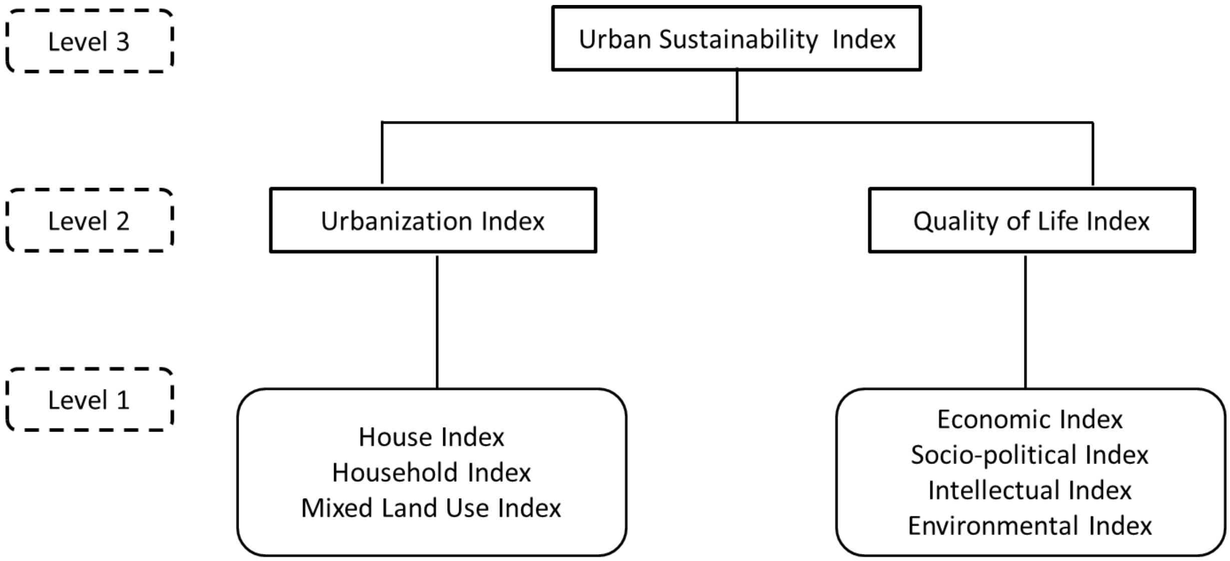


Figure 3.3 A three-level hierarchical index system for the improved USI model.

A brief description of indicator measurements and index calculation is provided in Figure 3.4 for quantification of the proposed USI model. First, Level 1 USI indices can be easily calculated because they are either single ratio indices or can be derived from a group of such indicators based on census data or satellite information. For example, *House Index* is defined as the percentage of number of owned houses in total number of houses within each neighborhood. Or *Household Index* can be derived from the percentage of non-family households in the total number of households in each neighborhood. Other indices such as *Economic Index* can be retrieved by summing group indictors (*Family average income, Housing affordability index,* and *Supermarket access*) after standardization of each individual one. All of the input data can be provided by the census data. Or *Mixed Land Use Index* can be extracted through calculating the standard deviation of the total area of different land use types in each neighborhood. The input land use information can be obtained from classified satellite imagery. Second, Level 2 indices can be quantified based on a weighted addition of all Level 1 indices in its subset. Weights for objective *Urbanization index* are set equal because it is assumed no priority for objective change of urban development. Weights for the composite *Quality of Life Index* are set according to the social survey results since human well-being is co-determined by both objective conditions and subjective perceptions. For the final *Urban Sustainability Index*, two input Level 2 indices are given equal weights because they are considered to be equally important in determining urban sustainability. However, concerning the different urban sustainability goals under particular urban polies, the weights should be flexibly set for the identified USIs. As Gosselin et al. (1991) suggested the balance of different domains within urban sustainability and the reference from other studies should be taken into consideration. This hierarchical system can provide good quantification of the USI model. All the Level 1 and Level 2 indices are developed according to different domains and themes of the integrated USI model shown in Figure 3.2. In particular, the Level 3 *Urban Sustainability Index* enables an overall quantitative evaluation of the progress towards urban sustainability from a spatial-temporal perspective.

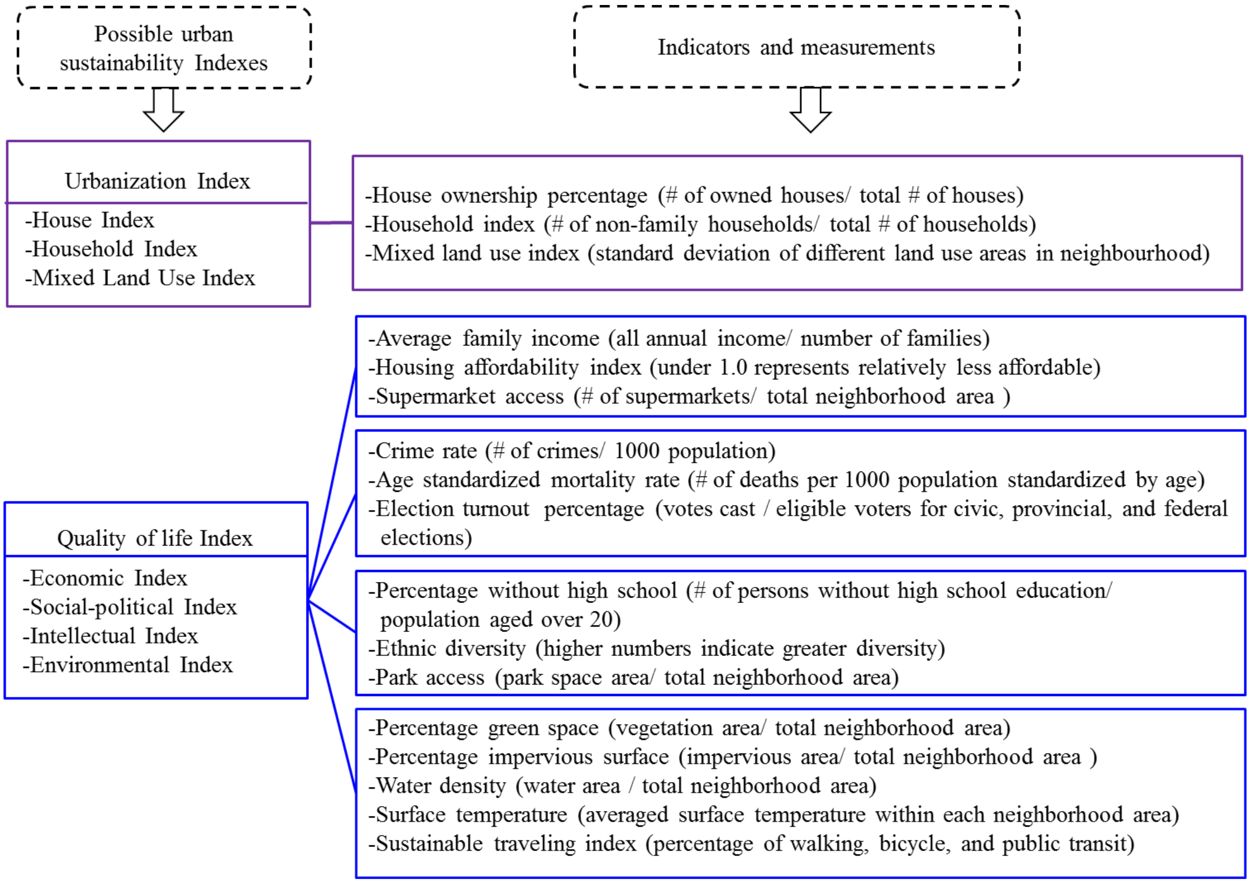


Figure 3.4 Description and measurements of potential USIs for the improved USI model.

3.5.4 Indicator evaluation and determination

To build reliability of the proposed USI model, the initial indicators will be evaluated against the identified selection criteria to fit the context of specific urban sustainability study. To maintain the integrity and hierarchy of the proposed USI model, the actual evaluation should be directly conducted on the specific measurements (e.g., *Household ownership percentage, Percentage green space, Crime rate*) in replace of urban sustainability indices (Gosselin et al. 1991; Carruthers, 1994). Equal weights are supposed to give each USI selection criteria based on a simple dichotomy by giving *yes* or *no*. Measurements with more than three criteria marked *yes* should be selected as the final USI measurement for calculating the indicators in the integrated

USI system. The evaluation for the potential indicators used in this study were performed in Appendix A. Alternatives in more consistency with the selection criteria are possibly included in the original list of USI measurements.

3.6 DISCUSSION AND CONCLUSIONS

Existing studies on the development of urban sustainability indicator models revealed that the main research problems include a weak integration of potential subjective and objective information, poor measurement and quantification, and insufficient spatiotemporal analysis. To address these concerns, this chapter attempts to establish an integrated USI model based on an improved interpretation of urban sustainability by incorporating subjective well-being into the well acknowledged concept of triple bottom line. A hierarchical index system was constructed for presenting quantitative results at different aggregated levels for multiple target audience. In addition, this proposed model can be applied by quantifying indicators using both traditional statistical approaches and advanced geomatic techniques (remote sensing and GIS) to provide the spatiotemporal distribution and patterns of urban sustainability changes. The proposed integrated USI model has potential for improving urban sustainability evaluation by providing a more comprehensive evaluation of possible domains relevant to urban sustainability, which is well suited for extracting the cause-effect relationships or statistical linkages among different domains. Also, the hierarchical multiple index system possibly allow for more comparison analysis in different case cities.

In spite of the potential advantages of the proposed integrated USI model, it cannot still guarantee an absolutely precise evaluation of urban sustainability. Urban sustainability is a very broad concept which involves a wide range of urban life, such as biodiversity, energy use, water consumption, air pollution, noise level, transportation mode, mental health, etc. Different cities have diverse definitions or goals for urban sustainability concerning their own specific development status. This proposed USI model covers, arguably, the most fundamental domains of urban sustainability (social, economic, environmental, and human well-being). It is impossible to include all aspects of urban sustainability. However, the intent of the proposed USO model is to perform more as an open model - its integrity and comprehensiveness can be strengthened by incorporating additional domains or indicators specific to different urban circumstances or development goals. Accordingly, the hierarchical indices system can also be expanded to a larger one.

In summary, the integrated USI model development is a first step towards a more accurate evaluation of urban sustainability. It not only lays a conceptual basis for a more comprehensive interpretation of urban sustainability, but also provides an open framework for future research to exploit multiple techniques and multiple data sources. It also has practical value in urban planning, city development, public policy, and environmental impact assessment. The USI hierarchical system could play an important role in formulating a holistic or specific analysis of urban sustainability based on the multiple indices derived at different levels. For future application of this proposed model, it is vital to reach public audiences (e.g., policy makers, planners, engineers, and even individual residents) for sharing information to increase the awareness of urban sustainability as well as linking policy-making with public participation as well as academic communities. Since the advantages of geomatic techniques suggested in the quantification of parameters in the USI model, visual simulations or demonstrations can be effective strategies for vividly demonstrating the dynamic change of urban sustainability progress to the public.

CHAPTER 4

THE APPLICATION OF THE INTEGRATED URBAN SUSTAINABILTIY INDICATOR MODEL IN A CASE STUDY (THE CITY OF SASKATOON, SK, CANADA)

4.1 ABSTRACT

The goal of this chapter is to apply the integrated USI model established in Chapter 3 for practical measurements with the city of Saskatoon as a case study. The USI model was subjectively weighted and spatially quantified based on a geodatabase with multiple data sources. A Hierarchical system of indices was derived from spatial calculation on the GIS platform. Spatial statistical analysis were conducted to demonstrate how urban sustainability was spatially distributed within Saskatoon neighbourhoods and what spatial patterns (random, dispersed, or clustered) can be characterized for different individual and aggregated domains of the USI model. Both visually qualitative and statistically quantitative information were extracted through the USI analysis to provide valuable insights for minimizing disparities and balancing development in future planning and implementation. The correlation between urban sustainability and demographic factors were also investigated to show how population change affects urban sustainability.

4.2 INTRODUCTION

Since urban sustainability demonstrates profound relevance to local, regional, national, and global development, how to effectively monitor and report urban status towards, maintain, or away from sustainability are critical for strategy formulation and policy implementation (Maclaren, 1996; Mori and Christodoulou, 2011; Wu and Wu, 2012). To address this challenge, diverse urban sustainability indicators (USIs) have been proposed as a promising tool in qualitatively and quantitatively monitoring sustainable development (Harvey, 1991). Helpful USIs are regarded as good reflections of the real urban conditions which can benefit target setting, performance evaluation, and effective communication among administrators, academia, and the general public (Shen et al., 2011). Numeric values calculated for USIs can further provide feedback information to support operative decision making of different municipal sectors (e.g., Community development, Land use and planning, Infrastructure services) (Huang et al., 1998; Li and Huang, 2007). In comparison to direct urban environmental indicators, Opschoor and Reijnders (1991) pointed out that USI has more meaning of the overall interactions between different urban development dimensions. However, existing literature identified that it is difficult for most USI frameworks and indicators to meet the requirements of simplicity, reliability, and spatiotemporal suitability in practical measurements (Huang et al. 1998; Tanguay et al., 2010; Wu and Wu, 2012). Therefore, there is a need to establish an integrated USI model using a hierarchical index system and test it in practical urban sustainability measurement. Can we measure urban sustainability by incorporating subjective information into objective data sources for further spatial pattern analysis?

Demographic factors are considered as key drivers of economic, socio-political, and intellectual development in urban development (Xiao et al., 2006, Townshend & Walker, 2010). Demographical USIs (e.g., population density, population growth rate, birth rate, etc.) have been widely used in many urban sustainability systems such as the United Nations Center for Human Settlements (UNCHS), the Europe Environment Agency (EEA), the World Health Organization Healthy Cities Indicators (WHOHCI), Sustainable Seattle Report Card (SSRC), and so on. It is quite dependent on the level of local socioeconomic development as to whether positive or negative population change can contribute to or detract from overall sustainability within a given urban area (Donald and Hall, 2010). Comparison between demographic growth and specific urban carrying capacity e.g., facilities, service, ecological environment, economy) is thus necessary for sustainability evaluation (Alberti, 1996; Graymore, 2010). In most North American cities, urban forms characterized by higher population density and greater mix of land uses have been widely accepted as neo-traditional urban designs or new urbanism to promote sustainability (Wells and Yang, 2008; Song and Ouercia, 2008). This is because the intensification process allows for a huge saving of energy use, a dramatic reduction of pollution, and for effective protection of impervious land uses (Connelly and Roseland, 2010). For example, Congress of New Urbanism (2004) reported that there were 380 neo-traditional urban developments implemented in 38 states of the US. Another example can be found in the inner city of Vancouver where high-rise buildings have been boomed since 1960s to meet the growing requirement of accommodation (Berelowitz, 2005; Grant and Filion, 2010). However, this intensification strategy should be applied properly with the guidance of place-based policies under specific circumstances such as how to protect privacy and prevent gated communities (Grant and Filion, 2010). Therefore, demographic indictors should be carefully considered before being added into the USI model to avoid confusion and uncertainty in further interpretation. Alternative ways such as correlation analysis or principal component analysis should be used to examine the impact of demographic change on urban sustainability.

In this chapter the integrated USI model developed in Chapter 3 was applied in a real urban context with a case study in the city of Saskatoon, Saskatchewan, Canada. The integrated USI model proposed in Chapter 3 was subjectively weighted and spatially quantified based on a geodatabase of multiple data sources. A hierarchical index system was quantified based on spatial calculation on GIS platform. This study discusses how urban sustainability was spatially distributed and what spatial patterns (random, dispersed, or clustered) of ten indices were characterized across Saskatoon neighbourhoods in 2006. The last section of the chapter statistically examines the relationships between demographic factors and urban sustainability indices. Both qualitative and quantitative information are visually demonstrated to provide insights for minimizing disparities and balancing developments in future urban planning.

4.3 STUDY AREA

Located in the province of Saskatchewan, Canada, Saskatoon (52.12 °N, 106.67 °W) is a medium sized prairie, geographically situated in townships 36 and 37, ranging 4, 5 and 6 over 300 km north of the U.S. border (Figure 4.1). The city of Saskatoon was formed during the Great Transitions of Canadian cities (1850-1945) with an extent of approximately 218 km^2 (Bunting et al., 2010). Saskatoon is the commercial and educational center of Saskatchewan province. So far, it has become the fastest growing city in Canada because of its highest population growth rate driven by a dramatic increase in annual immigration (Shannon Proudfoot, 2011). Urban sustainability has been set as a goal for future development by the city council (City of Saskatoon, 2012). The total population within Saskatoon increased from less than 50,000 in the 1950s to more than 236,600 in the 2012 (Shen et al., 2013). Concomitant with the rapid population growth is the dramatic urbanization processes (e.g., urban sprawl, land use change, etc.), which have posed great challenges on the city's sustainable development (e.g., bare soil or green land is converted to urban areas every year). In 2007 the City of Saskatoon was seperated into 86 intra-city units, 64 of which were residential neighborhoods and 22 were industrial, management areas, development areas, and recreational parks. Of the 64 residential neighbourhoods only 60 were included in the current study due to the lack of availability of data for the other 6 neighbourhoods (Blairmore Suburban Centre, Hampton Village, Rosewood, and University Heights DA) in 2007 (Figure 4.2).

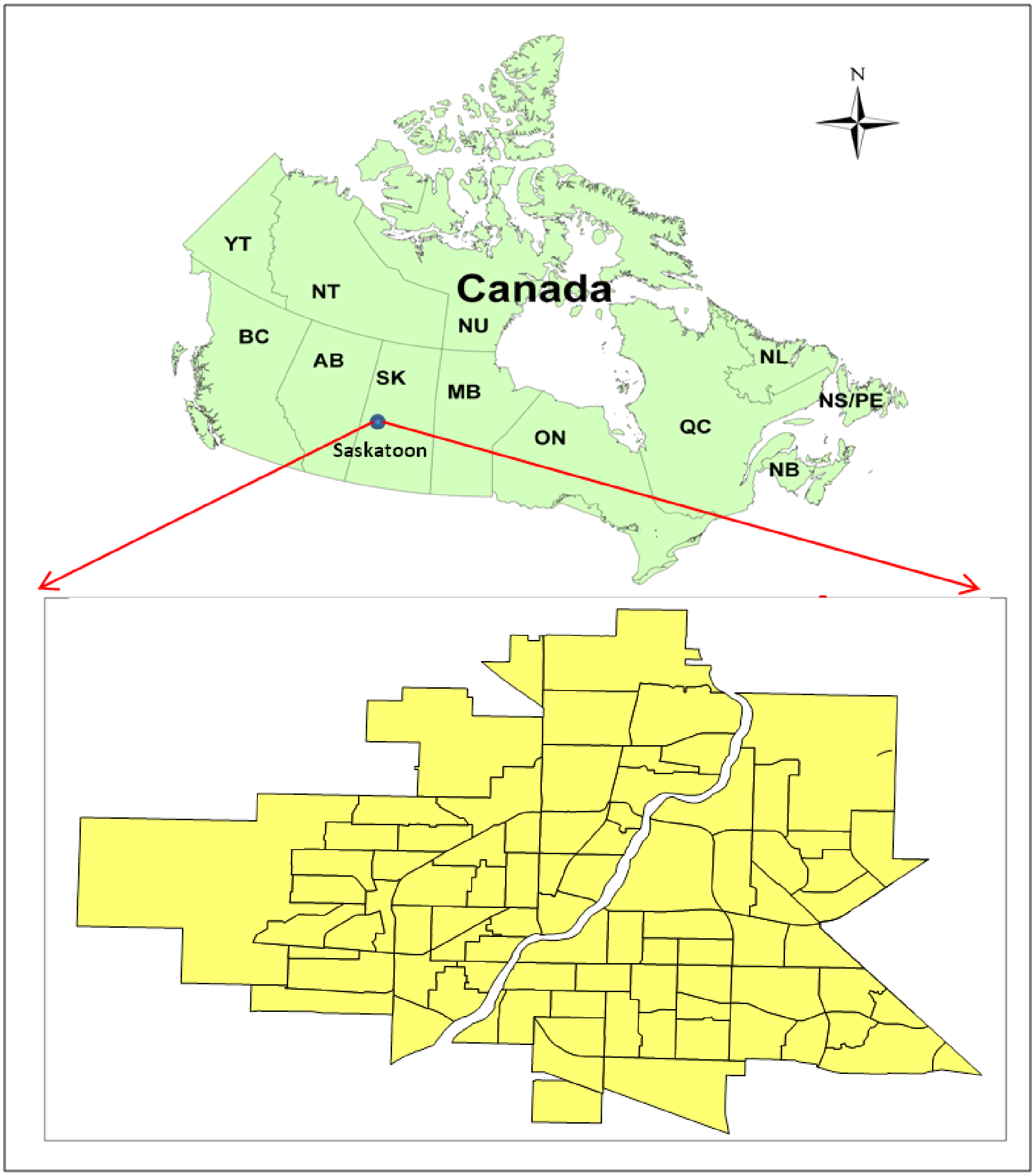
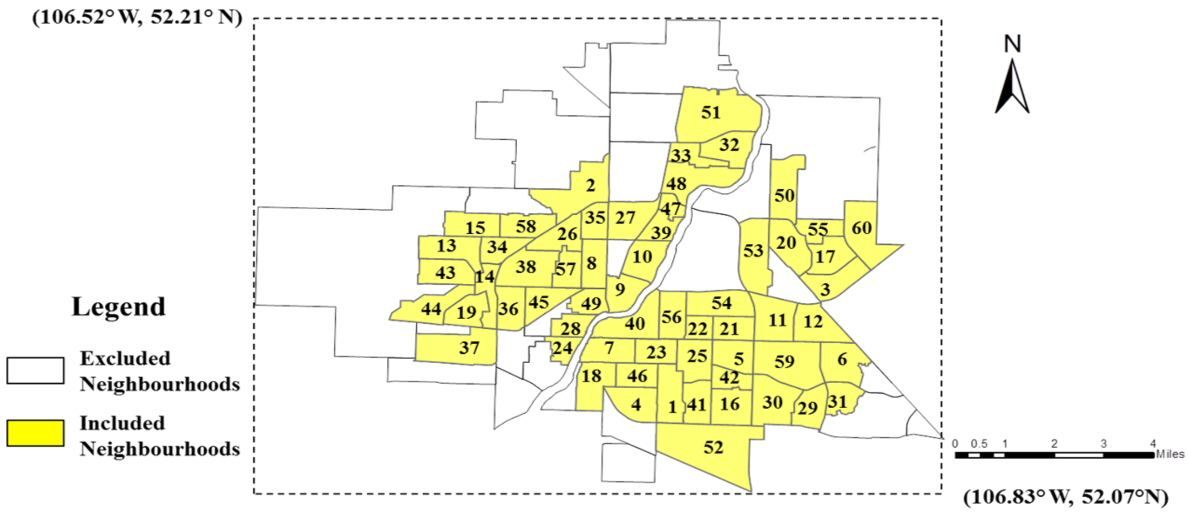


Figure 4.1 Study area: the city of Saskatoon, Saskatchewan, Canada.



#	Neighbourhood	#	Neighbourhood	#	Neighbourhood	#	Neighbourhood
1	Adelaide Churchill	16	Eastview	31	Lakewood Suburban Centre	46	Queen Elizabeth
2	Airport Business Area	17	Erindale	32	Lawson Heights	47	Richmond Heights
3	Arbor Creek	18	Exhibition	33	Lawson Heights Suburban Centre	48	River Heights
4	Avalon	19	Fairhaven	34	Massey Place	49	Riversdale
5	Brevoort Park	20	Forest Grove	35	Mayfair	50	Silverspring
6	Briarwood	21	Greystone Heights	36	Meadowgreen	51	Silverwood Heights
7	Buena Vista	22	Grosvenor Park	37	Montgomery Place	52	Stonebridge
8	Caswell Hill	23	Haultain	38	Mount Royal	53	Sutherland
9	Central Business District	24	Holiday Park	39	North Park	54	U of S Lands South Management Area
10	City Park	25	Holliston	40	Nutana	55	University Heights Suburban Centre
11	College Park	26	Hudson Bay Park	41	Nutana Park	56	Varsity View
12	College Park East	27	Kelsey-Woodlawn	42	Nutana Suburban Centre	57	Westmount
13	Confederation Park	28	King George	43	Pacific Heights	58	Westview
14	Confederation Suburban Centre	29	Lakeridge	44	Parkridge	59	Wildwood
15	Dundonald	30	Lakeview	45	Pleasant Hill	60	Willowgrove

Figure 4.2 Included and excluded neighborhoods in the city of Saskatoon.

4.4 METHODS

4.4.1 A subjectively weighted USI model

The integrated USI model developed in Chapter 3 was adopted to provide a practical application by incorporation of subjective information. Figure 4.3 demonstrates the characteristics and measurements for two fundamental categories of USIs: objective and subjective indicators. Due to the complexities in data collection which requires extensive time, labour, financial support, and participation of local community organizations, it is difficult to develop specific subjective indicators and obtain their measurements in neighbourhoods of Saskatoon. Therefore, the social surveys were conducted to collect subjective weights to understand what the residents in Saskatoon consider as the most influential, influential, less influential, as well as the least influential domains in regards to their quality of life (QOL). The overall urban sustainability index was calculated with this subjectively weighted QOL index as one input parameter.

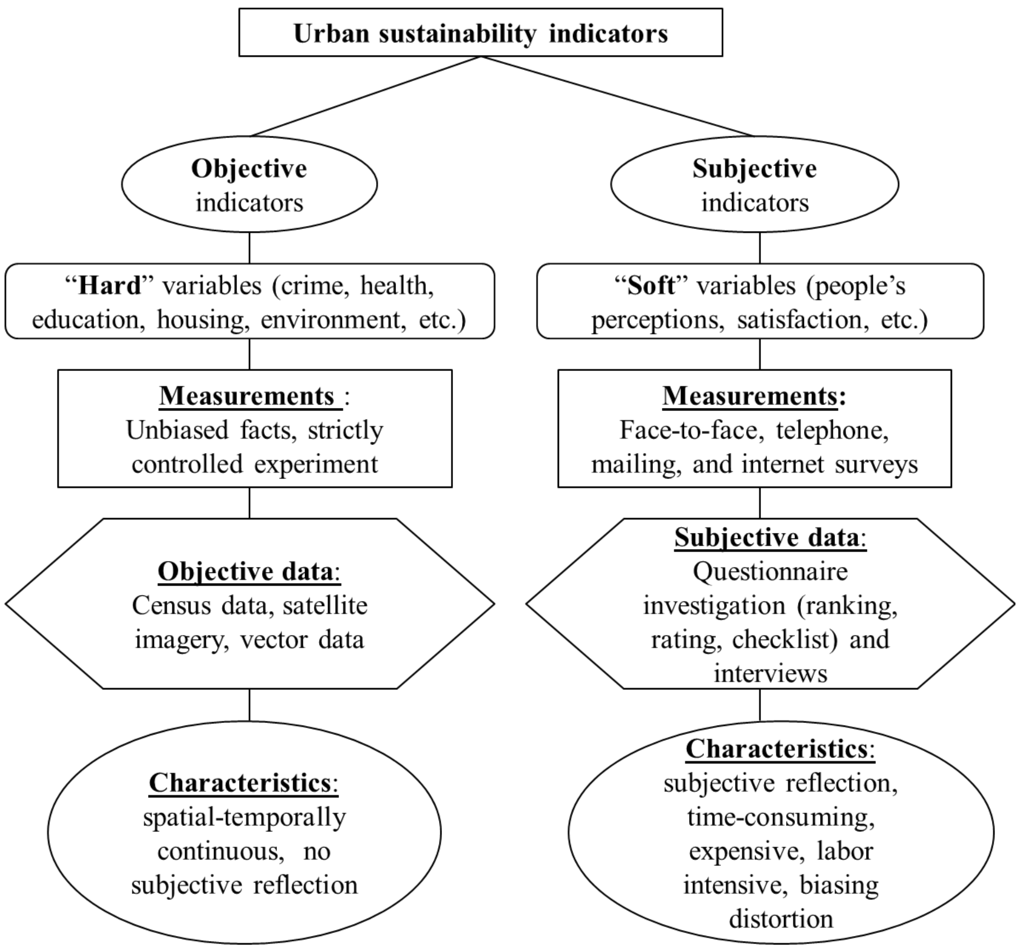


Figure 4.3 Characteristics and measurements for two fundamental categories of USIs.

4.4.2 Objective data preparation

4.2.2.1 Census data preparation

A major part of the census data used in this research was extracted from Saskatoon neighborhood Profiles reported by the Planning and Development branch in the City of Saskatoon every five years since 1976. Those profiles contain abundant neighborhood demographic information such as population, household income, ethnic diversity, total dwellings, housing affordability, major occupation, educational level, unemployment rate, total park area, voter turn-out, and commuter modes. The original customer data for the profiles were collected from the Federal Census results every five years due to the labor intensive and expensive processes. The most recent neighborhood profile was based on demographic census in 2006, which was selected as the base year of study. In addition to neighborhood profiles, other census data were also used including safety data (crime rate) and health data (Age standardized mortality rate) acquired online from CommunityView (http://www.communityview.ca/Catalogue). This is a website which provides a reliable collection of Saskatoon data contributed by different human service sectors and community organizations for policy-making, plan formulation, and project conduction (CommunityView, 2013). All data for this research were compiled and tabulated into an attribution database based on Excel software.

4.2.2.2 Spatial data for indicator measurements

As one important type of spatial data, satellite imagery derived information can meet the requirements of neutrality, objectivity, and technical proficiency for measuring urban sustainability indicators (Astleithner et al., 2004). In addition, such data can significantly reduce the cost of creating an indicator set to facilitate time-series analysis (Keirstead and Leach, 2008).

After previewing all available Landsat imagery for the city of Saskatoon in 2006 from the USGS online archive, one Landsat Thematic Mapper (TM) image on April 28, 2006 with the cloud cover less than 10% was obtained to provide spatial quantitative measurements for certain USI indicators. Table 4.1 shows the configuration of Landsat TM image. Urban land cover land use information was extracted based on Neural Net remote sensing classification approach with an overall accuracy of 94.79 % and Kappa coefficient of 0.93 in Figure 4.4 and Table 4.2. Also, urban surface brightness temperature, referred to as LST, was retrieved for each neighbourhood based on Landsat thermal band algorithms. Both land over land use and LST data served as the input measurements for the USI model quantification.

Vector data, also provided by the City of Saskatoon, is another type of spatial data used to show the geographic positions and administrative boundaries of the city as well as each neighborhood (Figure 4.1 and 4.2). In this research, the study neighbourhoods were sorted out from the excluded neighbourhoods as separate features. Vector data served as a bridge to join the census data and satellite data into a one-to-one relationship with each neighborhood by geographical entity coding.

Table 4.1 The Landsat TM image obtained in 2006 for this study.

Data types	**Data time**	**Data parameters**
Landsat TM	2006-04-28	Temporal resolution: 16 days Spatial resolution: 30 m (Blue, Green, Red, NIR, MIR1, MIR2); 120 m (TIR) Spectral resolution: 7 (Blue, Green, Red, NIR, MIR1,MIR2, TIR,)

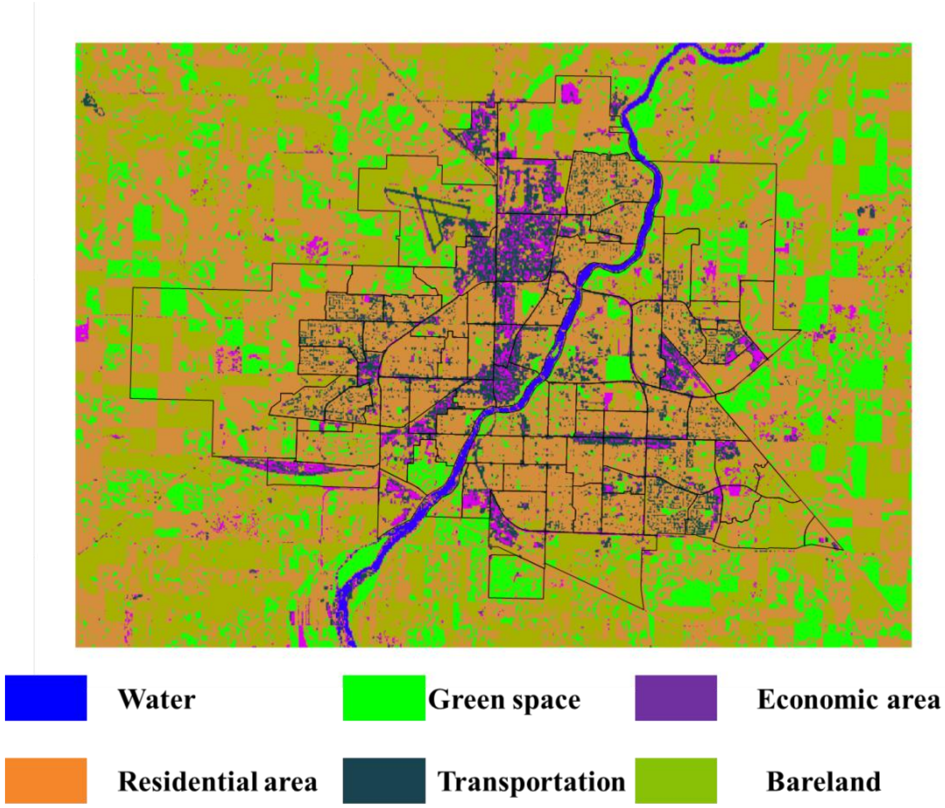


Figure 4.4 Land use classification for Saskatoon in 2006 summer.

Table 4.2 Accuracy assessment of land use classification for Saskatoon in 2006 summer.

Land use classes	Producer	User accuracy	Commission	Omission
Green space	100%	97.14%	2.86%	0
Water	100%	100%	0	0
Bareland	80.52%	100%	0	19.48%
Economic area	100%	100%	0	0
Residential area	95%	98.58%	1.42%	5%
transportation	100%	73.81%	26.19%	0

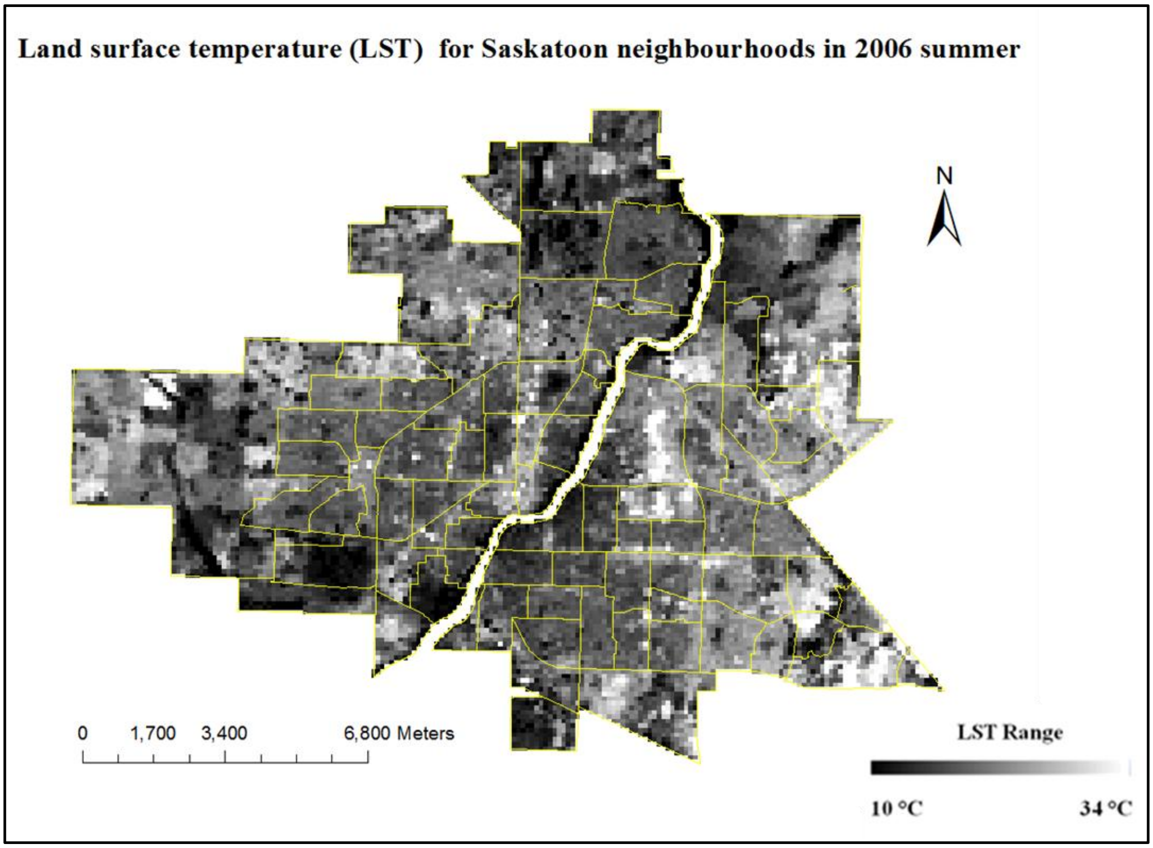


Figure 4.5 Land surface temperature distributions for Saskatoon in 2006.

4.4.3 Subjective weights from social surveys

A social survey plan was developed and then approved by the University of Saskatchewan Behavioral Ethics Board. The Survey and Group Analysis Laboratory (SGAL) at University of Saskatchewan helped carry out a telephone-based survey to collect subjective data from urban residents between February 21, 2013 and February 25, 2013. A computer program was developed to enhance the survey efficiency (Figure 4.6). Training was provided to eight research interviewers before their first shift in the laboratory. The first day of data collection included a field test with live respondents to ensure that survey performance was correct. The laboratory collected 388 completed surveys based on Saskatoon phone numbers provided by ASDE Survey Sampler Company in Gatineau, QC. The margin of error was +/- 5.0% with a confidence level of

95% so the data was statistically significant for the city of Saskatoon. The survey questions can be seen in Appendix B.

The 4 ranking domains of urban quality of life (QOL) included *material well-being, social-political well-being, intellectual well-being, and environmental well-being*. The respondents were requested to rank 1, 2, 3, and 4 for those four domains to indicate the most influential domain to the least influential one. The domain with the highest percentage of people who ranked it as ‘1’ was identified as the most influential aspect of Saskatoon residents’ QOL. Domains ranked with 2, 3, 4 were determined as influential, less influential, and the least influential aspects of QOL respectively. The survey data analysis revealed that Saskatoon residents’ valued *Environmental well-being* as the most influential domain of their QOL, followed by *Material well-being*, *Intellectual well-being,* and *Socio-political well-being* respectively (Table 4.3). The more influential a domain was, the more weight would be attributed to it. Therefore, the ranking domains *Environmental well-being, Material well-being, Intellectual well-being,* and *Sociopolitical well-being* were assigned with 1, 0.75, 0.50, and 0.25 respectively as their subjective weights for the *QOL Index* calculation in Table 4.3. This shows how the subjective information was incorporated into monitoring QOL and urban sustainability. The four subjective weights with an interval of 0.25 are relative weights rather than absolute ones calculated in proportion to the exact percentage response from the survey. They are used to reflect the four levels of relative priority of importance within the overall *QOL index*. In addition, the weight values set from 0 to 1 are purposed to guarantee positive indices ranging from 0 to 1 for easy comparison and interpretation quantitatively.

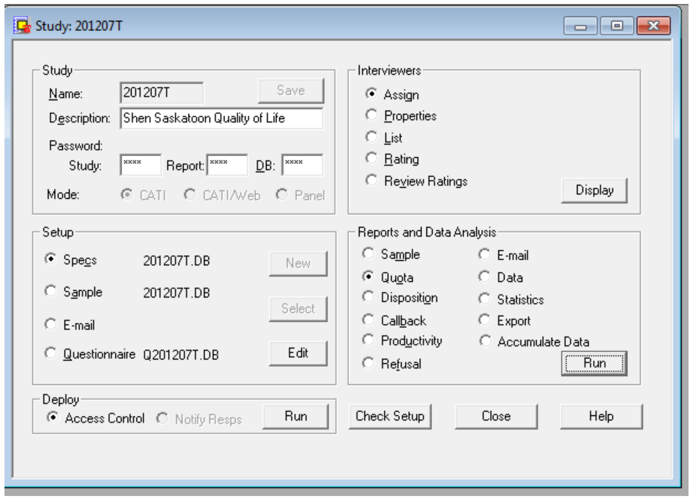


Figure 4.6 The computer program developed to collect subjective data for Saskatoon QOL.

Table 4.3 Subjective ranking of the four OOL dimensions based on telephone surveys with 388 respondents from the city of Saskatoon.

Rank	**Percentage of people for evaluating the four dimensions of Saskatoon QOL**				**Subjective weights for QOL dimensions**
	Material well-being	**Sociopolitical well-being**	**Intellectual well-being**	**Environmental well-being**	
1	20.50%	22.93%	26.41%	**30.13%**	Environmental well-being (**1.00**)
2	**34.40%**	28%	18.93%	18.67%	Material well-being (**0.75**)
3	17.37%	20.53%	**31.73%**	30.40%	Intellectual well-being (**0.50**)
4	27.73%	**28.53%**	22.93%	20.80%	Social-political well-being **(0.25)**
Equation for QOL Index calculation	*QOL Index* = *Environmental Index* + **0.75** * *Material Index* + **0.5*** *Intellectual Index* + **0.25****Social-political Index*				

4.4.4 An integrated geodatabase and indices calculation

The Environmental Systems Research Insitute's (ESRI) ArcGIS 10.1 was used to construct a geodatabase (also referred to spatial database) for the purpose of integrating multiple data sets (census data, satellite data, vector data, and surveyed data) into a GIS-compatible mode under the same neighborhood ID (Figure 4.7). Using the intersect and dissolve tools of ArcGIS, all land cover land use classes were split up into each neighborhood they occupied. For example, the intersect function allocated each green space to its corresponding neighborhood and the dissolve tool combined all the green spaces into a single green space feature within each neighborhood. The total area of that single green space feature was calculated for each neighborhood and furthers the specific measurement *Percentage green space* was obtained. In this way, measurements *Percentage impervious surface* and *Water density* were also extracted. Other measurements in Figure 3.4 were obtained either directly from census data or from simple calculation of census data. After geographic coding and unifying projection system, all of those data were linked to their spatial objects within the same city base-map.

Then the input measurements were first standardized, corrected for direction, and then mathematically aggregated to obtain the urban sustainability indices at three hierarchical levels presented in Figure 3.3. The objective data were originally acquired in different units of measurements and therefore needed standardization before application in index calculation based on Equation 4.1. For the correction of direction, if the measurement had negative influence on urban sustainability, then its input data for index calculation would be replaced with its deduction by 1. If the measurement positively impact urban sustainability then its values were unchanged. Those two adjustments were purposed to guarantee a set of positive urban sustainability indices ranging from 0 to 1 for easy quantitative interpretation, understanding, and comparison. In addition, this standardization method can reduce the complexity and time demand for computation and graphing particularly useful for calculating a group of indices. In other case without standardization, how to define the sustainability thresholds for the maximum and minimum values is challenging and controversial task. It is also difficult to calculate a parent index at a more aggregated level if the input sub-indices are within numerical scales largely different. In the operation of QOL, the subjective weights were incorporated to each domain before summing them into an overall *QOL Index*. The derived urban sustainability index set for each neighborhood was stored in the geodatabase shown in Figure 4.7.

$$Standardized\ index\ value = \frac{Index\ value - Minimum\ value}{Maximum\ value - Minimum\ value} \tag{4.1}$$

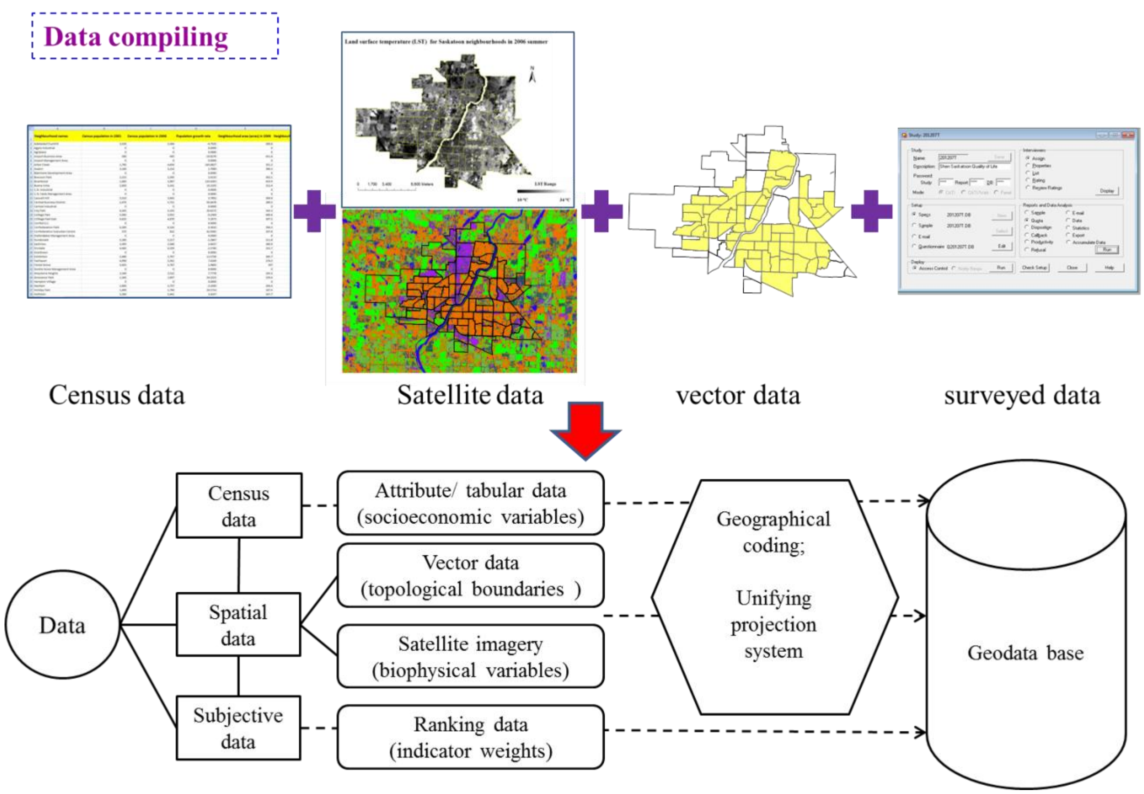


Figure 4.7 Multiple data sources and the integrated geodatabase.

4.4.5 Statistical analysis

In this study, all the included 60 neighbourhoods were the individuals described by the urban sustainability index set. For each individual, the dataset contains ten standardized urban sustainability indices listed in Figure 3.3 as quantitative variables with unitless values ranging from 0 to 1 (See Appendix C). The specific indicators and measurements are shown in Appendix D. The descriptive statistical analysis in this study can help summarize the general characteristics of different urban sustainability indices within Saskatoon residential neighbourhoods. In addition to descriptive statistics, Pearson correlation analysis was applied to extract the relationships between the ten urban sustainability indices and two important demographic indicators (population density and population growth rate) for the included 60 residential neighbourhoods across Saskatoon in 2006.

4.4.6 Spatial classification and pattern analysis

The spatial classification of urban sustainability targets at the neighbourhood polygons with assigned index values. It is meaningful to group the spatial observation of each urban sustainability index into classes for detecting its comparative distribution. Different classes presented in distinguishable colors or textures can visually convey geospatial information for conducting a clear and easy interpretation. In addition, the number of vectors in each class also helps provide basic explanation of the quantitative levels of certain variables. In this study, three classification schemes including the equal interval, quantile interval, and standard deviation were applied to extract the spatial comparison of urban sustainability indices among the 60 neighbourhoods in Saskatoon for the year 2006 (ESRI, 2013). With five as the specified number of classes, the equal interval scheme splits the range (0-1.00) of each standard index into five equal-sized subranges of 1-0.20, 0.21-0.40, 0.41-0.60, 0.61-0.80, and 0.81 -1.00 (Figure 4.10). The number and spatial location of neighbourhoods within each subrange can be highlighted for the ten indices. The classes created by quantile interval have equal number of individuals to reflect the percentile statistics for each index (Appendix E). The standard deviation classification demonstrates how much a neighbourhood's index varies from the mean (Appendix F). The neighbourhoods within positive ranges had index values above the mean while the ones within negative ranges had index values below the mean. This scheme can also show the typical neighbourhoods with the index value close to the mean and the outlier neighbourhoods with the index value far from the mean.

The spatial pattern analysis was conducted based on the geospatial statistics consisting of global and local autocorrelations (Wong et al., 2005; Zhang et al., 2008). Moran's *I* is a global pattern analysis which provides an overall evaluation of autocorrelation status based on three statistical values: the Moran's *I* index (ranging from -1.0 to 1.0), a *Z*-score, and a *p*-value (ESRI, 2013a). A positive Moran's *I* means that neighbouring polygons have similar values under positive autocorrelation in a clustered spatial pattern; whereas a negative index indicates that the adjacent polygons have dissimilar values under negative autocorrelation in a dispersed spatial pattern (Figure 4.8). The absolute value itself can reflect the strength of that autocorrelation. The *Z*-score (standard deviation) and *p*-value (probability) are used to determine if the interpretation is statistically significant at an expected confidence level of 90%, 95%, or 99%. The confidence level selected for this study was 95%. The desired *Z*-score was < -1.96 or $> +1.96$ and the corresponding *p*-value was <0.05. To further identify the cluster and outlier from a local perspective of autocorrelation, the *Anselin Local Moran's I (LISA)*, as a local autocorrelation analysis, was applied for each neighbourhood polygon with four statistics calculated including a Local Moran's *I* value, codes representing the cluster/outlier types (HH, LL, HL, and LH), a *Z*-score, and a *p*-value (Anselin, 1995; ESRI, 2013b). HH refers to a cluster of similar high values and LL means a cluster of similar low index values. HL represents a high index value outlier surrounded by lower index values while LH is an outlier surrounded by high index values (ESRI, 2013b). Another local autocorrelation statistic known as *Getis-Ord Gi** was also employed to detect the hot spots. Hot spots are characterized by clustered neighbourhoods of high index values with statistically significant large positive *Z*-scores (Getis and Ord, 1996; ESRI, 2013). Statistically significant small negative *Z*-scores signify cold spots for clustered neighbourhoods of low index values (ESRI, 2013c). Spatial relationships must be defined for the implementation of local spatial statistics. Therefore for both local autocorrelation analyses, two types of spatial weight matrix - the continuity edges and corners conceptualization and the K-nearest conceptualization were adopted as the quantification of spatial relationships that describe how the polygon features interact with each other (ESRI, 2013). The continuity edges and corners conceptualization can reflect the influence of the surrounding neighbourhoods on the target one which shares a common edge or corner. The K-nearest conceptualization ensures that each polygon has at least eight neighbours as a rule of thumb. The global autocorrelation analysis was shown in Table 4.5 while the local autocorrelation results were mapped by ArcGIS functions, shown in Figure 4.11, Figure 4.12, Appendix G, and Appendix H. The names that the numbers represent can be referred in Figure 4.2.

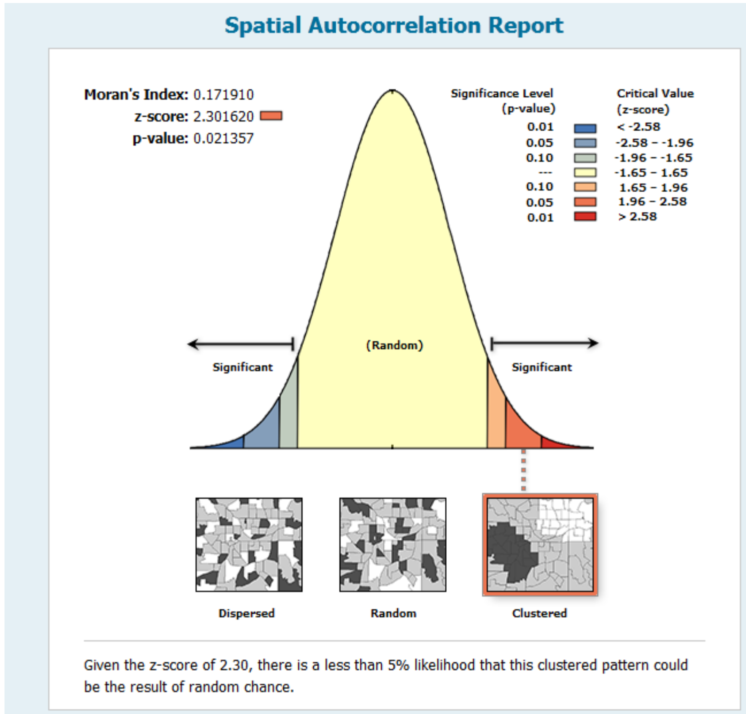


Figure 4.8 Three statistic variables returned from Moran'I analysis to signify global spatial autocorrelation patterns (an example of the Environmental index).

4.5 RESULTS AND DISCUSSION

4.5.1 Univariate statistics of Saskatoon urban sustainability indices

Table 4.4 shows the descriptive statistics of ten urban sustainability indices at three aggregated levels for Saskatoon neighbourhoods in 2006 based on 9 univariate variables. The statistical information is graphically demonstrated by the frequency histograms of Saskatoon neighbourhoods for ten sustainability indices respectively in Figure 4.9.

According to both the mean (0.35) and the median (0.37), the averaged urban sustainability index for Saskatoon residential neighbourhoods in 2006 was at a relatively low level with an overall Urban Sustainability Index of approximately 0.36. Further, 35 neighbourhoods (59%) in

2006 had the overall *Urban sustainability Index* below 0.4 (Figure 4.9). The negative skewness value suggests that most neighbourhoods were in a comparatively low sustainability status. This can be mainly attributed to the low averaged *Environmental Index* and *Economic Index* shown in Table 4.4. Most neighbourhoods had a high percentage of impervious area (for roads and parking lots) and high levels of carbon emissions from automobile use due to a major group of people in unsustainable traveling modes. Those two factors therefore were responsible for the low values of the *Environmental Index* for most neighbourhoods in Saskatoon in 2006. Another important factor in leading to the lower averaged *QOL index* and *Urban Sustainability Index* can be attributed to the influence of the higher subjective weights of environmental and economic domains collected from the social surveys. Since the weights of *Environmental Index* and *Economic Index were higher*, those two indices have greater influence on the calculation of the overall *Urban Sustainability Index.* Small *Environmental Index* and *Economic Index* values possibly contribute to the small overall *Urban Sustainability Index.*

A very few neighbourhoods (approximately 3%) with evident economic advantages have been identified to cause the dramatic difference in the overall *USI* across the city. Those neighbourhoods with high *Urban Sustainability Index* including Willowgrove, Stonebridge, Lakeview, Lakewood Suburban Centre, and Arbor Creek were typically located in the suburban areas, and have grown significantly compared to the declining inner-city neighbourhoods. The disparity between the 2 neighbourhoods (Lakewood Suburban Centre and Montgomery Place) with the *Urban Sustainability Index* above 0.8 and the remainder 58 neighbourhoods with the *Urban Sustainability Index* below 0.6 also partly explains the relatively low values of the averaged overall urban sustainability index across Saskatoon in 2006. This phenomenon can be further examined in the following spatial pattern analysis. In addition, the percentiles in Table 4.4 also indicate that over half of the neighbourhoods have *Urban Sustainability Index* values below the mean. The positive kurtosis of 0.06 similarly shows that the majority of neighbourhoods in Saskatoon were concentrated over a certain range of values (0.2-0.4) towards the *Urban Sustainability Index*.

Since this comparative analysis among neighbourhoods was based on standardized metrics, it may not be meaningful to rank those neighbourhoods using absolute high or low scores. Also, the indicators for calculating the urban sustainability indices can be debated because the total 60 neighbourhoods were evaluated based on the assumption that all the residents have common subjective perceptions of the influential factors to their quality of life. This is actually not the reality (Kitchen and Allison, 2008) but presents a limitation to this research due to the difficulties in collecting subjective information for each individual investigated neighbourhood. Therefore, a most noticeable phenomenon that has arisen as a result of this research is the obvious disparity in urban sustainability existing among the studied 60 neighbourhoods for Saskatoon in 2006. The disparity was particularly concerning the environmental (particularly the percentage of impervious area and rate of sustainable traveling modes) and people's material well-being. The majority of neighbourhoods had a relatively low *Urban Sustainability Index* in comparison to a few with a much higher one.

Table 4.4 Univariate statistics of USI indices across Saskatoon neighborhoods in 2006.

Descriptive statistics	Environmental Index	Economic Index	Sociopolitical Index	Intellectual Index	QOL Index	Mixed Land Use Index	House Index	Household Index	Urbanization Index	Urban Sustainability Index
Mean	0.37	0.39	0.62	0.49	0.35	0.67	0.64	0.55	0.49	0.37
Median	0.35	0.35	0.68	0.49	0.28	0.72	0.67	0.58	0.45	0.35
SD	0.20	1.78	0.23	0.20	0.24	0.21	0.23	0.24	0.24	0.21
Skewness	0.99	1.35	-0.72	0.22	1.35	-1.37	-0.74	-0.28	0.26	0.54
Kurtosis	1.68	2.84	-0.4	0.21	1.47	1.89	0.25	-0.27	-0.39	0.06
Range	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Percentiles (25)	0.28	0.28	0.45	0.34	0.22	0.61	0.51	0.40	0.31	0.22
Percentiles (50)	0.35	0.35	0.68	0.49	0.28	0.72	0.67	0.58	0.45	0.35
Percentiles (75)	0.43	0.45	0.80	0.61	0.40	0.78	0.79	0.73	0.65	0.54

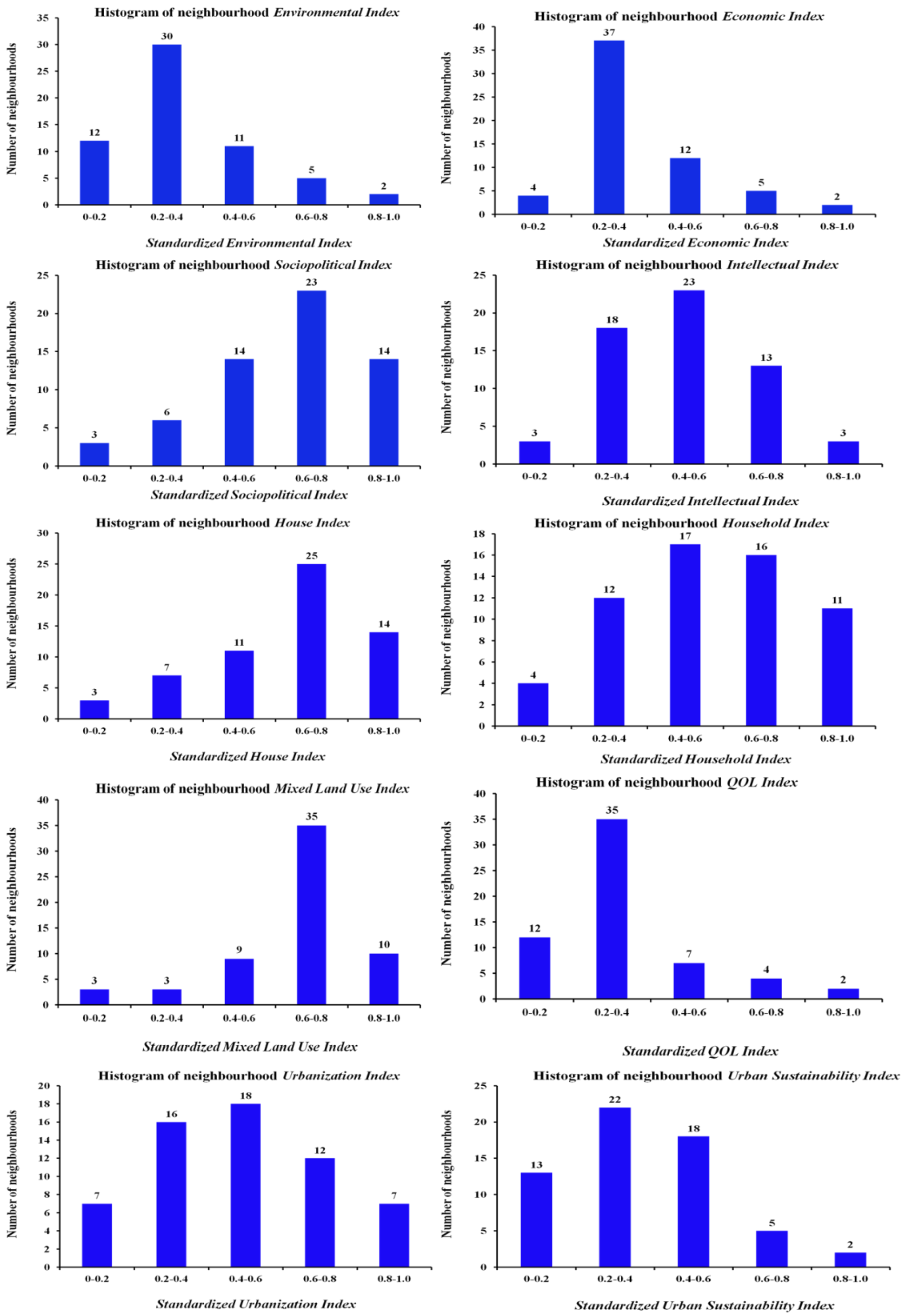
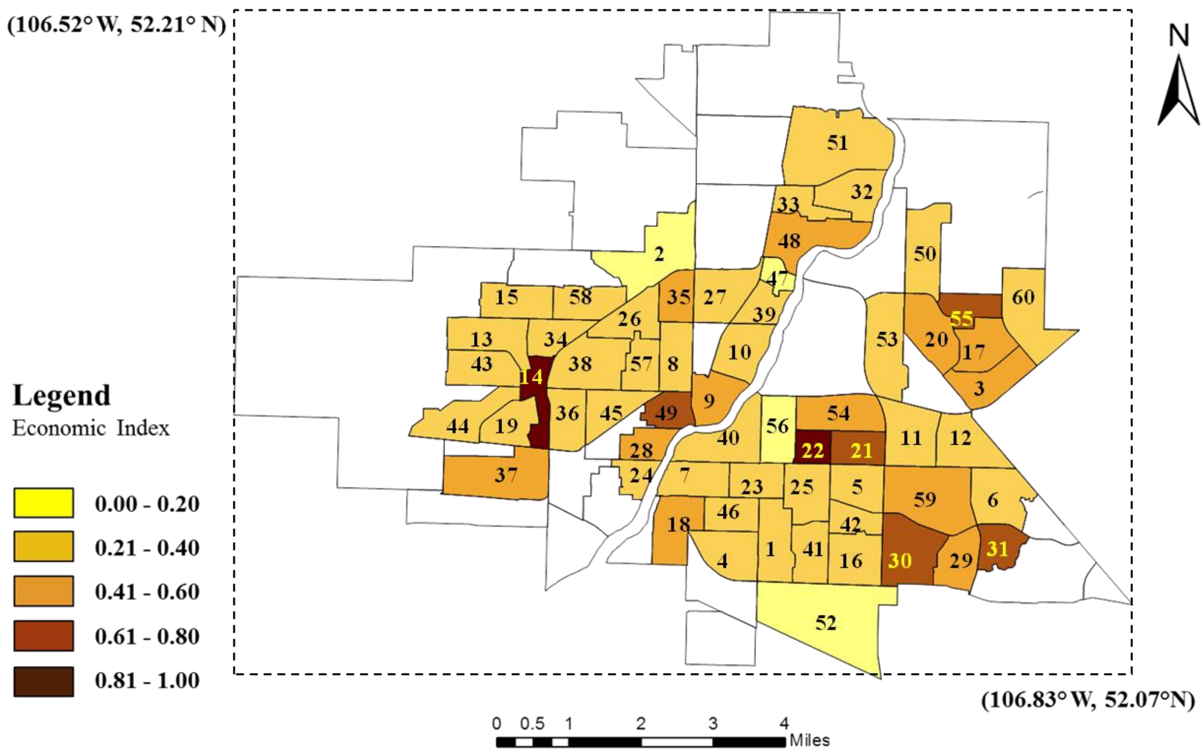


Figure 4.9 Histogram of Saskatoon neighborhood frequency for 10 standardized urban sustainability indices in 2006.

4.5.2 Spatial classification of Saskatoon urban sustainability indices

The mapped classification of ten urban sustainability indices derived from three schemes (Figure 4.10, Appendix E and F) further confirm the findings revealed by the descriptive statistics. The general urban sustainability status in 2006 had an uneven distribution across Saskatoon neighbourhoods, especially with distinct differences between the west and the east sides of the Saskatchewan River. The majority of the neighbourhoods in the southeast (e.g., Lakeview, Wildwood, Briarwood, and Lakewood S.C.) had higher sustainability index values as compared to the ones in the core area of the west side (e.g., Mayfair, Mount Royal, Massey Place, Meadow Green, North Park, Central Business District, and Pleasant Hill). This can be attributed to the spatial distributions of their corresponding *QOL index* and the *Urbanization Index*, because the neighbourhoods in the southeastern part of the study area had evident advantages in economic, sociopolitical, and intellectual development indices as well as less homelessness. In addition, neighbourhoods with high *Urban Sustainability Index* were also found in the newly developed suburban areas including Willowgrove and Stonebridge, primarily owing to their high socio-political index and urbanization index shown by the spatial classification results and the geostatistical maps in later discussion. On the other hand, an outlier revealed by the visual examination was the neighbourhood Montgomery Place, which had extremely high *Urban Sustainability Index* compared to the rest of the neighbourhoods on the west side of the city, as a result of its high environmental, sociopolitical, and urbanization rankings.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(106.83° W, 52.07°N)
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Legend
Economic Index
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0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
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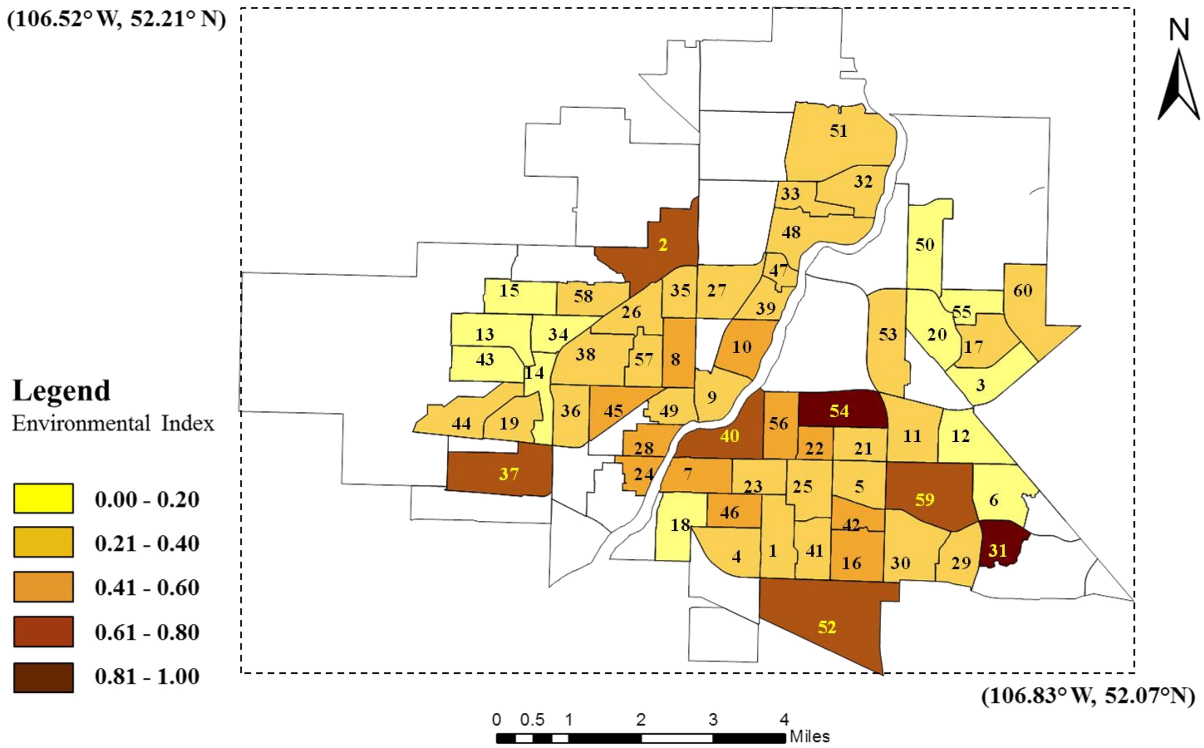
Miles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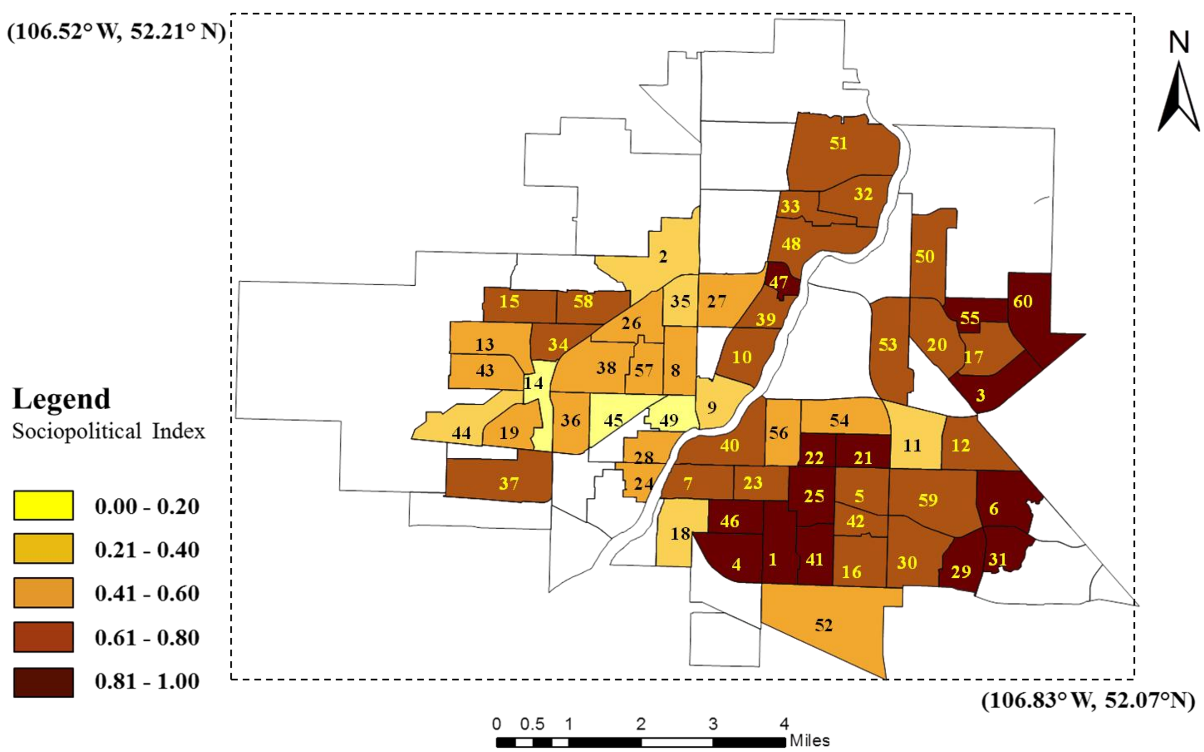
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Sociopolitical Index
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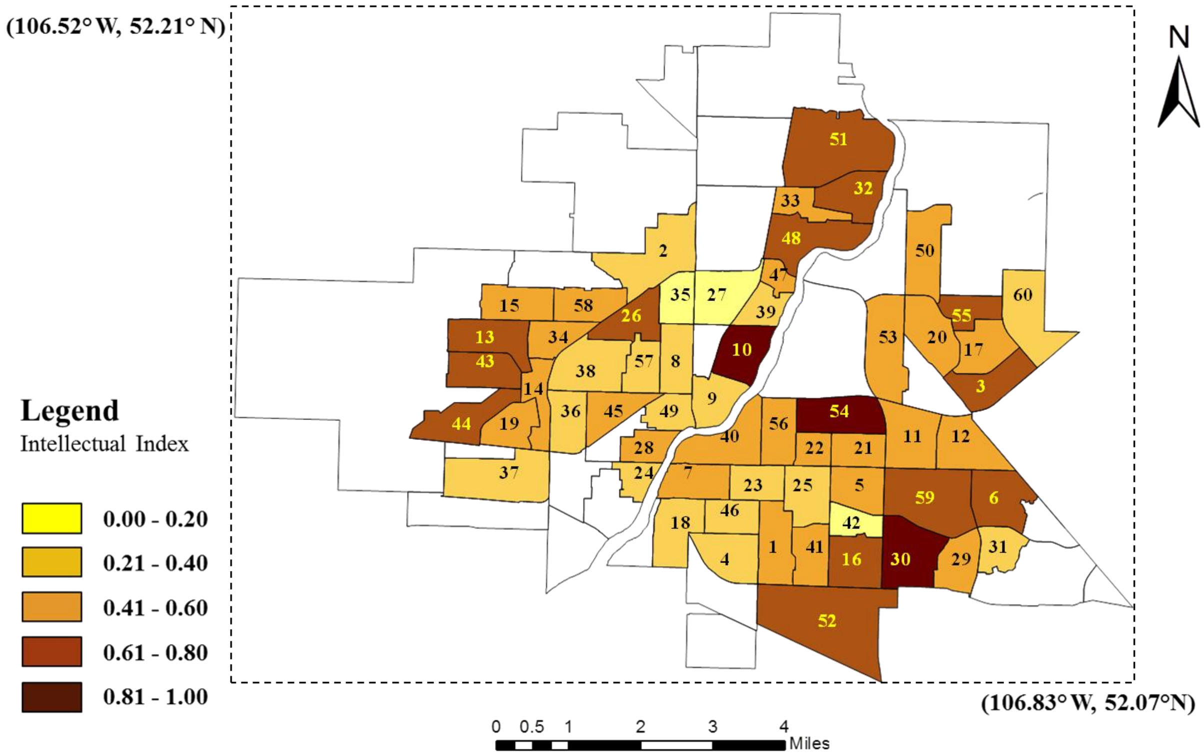
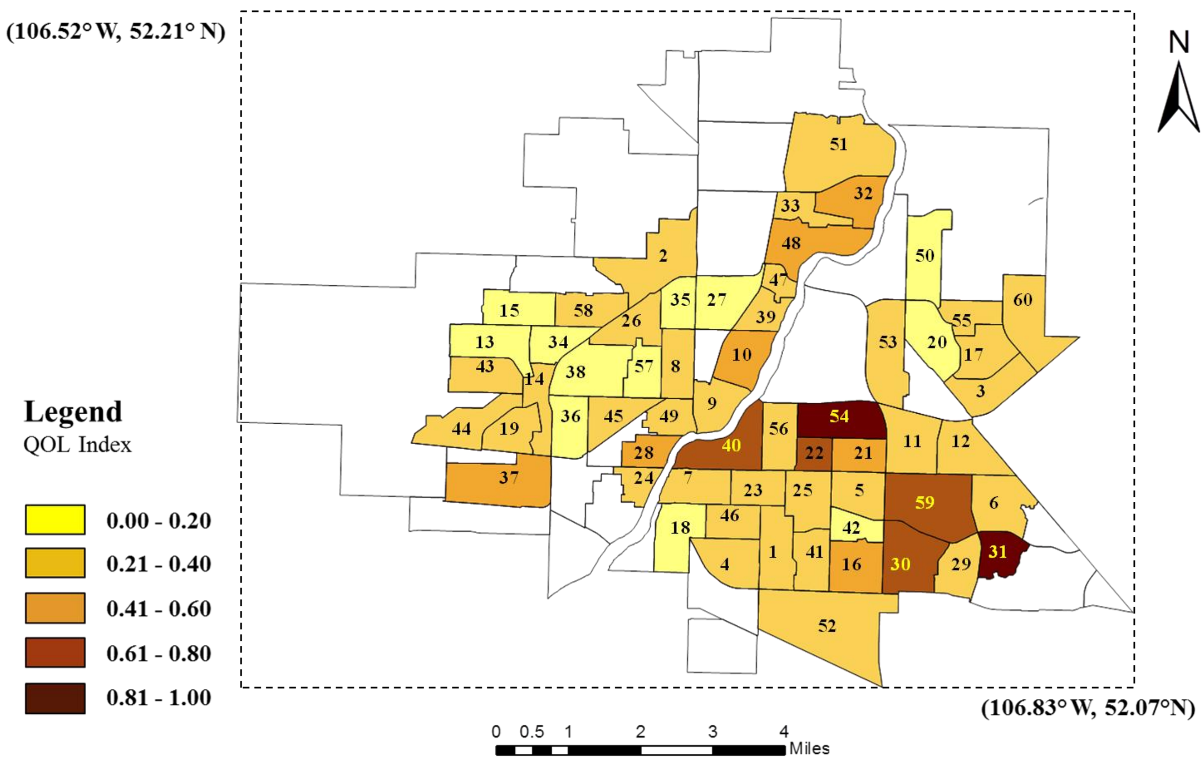
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Intellectual Index
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
0 0.5 1 2 3 4
Miles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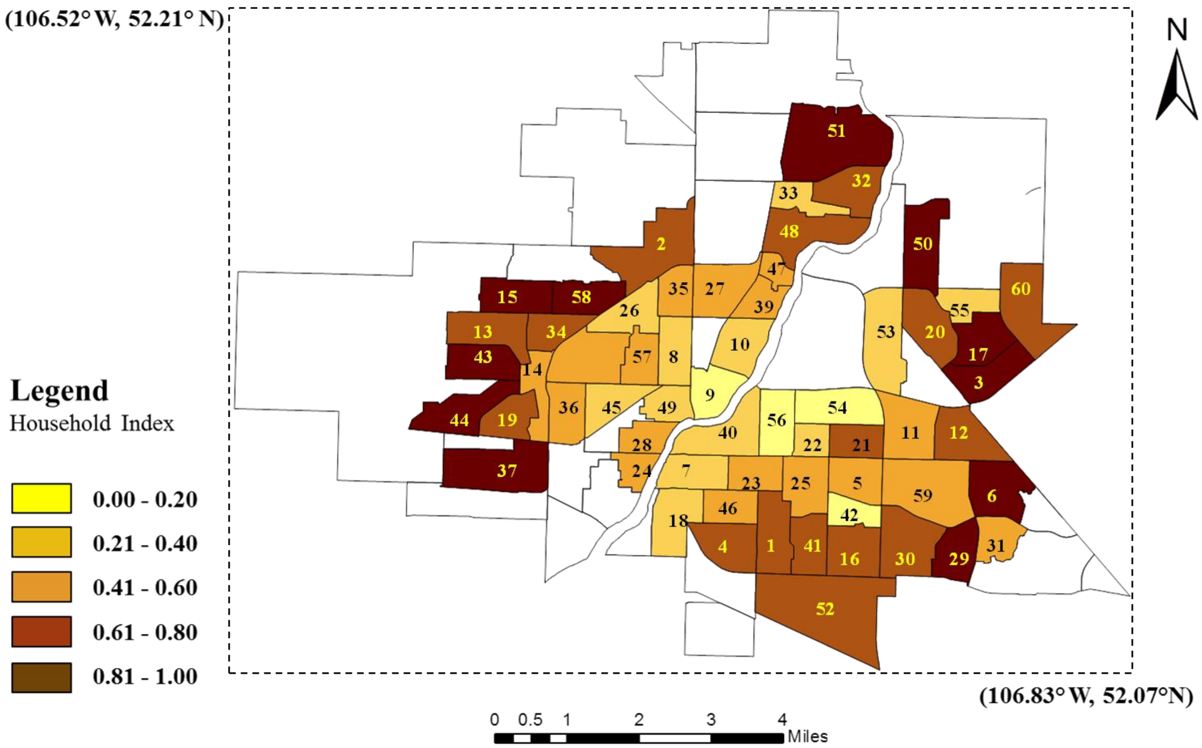
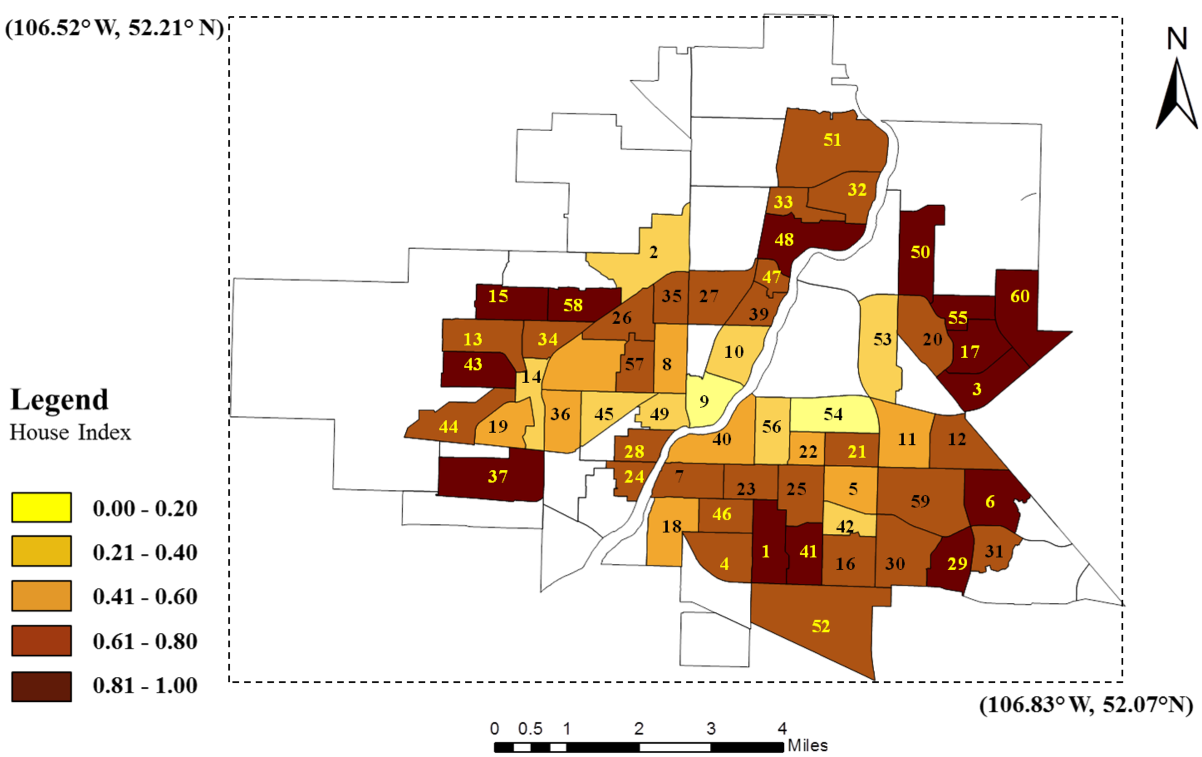
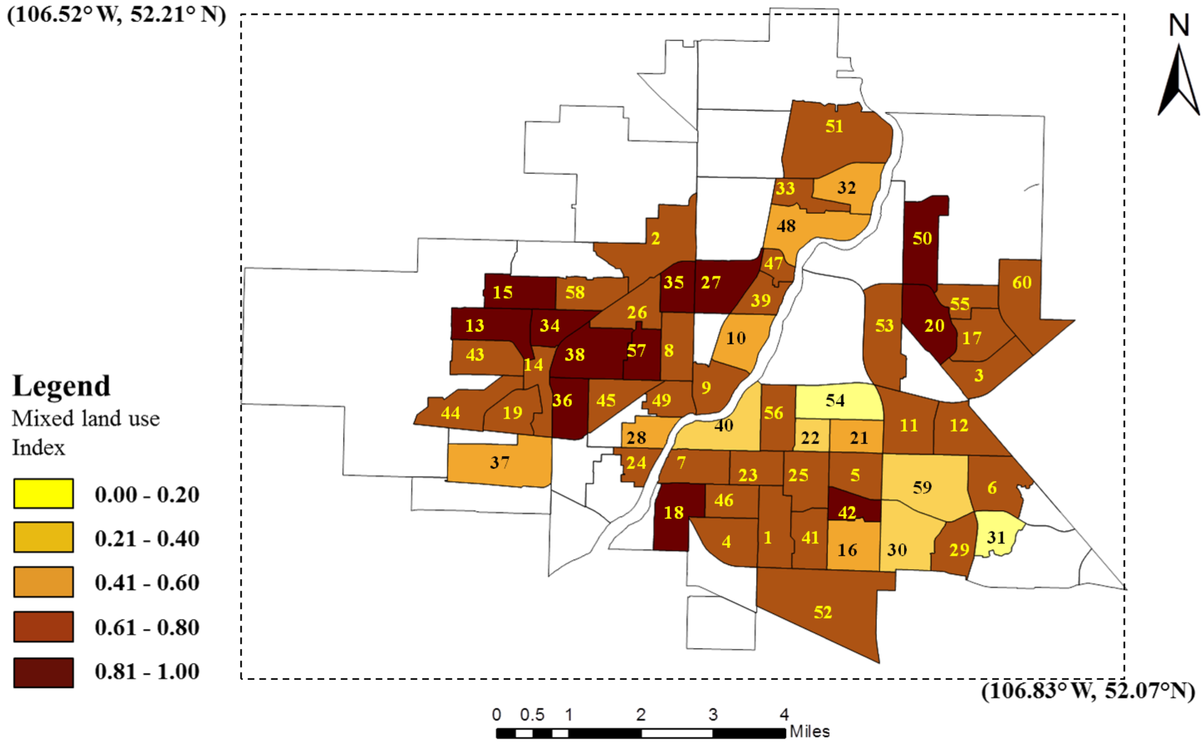
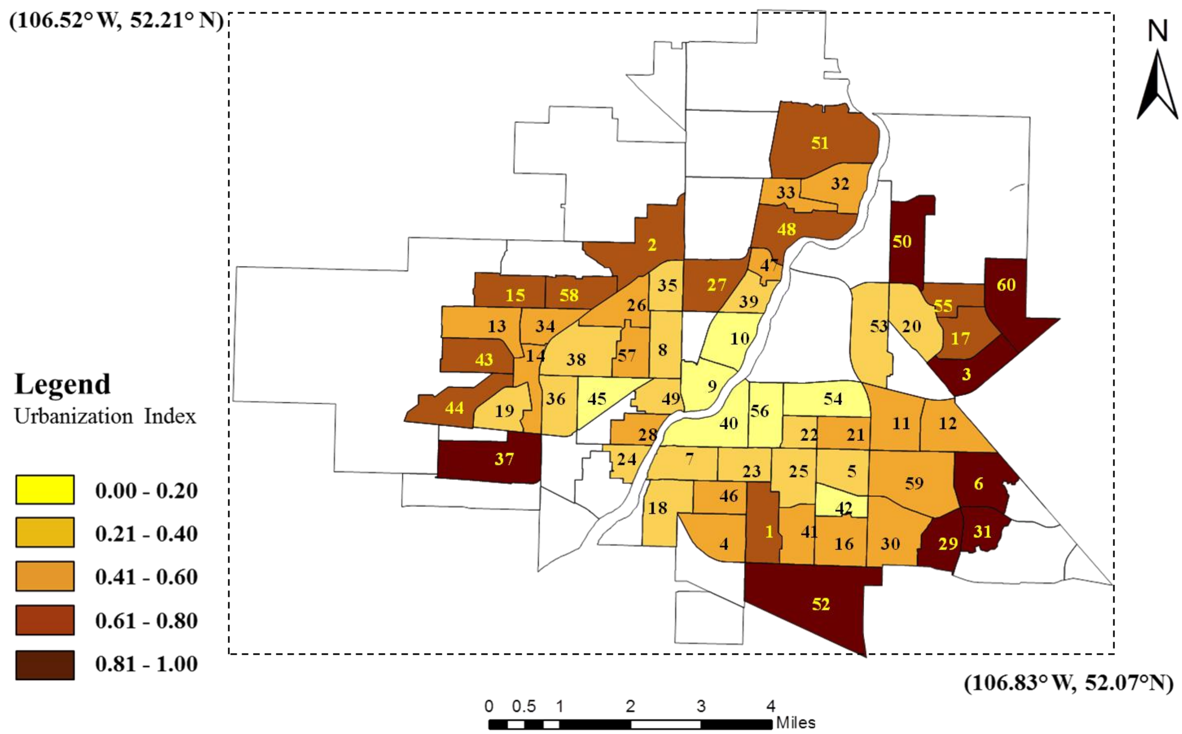
(106.83° W, 52.07°N)
N
Legend
QOL Index
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
Household Index
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
House Index
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Mixed land use Index
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Urbanization Index
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
0 0.5 1 2 3 4
Miles

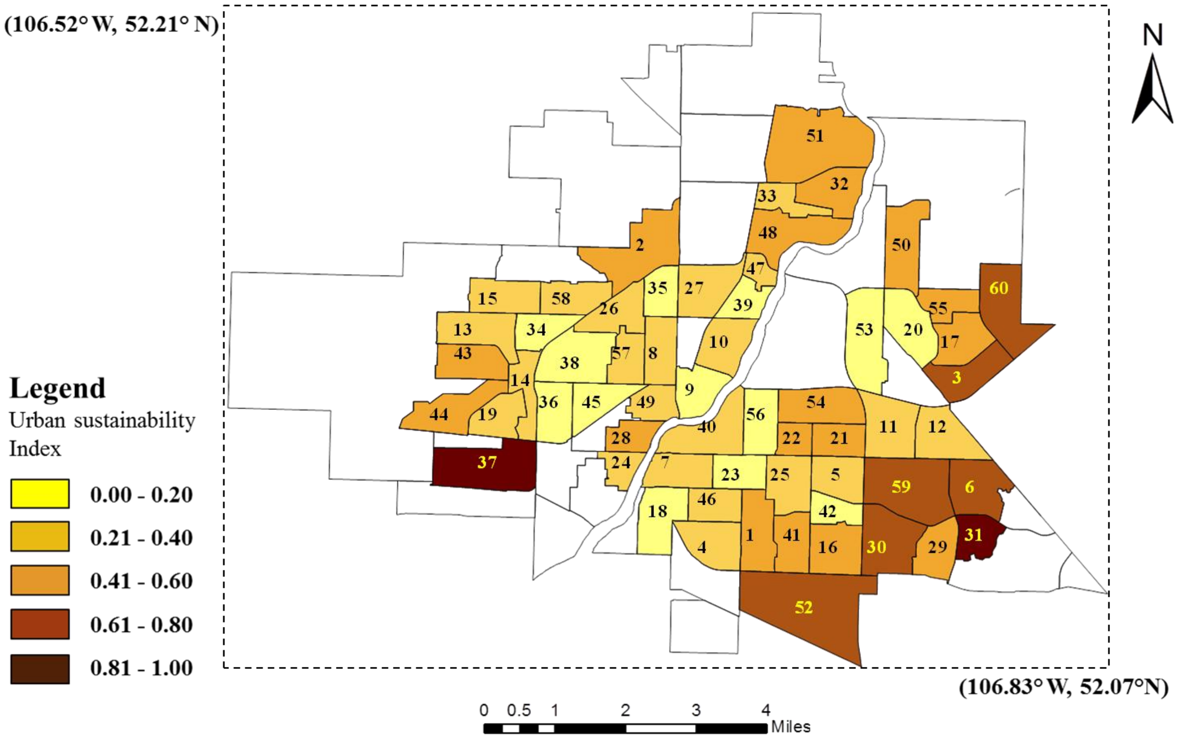


Figure 4.10 Equal interval classification of urban sustainability indices for Saskatoon in 2006.

4.5.3 Spatial pattern analysis of Saskatoon urban sustainability indices

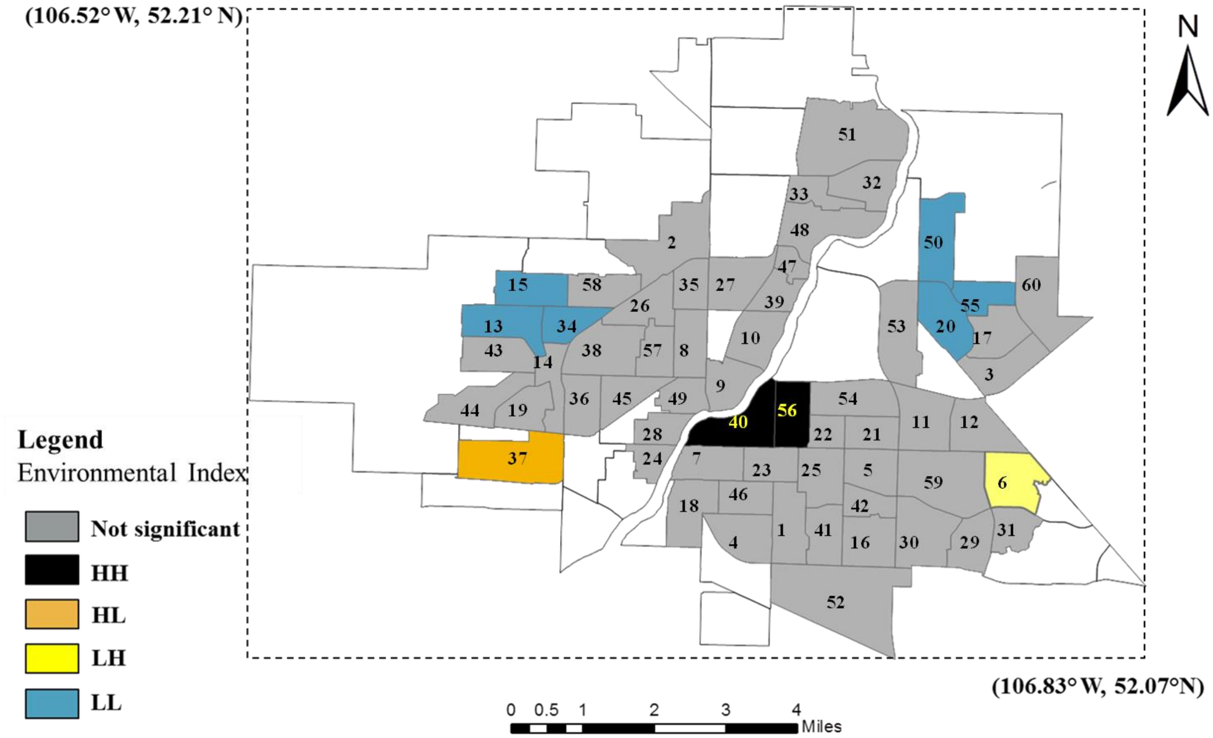
The results of geostatistical analysis further statistically confirmed the spatial patterns of Saskatoon urban sustainability in 2006 found by simply visual examination. The Moran's I values returned by both spatial conceptualizations demonstrated positive spatial autocorrelations for eight of the ten urban sustainability indices, suggesting that their spatial patterns were statistically clustered across the Saskatoon neighbourhoods. Both the *p*-values and *Z*-scores retrieved for those eight indices prove the identified patterns as significant at a confidence level of 99% (Table 4.5).

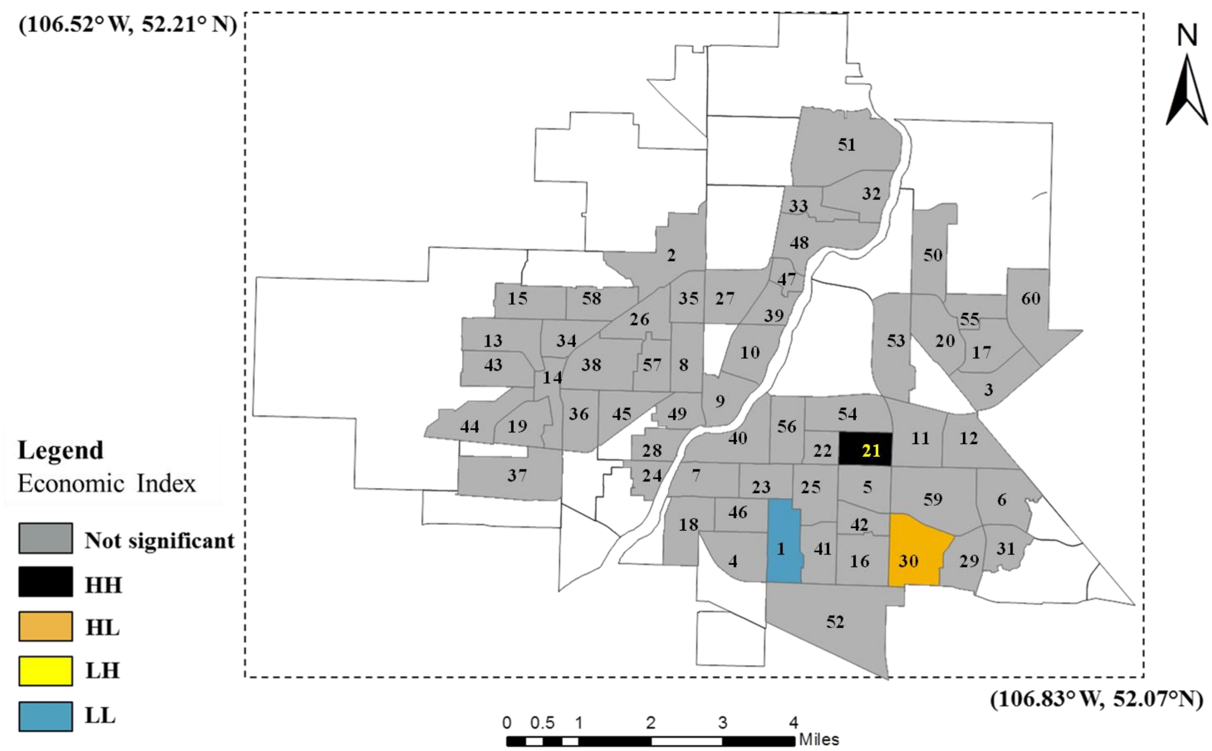
Both mapped LISA results in Figure 4.11 and Appendix G reveal a cluster of neighbourhoods with low *Urban Sustainability Index* in the core area of the west side, and a cluster of neighbourhoods with high *Urban Sustainability Index* in the southeast corner of Saskatoon. This is consistent with the results conclusion drawn in section 4.5.2. Those clustered neighbourhoods (e.g., Pleasant Hill) with low *Urban Sustainability Index* are older inner city neighbourhoods with increased concentration of poverty due to a high percentage of aboriginal residents and low income households (Saskatoon Poverty Reduction Partnership, 2011; City of Saskatoon, 2009-2010; Lemstra and Neudorf, 2008; Kitchen, 2001). The mapped sustainability indices indicate that the disparity between the two different clusters particularly exists in sociopolitical aspects such as health and crime. This is consistent with previous research by Lemstra and Neudorf (2008) and Kitchen and Williams (2009). In respect to the outliers, the continuity edges and corners conceptualization recognizes Montgomery Place as a HL outlier feature as a highly sustainable neighbourhood surrounded by lower sustainable neighbourhoods. The K-nearest conceptualization shows Nutana SC as a LH outlier with a low sustainability index surrounded by highly sustainable neighbourhoods. Montgomery Place, known as "west side oasis", was developed in the mid-1940s as a special neighbourhood to accommodate veterans and their families returned from World War II. Although located on the outskirt of the city, it was more like a resort village than merely a neighbourhood. It has higher sociopolitical and urbanization indices compared to other neighbourhoods in the western core area of the city (Shen et al., 2013). The LH outlier Nutana SC can be primarily attributed to the age structure of its residents with senior citizens in the majority. Therefore, the *QOL Index* and *Urbanization Index* were rated lower, influenced by the age factor (Williams, 2001).

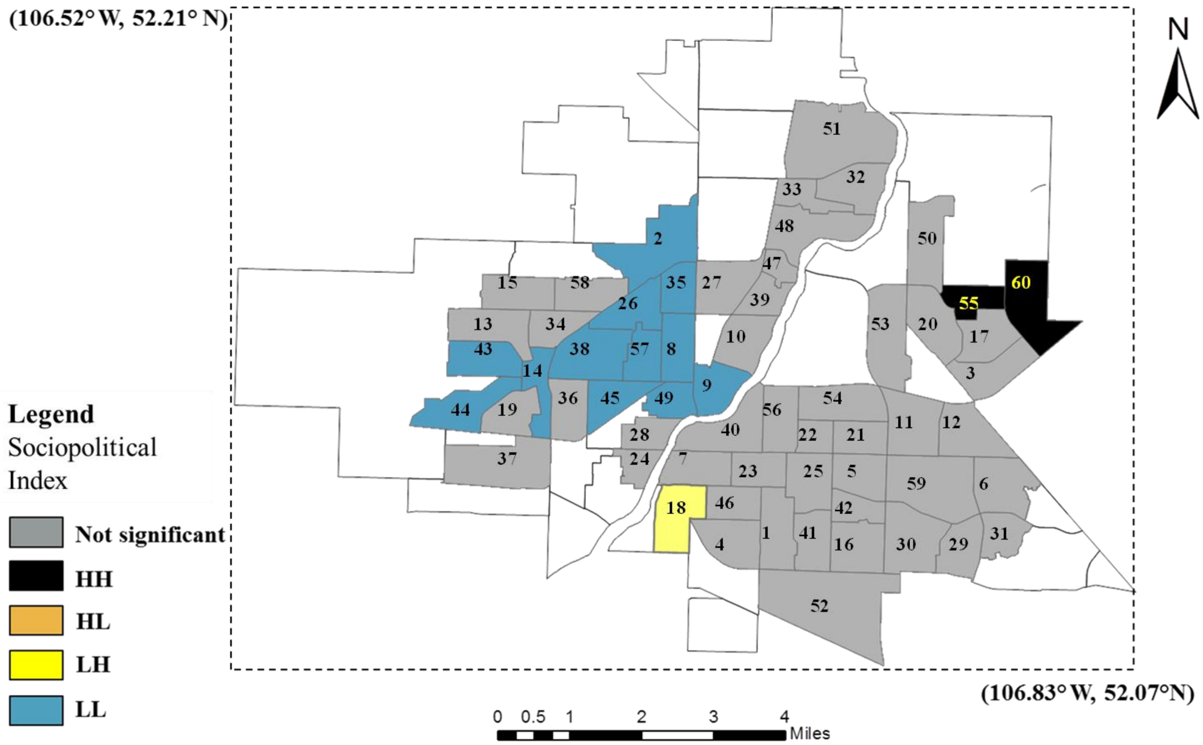
The findings of Getis-Ord Gi* analysis supports the observations above. Both spatial conceptualizations have clearly detected the cold spot of neighbourhoods with low urban sustainability index surrounded by similar neighbourhoods in the west side of Saskatoon and the hot spot of neighbourhoods with high urban sustainability index surrounded by similar neighbourhoods in the southeast part (Figure 4.12 and Appendix H). However both the cold spots and hot spots were more expansive than reported by LISA. Moreover, the continuity edges and corners conceptualization also identifies another hot spot in the northeast neighbourhood Willowgrove which is a middle to high-income area with a high homeownership of 84.8%.

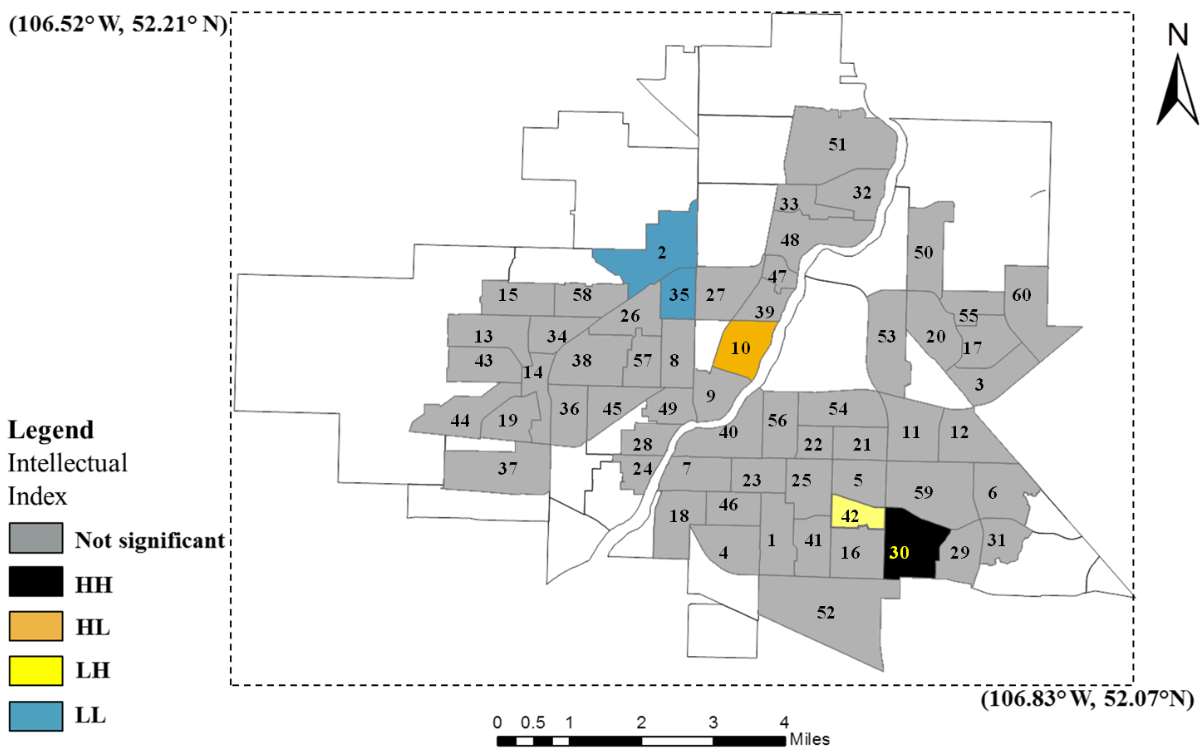
Table 4.5 Global spatial pattern analysis - Moran's I based on two spatial conceptualizations.

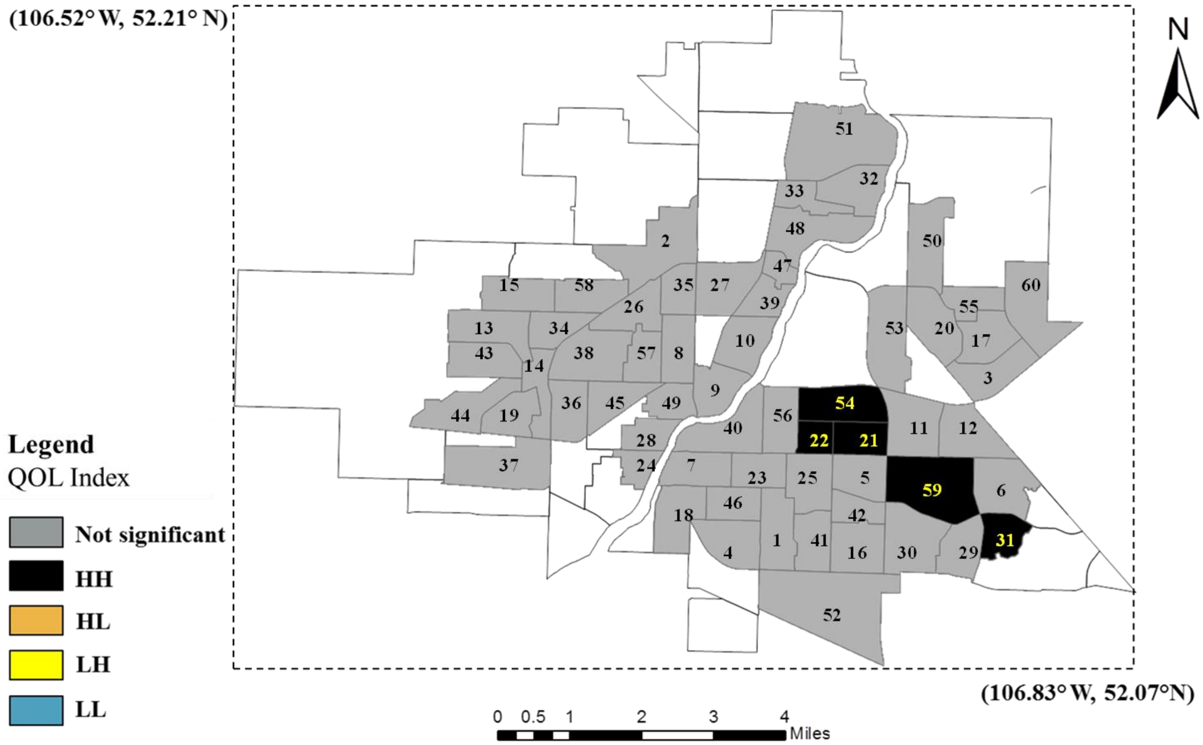
Urban sustainability Indices	**Conceptualization of spatial relationships**	**Moran's I Index**	**z-score* (Significant at the 0.05 level)**	**p-value**	**Global spatial pattern**
Environmental Index	Continuity edges and corners	0.17	2.30	0.02	Clustered
Environmental Index	K-nearest Neighbor	0.13	2.30	0.02	Clustered
Economic Index	Continuity edges and corners	0.02	0.41	0.67	Random
Economic Index	K-nearest Neighbor	0	0.17	0.86	Random
Sociopolitical Index	Continuity edges and corners	0.55	6.80	0	Clustered
Sociopolitical Index	K-nearest Neighbor	0.51	7.92	0	Clustered
Intellectual Index	Continuity edges and corners	0.09	1.23	0.21	Random
Intellectual Index	K-nearest Neighbor	0.05	1	0.32	Random
House Index	Continuity edges and corners	0.21	2.71	0	Clustered
House Index	K-nearest Neighbor	0.19	3.23	0	Clustered
Household Index	Continuity edges and corners	0.22	2.89	0	Clustered
Household Index	K-nearest Neighbor	0.25	3.99	0	Clustered
Mixed land use Index	Continuity edges and corners	0.17	2.33	0.02	Clustered
Mixed land use Index	K-nearest Neighbor	0.12	2.11	0.04	Clustered
Urbanization Index	Continuity edges and corners	0.37	4.63	0	Clustered
Urbanization Index	K-nearest Neighbor	0.33	5.16	0	Clustered
QOL Index	Continuity edges and corners	0.17	2.33	0.02	Clustered
QOL Index	K-nearest Neighbor	0.12	2.11	0.04	Clustered
Urban Sustainability	Continuity edges and corners	0.27	3.51	0	Clustered
Urban Sustainability	K-nearest Neighbor	0.21	3.34	0	Clustered

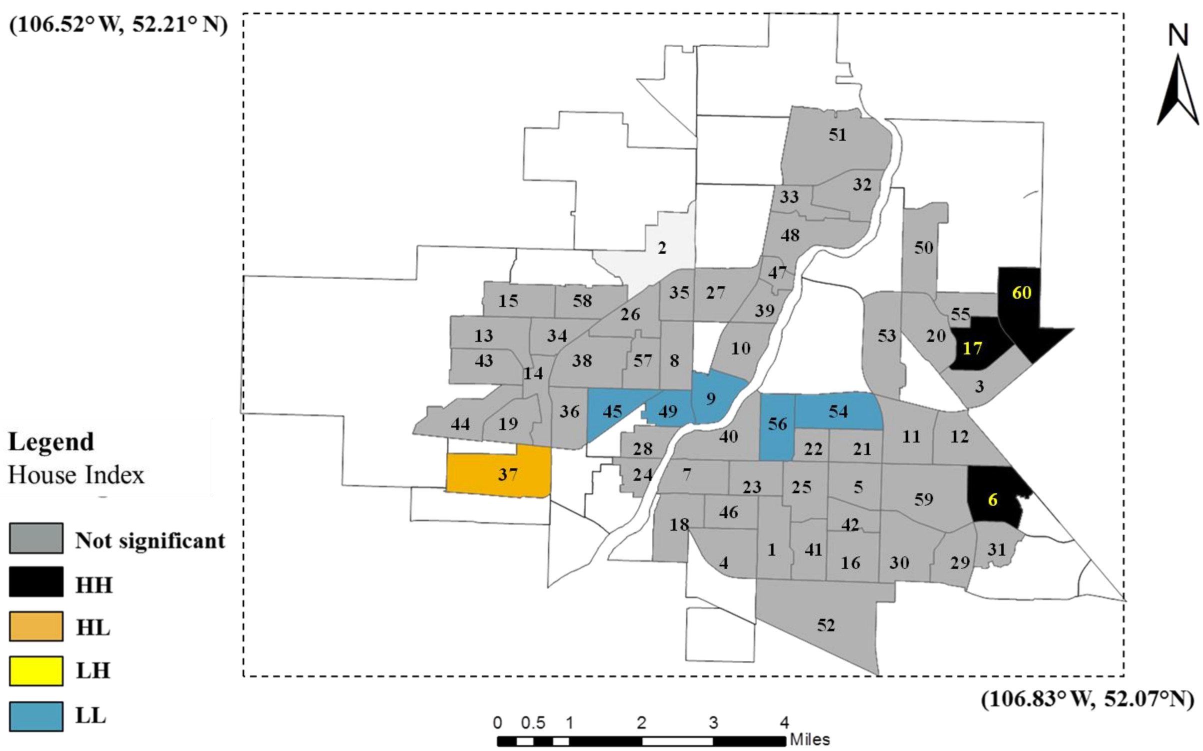

(106.52° W, 52.21° N)
N
Legend
Environmental Index
Not significant
HH
HL
LH
LL
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

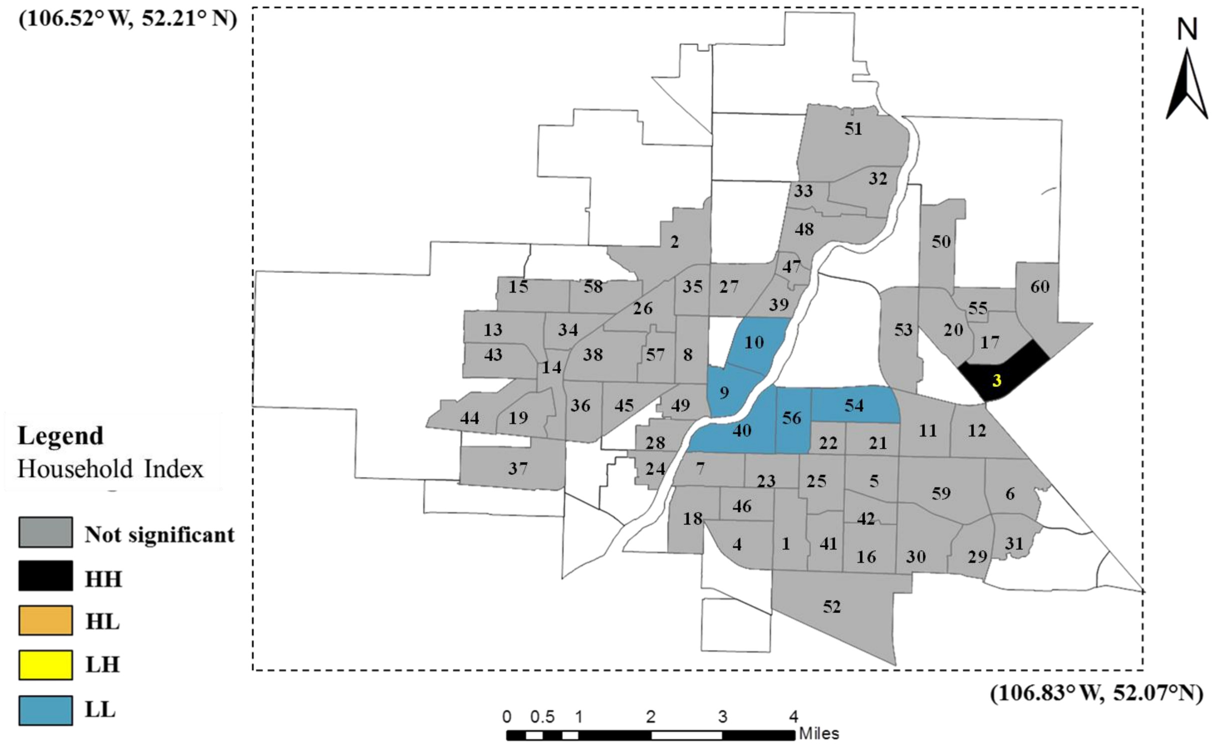

(106.52° W, 52.21° N)
N
Legend
Economic Index
Not significant
HH
HL
LH
LL
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

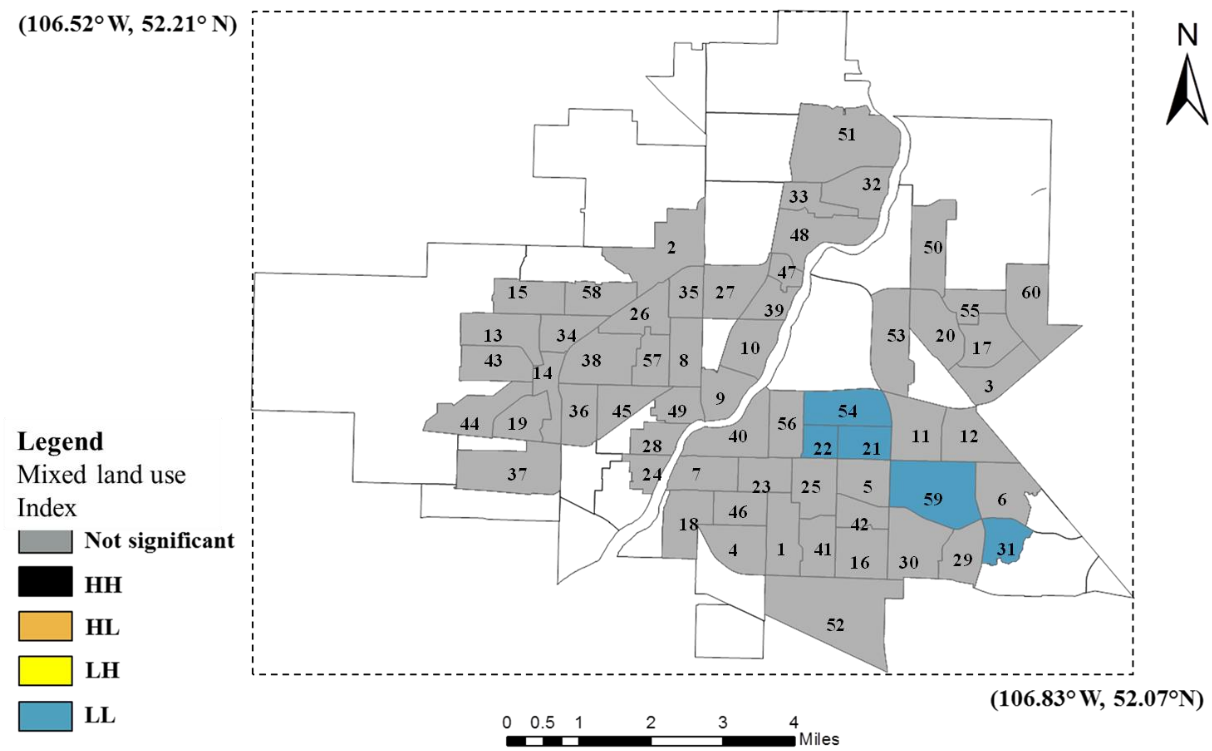

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Sociopolitical Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Intellectual Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
QOL Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4 Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
House Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4 Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Household Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Mixed land use Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles

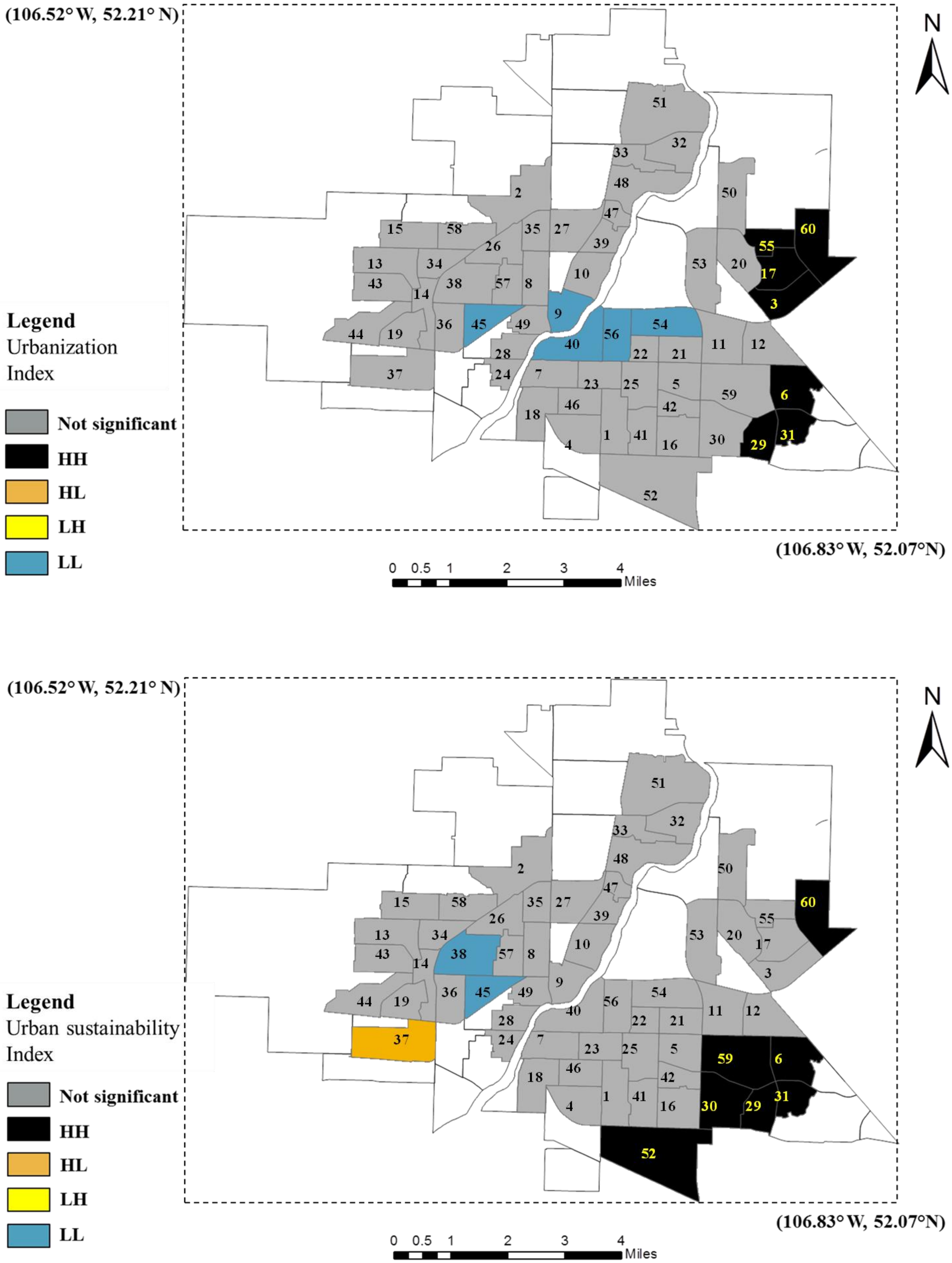
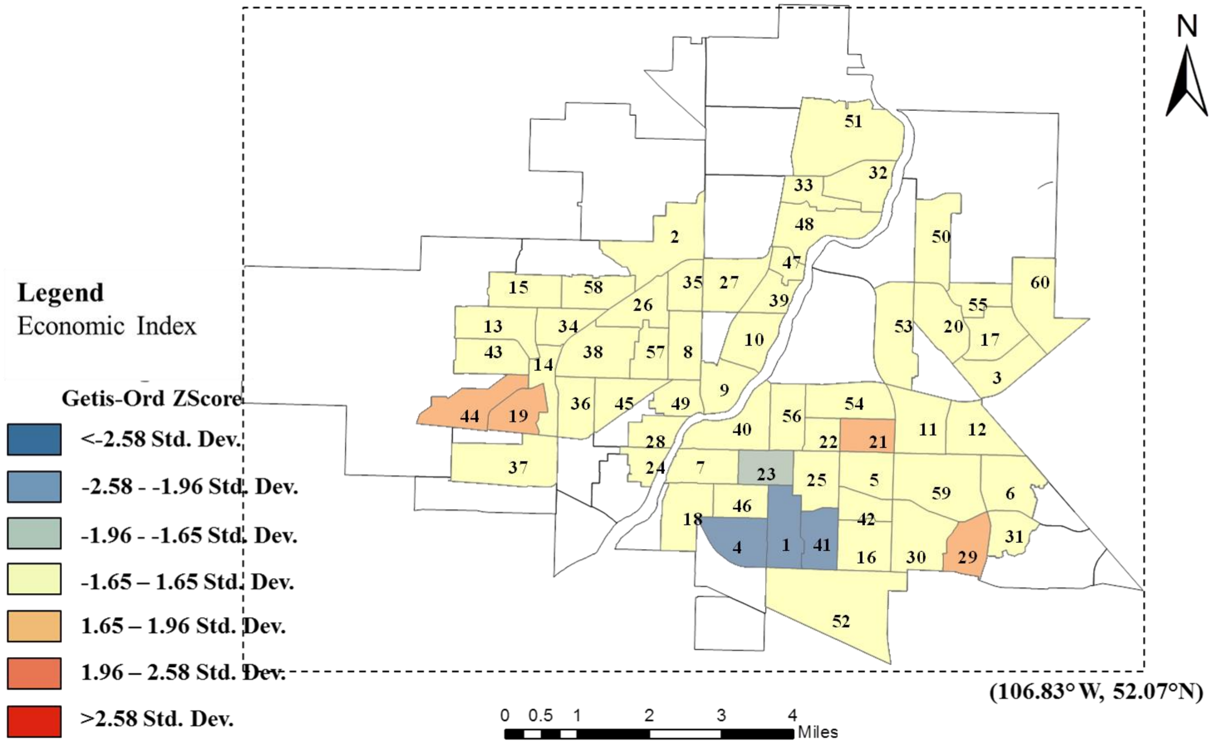
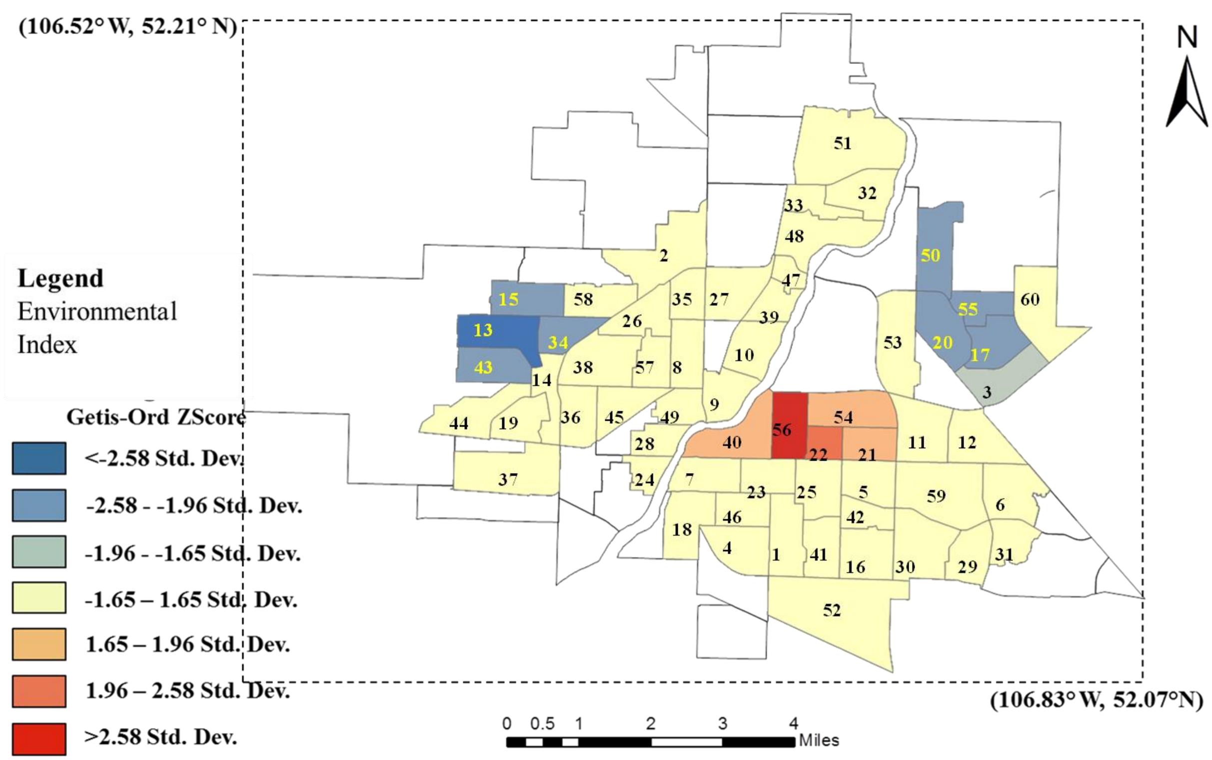
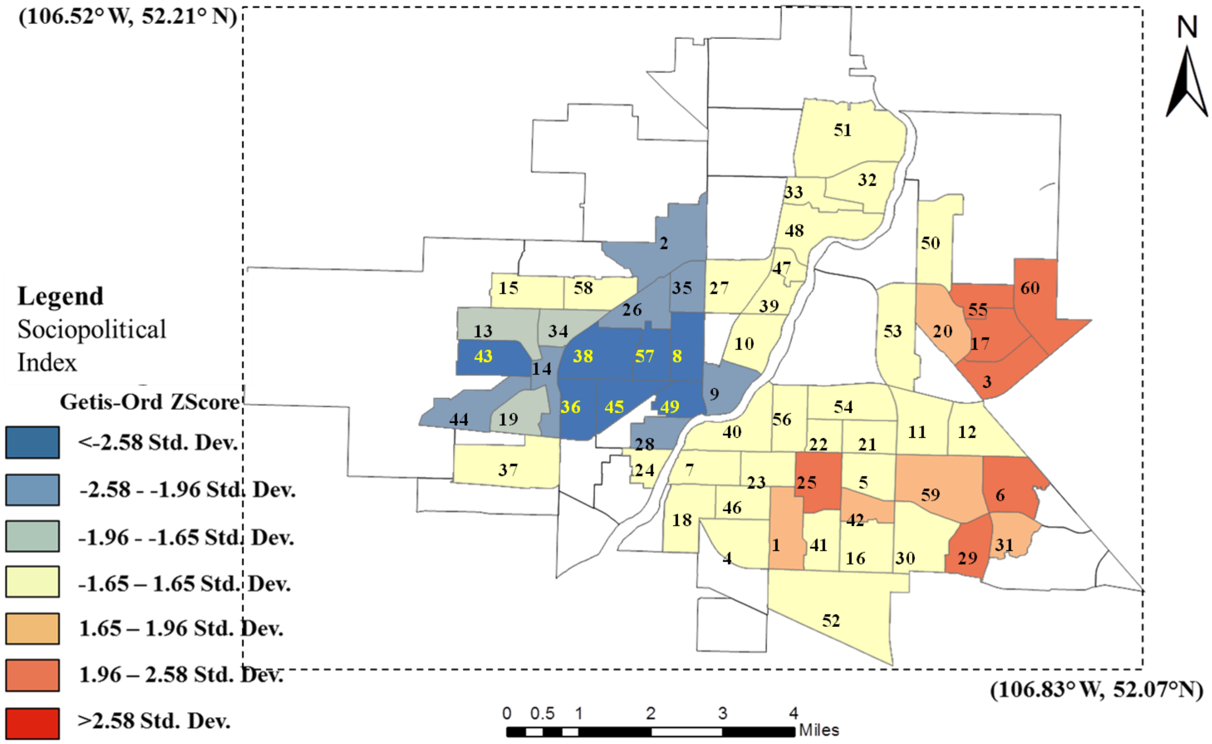
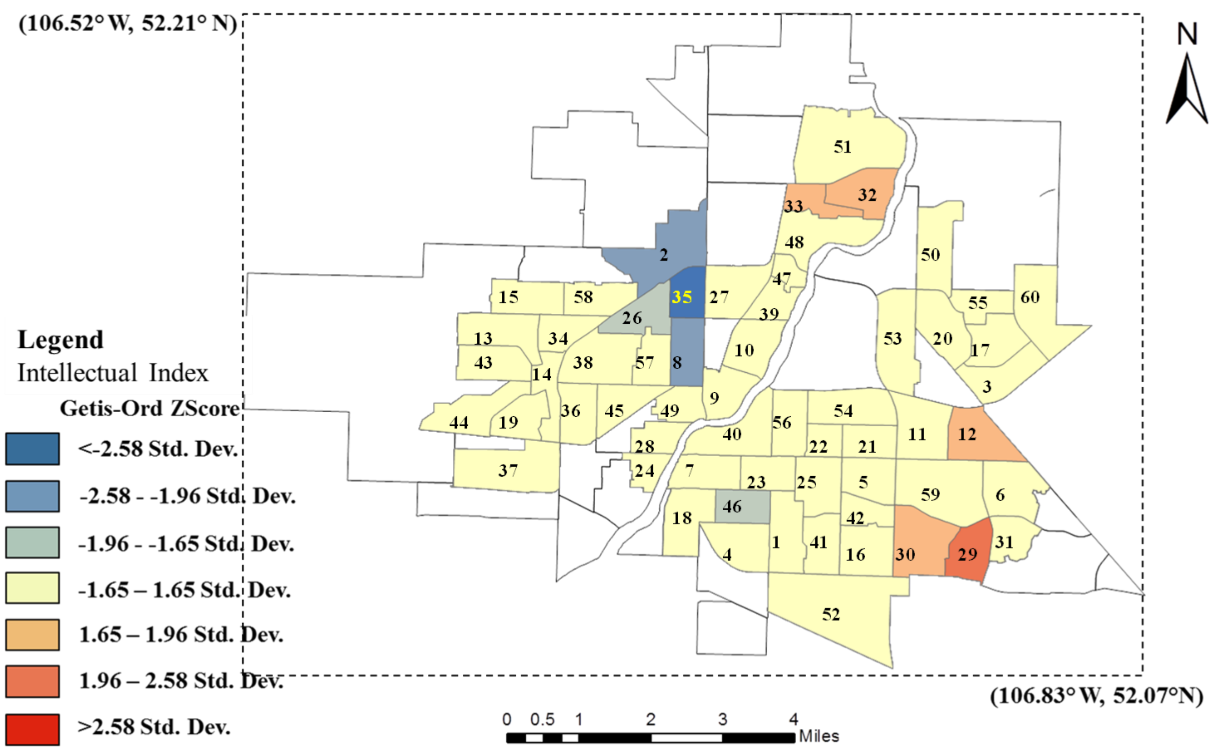


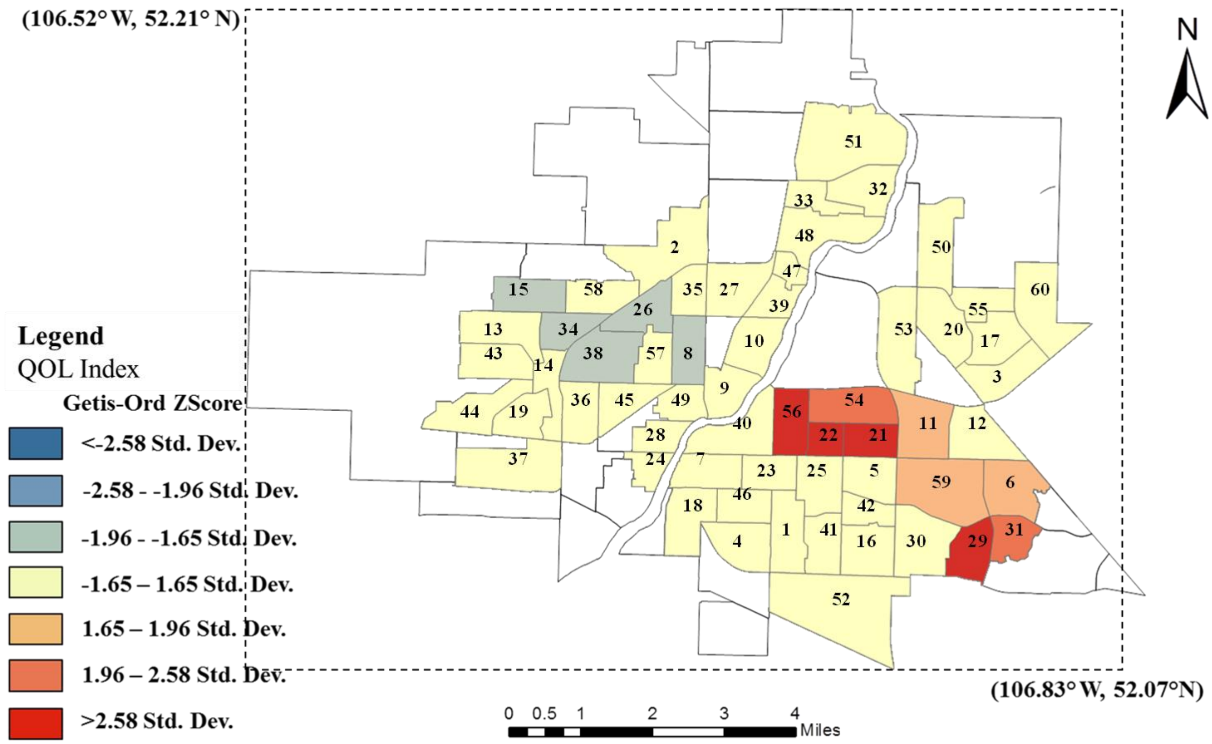
Figure 4.11 LISA spatial analyses of urban sustainability indices with continuity edges and corners as the conceptualization of spatial relationships for Saskatoon in 2006.


N
Legend
Economic Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4 Miles


(106.52° W, 52.21° N)
N
Legend
Environmental Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4 Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Sociopolitical Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
0 0.5 1 2 3 4 Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Intellectual Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
0 0.5 1 2 3 4 Miles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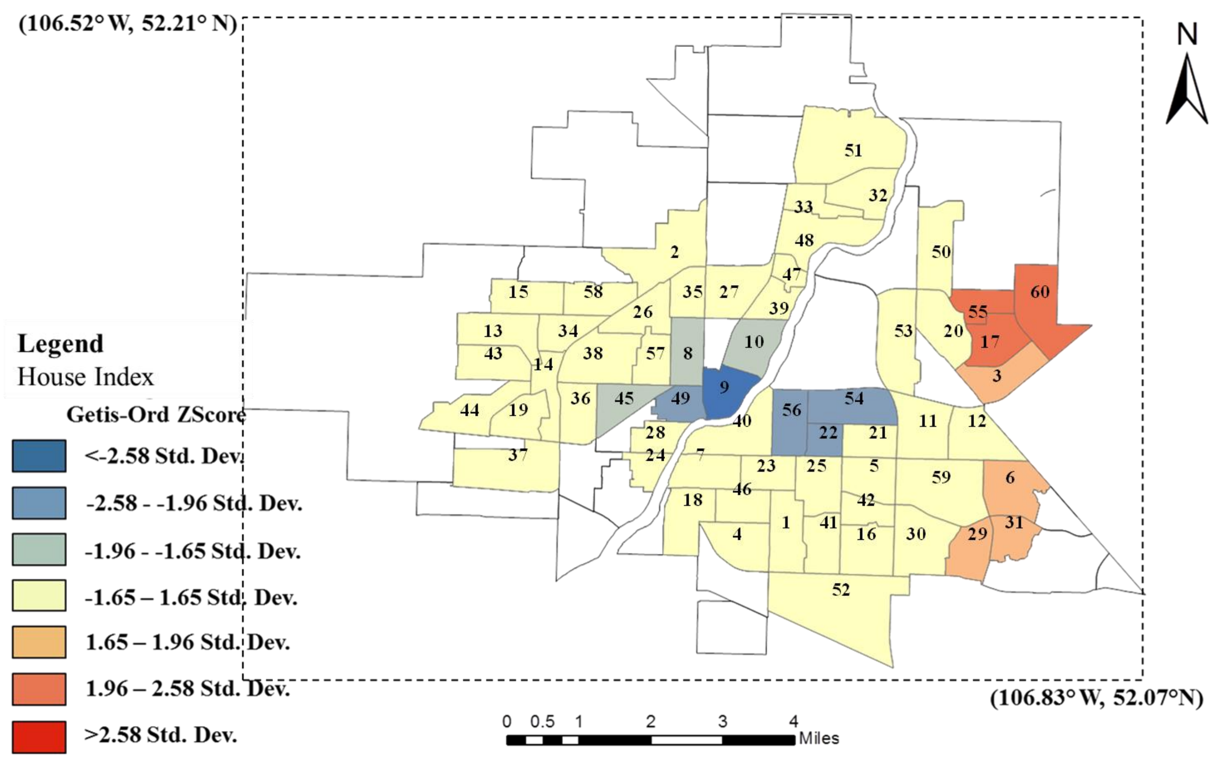
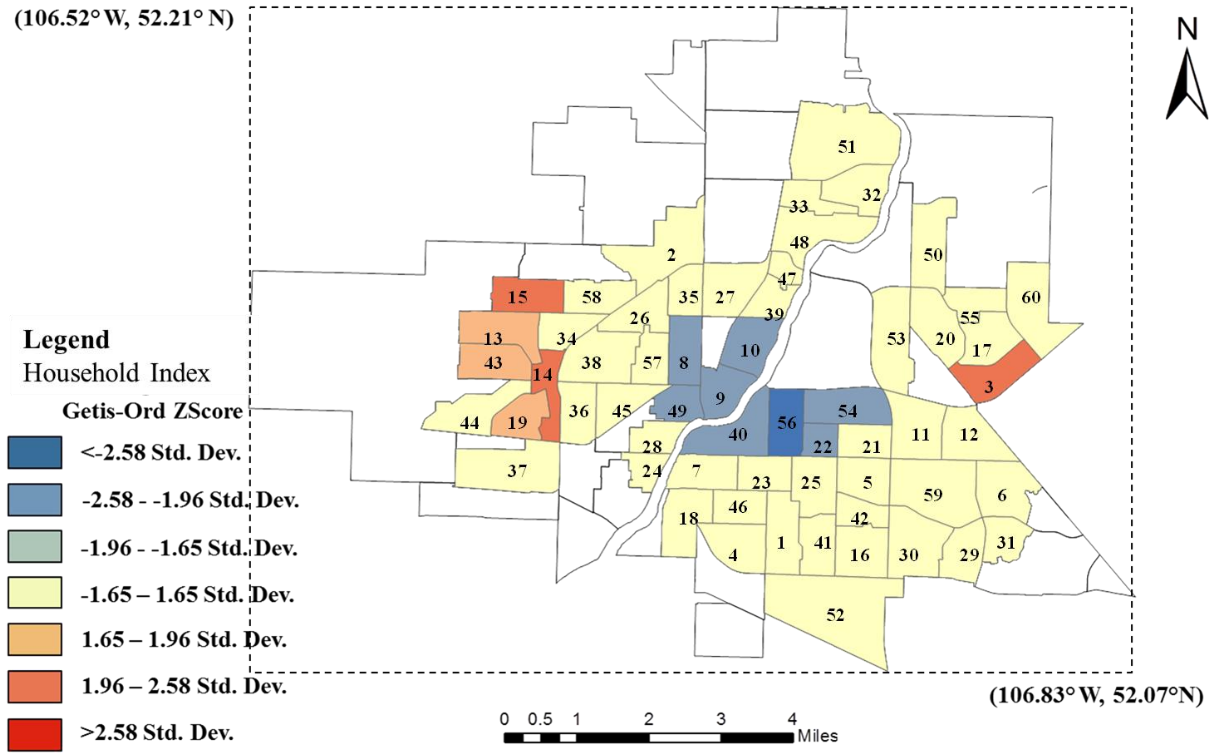
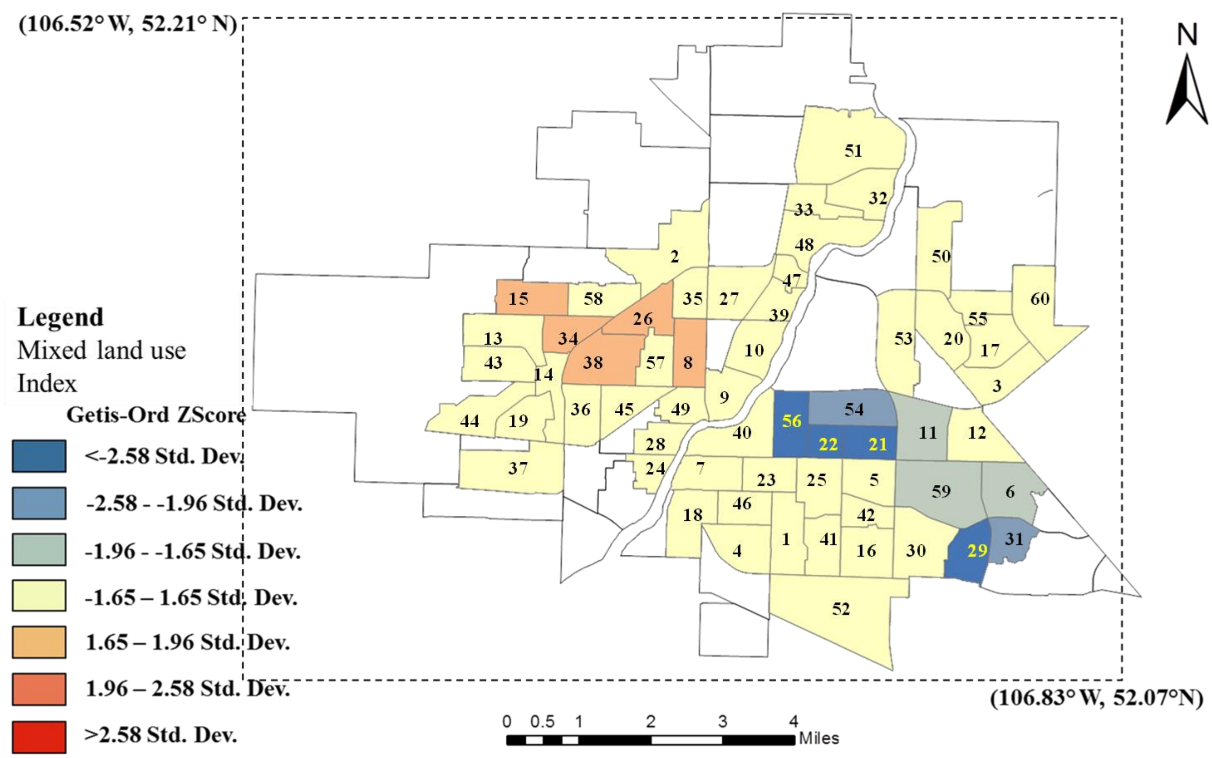
N
Legend
QOL Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4 Miles


(106.52° W, 52.21° N)
N
Legend
House Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4 Miles


(106.52° W, 52.21° N)
N
Legend
Household Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
Mixed land use Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

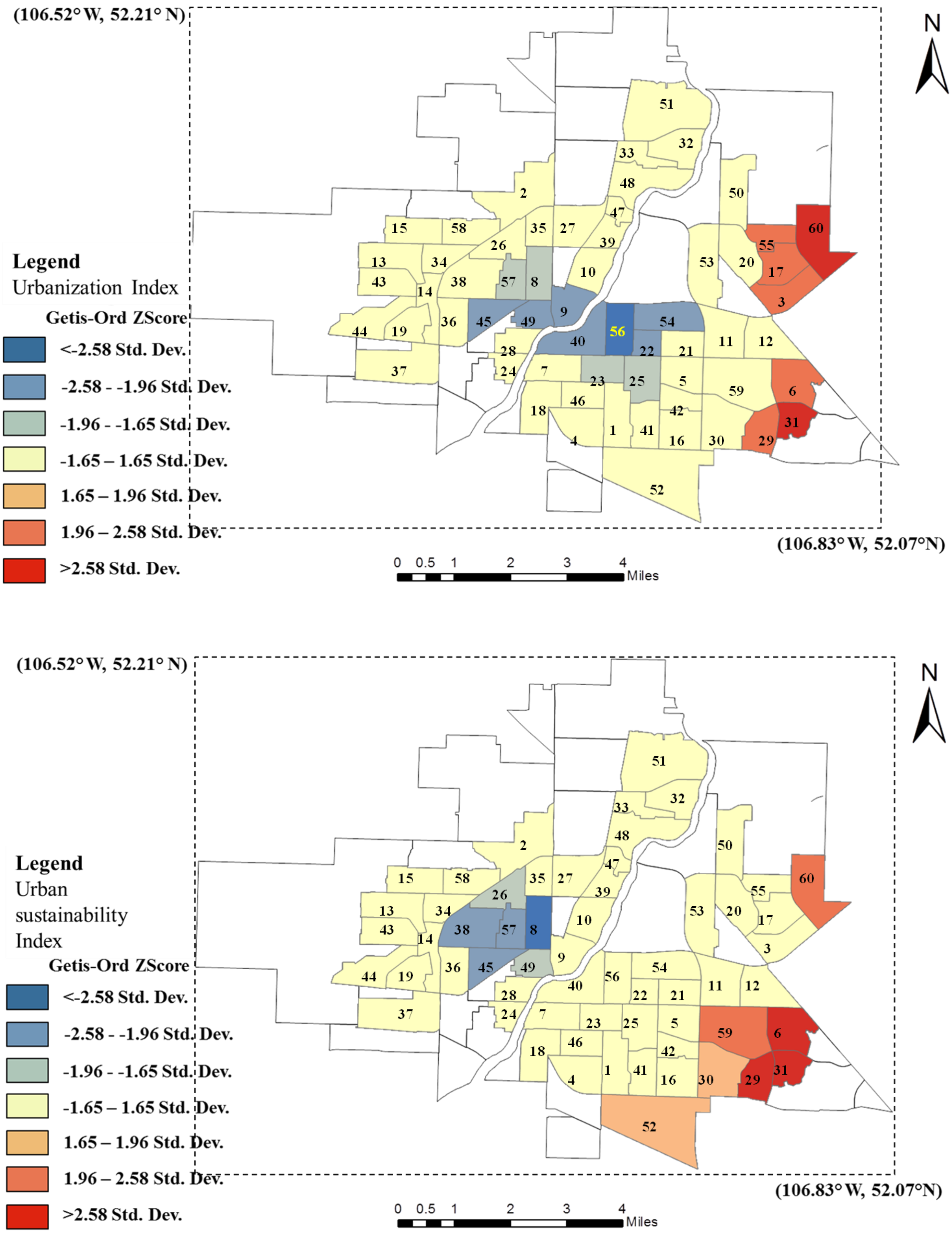


Figure 4.12 Getis-Ord Gi* spatial analyses of urban sustainability indices with continuity edges and corners as the conceptualization of spatial relationships for Saskatoon in 2006.

4.5.4 Correlation between urban sustainability indices and demographic factors

The Pearson correlation between urban sustainability indices and two demographic factors show that the *Environmental Index*, the *Intellectual Index*, and the overall *Urban Sustainability Index* were significantly related ($p<0.05$ or $p<0.01$) to population density in the city of Saskatoon in 2006 (Table 4.6). In addition, the *Economic Index* and the *Mixed land use Index* were found to have a significant positive correlation ($p<0.05$ or $p<0.01$) with population growth rate from the year 2001 to 2006 (Table 4.7). Those results suggest that population increases can possibly improve intellectual and economic well-being as well as promote urbanization progress. However, it can also cause environmental degradation and lead to a decline in the overall urban sustainability.

Table 4.6 Significant correlation between urban sustainability indices and population density.

Urban sustainability indices	**Correlation coefficient with Population density**	**P-value**
Environmental Index	-0.302*	0.02
Intellectual Index	0.267*	0.04
Urban sustainability Index	-0.342**	0.007

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

**. Correlation is significant at the 0.01 level (2-tailed)

Table 4.7 Significant correlation between urban sustainability indices and population growth rate.

Urban sustainability indices	**Correlation coefficient with Population growth rate (2001 to 2006)**	**P-value**
Economic Index	0.275*	0.033
Mixed land use Index	0.365**	0.004

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

**. Correlation is significant at the 0.01 level (2-tailed)

These findings are consistent with, and supported by, previous research that population growth can have both positive and negative implications for achieving sustainability (Downs, 1994). On Accelerating population can pose a threat to natural capital in terms of environmental degradation and resource depletion. Such damages include loss of farmland due to rising habitat demand, increasing pollutants from auto-oriented transportation and life waste, and declining natural resource per capita. However, adequate population growth can also promote the increase of certain community capital. For example, Gertler at al. (2002) pointed out that high population diversity indicates a noticeable improvement of social and cultural capital. In addition, economic capital can also be strengthened by an enlarged tax base as a result of population increase, which can facilitate investment in urban infrastructure (e.g., public infrastructure, and transit services) and human capital (e.g., education and entertainment facilities).

However, the existing literature has simultaneously generated some areas of disagreement to give rise to debate. Hall & Hall (2008) argued that unprecedented population growth can deteriorate social capital by intriguing conflicts and tensions such as polarization between the rich and poor, inequity of employment opportunities, homelessness because of inaccessible houses, protests, riots, crime, and so on. Also, the efficient use of economic and physical capitals is likely to be threatened attributed to serious strain exerted by a rising number of urban habitants on the provision and maintenance of infrastructure, services, and commodity (Hoernig et al., 2005; Huang et al., 1998). Therefore, from a long-term perspective, considerable consensus has been achieved that a slightly growing or stable population is desirable to promote sustainability with the natural environmental and resources managed effectively to avoid irreversible degradation (Hall, 2009; Simard & Simard, 2005; Sustainable Seattle, 1993).

4.6 LIMITATIONS AND OPPORTUNITIES

This study indicated that suburban neighbourhoods in Saskatoon have a higher urban sustainability index value than the urban core areas (Figure 4.10). This contradicts the urban sustainability literature which argues that inner city areas are of higher sustainability than suburban areas (Song and Quercia, 2008; Wells, et al., 2008; Grant and Fillion, 2010). Three main reasons can possibly explain the findings in this study. First, the unsustainable status of suburban areas is mainly driven by urban sprawl and population growth. This study focuses on intra urban sustainability with neighbourhood as the fundamental unit based on neighbourhood-by-neighbourhood comparison analysis rather than the whole city as a holistic target. Therefore, the urban sprawl indicator is not included in the USI model due to the stable areal size for most neighbourhoods in Saskatoon over time. Population indicator is also not selected into this USI model because it is difficult to identify whether population growth promote or decrease the urban sustainability in the medium size prairie city – Saskatoon. The calculated high socio-political index and high urbanization index (household index, house index) are the primary contributors to the overall high urban sustainability index. The specific indicators with significant influence include very low crime rate, high election turnout percentage, high house ownership percentage, and high household percentage (Figure 4.10, 4.11, and 4.12; Appendix C, D, E, F, G, and H).

Second, although the most fundamental domains of urban sustainability (social, economic, environmental, and human well-being) have been selected in this USI model, additional objective indicators still need to be included to make the sustainability measurement more theoretically sound such as *air quality, soil quality, water quality, energy consumption, waste recycled* for the environmental domain, *percentage of participation in voluntary activities* for the socio-political domain, *library and community center usage rate, and participation in the arts* for the intellectual domain, *percentage living below the poverty line* for the economic domain. Measuring QOL requires both objective and subjective indicators (Winston and Eastaway, 2008). In addition to use the subjective weights to improve the USI model in this study, it is necessary to directly develop subjective indicators or translate the objective indicators into subjective ones based on collecting perception data. For example, *feelings of belonging, trust, and safety, life satisfaction scale, happiness scale, and personal well-being.* Due to the data availability, time demand, financial requirement, and the intensive labour work involved, at current stage it is difficult to cover all the aforementioned indicators for the application of this USI model in the case of the Saskatoon city. However, this USI model performs more as an open framework which can be adapted by adding more potential indicators or deleting some unnecessary indicators through public participation in formats of workshops, focus groups, or social surveys.

Furthermore, the subjective information collected for this research is still insufficient to represent residents' real perceptions. First, people in different neighbourhoods may have different rankings of the influential factors to their quality of life. It is possible that certain factors slightly affect one neighbourhood's QOL but highly impact residents' well-being in another neighbourhood. More specific social surveys should be conducted for each neighbourhood to obtain the neighbourhood-based subjective weights. In addition, there is time gap between the subjective and objective data since the social surveys was conducted in 2013 but the objective measurements were based on data in 2006. Since land use composition of some neighbourhoods has changed since 2006, there may be potential problems with integrating 2013 surveyed data to 2006 land use and neighbourhood profile data. Residents' perspectives can also change over time as other conditions or drivers change. For this study conducted in 2013, it is impossible to collect surveyed data for the year 2006. However, in further research careful attention should be paid to this concern to ensure the temporal consistency of all the data sources.

To investigate the different role of those indicators in measuring the overall urban sustainability, sensitivity analysis based on the numeric values of all specific indicators (Appendix D) is a necessary step to improve the accuracy of this USI model and continue the urban sustainability study (Huang et al., 2009). The methodological procedures can be as follows. First, three aggregated levels of urban sustainability indices should be extracted with one specific indicator withheld for each time. The process of index calculation will be repeatedly performed until each specific indicator has been removed once. Next, comparison analysis is conducted between those newly calculated indices with the originally obtained ones with all specific indicators as the input data. Both descriptive statistics and spatial detection (classification and geostatistics) need to be applied to qualitatively and quantitatively identify the similarity and difference. Similarity trends indicate the excluded indicator is less sensitive to the USI model while distinct patterns mean the withheld indicator has a significant impact on the USI model. Therefore, the relative importance of each individual indicator and how it affects the accuracy of the USI model can be understood in this way.

4.7 CONCLUSIONS

This chapter demonstrated the application and quantification of the weighted USI model with the city of Saskatoon as a case study based on a hierarchical urban sustainability index system. The descriptive statistics and spatial classifications showed that there was evident disparity in urban sustainability status, especially in respect to environmental and material well-being across the 60 residential neighbourhoods for Saskatoon in 2006. This is in large part because 97% of the neighbourhoods had a relatively low *Urban Sustainability Index*, below 0.6, whereas only 3% of neighbourhoods, in suburban areas, had higher index values, over 0.8. The gap existed in the west and east sides of the city; it was particularly higher in the southeast suburban areas and lower in the center-west of the inner city. The geostatistical analysis investigated the spatial patterns of autocorrelations from global and local perspectives, and found that eight of ten urban sustainability indices (*Environmental Index, Socio-political Index, House Index, Household Index, Mixed land use Index, QOL Index, Urbanization Index*, and *Urban sustainability Index*) showed statistically clustered patterns in the inner-city neighbourhoods and the suburban areas. In addition, Montgomery Place neighbourhood was identified as a neighbourhood with a high sustainability index surrounded by neighbourhoods with a low sustainability index while Nutana SC was detected as a neighbourhood with a low sustainability index but surrounded by neighbourhoods with a high sustainability index. Also, the research shows that population increase can possibly improve the intellectual and economic well-being as well as promote urbanization progress. However, it may cause environmental degradation and lead to a decline in the overall urban sustainability.

Compared to the application of other existing USI models, this study presents a comprehensive investigation of urban sustainability in three aspects. First, it lies in the interpretation of urban sustainability. The incorporation of urban residents' subjective well-being (feelings and perceptions) into the commonly accepted triple bottom line domains (economy, society, and environment) can improve the inclusiveness and authenticity of urban sustainability because as a critical actor in urban life people can significantly impact and be impacted by urban development. Second, the integrated USI model with a hierarchical index system can provide not only a synthetic evaluation of the overall urban sustainability but also specific information from different domains at multiple aggregated levels. This is well suited for effective communication among different target audience public residents, government administrators, and academic communities for education, policy making, and research respectively. Furthermore, this research proves that geospatial technique (remote sensing and GIS) presents a promising opportunity to investigate urban sustainability patterns from a spatiotemporal perspective through combining multiple data sources into one geodatabase, breaking the constraints of merely relying on the census data. Thus, the use of geospatial technique in this case study may provides some useful insights into the development and quantification of USI models with a geographical philology of spatial and temporal aspects instead of merely statistical reports.

Potential advantages beyond the academic community can also be found from this research. Based on the mapped urban sustainability indices at different aggregated levels for relevant dimensions, multiple stakeholders can obtain acknowledgement of urban sustainability according to their own interpretation requirements. The spatiotemporal distribution of urban sustainability can be revealed and reported through community participation processes such as establishing voluntary networks and civic forums. Such public participation will also facilitate forming effective feedback mechanism to decision making and providing directions for both urban residents and administrators in good sustainability practice.

CHAPTER 5

SPATIOTEMPORALLY CHARACTERIZING URBAN ENVIRONMETNAL SUSTAINABILITY IN THE CITY OF SASKATOON

5.1 CHPATER SUMMARY

The purpose of this chapter is to spatiotemporally explore the characteristics of urban environmental sustainability based on multi-temporal Landsat, MODIS data, and historical *in situ* measurements. As one of the most rapidly urbanized city in Canada, Saskatoon (SK) was selected as our study area. Surface brightness retrieving, person correlation, bivariate and multiple linear regression modeling, and buffer analysis were applied to different datasets. Results indicated that both Landsat and MODIS data can yield pronounced estimation of daily air temperature with significant adjusted R^2 of 0.803 and 0.518 at the spatial scales of 120 m and 1000 m respectively. MODIS monthly LST data is highly suitable for monitoring the trend of urban monthly air temperature in summer (June, July, and August) due to a high averaged R^2 of 80% ($P<0.05$), especially for the warmest month July. Our findings also revealed that both the Saskatchewan River and green spaces have significant cooling effects on the surrounding urban LST within 500 m and 200 m respectively. In addition, sustainable travelling modes also helps mitigate urban temperatures while increasing impervious surface can cause heating up to form urban heat islands. A multiple linear regression model based on four independent variables can be used to estimate urban surface temperature with a highest adjusted R^2 of 0.649 and a lowest standard error of 0.076.

5.2 INTRODUCTION

Air temperature and surface temperature are identified as commonly used variables to investigate local, regional, and global climate characteristics (Hansen et al., 1981; Dash et al., 2002; Hung et al., 2006). As a vulnerable system, the urban microclimate is more sensitive to temperature changes which escalate with the unprecedented urbanization by converting pervious surfaces into impervious land covers (Benali et al., 2012; Bristow and Campbell, 1984). Water-persistent materials have lower specific heat capacity to store and conduct energy, resulting in a rapid rise of air temperature in comparison with pervious substances. Urban landscape is in high percentage of impermeable surfaces for the purposes of transportation, commercial use, industrial zones, as well as the residential spaces (Jin and Dickinson, 2010). Consequently, in comparison to the surrounding suburbs, the central city undergoes a warming microclimate caused by the mounting air temperature, which is generally referred to as the *urban heat island* (UHI) effect (Rinner and Hussain, 2011; Liu and Zhang, 2011; Fabrizi et al., 2010; Hamdi, 2010; Jin et al., 2011). UHI effects can cause tremendous damage to both environmental conditions and public health by inducing poisonous gases release, causing species distinction, and exacerbating premature human deaths (Changnon et al., 1996). A number of previous studies have pointed out that urban vegetation and water play a critical role in regulating air temperatures and mitigating UHI effect (Doick and Hutchings, 2013; Li et al., 2013; Huang et al., 2008). The abundance and spatial distribution of urban green space can form a cooling mechanism due to vegetation's unique interaction with the incoming solar radiation (Kwarteng and Small, 2010). Therefore, characterizing urban temperatures at different spatiotemporal scales can contribute to our understanding of the UHI effect and the impacts of anthropogenic activities on urban climate change (Prihodko and Goward, 1997).

The demand for long-term continuous and spatial input information has given widespread interest to satellite imagery to overcome the disadvantages in the conventional methods (Nicole, 1996). The point-based field measurements are time-consuming, expensive for maintaining, and limited in spatial exploration due to unavoidable errors emerging in data interpolation (Prihodko and Goward, 1997; Nicole, 1996). In the opposite way, satellite remote sensing developed in the 1970s, has become a practical tool for real-time, long-term, cost-effective, and labor-efficient monitoring of urban environmental conditions, particularly for the areas poorly covered by weather stations (Benali et al., 2012; Madden et al., 1993; Jones, 1995; Karl et al., 1995). Multiple spatial and temporal resolutions can provide observations of high frequency (daily, weekly, monthly, and annually) at different geographical scales (local, regional, national, and global). The thermal infrared potion (3.0-14 μm) of the electromagnetic spectra are well designed in most optical satellite sensors to detect the surface temperatures of landscape features (e.g., vegetation, soil, water, impervious surface) (Jensen, 2007).

Land surface temperature (LST) measured at the Earth's surface has been proved to highly associate with near surface air temperature (Jin and Dickinson, 2010). As the two types of temperatures have strong similarities in variation and trends, satellite-retrieved LST presents great opportunities in characterizing air temperatures at different spatiotemporal scales (Strahler and Archibold, 2011). While there has been extensive controversy on this research due to the uncertainties in the measurements of the two temperatures and their property difference (Vukovich, 1983; Vogt et al., 1997; Mostovoy et al., 2006), increasing consensus can still be achieved to confirm the unique role of remote sensing data in providing continuous synoptic views of dense grid air temperatures over a large area (Prihodko and Goward, 1997; Nicole, 1996; Seto and Christensen, 2013). A comparison analysis between the *in situ* air temperature and LST extracted from Landsat Thematic Mapper (TM) by Nichol (1996) in the city of Singapore suggests a significant correlation existing for both the horizontal and vertical surfaces. Similar attempts were also carried out for satellite imagery with coarse spatial resolutions at large spatial scales. For instance, Prihodko and Goward (1997) applied a temperature-vegetation index (TVX) contextual approach to detect the air temperature pattern based on the 1100 m Advanced Very High Resolution Radiometer (AVHRR) thermal information, which yielded a good agreement between satellite thermal measurements and ground observed air temperature. In addition, Benali et al. (2012) have explored the capability of weekly 1000 m Moderate Resolution Imaging Spectroradiometer (MODIS) in capturing the annual and biweekly variation of LST in Portugal with some degree of success in improving the accuracy.

Existing literature suggests that most attention has been paid to the improvement of thermal information in estimating air temperature for each individual instrument by minimizing errors to increase the accuracy. Limited work has been shown in the comparison of multiple satellite data in spatiotemporally characterizing the urban temperatures. It is also important to acknowledge whether some relevant factors from both biophysical and anthropogenic aspects can statistically impact the urban surface temperatures. The spatial influence especially from rivers and green spaces needs to be specifically focused for mitigating UHI effects. Therefore, the main purpose of this study is to compare Landsat and MODIS data in characterizing urban temperatures at different spatiotemporal scales in the city of Saskatoon. The influences of some relevant factors on urban surface temperatures were statistically analyzed. Buffer analysis of the Saskatchewan

River and urban green spaces was conducted to spatially investigate the cooling effect of those agents on the surrounding surface temperature.

5.3 STUDY AREA

Considering the rapid urbanization in the past decade, the city of Saskatoon (52.12°N, 106.67°W) was selected as our study area (Figure 5.1). Saskatoon is situated in middle-southern Saskatchewan Province, Canada with an elevation of 481.5 m above the sea level declining from the west to east (Shen et al., 2013c). The South Saskatchewan River splits the city into two parts (the east and the west). Saskatoon experiences four distinct seasons with the maximum 30 ℃ in summer and - 30 ℃ minimum in winter (City of Saskatoon, 2010). The city typically receives less than 350 mm precipitation for annual average and a high level of sunshine over 2380 hours annually. As a medium prairie city with a total area of approximately 218 km^2, Saskatoon has become the fastest growing city in Canada due to its dramatic population growth rate predominately contributed by international immigration (Proudfoot, 2011). The significant population accumulation in Saskatoon has facilitated dramatic urbanization processes in terms of land use change and urban sprawl especially for the past decade, posing adverse effects on the city's sustainable development such as ecological problems and UHI issues. Thus, urban sustainability in environment, economy, and society has been approved by the city council as the foremost goal for Saskatoon's future development (City of Saskatoon, 2010).

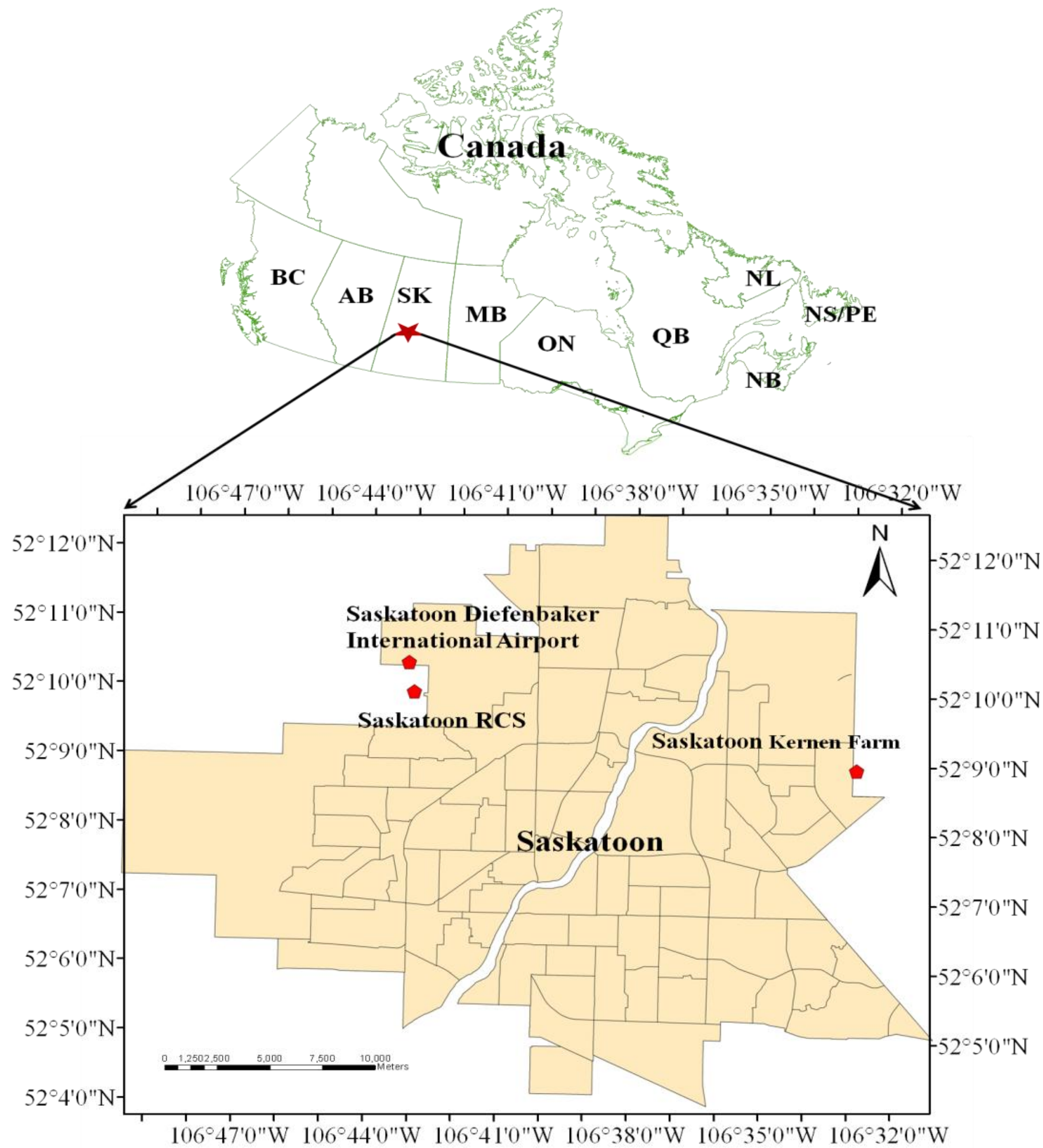


Figure 5.1 The city of Saskatoon (SK, Canada) with three weather stations (red pentagons) for providing the *in situ* air temperature data used in this study.

5.4 METHODOLGOIES

5.4.1 Satellite imagery preparation

The satellite imagery for this study includes four data sources which are Landsat TM, ETM+, MODIS Daily LST in daytime, and MODIS monthly average LST in daytime for the city of Saskatoon from 1991 to 2011. Landsat has band 6 (10.4-12.5 μm) as the thermal infrared region with spatial resolution 120 m for TM imagery and 60 m for ETM+ data (USGS, 2013; NASA, 2013a), and MODIS Daily LST data has spatial resolution of 1 km (NASA, 2013b). After previewing all available data in the archive of USGS website for the study area in the past decade, nine Landsat TM and one Landsat ETM+ imagery with the cloud cover less than 10% and seven MODIS daily LST data were selected (Table 5.1). The monthly average LST imagery used in this study was MODIS/Terra Land Surface Temperature and Emissivity Monthly L3 Global 0.05Deg CMG. It can cover the global area from March, 2000 with a spatial resolution of 5.6 km at the equator (USGS, 2013). The original geographic projection was transformed into the UTM NAD 1983 Canada Altas Lambert projection to be consistent with the other data sets. An illustration of the thermal information from three types of satellite data is provided by Figure 5.2.

Table 5.1 Multi-temporal Landsat TM, ETM+, and MODIS daily imagery selected for the city of Saskatoon from Year 1991 to 2011.

Satellite imagery	Dates	Spatial resolution
Landsat TM and ETM+	1991/08/09;1994/07/23;1994/09/02;1999/07/29;2003/08/10; 2004/08/28;2005/07/1;2011/06/29;2011/07/15;2011/07/31	120 m
MODIS/Terra LST and Emissivity Daily L3 Global	2003/08/10;2004/08/28;2005/07/1;2006/04/28;2011/06/29; 2011/07/15;2011/07/31	1 km

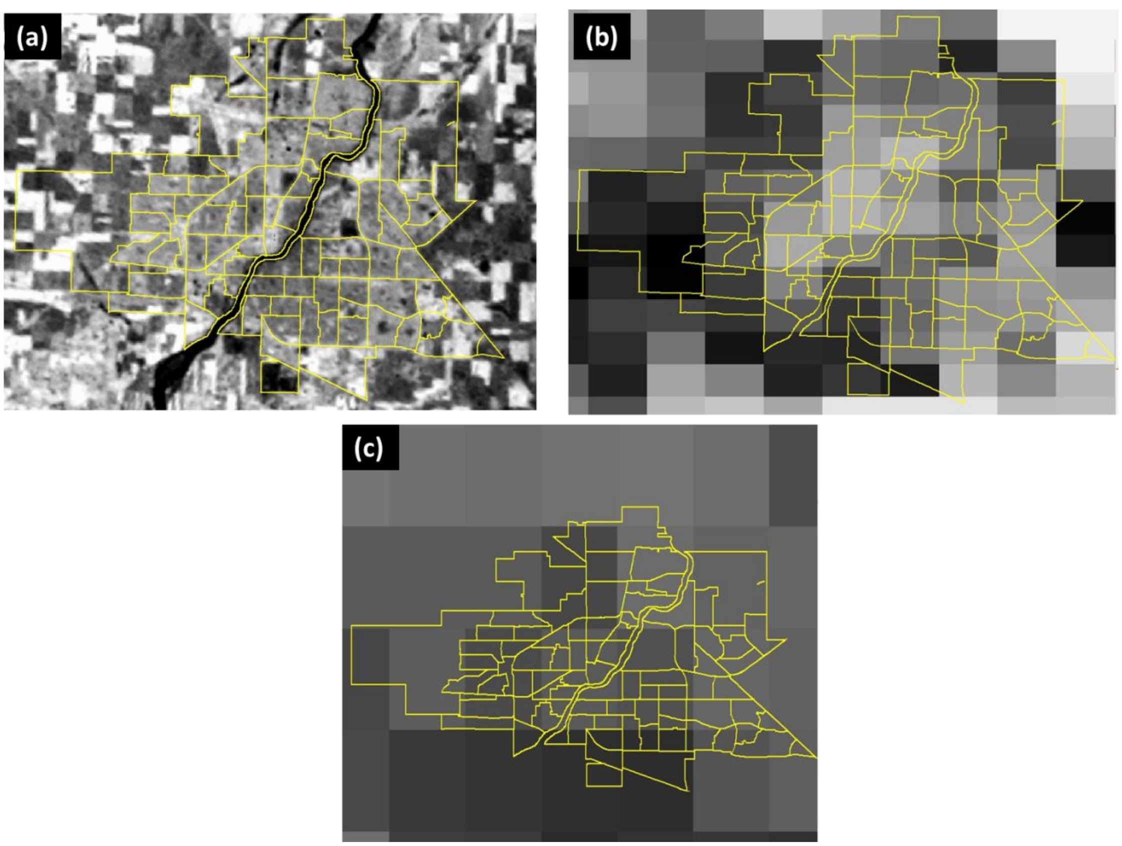


Figure 5.2 Different satellite imagery used for characterizing daily air temperature in the city of Saskatoon. a) Landsat TM with 120 m spatial resolution of the thermal band on August 9, 1991 b) Daily MODIS LST product with 1000 m spatial resolution on August 10, 2003 c) MODIS 5600 m LST product in July, 2001.

5.4.2 Meteorological station data

As supplement of remotely sensed data, historical *in situ* weather observations (hourly and monthly average air temperatures) were recorded by three weather stations in Saskatoon and reported by Environment Canada from 2003 to 2007 (Figure 5.1 and Table 5.2). The elevation is commonly defined as the above sea level height of the observation location where the thermometers and other instruments (barometer cistern, humidiometer) are located. The Climate ID represents the specific location of measurements by the Meteorological Service of Canada. The first digit is the province while the second and third ones indicate the climatologic district within the province. Other digits refer to discontinued observations in different stations (Environmental Canada, 2013). Since the observation time of Landsat and MODIS daily data is recorded based on Greenwich Mean Time (GTM), we firstly converted GTM to Saskatoon local standard time for all satellite imagery. Then the hourly air temperatures were averaged every 15 minutes to match Landsat imagery in Saskatoon local standard time as close as possible (Table 5.3).

Table 5.2 Geospatial information of Saskatoon weather stations for providing hourly and monthly average air temperature data.

Weather Station Name	Location (Latitude, Longitude)	Elevation (m)	Climate ID
Saskatoon Diefenbaker	(52 °10' 00.000'' N, 106 °43' 00.000'' W)	504.10	4057120
Saskatoon Kernen Farm	(52 °09' 00.000'' N, 106 °33' 00.000'' W)	510.00	4057155
Saskatoon RCS	(52 °10' 25.000'' N, 106 °43' 08.001'' W)	504.10	4057165

Table 5.3 Saskatoon Local Standard Time of collecting *in situ* air temperature and acquiring the Landsat and MODIS daily satellite imagery.

Image acquisition date	Landsat image scanning time (am)	Air temperature acquisition time for comparison with Landsat data (am)	MODIS daily image scanning time (pm)	Air temperature acquisition time for comparison with MODIS data (pm)
1991/08/09	11:22:21	11:30:00 (29.65 ℃)	-	-
1994/07/23	11:22:56	11:30:00 (22.27 ℃)	-	-
1994/09/02	11:15:14	11:15:00 (18.1 ℃)	-	-
2003/08/10	11:48:00	11:45:00 (26.7 ℃, 27.5 ℃)	12:00:00	12:00:00 (26.7 ℃, 27.5 ℃)
2004/08/28	11:42:13	11:45:00 (18.3 ℃, 17.65 ℃)	12:00:00	12:00:00 (18.3 ℃, 17.65 ℃)
2005/07/14	11:15:14	11:15:00 (21.15 ℃, 23.3 ℃)	12:00:00	12:00:00 (21.6 ℃, 23.7 ℃)
2011/06/29	11:48:00	11:45:00 (27 ℃, 26.55 ℃)	12:00:00	12:00:00 (27 ℃, 26.55 ℃)
2011/07/15	11:48:00	11:45:00 (21.43 ℃, 21.35 ℃)	12:00:00	12:00:00 (21.43 ℃,
2011/07/31	11:48:00	11:45:00 (25.43 ℃, 25.43 ℃)	12:00:00	12:00:00 (25.43 ℃,

5.4.3 Landsat pre-processing and LST retrieval

Owing to the inherent errors of the original Landsat data, radiometric and geometric corrections were implemented to Landsat data before deriving LST. For radiometric correction, we set the appropriate *gain* and *offset in the* calibration files for each image using the header file information. Then the radiometric corrected values were extracted by performing the ATmospheric CORrection-2 (ATCOR-2) module in the PCI Geometica software based on Chavez's improved dark object theory (Chavez, 1988; Shen et al., 2013a). For geometric correction, we applied a geo-coded SPOT image with higher resolution (20 m) acquired on June 13, 2010 to rectify the 30 m Landsat imagery in a common UTM coordinate system with the correction accuracy better than 0.1 Root Mean Square Error (RMSE) (Jensen, 2007; Shen et al., 2013b). No pre-processing is required for both daily and monthly MODIS LST products since they can be used directly.

Then we applied the most popular algorithm to retrieve the surface brightness temperatures from thermal infrared emission observed at the top of the atmosphere (TOA) (Qin et al., 2001; Chen et al., 2006). First the original thermal DN values of Landsat band 6 were converted to integrated radiance at sensor based on formula (1),

$$L(\lambda) = L_{min}(\lambda) + \left(\frac{L_{max}(\lambda) - L_{min}(\lambda)}{255}\right) * DN \quad (1)$$

where $L(\lambda)$ ($W*m^{-2}*sr^{-1}*\mu m^{-1}$) is the integrated band radiance at the specific wavelength λ (μm). $L_{max}(\lambda)$ and $L_{min}(\lambda)$ respectively represent the maximum and minimum radiation brightness that the sensor can detect at the specific wavelength λ (μm). Those two values can be acquired from the image header files. Then based on the approximation formula of Plank's radiance in equation (2), spectral radiance was converted to surface brightness temperature with the assumption of uniform emissivity (Li et al., 2012).

$$T_s = C_2 / \ln\left[C_1 / L(\lambda) + 1\right] \quad (2)$$

where Ts (K) represents the effective at-sensor brightness temperature in K for TM band 6. C_1 and C_2 are pre-launch calibration constants for the purpose of optimizing the approximation. For Landsat TM, C_1 = 607.76 $W*m^{-2}*sr^{-1}*\mu m^{-1}$ and C_2 = 1260.56 $W*m^{-2}*sr^{-1}*\mu m^{-1}$ while for Landsat ETM+ C_1 = 666.09 $W*m^{-2}*sr^{-1}*\mu m^{-1}$ and C_2= 1282.71 $W*m^{-2}*sr^{-1}*\mu m^{-1}$ (Landsat Project Science Office, 2013). Then the surface brightness temperature was deducted by 273.5 to be in the unit of Celsius. Since we did not account for the emissivity in this study, the Landsat TM derived LST for all the analysis was the brightness temperatures.

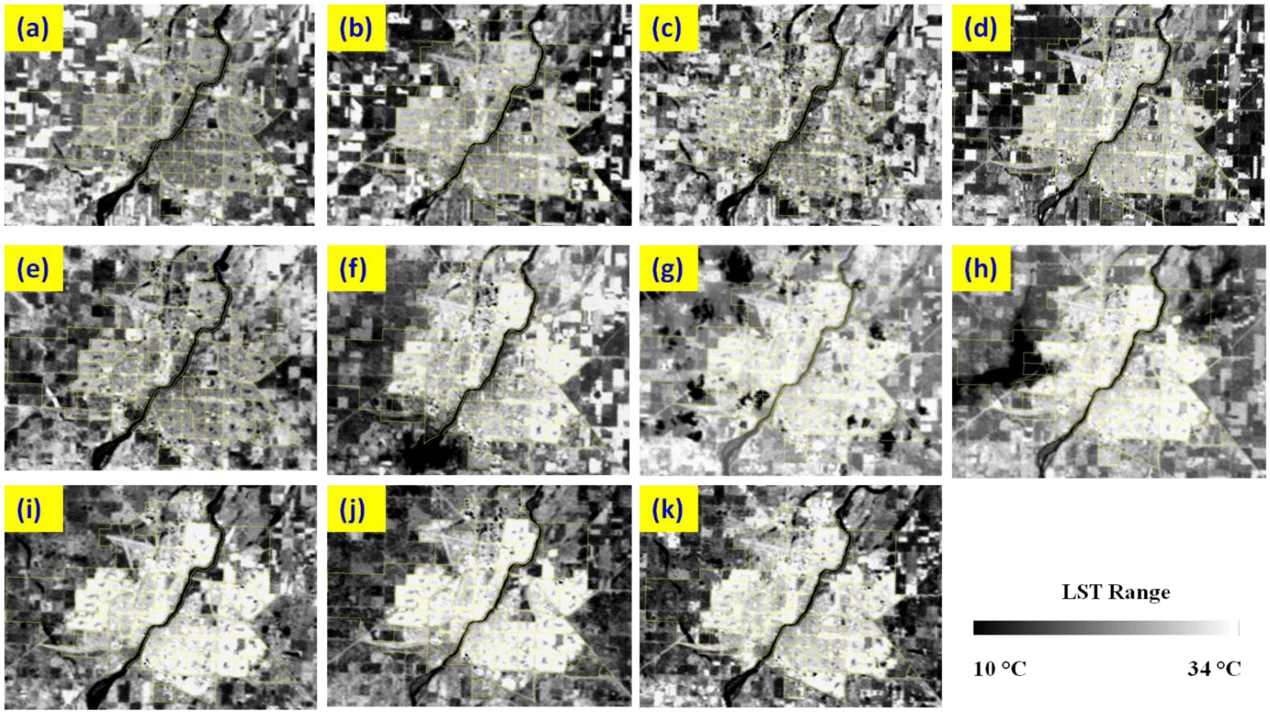


Figure 5.3 Multi-temporal Landsat derived daily land surface brightness temperatures for the city of Saskatoon from Year 1991 to 2011. (a) Aug.9, 1991; (b) Jul.23, 1994; (c) Sep.2, 1994; (d) Jul.29, 1999; (e) Aug.10, 2003; (f) Aug.28, 2004; (g) Jul.14, 2005; (h) Apr.28, 2006; (i) Jun.29, 2011; (j) Jul.15, 2011; (k) Jul.31, 2011.

5.4.4 Regression analysis between air temperature and LST

To investigate the capability of different satellite imagery in estimating daily urban air temperature, the historical *in situ* air temperatures collected by three Saskatoon weather stations were respectively regressed with LST derived from Landsat TM and MODIS LST data. Since there was only 1 Landsat ETM+ image available during the study period, it will contribute little to the result based on the TM data alone. We merely conducted this comparison analysis between Landsat TM and MODIS daily data. We obtained 15 field measurements available to match with the TM imagery from 1991 to 2011, and 12 points for MODIS daily LST (from 2003 to 2011). Since UHI effects become more prominent in summer (Weng et al., 2004; Rouse et al., 1974), the regression analysis was also performed between urban monthly average air temperature and the MODIS monthly LST during the summer months (June, July, and August) to identify if coarse resolution imagery can characterize long-term average urban air temperature.

The pre-processing of the datasets showed that all the data were tested to be in normal distribution so no log-normal transformation was necessary. The adjusted coefficients of determination (R^2) were used to validate the model because it is based on an optimization algorithm (the Jackknife method) to limit the overestimation and absolute difference between the dependent variable and predicators (Liao and McGee, 2003; Benali et al., 2012). It is particularly applicable for small sample size due to the remaining data with one point withheld for each time. The whole procedure is repeatedly performed until each sample point has been removed once (Zhang et al., 2008). All the statistical analysis was implemented using SPSS 16.0 software.

5.4.5 Buffer analysis for the impacts of the Saskatchewan River and green space on SLST

To quantitatively explore the mitigation impacts of the Saskatchewan River and urban green spaces on surrounding LST at different spatial scales, we conducted buffer analysis using ArcGIS 10.1 software. Buffer analysis was purposed to characterize the specific areas at different distances from the vector features. In this study, the Saskatchewan River and urban green spaces were all represented by vector features provided by the City of Saskatoon. The buffer distances from the center of the Saskatchewan River were 100 m, 200 m, 500 m, 1000 m, and 2000 m (Figure 5.4) while those from the center of each green space polygon were 50 m, 100 m, 200 m and 500 m (Figure 5.5). To simplify the analysis and limit the season change influence, we normalized the surface brightness temperature to standard land surface temperature (SLST) based on the formula as follows:

$$SLST = \frac{T_{si} - T_{smin}}{T_{smax} - T_{smin}} \quad (3)$$

where T_{si} is the ith-pixel surface brightness temperature. T_{smin} represents the minimum surface brightness temperature in the study area while T_{smax} is the maximum surface brightness temperature. *SLST* ranges from 0 to 1. We calculated multi-temporal averaged *SLST* and its standard deviation (SD) within each buffer zone for both the Saskatchewan River and urban green spaces.

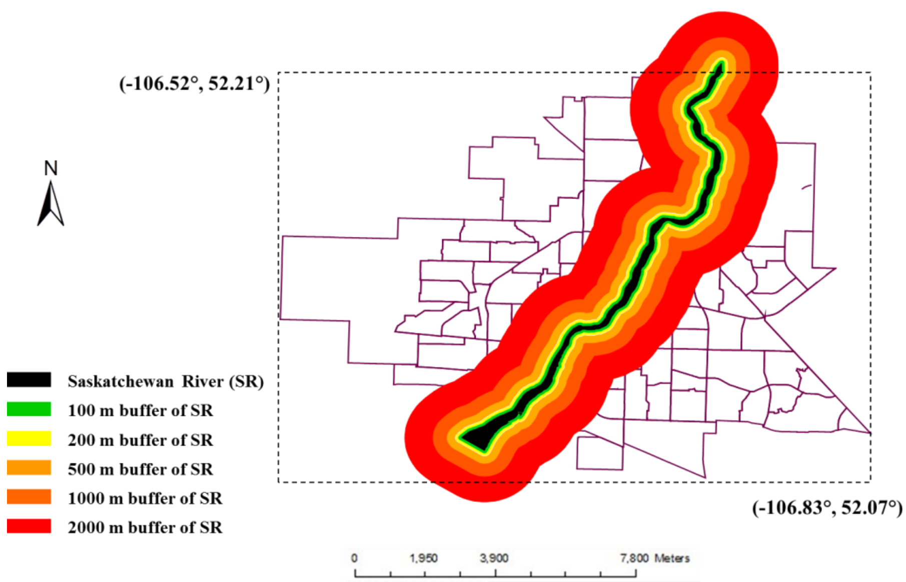


Figure 5.4 Buffer zones of the Saskatchewan River at 100 m, 200 m, 500 m, 1000 m, and 2000 m for urban *SLST* impact analysis.

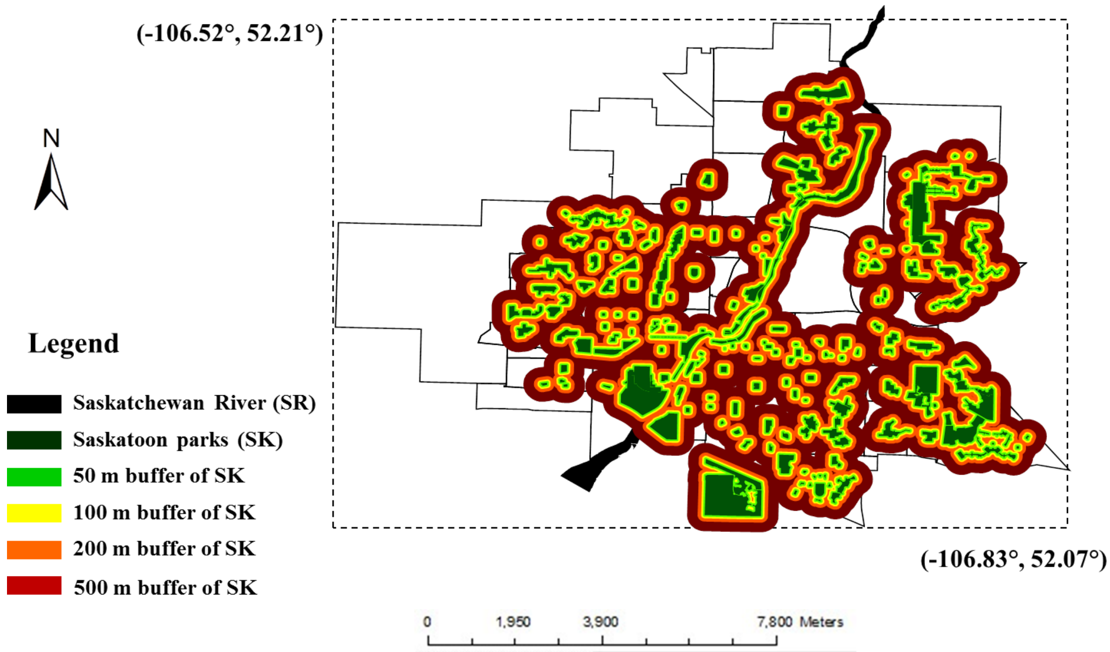


Figure 5.5 Buffer zones of Saskatoon green spaces at 50 m, 100 m, 200 m, and 500 m for urban *SLST* impact analysis.

5.4.6 Multiple linear regressions between LST and its relevant influential factors

To investigate the anthropogenic effect from human activities on urban temperatures, we analyzed the relationship between SLST and its relevant influential factors including green space percentage, impervious surface percentage, water percentage, and sustainable traveling index for the 64 residential neighborhoods in Saskatoon. The land use land cover information can be extracted based on satellite image classification to serve as effective input data for diverse urban applications (Zhu et al., 2012). Sustainable traveling index can be defined as the percentage of people that choose walking, bicycle, and public transit as their traveling modes for each neighborhood. Since such census information was provided by the city council based on the survey data in the year 2006. We applied Neural Net classification approach to the Landsat TM image obtained on April 28, 2006 using ENVI 4.6 software. The classification result produced an overall accuracy of 94.79 % and Kappa coefficient of 0.93 which can satisfy the requirement of input data. After a standardization process as SLST for all variables, then we conducted statistically dependence analysis for those four independent variables (green space percentage, impervious surface percentage, water percentage, and sustainable traveling index) and found they were significantly uncorrelated. The model summary based on stepwise multiple linear regression is present in Table 5.4.

5.5 RESULTS AND DISCUSSION

5.5.1 Comparison of Landsat and MODIS data in temporally estimating daily air temperature

Our linear regression analysis between historical daily air temperatures and image derived LST yielded a good fit line with the adjusted R^2 of 0.803 for Landsat TM data in Figure 5.6 (a). In comparison with the moderate resolution observation, MODIS daily LST product showed slightly weaker capability in estimating urban daily air temperature but still a significant relationship with an adjusted R^2 of 0.518 in Figure 5.6 (b). In other words, for 60 m spatial scale approximate 80% of the variation in urban air temperatures can be attributed to the corresponding variation in LST while for 1000 m spatial scale LST can explain 50% of the variation in urban air temperature. Those results further prove that Landsat TM data possibly has greater potential in estimating daily air temperatures for urban areas in comparison with MODIS daily LST data. Daily urban air temperature is more strongly correlated with LST at a moderate spatial scale of 120 m than at a coarse spatial scale over 1000 m. This result can be explained by the huge discrepancy in the pixel cell (1000 m) of MODIS LST data and the several squared meters for actual air temperature measurements. Substantial surface information could be missed by the averaging observation within a 1000-meter instantaneous field of view. As Kustas and Norman (2000) suggested, Landsat imagery can be used as effective ancillary information to validate and extract subpixel variability of low-resolution data.

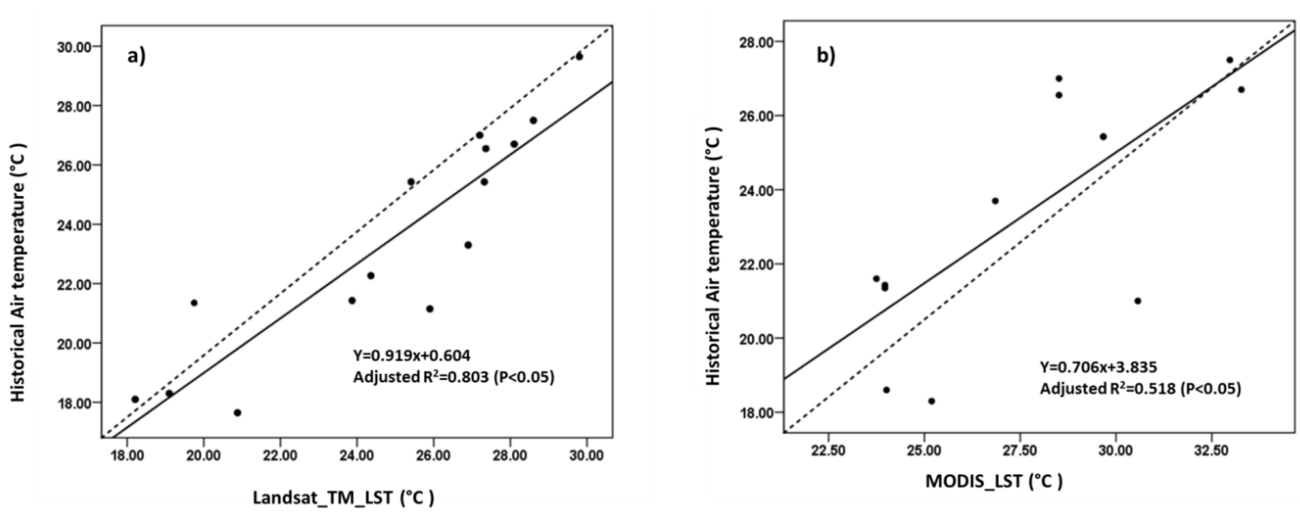


Figure 5.6 Comparison of different satellite data in temporally estimating daily urban air temperatures based on linear regression models between imagery derived LST and field measured air temperatures for the city of Saskatoon from 1991 to 2011. a) Daily urban air temperature and 120 m Landsat TM derived LST based on 15 points, b) Daily urban air temperature and 1000 m MODIS daily LST based on 12 points.

5.5.2 Interpretation of in situ Saskatoon monthly air temperatures in summer

Based on the historical meteorological data provided by the three Saskatoon weather stations, we graphed the trend line of the monthly average air temperature for the city of Saskatoon from 1991 to 2007. Figure 5.7 shows the monthly air temperature increases from below zero in January to above zero approximately in middle March. The air temperature continues rising to a peak value in July or August then drops down to below zero in middle October. The negative air temperature persists until the following year in middle of March. From Figure 5.7, we can also identify December and January as the coldest months with air temperature ranging nearly from -

20 ℃ to -25 ℃ in Saskatoon. This is possibly driven by the declined energy budget as the sun angle and period of day-light decline. According to the description of Köppen climate classification system (Köppen, 1936; Peel et al., 2007), the city of Saskatoon is clearly characterized as a typical *Dfb* climate category in the Northern hemisphere with the average air temperature in the coldest month below -3 ℃ and in the warmest month above 10 ℃. Distinct seasonal variation occur in spring (March to May), summer (June to August), autumn (September to November), and winter (December to January). In addition, the earth revolution, planet's axial tilt, cloud effect, and geographic coordinates also contribute to the annual cycle of air temperature in Saskatoon (Strahler and Archibold, 2011).

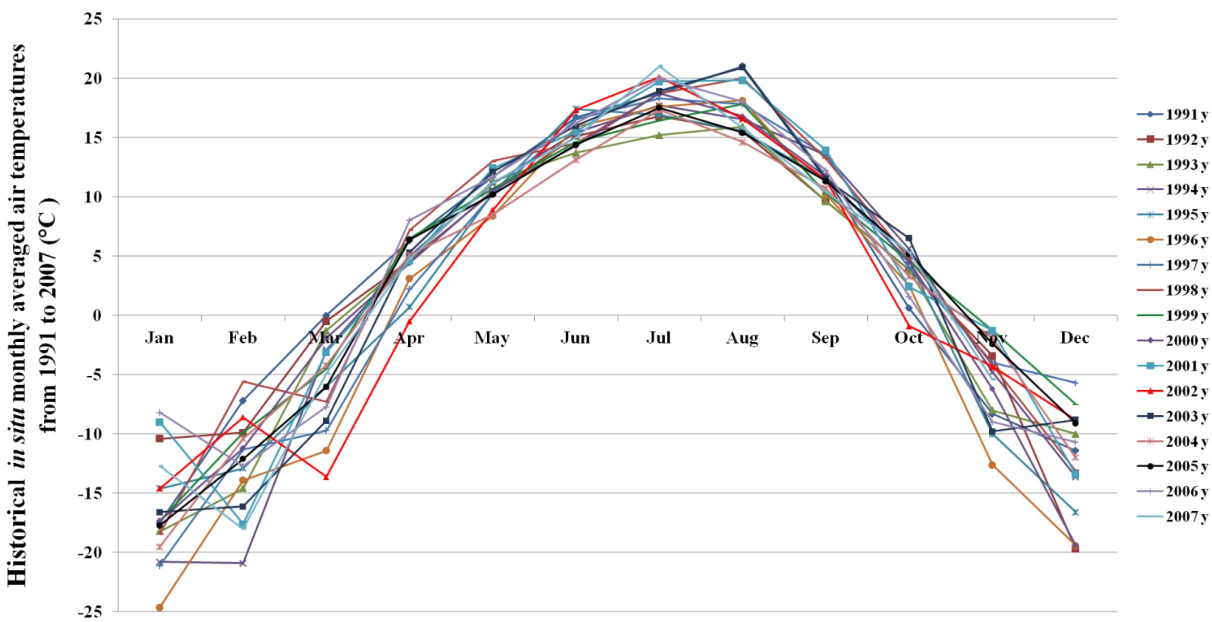


Figure 5.7 Average monthly air temperatures for the city of Saskatoon from year 1991 to 2008 (Environment Canada, 2013).

5.5.3 Estimation of summer monthly air temperature using MODIS monthly data

A comparison analysis of the *in situ* monthly air temperature and MODIS derived monthly LST were conducted for summer (June, July, and August) from 2000 to 2007. This is because MODIS monthly LST started to be accessed in 2000 and the available *in situ* monthly air temperature can only be tracked to 2007. The linear regression results in Figure 5.8 demonstrate a close relationship existing between them in summer for the city of Saskatoon. An average of 80% of variation in monthly air temperature can be significantly explained by the monthly LST at a spatial scale of 5600 m for the three summer months. The best fit with highest adjusted R^2 was obtained for the warmest month July in Saskatoon based on those 8-year data. It also suggests that the 5600 m MODIS LST data can provide good estimates of summer monthly air temperature in urban area at 5 % significance level. Such high agreements between *in situ* air temperature and satellite LST data have great relevance for studying urban climate change at large spatiotemporal scales.

Figure 5.9 shows two similar overall trends of the *in situ* monthly air temperature and MODIS derived monthly LST attributed to their close relationship based on heat transferring. However, surface temperature differs from air temperature in numeric values at different times during a day, which can be explained by the 24-hour cycle of net radiation distinct in the daytime and nighttime. In the daytime, surface temperature experiences a rapid increase due to the rising insolation and positive net radiation, showing a higher numerical value. Conversely, in the late afternoon and evening poor insolation and constant outgoing radiation lead to a negative net radiation. As a primary energy source for the air, the ground surface transfers heat to the upper air and the extreme surface temperature is mitigated quickly. In addition, the movement of convection currents in the early afternoon also contributes to the reduction of surface temperature by raising warm air and pushing down cooler air. In comparison to the LST, air temperature has a smaller range of diurnal variation. The average monthly air temperature and LST in Figure 5.9 were obtained approximately at noon, in consistent with the diurnal characteristics of urban temperatures.

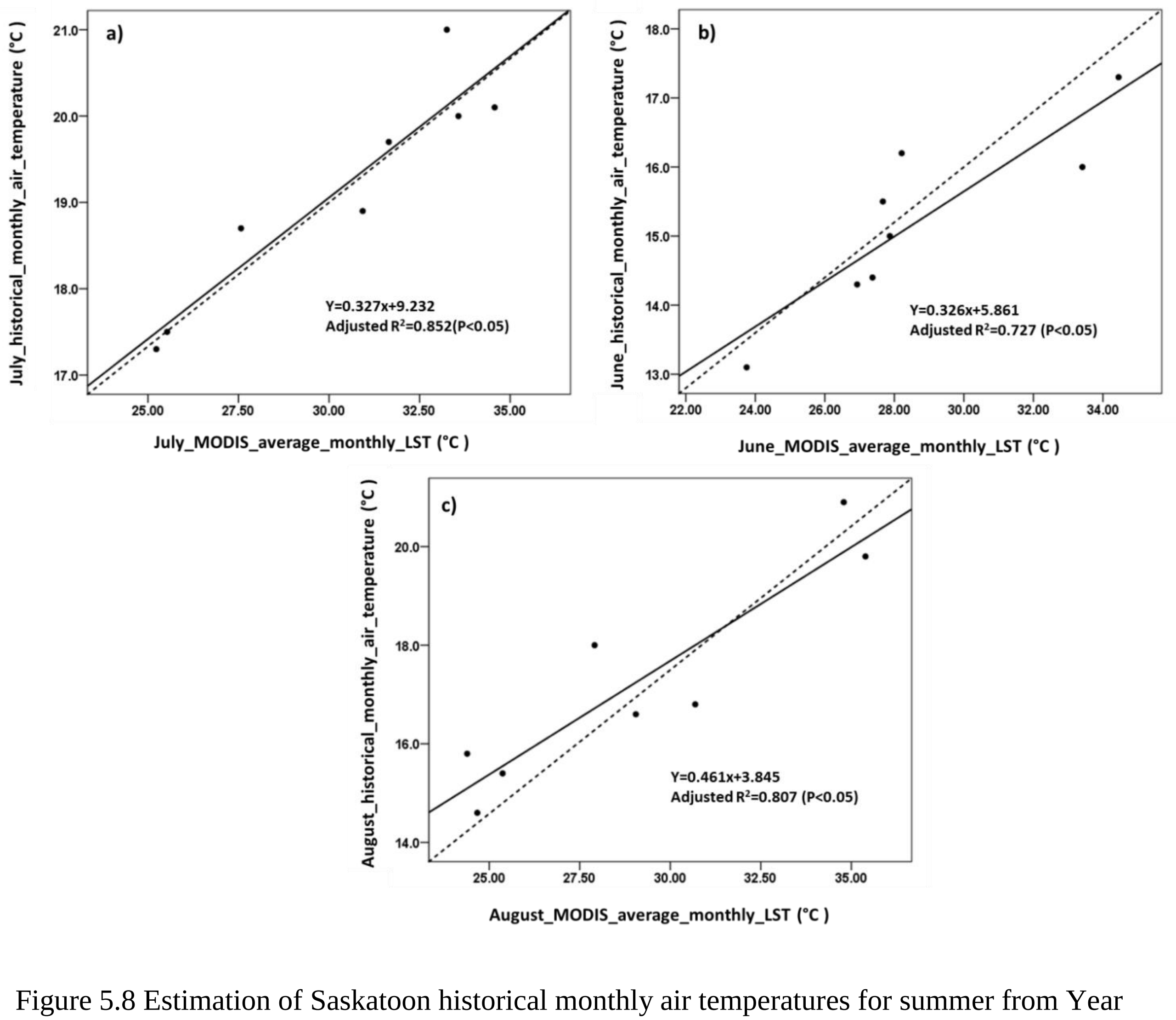


Figure 5.8 Estimation of Saskatoon historical monthly air temperatures for summer from Year 2000 to 2007 using MODIS monthly LST data. (a) June. (b) July. (c) August.

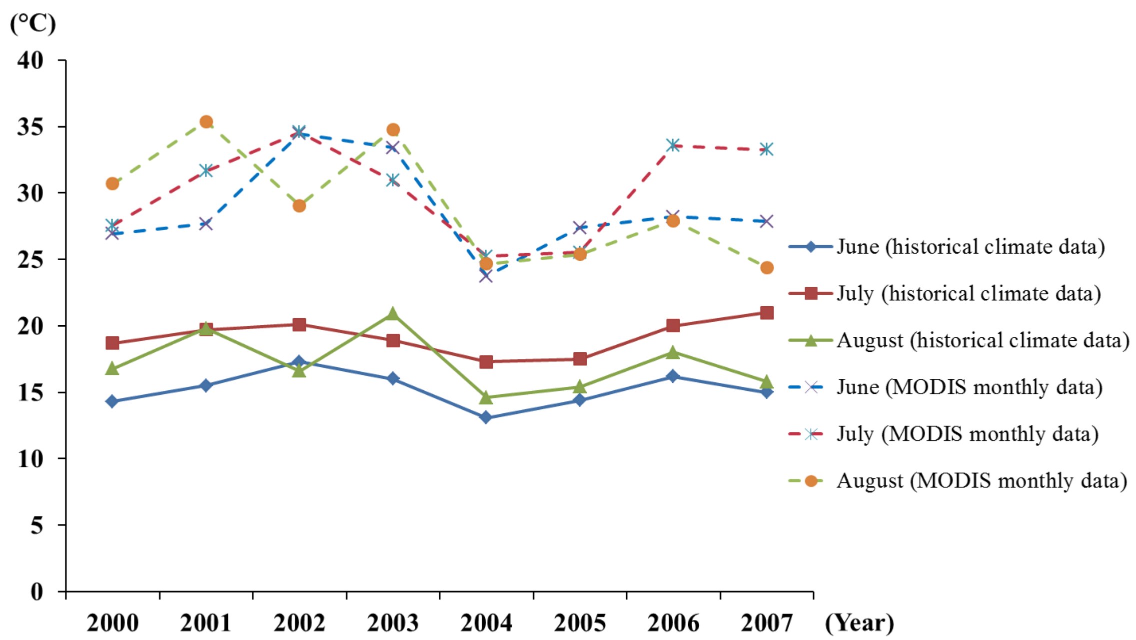


Figure 5.9 Comparison of historical climate data (average monthly air temperature) and MODIS monthly LST in the city of Saskatoon for summer (June, July, and August) from Year 2000 to 2007.

5.5.4 The impacts of Saskatchewan River and urban green spaces on surrounding LST

The buffer analysis of the Saskatchewan River (Figure 5.10, 5.11) demonstrate that the averaged surface brightness temperature rises more dramatically within 500 m radius of the river center line in comparison to that beyond 500 m. The standard deviation also indicates a significant threshold of 500 m where the influence of the Saskatchewan River on the surrounding surface temperature changes. Within 500 m, an increasing standard deviation shows a growing variation in the averaged surface brightness temperature with the surrounding region more distant from the river center. This suggests that the mitigation impact of the Saskatchewan River on the adjacent surface temperature declines as the geographic zone becomes further away. Beyond 500 m of the river it is possible that the high radiation rate of underlying surface plays a leading role in affecting the surface temperature with less influence from the water body. Similarly, based on Figure 5.12 and 5.13, we can conclude that urban green spaces perform the cooling effect on the surrounding surface temperatures of Saskatoon within an approximate range of 200 m. However, so far the interactive cooling effect between the river and green spaces on the surrounding LST is still difficult to be clearly understood.

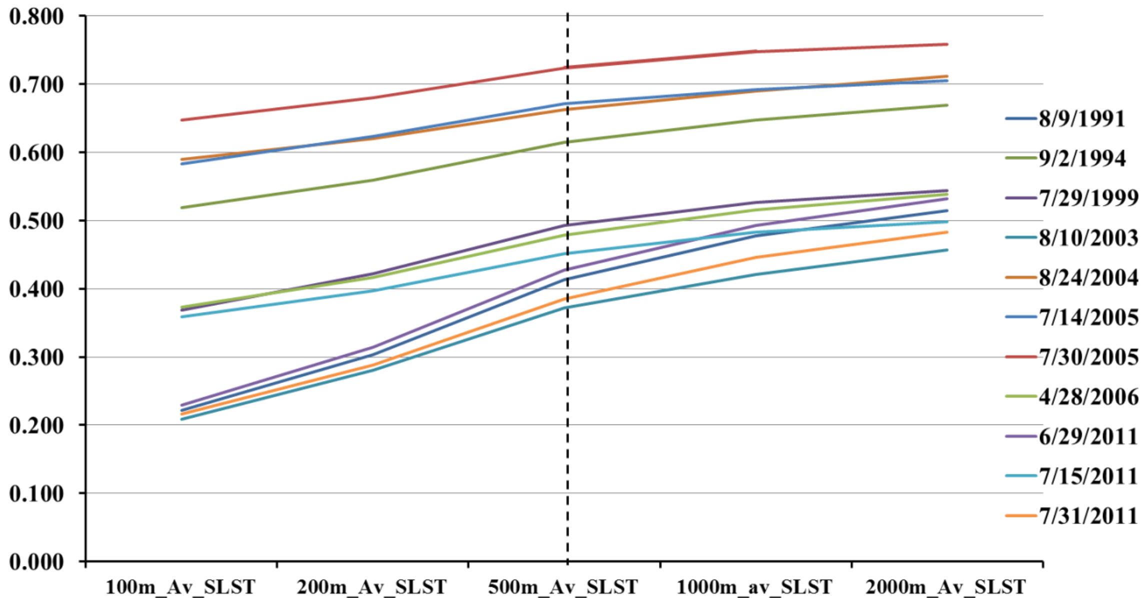


Figure 5.10 Buffer analysis of averaged standardized land surface temperature (SLST) within 100 m, 200 m, 500 m, 1000 m, and 2000 m from the Saskatchewan River.

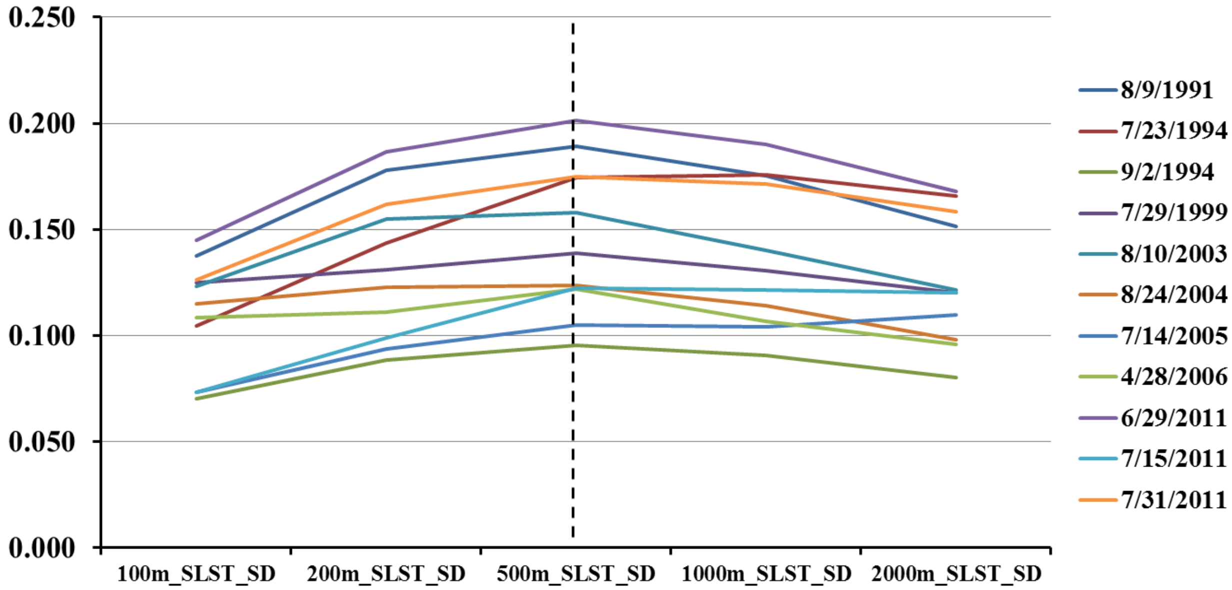


Figure 5.11 Buffer analysis of standard deviation (SD) of the standardized land surface temperature (SLST) within 100 m, 200 m, 500 m, 1000 m, and 2000 m from the Saskatchewan River.

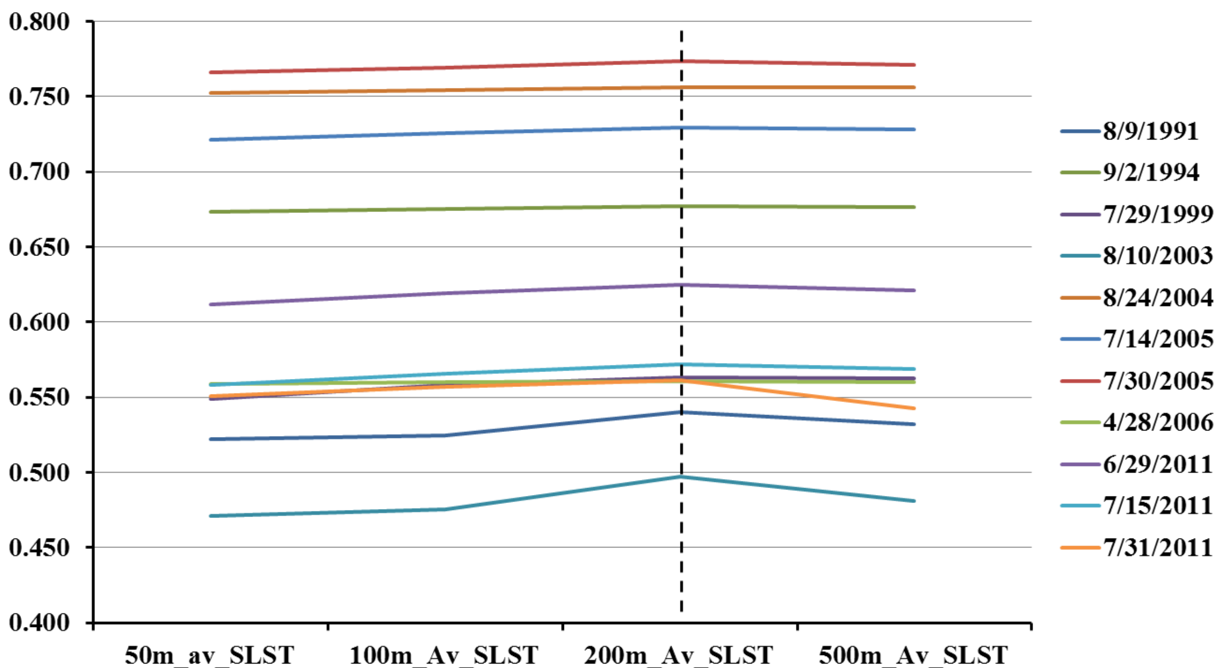


Figure 5.12 Buffer analysis of averaged standardized land surface temperature (SLST) within 50 m, 100 m, 200 m, and 500 m from the urban green spaces.

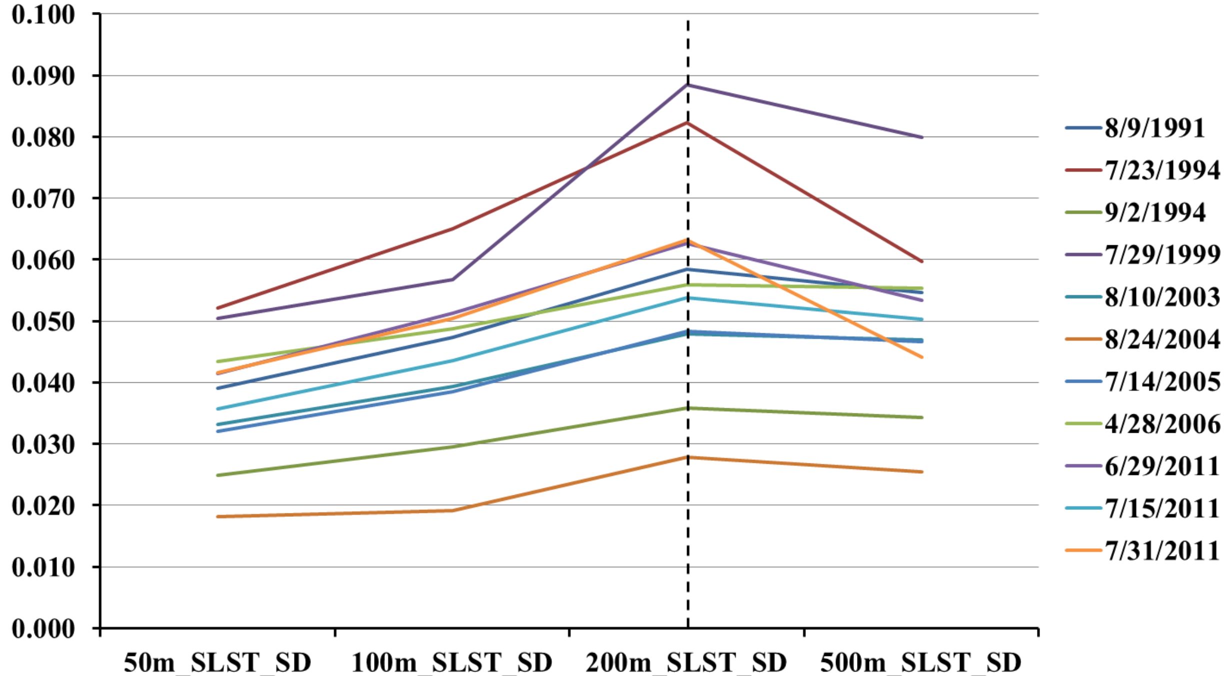


Figure 5.13 Buffer analysis of standard deviation (SD) of the standardized land surface temperature (SLST) within 50 m, 100 m, 200 m, and 500 m from the urban green spaces.

5.5.5 Relevant influential factors of urban LST

The multiple linear regression analysis helps determine whether the four relevant variables can statistically contribute to the variation in the urban surface temperatures. Our results in Table 5.4 present four models based on stepwise methods significantly effective to explain the urban land surface temperature. Green space percentage, water percentage, and sustainable traveling are negatively correlated with SLST while impervious surface positively contributes to SLST. This conclusion is consistent with the reality that green space, water, and sustainable traveling modes can help mitigate urban temperatures while increasing impervious surface can cause the temperature to accelerate in urban areas. The residuals were examined to be in binomial distribution which indicates no reason to reject the fit of the models. The 4-variable model has the highest adjusted R^2 (0.694) in comparison to the other three models with less independent variables. The four variables in model 4 can account for approximate 69.4% of the variation in urban land surface temperature, followed by model 3, 2, 1 respectively with 66.1%, 63.4%, and 50.6%. All of the models should be further tested into other datasets for mapping the standard land surface temperatures when census data and land cover land use information are available.

Table 5.4 Summary of the stepwise multiple linear regression model between standard land surface temperature (SLST) and its relevant factors green space percentage (ST_GP), water percentage (ST_WS), impervious surface percentage (ST_IP), and sustainable traveling index(ST_STI).

Models	**Sig. for the model**	**Sig. for variables**	**Adjusted R^2**	**Std. error of the estimate**
SLST= - 0.441 *ST_GP* + 0.893	0.000	Constant (0.000) *ST_GP* (0.000)	0.506	0.097
SLST = - 0.415 *ST_GP* + 0.228 *ST_IP* + 0.802	0.000	Constant (0.000) *ST_GP* (0.000) *ST_IP* (0.000)	0.634	0.083
SLST = - 0.397 *ST_GP* + 0.215 *ST_IP – 0.146 ST_STI* + 0.828	0.000	Constant (0.000) *ST_GP* (0.000) *ST_IP* (0.000)	0.661	0.080
SLST = - 0.331 *ST_GP* + 0.227 *ST_IP – 0.170 ST_STI – 0.223 ST_WS* + 0.826	0.000	Constant (0.000) *ST_GP* (0.000) *ST_IP* (0.000) *ST_STI* (0.006)	0.694	0.076

5.6 UNCERTAINTIES AND OPPORTUNITIES

As a preliminary research, several limitations and uncertainties are of concern in our study. First, the materials of urban surface are not perfect blackbodies with a range of emissivity from 0 to 1; we approximated those land covers to ideal blackbodies. This may result in underestimating the surface leaving radiance and overestimating the atmospheric path radiance. Even for specific material, its emissivity might also vary in different atmospheric conditions (Li et al., 2004). Therefore, the existing approaches in retrieving land surface temperature from satellite data need to be improved through transferring the brightness temperature to surface radiant temperature using accurate surface emissivity and a validated radiative transfer model. There are still many opportunities to develop empirical or physical algorithms for quantification of parameters based on experimental measurements.

Other limiting factors may include data quality and completeness either for *in situ* measurements or satellite observations. The data availability for our study was merely based on limited satellite scenes which need to be enlarged by applying downscaling techniques. The historical air temperatures along with other climate data (precipitation, humidity, wind speed, wind direction, atmospheric pressure, and visibility) collected by Saskatoon weather stations can hardly guarantee a precise description of the environmental condition beyond a limited adjacency of the observation stations. In addition, although the satellite imagery used in this study was obtained with minimized cloud effect, the residual cloud cover might still weaken the insolation dramatically. Therefore, LST retrieved from such satellite imagery correspondingly suffers from the uncertainties in further data preprocessing and calculation (Benali et al., 2012; Jacobson, 2000).

Third, this study shows the potential in comparing multi-temporal Landsat and MODIS data for characterizing urban temperatures in semi-arid cities (e.g., Saskatoon) at higher latitudes. However, the investigation of urban temperatures in other areas should take into account the influence imposed by latitudes, topography features (mountainous, coastal, or plain regions), and surface conditions at various spatial scales.

In addition, land surface temperature is not only influenced by biophysical features such as water and vegetation, but also highly impacted by human activities. This research conducted limited discussion on the anthropogenic effects merely from land use land cover and travelling mode perspectives. However, more anthropogenic influential factors (demographic characteristics, economic development, and energy consumption) are supposed to be also involved to provide a more complete understanding of the urban temperature mechanism.

5.7 CONCLUSIONS

The results in our study indicate that it is possible to spatiotemporally characterize urban temperatures based on multi-temporal satellite thermal information and corresponding *in situ* measurements. Both Landsat TM and MODIS LST data can yield pronounced estimation of daily air temperature respectively at the spatial scales of 120 m and 1000 m with significant adjusted R^2 of 0.803 and 0.518.

In addition, the 5600 m MODIS monthly LST data is highly suitable for monitoring the trend of urban monthly air temperature in summer (June, July, and August) due to its good agreement with the *in situ* observation based on an averaged R^2 of 80% ($P<0.05$), which is especially for the warmest month July. The Landsat moderate satellite imagery can provide more spatial details while the low-resolution MODIS LST data can be used in temporally continuous monitoring for routine record.

For the spatial impacts on urban surface temperatures from biophysical and anthropogenic aspects, the findings revealed that both the Saskatchewan River and green spaces have significant cooling effects on the surrounding urban LST within 500 m and 200 m respectively. Beyond those thresholds, it is possible that the high radiation rate of underlying surface plays a leading role in affecting the surface temperature. In addition, increasing green space percentage, water space percentage, and sustainable travelling modes can help mitigate urban temperatures while escalating impervious surface can cause heating up and even the formation of UHIs. A multiple linear regression model based on those four variables can be used to estimate urban surface temperature based on census and imagery derived information with a highest adjusted R^2 of 0.649 and a lowest standard error of 0.076.

In summary, our research draws together both satellite and ground evidence to prove the potential of different satellite thermal data in spatiotemporally characterising urban temperatures. For suggestions to prevent and alleviate UHI in Saskatoon, it is necessary to protect the Saskatchewan River and urban green spaces, to encourage sustainable travelling modes and meantime restrict impervious surface sprawl (e.g., parking lots). In regions beyond 200 m of the green spaces and 500 m of the Saskatchewan River, available cooling strategies are highly recommended. However, how to take different advantages of multi-source imagery based on fusion techniques has great implications for a better understanding of the urban temperature mechanisms in future studies.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Since increasing urbanization problems (Holden, 2008; Keivani, 2009; Pearsall & Pierce, 2010; Birch, 2011) have markedly impacted urban residents' quality of life and the overall urban sustainability, urban sustainability measurement and evaluation have gained increasing popularity amongst governments, urban planners, scientific communities, and the general public all over the world (Tsenkova, 2005; Tamagawa, 2006; Nijkamp and Perrels, 2009; Huang et al., 2009; Sanders, 2010; Slavin, 2011). Numerous urban sustainability indicator models have been established to monitor urban sustainability and provide both quantitative and qualitative assessments of the development either towards or away from sustainability goals (Keirstead and Leach, 2008; Mascarenhas et al., 2010; Mori and Chirstodoulou, 2011). However, these USI models require a higher integration of urban domains to provide a comprehensive interpretation of urban sustainability (Walton et al., 2005; Li and Huang, 2007). Both "a synthetic value" and "specific indices" are required to quantify urban sustainability at multiple aggregated levels for serving different audiences (Gosselin et al., 1991; Kondyli, 2010; Tanguay et al., 2010). In addition, as principal participants in urban activities, urban residents with their living experience and perspectives can greatly impact and be impacted by the urban development. Most existing USI models are highly dependent on objective census data and generally lack an interpretation of urban sustainability from subjective (peoples' feelings and sense) perspectives (Li and Weng, 2007; Ojala, 2013). Furthermore, it is found that current urban sustainability research paid limited attention to explore the spatiotemporal characteristics of urban sustainability patterns with the aid of geomatic approaches (Sutton, 2003; Wu and Wu, 2012; Shen et al., 2013). This study attempted to address all the aforementioned research problems and has made some contributions to the existing studies.

Chapter 1 provided a research context to present the research question, objectives, and the thesis structure. Chapter 2 and 3 discussed the characteristics of good indicators for applicable urban sustainability assessment and established an integrated USI framework model with a hierarchical index system. This model realized a higher integration of urban domains by combining both objective development status and subjective well-being. The hierarchical index system can quantify urban sustainability with both synthetic and specific index values at three aggregated levels for different audiences (e.g., the general public, the administrators, and the academic community). In Chapter 4 a case study in the City of Saskatoon (SK, Canada) was conducted to prove the feasibility and practicability of the USI framework model proposed in Chapter 3. A geodatabased was established based on GIS platform and some indicator measurements were derived from remote sensing data. Further spatial classification and pattern analysis demonstrated the capability of geomatic approaches in extending and advancing urban sustainability research to a spatiotemporal perspective. Chapter 5 furthermore spatiotemporally characterized urban temperatures and relevant influential factors for urban environmental consideration. In a word, the results show that it is feasible to develop an integrated urban sustainability indicator model by combining both subjective and objective information based on a hierarchical index system using geomatic approaches for applicable urban sustainability measurement.

6.1 CONCLUSIONS

6.1.1 Development of an integrated USI conceptual model

The proposed integrated USI model has improved urban sustainability measurement by overcoming the shortages found in most of the existing USI models. First, it is capable of quantitatively integrating relevant domains for a comprehensive understanding of urban sustainability using a hierarchical index system. Second, it incorporates subjective information into objective data based on multiple data compiling to improve urban sustainability evaluation. Third, this is a spatiotemporally characterized model that allows for comparison analysis at different spatiotemporal scales.

6.1.2 Application of the proposed USI model in the case study of Saskatoon

The subjectively weighted USI model was tested in the city of Saskatoon as a case study based on quantification of the hierarchical urban sustainability index system. The descriptive statistics and spatial classifications demonstrated that there was evident disparity in urban sustainability status across the 60 residential neighbourhoods for Saskatoon in 2006. The gap spatially existed in the west and east sides of the city, particularly higher in the southeast suburban areas and lower in the center-west of the inner city. It was lies in the fact that 97% of the total neighbourhoods had a relatively low *Urban Sustainability Index* below 0.6 whereas the rest 3% neighbourhoods in suburban areas with a much higher value over 0.8. Another reason can be attributed to the sharp distinctions among neighbourhoods in respect to environmental and material well-beings as well as their greater subjective weights in the calculation of the overall *Urban Sustainability Index.* The global and local autocorrelation analysis found that eight of the ten urban sustainability indices (*Environmental Index, Socio-political Index, House Index, Household Index, Mixed land use Index, QOL Index, Urbanization Index*, and *Urban sustainability Index*) have statistically clustered patterns in the inner-city neighbourhoods and the suburban areas. Montgomery Place was identified as a neighbourhood with high sustainability index surrounded by neighbourhoods with a low sustainability index while Nutana SC was detected as neighbourhood with a low sustainability index but surrounded by neighbourhoods with a high sustainability index. In addition, the research also shows that population increase can possibly improve the intellectual and economic well-beings as well as promote urbanization progress. However, it may cause environmental degradation and lead to a decline in the overall urban sustainability.

6.1.3 Spatiotemporal investigation of urban environmental sustainability

Urban environmental sustainability was spatiotemporally characterized based on multi-temporal satellite thermal data and corresponding in situ measurements. Results indicated that both Landsat TM and MODIS LST data can yield pronounced estimation of daily air temperature respectively at the spatial scales of 120 m and 1000 m with significant adjusted R2 of 0.803 and 0.518. 5600 m MODIS monthly LST data is highly suitable for monitoring the trend of urban monthly air temperature in summer (June, July, and August) due to its good agreement with the *in situ* observations based on an averaged R^2 of 80% ($P<0.05$), especially for the warmest month July. For the spatial impacts on urban surface temperatures from biophysical and anthropogenic aspects, both the Saskatchewan River and green spaces have significant cooling effects on the surrounding urban LST within 500 m and 200 m respectively. Beyond those thresholds, it is possible that the high radiation rate of underlying surface plays a leading role in affecting the surface temperature. In addition, increasing green space percentage, water space percentage, and sustainable travelling modes can help mitigate urban temperatures while escalating impervious surface can cause the formation of UHIs. A multiple linear regression model with those four variables as independent variables can be used to estimate urban surface temperatures with a highest adjusted R^2 of 0.649 and a lowest standard error of 0.076.

6.2 OVERALL CONTRIBUTIONS

As an interdisciplinary research, this study has well addressed some research gaps identified in existing literature and made several contributions to diverse groups of interest in urban sustainability monitoring and evaluation from both scientific and practical perspectives.

First, it proposed an integrated USI model by broadening the interpretation of urban sustainability through incorporating subjective well-being to the traditional triple bottle line domains (environment, economy, and society). The inclusiveness of this model can improve our understanding of urban sustainability in a comprehensive perspective. The hierarchical system with ten urban sustainability indices can provide not only a “synthetic value” but also multiple “specific indices” at three aggregated levels for different stakeholders to capture both the whole picture and the specific status of an urban system. The level 1 index can be identified as a highly composite urban sustainability indictor while level 2 and level 3 indices are moderately and slightly composite indicators respectively. A hierarchical index system serves as an effective way to quantify urban sustainability due to the reduction of complexity and coverage of information content. This is the research opportunities pointed by most urban sustainability literature (Gosselin et al., 1991; Maclaren, 1996; Li and Weng, 2007; Mori and Christodoulou, 2011).

Second, it is relatively original and significant with respect to improving urban sustainability measurements based on compiling and integrating multiple data sources into one dataset. Not only is the traditional census data included but also surveyed data (people's subjective rankings for their quality of life) as well as spatial data (satellite imagery derived information and vector data) are used. This methodology realized the incorporation of subjective well-being into the objective measurements to reflect public participation in the priority identification, goal setting, and policy making, which further help promote democracy and balanced interest of multiple stakeholders including governments, grassroots groups, and the academic communities.

Last but not least, this study considerably explores the capability and potential of advanced geomatic approaches in investigating urban sustainably especially the urban environmental aspect. The spatial patterns of urban sustainability indices can be visually detected in both qualitative (spatial classifications) and quantitative (global and local autocorrelation analysis) ways. Different types of patterns (clusters, random distribution, and dispersed patterns) can be identified to reflect the spatial disparity for the administrators and urban planners to capture the very direction in future policy formulation and implementation to ensure intra urban equity base on spatially balanced development. The temporally tracking urban sustainability can be found in the research work to investigate urban environmental conditions for objective 3. The time series change of urban temperatures can be estimated based on different satellite imagery at different spatial scales. Also the influential factors of urban surface temperatures has been statistically discussed to help better understanding urban heat island effect and mitigate it. This research also provides the possibility to continue with the similar research in next five or ten years for time series analysis of urban sustainability in the city of Saskatoon if the data is available. In this regard, this research can be a good practice of following the important philosophy of urban geography—spatial and temporal analysis.

Potential advantages of this research can be also found beyond the academic community. It has practical values in urban planning, city development, public polices, and environmental impact assessment. Based on the mapped urban sustainability indices at different aggregated levels for relevant dimensions, multiple stakeholders can obtain acknowledgement of urban sustainable development according to their own interpretation requirements. The general public need the highest aggregated index for an easy understanding of the overall urban sustainability. The governments and administrators may require moderate aggregated indices of the main sustainability domains to formulate and implement urban sustainability planning and initiatives. The academic communities can access the most specific indices for further data processing and model improvement. Also, the spatiotemporal trends of urban sustainability provided by such research can be used as a useful tool for effective communication in community participation processes such as establishing voluntary networks and civic forums. The public participation will further facilitate forming feedback mechanism to decision making and to provide guidance for both urban residents and administrators in good sustainability practice.

6.3 LIMITATIONS AND SUGGESTIONS

As a preliminary study, this research also suffers from several unavoidable limitations that need to be addressed in future endeavour.

1) Urban sustainability is a very broad topic which involves a wide range of aspects, such as biodiversity, energy use, water consumption, air pollution, noise level, mental health, etc. Cities have different priorities respecting urban sustainability. Indicators designed to measure a city's progress towards sustainability may not be appropriate for another city.
2) My proposed USI model covers the most fundamental domains of urban sustainability (social, economic, environmental, and human well-being). It is impossible to include all existing aspects of urban sustainability because of data availability, time to collect data, and also intensive labour work involved. However, this USI model performs more as an open framework which can be adapted to different urban contexts.
3) Conflicts cannot be completely avoided in this research when it comes to select indicators for the integrated USI model. There exists trade-offs between the indicators that possibly affect the accuracy of urban sustainability measurement. For example, mixed land use increase is an indicator to promote sustainability by intensification but at the same time it may contribute to escalating land and housing prices which weakens sustainability. Therefore, those trade-offs need to be considered before establishing the final USI model for practical implementation.
4) The subjective information collected for this research is still insufficient to represent residents' real perceptions. This is because people in different neighbourhoods may have different rankings of the influential factors to their quality of life. It is possible that certain factors slightly affect one neighbourhood's QOL but highly impact residents' well-being in another neighbourhood. More specific social surveys should be conducted for each neighbourhood to obtain the neighbourhood-based subjective weights. Also, there is time gap between the subjective and objective data since the social surveys was conducted in 2013 but

the objective measurements were based on data in 2006. This concern should be paid careful attention to in the future because residents' perspectives can change over time.

5) Measuring QOL requires both objective and subjective indicators (Winston and Eastaway, 2008). In addition to use the subjective weights to improve the USI model in this study, it is necessary to directly develop subjective indicators or translate the objective indicators into subjective ones based on collecting perception data. For example, *feelings of belonging, trust, and safety, life satisfaction scale, happiness scale, and personal well-being.*

6) For future application of this proposed model, it is vital to reach public audiences (e.g., policy makers, planners, engineers, and even individual residents) for sharing information to increase the awareness of urban sustainability as well as linking policy-making with public participation as well as academic communities. Since the advantages of geomatic techniques used in the quantification of USI model, visual simulations or demonstrations can be effective strategies for vividly demonstrating the dynamic change of urban sustainability progress to the public.

7) Since both inter-generational equity and intra-generational equity are emphasized as the fundamental characteristics almost in all the definitions of urban sustainability, a spatiotemporal urban sustainability model would make a significant contribution towards understanding the dynamics of urban sustainability. Spatial detection can help characterize the distribution within a target geographic system for comparison analysis (e.g., neighbourhoods within a city, cities within a province, cities within a region, cities within a country, cities within the planet) while temporally tracking measurements can detect the dynamic change of sustainability over generations. My case study focuses on the spatial perspective due to the unavailability of objective census measurements and subjective

surveyed data over time. However, investigating urban sustainability from both the spatial and temporal perspective is a very promising direction for future endeavor in urban sustainability studies if there is no financial or data constraints.

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APPENDIX A

EVALUATION OF PRELIMINARY URBAN SUSTAINABILTIY INDICATORS FOR DEVELOPING AN URBAN SUSTAINABILITY INDICATOR MODEL FOR THE CITY OF SASKATOON

Urban sustainability domains	**Indicators measurements**		**Selection Criteria**					
			1	**2**	**3**	**4**	**5**	**6**
Urbanization Index	-Housing ownership percentage (# of owned houses / total number of houses)		x	x	x	x	x	x
	-Household index (# of non-family households/ total # of households)		x	x	x	x	x	x
	-Mixed land use index (standard deviation of different land use areas in neighbourhood)		x	x	x	x	x	
Quality of life	Economic well-being	Average family income (all annual income/ number of families)	x	x	x	x	x	
		-Housing affordability index (Under 1.0 represents relatively less affordable)	x	x	x	x	x	
		-Supermarket access (# of supermarkets of total neighbourhood area)	x	x	x	x		x
	Environmental well-being	-Percentage green space (vegetation area/ total neighbourhood area)	x	x	x	x	x	x
		-Percentage impervious surface (impervious area/ total neighbourhood area)	x	x	x	x	x	x
		-Water density (water area / total neighbourhood area)	x	x	x	x	x	x
		-Surface temperature (averaged surface temperature within each neighbourhood area)	x	x		x	x	
		-Sustainable traveling index (percentage of walking, bicycle, and public transit)	x	x	x	x	x	
	Social-political well-being	-Crime rate (number of crimes/ 1000 population)	x	x	x	x	x	x
		-Election turnout percentage (votes cast / eligible voters for civic, provincial, and federal elections)	x	x		x	x	x

Evaluation of preliminary urban sustainability indicators and their measurements for developing an urban sustainability model at the neighbourhood level (continued)

Urban sustainability domains	**Indicators measurements**		**Selection Criteria**					
			1	**2**	**3**	**4**	**5**	**6**
Quality of life	Social-political Well-being	-Age standardized mortality rate (# of deaths per 1000 population standardized by age)	x	x	x	x	x	x
	Intellectual well-being	-Park access (park space area/ total neighbourhood area)	x	x	x	x	x	x
		-Percentage without high school (number of persons without high school education/ population aged over 20)	x	x	x	x	x	x
		-Ethnic diversity (Higher numbers indicate greater diversity)	x	x	x	x	x	

Selection criteria (Maclaren, 1996; Jeroen et al., 1999; Devuyst, 2000; Xing et al., 2009; Putzhuber and Hasenauer, 2010; Shen et al., 2013) that numbers represent:

1-Clearly defined and scientifically representable;
2-Responsive to target goals and audience;
3-Data available;
4-Numerically measurable;
5-Spatially and temporally comparable;
6-Cost-effective.

APPENDIX B

SASKATOON QUALITY OF LIFE STUDY QUESTIONNAIRE (By SSRL)

INTRO1./INTRO3.

Hello, my name is **(FIRST NAME ONLY)** and I am calling on behalf of Dr. Xulin Guo at the University of Saskatchewan.

We are conducting a short 5-minute telephone survey on the quality of life in Saskatoon neighbourhoods.

INTRO2.

May I please speak with the person in your household who is 18 years of age or older and who is having the next birthday?

1. Yes, speaking **CONTINUE**
2. Yes, I'll get him/her **REPEAT INTRODUCTION AND CONTINUE**
3. Not available **ARRANGE CALLBACK - REQUEST RESPONDENT FIRST NAME (RECORD IN NOTES) AND ARRANGE CALLBACK (PRESS THE CTRL AND END KEYS)**

INTRO4.

I would like to invite you to participate in this short survey. Participation is voluntary, and you can stop the survey at any time. Let me assure you that the information we collect is kept strictly confidential and none of the answers that you provide will be attributed to you personally. If you have any concerns or questions about the survey, you may contact the Research Ethics Office at the University of Saskatchewan at (306) 966-2084.

Are you willing to participate in the survey?

1. Yes **CONTINUE**
2. No **THANK AND END INTERVIEW**
3. Later/Not right now **ARRANGE CALLBACK - REQUEST RESPONDENT FIRST NAME (RECORD IN NOTES) AND ARRANGE CALLBACK <u>(PRESS THE CTRL AND END KEYS)</u>**

INTRO5.

Before we begin, can I please have the first three characters of your postal code?

(DO NOT READ)

SELECT ONE

IF RESPONDENT IS RELUCTANT, YOU CAN ASSURE THEM THAT THE FIRST THREE CHARACTERS OF THEIR POSTAL CODE WILL BE USED FOR STATISTICAL PURPOSES ONLY (TO UNDERSTAND DIFFERENCES BY REGION/GEOGRAPHY OF THE CITY) AND WILL NOT BE USED TO IDENTIFY THEM IN ANY WAY.

THE FIRST THREE CHARACTERS ALL POSTAL CODES MUST BEGIN WITH AN 'S' AND APPEAR ON THE LIST, OTHERWISE THANK AND END THE INTERVIEW *NOW* <u>(SIMULTANEOUSLY PRESS THE CTRL AND END KEYS)</u> AND CODE AS 'NOT QUALIFIED'.

1. S7H
2. S7J
3. S7K
4. S7L
5. S7M
6. S7N
7. S7P
8. S7R
9. S7S

10. S7T

11. S7V

INTRO6.

(DO NOT READ)

RECORD SEX FROM RESPONDENT VOICE.

1. Male
2. Female

SECTION A, MAIN QUESTIONNAIRE

For the remainder of this survey, I would like you to consider the quality of life in your neighbourhood.

A1.

There are four categories that we use to measure Quality of Life. These four categories are material wellbeing, social-political wellbeing, intellectual well-being, and environmental wellbeing. Please rank each of these categories in order of importance to you, with 1 being the most important and 4 being the least important. Again the categories are:

1. Material wellbeing (such as family income or home ownership)
2. Social-political wellbeing (such as safety)
3. Intellectual wellbeing (such as education, cultural diversity, entertainment)
4. Environmental wellbeing (such as percentage of green space, water quality)
98. (Don't know)
99. (Refused)

A2.

Please rank the following material wellbeing indicators in order of importance, with 1 as the most important and 3 as the least important: (Interviewer note: provide respondents with bracketed examples if needed!)

1. Income (e.g., average family income)
2. Housing (e.g., housing affordability)
3. Proximity to services and goods (e.g., food access)
98. (Don’t know)
99. (Refused)

A3.

Please rank the following social-political wellbeing indicators in order of importance, with 1 as the most important and 3 as the least important:

(Interviewer note: provide respondents with bracketed examples if needed!)

1. Safety (Crime rates)
2. Health (Mortality rate)
3. Democratic Participation (the right to vote)
98. (Don’t know)
99. (Refused)

A4.

Please rank the following intellectual wellbeing indicators in order of importance, with 1 as the most important and 3 as the least important:

(Interviewer note: provide respondents with bracketed examples if needed!)

1. Education (high-school education)
2. Cultural diversity (ethnic diversity)
3. Entertainment (park space)
98. (Don’t know)
99. (Refused)

SECTION B, DEMOGRAPHICS

To make sure that we are talking to a cross section of Saskatchewan residents, we need to get a little information about your background.

B1.

In what year were you born?

0001. (ENTER YEAR OF BIRTH)

9999. (Refused)

B2.

What is the highest level of education that you have completed? **(READ LIST IF NECESSARY)**

1. No Schooling
2. Some Elementary School
3. Completed Elementary School
4. Some Secondary / High School
5. Completed Secondary / High School
6. Some Technical or Community College
7. Completed Technical or Community College

8. Some University

9. Bachelor's Degree

10. Master's Degree

11. Professional Degree (e.g., Law Degree, Medical Degree)

12. Doctorate

99. (Refused)

B3.

Are you currently self-employed, working for pay, retired, unemployed or looking for work, a student, caring for a family, or something else? **(READ LIST IF NECESSARY)**

IF RESPONDENT PROVIDES TWO ANSWERS, ASK FOR THE CATEGORY THAT DESCRIBES THEM BEST. DO NOT USE THE ‘OTHER’ OPTION UNLESS THE CATEGORIES PROVIDED ARE UNSUITABLE.

01. Self-employed (with or without employees)

02. Working for pay (full or part time, includes on paid leave)

03. Student and working for pay

04. Caring for children or other family members and working for pay

05. Retired and working for pay

06. Retired and not working

07. Unemployed / Looking for work

08. Student and not working

09. Caring for children or other family members full time

10. Disabled

11. Other

99. (Refused)

B4.

Are you a member of a First Nation, Metis or Inuit?

1.	Yes	**(CONTINUE)**
2.	No	**(SKIP TO B6)**
8.	(Don’t Know)	**(SKIP TO B6)**
9.	(Refused)	**(SKIP TO B6)**

B5.

Which of the following best describes you? Are you a/an… ? **(READ LIST)**

1. Status Indian living full time on a reserve
2. Status Indian living off-reserve
3. Non-Status Indian
4. Métis
5. Inuit
6. (No Particular Category)
8. (Don't Know)
9. (Refused)

B6.

Could you please tell me your total annual household income from all sources in 2011. Was it… ? **(READ LIST)**

IF ASKED, ALL SOURCES INCLUDE EMPLOYMENT INCOME (WAGES OR SALARY), SAVINGS, PENSIONS, RENT, ETC.

01. Less than $20,000

02. $20,000 to less than $30,000

03. $30,000 to less than $40,000

04. $40,000 to less than $50,000

05. $50,000 to less than $60,000

06. $60,000 to less than $70,000

07. $70,000 to less than $80,000

08. $80,000 to less than $90,000

09. $90,000 to less than $100,000

10. $100,000 to less than $150,000

11. $150,000 to less than $200,000

12. $200,000 to less than $250,000

13. $250,000 or more

98. (Don't Know)

99. (Refused)

CONCLUSION

Thank you very much. Those are all the questions that I have!

APPENDIX C

URBAN SUSTAINABILITY INDICES FOR 60 RESIDENTIAL NEIGHOUHOODS IN THE CITY OF SASKATOON IN 2006

Neighbourhood_names	**EnvInd**	**EcoInd**	**SopInd**	**IntInd**	**QQLInd**	**MldInd**	**HosInd**	**FhdInd**	**UrbInd**	**UrSInd**
Holiday Park	0.44	0.34	0.51	0.37	0.29	0.71	0.62	0.46	0.31	0.23
Montgomery Place	0.72	0.46	0.76	0.27	0.59	0.41	0.94	0.97	0.84	0.81
Fairhaven	0.32	0.37	0.46	0.57	0.28	0.72	0.5	0.62	0.31	0.22
Parkridge	0.29	0.37	0.31	0.63	0.25	0.75	0.76	0.91	0.69	0.47
Pacific Heights	0.19	0.39	0.45	0.66	0.23	0.77	0.89	0.85	0.63	0.41
Confederation Park	0.13	0.31	0.43	0.75	0.17	0.83	0.75	0.76	0.55	0.31
Dundonald	0.12	0.36	0.65	0.49	0.13	0.87	0.81	0.83	0.65	0.35
Westview	0.26	0.37	0.63	0.48	0.23	0.77	0.9	0.82	0.61	0.4
Massey Place	0.1	0.3	0.62	0.45	0.06	0.94	0.64	0.74	0.44	0.15
Meadowgreen	0.32	0.27	0.46	0.39	0.16	0.84	0.5	0.54	0.33	0.14
King George	0.51	0.59	0.46	0.58	0.57	0.43	0.69	0.56	0.44	0.51
Pleasant Hill	0.41	0.32	0	0.56	0.23	0.77	0.24	0.32	0.09	0.02
Riversdale	0.36	0.61	0.08	0.31	0.28	0.72	0.33	0.39	0.35	0.24
Mount Royal	0.32	0.35	0.45	0.3	0.16	0.84	0.55	0.47	0.27	0.1
Westmount	0.32	0.38	0.41	0.36	0.2	0.8	0.68	0.58	0.41	0.23
Caswell Hill	0.47	0.32	0.41	0.34	0.27	0.73	0.58	0.4	0.32	0.21
Hudson Bay Park	0.3	0.38	0.41	0.63	0.29	0.71	0.76	0.39	0.41	0.29

Mayfair	0.34	0.51	0.39	0.14	0.2	0.8	0.66	0.46	0.28	0.13
Central Business District	0.34	0.57	0.33	0.29	0.29	0.71	0.15	0	0.12	0.08
Nutana	0.73	0.34	0.8	0.59	0.66	0.34	0.5	0.27	0.17	0.38
Buena Vista	0.5	0.29	0.69	0.47	0.38	0.62	0.78	0.4	0.34	0.3
Exhibition	0.18	0.41	0.29	0.3	0.06	0.94	0.5	0.24	0.38	0.11
Avalon	0.36	0.28	0.85	0.27	0.22	0.78	0.79	0.61	0.55	0.35
Queen Elizabeth	0.41	0.26	0.84	0.37	0.29	0.71	0.66	0.6	0.41	0.29
Haultain	0.38	0.27	0.66	0.32	0.22	0.78	0.62	0.45	0.28	0.15
Varsity View	0.59	0.16	0.59	0.49	0.36	0.64	0.38	0.14	0	0.05
Grosvenor Park	0.45	0.94	0.87	0.5	0.77	0.23	0.5	0.34	0.3	0.56
Holliston	0.4	0.31	0.82	0.36	0.3	0.7	0.66	0.48	0.38	0.28
Stonebridge	0.67	0	0.49	0.68	0.39	0.61	0.72	0.62	0.96	0.75
Adelaide/Churchill	0.35	0.22	0.84	0.45	0.25	0.75	0.91	0.74	0.67	0.45
Nutana Park	0.35	0.28	0.85	0.56	0.33	0.67	0.86	0.71	0.53	0.41
Eastview	0.45	0.22	0.77	0.69	0.41	0.59	0.71	0.65	0.49	0.43
Nutana Suburban Centre	0.41	0.24	0.66	0.17	0.16	0.84	0.27	0.02	0.13	0
Brevoort Park	0.31	0.32	0.75	0.4	0.24	0.76	0.53	0.53	0.37	0.23
Greystone Heights	0.36	0.66	0.82	0.59	0.56	0.44	0.67	0.67	0.49	0.55
Lakeview	0.38	0.78	0.79	1	0.8	0.2	0.71	0.66	0.49	0.72
Wildwood	0.67	0.42	0.79	0.79	0.73	0.27	0.64	0.44	0.48	0.66
College Park	0.27	0.39	0.36	0.51	0.22	0.78	0.58	0.6	0.44	0.26

College Park East	0.16	0.4	0.75	0.59	0.24	0.76	0.77	0.67	0.51	0.33
Sutherland	0.38	0.25	0.61	0.42	0.23	0.77	0.39	0.36	0.24	0.13
Forest Grove	0	0.42	0.71	0.53	0.1	0.9	0.62	0.63	0.36	0.12
City Park	0.59	0.23	0.63	0.93	0.59	0.41	0.26	0.3	0.18	0.34
North Park	0.39	0.3	0.73	0.23	0.22	0.78	0.65	0.41	0.29	0.16
Richmond Heights	0.28	0.2	0.86	0.56	0.23	0.77	0.67	0.46	0.44	0.27
River Heights	0.33	0.51	0.77	0.66	0.47	0.53	0.84	0.71	0.62	0.57
Lawson Heights Suburban Centre	0.36	0.27	0.73	0.5	0.28	0.72	0.6	0.22	0.52	0.36
Lawson Heights	0.38	0.32	0.7	0.77	0.43	0.57	0.6	0.62	0.45	0.42
Silverwood Heights	0.34	0.36	0.73	0.69	0.39	0.61	0.79	0.81	0.63	0.52
Confederation Suburban Centre	0.09	1	0.15	0.44	0.36	0.64	0.2	0.58	0.48	0.39
Lakeridge	0.21	0.45	0.85	0.46	0.28	0.72	1	1	0.83	0.59
Arbor Creek	0.18	0.59	0.87	0.61	0.4	0.6	0.91	0.92	0.84	0.68
Erindale	0.28	0.46	0.76	0.55	0.36	0.64	0.96	0.84	0.72	0.56
Silverspring	0.11	0.23	0.79	0.51	0.08	0.92	0.99	0.91	0.82	0.43
Willowgrove	0.32	0.28	1	0.28	0.22	0.78	0.85	0.79	0.91	0.6
Briarwood	0.06	0.35	0.85	0.79	0.24	0.76	0.98	0.87	1	0.68
University Heights Suburban Centre	0.14	0.61	0.97	0.61	0.4	0.6	0.86	0.33	0.7	0.58
Lakewood Suburban Centre	0.93	0.67	0.83	0.29	0.89	0.11	0.77	0.44	0.8	1
Airport Business Area	0.68	0.14	0.25	0.27	0.27	0.73	0.22	0.64	0.61	0.42

Kelsey - Woodlawn	0.29	0.3	0.48	0	0	1	0.73	0.49	0.66	0.27
U of S Lands South Management Area	1	0.44	0.52	0.93	1	0	0	0.05	0.1	0.58
Holiday Park	0.44	0.34	0.51	0.37	0.29	0.71	0.62	0.46	0.31	0.23

APPENDIX D

SPECIFIC INDICATORS FOR 60 RESIDENTIAL NEIGHOUHOODS IN THE CITY OF SASKATOON IN 2006

Neighbourhood_names	**AFI**	**HOI**	**MI**	**LST**	**GP**	**WP**	**IP**	**STI**	**NHS**	**ED**	**PA**	**CR**	**SAM**	**ET**
Adelaide/Churchill	0.49	0.10	0.14	0.91	0.02	0.00	0.23	0.11	0.10	0.17	0.17	0.05	0.30	0.96
Airport Business Area	0.15	0.48	0.00	0.54	1.00	0.23	0.62	0.23	0.16	0.02	0.09	0.60	0.00	0.00
Arbor Creek	1.00	0.19	0.00	0.89	0.03	0.12	0.53	0.00	0.00	0.21	0.28	0.03	0.29	0.96
Avalon	0.38	0.43	0.00	0.84	0.06	0.03	0.20	0.11	0.22	0.11	0.06	0.06	0.27	0.95
Brevoort Park	0.32	0.36	0.17	0.88	0.03	0.00	0.36	0.19	0.18	0.15	0.18	0.10	0.22	0.73
Briarwood	0.83	0.07	0.00	0.88	0.05	0.16	0.78	0.00	0.04	0.45	0.37	0.02	0.22	0.86
Buena Vista	0.33	0.48	0.00	0.65	0.24	0.02	0.06	0.22	0.16	0.19	0.24	0.08	0.27	0.65
Caswell Hill	0.21	0.66	0.00	0.76	0.18	0.00	0.20	0.29	0.17	0.15	0.08	0.22	0.53	0.47
Central Business District	0.29	0.52	0.37	0.99	0.17	0.06	1.00	0.58	0.41	0.21	0.19	0.56	0.49	0.61
City Park	0.19	0.55	0.00	0.79	0.30	0.01	0.33	0.47	0.28	0.68	0.59	0.10	0.39	0.67
College Park	0.33	0.48	0.12	0.86	0.15	0.00	0.49	0.16	0.18	0.40	0.12	0.09	0.91	0.61
College Park East	0.47	0.48	0.00	0.86	0.03	0.00	0.45	0.04	0.10	0.19	0.38	0.04	0.26	0.71
Confederation Park	0.30	0.55	0.00	0.89	0.12	0.00	0.63	0.05	0.21	0.60	0.31	0.13	0.44	0.32
Confederation Suburban Centre	0.16	0.67	0.86	0.96	0.05	0.02	0.83	0.15	0.42	0.05	0.58	1.00	0.00	0.18
Dundonald	0.39	0.52	0.00	0.96	0.04	0.02	0.66	0.04	0.13	0.22	0.19	0.06	0.27	0.54
Eastview	0.34	0.40	0.00	0.80	0.25	0.00	0.21	0.15	0.19	0.43	0.38	0.04	0.22	0.71
Erindale	0.79	0.24	0.00	0.97	0.02	0.15	0.48	0.03	0.04	0.11	0.32	0.03	0.43	0.90

Exhibition	0.23	0.57	0.16	0.62	0.14	0.03	0.44	0.16	0.18	0.15	0.03	0.11	0.82	0.39
Fairhaven	0.29	0.62	0.00	0.98	0.13	0.00	0.42	0.07	0.25	0.45	0.23	0.07	0.45	0.34
Forest Grove	0.37	0.60	0.00	0.96	0.02	0.01	0.89	0.11	0.04	0.24	0.15	0.08	0.17	0.59
Greystone Heights	0.41	0.43	0.44	0.87	0.07	0.00	0.31	0.19	0.10	0.38	0.19	0.12	0.22	0.89
Grosvenor Park	0.37	0.26	1.00	0.93	0.03	0.00	0.36	0.40	0.10	0.22	0.18	0.11	0.00	0.76
Haultain	0.30	0.50	0.00	0.83	0.02	0.00	0.16	0.18	0.14	0.11	0.06	0.09	0.30	0.62
Holiday Park	0.24	0.64	0.00	0.66	0.25	0.03	0.13	0.15	0.33	0.09	0.35	0.11	0.40	0.43
Holliston	0.29	0.40	0.15	0.90	0.05	0.00	0.24	0.19	0.16	0.19	0.07	0.09	0.20	0.85
Hudson Bay Park	0.20	0.55	0.17	0.74	0.12	0.00	0.31	0.18	0.37	0.19	0.70	0.12	0.68	0.52
Kelsey - Woodlawn	0.19	0.64	0.00	0.69	0.30	0.01	0.50	0.22	0.53	0.02	0.03	0.39	0.00	0.24
King George	0.18	0.76	0.26	0.74	0.39	0.02	0.22	0.18	0.34	0.13	0.65	0.25	0.30	0.37
Lakeridge	0.81	0.21	0.00	1.00	0.09	0.01	0.54	0.01	0.08	0.17	0.17	0.02	0.21	0.85
Lakeview	0.75	0.67	0.00	0.99	0.04	0.07	0.29	0.05	0.07	1.00	0.17	0.04	0.17	0.70
Lake Wood Suburban Centre	0.29	0.54	0.46	0.47	0.66	1.00	0.37	0.08	0.12	0.02	0.09	0.01	0.00	0.59
Lawson Heights	0.49	0.36	0.00	0.93	0.13	0.02	0.31	0.10	0.16	0.38	0.53	0.04	0.35	0.69
Lawson Heights Suburban Centre	0.26	0.54	0.00	0.87	0.46	0.07	0.64	0.07	0.84	0.15	1.00	0.11	0.18	0.67
Massey Place	0.25	0.59	0.00	0.86	0.01	0.00	0.52	0.03	0.24	0.30	0.17	0.13	0.18	0.46
Mayfair	0.22	0.64	0.23	0.76	0.00	0.00	0.11	0.15	0.41	0.11	0.04	0.23	0.46	0.36
Meadowgreen	0.19	0.60	0.00	0.82	0.01	0.05	0.29	0.18	0.43	0.47	0.09	0.17	0.39	0.39
Montgomery Place	0.62	0.33	0.09	0.50	0.86	0.05	0.00	0.05	0.16	0.05	0.05	0.05	0.43	0.91

Mount Royal	0.19	0.59	0.11	0.84	0.03	0.00	0.27	0.16	0.53	0.36	0.16	0.18	0.55	0.52
North Park	0.30	0.54	0.00	0.79	0.01	0.03	0.14	0.21	0.16	0.04	0.00	0.06	0.26	0.69
Nutana	0.40	0.36	0.12	0.59	0.38	0.15	0.04	0.40	0.11	0.26	0.31	0.11	0.20	0.82
Nutana Park	0.42	0.38	0.00	0.85	0.08	0.00	0.16	0.05	0.11	0.19	0.33	0.05	0.25	0.90
Nutana Suburban Centre	0.12	0.36	0.28	0.87	0.36	0.00	0.57	0.26	1.00	0.22	0.56	0.07	0.59	0.88
Pacific Heights	0.38	0.57	0.00	0.84	0.13	0.00	0.51	0.07	0.16	0.41	0.31	0.09	0.55	0.43
Parkridge	0.44	0.48	0.00	0.82	0.24	0.02	0.41	0.04	0.16	0.43	0.24	0.07	0.88	0.47
Pleasant Hill	0.08	0.78	0.00	0.84	0.02	0.00	0.32	0.38	0.73	0.92	0.21	0.35	0.79	0.03
Queen Elizabeth	0.35	0.43	0.00	0.90	0.12	0.00	0.26	0.16	0.10	0.09	0.11	0.08	0.33	1.00
Richmond Heights	0.32	0.38	0.00	0.81	0.17	0.01	0.29	0.00	0.46	0.02	0.85	0.04	0.13	0.80
River Heights	0.51	0.47	0.11	0.84	0.12	0.02	0.27	0.08	0.08	0.15	0.50	0.05	0.25	0.75
Riversdale	0.13	0.85	0.25	0.89	0.06	0.01	0.65	0.52	0.90	0.72	0.19	0.54	0.65	0.22
Silverspring	0.59	0.16	0.00	0.78	0.16	0.00	0.57	0.01	0.04	0.22	0.14	0.01	0.35	0.86
Silverwood Heights	0.57	0.28	0.06	0.87	0.16	0.03	0.30	0.04	0.07	0.43	0.26	0.03	0.30	0.70
Stonebridge	0.29	0.00	0.17	0.48	0.76	0.20	0.20	0.12	0.09	0.02	0.68	0.04	1.00	0.92
Sutherland	0.26	0.52	0.00	0.79	0.21	0.03	0.29	0.12	0.15	0.21	0.13	0.11	0.25	0.49
U of S Lands South Management Area	0.00	1.00	0.00	0.35	0.65	0.06	0.09	1.00	0.01	0.79	0.22	0.15	0.00	0.09
University Heights Suburban Centre	0.29	0.45	0.47	0.73	0.23	0.08	0.75	0.16	0.15	0.07	0.56	0.00	0.00	0.86
Varsity View	0.31	0.35	0.00	0.74	0.08	0.02	0.07	0.48	0.15	0.30	0.15	0.11	0.46	0.65

Westmount	0.21	0.73	0.00	0.78	0.01	0.00	0.13	0.10	0.52	0.17	0.45	0.25	0.44	0.42
Westview	0.35	0.57	0.00	0.83	0.14	0.00	0.41	0.10	0.28	0.26	0.31	0.08	0.37	0.61
Wildwood	0.33	0.57	0.08	0.86	0.63	0.07	0.32	0.14	0.16	0.62	0.31	0.05	0.20	0.75
Willowgrove	0.54	0.16	0.10	0.79	0.38	0.09	0.49	0.00	0.05	0.00	0.01	0.02	0.00	0.94

NOTES:

AFI – Standardized average family income

MI – Standardized market access index

GP – Standardized percentage green space

IP – Standardized percentage impervious surface

NHS – Standardized percentage without high school

PA – Standardized park access

SAM – Standardized age standardized mortality rate

HOI – Standardized house index

LST- Standardized land surface temperature

WP – Standardized percentage water

STI – Standardized sustainable traveling index

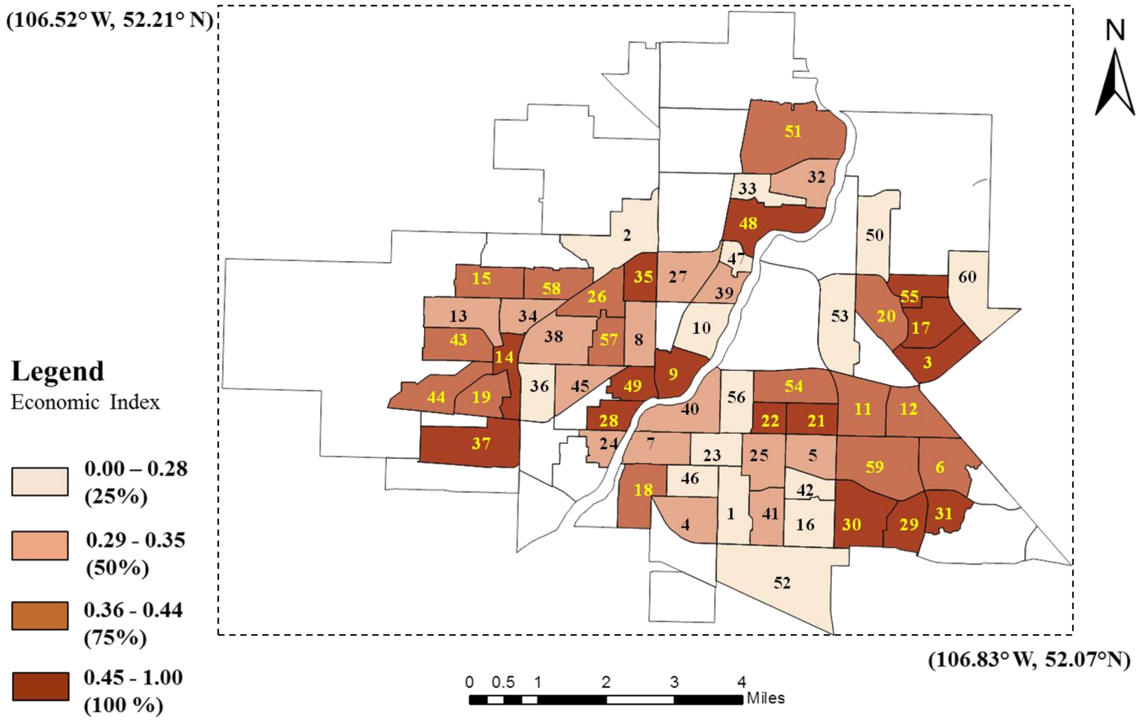
ED – Standardized ethnic diversity

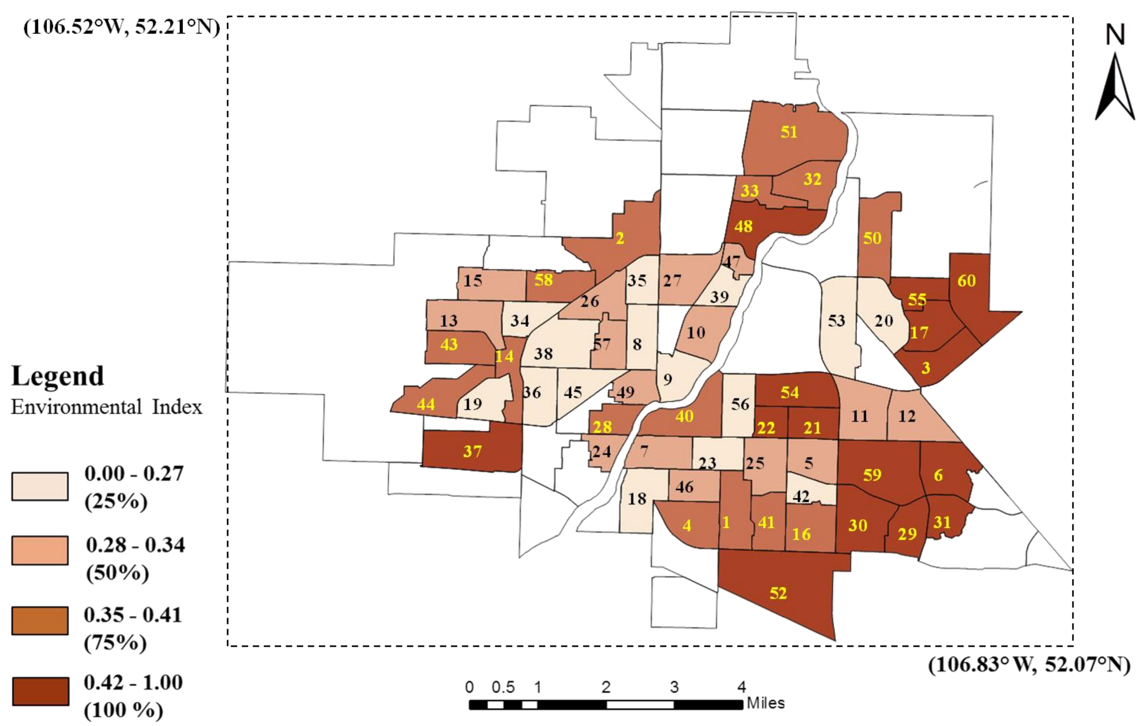
CR – Standardized crime rate

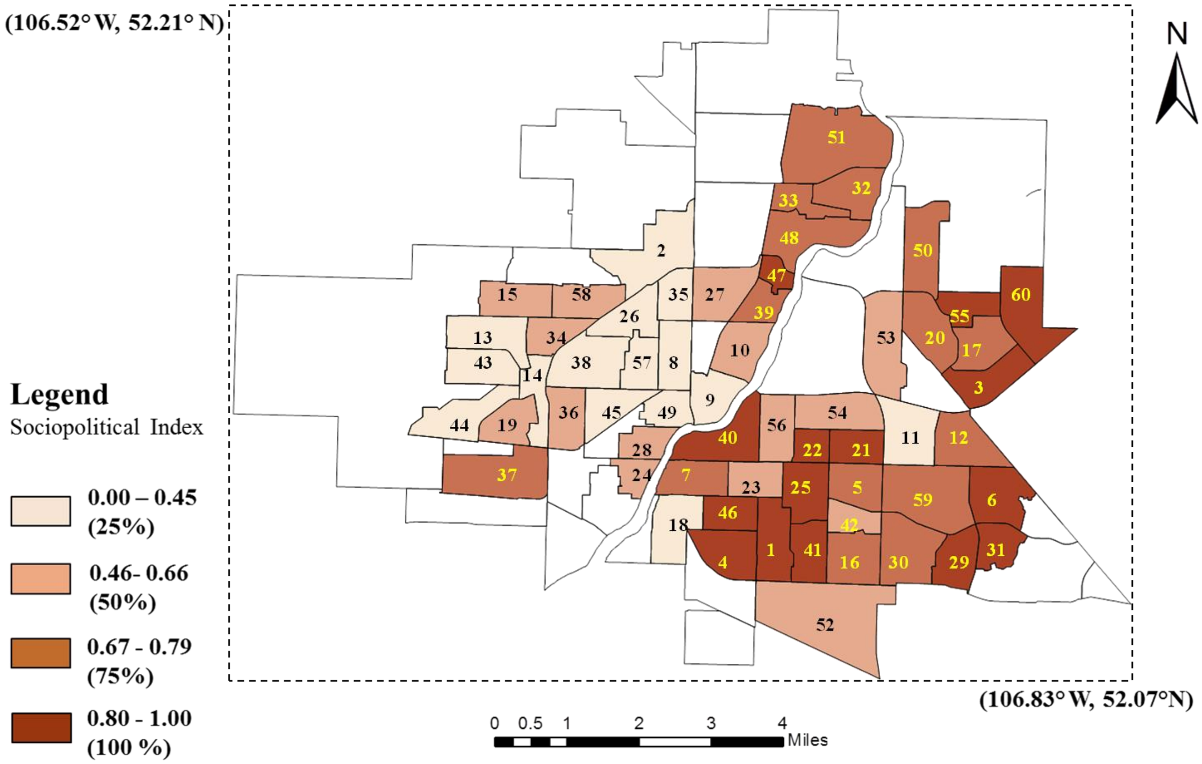
ET – Standardized election turnout percentage

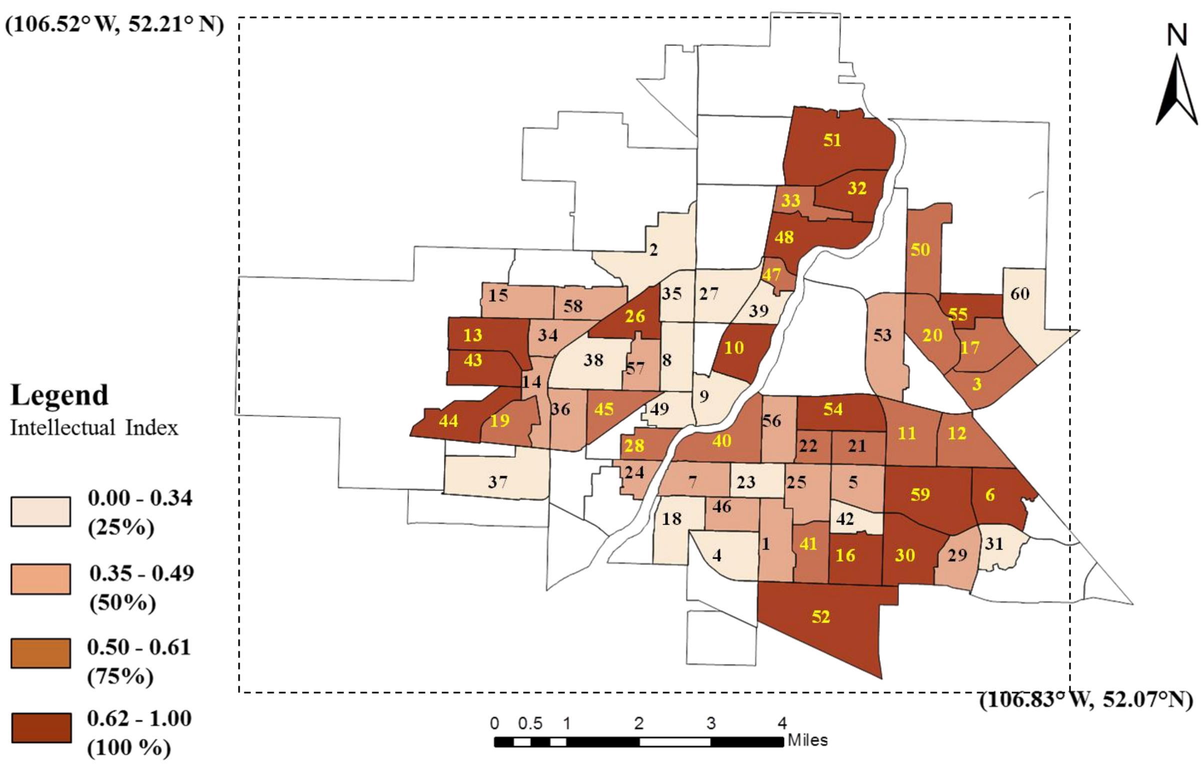
APPENDIX E

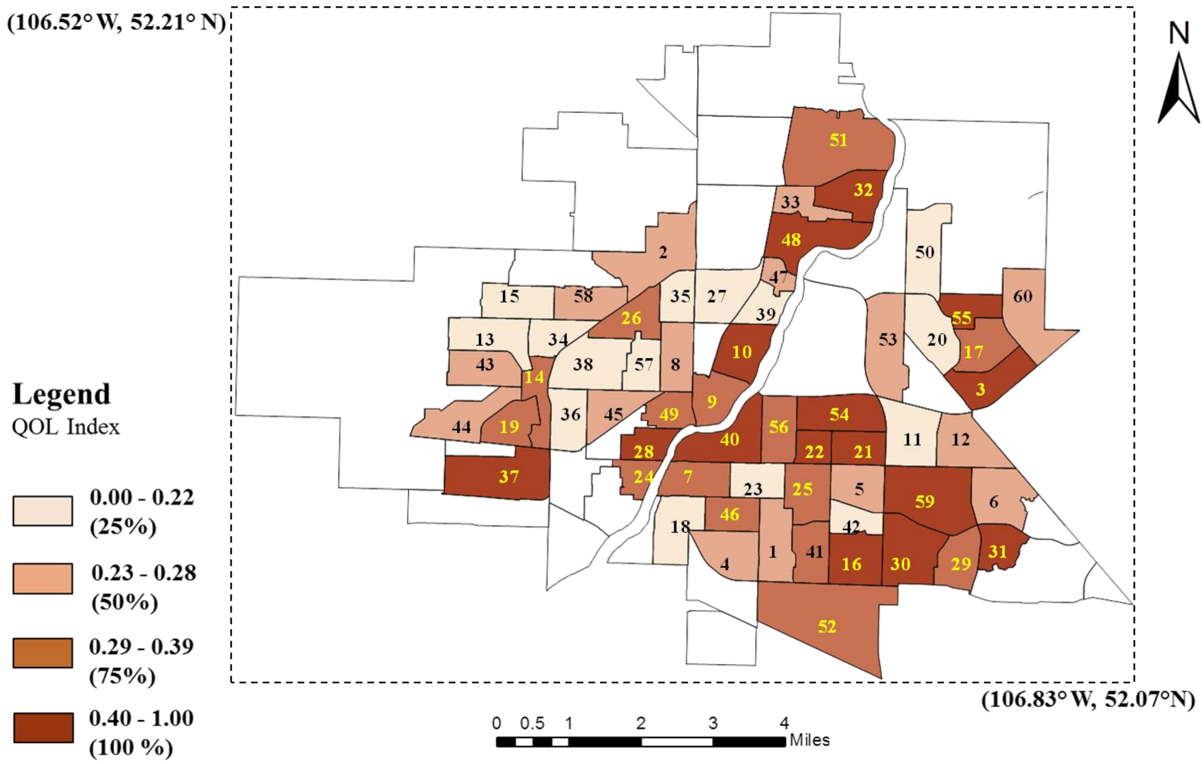
QUANTILE CLASSIFICATION OF URBAN SUSTAINABILTIY OF URBAN SUSTAINABILITY INDICES FOR SASKATOON IN 2006

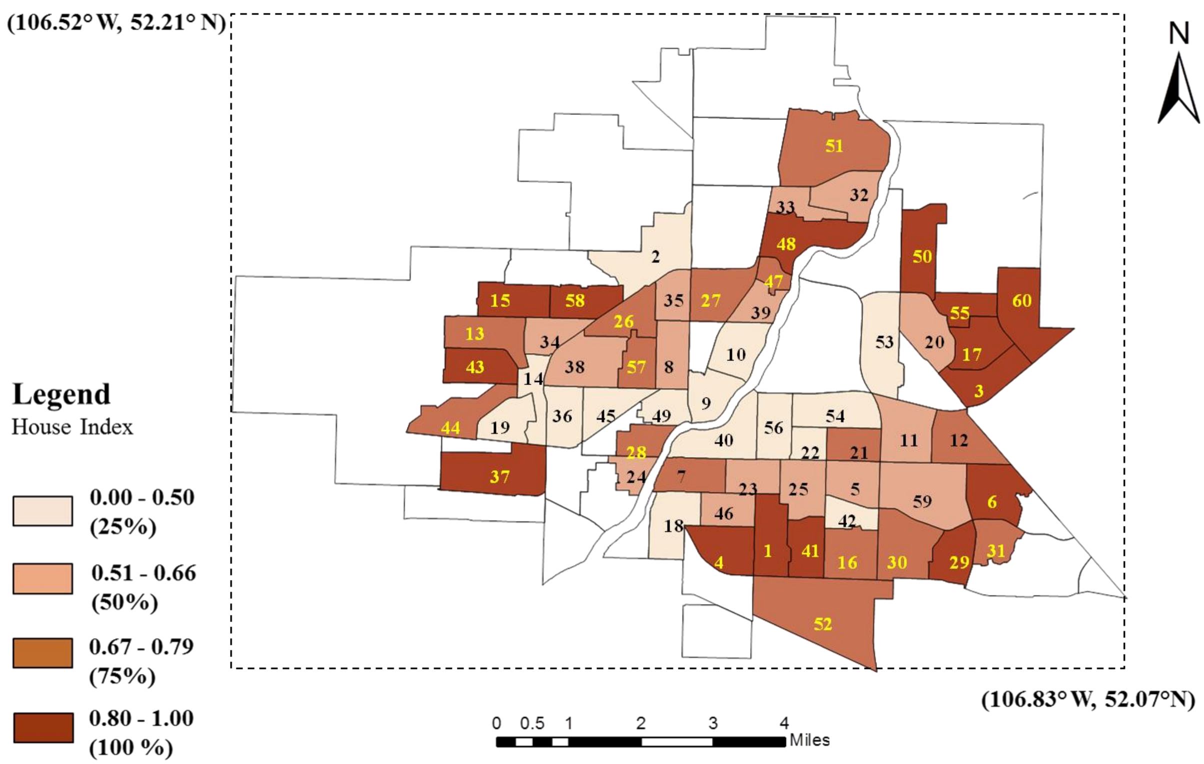


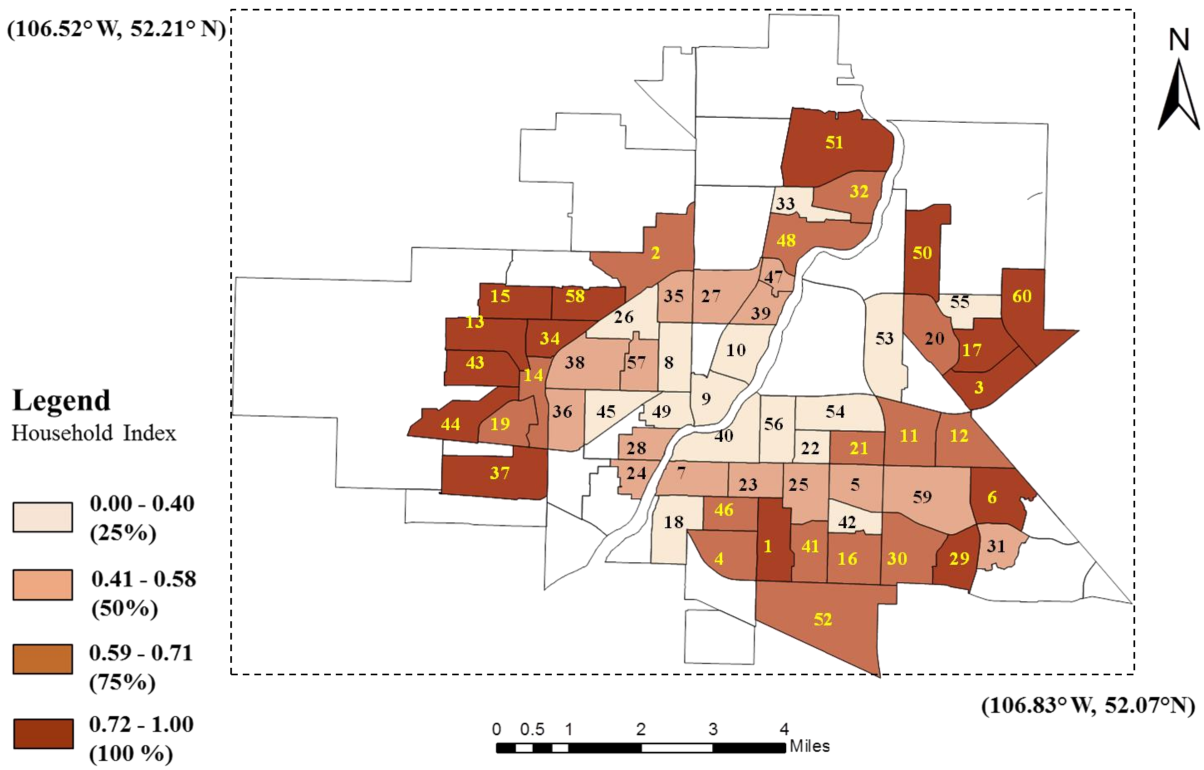


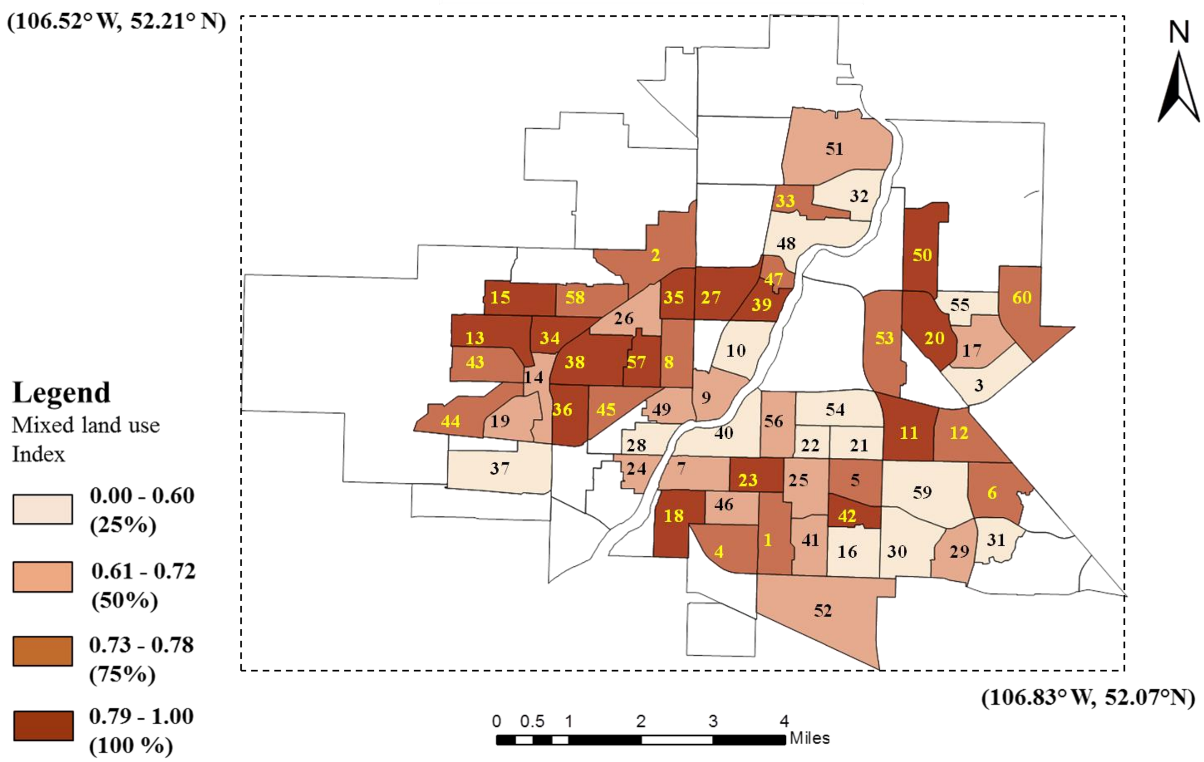

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Sociopolitical Index
0.00 – 0.45 (25%)
0.46- 0.66 (50%)
0.67 - 0.79 (75%)
0.80 - 1.00 (100 %)
0 0.5 1 2 3 4 Miles

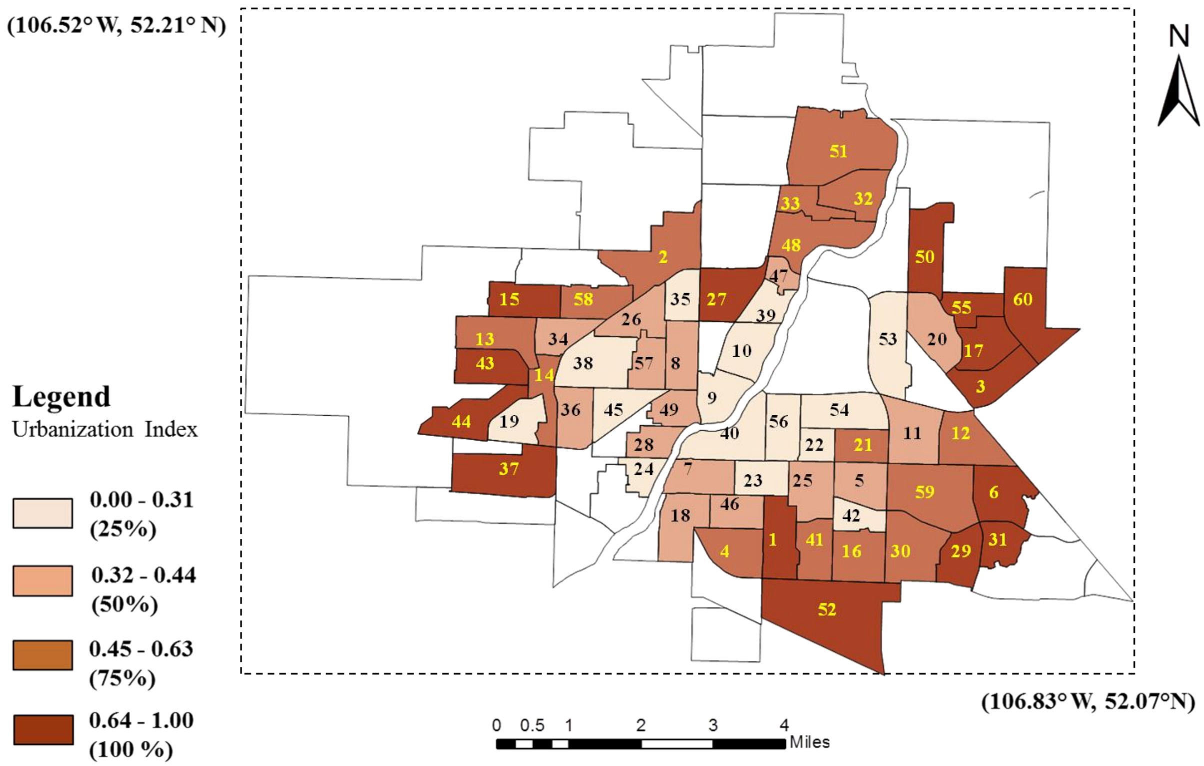

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Intellectual Index
0.00 - 0.34 (25%)
0.35 - 0.49 (50%)
0.50 - 0.61 (75%)
0.62 - 1.00 (100 %)
0 0.5 1 2 3 4 Miles

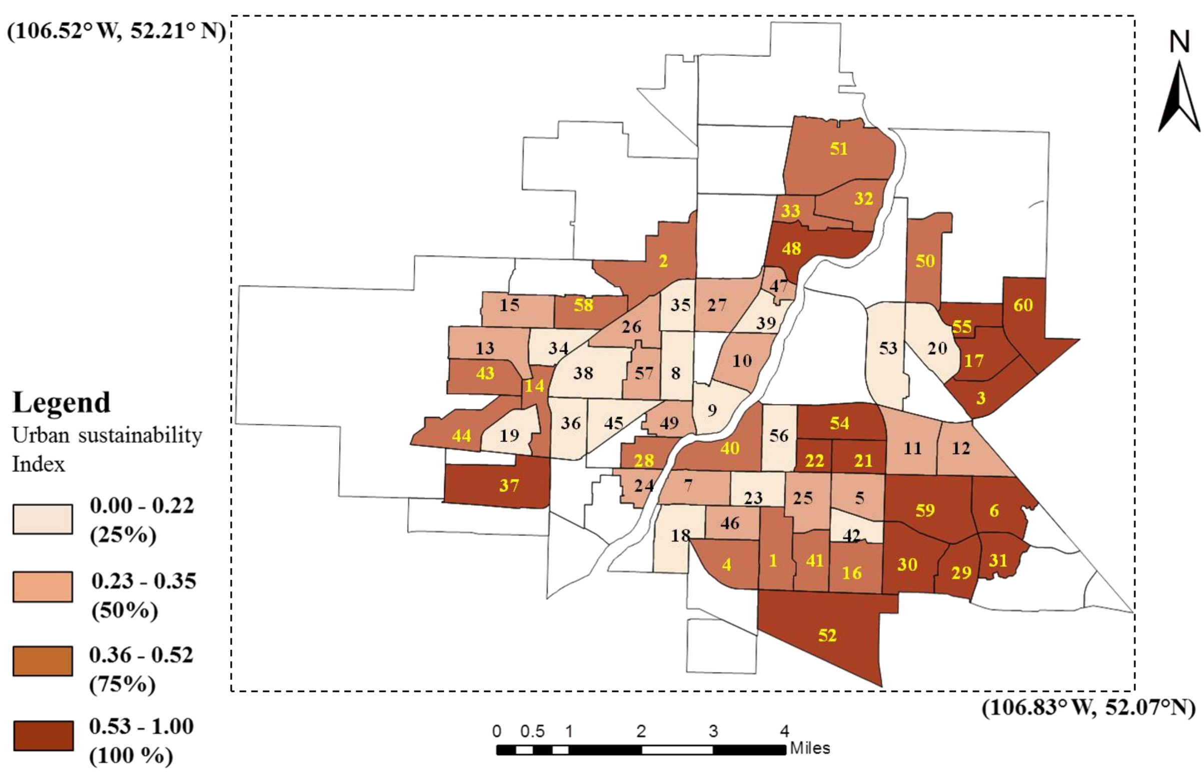

(106.52° W, 52.21° N)
N
Legend
QOL Index
0.00 - 0.22
(25%)
0.23 - 0.28
(50%)
0.29 - 0.39
(75%)
0.40 - 1.00
(100 %)
0 0.5 1 2 3 4
Miles
(106.83° W, 52.07°N)


(106.52° W, 52.21° N)
N
Legend
House Index
0.00 - 0.50
(25%)
0.51 - 0.66
(50%)
0.67 - 0.79
(75%)
0.80 - 1.00
(100 %)
0 0.5 1 2 3 4
Miles
(106.83° W, 52.07°N)

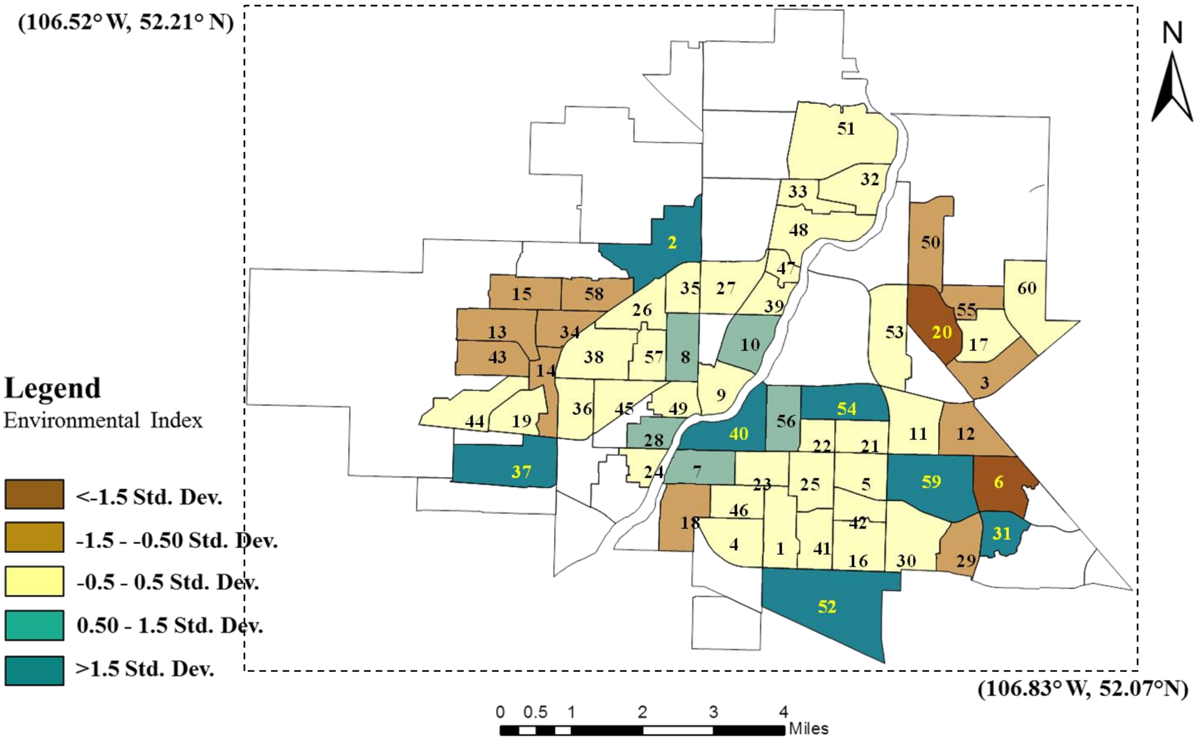

(106.52° W, 52.21° N)
N
Legend
Household Index
0.00 - 0.40
(25%)
0.41 - 0.58
(50%)
0.59 - 0.71
(75%)
0.72 - 1.00
(100 %)
0 0.5 1 2 3 4
Miles
(106.83° W, 52.07°N)

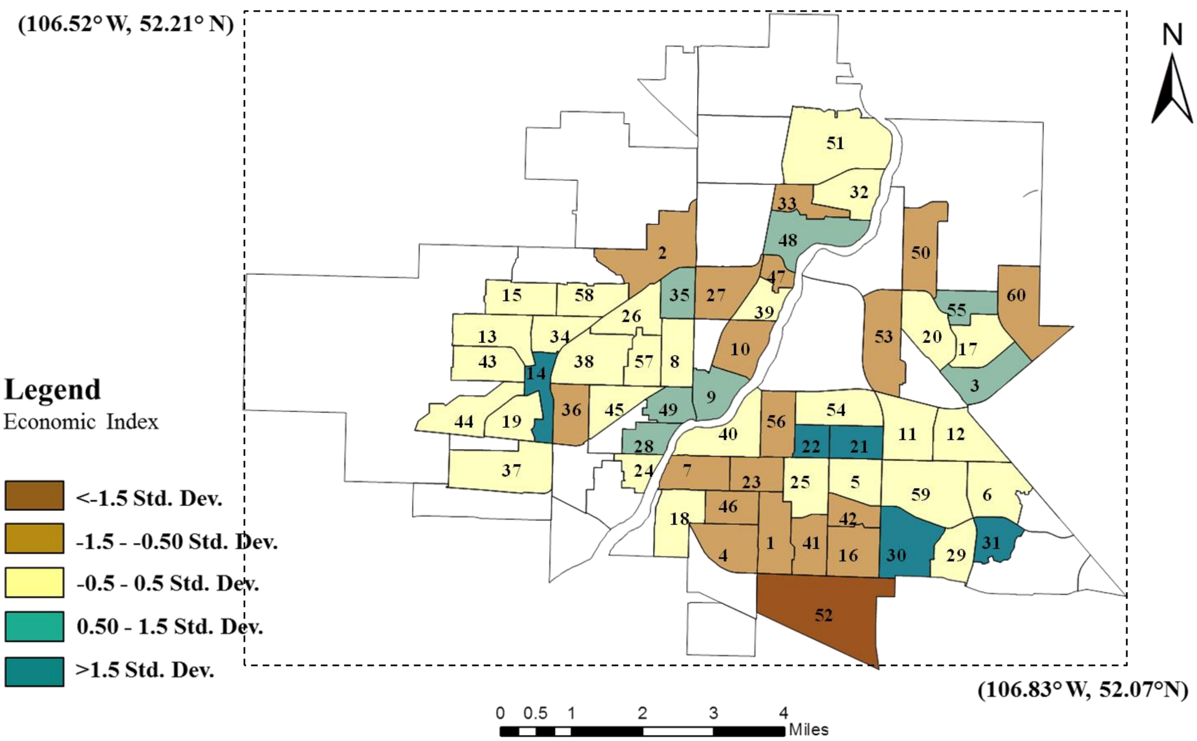

(106.52° W, 52.21° N)
N
Legend
Mixed land use
Index
0.00 - 0.60
(25%)
0.61 - 0.72
(50%)
0.73 - 0.78
(75%)
0.79 - 1.00
(100 %)
0 0.5 1 2 3 4
Miles
(106.83° W, 52.07°N)

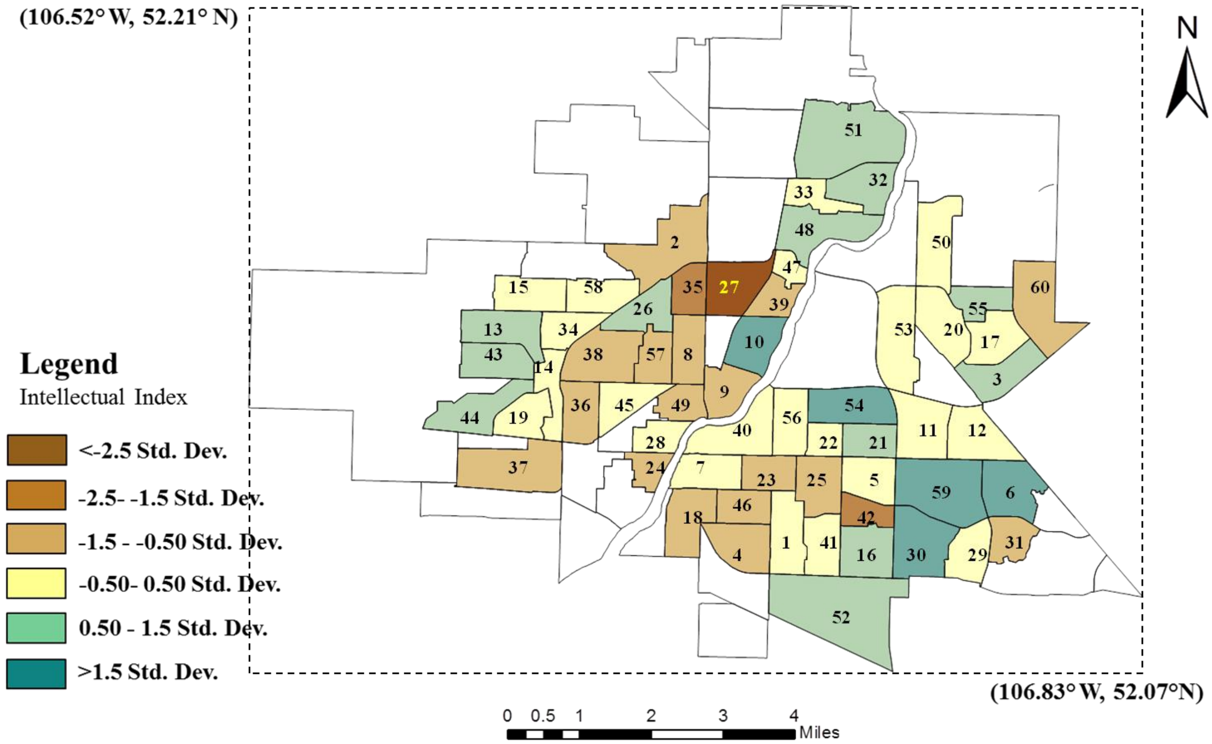

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Urbanization Index
0.00 - 0.31 (25%)
0.32 - 0.44 (50%)
0.45 - 0.63 (75%)
0.64 - 1.00 (100 %)
0 0.5 1 2 3 4 Miles

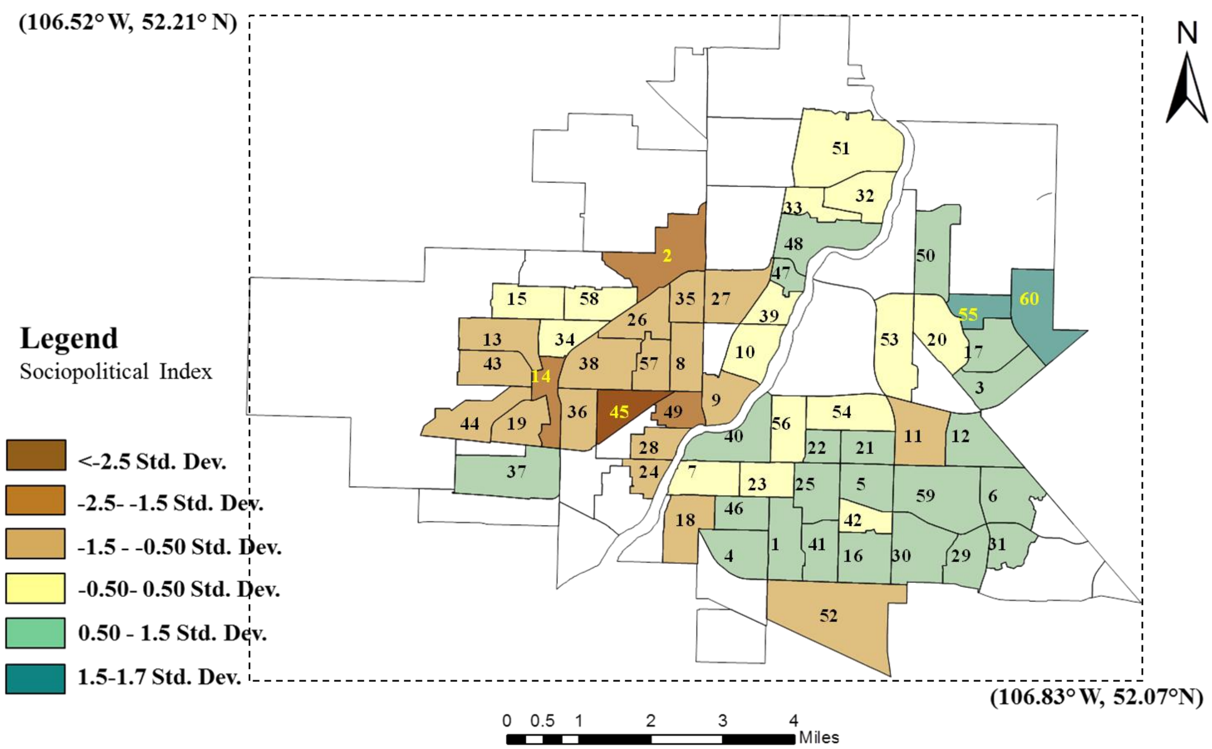

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Urban sustainability Index
0.00 - 0.22 (25%)
0.23 - 0.35 (50%)
0.36 - 0.52 (75%)
0.53 - 1.00 (100 %)
0 0.5 1 2 3 4 Miles

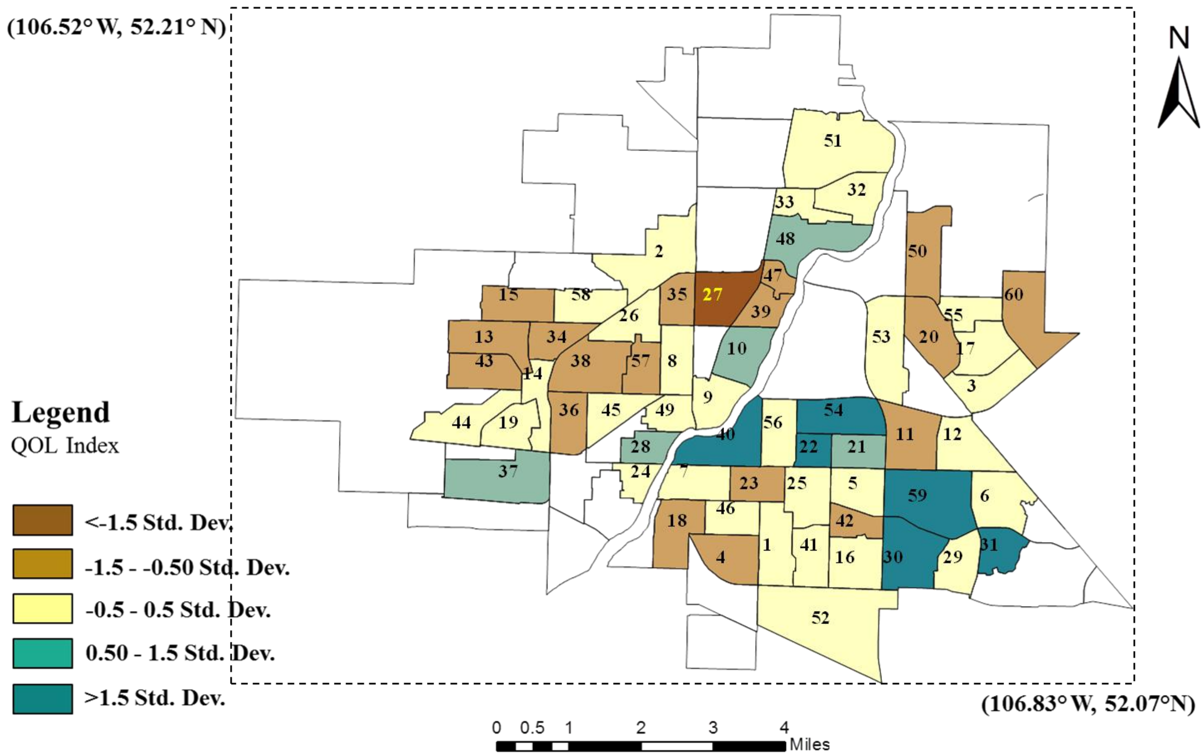
APPENDIX F
STANDARD DEVEIATION CLASSIFICATIONS OF URBAN SUSTAINABILITY INDICES
FOR SASKATOON IN 2006

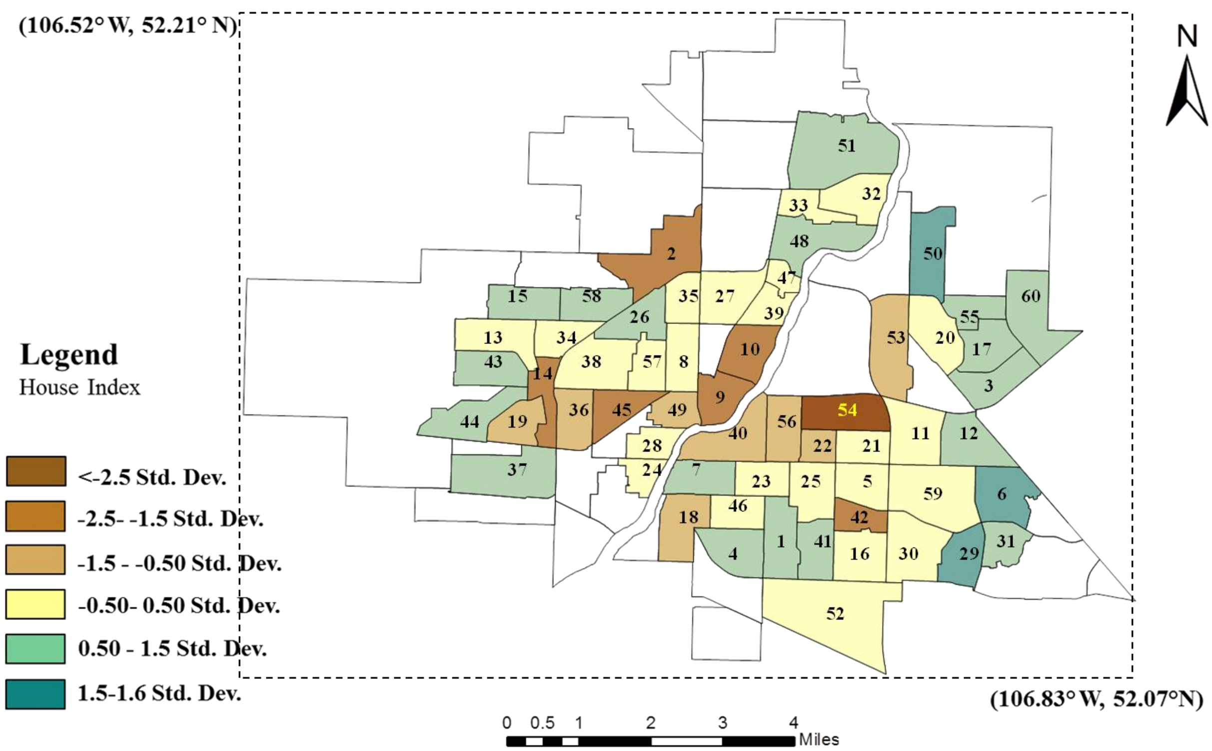


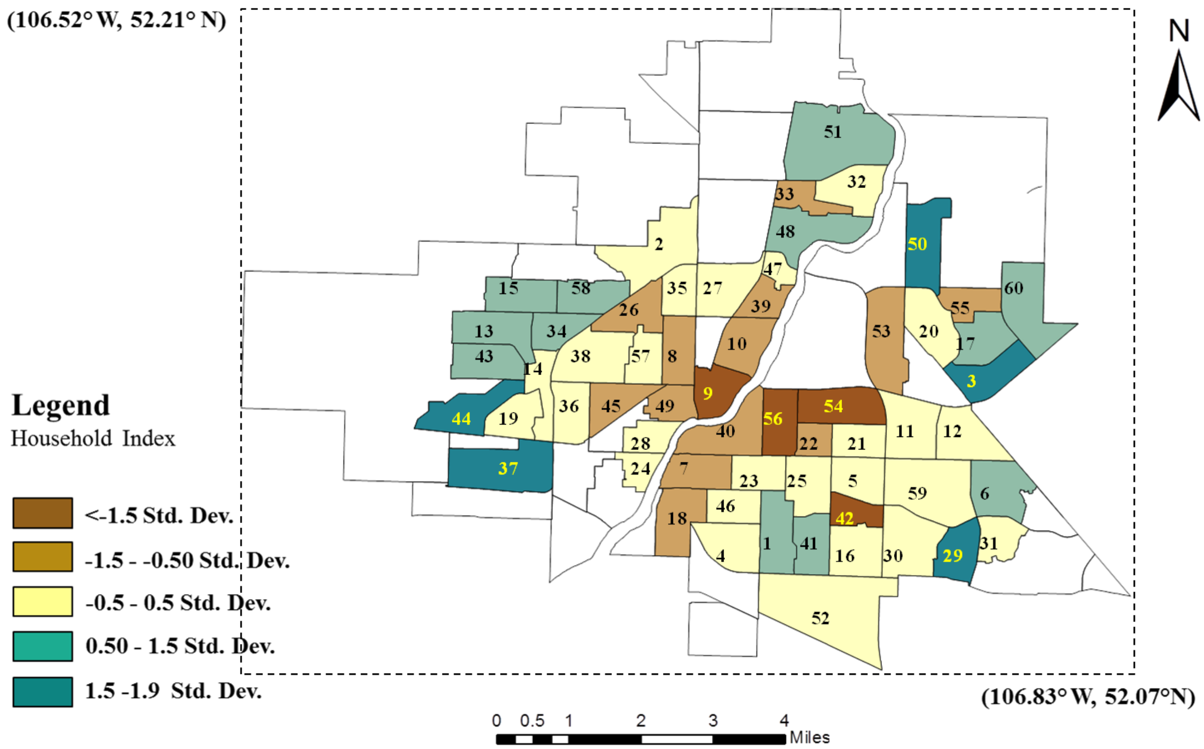


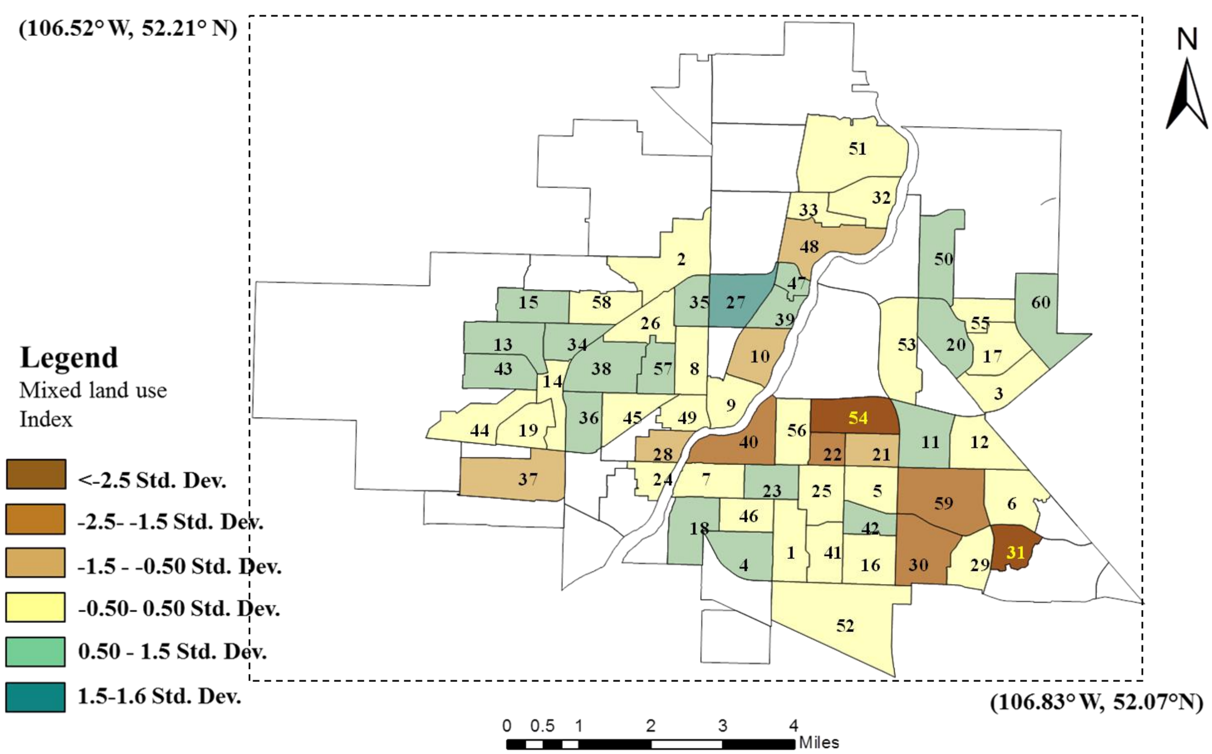

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Intellectual Index
<-2.5 Std. Dev.
-2.5- -1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.50- 0.50 Std. Dev.
0.50 - 1.5 Std. Dev.
>1.5 Std. Dev.
0 0.5 1 2 3 4
Miles

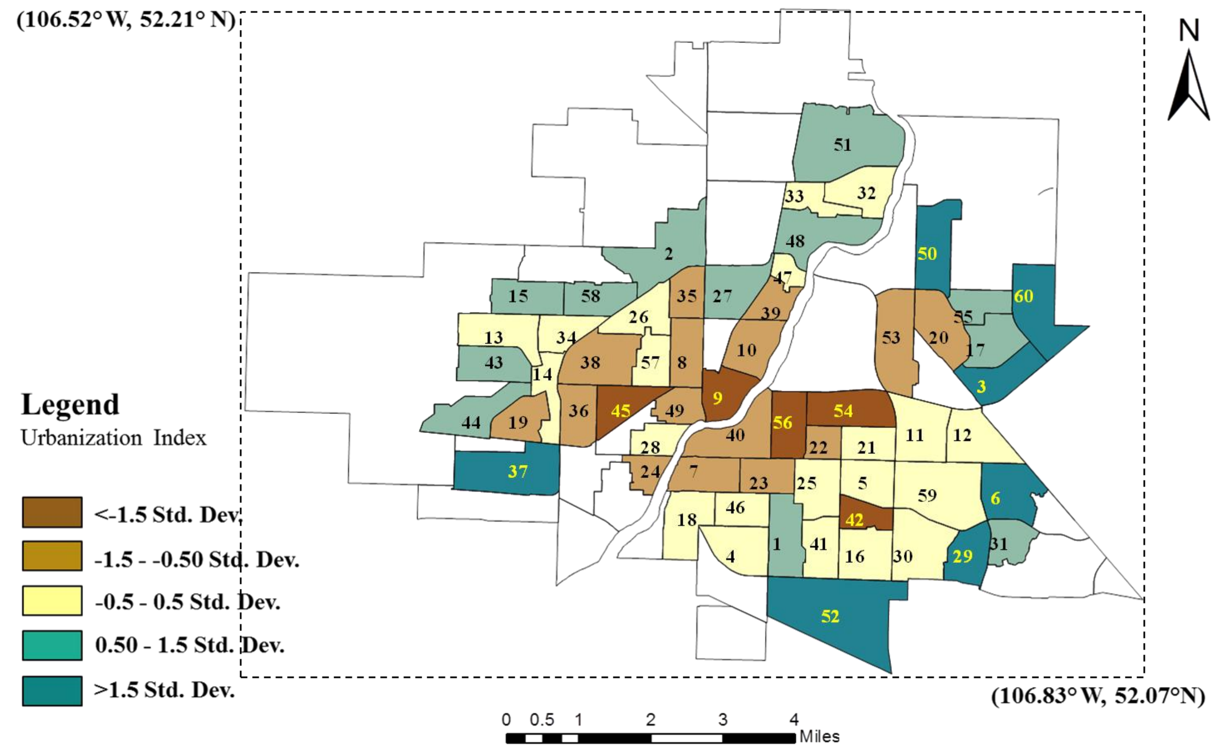

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Sociopolitical Index
<-2.5 Std. Dev.
-2.5- -1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.50- 0.50 Std. Dev.
0.50 - 1.5 Std. Dev.
1.5-1.7 Std. Dev.
0 0.5 1 2 3 4
Miles

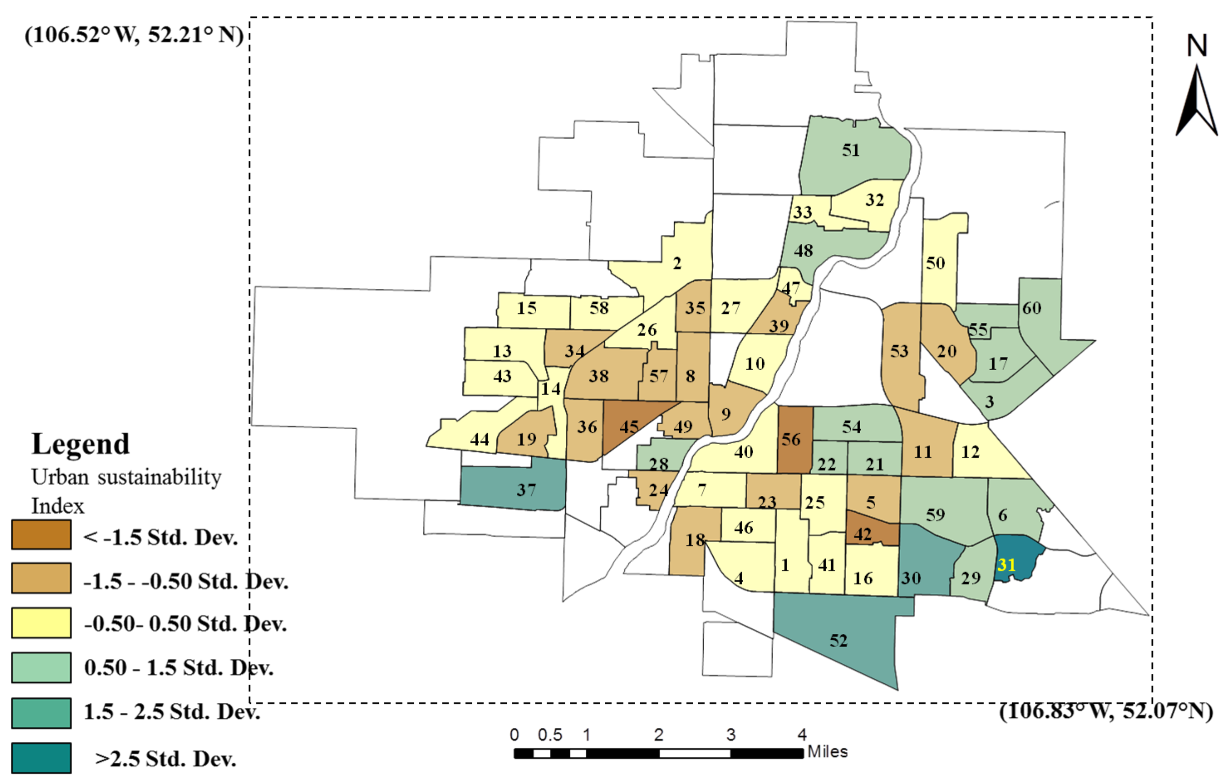

(106.52° W, 52.21° N)
N
Legend
QOL Index
<-1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.5 - 0.5 Std. Dev.
0.50 - 1.5 Std. Dev.
>1.5 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
House Index
<-2.5 Std. Dev.
-2.5- -1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.50- 0.50 Std. Dev.
0.50 - 1.5 Std. Dev.
1.5-1.6 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

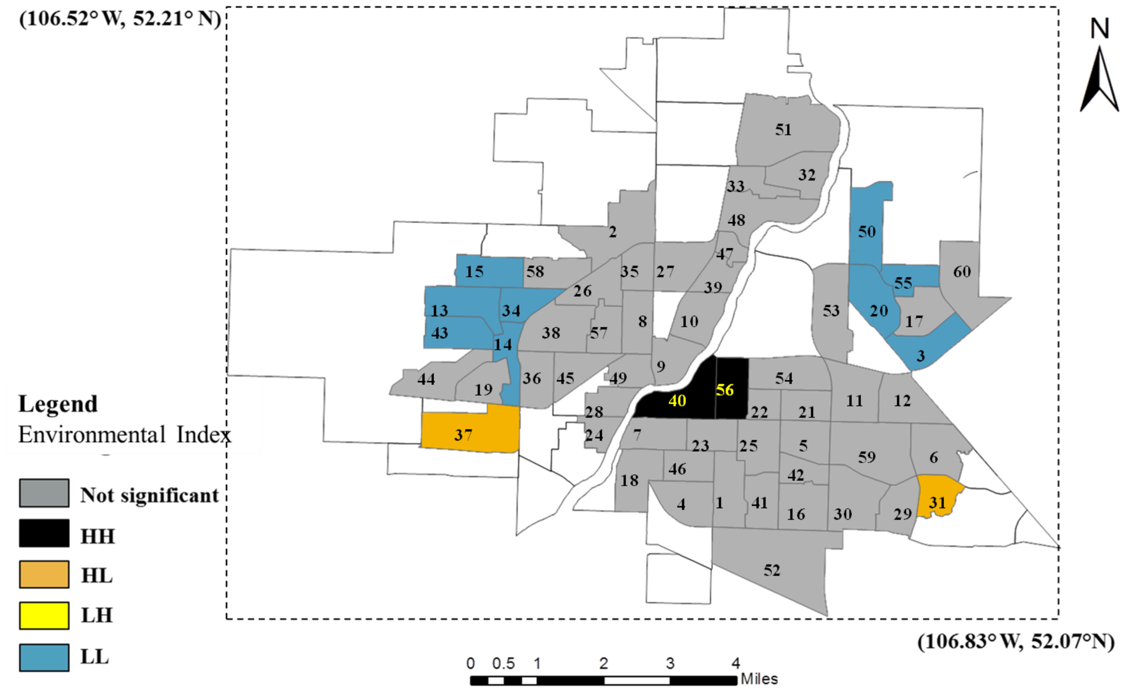

(106.52° W, 52.21° N)
N
Legend
Household Index
<-1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.5 - 0.5 Std. Dev.
0.50 - 1.5 Std. Dev.
1.5 -1.9 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

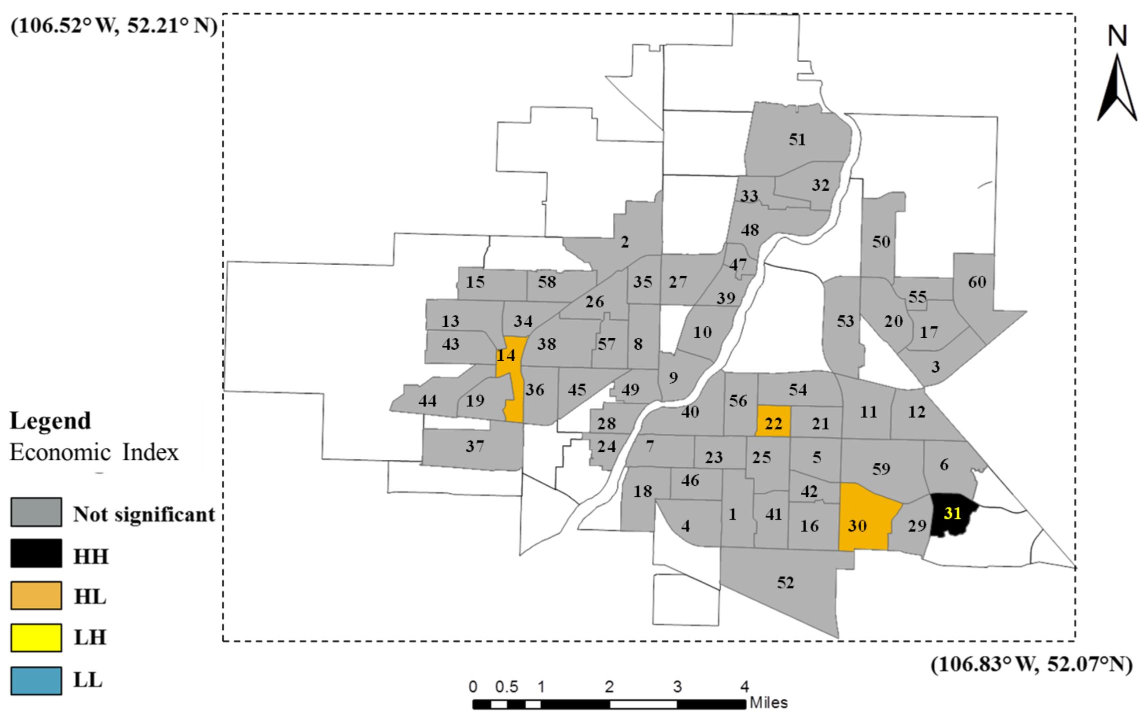

(106.52° W, 52.21° N)
N
Legend
Mixed land use
Index
<-2.5 Std. Dev.
-2.5- -1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.50- 0.50 Std. Dev.
0.50 - 1.5 Std. Dev.
1.5-1.6 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

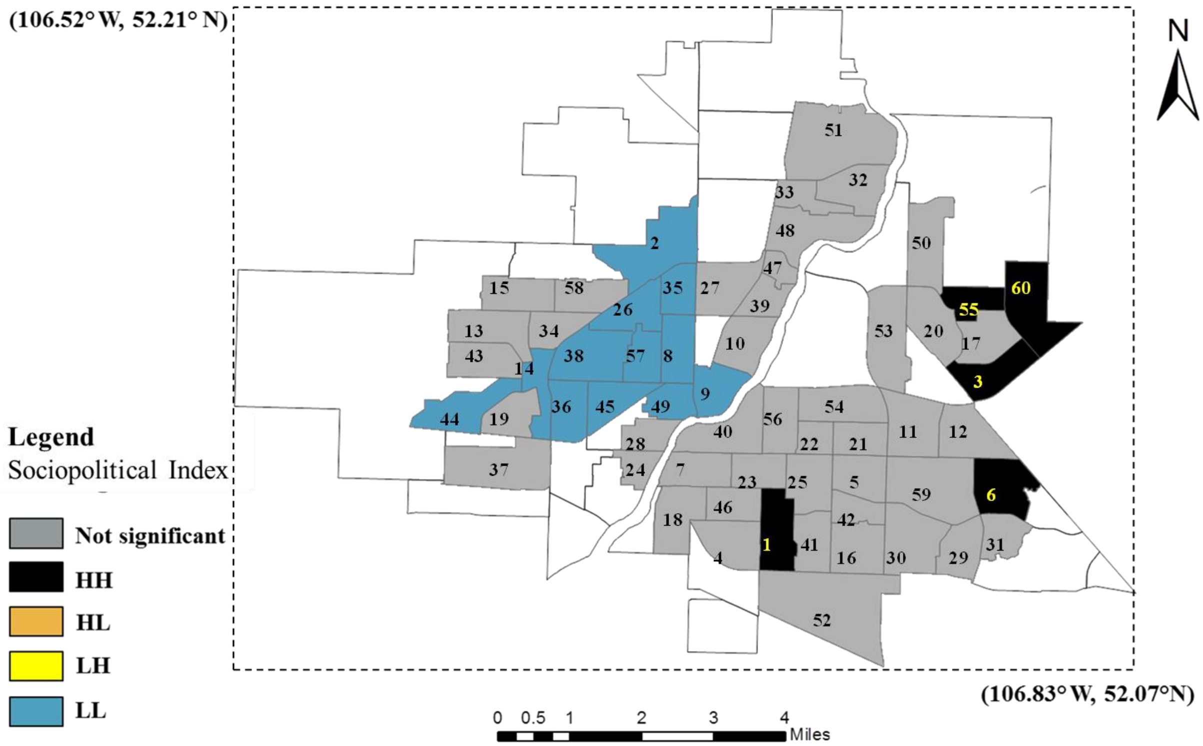

(106.52° W, 52.21° N)
N
Legend
Urbanization Index
<-1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.5 - 0.5 Std. Dev.
0.50 - 1.5 Std. Dev.
>1.5 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

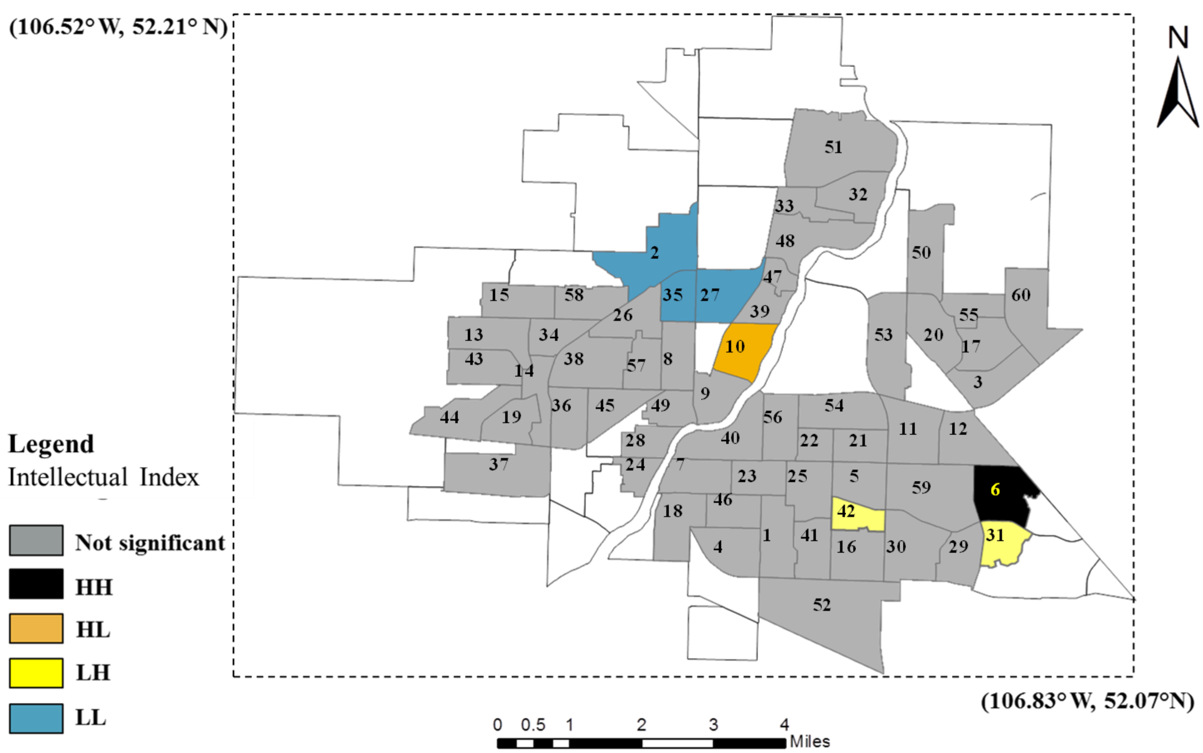

(106.52° W, 52.21° N)
N
Legend
Urban sustainability Index
< -1.5 Std. Dev.
-1.5 - -0.50 Std. Dev.
-0.50- 0.50 Std. Dev.
0.50 - 1.5 Std. Dev.
1.5 - 2.5 Std. Dev.
>2.5 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

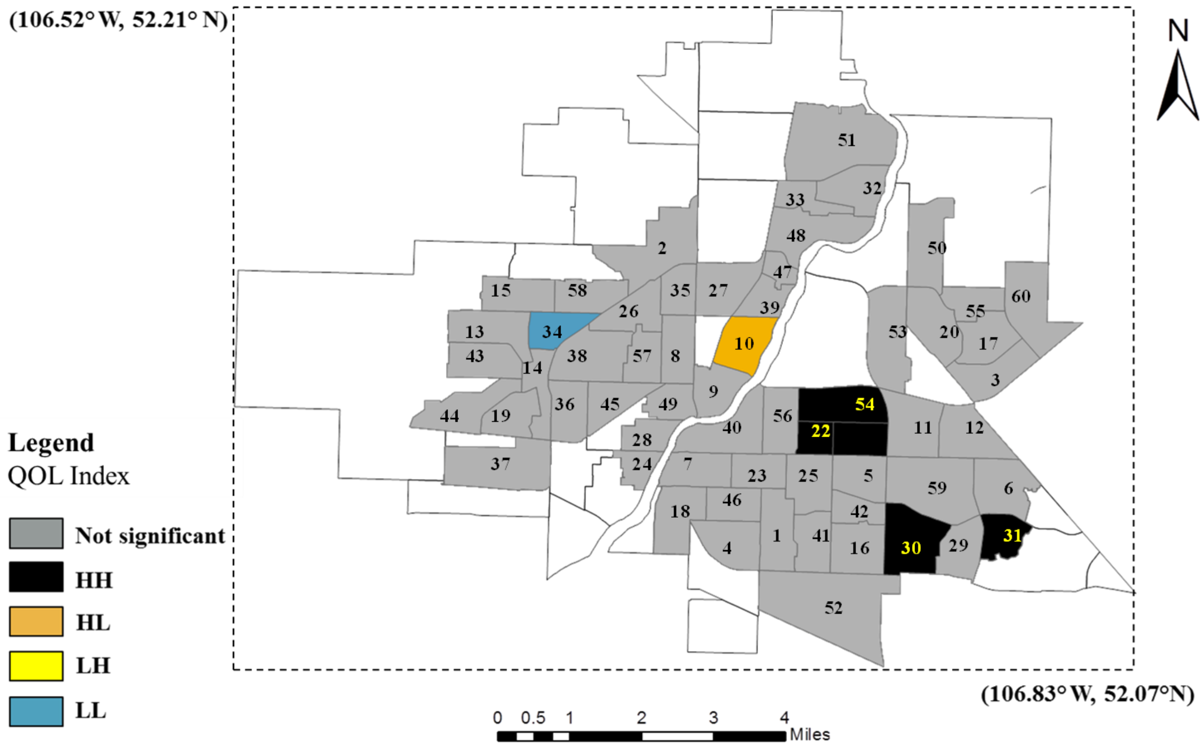
APPENDIX G
LISA SPATIAL ANALYSIS OF URBAN SUSTAINABILITY INDICES WITH K-NEAREST NEIGHBOUR AS THE CONCEPTUALIZATION OF SPATIAL RELATIONSHIPS FOR SASKATOON IN 2006

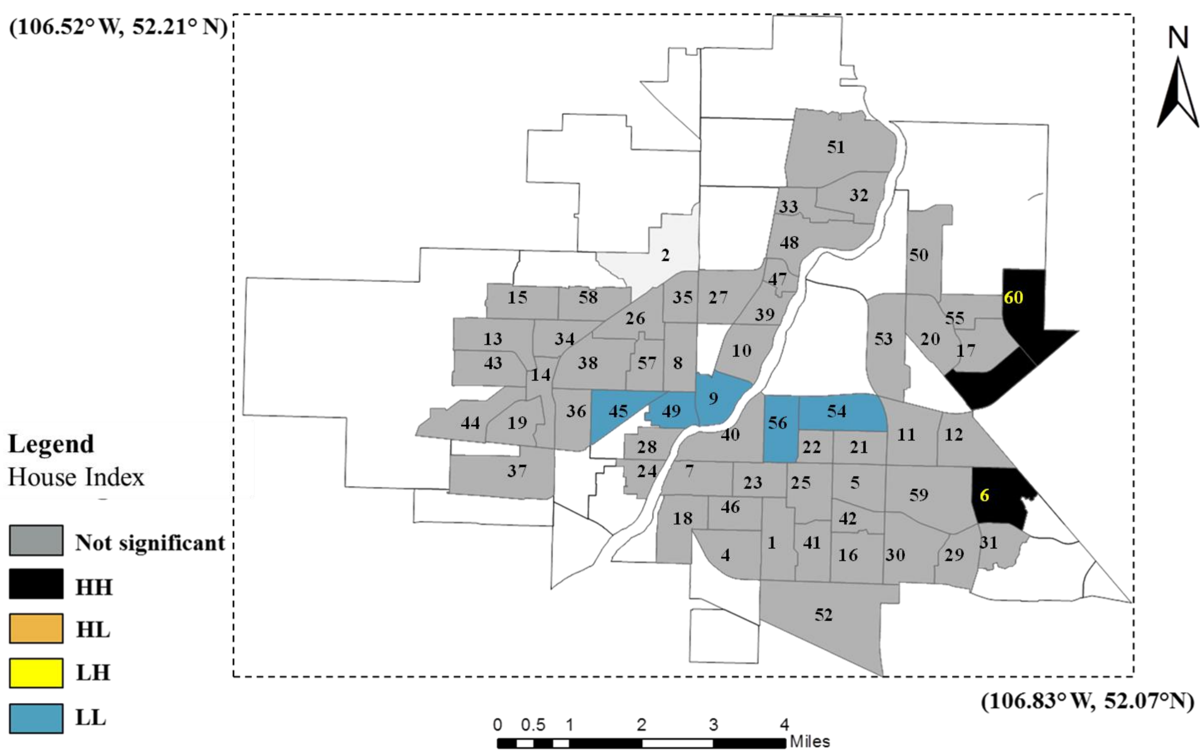


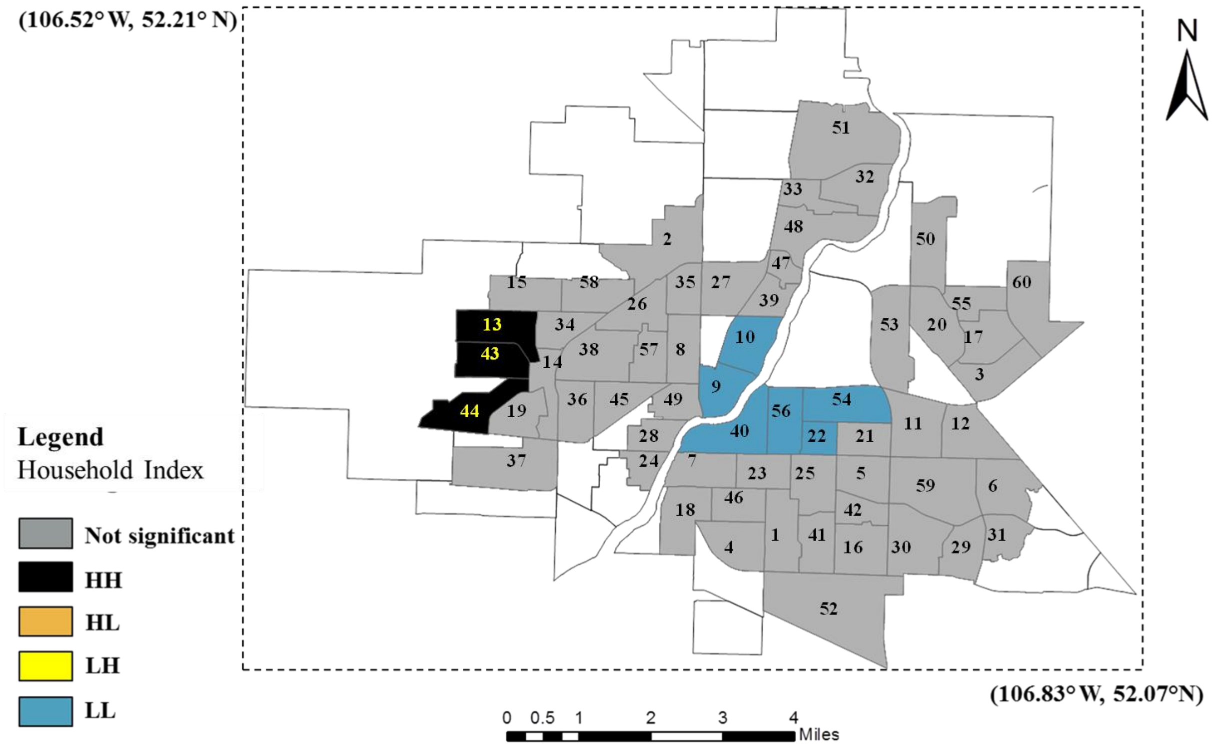



(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Sociopolitical Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles

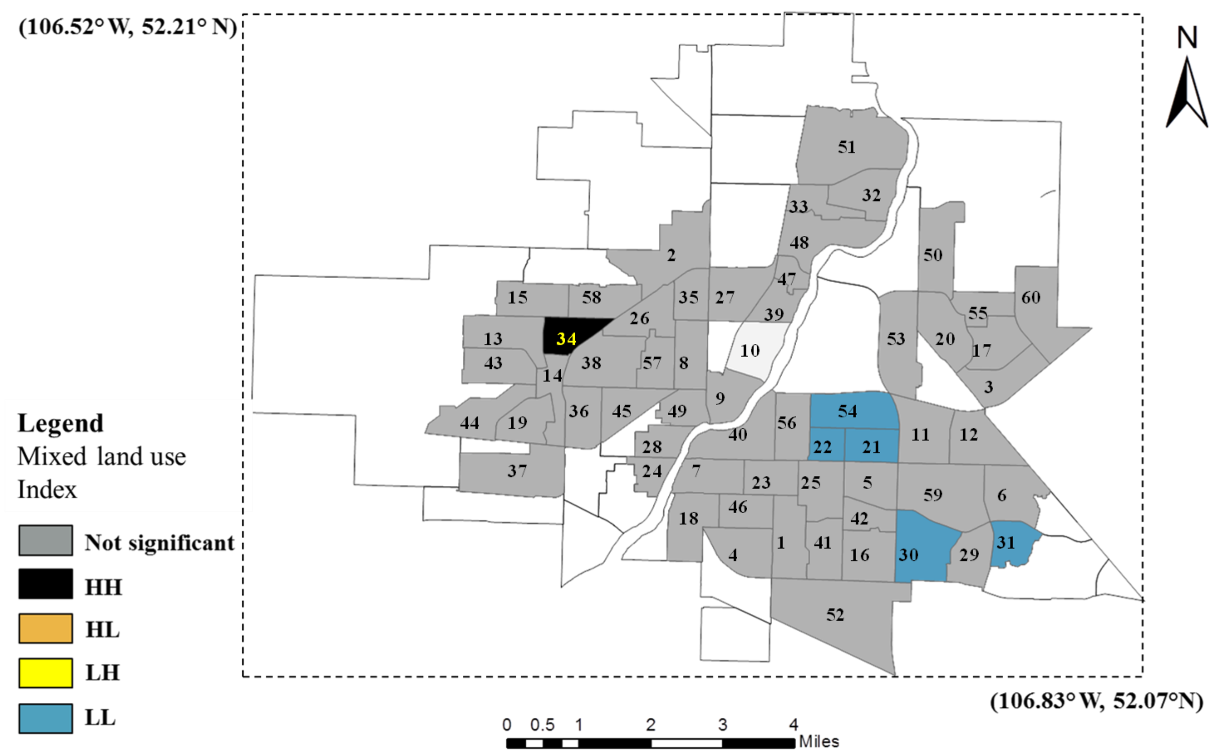

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
Intellectual Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
QOL Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles

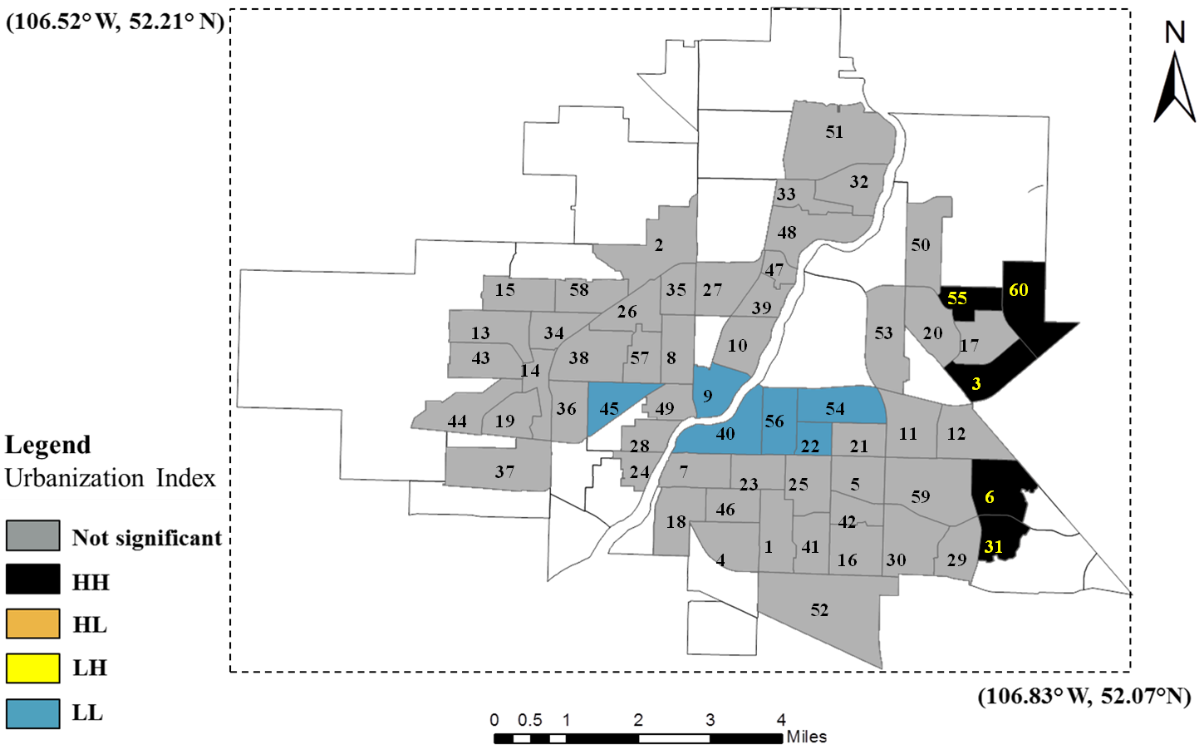

(106.52° W, 52.21° N)
(106.83° W, 52.07°N)
N
Legend
House Index
Not significant
HH
HL
LH
LL
0 0.5 1 2 3 4
Miles

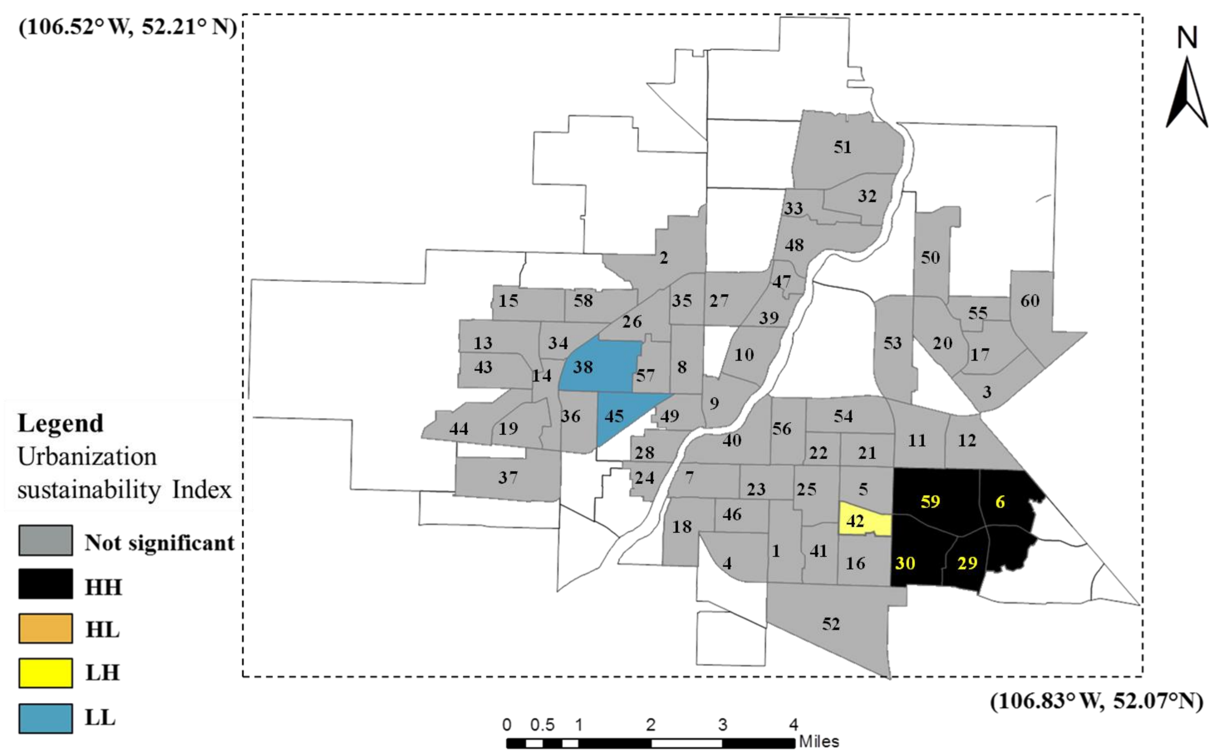


(106.52° W, 52.21° N)
N
Legend
Household Index
Not significant
HH
HL
LH
LL
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

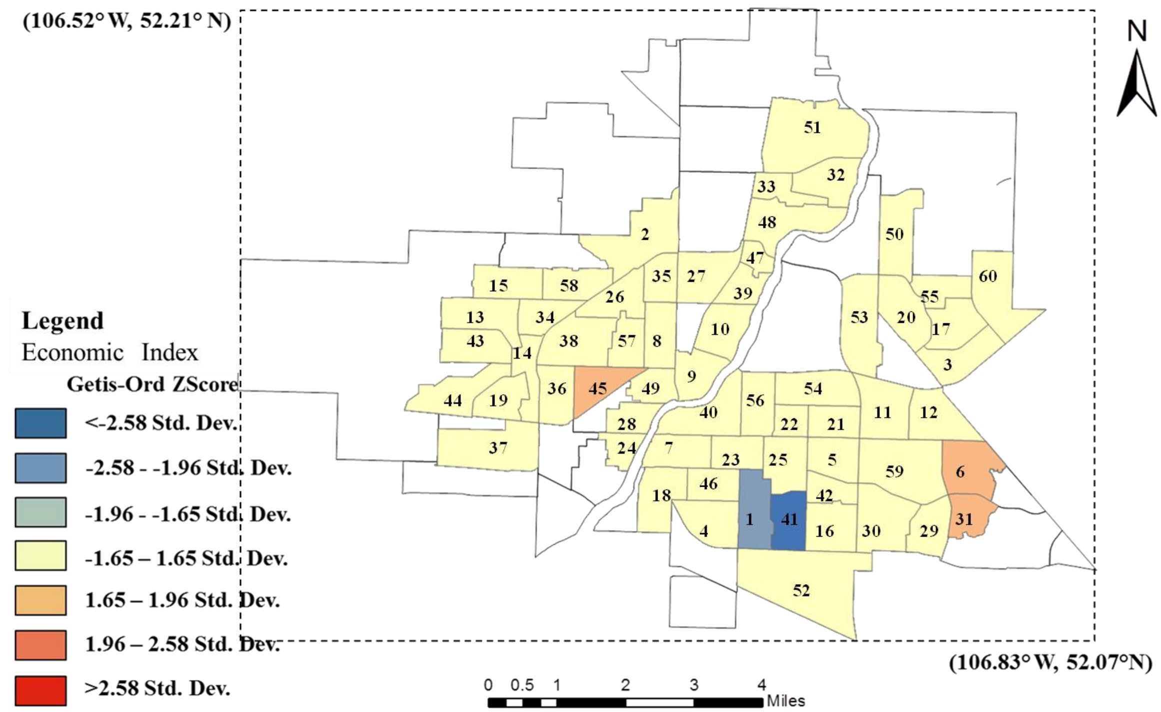


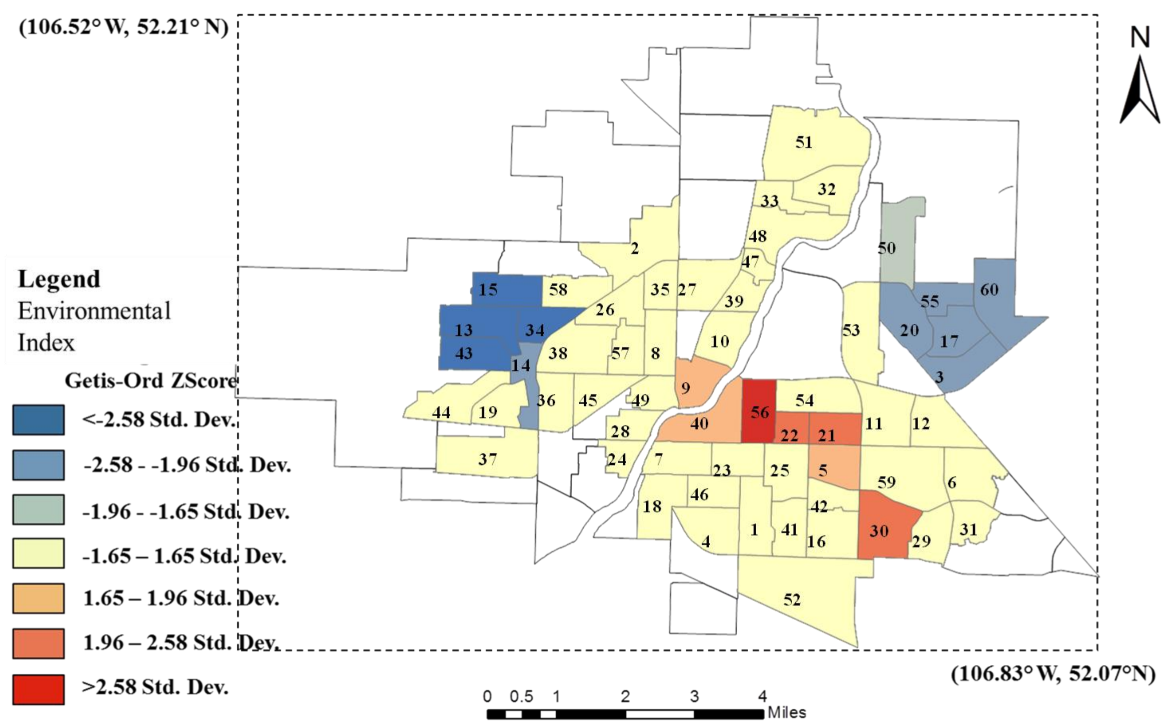
(106.52° W, 52.21° N)
N
Legend
Mixed land use Index
Not significant
HH
HL
LH
LL
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

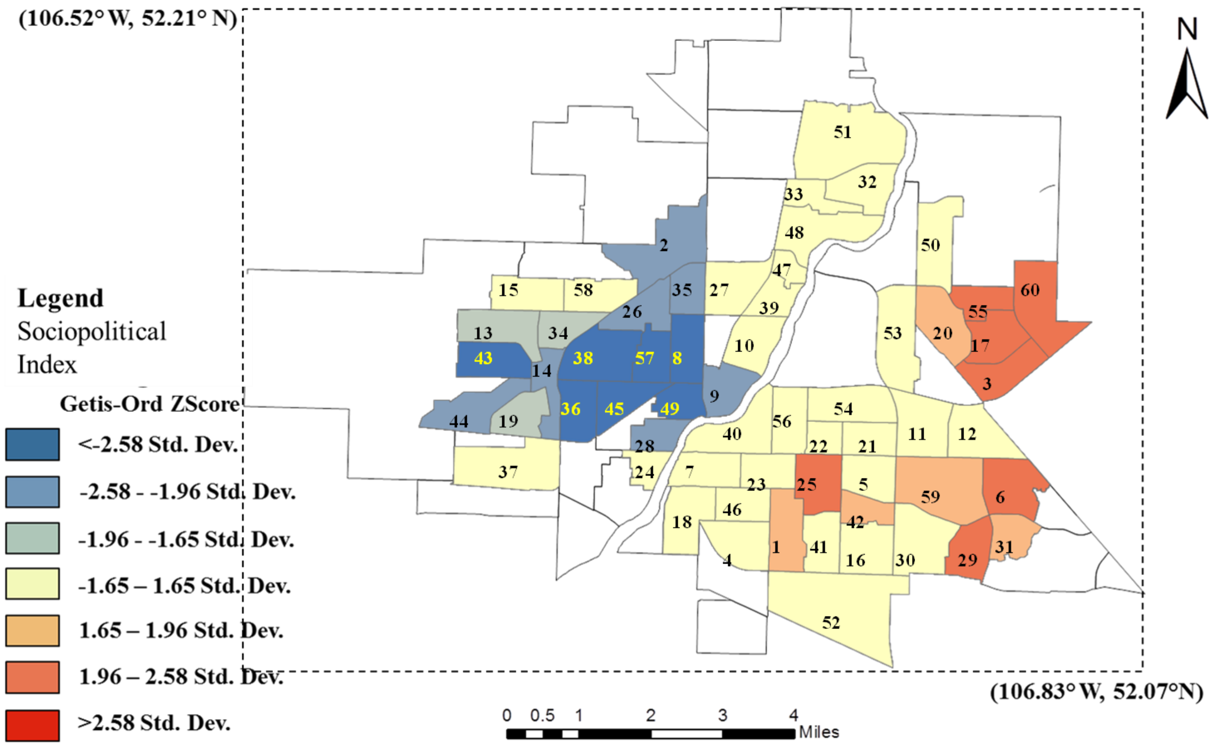

(106.52° W, 52.21° N)
N
Legend
Urbanization Index
Not significant
HH
HL
LH
LL
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

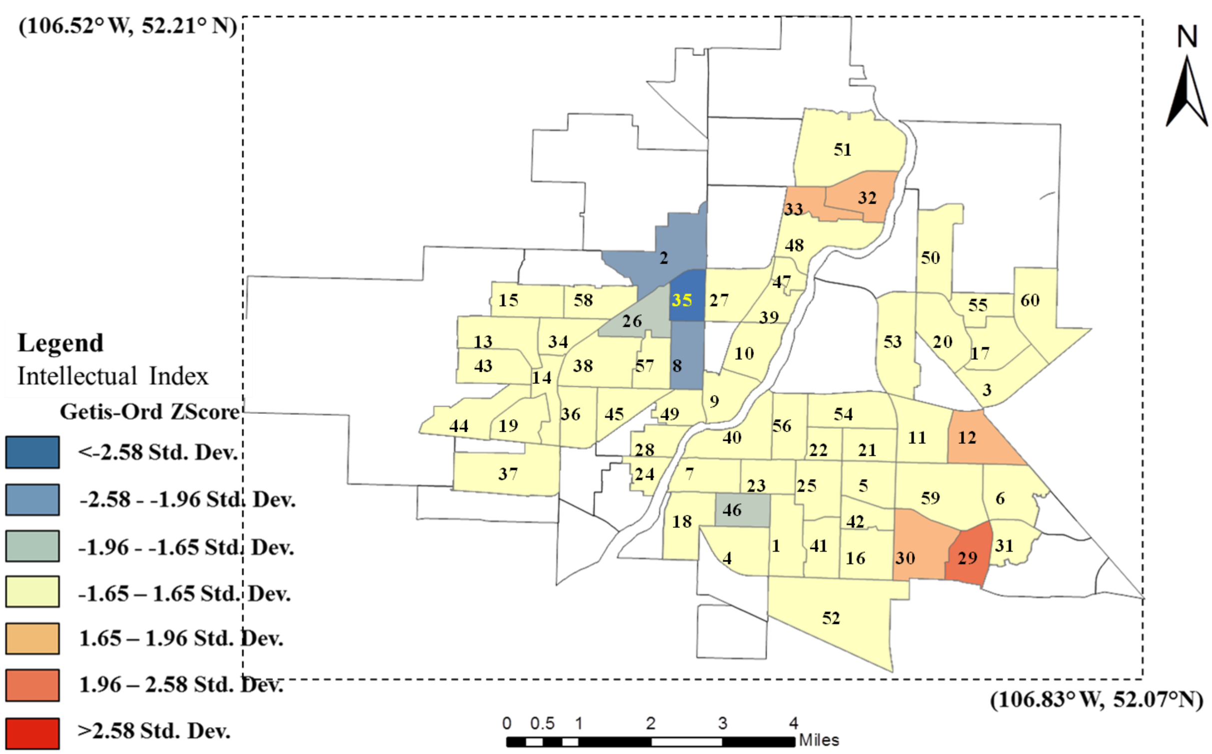

(106.52° W, 52.21° N)
N
Legend
Urbanization sustainability Index
Not significant
HH
HL
LH
LL
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles

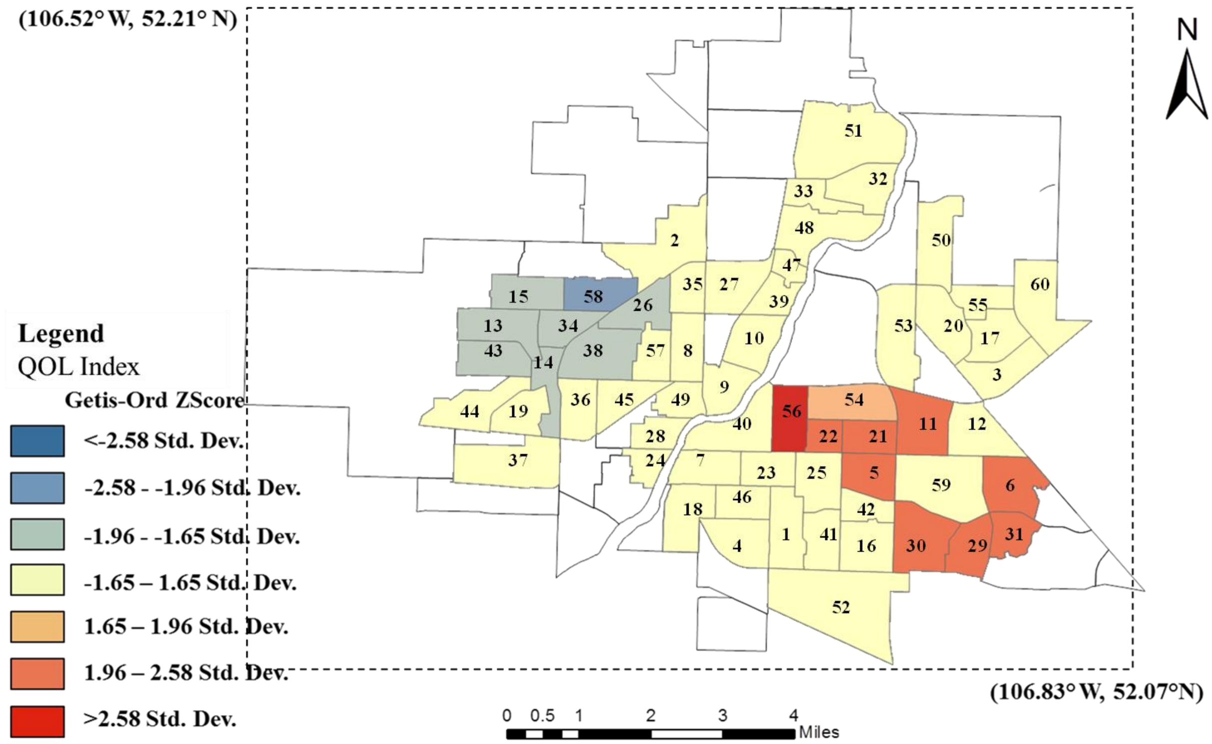
APPENDIX H
GETIS-ORD Gi* SPATIAL ANALYSIS OF URBAN SUSTAINABILITY INDICES WITH K-NEAREST NEIGHBOUR AS THE CONCEPTUALIZATION OF SPATIAL RELATIONSHIPS FOR SASKATOON IN 2006

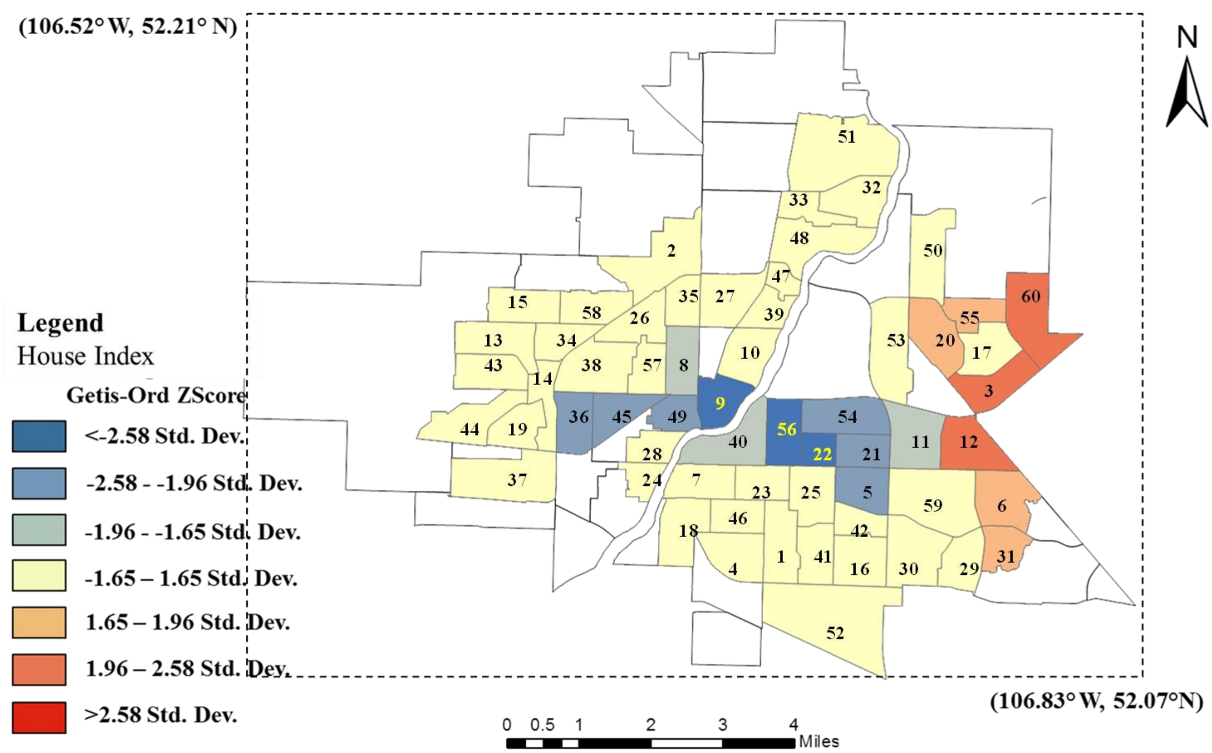


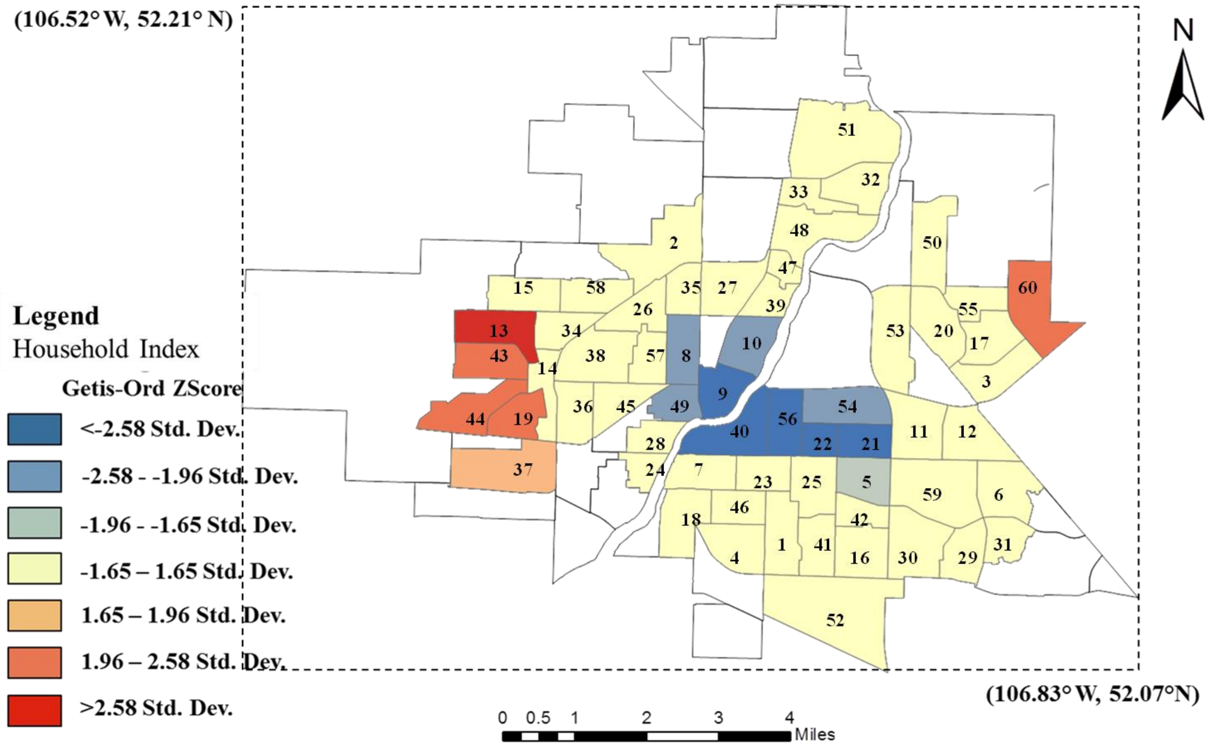


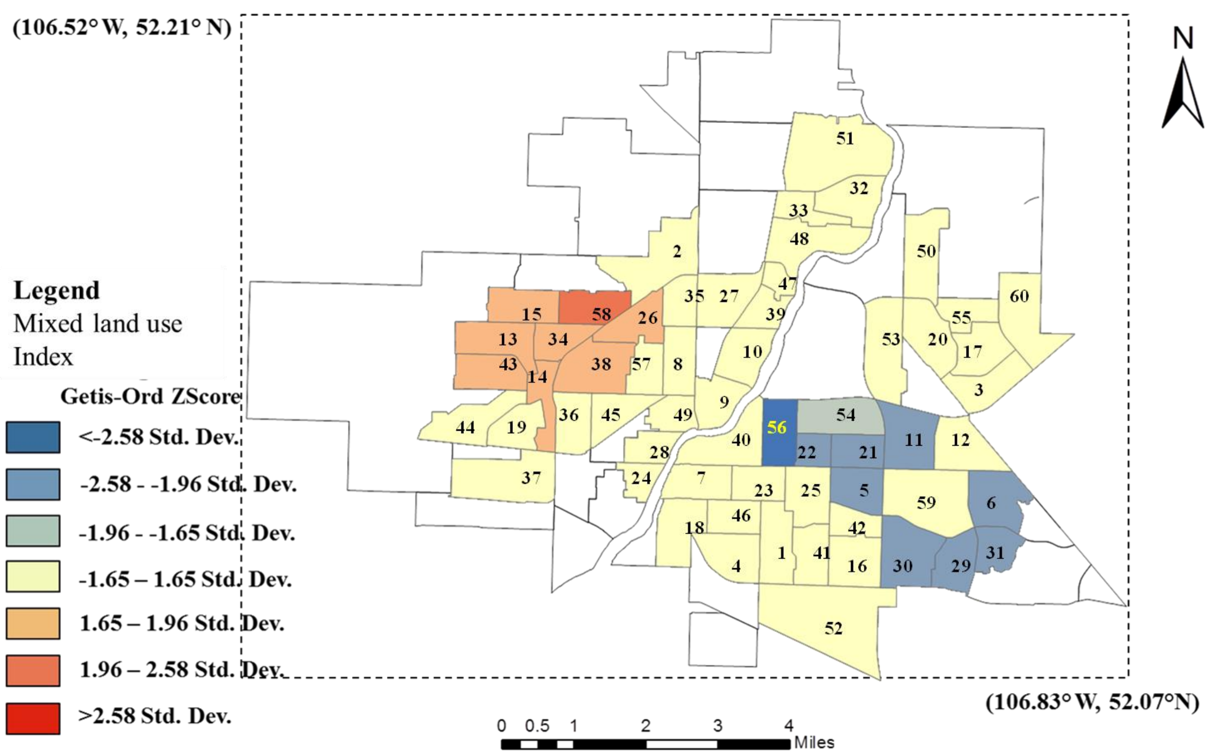

(106.52° W, 52.21° N)
N
Legend
Sociopolitical Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4 Miles

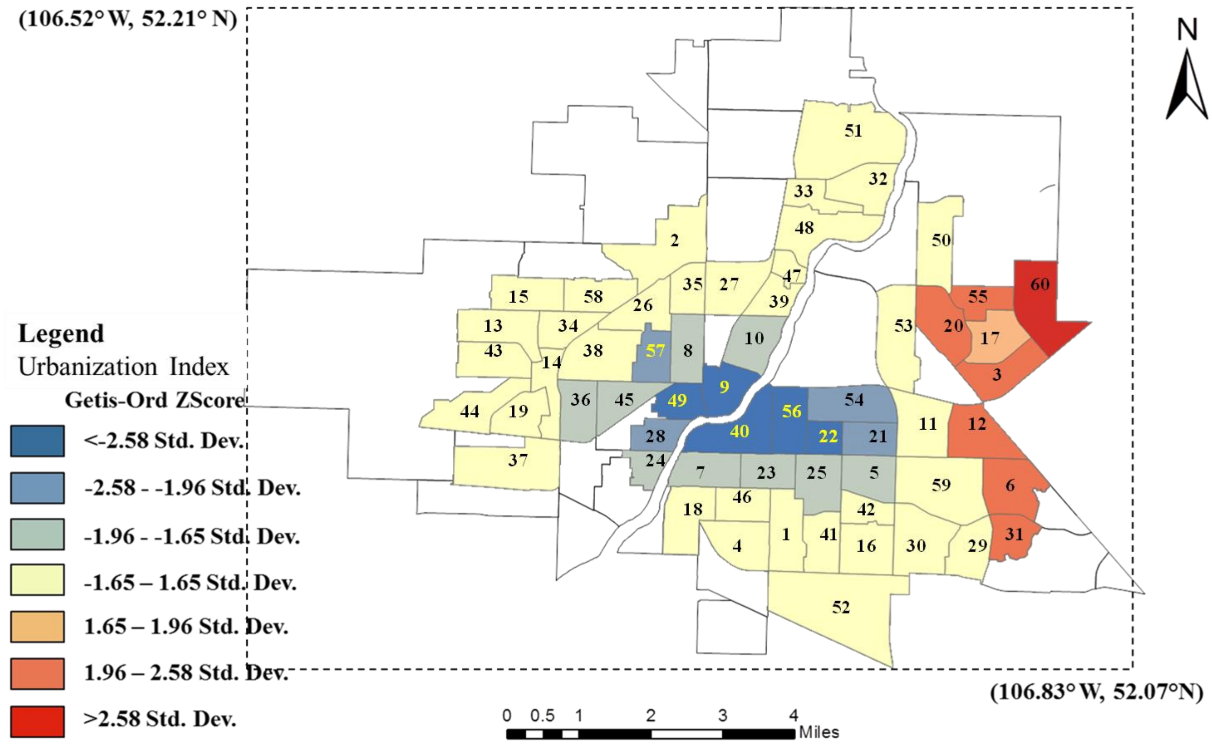

(106.52° W, 52.21° N)
N
Legend
Intellectual Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4 Miles

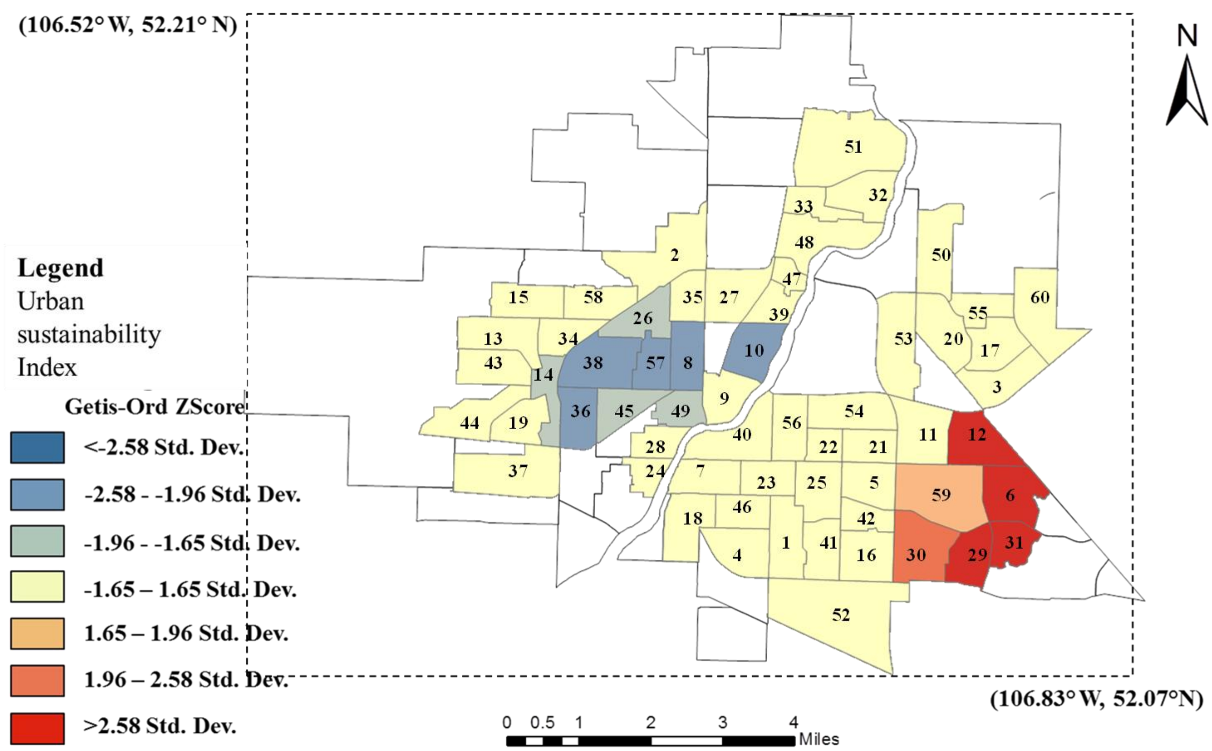

(106.52° W, 52.21° N)
N
Legend
QOL Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
House Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
Household Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
Mixed land use Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
Urbanization Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles


(106.52° W, 52.21° N)
N
Legend
Urban sustainability Index
Getis-Ord ZScore
<-2.58 Std. Dev.
-2.58 - -1.96 Std. Dev.
-1.96 - -1.65 Std. Dev.
-1.65 – 1.65 Std. Dev.
1.65 – 1.96 Std. Dev.
1.96 – 2.58 Std. Dev.
>2.58 Std. Dev.
(106.83° W, 52.07°N)
0 0.5 1 2 3 4
Miles