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Measuring Urban Growth, Urban Form and Accessibility as Indicators of Urban Sprawl in Hamilton, New Zealand

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Cover photo: Urban development 2001-2014 in northern Hamilton.

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Master thesis, 30 credits, in Geographical Information Science

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Abstract

Urban sprawl is a complex phenomenon with a wide range of definitions and associated measurement methods. Hamilton City is currently the fourth most populous territorial authority in New Zealand. The city boundary was extended in 1989 in order to provide sufficient land for urban growth for at least 25 years. Despite being neither unplanned nor unchecked, urban growth within this boundary has been branded by the media as urban sprawl. Remote sensing and GIS techniques have been used to measure urban growth, urban form and accessibility in order to determine whether the post-1989 urban growth in Hamilton should be categorised as urban sprawl. Supervised classification of Landsat imagery acquired in 1990, 2001 and 2014 showed that urban growth occurred at a comparable rate to population growth, and hence on this basis should not be categorised as urban sprawl. However there are statistically significant differences in urban form and accessibility metrics between new (developed from 1990 to 2014) and old (developed prior to 1990) neighbourhoods. New neighbourhoods exhibit characteristics typically associated with areas of urban sprawl, such as being more homogeneous with lower dwelling densities, high proportions of single dwellings, poorer street connectivity, increased travelling distances, and reduced accessibility and walkability. Hence on this basis the post-1989 urban growth in Hamilton should be categorised as urban sprawl. These contradicting conclusions demonstrate the complexity of the urban sprawl phenomenon and that whether the post-1989 urban growth should be categorised as urban sprawl depends upon the particular definition of urban sprawl that is adopted and the measurement method used. As these metrics reflect a particular point it time it is recommended that they be recalculated at regular intervals in the future as the city continues to evolve. Existing and prospective residents should be aware that those living in new neighbourhoods on the city fringe are currently exposed to the negative public health effects of urban sprawl. However, these effects may be reduced if policymakers take steps to reduce homogeneity, increase dwelling density, and reduce travelling distances.

Keywords: urban sprawl, urban growth, urban form, accessibility, New Zealand

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List of Abbreviations

ArcGIS	Suite of GIS software products developed by ESRI
df	Degrees of freedom
ESRI	Environmental Systems Research Institute
GCS	Geographic coordinate system
GeoTIFF	TIFF file with embedded georeferencing information
GIS	Geographic information system
JPEG	Joint Photographic Experts Group
km	Kilometres
LINZ	Land Information New Zealand
M	Mean
m	Metres
n	Number in sample
n/a	Not applicable
NASA	National Aeronautics and Space Administration
NIR	Near-infrared
N.Z.	New Zealand
NZGD	New Zealand Geodetic Datum
NZMG	New Zealand Map Grid
NZMS	New Zealand Map Series
NZTM	New Zealand Transverse Mercator
p	Probability
PCS	Projected coordinate system
PDF	Portable Document Format
s	Standard deviation
SD	Standard deviation
SWIR	Shortwave infrared
TIFF	Tagged Image File Format
U.S.	United States
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic Datum

Chapter 1: Introduction

1.1 Background and Motivation

In November 1989 the boundary of Hamilton City was extended to include 2678 hectares of rural land, bringing the total city area to 9427 hectares. The largest areas of extension were in the northeast (in an area known as Rototuna), northwest (Rotokauri) and southwest (Peacocke). This boundary extension occurred at the direction of the New Zealand Local Government Commission who envisaged that it would provide sufficient land to cater for the city's urban growth for at least the next 25 years. Development of the new areas was planned to occur in stages with Rototuna to be developed first (Hamilton (N.Z.) City Planning Division 1991).

Over the following 25 years urban development in Hamilton has occurred within the city boundary established in 1989, and there is still much capacity for future expansion. As was originally planned, much of the urban growth has been in the north. Despite being neither unplanned nor unchecked, recent media attention has branded Hamilton's urban growth as urban sprawl, in particular targeting the "sprawling northern suburb of Rototuna" (Adams 2012; Fox 2012a, b).

Urban sprawl is a complex phenomenon and the literature yields a wide range of definitions incorporating aesthetic judgements, unwanted externalities, policy consequences, land development patterns, and urban growth rates (Galster et al. 2001). There are many potential causes of urban sprawl including population growth, transportation facilities, poor urban planning, housing availability and the personal preference of residents (Bhatta 2010). The negative economic, environmental, social and public health effects of urban sprawl are widely considered to outweigh any positive effects, leading to the term having a negative connotation.

Just as there are many ways to define urban sprawl, there are also many ways to measure the phenomenon including urban area growth rates, density measurements, and spatial geometry, as well as differences in access to public services, employment opportunities and commercial areas (Frenkel and Ashkenazi 2008). Measures of urban sprawl related to urban form and accessibility are considered to be of particular relevance to policymakers and residents as they can aid in quantifying the public health effects experienced by residents, help policymakers identify the steps necessary to reduce these effects, and allow existing and prospective residents to make more informed choices when deciding between central and city-fringe living options.

1.2 Research Questions and Hypotheses

The primary research question to be addressed in this study is whether the post-1989 urban growth in Hamilton should be categorised as urban sprawl? To investigate this research question urban growth, urban form, and accessibility will be measured in order to address three sub-questions which reflect different ways of defining and measuring urban sprawl:

- Has growth in the Hamilton urban area occurred at a greater rate than the city’s population growth?
- Are new neighbourhoods more homogeneous, having a higher proportion of single family dwellings on larger land parcels, and do they lack street connectivity?
- Do residents of old and new neighbourhoods have different access to essential services, commercial areas, employment areas, and public transport?

The two hypotheses to be tested are:

- The rate of growth in the Hamilton urban area has not occurred at a greater rate than the city’s population growth.
- There is no difference in urban form and accessibility metrics between old and new neighbourhoods.

If these hypotheses are accepted then it can be concluded that the post-1989 urban growth in Hamilton should not be categorised as urban sprawl.

1.3 Study Area

Hamilton City lies within the Waikato Region in the upper North Island (Figure 1), and is currently the fourth most populous of the 67 territorial authorities that comprise the second tier of local government in New Zealand (Statistics New Zealand 2013).

The first European settlement was established in 1864 near the abandoned Maori village of Kirikiriroa on the west bank of the Waikato River. Hamilton initially developed as

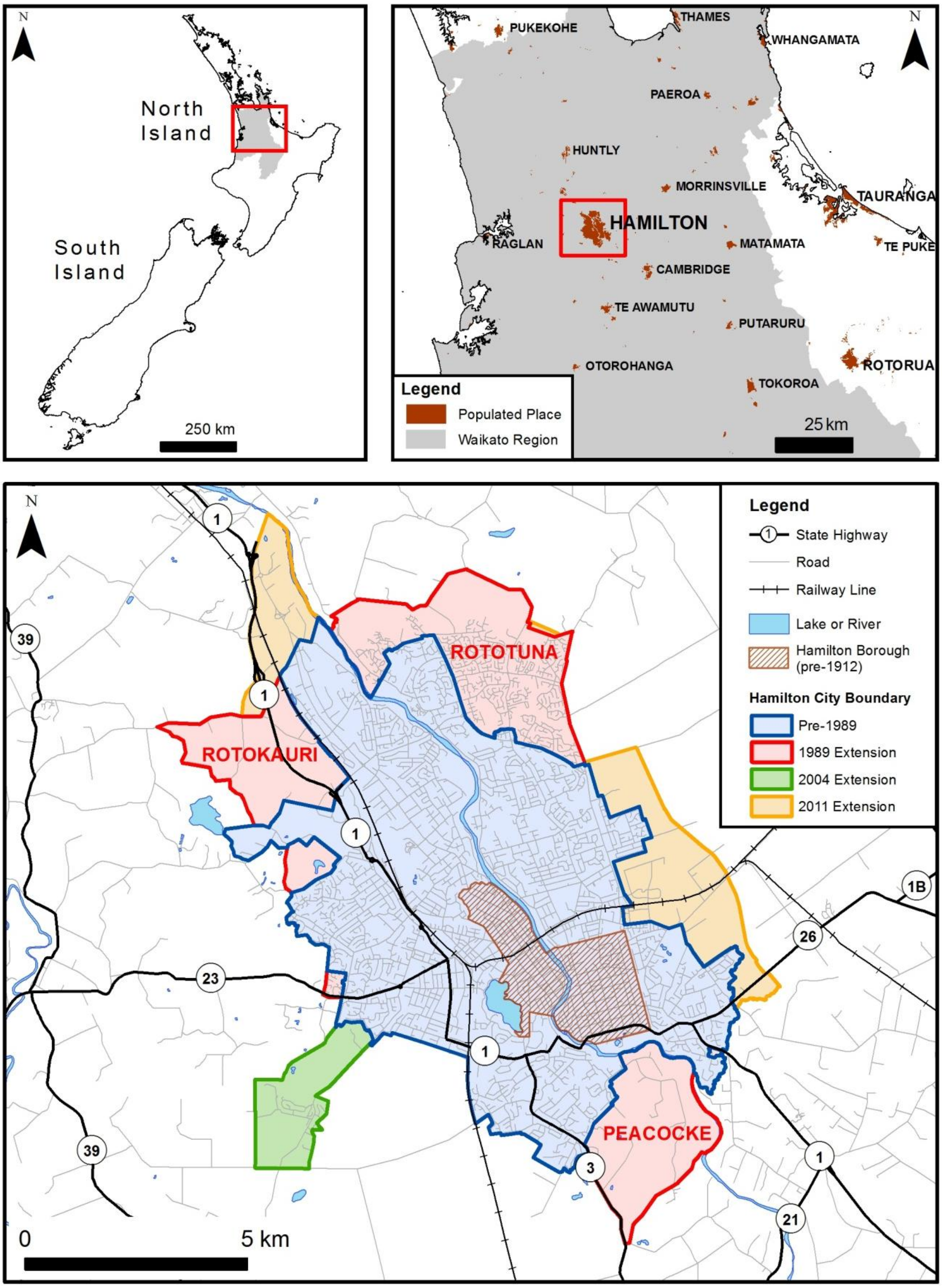


Figure 1: Hamilton City boundary extensions 1989 to present showing extension into the Rototuna, Rotokauri and Peacocke areas in 1989.

two separate settlements on either side of the river, Hamilton East and Hamilton West, which were joined administratively into a single borough in 1877 and physically by a traffic bridge in 1879 (Swarbrick 2012). In 1917 Hamilton absorbed the adjacent Frankton borough, which was an important junction on the main trunk railway line. This, in addition to being a major river port and its location on the main north-south road, saw the town develop as a regional transport hub. By 1945 the population exceeded 20,000 and Hamilton gained city status (Swarbrick 2012).

Since 1877 there have been twelve extensions to the Hamilton Borough/City boundary, the earliest in 1912 and the most recent in 2011 (Westwood 1954; Hamilton (N.Z.) City Council 2011). Relative to the original borough boundary, the cumulative effect of these extensions has been growth of the urban area predominantly to the north and northwest on both sides of the Waikato River (Figure 1).

The 10th extension occurred in November 1989 when the city boundary was extended to include 2678 hectares of rural land, bringing the total city area to 9427 hectares. The largest areas of extension occurred to the northeast (in an area known as Rototuna), northwest (Rotokauri) and southwest (Peacocke) (Figure 1). This boundary extension occurred at the direction of the New Zealand Local Government Commission who envisaged that it would provide sufficient land to cater for the city's urban growth for at least the next 25 years. Development of the new areas was planned to occur in stages with Rototuna to be developed first (Hamilton (N.Z.) City Planning Division 1991).

The 11th extension occurred in July 2004 when the city boundary was extended to include 433 hectares of land in order to bring the existing Temple View community and adjoining rural land into Hamilton City (Figure 1). This extension brought the total city area to 9860 hectares (Hamilton (N.Z.) City Council 2005).

The 12th extension occurred in July 2011 when the city boundary was extended to include 1220 hectares of predominantly rural land to the east (Ruakura) and north (Te Rapa North) (Figure 1), bringing the total city area to 11,080 hectares (Hamilton (N.Z.) City Council 2011). This extension occurred in order to provide for the city's future requirements and to allow for peri-urban development to be more appropriately managed, with the new city boundaries based on land designated for proposed major roads (the Waikato Expressway and Horotiu/Te Rapa Bypass) (Hamilton (N.Z.) City Council & Waikato (N.Z.) District Council 2005).

The focus of this study is the 1989 boundary extension and growth in the urban area that has occurred between 1989 and 2014 within this boundary. Areas added to Hamilton City in 2004 and 2011, which were predominantly rural at the time of their addition and remain so today, are excluded from measurements of urban growth, urban form and accessibility.

1.4 Thesis Outline

This chapter presents the background to and motivation for the study, the research questions to be answered and hypotheses to be tested, and an introduction to the study area.

Chapter 2 presents a review of recent literature on urban sprawl including its definition, causes, effects and measurement. This is followed by a review of the literature on urban sprawl in New Zealand.

Chapter 3 outlines the sources of data used in this study, associated metadata, and preliminary data management processes. It then goes on to describe the urban sprawl measurement methods used in this study and the application of remote sensing and GIS techniques to carry out these measurements using ArcGIS.

Chapter 4 presents the results of the urban growth, urban form and accessibility analysis. Urban growth is compared to population growth, and the significance of any difference in urban form and accessibility metrics between old and new neighbourhoods is explored. Future predictions for urban form and accessibility metrics for new neighbourhoods are also presented.

Chapter 5 discusses the key findings of the study with respect to each of the research questions, as well as study limitations and recommendations for further research.

Chapter 6 presents the conclusions of the study with respect to the research hypotheses, and is followed by a list of cited references and appendices containing additional information.

Chapter 2: Literature Review

2.1 Introduction

Modern usage of the term “urban sprawl” was first coined in the late 1930s by city planners in the south-eastern United States (Nechyba and Walsh 2004). However it was not until the boom in suburban growth in the United States following World War II that widespread apprehension emerged as to its costs. The rise of the modern environmental movement in the 1960s and 1970s saw a focus placed on the environmental and social implications of urban sprawl, and it is increasingly viewed as a significant and growing problem (Bengston et al. 2004). Although much of the literature focuses on the United States, urban sprawl is by no means a phenomenon restricted to North America with recent studies based in Asia, South America and Europe (e.g. Jaeger et al. 2010; Hammann 2012; Yue at al. 2013).

The chapter presents a review of recent literature on urban sprawl including its definition, causes, effects and measurement. The final section presents a review of the literature on urban sprawl in New Zealand.

2.2 Definition of Urban Sprawl

A review of the literature highlights that urban sprawl is a complex phenomenon with no single definition. Studies often end up describing the phenomenon rather than actually defining it, and the term “urban sprawl” is used both as a noun (condition) and verb (process). Despite this lack of clarity in its definition, many would claim to “know it when they see it” (Galster et al. 2001).

Galster et al. (2001) provided the most detailed analysis of urban sprawl as at the time of publication. They noted however that the literature yielded no common definition of sprawl and that the wide range of definitions available could be divided into six groups:

- Definition by example (e.g. Los Angeles).

- Aesthetic judgement (e.g. an ugly development pattern).

- The cause of an unwanted externality (e.g. traffic congestion, environmental contamination, conversion of farmland to urban uses).

- A consequence of some independent variable (e.g. poor planning, zoning policies).

- An existing pattern of land development (e.g. low density, leapfrogging, dispersion of employment and residential development).

- A stage in the development process that occurs over a period of time as an urban area expands.

Galster et al. (2001) also noted that despite these different definitions the literature does agree that all development is not sprawl, and that simply because an urban area is larger does not mean that it is sprawled. In addition, they acknowledge that all sprawl does not have the same characteristics or dimensions, and go on to propose a conceptual definition of sprawl as a pattern of land use in an urbanized area that exhibits low levels of some combination of eight distinct dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses and proximity.

The United States Environmental Protection Agency (as cited in Barnes et al. 2001) provided a more specific definition when it came to urban growth, considering urban sprawl to occur when the rate of land conversion to non-agricultural or non-natural uses (i.e. urban growth) exceeds the rate of population growth.

In a more recent review of the literature, Bhatta (2010) concludes that a black and white definition of urban sprawl does not exist and that, while there is debate over the definition, there is consensus that it is characterised by an unplanned and uneven pattern of urban growth, at a rate which exceeds the rate of population growth, driven by a multitude of processes and leading to inefficient resource utilisation.

2.3 Causes and Effects of Urban Sprawl

There are many potential causes of urban sprawl and any two occurrences of the phenomenon may have different causes. Bhatta (2010) divides the potential causes into two groups:

- Factors which contribute to urban growth in general such as population growth, economic growth, industrialisation and transportation facilities. Whether the urban growth resulting from these factors is considered to be urban sprawl depends on its pattern, process and consequences.

- Factors which may directly facilitate urban sprawl such as poor urban planning, land values, physical geography, development and property taxes, housing availability, and the personal preference of residents.

The consequences of urban sprawl are as varied as its causes and may be both positive and negative. Bhatta (2010) summarises the positive effects of urban growth in general such as higher economic production, increased opportunities for the unemployed, and improved public services such as transportation and water supply. Other studies identify the positive effects of urban sprawl specifically, including increased satisfaction in housing preferences, easy access to open space, the benefits of later infilling “leapfrogged” land, the generation of suburban local governments which are likely to have lower crime rates and better public schools, and relatively short commuting times for those who both live and work in the suburbs (Kaplan and Austin 2004; Frenkel and Ashkenazi 2008; Wassmer 2008).

However the negative effects of urban sprawl are widely considered to outweigh any positive effects, leading to the term having a negative connotation. The negative effects, as summarised by Bhatta (2010), can be divided into three groups:

- Economic effects including loss of productive farmland and increased public service and infrastructure costs.

- Environmental effects including loss and fragmentation of habitats, reduced air and water quality, and increased land surface temperatures.

- Social and public health effects including reduced accessibility and walkability, increased dependence on private motor vehicles, and race and income based segregation.

Song and Knaap (2004) provide more detail as to the link between urban sprawl and reduced public health. They state that, according to critics of urban sprawl, contemporary suburban developments:

- Are homogeneous and lack a mix of land uses, being dominated by single-family dwelling units on large lots.

- Contain too many winding streets and cul-de-sacs, creating blocks that are too big and thus lack connectivity.

As a result contemporary suburban developments are characterised by too much separation between land uses and increased travelling distances. This leads to a reduction in accessibility, walking and biking, and an increase in the use of private motor vehicles (Song and Knaap 2004).

2.4 Measuring Urban Sprawl

Just as there are many ways to define urban sprawl, there are also many ways to measure the phenomenon. Frenkel and Ashkenazi (2008) divide measurement methods suggested in the literature into five major groups, and each group addresses different definitions of urban sprawl:

- Growth rates – measures include comparison of the growth rate of an urban area versus the population living in that area (e.g. Jat et al. 2008; Pijanowski and Robinson 2011; Bagan and Yamagata 2012; Hammann 2012).

- Density – measures include determining the ratio between the amount of a certain urban activity (e.g. residential units) and the area in which it takes place (e.g. Galster et al. 2001; Song and Knaap 2004; Knaap et al. 2005; Lowry and Lowry 2014).

- Spatial geometry – measures involve determining the geometric configuration and composition of an urban area including the degree to which its configuration is irregular, scattered and fragmented, and composition homogeneous and segregated (e.g. Torrens and Alberti 2000; Galster et al. 2001; Song and Knaap 2004; Knaap et al. 2005; Lowry and Lowry 2014).

- Accessibility – measures include determining household travelling distances and/or times to public service facilities, employment areas and commercial areas (e.g. Song and Knaap 2004; Knaap et al. 2005; Sohn et al. 2012; Lowry and Lowry 2014).

- Aesthetics – measures include resident surveys and comparison of landscapes with defined archetypes of urban sprawl (e.g. Torrens and Alberti 2000). Being subjective by definition, it is difficult to measure and quantify the aesthetics of sprawl (Frenkel and Ashkenazi 2008).

Urban form may be defined as the spatial configuration of fixed elements within a metropolitan region, including the spatial pattern of land uses and their densities as well as the spatial design of transport infrastructure (Anderson et al. 1996). Hence three of the groups of urban sprawl measurement methods are directly (density, spatial geometry) or indirectly (accessibility) measuring aspects of urban form.

The approach of Galster et al. (2001) to measuring urban sprawl focused on spatial geometry and involved proposing eight distinct dimensions of sprawl: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses and proximity. Each dimension reflects spatial relationships among units of analysis, with units defined by assigning housing units from census blocks into 1 mile (1600m) or ½ mile (800m) grids. The dimensions were then tested by applying them to thirteen large urbanized areas in the United States. Finally they calculated an overall sprawl ranking for each area. Galster et al. (2001) concluded that the dimensions make intuitive sense, and the relative rankings of the thirteen urbanized areas do not appear to be unreasonable.

Song and Knaap (2004) consider the dimensions proposed by Galster et al. (2001) to be of little use to urban residents and policymakers. They question whether public officials should be concerned or pleased if an urban area is, for example, ranked high in clustering and low in nuclearity. And if they are concerned, how should they respond? Song and Knaap (2004) go on to propose fifteen policy-relevant metrics of urban form that address the major criticisms of urban sprawl of direct concern to citizens and policymakers, primarily factors that contribute to the negative public health effects. These metrics are applied at the neighbourhood level (with neighbourhood boundaries defined by census blocks) and relate to street design and circulation systems (four metrics of connectivity within a neighbourhood, one metric of connectivity between neighbourhoods), single family dwelling density (three metrics including lot size and floor space), land use mix (two metrics of actual and planned land uses), accessibility (three metrics of distance to commercial use, bus stop and public park) and pedestrian access (two metrics of the percentage of single family dwellings within walking distance of commercial uses or bus stops). Song and Knaap (2004) calculated each of these metrics for 186 neighbourhoods in Portland, Oregon. Analysis of the results relative to neighbourhood age identified a trend in urban form since 1990 toward denser, more internally connected, and more pedestrian friendly yet relatively homogeneous neighbourhoods. It was concluded that such changes in urban form may have occurred in response to the region's urban growth management policies, although no attempt was made to isolate any particular policy instrument (Song and Knaap 2004).

Knaap et al. (2005) applied six of the metrics of Song and Knaap (2004) to neighbourhoods of varying age in five urban areas in the United States, with neighbourhoods defined by Traffic Analysis Zones (which are roughly coincident with census blocks). In addition they proposed a land use mix diversity index, and used all seven metrics to illustrate how urban development patterns differ within and across the urban areas since the 1940s. Their results showed that, in all of the urban areas, single family dwelling lot sizes have fallen and neighbourhoods have become more internally connected since the 1970s, while land use mix exhibited no obvious trend over time. Hence some metrics indicated that anti-sprawl policies may be having an impact, but other metrics suggested there is much room for further improvement (Knaap et al. 2005).

Lowry and Lowry (2014) applied seven of the metrics of Song and Knaap (2004) to 542 neighbourhoods in three age groups in Salt Lake City County, Utah, with neighbourhoods defined as the residential portions of census blocks. In addition they proposed another eleven metrics and aimed to evaluate the eighteen metrics' relative effectiveness in capturing four dimensions of urban form: density, centrality, accessibility, and neighbourhood mix. Neighbourhoods developed following World War II (1945-1990) were seen to exhibit characteristics of urban sprawl with increased residential lot sizes, decreased housing density, more homogeneous land use, and a more dendritic street pattern (more cul-de-sacs). Despite policy efforts to encourage "smart growth" many of the same trends continued in neighbourhoods developed after 1990, albeit not nearly as drastically (Lowry and Lowry 2014).

2.5 Urban Sprawl in New Zealand

Historically urban development in New Zealand has been characterised by so called "greenfield" development, with detached homes on large sites in new subdivisions, often on the city fringe (Abrahamse and Witten 2011). With the country's population increasing, a lack of affordable housing in some urban areas, and a desire to build more sustainable urban neighbourhoods, there has been a reassessment of traditional approaches and the associated dangers and risks of different urban forms (Abrahamse and Witten 2011; Scott 2011).

There is very little literature attempting to measure urban sprawl in New Zealand cities, and the studies that are available focus on population density based measurement methods. Zhao et al. (2011) consider the gross density (persons/km^2) of New Zealand cities based on the territorial authority area of the city (i.e. including all land use types). They conclude that, generally speaking, New Zealand cities are low density with almost half having a gross density below 300 persons/km^2. However they do note that Hamilton City had the second highest density (1310 persons/km^2) and that this could be attributed to Hamilton's urban area being compact, with relatively high housing densities, and no large regional parks within the territorial authority area. When considering the change in gross density of cities in New Zealand between 1996 and 2006 they observe that most cities became denser, with Hamilton's gross density increasing by 18%. Zhao et al. (2011) also compare the net density (persons/km^2 excluding non-built up land use types) of Auckland and Wellington, two of New Zealand's largest urban areas, to large cities in North America, Europe and Asia. They found that the net densities of Auckland and Wellington were slightly higher than some of the typically sprawling cities in North America such as Las Vegas and Atlanta. However, when compared to the net densities of large cities in Europe, Asia and South America, Auckland and Wellington are considered to be fairly sprawling cities (Zhao et al. 2011).

The Auckland and Wellington territorial authorities have both recently released planning documents outlining their intensions to address an increasing population and shortage of affordable housing by promoting higher density residential development over detached homes in new, lower density suburbs in outer areas. In 2013 the Auckland Council released a Proposed Auckland Unitary Plan which uses the boundary of the metropolitan area as at 2010 as a baseline for monitoring future urban growth. The plan promotes future urban growth primarily within the 2010 metropolitan area, with a target of no less than 70% of consents issued for new residential dwellings up to 2040 being within the 2010 metropolitan area (Auckland (N.Z.) Council 2013). In 2014 the Wellington City Council released a Draft Urban Growth Plan to 2043 with new housing targets of 25% low density, 35% medium density and 40% high density, and with greenfield development encouraged only in areas where infrastructure is existing or already planned (Wellington (N.Z.) City Council 2014).

Following expansion of the city boundary in 1989, the Hamilton City Council has been mindful of the way the Hamilton urban area is growing and of the need to proactively limit sprawl. The 1997-2017 Hamilton Strategic Plan highlighted that residential growth had been directed mainly toward the north with low to medium density suburbs predominating, and that infill housing and inner city apartments had played a relatively limited role. This pattern of development was considered undesirable in terms of resource use and environmental impact, and the need for a more consolidated form of urban development was acknowledged. A future goal was identified to absorb new growth in part by increased density in established urban areas and in part by balanced, relatively dense, peripheral expansion. This balanced peripheral expansion was to be achieved by extending urban development into the Rotokauri (northwest) and Peacocke (southwest) areas (Hamilton (N.Z.) City Council 1996). The Hamilton Urban Growth Strategy (2010) promoted more compact living environments in order to proactively limit sprawl and manage the city's urban footprint. The council considered that over the next 10-20 years approximately 50% of Hamilton's new dwellings would be increasingly provided through regeneration of existing parts of the city. They acknowledged however that there would still be a need to provide greenfield options to cater for the remainder and considered that these options could be accommodated within the Rototuna area, which was estimated to still have 10 years capacity, and stage 1 of the Rotokauri and Peacocke areas (Hamilton (N.Z.) City Council 2010).

Chapter 3: Data and Methodology

3.1 Introduction

As discussed in Chapter 2 there are a wide range of definitions of urban sprawl and hence many ways have been identified to measure the phenomenon. The approach taken to measuring urban sprawl in this study was to employ a range of measures involving urban growth, urban form and accessibility which span four of the five measurement method groups identified by Frenkel and Ashkenazi (2008). Hence this study differs from many others which focus on just one or two of the measurement method groups.

This chapter begins by outlining the sources of data used in this study, associated metadata, and preliminary data management processes. It then goes on to describe the urban sprawl measurement methods used in this study and the application of remote sensing and GIS techniques to carry out these measurements using ArcGIS.

3.2 Data Collection and Management

3.2.1 Data Formats and Sources

The sources of geographic data used in this study, as well as associated metadata, are given in Appendix 1. The data encompassed the three fundamental formats for geographic data:

- Raster data e.g. Landsat satellite images and orthophotos.

- Vector data (point, line or polygon) e.g. administrative and census block boundaries (polygon), land parcels (polygon), roads (line), and bus stops (point).

- Tabular data (vector data attributes) e.g. census block population and dwelling count.

The majority of the data used in this study were collated from existing sources predominantly via internet-based data services. The three major data sources were:

- The United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) who provided Landsat satellite images.

- Land Information New Zealand (LINZ) who provided orthophotos and land parcel, road and topographic feature shapefiles.

- Statistics New Zealand who provided administrative and census block boundary shapefiles, and census block population and dwelling count data.

Some existing data was not available in a GIS-ready format and therefore required pre-processing, for example:

- Land use was obtained from zoning maps in the Hamilton City Council Proposed District Plan downloaded in PDF format (Hamilton (N.Z.) City Council 2012). These maps were converted to JPEG format, imported into ArcGIS, and georeferenced to the land parcels shapefile. A "land use" attribute was added to the land parcels shapefile attribute table and land use for each parcel was assigned as Residential, Commercial, Industrial, Open Space, Community Facilities or Other based on the zoning maps. Aerial photos taken in 2012 and local knowledge were used to verify assigned land use classes, identify vacant parcels, and to further subdivide the residential parcels into single-dwelling residential or multi-dwelling residential.

- Addresses for police, fire and ambulance stations listed on relevant organisation websites were geocoded using Google Maps. The coordinates were then imported into ArcGIS and converted to shapefile (point) format.

- A hard copy map of employment areas was scanned to JPEG format, imported into ArcGIS and georeferenced, and then digitised to shapefile (polygon) format.

3.2.2 Coordinate Systems

Existing data sets were obtained in one of three projected coordinate systems:

- Universal Transverse Mercator (UTM) zone 60S based on the World Geodetic System Datum 1984 (WGS1984) using the WGS 1984 reference ellipsoid.

- New Zealand Map Grid (NZMG) based on the New Zealand Geodetic Datum 1949 (NZGD1949) using the International 1924 reference ellipsoid.

- New Zealand Transverse Mercator 2000 (NZTM2000) based on the New Zealand Geodetic Datum 2000 (NZGD2000) using the GRS 1980 reference ellipsoid.

As Landsat satellite images were obtained in UTM the classification of these images and measurement of urban growth was carried out in UTM. Urban form and accessibility measurements were carried out in NZTM2000, with all required data sets obtained in other coordinate systems reprojected to NZTM2000. Reprojections were performed in ArcGIS.

3.2.3 Spatial Extent

The area of focus for this study was within the Hamilton City Territorial Authority boundary and therefore this was the extent of many data sets. The more extensive land parcel shapefile was clipped to this boundary. In order to clip the more extensive Landsat images and roads shapefile to reduce computer processing time, a rectangular "study area" was defined beyond the territorial authority boundary (extent shown in Figure 1, coordinates given in Appendix 1). Clipping the Landsat images and roads shapefile to this study area eliminated edge effects that may have arisen if they were clipped to the territorial authority boundary. Landsat image edge effects would include isolated regions of less than 10 pixels adjacent to the territorial authority boundary being removed during post-classification processing (see section 3.3.1), when these pixels are actually part of a larger region that straddles the boundary. Roads shapefile edge effects would include roads truncated at the territorial authority boundary being treated as cul-de-sacs during creation of the road network dataset, preventing calculation of shortest road network distances that include travel outside the boundary.

3.3 Urban Growth

Post-classification comparison of satellite imagery is a commonly used method for urban change detection in studies of urban sprawl (e.g. Jat et al. 2008; Bhatta 2010; Hammann 2012). In this method satellite images taken at different times are classified independently into a common land cover schema. The resulting land cover classification maps are then compared on a pixel by pixel basis in order to identify land cover change. The classification performed may be either supervised or unsupervised. In a supervised classification the classes of the land cover schema are defined based on local knowledge and examples of image pixels comprising each class are identified. The spectral properties of these examples, known as training samples, are then used to classify all remaining pixels in the image into one of the classes. In an unsupervised classification knowledge of land cover in the study area is not necessary and only the number of land cover classes is defined. All image pixels are classified into one of these classes based on naturally occurring groupings in the spectral properties of the image pixels.

Ideal conditions for using remote sensing data to map land cover change include using images collected by the same sensor, under clear atmospheric conditions, at the same time of the year (Bhatta 2010). In addition to its conceptual simplicity, the post-classification comparison method is favoured because corrections are not required to account for sensor, atmospheric and illumination differences between images if these ideal conditions cannot be met, as the comparison is carried out between the resulting land cover classification maps and not the satellite imagery itself (Bhatta 2010).

Figure 2 summarises the steps that were taken in this study to apply the post-classification comparison method in order to measure urban growth in Hamilton City. A supervised classification was performed, using the maximum likelihood classifier, due to considerable local knowledge and availability of ancillary data to assist in class definition. This was followed by an assessment of classification accuracy and post-classification change detection.

3.3.1 Image Classification

Landsat satellite imagery was used in this study as images were available for the time period of interest and they are of an acceptable spatial resolution for urban growth detection (30m x 30m cell size) (Bhatta 2010). Three images acquired on 4 April 1990, 25 September 2001 and 9 February 2014 were selected based on the need for the earliest image to coincide as closely as possible with the November 1989 Hamilton City boundary extension, and for all three images to coincide with the national population census (March 1991, March 2001 and September 2013). The three images covering a 24 year period were acquired by three different sensors (details given in Appendix 1). In order to ensure that there was no cloud cover over the study area, the selected images were taken at different times of the year. Post-classification comparison is an ideal method to use for urban change detection given these conditions.

Initial exploration of the satellite data involved creation of multi-band natural colour (blue, green, red) and false colour (green, red, NIR) composite images for each year and comparison of these with ancillary data including orthophotos and field observations. A multi-band composite image was created of the bands to be used in each classification

(Table 1). Pre-processing of band data was found to be unnecessary as all bands were essentially normally distributed and had a similar range of pixel values.

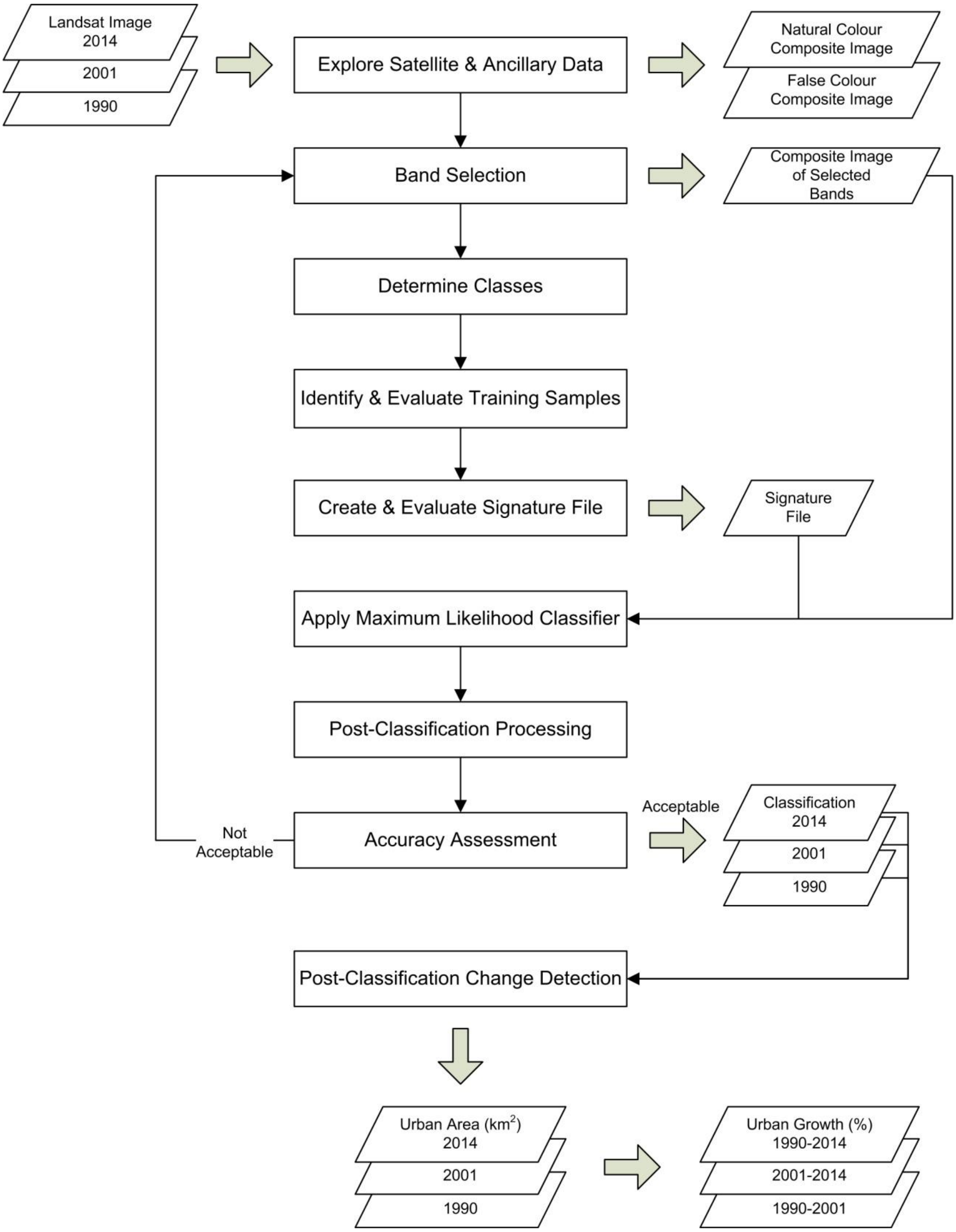


Figure 2: Flow chart of the post-classification comparison methodology used to measure urban growth in Hamilton City.

Table 1: Spectral range of Landsat bands used in the supervised classification

Composite Image Band	1990 Landsat 4		2001 Landsat 7		2014 Landsat 8	
	Band	Wavelength (μm)	Band	Wavelength (μm)	Band	Wavelength (μm)
1	1 (blue)	0.45 – 0.52	1 (blue)	0.45 – 0.52	2 (blue)	0.45 – 0.51
2	2 (green)	0.52 – 0.60	2 (green)	0.52 – 0.60	3 (green)	0.53 – 0.59
3	3 (red)	0.63 – 0.69	3 (red)	0.63 – 0.69	4 (red)	0.64 – 0.67
4	4 (NIR)	0.76 – 0.90	4 (NIR)	0.77 – 0.90	5 (NIR)	0.85 – 0.88
5	5 (SWIR)	1.55 – 1.75	5 (SWIR)	1.55 – 1.75	6 (SWIR)	1.57 – 1.65
6	7 (SWIR)	2.08 – 2.35	7 (SWIR)	2.09 – 2.35	7 (SWIR)	2.11 – 2.29

Source: U. S. Geological Survey (2014).

Table 2: Supervised classification land cover schema

Final Land Cover Class	Supervised Classification Class	Description
1 Urban	1 Urban – Residential	Land where residential rooftops, driveways and local roads dominate, with a small amount of vegetation.
	2 Urban – Commercial/Industrial	Land where rooftops of large buildings, car parks, multilane roads and railway yards dominate.
	3 Cleared Land	Land cleared predominantly as a precursor to urban development.
2 Non-Urban	4 Grassland	Includes grazing pasture, golf courses, and parks within the urban area.
	5 Natural Vegetation	Includes pockets of original indigenous vegetation and vegetation lined gullies within the urban area.
	6 Agriculture – Crops	Agricultural land where crops grow (predominantly maize).
	7 Agriculture – Fallow	Idle / recently ploughed agricultural land where no vigorous vegetation grows.
3 Water	8 Water	Includes rivers and lakes.

The land cover schema required to detect growth in the urban area was relatively simple, with image pixels classed as either urban, non-urban or water. However, due to the spectral variability within both urban and non-urban areas, the supervised classification was initially performed with eight classes which were then reclassified to three (Table 2). Subdivision of the urban and non-urban classes, and identification of training samples representative of each of the eight resulting classes, was based on local knowledge, field observations (for the 2014 classification), orthophotos (for the 1990 and 2001 classifications) and spectral differences observed in the false colour (green, red, NIR) composite images (Figure 3).

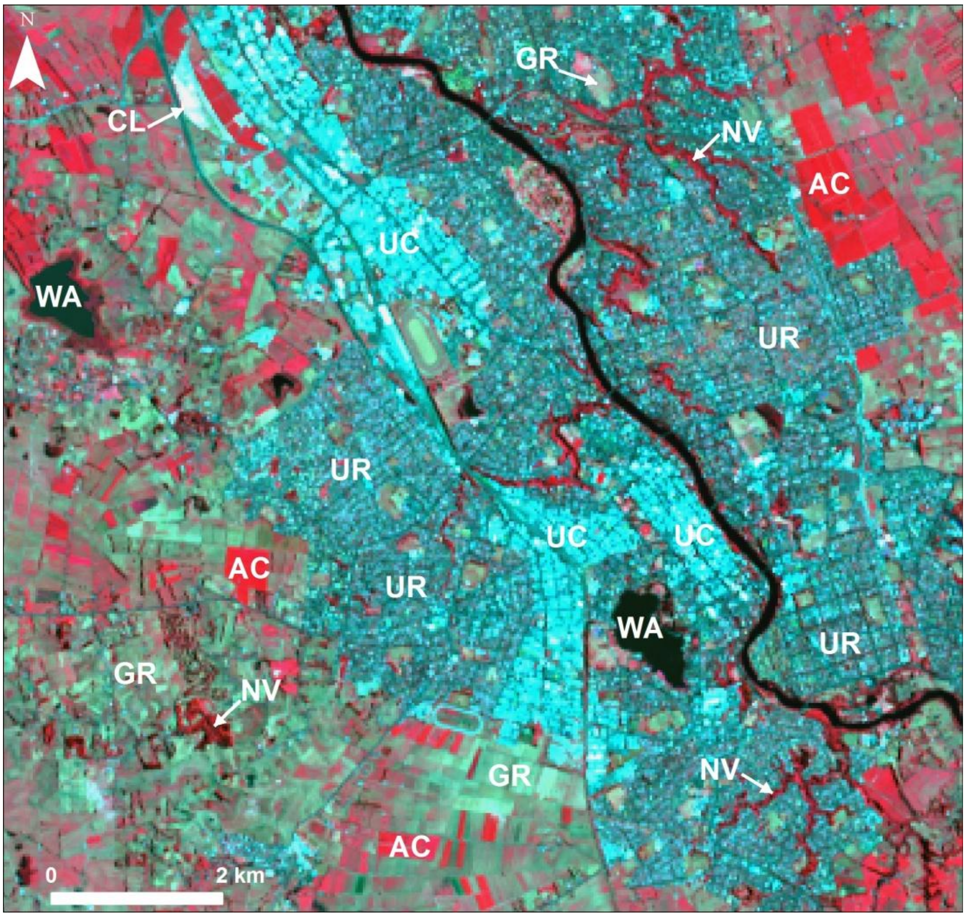


Figure 3: False colour composite image of Hamilton City (2014). The green, red, and NIR bands are displayed in blue, green and red respectively. Examples of the supervised classification classes are identified: UR = Urban – Residential, UC = Urban – Commercial/Industrial, CL = Cleared Land, GR = Grassland, NV = Natural Vegetation, AC = Agriculture – Crops, WA = Water. Fallow agricultural land is rare in this mid-summer image and does not occur within the area shown.

Li et al. (2014) compared classification algorithms and training sample sizes for urban land classification using Landsat imagery. They found that the maximum likelihood classifier required only 60 training sample pixels per class to reach its highest accuracy, irrespective of whether the classification involved 4 or 6 bands. They considered this to indicate that the classifier had a high level of robustness and capability of generalisation. For each of the three classifications performed in this study, 60 pixels per class was therefore considered to be the minimum requirement. Training samples actually ranged in size between 100 and 1800 pixels per class dependant on class abundance and spectral variability, with more abundant and/or variable classes having a higher number of training sample pixels. The spectral characteristics of training samples were evaluated to ensure sufficient separation between classes for each classification. Figure 4 shows two of the band scatterplots used in this evaluation (all scatterplots are given in Appendix 2). To determine if there is overlap between classes all band combinations were considered. For example, while the Urban - Residential and Agriculture - Fallow classes overlap in the Band 2 - Band 4 space, they are distinct in the Band 1 - Band 5 space. Most of the overlap between Cleared Land and Agriculture - Fallow in the Band 2 - Band 4 space is also eliminated in the Band 1 - Band 5 space.

A signature file was created for each classification containing the multivariate statistics for each class, including the class mean and variance-covariance matrix. Signature file evaluation utilised a dendrogram (Figure 5 and Appendix 3) which shows the distance in multidimensional attribute space between sequentially merged classes. The dendrograms supported the conclusions drawn from the band scatterplots that there was sufficient separation between the eight classes for each classification. For the 2001 and 2014 classifications the two closest classes were Urban – Commercial/Industrial (class 2) and Cleared Land (class 3). Confusion between these two classes is not overly problematic given that they were both reclassified to urban in the final classification. For the 1990 classification the two closest classes were Cleared Land (class 3) and Agriculture – Fallow (class 7), which were reclassified to urban and non-urban, respectively, in the final classification. Despite this the post-classification accuracy assessment involving comparison of the map with reference data points, creation of an error matrix, and calculation of common accuracy measures (see section 3.3.2 and Appendix 4) did not find a higher level of misclassification between urban and non-urban pixels in the 1990 classification.

Inputs for the maximum likelihood classifier were a multi-band composite image of the bands to be used in the classification and the signature file containing class multivariate statistics. The maximum likelihood classifier is based on maximum likelihood probability theory. For each pixel, the probability of it belonging to each class is calculated based on the band attributes of the pixel and the class attributes stored in the signature file. The pixel is then assigned to the class with the highest probability (or “maximum likelihood”) (ESRI 2011). In this study all image pixels were classified into one of the eight classes and all classes were considered to be equally likely, hence classes were not weighted during the classification. In their comparison of classification algorithms, Li et al. (2014) found that the conventional maximum likelihood classifier had superior performance to other algorithms, including newer machine learning algorithms, producing the highest accuracy for a 4 band classification and the second highest for a 6 band classification.

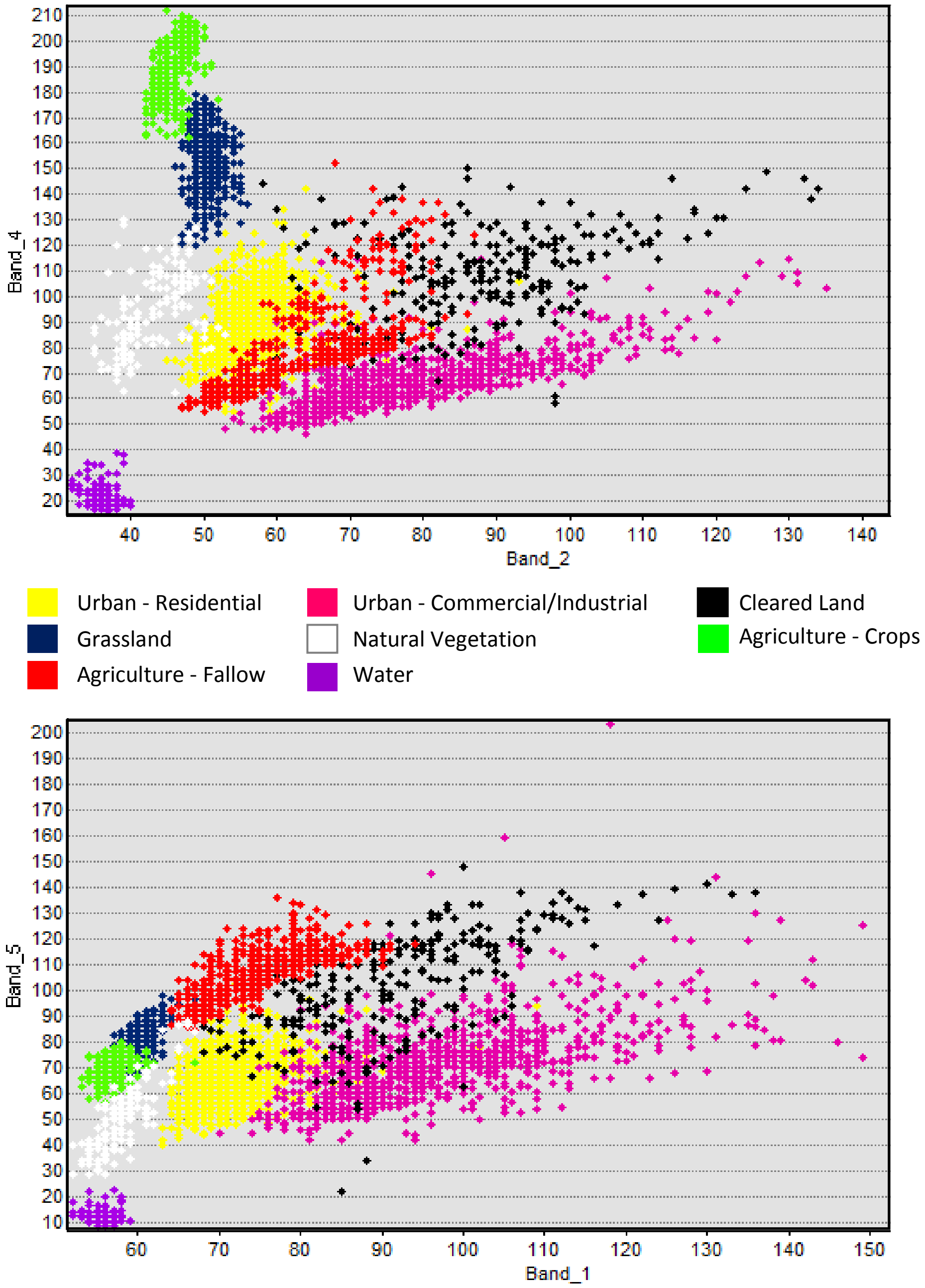
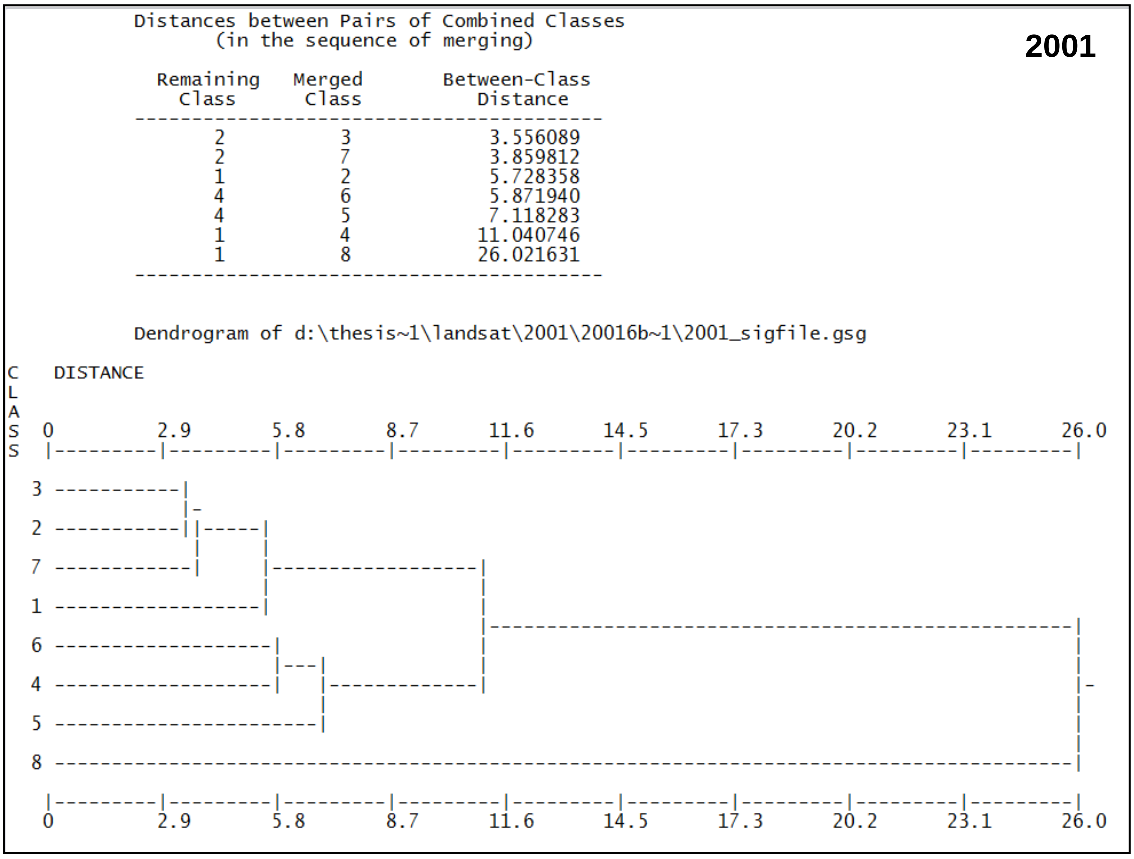


Figure 4: Band scatterplots used to assess training sample separability (2001). Top: Band 2 (green) vs. Band 4 (NIR). Bottom: Band 1 (blue) vs. Band 5 (SWIR).



2001

```
           Distances between Pairs of Combined Classes
                  (in the sequence of merging)

             Remaining   Merged        Between-Class
               Class      Class          Distance
           ------------------------------------------
                  2          3             3.556089
                  2          7             3.859812
                  1          2             5.728358
                  4          6             5.871940
                  4          5             7.118283
                  1          4            11.040746
                  1          8            26.021631
           ------------------------------------------


           Dendrogram of d:\thesis~1\landsat\2001\20016b~1\2001_sigfile.gsg

C   DISTANCE
L
A
S  0         2.9       5.8       8.7      11.6      14.5      17.3      20.2      23.1      26.0
S  |---------|---------|---------|---------|---------|---------|---------|---------|---------|

  3 -----------|
               |-
  2 -----------||-----|
                |     |
  7 ------------|     |------------------|
                      |                  |
  1 ------------------|                  |
                                         |---------------------------------------------------|
  6 -------------------|                 |                                                   |
                       |---|             |                                                   |
  4 -------------------|   |-------------|                                                   |-
                           |                                                                 |
  5 -----------------------|                                                                 |
                                                                                             |
  8 -----------------------------------------------------------------------------------------|

   |---------|---------|---------|---------|---------|---------|---------|---------|---------|
   0         2.9       5.8       8.7      11.6      14.5      17.3      20.2      23.1      26.0
```

Figure 5: Dendrogram of the signature file for the 2001 classification.

Post-classification processing of the land cover classification maps created by the maximum likelihood classifier involved five steps:

1. The eight land cover classes were reclassified to three classes (urban, non-urban and water) as indicated in Table 2.

2. Isolated pixels were removed using the ArcGIS Majority Filter tool which gives each pixel the same class as the majority of their contiguous neighbouring pixels.

3. Boundaries between classes were smoothed and adjacent regions belonging to the same class were connected using the ArcGIS Boundary Clean tool.

4. Classes were generalised by removing isolated regions of less than 10 pixels using the ArcGIS Region Group, Set Null and Nibble tools. Each pixel in a region of less than 10 pixels was given the same class as its nearest neighbour outside the region.

5. The 1990 and 2001 maps were adjusted to eliminate the occurrence of urban pixels becoming non-urban over time as this is not probable within the timeframe of the study. Hence the 2001 and 2014 maps were compared to ensure non-urban pixels in 2014 were also non-urban in 2001, and then the 1990 and 2001 maps were compared to ensure non-urban pixels in 2001 were also non-urban in 1990. The 1990 and 2001 images were adjusted using the ArcGIS Con tool with conditional if/else evaluations (Equation 1). If the value of a pixel in the input raster was equal to 2 (non-urban) the value of the pixel in the output (adjusted) raster was set to 2 (non-urban), else the value of the pixel in the output (adjusted) raster remained unchanged:

   Output Raster = Con (Input Raster, True Value, False Value, Where Clause) (1)

   2001_adjusted = Con (2014_classification, 2, 2001_classification, “Value = 2”)

   1990_adjusted = Con (2001_adjusted, 2, 1990_classification, “Value = 2”)

Post-classification processing steps 2, 3 and 4 are suggested by ESRI (2010) as commonly used techniques to improve the classification.

3.3.2 Accuracy Assessment

Following post-classification processing each classified map was subjected to an accuracy assessment which involved comparison of the map with reference data points, creation of an error matrix, and quantification of map accuracy. Since the mid-1980s the error matrix has been accepted as the standard descriptive reporting tool for accuracy assessment of remotely sensed data (Congalton 2004). In the selection of reference data points there is a need for balance between what is statistically sound and practically attainable, and a generally accepted rule of thumb is to use a minimum of 50 points for each class in the error matrix, increased to 75-100 points if the mapped area is especially large or the classification involves more than 12 classes (Congalton 2004).

Reference data points used in this study were determined by stratified random sampling. For the 1990 and 2001 classifications the land cover class for each point was determined from orthophotos taken in 1995/96 and 2001/02, respectively. Given the time difference between satellite image and orthophoto acquisition (over 5 years in the case of the 1990 classification and several months in the case of the 2001 classification) any reference data points lying near the urban area boundary in the orthophotos were discarded as land cover change may have occurred in this area during the intervening time. For the 2014 classification the locations of reference data points determined by stratified random sampling were loaded onto a handheld GPS device. The land cover class for each point was recorded as urban, non-urban or water through field observation from the nearest point of public access 6 days after satellite image acquisition. For each classification the reference data set consisted of 100 points for both the urban and non-urban classes, and 50 points for the water class. From the error matrix map accuracy was quantified through calculation of several measures including the overall, user's and producer's accuracies, and kappa estimation.

Although the accuracy of the 1990, 2001 and 2014 classifications using 6 bands were considered to be acceptable, the supervised classification process was repeated using only 4 bands (excluding the two SWIR bands) to see if any gain in accuracy could be achieved. The 4 band classifications resulted in reduced accuracy and therefore the 6 band classifications were used in post-classification change detection.

3.3.3 Post-Classification Change Detection

The final step in the post-classification comparison methodology involved comparison of the 1990, 2001 and 2014 land cover classification maps to determine where urban growth has occurred. The urban area within the Hamilton City boundary was quantified as shown in Equation (2).

$$\begin{aligned} \text{Urban Area (km}^2\text{)} &= \text{No. of Urban Pixels} \ \times \ \text{Pixel Size} \\ &= \text{No. of Urban Pixels} \ \times \ \frac{\text{30m x 30m}}{1000000} \end{aligned} \tag{2}$$

While the city boundary remained unchanged between 1989 and 2003, it was extended in 2004 and 2011 to include the neighbouring community of Temple View and non-urban areas adjacent to the city. In order to provide a consistent basis for comparison between the 1990, 2001 and 2014 land cover classification maps, and a consistent basis for comparison with population data, only urban pixels lying within the 1989 – 2003 Hamilton City boundary were included in the urban area calculation for all three classification maps. The use of this common boundary when counting urban pixels prevented an increase to the calculated urban area in 2014 as a result of boundary extension bringing pre-2004 urban pixels into the city (such as those representing the Temple View community). Use of the 1989 – 2003 city boundary did not introduce a significant artificial limit to the calculated size of the urban area in 2014 as little urban growth has occurred beyond the 1989 – 2003 boundary.

Urban growth between 1990 and 2001, 2001 and 2014, and 1990 and 2014 was calculated and compared to population growth calculated from census counts of the population residing within the Hamilton City Territorial Authority in 1991, 2001 and 2013. The population count obtained in 2013 was adjusted to the 1989 – 2003 city boundary through subtraction of the population residing in areas brought into the city though boundary extensions in 2004 and 2011.

3.4 Urban Form

3.4.1 Metrics of Urban Form

Song and Knaap (2004) and Knaap et al. (2005) proposed a range of metrics of urban form for quantifying urban sprawl at the neighbourhood level. Four of these metrics related to land use mix, single-dwelling parcel size and street connectivity were chosen for use in this study. Song and Knaap (2004) were limited to measuring single-residential dwelling density rather than overall residential dwelling density as they lacked data for multi-residential dwellings. In interpreting their results they noted the limitations of this metric as any changes in time or space could be attributed to changes in the area occupied by multi-residential dwellings. Data collected for the Hamilton City Territorial Authority in the 2013 census included the total number of dwellings in each census block, including counts of individual dwellings on multi-dwelling land parcels, therefore allowing measurement of overall residential dwelling density.

In this study the following six metrics of urban form were calculated for each of the 37 residential neighbourhoods in Hamilton. They encompass critical aspects that contribute to a metropolitan area's urban form such as the spatial pattern of land uses and their densities, and the spatial design of transport infrastructure:

- Land Use Mix – measured by a diversity index (H_1) (Equation 3) where p_i is the proportion of each land use type in the neighbourhood and s is the number of land uses. The higher the value of the index, the more evenly distributed the land uses (Knaap et al. 2005). Five land use types were used to calculate this index: residential, commercial, industrial, community facilities and open space.

$$H_1 = \frac{-\sum_{i=1}^{s}(p_i)\ln(p_i)}{\ln(s)} \tag{3}$$

- Dwelling Density – number of dwellings in the neighbourhood divided by the residential area of the neighbourhood (dwellings per km^2). The higher the ratio, the higher the dwelling density.

- Single-Dwelling Proportion – residential area of the neighbourhood occupied by single-dwellings divided by the total residential area of the neighbourhood. The higher the ratio, the higher the single-dwelling proportion.

- Single-Dwelling Parcel Size – median single-dwelling parcel size (m^2) in the neighbourhood. The smaller the parcel size, the higher the single-dwelling parcel density (Song and Knaap 2004; Knaap et al. 2005).

- Internal Street Connectivity – number of street intersections in the neighbourhood divided by the sum of the number of intersections and the number of cul-de-sacs. The higher the ratio, the greater the internal street connectivity (Song and Knaap 2004; Knaap et al. 2005).

- External Street Connectivity – median distance (metres) between neighbourhood ingress/egress points. The shorter the distance, the greater the external street connectivity (Song and Knaap 2004; Knaap et al. 2005)

The four land use based metrics of urban form were calculated using the land parcels shapefile and the land use attribute. Following delineation of residential neighbourhoods (see section 3.4.2) the ArcGIS Identity tool was used to perform a geometric intersection of the neighbourhoods and land parcels shapefiles, with each land parcel being assigned the attributes of the neighbourhood in which it lies. The area of each land parcel was then calculated and the total area in each neighbourhood occupied by single-residential, multi-residential, commercial, industrial, community facilities, and open space was determined. Community facilities include schools, medical facilities and churches. Open space includes sports grounds, parks and natural open space.

To calculate the two street connectivity based metrics of urban form, road shapefiles from the BD33 and BD34 sheets of the Topo50 map series were merged and clipped to the study area. New roads were then digitised and the ArcGIS Extend Line and Trim Line tools were used to clean up connection errors at line intersections. The Integrate tool was used to planarize the data by ensuring vertices at all line intersections. Attributes were added for travel direction (for one-way roads), elevation (for over/under passes), and road length.

The ArcGIS Intersect and Feature Vertices To Points tools were used to identify line intersections (street intersections) and dangle points (cul-de-sacs), respectively. The resulting point shapefiles were intersected with the neighbourhoods shapefile to determine the number of street intersections and cul-de-sacs in each neighbourhood, from which internal connectivity was then calculated.

Calculation of external connectivity required identification of neighbourhood ingress/egress points and creation of a road network dataset with which to calculate the distance between these points. Ingress/egress points were identified and digitised through visual comparison of the road and neighbourhoods shapefiles. A road network dataset was created using the ArcGIS Network Analyst extension with road length as the cost attribute, and taking into account road elevation and one-way restrictions. Note that no city-wide information was available regarding intersection turn or median-strip traverse restrictions. Therefore the road network has been created assuming that both left and right-hand turns are possible at all intersections (except where prevented by one-way roads) and that all median-strips on two-way roads can be crossed at any point. The shortest road network distance between all pairs of ingress/egress points was determined by origin-destination (OD) cost matrix analysis using the ArcGIS Network Analyst extension. All ingress/egress points were used as both origins and destinations for the analysis with road length set as the impedance. External connectivity was then calculated as the median distance between a neighbourhood's origin-destination point pairs.

3.4.2 Delineating Residential Neighbourhoods

While researchers define the term "neighbourhood" based on the objectives of their research (Buslik 2012), most studies rely on census geography or political jurisdictions to operationalise the neighbourhood units (Coulton 2012). Song and Knaap (2004) noted that the neighbourhood has long been regarded as the basic building block of urban form but that what constitutes a neighbourhood is disputed. For the purpose of measuring urban form as an indicator of urban sprawl they delineated neighbourhoods based on the boundaries of intermediate-sized census blocks. Lowry and Lowry (2014), who applied many of the metrics of urban form proposed by Song and Knaap (2004), also used intermediate-sized census blocks. Since the metrics of urban form being used in this study are the same as, or comparable to, those employed by Song and Knaap (2004), it was appropriate to delineate neighbourhoods in a similar way.

In New Zealand territorial authorities are subdivided into meshblocks for the purposes of collecting and collating census data. Area units are aggregations of meshblocks that are of a size intermediate between meshblocks and territorial authorities. At the time of the 2013 census the Hamilton City Territorial Authority was subdivided into 1178 meshblocks, aggregated into 46 area units. Visual comparison of meshblock boundaries, land parcel boundaries and roads revealed that neighbourhoods based on meshblock boundaries would be too small to provide meaningful results for the metrics of urban form calculated in this study. Area units have therefore been used as the basis for delineating neighbourhoods.

As the aim was to delineate current urban residential neighbourhoods, nine area units were excluded either because they currently comprise predominantly non-urban land uses or because less than 20% of developed land within the area unit is residential. The former includes areas brought into the city through boundary extensions in 2004 and 2011, while the latter includes the central business district and main industrial areas. Boundaries of the remaining 37 area units were used as neighbourhood boundaries, with area unit names retained as neighbourhood names. Comparison of these boundaries with the urban area identified from supervised classification of Landsat imagery acquired in 1990 allowed the neighbourhoods to be classed as either old (developed prior to 1990) or new (developed from 1990 to 2014). The 31 old neighbourhoods contained between 52% and 98% urban area in 1990, while the 6 new neighbourhoods contained between 0.6% and 22% urban area (Figure 6).

3.4.3 Statistical Approach

For each of the metrics of urban form the significance of the difference in mean values for old and new neighbourhoods was assessed with a two-independent samples t-test. The t-test is an appropriate statistical hypothesis test when comparing two groups of observations (old and new neighbourhoods) of a single continuous variable (metric of urban form). In this case the two groups comprise independent (not paired) observations, and hence the two-independent samples variant of the t-test was used. Two assumptions made when using this test are that the observations in each group are drawn from normally distributed populations and that the variances of the two groups are equal. In a comparison of four tests of normality commonly available in statistical software, Razali and Wah (2011) found the Shapiro-Wilk test to be the most powerful for all types of distribution and sample sizes. The Shapiro-Wilk test found that the dwelling density and single-dwelling parcel size metrics were from non-normal distributions. Therefore prior to performing the t-test the values of these two metrics were transformed to normal distributions by taking the logarithm of each value. The F-test is commonly used to test for equal variances when comparing two groups from normally distributed populations. Levene’s test is a popular alternative to the F-test that is known to be robust to nonnormality (Gastwirth et al. 2009). Both the F-test and Levene's test found the assumption of equal variances to be justified for all metrics of urban form at the 0.05 level of significance with the exception of internal street connectivity. Adjustments were therefore made to account for unequal variances when calculating the test statistic and degrees of freedom for this metric.

For all metrics of urban form the null hypothesis (H_0) for the two-independent samples t-test was that there is no difference between old and new neighbourhoods. The alternative hypothesis (H_A) for each test reflected the expected difference between old

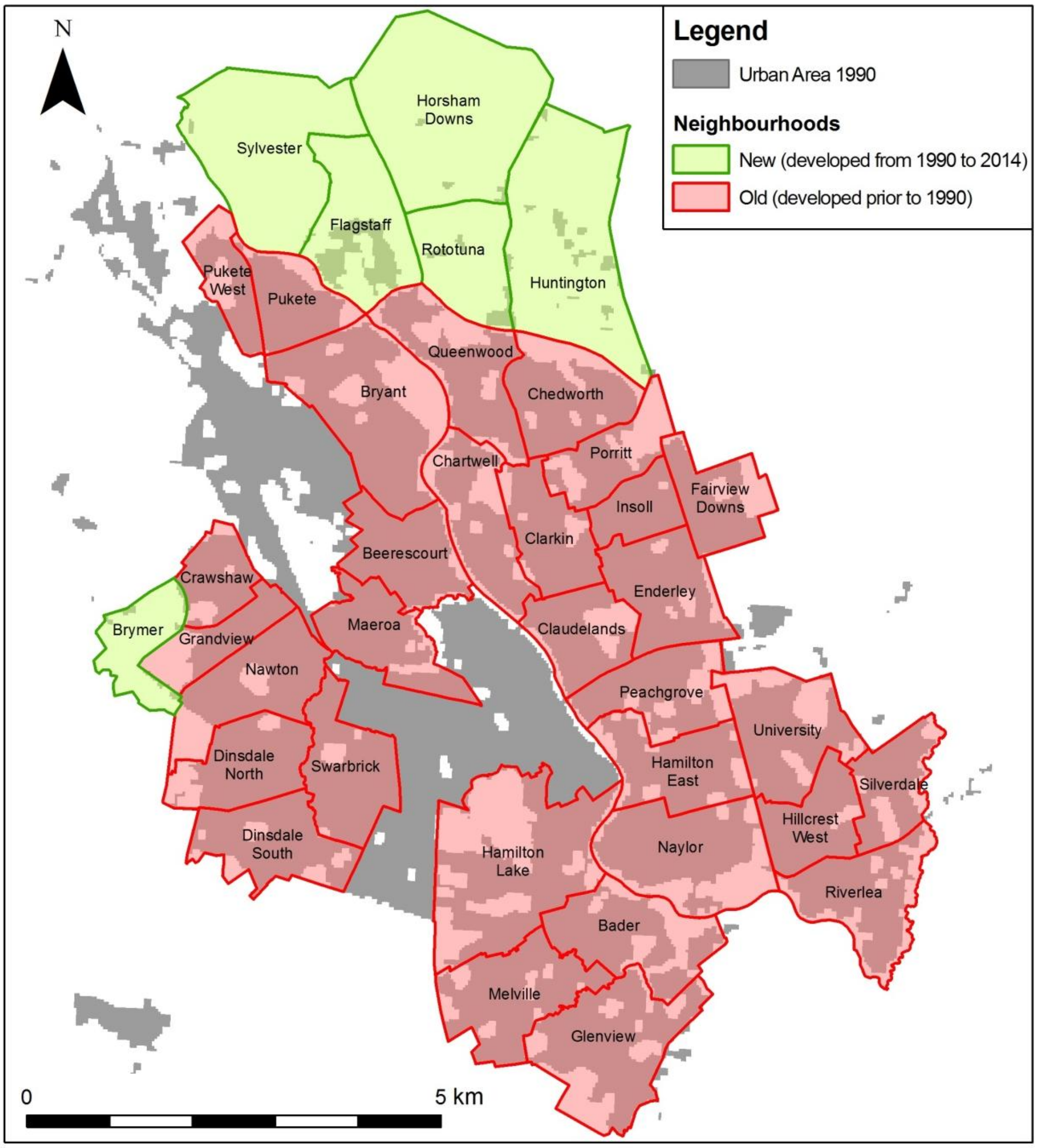


Figure 6: Boundaries of old and new residential neighbourhoods in Hamilton City.

and new neighbourhoods in the event that new neighbourhoods exhibit elements of urban form characteristic of urban sprawl. That is, that old neighbourhoods have greater land use mix, dwelling density and internal street connectivity, and lower single-dwelling proportion, single-dwelling parcel size and distance between ingress/egress points than new neighbourhoods. All t-tests were therefore one-sided.

Calculation of test statistics for the Shapiro-Wilk, F-, Levene's and t-tests were made using the open source PAST software package (Hammer et al. 2001). The degrees of freedom were calculated as shown in Equations (4) and (5).

$$df = n_{old} + n_{new} - 2 \qquad \text{(equal variances)} \qquad (4)$$

$$df = \frac{[(s_{old}^2 / n_{old}) + (s_{new}^2 / n_{new})]^2}{[(s_{old}^4 / n_{old}^2 (n_{old} - 1)] + [(s_{new}^4 / n_{new}^2 (n_{new} - 1)]} \qquad \text{(unequal variances)} \qquad (5)$$

3.5 Accessibility

3.5.1 Metrics of Accessibility

Song and Knaap (2004) and Knaap et al. (2005) proposed several metrics of accessibility and pedestrian access for quantifying urban sprawl at the neighbourhood level. Accessibility metrics involved calculation of median distances between residential land parcels and urban functions (commercial land uses and bus stops) and open spaces (parks), while metrics of pedestrian access involved calculation of the percentage of residential parcels within an acceptable walking distance of such facilities. Similar metrics concerning access to commercial land uses and bus stops were chosen for use in this study.

The concept of "acceptable walking distance" forms the basis of studies concerning pedestrian access or "walkability", however the literature yields no single definition. Song and Knaap (2004) and Knaap et al. (2005) defined acceptable walking distance as 0.25 miles (400 metres). While this distance is often used in studies based in the United States, Yang and Diez-Roux (2012) found 65% of walking trips to be longer than 0.25 miles, and substantial variation in distance depending on trip purpose with trips for recreation considerably longer than trips for other purposes. Millward et al. (2013) focused on active-transport walking behaviour (as opposed to recreational behaviour) and found an overall mean walking distance of 670 metres, with mean distances for shopping and education of 620 metres and 770 metres, respectively. A New Zealand based study found a mean walking distance of 800 metres for train users in Auckland and Wellington (Walton and Sunseri 2010). In a study of walkability in New Zealand cities Mavoa et al. (2009) considered 800 metres to be a reasonable walking distance. For the purpose of this study 800 metres was selected to represent an acceptable walking distance.

In addition to access to urban functions and open spaces, another aspect of accessibility which may be influenced by urban sprawl concerns emergency service response times. Trowbridge et al. (2009) found a significant association between urban sprawl and increased ambulance response time, while Lambert et al. (2012) identified urban sprawl as a factor in delayed response to fire emergencies. As increased travelling distances in areas of urban sprawl are likely a significant factor contributing to increased response times, there is value in considering median distances between emergency service stations and residential land parcels.

In this study eleven metrics of accessibility were calculated for each of the 37 residential neighbourhoods in Hamilton, five related to urban functions, three to emergency services and three to pedestrian access:

Urban Functions (the shorter the distance, the greater the accessibility):

- Commercial Distance – median distance (metres) to the nearest commercial land use (Song and Knaap 2004; Knaap et al. 2005).

- Bus Stop Distance – median distance (metres) to the nearest bus stop (Song and Knaap 2004).

- Primary School Distance – median distance (metres) to the nearest state funded primary school.

- Employment Area Distance – median distance (metres) to the nearest existing employment area as identified in the Hamilton Urban Growth Strategy (Hamilton (N.Z.) City Council 2010).

- Medical Clinic Distance – median distance (metres) to the nearest medical clinic.

Emergency Services (the shorter the distance, the greater the accessibility):

- Police Station Distance – median distance (metres) from the nearest police station.
- Fire Station Distance – median distance (metres) from the nearest fire station.
- Ambulance Station Distance – median distance (metres) from the nearest ambulance station.

Pedestrian Access (the higher the percentage, the greater the walkability):

- Commercial Walkability – percentage of residential parcels within 800m of a commercial land use.
- Bus Stop Walkability – percentage of residential parcels within 800m of a bus stop.
- Primary School Walkability – percentage of residential parcels within 800m of a state funded primary school.

For accessibility metrics involving urban functions, the shortest road network distance from each residential land parcel to the nearest location of each function was determined by origin-destination (OD) cost matrix analysis using the ArcGIS Network Analyst extension. In the analysis residential parcel centroids were used as origins and function location centroids were used as destinations, with a road network location created for each centroid at the closest point on the road network. As some of the employment areas are quite large, employment area destinations were defined as the points where employment area boundaries intersect roads rather than using a single centroid point for each area. For each cost matrix road length was set as the impedance with the number of destinations to find set to one. The median distance to the closest function location was then calculated for each neighbourhood. For commercial land use, bus stop and primary school destinations the percentage of origins in each neighbourhood with a distance of less than 800m (i.e. within walking distance) was also calculated. The assumption has been made that pedestrians are restricted to walking on footpaths that follow the road network and that this access for pedestrians exists adjacent to all roads. Due to a lack of data pedestrian-only access routes were not included when determining walking distances.

For accessibility metrics involving emergency services where direction of travel is towards (rather than away from) residential land parcels, the shortest road network distance from the nearest emergency service station to each residential land parcel was determined by closest facility analysis using the ArcGIS Network Analyst extension. In the analysis residential parcel centroids were used as incidents and emergency service station centroids were used as facilities, with a road network location created for each centroid at the closest point on the road network. For each analysis road length was sent as the impedance, the number of facilities to find set to one, and travel direction was specified as from facility to incident. The median distance from the closest emergency service station was then calculated for each neighbourhood.

3.5.2 Statistical Approach

For nine of the eleven metrics of accessibility the significance of the difference in mean values for old and new neighbourhoods was assessed with a two-independent samples t-test. Two assumptions made when using this test are that the observations in each group are drawn from normally distributed populations and that the variances of the two groups are equal. The Shapiro-Wilk test for normality found that the bus stop distance, employment area distance, commercial walkability and bus stop walkability metrics were from non-normal distributions. Prior to performing the t-test the bus stop distance and employment area distance values were transformed to normal distributions by taking the logarithm of each value. Commercial walkability and bus stop walkability values could not be transformed to normal distributions and therefore these metrics could not be assessed with a two-independent samples t-test. Both the F-test and Levene’s test found the assumption of equal variances to be justified for accessibility metrics at the 0.05 level of significance with the exception of commercial distance, bus stop distance, primary school distance and primary school walkability. Adjustments were therefore made to account for unequal variances when calculating the test statistic and degrees of freedom for these metrics.

Commercial walkability and bus stop walkability metrics were assessed using the Mann-Whitney test, a non-parametric alternative to the t-test which does not require values to be normally distributed. Where the t-test assesses the significance of the difference in mean values for old and new neighbourhoods, the Mann-Whitney test assesses the significance of the difference in the ranks of values for old and new neighbourhoods.

Despite differences in the way the test statistic is calculated for the two-independent samples t-test and the Mann-Whitney test, the null and alternative hypotheses can be stated in a similar fashion. Hence for all metrics of accessibility the null hypothesis

(H_0) was that there is no difference between old and new neighbourhoods. The alternative hypothesis (H_A) for each test reflected the expected difference between old and new neighbourhoods in the event that new neighbourhoods exhibit the reduced accessibility characteristic of urban sprawl. That is, that old neighbourhoods have shorter distances to urban functions, shorter distances from emergency services, and greater percentages of residents within walking distance of urban functions than new neighbourhoods. In the case of commercial walkability and bus stop walkability this will translate to higher ranks for old neighbourhoods. All t-tests and Mann-Whitney tests were therefore one-sided.

Calculation of test statistics for the Shapiro-Wilk, F-, Levene’s, t-, and Mann-Whitney tests were made using the open source PAST software package (Hammer et al. 2001). The degrees of freedom for the t-test were calculated as in section 3.4.3.

Chapter 4: Results

4.1 Introduction

This chapter presents the results of the study in three sections. The first section discusses change in the Hamilton urban area between 1990 and 2014, and compares urban growth with population growth. The second section explores urban form metrics for old and new neighbourhoods, the significance of any difference between the two neighbourhood groups, and future predictions for new neighbourhoods. The third section explores accessibility metrics for old and new neighbourhoods, the significance of any difference between the two neighbourhood groups, and future predictions for new neighbourhoods.

4.2 Urban Growth

4.2.1 Land Cover Classification and Change Maps

Land cover classification maps for 1990, 2001 and 2014 are shown in Figure 7. The urban area within the Hamilton City boundary has grown between 1990 and 2014, and that the majority of this growth has been in the north of the city. Also evident, although outside the area of interest in this study, is the increase in small discontinuous clusters of urban pixels occurring beyond the city boundary. These pixels represent an increase in typically urban features (e.g. roads and buildings) in otherwise non-urban areas.

In Figure 8 the urban areas from the three land cover classification maps have been overlaid to highlight where urban growth has occurred within the Hamilton City boundary. The areas of urban growth that occurred between 1990 and 2014 fall into four groups:

- Expansion of the urban area into non-urban areas brought into the city when the city boundary was extended in 1989 (Figure 8 Insert A). This accounts for the majority of urban growth and, as was planned at the time of this boundary extension, has occurred predominantly to the northeast in the Rototuna area. Between 2001 and 2014 relatively smaller amounts of urban growth occurred in the Rotokauri and Peacocke areas. In the Peacocke area this growth is seen as small isolated clusters of pixels representing an increase in typically urban features in an otherwise non-urban area.

- Expansion of the urban area into non-urban areas within the pre-1989 city boundary. The majority of this type of growth occurred between 1990 and 2001 on the northern and western edges of the city.

- Infill of non-urban areas enclosed by the 1990 urban area (Figure 8 Insert B). This accounts for only a small proportion of the overall increase in urban area between 1990 and 2014, and represents development of vacant land and/or open space within the city.

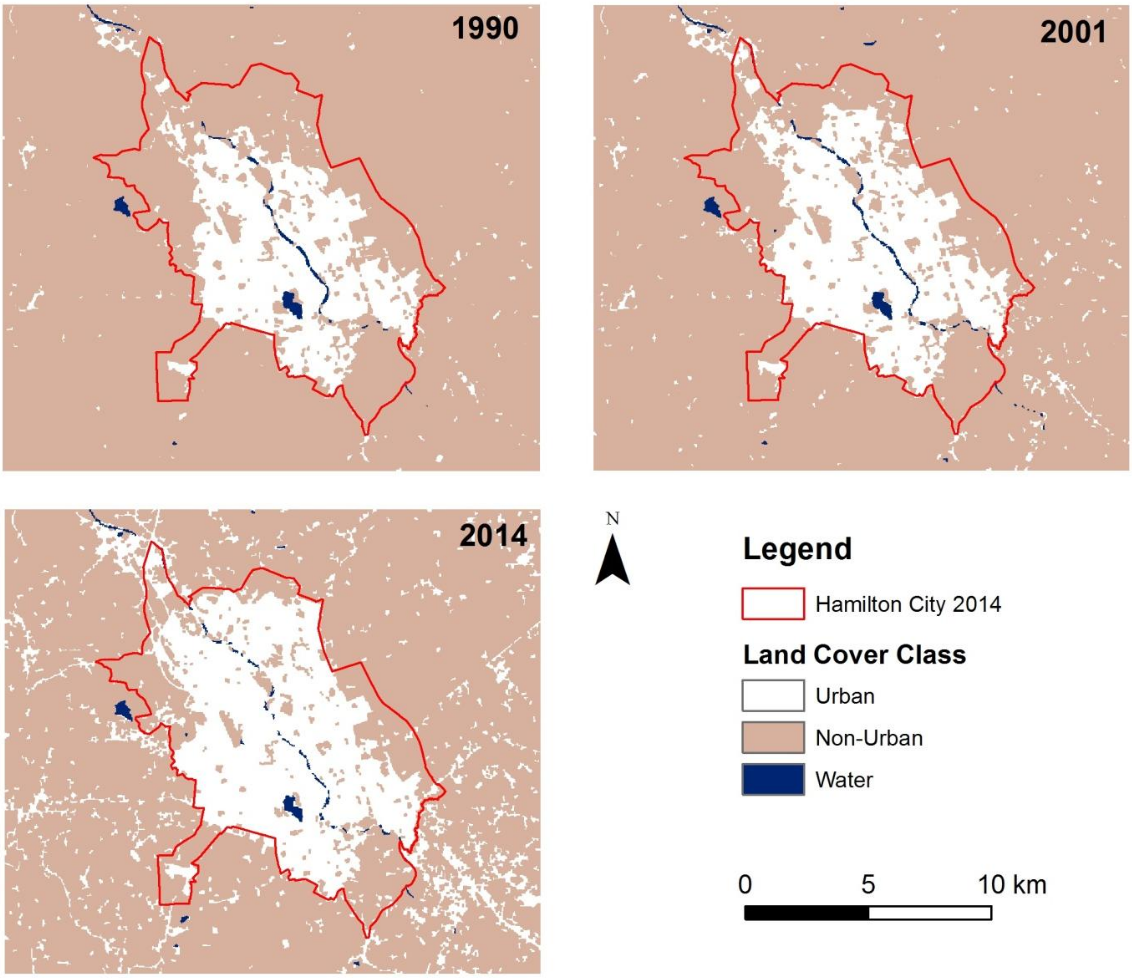


Figure 7: Land cover classification maps for 1990, 2001 and 2014.

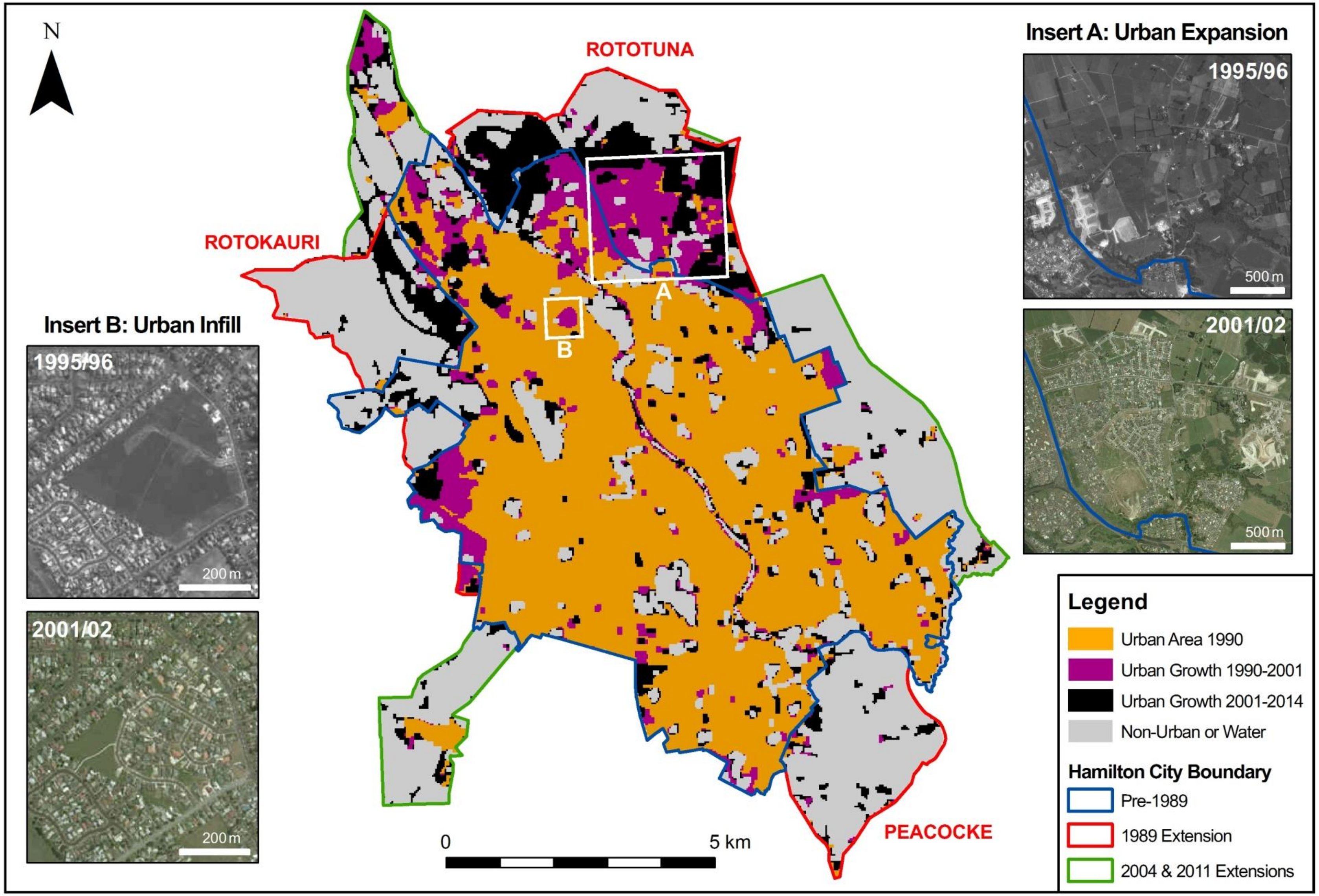


Figure 8: Hamilton City urban area growth between 1990 and 2014.

- Increase in the urban area within the non-urban areas brought into the city when the city boundary was extended in 2004 and 2011. This accounts for only a small proportion of the overall increase in urban area between 1990 and 2014, and mostly occurred as small isolated clusters of urban pixels in these otherwise non-urban areas. The exception is a sizeable area of growth that occurred between 1990 and 2001 in the northern area, prior to this area being brought into the city.

4.2.2 Comparison of Urban Growth and Population Growth

The size of the Hamilton City urban area in 1990, 2001 and 2014 as calculated from the land cover classification maps is given in Table 3. Note that areas brought into Hamilton City through boundary extensions in 2004 and 2011 have been excluded from these calculations (for further discussion see section 3.3.3). Between 1990 and 2014 the Hamilton City urban area increased from 47.3 km^2 to 68.8 km^2. The urban area grew by 19% between 1990 and 2001 and 22% between 2001 and 2014, with overall growth of 45% between 1990 and 2014. In comparison the population residing within Hamilton City grew by 16% between 1991 and 2001 and 22% between 2001 and 2013, with overall growth of 41% between 1991 and 2013.

Table 3: Urban area and population growth between 1990/1991 and 2013/2014

	Urban Area(1)	**Population**(2)
1990/1991	47.3 km^2	99,414
2001	56.3 km^2	114,921
2013/2014(3)	68.8 km^2	140,070
Growth 1990/1991 - 2001	19 %	16 %
Growth 2001 - 2013/14	22 %	22 %
Growth 1990/1991 - 2013/2014	45 %	41 %

(1) Urban area based on supervised classification of Landsat imagery acquired in 1990, 2001 and 2014.

(2) Census population counts obtained in 1991, 2001 and 2013 (Source: Statistics New Zealand).

(3) Excluding areas brought into Hamilton City through boundary extensions in 2004 and 2011.

4.2.3 Land Cover Classification and Change Accuracy

Measures of accuracy for the 1990, 2001 and 2014 land cover classification maps are summarised in Table 4. Error matrices and full details of all accuracy calculations are given in Appendix 4. Accuracy measures were calculated for the reference data set of 250 pixels, but can generally be considered estimates of accuracy for the classified map as a whole.

Table 4: Summary of Landsat classification accuracies (%) for 1990, 2001 and 2014

		1990		**2001**		**2014**	
		User's Accuracy	**Producer's Accuracy**	**User's Accuracy**	**Producer's Accuracy**	**User's Accuracy**	**Producer's Accuracy**
Land Cover Class	Urban	98	100	97	100	90	100
	Non-Urban	88	98	96	98	97	97
	Water	100	74	100	90	100	78
Overall Accuracy		94		97		94	
Kappa Estimation		90		96		91	

Overall accuracy is the percentage of correctly classified pixels. Hence 94% of pixels in the 1990 and 2014 classifications and 97% of pixels in the 2001 classification were correctly classified. The Kappa estimation takes into account the influence of chance when estimating map accuracy and shows that the 1990, 2001 and 2014 supervised classification maps were 90%, 96% and 91%, respectively, better than classifications made by chance.

While overall accuracy and the kappa estimation reflect the accuracy of the map as a whole, they do not reveal whether the map error is evenly distributed across classes or if some classes are more error prone than others. For the purposes of this study the error associated with the urban class was of particular interest. The user's and producer's accuracies calculated for individual classes were consistently high, ranging from 74% to 100%. The user's accuracy is the probability that a pixel of a certain class on the map has the same class in the field (and has therefore been correctly classified). Hence 98%

of urban pixels in the 1990 classification, 97% in 2001, and 90% in 2014 were also urban in the field and are therefore correctly classified. The producer's accuracy is the probability that a point in the field has been correctly classified on the map. Hence 100% of urban points in the field were correctly classified as urban in the 1990, 2001 and 2014 classifications. The difference between these two measures reflects over-estimation of the urban area on the classification maps by 2% in 1990, 3% in 2001 and 11% in 2014 (see areal difference calculations in Appendix 4).

The greatest inaccuracy in all three classifications was in the misclassification of water reference data points, reflected in the lower producer's accuracy for the water class. These misclassified points are likely a result of the spatial resolution of the Landsat imagery (30m x 30m) being too low to accurately represent the Waikato River, therefore reference points lying in the river have been misclassified as urban or non-urban. Misclassification of water reference points accounts for 8% of the 11% over-estimation of urban area in the 2014 classification map.

A potential disadvantage of using the post-classification comparison method to detect urban change is that the errors of each individual classification are transferred to the change map (Bhatta 2010). Hence multiplying the individual classification overall accuracies from Table 4 gives expected change detection overall accuracies of 91% for 1990 – 2001, 91% for 2001 – 2014, and 88% for 1990 – 2014.

4.3 Urban Form

4.3.1 Current Urban Form

Metrics of urban form for residential neighbourhoods in Hamilton are given in Table 5 with the land use, dwelling and street network data used in these calculations provided in Appendix 5. The spatial patterns of neighbourhood urban form metrics are shown in Figure 9. Descriptive statistics for old and new neighbourhoods are given in Table 6 with the variability in values for each neighbourhood group illustrated using box plots in Figure 10.

Land use mix diversity index values ranged from 0.18 to 0.85 for old neighbourhoods and 0.17 to 0.46 for new neighbourhoods. Neighbourhoods with lower values had a higher proportion of residential land use. Dwelling density ranged from 1157 to 2479

Table 5: Metrics of urban form for old and new neighbourhoods

Neighbourhood	Land Use Mix Diversity Index	Dwelling Density (per km^2)	Single-Dwelling Proportion	Median Single-Dwelling Parcel Size (m^2)	Internal Street Connectivity	External Street Connectivity (metres)
OLD						
Bader	0.48	1585	0.77	735	0.64	1180
Beerescourt	0.39	1430	0.78	805	0.72	1231
Bryant	0.53	1436	0.83	729	0.70	1818
Chartwell	0.56	1210	0.85	862	0.66	940
Chedworth	0.45	1236	0.97	686	0.73	1198
Clarkin	0.50	1454	0.80	733	0.71	1129
Claudelands	0.63	1974	0.67	787	0.82	1279
Crawshaw	0.33	1692	0.71	646	0.65	891
Dinsdale North	0.33	1453	0.88	710	0.63	1279
Dinsdale South	0.41	1578	0.78	701	0.62	1402
Enderley	0.49	1718	0.73	709	0.73	1242
Fairview Downs	0.18	1475	0.94	684	0.67	897
Glenview	0.43	1320	0.86	709	0.65	1695
Grandview	0.36	1780	0.77	651	0.63	943
Hamilton East	0.73	2268	0.57	670	0.81	1232
Hamilton Lake	0.85	1777	0.68	764	0.76	1388
Hillcrest West	0.25	1546	0.86	723	0.66	1151
Insoll	0.21	1443	0.87	702	0.76	799
Maeroa	0.44	1667	0.71	679	0.76	1061
Melville	0.54	1483	0.87	683	0.61	1044
Nawton	0.49	1558	0.78	694	0.68	1530
Naylor	0.51	1870	0.72	664	0.75	1355
Peachgrove	0.79	2427	0.66	707	0.72	1689
Porritt	0.68	1509	0.87	718	0.73	983
Pukete	0.35	1351	0.95	746	0.64	855
Pukete West	0.43	1435	0.92	700	0.63	819
Queenwood	0.39	1157	0.91	808	0.70	1067
Riverlea	0.73	1229	0.87	804	0.62	761
Silverdale	0.55	1492	0.86	688	0.75	972
Swarbrick	0.55	2075	0.62	697	0.78	1206
University	0.57	2479	0.66	630	0.67	1395
NEW						
Brymer	0.21	1373	0.97	681	0.58	1157
Flagstaff	0.32	1360	0.84	753	0.60	1373
Horsham Downs	0.17	943	1.00	665	0.56	1416
Huntington	0.46	1317	0.96	680	0.56	1969
Rototuna	0.46	1472	0.95	720	0.54	1072
Sylvester	0.27	644	1.00	735	0.56	2043

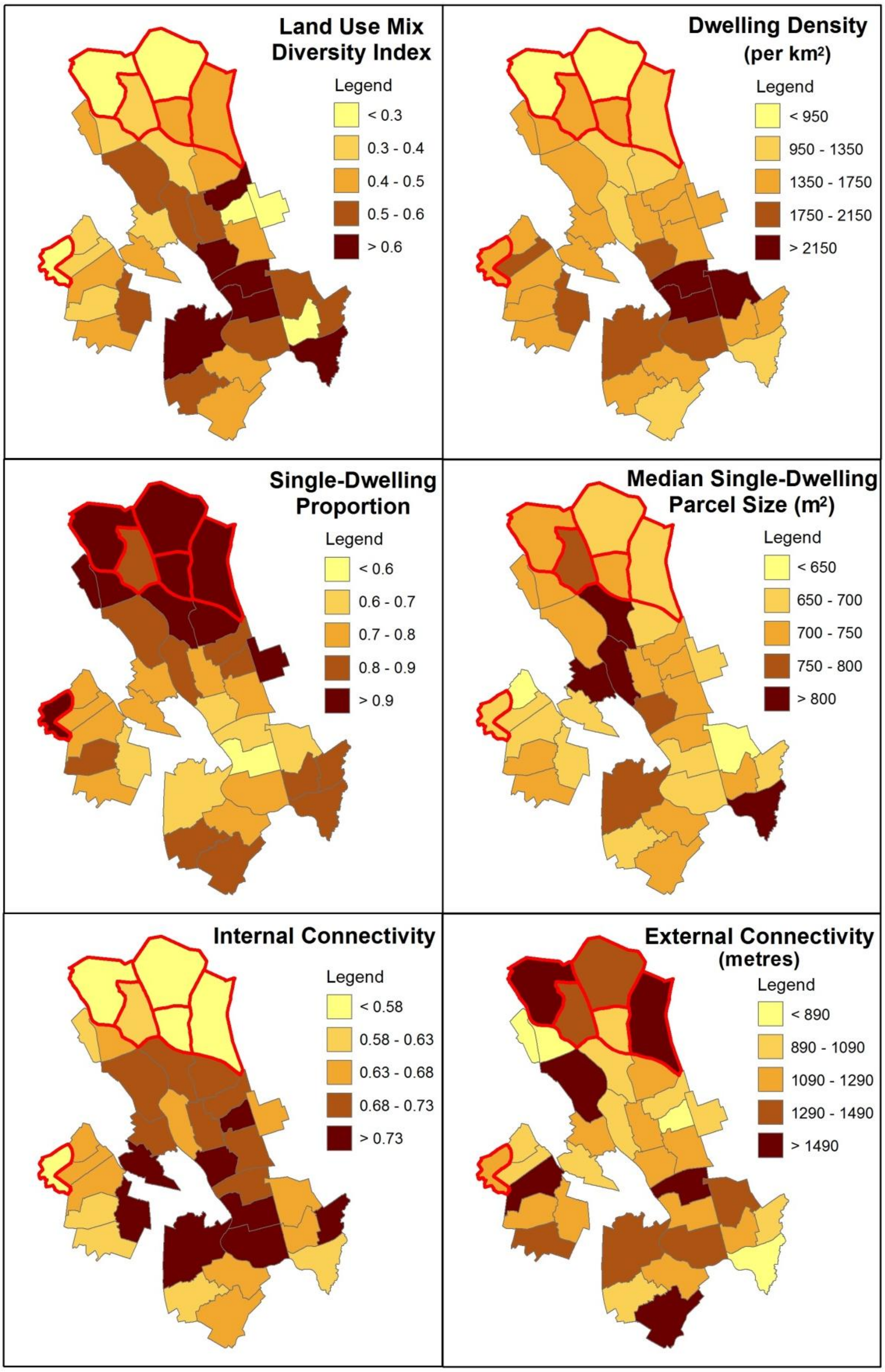


Figure 9: Maps of urban form metrics. New neighbourhoods are outlined in red.

Table 6: Descriptive statistics and t-test results for metrics of urban form

Urban Form Metric	**Neighbourhoods**						**t**	**df**
	Old			**New**				
	M	**SD**	**n**	**M**	**SD**	**n**		
Land Use Mix Diversity Index	0.49	0.16	31	0.32	0.12	6	2.48***	35
Dwelling Density (per km^2)	1616	336	31	1185	322	6	3.42***	35
Single-Dwelling Proportion	0.80	0.10	31	0.95	0.06	6	-3.52***	35
Median Single-Dwelling Parcel Size (m^2)	717	53	31	706	35	6	0.48	35
Internal Street Connectivity$^{(1)}$	0.70	0.06	31	0.57	0.02	6	9.47***	23
External Street Connectivity (metres)	1175	272	31	1505	410	6	-2.50***	35

* $p < 0.10$ **$p < 0.05$ ***$p < 0.01$

$^{(1)}$ Assuming unequal variances

dwellings per km^2 for old neighbourhoods and 644 to 1472 dwellings per km^2 for new neighbourhoods. Single-dwelling proportion ranged from 0.57 to 0.97 for old neighbourhoods and 0.84 to 1 for new neighbourhoods. These two metrics were seen to be negatively correlated such that as the proportion of single-dwellings increased, dwelling density decreased. While there is overlap between the two neighbourhood groups, new neighbourhoods generally had higher single-dwelling proportions and lower dwelling densities. Median single-dwelling parcel size ranged from 630m^2 to 862m^2 for old neighbourhoods and 665m^2 to 753m^2 for new neighbourhoods, with the spatial pattern and box plot suggesting no difference between the two neighbourhood groups. Internal street connectivity ranged from 0.61 to 0.82 for old neighbourhoods and 0.54 to 0.60 for new neighbourhoods. Lower values for new neighbourhoods reflected a higher proportion of cul-de-sacs in these areas. The median distance between neighbourhood ingress/egress points ranged from 761 to 1818 metres for old neighbourhoods and 1072 to 2043 metres for new neighbourhoods, with the spatial pattern and box plot suggesting new neighbourhoods generally had greater median distances, and therefore lower external connectivity, than old neighbourhoods.

Results of two-independent samples t-tests to assess the significance of differences in metrics of urban form between old and new neighbourhoods are given in Table 6. There were statistically significant differences, at the 0.01 level of significance, in terms

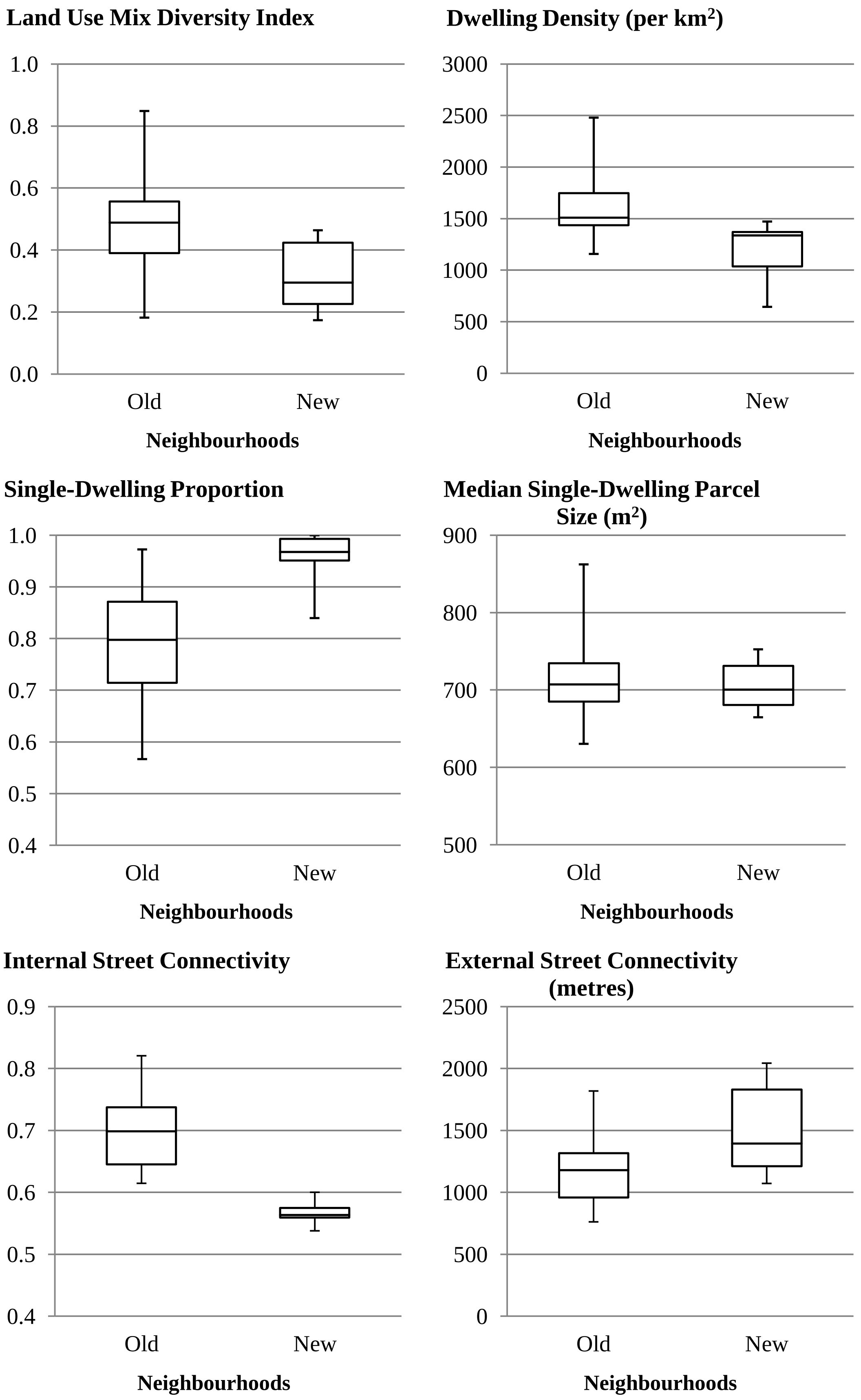


Figure 10: Box plots of urban form metrics for old and new neighbourhoods showing the median, lower and upper quartiles (box), and minimum and maximum (bars) values.

of land use mix, dwelling density, single-dwelling proportion, internal street connectivity and external street connectivity. Results showed that:

- Old neighbourhoods had higher land use mix diversity indices and therefore a more even distribution of land uses.
- Old neighbourhoods had higher dwelling densities.
- Old neighbourhoods had lower single-dwelling proportions.
- Old neighbourhoods had greater internal street connectivity.
- Old neighbourhoods had shorter median distances between neighbourhood ingress/egress points and therefore greater external street connectivity.
- No statistical difference existed between old and new neighbourhoods in terms of median single-dwelling parcel sizes and therefore single-dwelling parcel densities.

Figure 11 shows the development patterns in Hamilton East and Rototuna, as examples of old and new neighbourhoods respectively, and illustrates many of the differences in urban form between the two neighbourhood groups. The more even distribution of land uses in Hamilton East is obvious (land use mix diversity index of 0.73 compared to 0.46 for Rototuna), as is the lower single-dwelling proportion (0.57 compared to 0.95 for Rototuna). While both neighbourhoods had similar areas occupied by open space, Hamilton East had much larger areas of commercial, community facility and multi-residential land uses. Rototuna had only 300 fewer dwellings than Hamilton East, however they were distributed over an additional 148,523m^2 and therefore dwelling density was much lower (1472 dwellings per km^2 compared to 2268 dwellings per km^2 for Hamilton East). Also obvious is the difference in road network patterns. The intersection dominated grid-based pattern of Hamilton East had a higher internal connectivity than Rototuna with its higher proportion of cul-de-sacs (0.81 for Hamilton East compared to 0.54 for Rototuna). The difference in external connectivity between Hamilton East and Rototuna was the opposite of that found between old and new neighbourhoods overall. Hamilton East had a longer median distance between neighbourhood ingress/egress points than Rototuna (1232 metres for Hamilton East compared to 1072 metres for Rototuna). This is a reflection of limited access along the western and eastern sides of the Hamilton East neighbourhood due to the Waikato River and green belt, respectively.

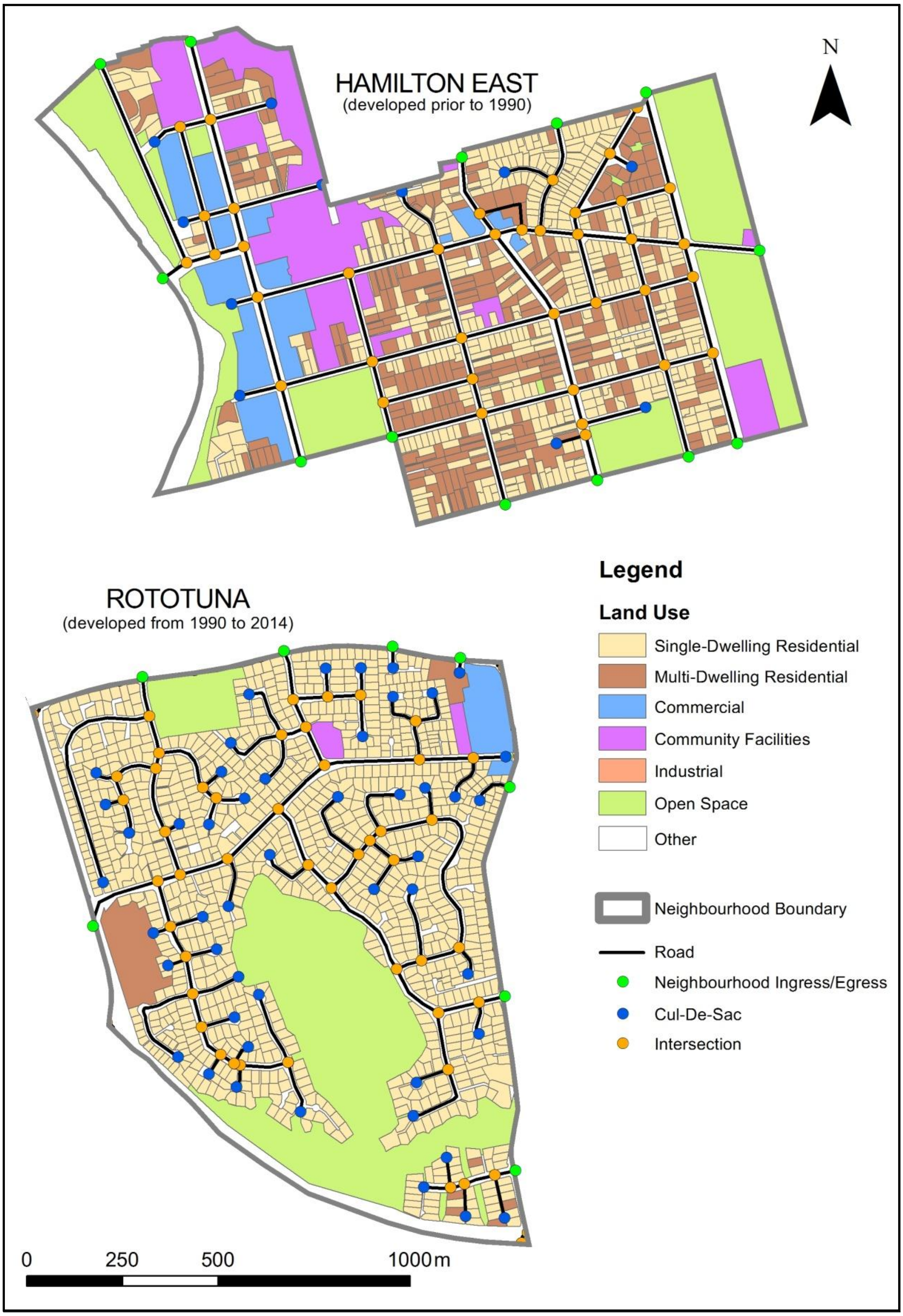


Figure 11: Examples of development patterns in old and new neighbourhoods.

4.3.2 Future Predictions for New Neighbourhoods

Two of the new neighbourhoods, Horsham Downs and Sylvester, are currently only partially developed and contain large areas of non-urban land. While the developed parts of these neighbourhoods are predominantly residential, planning maps in the Hamilton City Council Proposed District Plan (Hamilton (N.Z.) City Council 2012) suggest these undeveloped areas will eventually contain commercial, community facility and open space land uses in addition to further residential development. Hence when development is complete, the land use mix diversity indices for these two neighbourhoods will likely be higher than at present. The other four new neighbourhoods all have some (albeit small) portion of currently undeveloped land which was excluded from the land use mix diversity index calculations, including individual residential parcels that are yet to be built on and larger land parcels earmarked for future community facilities. Therefore use of current land use mix diversity index values for new neighbourhoods in the two-independent samples t-test does not give an accurate assessment of the difference in land use mix between old and new neighbourhoods when fully developed.

Taking into account the planned land use pattern for fully developed new neighbourhoods from the Hamilton City Council Proposed District Plan (Hamilton (N.Z.) City Council 2012), the land use mix diversity index was recalculated for each of the six new neighbourhoods (Table 7) and the t-test was repeated using these new values (Table 8).

Table 7: Current and predicted land use mix for new neighbourhoods

Neighbourhood	**Land Use Mix Diversity Index**	
	Current (Partial Development)	**Predicted (Full Development)**
NEW		
Brymer	0.21	0.20
Flagstaff	0.32	0.34
Horsham Downs	0.17	0.39
Huntington	0.46	0.44
Rototuna	0.46	0.46
Sylvester	0.27	0.34

Table 8: Descriptive statistics and t-test results for predicted future land use mix

Urban Form Metric	Neighbourhoods						t	df
	Old			New (Predicted)				
	M	SD	n	M	SD	n		
Land Use Mix Diversity Index	0.49	0.16	31	0.36	0.09	6	1.85**	35

* p < 0.10 **p < 0.05 ***p < 0.01

Brymer and Huntington will experience a small decrease in land use mix as remaining areas of undeveloped land are occupied by residential dwellings, while construction on currently vacant residential parcels in Rototuna will have no impact on land use mix. Flagstaff will experience a small increase in land use mix as community facilities are constructed on currently vacant land. Horsham Downs and Sylvester will experience a larger increase in land use mix as large areas of currently undeveloped land are occupied by commercial, community facility and open space land uses. The two-independent samples t-test shows that there is a statistically significant difference in land use mix between old and fully developed new neighbourhoods, with old neighbourhoods having higher land use mix diversity indices and therefore a more even distribution of land uses. However the level of significance of the difference between old and new neighbourhoods drops from 0.01 for current land use to 0.05 for predicted fully developed land use.

Insufficient information is available to allow quantitative predictions of dwelling density, single-dwelling proportion, single-dwelling parcel size, and street connectivity for fully developed new neighbourhoods. However, planning maps in the Hamilton City Council Proposed District Plan (Hamilton (N.Z.) City Council 2012) allow some qualitative predictions to be made. The maps show areas of medium or high density residential land use in currently undeveloped parts of Horsham Downs and Sylvester, which suggests multi-dwelling land parcels and hence a future decrease in the single-dwelling proportion for these two neighbourhoods. This may be accompanied by an increase in dwelling density. The maps also show planned transport corridors in currently undeveloped parts of Horsham Downs and Sylvester and their connection to roads running along the northern boundaries of these two neighbourhoods. Based on the location of these transport corridors it is likely that both neighbourhoods, but in particular Sylvester, will experience a future decrease in the median distance between neighbourhood ingress/egress points and therefore an increase in external connectivity.

4.4 Accessibility

4.4.1 Current Accessibility

Metrics of accessibility for residential neighbourhoods in Hamilton are given in Table 9. The spatial patterns of neighbourhood accessibility metrics are shown in Figure 12. Descriptive statistics for old and new neighbourhoods are given in Tables 10 and 11 with the variability in values for each neighbourhood group illustrated using box plots in Figure 13.

Median distance to the nearest commercial land use ranged from 283 to 889 metres for old neighbourhoods and 904 to 2261 metres for new neighbourhoods. Both the median distances and range in median distances were larger for new neighbourhoods, with median distance ranging from 904 metres in Flagstaff which has a small commercial area to 2261 metres in adjacent Sylvester which currently has no commercial land use. Median distance to the nearest bus stop ranged from 118 to 279 metres for old neighbourhoods and 214 to 1449 metres for new neighbourhoods. While the new neighbourhood of Brymer in the city’s west has a comparable median distance to many of the old neighbourhoods, new neighbourhoods in the city’s north have longer median distances, particularly Sylvester with a median distance of 1449 metres. Median distance to the nearest primary school ranged from 463 to 1636 metres for old neighbourhoods and 1163 to 3790 metres for new neighbourhoods. The new neighbourhoods of Flagstaff and Sylvester have the longest median distances of 2754 and 3790 metres, respectively, while Horsham Downs and Brymer have similar median distances to old neighbourhoods. Median distance to the nearest employment area ranged from 338 to 4105 metres for old neighbourhoods and 1974 to 5183 metres for new neighbourhoods. Employment areas include the cental business district, university, hospital, and main industrial zones. As these locations are more restricted than the locations of the other urban functions measured, the overall range in neighbourhood median distances was larger than for the other urban functions. While there is overlap between the two neighbourhood groups, the spatial pattern and box plot suggest new neighbourhoods have longer median distances to employment areas than old neighbourhoods. Median distance to the nearest medical clinic ranged from 540 to 2031 metres for old neighbourhoods and 982 to 2400 metres for new neighbourhoods. The old neighbourhood of Fairview Downs and the new neighbourhood of Sylvester had the longest median distances of 2031 and 2400 metres, respectively.

Median distance from the nearest police station ranged from 826 to 4659 metres for old neighbourhoods and 1017 to 3796 metres for new neighbourhoods, with the spatial pattern and box plot suggesting no difference between the two neighbourhood groups.

Table 9: Metrics of accessibility for old and new neighbourhoods

	Median Distance (metres) to the Nearest				
Neighbourhood	**Commercial Land Use**	**Bus Stop**	**Primary School**	**Employment Area**	**Medical Clinic**
OLD					
Bader	442	215	1366	1217	1503
Beerescourt	283	219	695	1015	727
Bryant	434	267	1307	826	1060
Chartwell	401	218	900	1769	884
Chedworth	423	221	851	4105	819
Clarkin	354	161	821	1885	665
Claudelands	351	196	1398	1104	861
Crawshaw	889	140	710	585	1352
Dinsdale North	514	238	649	1579	1220
Dinsdale South	569	152	1183	1535	1200
Enderley	325	256	1467	2106	715
Fairview Downs	702	196	1433	3613	2031
Glenview	547	163	1204	2567	1565
Grandview	737	177	979	1133	854
Hamilton East	360	168	1265	1306	1213
Hamilton Lake	514	255	1207	508	540
Hillcrest West	307	277	936	930	610
Insoll	514	279	622	2887	782
Maeroa	358	205	1191	439	1037
Melville	404	247	687	1565	1557
Nawton	540	246	786	1143	768
Naylor	295	118	1636	2271	1465
Peachgrove	422	216	1280	1451	1389
Porritt	482	217	988	3358	684
Pukete	710	197	754	1115	1356
Pukete West	601	154	463	762	1528
Queenwood	643	180	1061	3235	1111
Riverlea	621	243	863	1957	1183
Silverdale	581	182	609	819	1163
Swarbrick	422	259	706	338	943
University	379	131	1025	463	1966
NEW					
Brymer	1672	214	1317	1974	1549
Flagstaff	904	323	2754	3026	982
Horsham Downs	1334	475	1163	4501	1381
Huntington	1027	316	1801	5183	1483
Rototuna	959	339	1715	3651	1466
Sylvester	2261	1449	3790	4403	2400

Table 9 (continued): Metrics of accessibility for old and new neighbourhoods

	Median Distance (metres) from the Nearest		
Neighbourhood	**Police Station**	**Fire Station**	**Ambulance Station**
OLD			
Bader	2762	3027	4049
Beerescourt	3215	2998	2945
Bryant	3795	1770	4696
Chartwell	3290	3026	2572
Chedworth	3660	1107	1224
Clarkin	3678	2311	2748
Claudelands	2729	2505	2344
Crawshaw	1295	4221	4295
Dinsdale North	1237	4610	3536
Dinsdale South	1195	4412	3628
Enderley	3281	2635	3196
Fairview Downs	4659	2882	4188
Glenview	4612	4614	5439
Grandview	826	4994	4024
Hamilton East	898	3664	3883
Hamilton Lake	2248	2213	2530
Hillcrest West	1842	5301	5963
Insoll	4234	1779	2665
Maeroa	2347	3300	2009
Melville	3679	3643	4447
Nawton	992	4893	3584
Naylor	1998	3763	4337
Peachgrove	2039	2458	2677
Porritt	4494	770	2004
Pukete	2977	1481	4786
Pukete West	3149	1653	4958
Queenwood	2136	2326	1238
Riverlea	2828	5416	6438
Silverdale	2762	6072	6528
Swarbrick	1114	3231	2332
University	962	4592	4812
NEW			
Brymer	1530	5658	5044
Flagstaff	1017	3376	3614
Horsham Downs	2676	4659	3281
Huntington	3796	3446	2646
Rototuna	2638	4019	2330
Sylvester	2407	4706	4566

Table 9 (continued): Metrics of accessibility for old and new neighbourhoods

	Percentage of Residential Parcels Within Walking Distance of		
Neighbourhood	**Commercial Land Use**	**Bus Stop**	**Primary School**
OLD			
Bader	78	100	13
Beerescourt	97	100	62
Bryant	88	100	24
Chartwell	96	100	42
Chedworth	80	100	46
Clarkin	100	100	48
Claudelands	99	100	0
Crawshaw	39	100	62
Dinsdale North	78	95	59
Dinsdale South	77	100	17
Enderley	100	100	4
Fairview Downs	58	100	9
Glenview	68	100	24
Grandview	56	100	20
Hamilton East	100	100	6
Hamilton Lake	70	96	30
Hillcrest West	93	99	36
Insoll	86	100	72
Maeroa	97	100	15
Melville	87	93	65
Nawton	78	100	52
Naylor	100	100	0
Peachgrove	97	95	11
Porritt	83	100	28
Pukete	62	100	56
Pukete West	77	100	83
Queenwood	63	98	36
Riverlea	70	100	43
Silverdale	80	100	76
Swarbrick	98	99	60
University	90	100	36
NEW			
Brymer	0	100	16
Flagstaff	40	99	0
Horsham Downs	20	69	14
Huntington	34	91	5
Rototuna	34	96	3
Sylvester	0	6	0

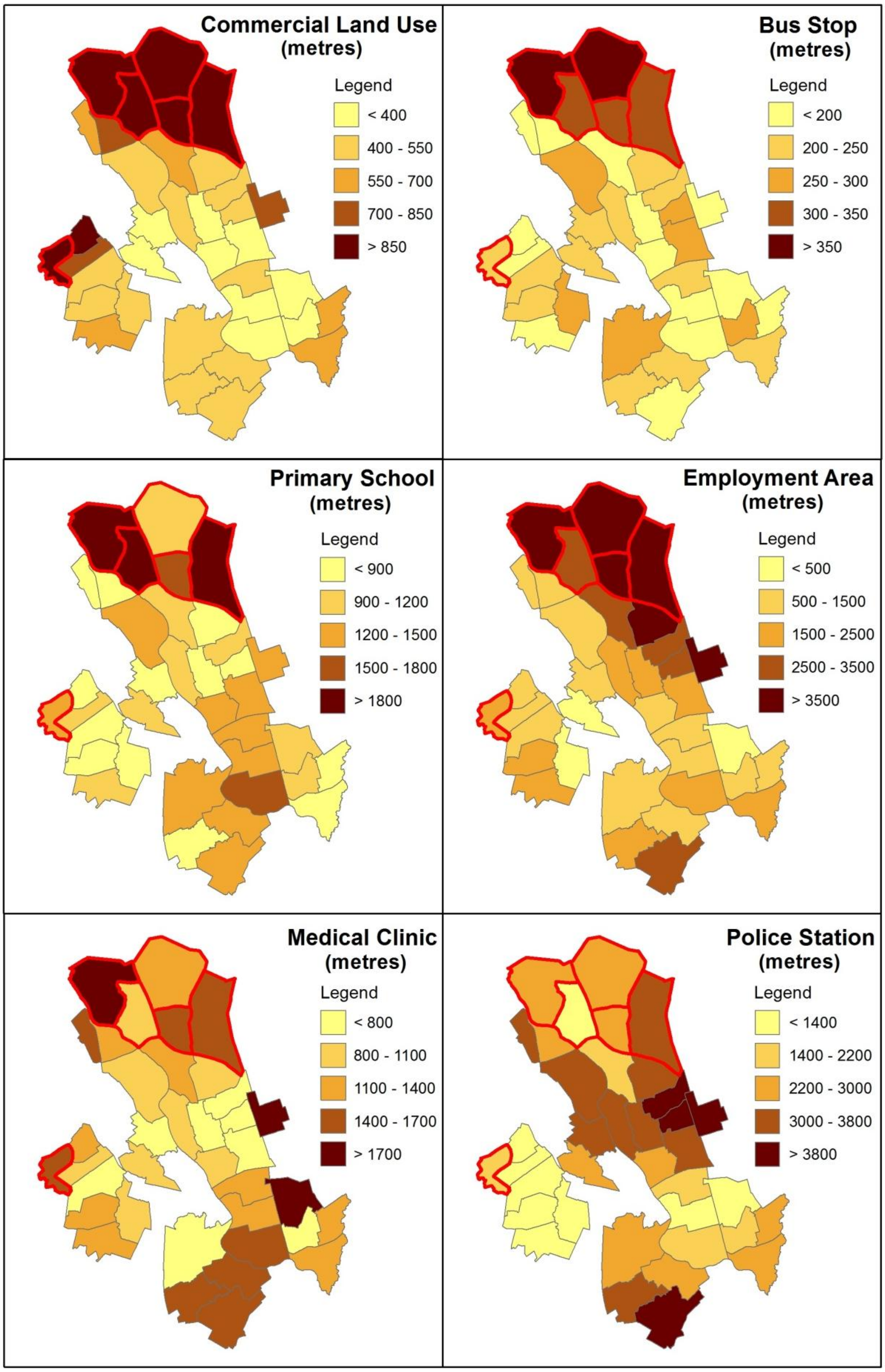


Figure 12: Maps of accessibility metrics. New neighbourhoods are outlined in red.

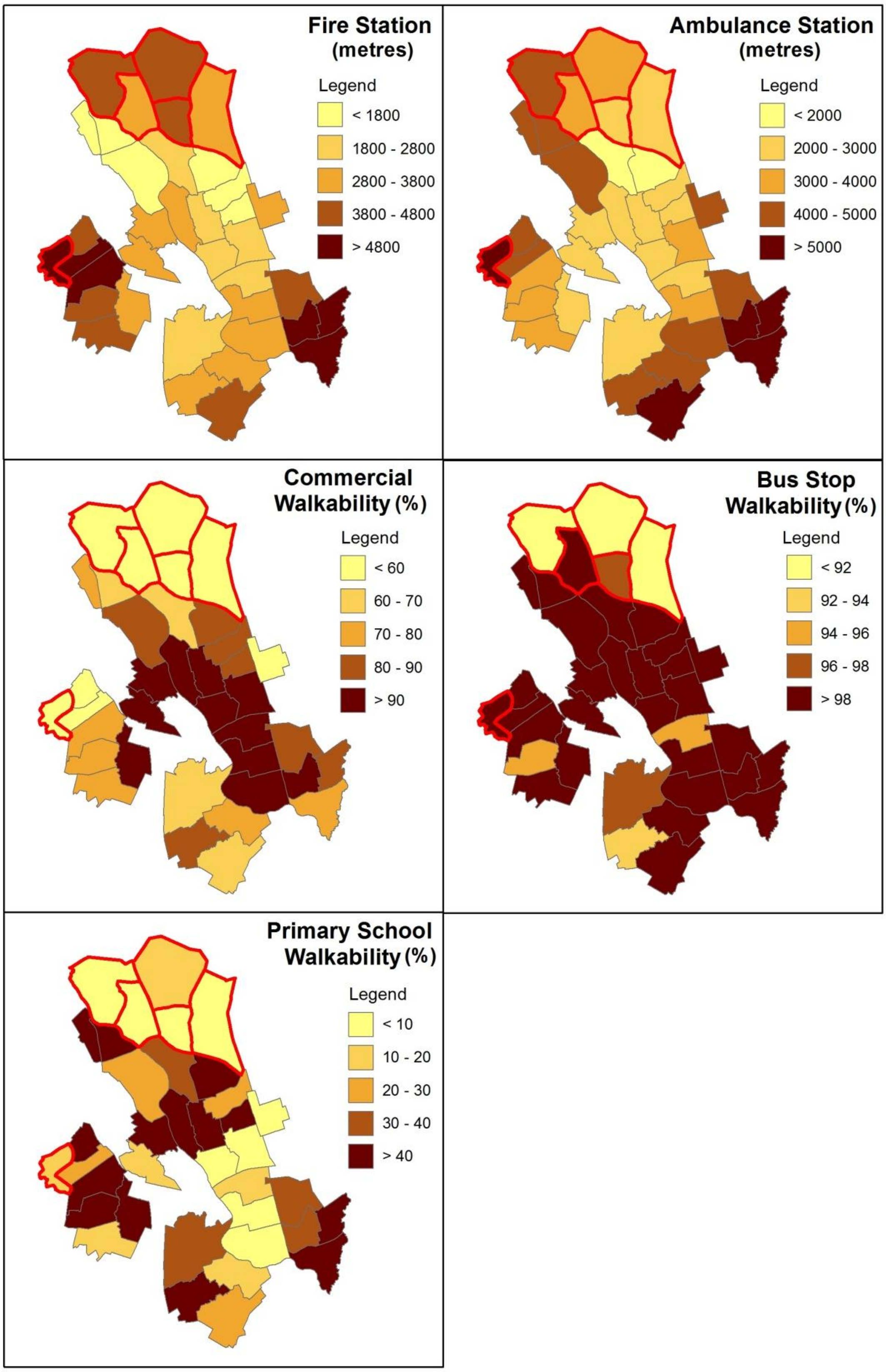


Figure 12 (continued): Maps of accessibility metrics. New neighbourhoods are outlined in red.

Table 10: Descriptive statistics and t-test results for metrics of accessibility

Accessibility Metric	**Neighbourhoods**						**t**	**df**
	Old			**New**				
	M	**SD**	**n**	**M**	**SD**	**n**		
Commercial Distance(1) (metres)	488	147	31	1360	527	6	-4.02***	5
Bus Stop Distance(1) (metres)	206	44	31	519	463	6	-2.64**	5
Primary School Distance(1) (metres)	1001	304	31	2090	1001	6	-2.64**	5
Employment Area Distance (metres)	1600	999	31	3790	1160	6	-3.66***	35
Medical Clinic Distance (metres)	1121	385	31	1543	466	6	-2.38**	35
Police Station Distance (metres)	2611	1183	31	2344	973	6	0.52	35
Fire Station Distance (metres)	3280	1371	31	4311	872	6	-1.76**	35
Ambulance Station Distance (metres)	3680	1398	31	3580	1062	6	0.16	35
Primary School Walkability(1) (%)	37	24	31	6	7	6	5.86***	28

* p < 0.10 **p < 0.05 ***p < 0.01

(1) Assuming unequal variances

Table 11: Mann-Whitney test results for metrics of accessibility

Accessibility Metric	**Neighbourhoods**						**Mann-Whitney *U***	***Z***
	Old			**New**				
	Median	**Sum of Ranks**	**n**	**Median**	**Sum of Ranks**	**n**		
Commercial Walkability (%)	83	681	31	27	22	6	1	-3.77***
Bus Stop Walkability (%)	100	654.5	31	93	48.5	6	27.5	-3.14***

* p < 0.10 **p < 0.05 ***p < 0.01

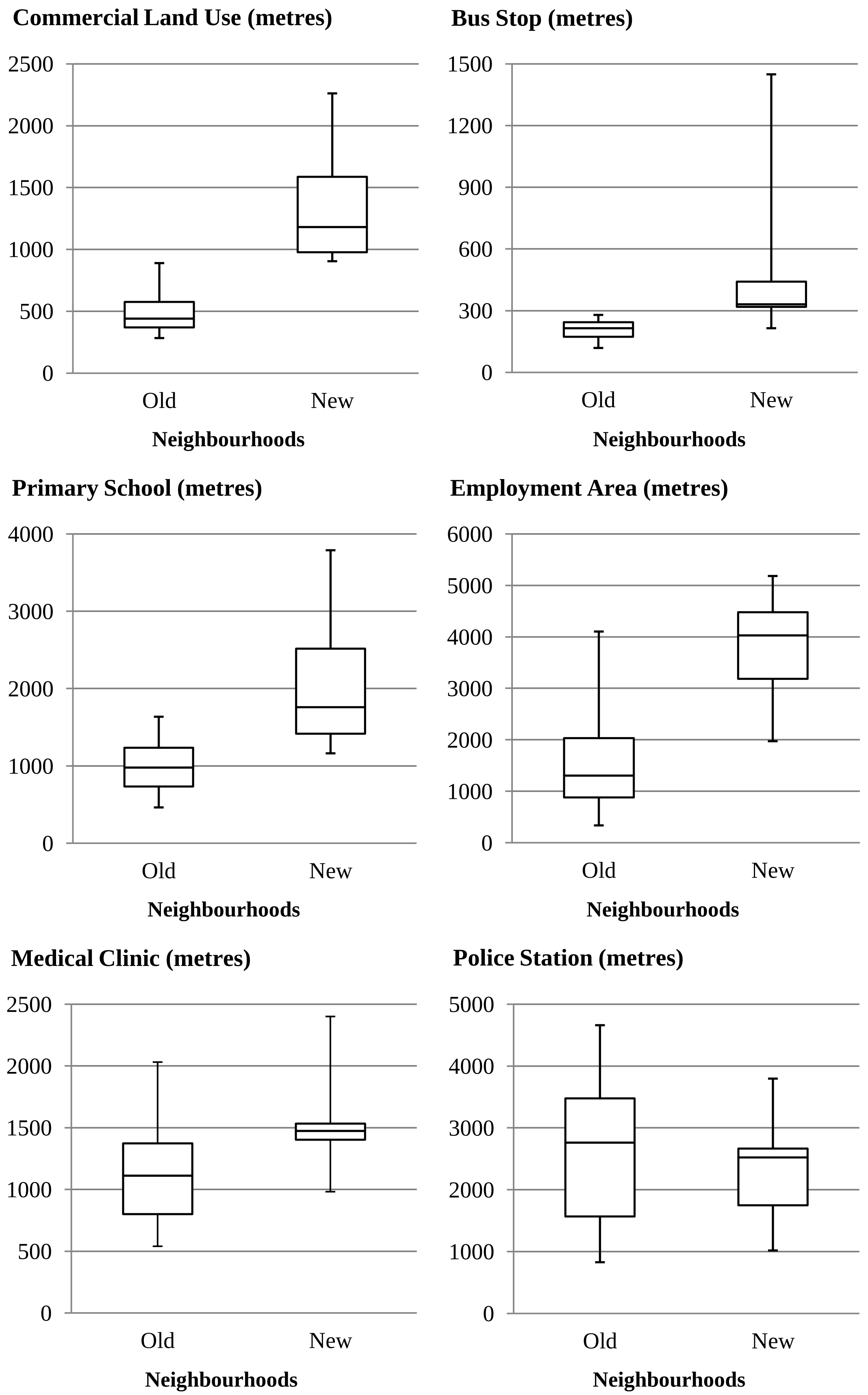
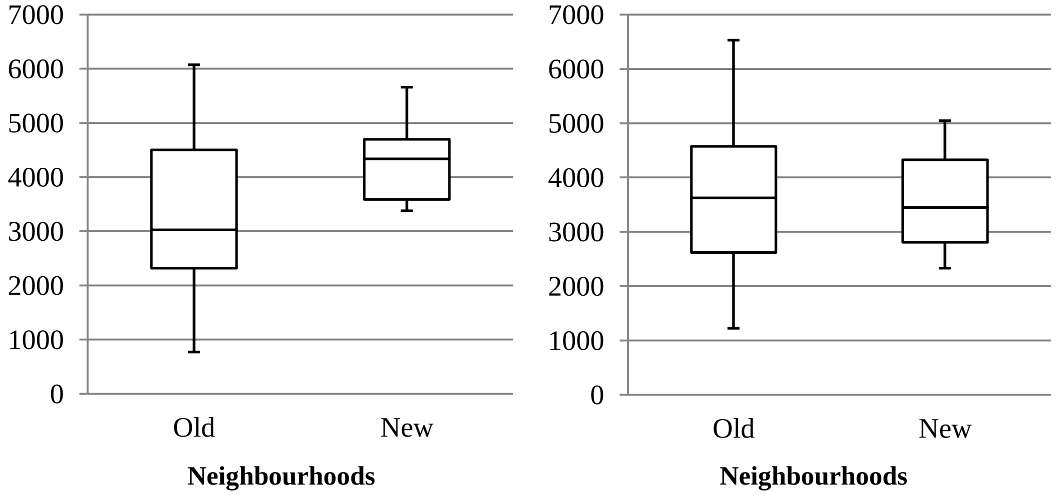
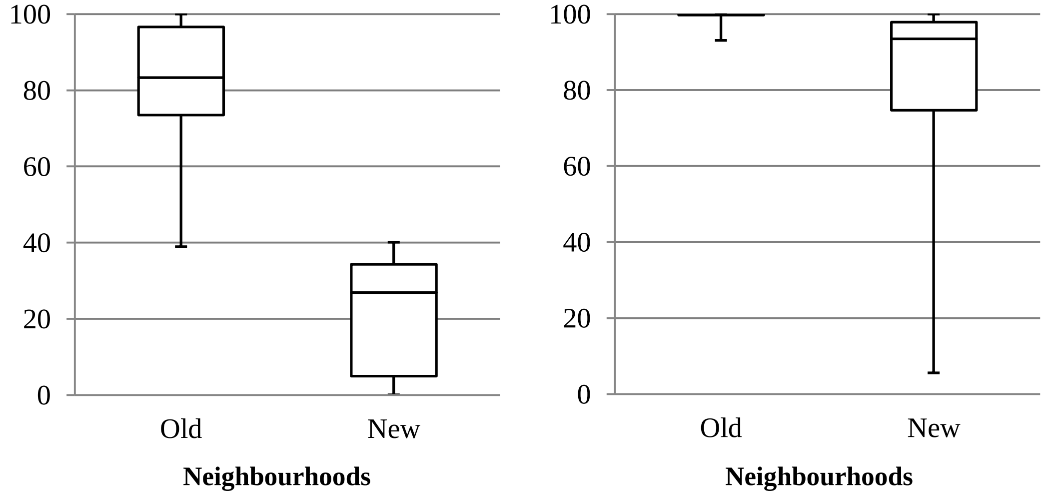


Figure 13: Box plots of accessibility metrics for old and new neighbourhoods showing the median, lower and upper quartiles (box), and minimum and maximum (bars) values.

Fire Station (metres) **Ambulance Station (metres)**



Commercial Walkability (%) **Bus Stop Walkability (%)**



Primary School Walkability (%)

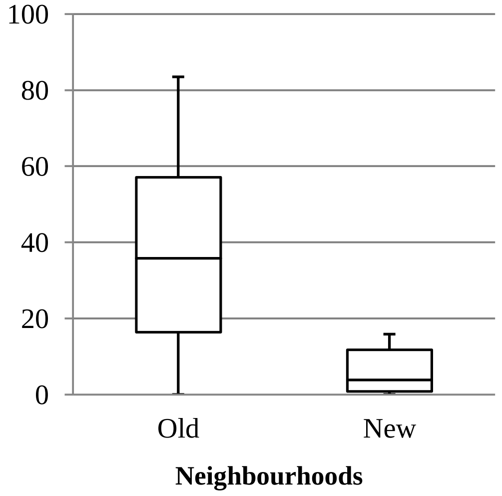


Figure 13 (continued): Box plots of accessibility metrics for old and new neighbourhoods showing the median, lower and upper quartiles (box), and minimum and maximum (bars) values.

Old neighbourhoods in the city's east and south have the longest median distances in excess of 4000 metres. Median distance from the nearest fire station ranged from 770 to 6072 metres for old neighbourhoods and 3376 to 5658 metres for new neighbourhoods. Porritt is the only residential neighbourhood to have a fire station and therefore has the shortest median distance of 770 metres. Old neighbourhoods in the city's southeast and the new neighbourhood of Brymer in the west had the longest median distances in excess of 5000 metres. Median distance from the nearest ambulance station ranged from 1224 to 6528 metres for old neighbourhoods and 2330 to 5044 metres for new neighbourhoods, with the spatial pattern and box plot suggesting no difference between the two neighbourhood groups. Chedworth is the only residential neighbourhood to have an ambulance station and therefore has the shortest median distance of 1224 metres. The old neighbourhoods of Riverlea and Silverdale in the city's southeast had the longest median distances in excess of 6000 metres.

The percentage of residential parcels within walking distance of a commercial land use ranged from 39% to 100% for old neighbourhoods and 0% to 40% for new neighbourhoods. The spatial pattern showed that central neighbourhoods had commercial walkability in excess of 90% while fringe neighbourhoods, including new neighbourhoods in the west and north, have commercial walkability less than 60%. The percentage of residential parcels within walking distance of a bus stop ranged from 93% to 100% for old neighbourhoods and 6% to 100% for new neighbourhoods. The new neighbourhoods of Sylvester and Horsham Downs have the lowest bus stop walkability of 6% and 69% respectively. Both of these neighbourhoods are currently only partially developed and, while the southern part of Horsham Downs is serviced by public transport, Sylvester does not currently have any bus stops. The percentage of residential parcels within walking distance of a primary school ranged from 0% to 83% for old neighbourhoods and 0% to 16% for new neighbourhoods. Of the 37 residential neighbourhoods in Hamilton, 21 have a primary school. Two old neighbourhoods (Claudelands and Naylor) and two new neighbourhoods (Flagstaff and Sylvester) currently have neither a primary school nor a primary school within walking distance in an adjacent neighbourhood, and therefore have no primary school walkability.

Results of two-independent samples t-tests and Mann-Whitney tests to assess the significance of differences in metrics of accessibility between old and new neighbourhoods are given in Tables 10 and 11. There are statistically significant differences, at the 0.01 or 0.05 levels of significance, in terms of commercial, bus stop, primary school, employment area, medical clinic and fire station accessibility, and commercial, bus stop and primary school walkability. Results showed that:

- Old neighbourhoods had shorter median distances to the nearest commercial land use, bus stop, primary school, employment area and medical clinic.

- Old neighbourhoods had shorter median distances from the nearest fire station.

- Old neighbourhoods had a higher percentage of residential parcels within walking distance of a commercial land use, bus stop and primary school.

- No statistical difference existed between old and new neighbourhoods in terms of median distances from the nearest police station and ambulance station.

4.4.2 Future Predictions for New Neighbourhoods

As discussed in section 4.3.2 the new neighbourhoods of Horsham Downs and Sylvester are currently only partially developed. It is not possible to predict accessibility for these two neighbourhoods when fully developed as future residential land parcels have yet to be delineated. However, it is possible to assess how accessibility for existing residential land parcels may change once these neighbourhoods are fully developed.

Future development in Horsham Downs and Sylvester is expected to include commercial land uses (Hamilton (N.Z.) City Council 2012). A new primary school is currently being constructed on previously vacant land in adjacent Flagstaff (Wilson 2014). Taking into account the locations of planned future commercial land uses and the new primary school, distances from existing residential land parcels in the five new neighbourhoods in northern Hamilton to the nearest commercial land use and primary school were recalculated. Median distances for each neighbourhood and the percentage of parcels within walking distance were also recalculated (Table 12).

For existing residential land parcels in Horsham Downs and Sylvester the median distance to the nearest commercial land use will decrease by 466 metres and 1044 metres, respectively, while the percentage of parcels within walking distance of a commercial land use will increase from 20% to 40% and 0% to 20%, respectively. Figure 14 shows the impact on primary school accessibility when the new primary school opens in Flagstaff. For existing residential land parcels in Flagstaff and Sylvester the median distance to the nearest primary school will decrease by 1880 metres and 1589 metres, respectively, with no change in Horsham Downs, Rototuna or Huntington. In Flagstaff the percentage of existing parcels within walking distance of a primary school will increase from 0% to 45%, with some parcels currently at a distance greater than 3000 metres becoming within walking distance (less than 800 metres). Although the distance to the nearest primary school will decrease for most of the existing residential land parcels in Sylvester, and the median distance will decrease, none of the parcels are within walking distance of the new primary school.

Table 12: Current and predicted accessibility metrics for new neighbourhoods

Neighbourhood$^{(1)}$	**Median Distance (metres) to the Nearest**				**Percentage of Residential Parcels Within Walking Distance of**			
	Commercial Land Use		**Primary School**		**Commercial Land Use**		**Primary School**	
	Current	**Predicted**	**Current**	**Predicted**	**Current**	**Predicted**	**Current**	**Predicted**
NEW								
Flagstaff	904	904	2754	874	40	40	0	45
Horsham Downs	1334	868	1163	1163	20	40	14	14
Huntington	1027	1027	1801	1801	34	34	5	5
Rototuna	959	959	1715	1715	34	34	3	3
Sylvester	2261	1217	3790	2201	0	20	0	0

(1) Existing residential land parcels only

It is not possible to assess how bus stop, employment area, medical clinic and emergency services accessibility for existing residential land parcels may change once Horsham Downs and Sylvester are fully developed as future locations for these facilities are unknown.

The use of current median distances and walkability percentages for new neighbourhoods in the two-independent samples t-tests and Mann-Whitney tests does not give an accurate assessment of the difference in accessibility between old and new neighbourhoods when fully developed. As it is not currently possible to predict accessibility for Horsham Downs and Sylvester when fully developed, these tests cannot be repeated using predicted future values for these two neighbourhoods. Hence it is not possible to predict the significance of the difference in accessibility between old and new neighbourhoods when fully developed.

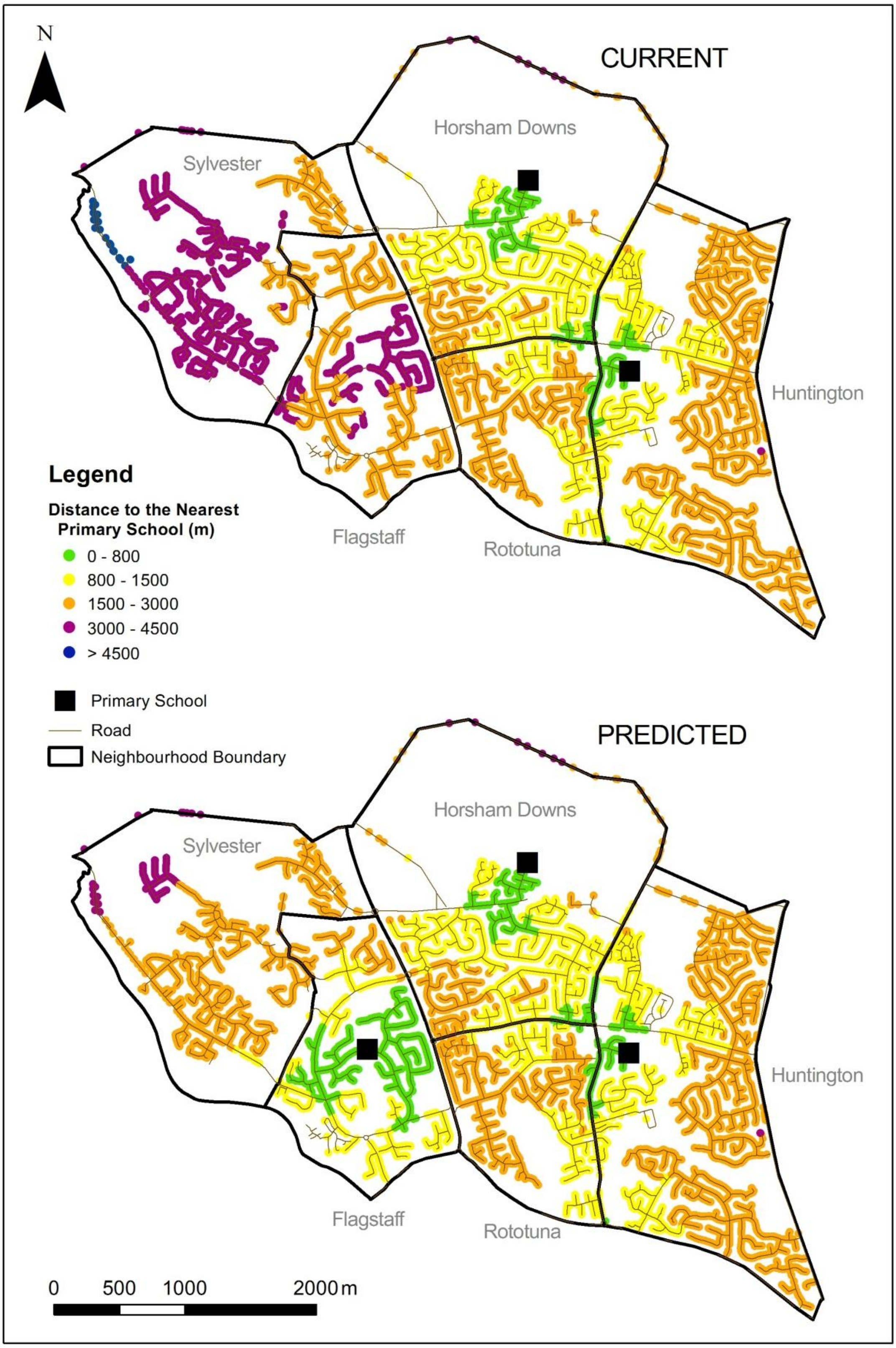


Figure 14: Current and predicted future primary school accessibility in new neighbourhoods in northern Hamilton. Points represent the road network locations of existing residential parcel centroids. Green points are those within walking distance (800m) of a primary school.

Chapter 5: Discussion

5.1 Introduction

The primary research question to be addressed in this study is whether the post-1989 urban growth in Hamilton should be categorised as urban sprawl? To investigate this research question urban growth, urban form, and accessibility have been measured in order to address three sub-questions which reflect different ways of defining and measuring urban sprawl. The following discussion addresses the key findings of the study with respect to each of these research questions, followed by a discussion of study limitations and recommendations for further research.

5.2 Key Findings

5.2.1 Urban Growth

The first research sub-question is whether growth in the Hamilton urban area occurred at a greater rate than the city's population growth? This sub-question addresses the definition of urban sprawl adopted by the United States Environmental Protection Agency (as cited in Barnes et al. 2001) and later Bhatta (2010) as urban growth at a rate which exceeds the rate of population growth.

Post-classification change detection of Landsat imagery shows that the Hamilton urban area grew by 45% between 1990 and 2014, while the population residing within Hamilton City grew by 41% between 1991 and 2013. Several sources of error must be considered when comparing these growth rates. Firstly, due to restrictions imposed by the timing of satellite images suitable for analysis and the population census, the period over which urban growth has been measured is 16 months longer than for population growth. Secondly, the population growth rate is based on the usually resident population within the Hamilton City Territorial Authority boundary, not just those residents living in the urban area within this boundary. Thirdly, the expected overall accuracy for urban change detection between 1990 and 2014 is 88%. In light of these sources of error it is reasonable to conclude that growth in the Hamilton urban area has occurred at a comparable rate to growth in the population residing within Hamilton City. Certainly other studies employing this method for measuring the occurrence of urban sprawl have identified significantly larger differences between urban and population growth rates. Pijanowski and Robinson (2011) found that the rate of urban growth was more than four times the rate of population growth between 1963 and 2000 in the Milwaukee Metropolitan Area, USA. Jat et al. (2008) found that the rate of urban growth was more than three times the rate of population growth between 1977 and 2002 in Ajmer City, India. Bagan and Yamagata (2012) and Hammann (2012) found that the rate of urban growth was more than double the rate of population growth between 1970 and 2011 in Tokyo, Japan, and between 1989 and 2010 in Campinas City, Brazil, respectively.

Hence in answer to the first research sub-question it has been found that growth in the Hamilton urban area has not occurred at a greater rate than the city's population growth. Therefore, based on this method of measuring urban sprawl, the post-1989 urban growth in Hamilton should not be categorised as urban sprawl.

5.2.2 Urban Form

The second research sub-question is whether new neighbourhoods are more homogeneous, having a higher proportion of single family dwellings on larger land parcels, and whether they lack street connectivity? This sub-question addresses definitions of urban sprawl as a pattern of land development, the cause of an unwanted externality, and the consequence of planning and zoning policies (Galster et al. 2001), and critics claims that areas of urban sprawl lack a mix of land uses, are dominated by single-family dwelling units on large lots, and contain too many winding streets and cul-de-sacs (Song and Knaap 2004).

Spatial geometry and density-based metrics, which encompass critical aspects that contribute to a metropolitan area's urban form, show statistically significant differences between old and new neighbourhoods in terms of their current land use mix, dwelling density, single-dwelling proportion, and street connectivity. New neighbourhoods are more homogeneous, with lower dwelling densities, higher proportions of single dwellings, and poorer internal and external street connectivity.

A source of error in these calculations is that all of the new neighbourhoods have some portion of currently undeveloped land. Recalculation of neighbourhood land use mix taking into account the planned land use pattern for new neighbourhoods when fully developed shows that the statistically significant difference between old and new neighbourhoods will persist. Although it is not possible to predict the future values of other urban form metrics for new neighbourhoods, it is considered unlikely that changes associated with the completion of development will eliminate the statistically significant differences that currently exist. Changes occurring in old neighbourhoods since their original development may also affect the reliability of the results found in this study. For example, the Hamilton City Council Proposed District Plan (Hamilton (N.Z.) City Council 2012) defines “Residential Intensification Zones” as existing residential areas suitable to accommodate higher density development, with the intent to encourage site redevelopment. The occurrence of these zones in old neighbourhoods (Figure 15) magnifies present-day differences in dwelling density and single-dwelling proportion between old and new neighbourhoods, and prevents analysis of any differences that may have existed at the time of original neighbourhood development.

There is no statistically significant difference between old and new neighbourhoods in terms of the median single-dwelling parcel size. Changes occurring in old neighbourhoods since their original development are also likely to have affected the reliability of this result. As redevelopment occurs original single-dwelling parcels may become multi-dwelling parcels (Figure 15) or they may be subdivided into multiple smaller single-dwelling parcels (Figure 16). In the case of the former they have not been included in calculation of neighbourhood median single-dwelling parcel size, while in the case of the latter it is the multiple smaller parcels that are included in the calculation. It is therefore possible that the original median single-dwelling parcel size in old neighbourhoods was larger than the current size. However no data is available in order to quantify the original parcel sizes or to assess the significance of any difference in comparison to new neighbourhoods. What can be assumed is that it is unlikely that the median single-dwelling parcel size in new neighbourhoods is larger than the original median single-dwelling parcel size in old neighbourhoods. This is the opposite of what would be expected in an area exhibiting characteristics of urban sprawl and may be a function of several factors including subdivision policies, market demand and land prices.

Hence in answer to the second research sub-question it has been found that new neighbourhoods are more homogeneous, that they have a higher proportion of single family dwellings and lack street connectivity. However these single family dwellings do not occupy larger land parcels. Therefore, based on five out of the six metrics of urban form, the post-1989 urban growth in Hamilton should be categorised as urban sprawl.

5.2.3 Accessibility

The third research sub-question is whether residents of old and new neighbourhoods have different access to essential services, commercial areas, employment areas, and public transport? This sub-question addresses definitions of urban sprawl as the cause

Figure 15: Redevelopment of single-dwelling parcels into multi-dwelling parcels in an old neighbourhood Residential Intensification Zone between 2008 (left) and 2013 (right). Parcel boundaries are shown in yellow. Aerial images: Google, City of Hamilton.

Figure 16: Redevelopment of a single-dwelling parcel into multiple parcels in an old neighbourhood between 2008 (top) and 2013 (bottom). Parcel boundaries are shown in yellow. Aerial images: Google, City of Hamilton.

of an unwanted externality (Galster et al. 2001) and a condition of poor accessibility (Frenkel and Ashkenazi 2008), and critics claims that because areas of urban sprawl are characterised by too much separation between land uses residents experience increased travelling distances and a reduction in accessibility and walkability.

Accessibility metrics show statistically significant differences between old and new neighbourhoods in terms of current access to primary schools, medical clinics, fire stations, commercial land uses, employment areas and bus stops. New neighbourhoods have longer median travelling distances to/from these facilities, and hence reduced access. Accessibility metrics also show statistically significant differences between old and new neighbourhoods in terms of current primary school, commercial land use and bus stop walkability. New neighbourhoods have a lower percentage of residential parcels within walking distance (800m) of these facilities, and hence reduced walkability.

There is no statistically significant difference between old and new neighbourhoods in terms of median travelling distances from the nearest police station and ambulance station. This suggests that the locations of these facilities are currently well-balanced with respect to the spatial distribution of residential land parcels in old and new neighbourhoods.

A source of error in these calculations is that two of the new neighbourhoods have large portions of currently undeveloped land, and it is not possible to predict accessibility for these two neighbourhoods when fully developed as future residential land parcels have yet to be delineated. Hence the results presented in this study as to the accessibility and walkability differences between old and new neighbourhoods only apply to the current situation. It was however found that commercial land use and primary school accessibility and walkability will be improved for existing residential land parcels in several new neighbourhoods as development progresses.

Hence in answer to the third research sub-question it has been found that residents of old and new neighbourhoods currently have different access to commercial areas, employment areas, public transport, and some essential services. Residents of new neighbourhoods currently experience increased travelling distances to/from these facilities and reduced accessibility and walkability compared to residents of old neighbourhoods. Therefore, based on nine out of the eleven metrics of accessibility the post-1989 urban growth in Hamilton should be categorised as urban sprawl.

5.3 Study Limitations

It is important to acknowledge that there are several limitations to the methods used in this study to measure urban sprawl including the resolution of satellite imagery, method of neighbourhood definition, development status of new neighbourhoods, and exclusion of pedestrian-only access routes. Each of these limitations will be discussed further below.

Landsat satellite imagery is commonly used in urban growth detection studies due to its long history of image acquisition, ease of availability, and acceptable spatial resolution (Bhatta 2010). The imagery used in this study has a spatial resolution (pixel size) of 30m x 30m and therefore urban growth has been measured in 900m^2 units. It is interesting to note that this cell size is larger than the median single-dwelling parcel size in both old and new neighbourhoods (Table 5). Pixels around the boundary of the urban area may comprise both urban and non-urban land cover and therefore have a spectral value that is an average of these two land cover types (known as mixed pixels). This may result in either over- or under-estimation of the size of the urban area. In this study the mixed pixel problem was also evident in the misclassification of pixels representing the Waikato River (section 4.2.3). The problem of mixed pixels seems inherent in the image classification process in heterogeneous areas, as their occurrence has been noted in studies using even higher resolution images (5.8m and 20m pixel sizes) (Bhatta 2010).

As the neighbourhood is the unit of measure for the urban form and accessibility analysis presented in this study it stands to reason that the results of the analysis may be different had a different set of neighbourhood boundaries been used. Since many of the metrics of urban form and accessibility used in this study are the same as, or comparable to, those employed by Song and Knaap (2004) it seemed appropriate to delineate neighbourhoods in comparable way. Hence the boundaries of intermediate-sized census blocks (area units) were used as neighbourhood boundaries. In addition a visual comparison of the boundaries of smaller census blocks (meshblocks), land parcel boundaries and roads revealed that neighbourhoods based on these smaller census blocks would be too small to provide meaningful results for the metrics of urban form calculated in this study. For example, some meshblocks contain no intersections or cul-de-sacs, while others are comprised of only a single land parcel. The use of area unit boundaries resulted in the definition of 37 residential neighbourhoods. In the interests of keeping neighbourhood definition simple and unbiased, these area unit boundaries were used “as is” and were not further subdivided despite some of the 37 neighbourhoods being bisected by natural barriers (e.g. stream gullies) or major roads, and/or being larger than what one might perceive as a neighbourhood.

The research questions addressed in this study required measurement and comparison of urban form and accessibility in old and new neighbourhoods to determine whether new neighbourhoods exhibit characteristics of urban sprawl. The value of this comparison is limited by the fact that two of the six new neighbourhoods are currently only partially-developed. For these two neighbourhoods urban form could only be measured for development to date and accessibility determined only for existing residential land parcels, not for those which have yet to be delineated. Hence the metrics of urban form and accessibility for these two neighbourhoods, and therefore the comparison of old and new neighbourhoods overall, is only relevant to the present-day situation. Repetition of the metrics of urban form and accessibility when these two neighbourhoods are fully-developed may yield different results to those presented in this study. Changes occurring in old neighbourhoods since their original development, such as parcel subdivision and residential intensification, are further reasons why the results of this study should be considered to represent a particular point in time.

An assumption made when calculating pedestrian accessibility was that pedestrians are restricted to walking on footpaths that follow the road network and that this access for pedestrians exists adjacent to all roads. Due to a lack of data pedestrian-only access routes have not been included when determining walking distances. Modern subdivisions are notorious for their winding streets and abundant cul-de-sacs contributing to poor street connectivity, and the new neighbourhoods in Hamilton are no exception. However these same subdivisions often contain pedestrian-only access routes with the aim of enhancing walkability. By excluding these pedestrian-only routes from the analysis it is possible that pedestrian accessibility, particularly in new neighbourhoods, has been underestimated in this study.

5.4 Recommendations for Further Research

Two main areas of further research are recommended. The first aims to improve the results of this study by taking steps to address some of the study limitations. The second aims to further add to the area of knowledge regarding urban sprawl in Hamilton and in New Zealand cities overall.

Limitations to the methods used in this study to measure urban sprawl have been discussed in section 5.3. In order to improve the results of this study I recommend that:

- Neighbourhood urban form and accessibility metrics be recalculated once all new neighbourhoods are fully developed. This will allow the metrics to be calculated for the whole neighbourhood, rather than just development to date, and will provide a more accurate estimate of any differences between old and new neighbourhoods.

- Neighbourhood pedestrian accessibility metrics be recalculated using a network which includes both roads and pedestrian-only access routes. This will provide a more accurate estimate of pedestrian accessibility, particularly in new neighbourhoods.

There is very little literature attempting to measure urban sprawl in New Zealand cities and the studies that are available focus on population density based measurement methods. Urban growth, urban form and accessibility have been used elsewhere in the world as measures of urban sprawl, however the results of these studies are of no relevance to this study and therefore no comparisons have been made. In order to add to the area of knowledge regarding urban sprawl in Hamilton, and in New Zealand cities overall, I recommend that:

- Urban growth, urban form and accessibility metrics used in this study be recalculated for Hamilton at regular intervals in the future.

- Similar studies are carried out for other New Zealand cities where the potential for urban sprawl is of concern.

- A sprawl index is developed which reflects differences in urban form and accessibility between old and new neighbourhoods and which can be used to compare the degree of sprawl in New Zealand cities.

As previously discussed the results of this study should be considered to represent a particular point in time. Repeating the calculations at regular intervals in the future will allow any differences between old and new neighbourhoods to be monitored as Hamilton City continues to evolve. It will also allow the impact of planning policies, such as the “Residential Intensification Zones”, to be monitored in the context of promoting or eliminating disparity between old and new neighbourhoods.

For similar studies in other New Zealand cities the basis for neighbourhood definition should be the same as in this study (census area units) to facilitate comparison between cities. The development of a sprawl index and the comparison of Hamilton to other New Zealand cities will provide a context for interpreting the results of this study. If

Hamilton is found to have a higher degree of sprawl than other New Zealand cities the reasons for this could then be investigated, the development plans and policies of the territorial authorities could be compared, and steps identified to address and potentially lessen the effects on residents.

Chapter 6: Conclusions

Urban sprawl is a complex phenomenon with a wide range of definitions and associated measurement methods. In this study urban growth, urban form and accessibility were measured using remote sensing and GIS techniques in order to test two hypotheses and conclude whether the post-1989 urban growth in Hamilton, New Zealand, should be categorised as urban sprawl.

The first hypothesis, that the rate of growth in the Hamilton urban area has not occurred at a greater rate than the city’s population growth, has been accepted. Hence based on this hypothesis it can be concluded that the post-1989 urban growth in Hamilton should not be categorised as urban sprawl.

However the second hypothesis, that there is no difference in urban form and accessibility metrics between old and new neighbourhoods, has been rejected. New neighbourhoods (developed from 1990 to 2014) were found to exhibit urban form and accessibility characteristics typically associated with areas of urban sprawl, such as being more homogeneous with lower dwelling densities, higher proportions of single dwellings, poorer street connectivity, increased travelling distances, and reduced accessibility and walkability. Hence based on this hypothesis it can be concluded that the post-1989 urban growth in Hamilton should be categorised as urban sprawl.

These contradicting conclusions demonstrate the complexity of the urban sprawl phenomenon and that whether the post-1989 urban growth in Hamilton should be categorised as urban sprawl depends upon the particular definition of urban sprawl that is adopted and the measurement method used.

This study has also concluded that these metrics of urban sprawl reflect a particular point in time. The calculations should be repeated in the future to accommodate the completion of development in new neighbourhoods and to monitor the impact of planning policies, changes occurring in neighbourhoods after their initial development, and future greenfield development.

Existing and prospective residents of Hamilton should be aware that those living in new neighbourhoods on the city-fringe are currently exposed to the negative public health effects of urban sprawl, with reduced accessibility and walkability leading to an increased dependence on private motor vehicles. Whether this exposure actually leads to poorer public health is another matter and would depend on individual behaviour, for example whether residents choose to make use of available facilities like walking paths and cycle routes. However it is possible for these effects to be reduced if policymakers take steps to reduce homogeneity, increase dwelling density, and reduce travelling distances through considered placement of important urban functions. There is also a role for policymakers in encouraging the use of alternatives to the private motor vehicle.

Remote sensing and GIS techniques have been essential for the image classification, spatial geometry and network analysis required to address the research questions and hypotheses of this study. These techniques will continue to be of value should the urban growth, urban form and accessibility metrics be recalculated at regular intervals in the future.

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Appendices

Appendix 1: Data Sources and Metadata

Table 13: Data sources and metadata

Dataset	Description	Spatial Extent	Format	Coordinate System[1]	Source
Landsat 1990	Image acquired on 4 April 1990 (LT40730861990094XXX02)	Path 073 Row 086	Raster GeoTIFF (one image for each band)	GCS: WGS1984 PCS: UTM (zone 60S)	USGS Global Visualization Viewer (GloVis) http://glovis.usgs.gov Satellite: Landsat 4 Sensor: TM Bands: 1-5 & 7 (30m x 30m) 6 (60m x 60m) Acquisition quality: 9 Cloud cover: 0%
Landsat 2001	Image acquired on 25 September 2001 (LE70730862001268HOA00)	Path 073 Row 086	Raster GeoTIFF (one image for each band)	GCS: WGS1984 PCS: UTM (zone 60S)	USGS Global Visualization Viewer (GloVis) http://glovis.usgs.gov Satellite: Landsat 7 Sensor: ETM+ SLC-on Bands: 1-5 & 7 (30m x 30m) 6 (60m x 60m) 8 (15m x 15m) Acquisition quality: 9 Cloud cover: 18%
Landsat 2014	Image acquired on 9 February 2014 (LC80730862014040LGN00)	Path 073 Row 086	Raster GeoTIFF (one image for each band)	GCS: WGS1984 PCS: UTM (zone 60S)	USGS Global Visualization Viewer (GloVis) http://glovis.usgs.gov Satellite: Landsat 8 Sensor: OLI & TIRS Bands: 1-7 & 9-11 (30m x 30m) 8 (15m x 15m) Acquisition quality: 9 Cloud cover: 6%

Table 13 (continued): Data sources and metadata

Dataset	**Description**	**Spatial Extent**	**Format**	**Coordinate System**[1]	**Source**
Orthophotos (1995/96, 2001/02)	Non-georeferenced orthophotos (timing of photos is generally a few months either side of Christmas) Pixel resolution: 2.5m x 2.5m	Map sheet S14 of the NZMS260 topographic map series	Raster JPEG (.jpg) (four black & white images for 1995/96 and four colour images for 2001/02)	GCS: NZGD1949 PCS: NZMG	Land Information New Zealand (LINZ) www.linz.govt.nz (a world file was created for each image in order to georeference)
Census population (1991, 2001 & 2013)	Usually resident population for area units within the Hamilton City Territorial Authority as at the time of the 1991 (March), 2001 (March) and 2013 (September) census	Hamilton City Territorial Authority	Microsoft Excel Table	n/a	Statistics New Zealand www.statistics.govt.nz
Census dwelling count (2013)	Total number of dwellings for area units within the Hamilton City Territorial Authority as at the time of the 2013 census	Hamilton City Territorial Authority	Microsoft Excel Table	n/a	Statistics New Zealand www.statistics.govt.nz
Area Units (2013)	Area unit boundaries within the Hamilton City Territorial Authority as at the time of the 2013 census	Hamilton City Territorial Authority	Shapefile (.shp) (polygon)	GCS: NZGD2000 PCS: NZTM2000	Statistics New Zealand www.statistics.govt.nz (extracted from a shapefile of all area unit boundaries in New Zealand)
Hamilton Borough Boundary (pre-1912)	Boundary of the Hamilton Borough prior to 1912	Hamilton Borough	Raster JPEG (.jpg)	n/a	Westwood (1954) via University of Waikato Digital Library http://digital.liby.waikato.ac.nz/nzc/map/047.html
Hamilton City Boundary (1986)	Boundary of the Hamilton City Territorial Authority as at the time of the 1986 census	Hamilton City Territorial Authority	Hard copy	n/a	Hamilton (N.Z.) City Planning Division (1991)

Table 13 (continued): Data sources and metadata

Dataset	**Description**	**Spatial Extent**	**Format**	**Coordinate System[1]**	**Source**
Hamilton City Boundary (1991)	Boundary of the Hamilton City Territorial Authority as at the time of the 1991 census	Hamilton City Territorial Authority	Shapefile (.shp) (polygon)	GCS: NZGD1949 PCS: NZMG	Statistics New Zealand www.statistics.govt.nz (extracted from a shapefile of all territorial authority boundaries in New Zealand)
Hamilton City Boundary (2006)	Boundary of the Hamilton City Territorial Authority as at the time of the 2006 census	Hamilton City Territorial Authority	Shapefile (.shp) (polygon)	GCS: NZGD1949 PCS: NZMG	Statistics New Zealand www.statistics.govt.nz (extracted from a shapefile of all territorial authority boundaries in New Zealand)
Hamilton City Boundary (2013)	Boundary of the Hamilton City Territorial Authority as at the time of the 2013 census	Hamilton City Territorial Authority	Shapefile (.shp) (polygon)	GCS: NZGD2000 PCS: NZTM2000	Statistics New Zealand www.statistics.govt.nz (extracted from a shapefile of all territorial authority boundaries in New Zealand)
Waikato Region (2013)	Boundary of the Waikato Region as at the time of the 2013 census	Waikato Region	Shapefile (.shp) (polygon)	GCS: NZGD2000 PCS: NZTM2000	Statistics New Zealand www.statistics.govt.nz (extracted from a shapefile of all region boundaries in New Zealand)
Land parcels	Approved current cadastral parcels (as at 8 February 2014)	1787861-1809584 E 5807481 - 5827178 N	Shapefile (.shp) (polygon)	GCS: NZGD2000 PCS: NZTM2000	Land Information New Zealand (LINZ) www.linz.govt.nz
Land use	Land use of cadastral parcel polygons	Hamilton City Territorial Authority	Raster PDF (.pdf)	n/a	Hamilton (N.Z.) City Council (2012)
Aerial Photos (2012)	Aerial photos	Hamilton City Territorial Authority	Viewed online	n/a	Hamilton City Council http://gisviewer.hcc.govt.nz/templates/PropQuery/
Roads	Roads as seen on the Topo50 map series	Map sheets BD33 (v.1.04 July 2013) & BD34 (v.1.02 Nov 2012)	Shapefile (.shp) (line)	GCS: NZGD2000 PCS: NZTM2000	Land Information New Zealand (LINZ) www.linz.govt.nz

Table 13 (continued): Data sources and metadata

Dataset	**Description**	**Spatial Extent**	**Format**	**Coordinate System[1]**	**Source**
Medical clinics	Medical Clinics listed in the telephone directory as at 28 March 2014 (excluding specialist clinics)	Hamilton City Territorial Authority	Street addresses viewed online	n/a	www.yellow.co.nz www.whitepages.co.nz
Police stations	Central police station and community policing centres as at 25 April 2013	Hamilton City Territorial Authority	Street addresses viewed online	n/a	New Zealand Police www.police.govt.nz
Fire stations	New Zealand Fire Service stations as at 18 February 2014	Hamilton City Territorial Authority	Street addresses viewed online	n/a	New Zealand Fire Service www.fire.org.nz
Ambulance Stations	Emergency Road Ambulance Service stations as at 18 February 2014	Hamilton City Territorial Authority	Street addresses viewed online	n/a	St John www.stjohn.org.nz
State Primary Schools	State funded full primary (Year 1-8) and contributing (Year 1-6) schools as at 1 April 2013 (excludes religion-based and Maori language schools)	Hamilton City Territorial Authority	Microsoft Excel Table	GCS: WGS 1984	New Zealand Ministry of Education www.educationcounts.govt.nz
Employment Areas	Existing employment areas (2010)	Hamilton City Territorial Authority	Hard copy	n/a	Hamilton (N.Z.) City Council (2010)
Bus Stops	Bus stops as at 28 February 2014	Hamilton City Territorial Authority	Shapefile (.shp) (point)	GCS: NZGD2000 PCS: NZTM2000	Provided by Waikato Regional Council on request
Topographic Features (rivers, lakes, railway lines)	Topographic features as seen on the Topo50 map series	Map sheets BD33 (v.1.04 July 2013) & BD34 (v.1.02 Nov 2012)	Shapefiles (.shp) (polygon & line)	GCS: NZGD2000 PCS: NZTM2000	Land Information New Zealand (LINZ) www.linz.govt.nz
New Zealand Coastline	New Zealand coastline and islands as seen on the Topo50 map series	New Zealand	Shapefile (.shp) (polygon)	GCS: NZGD2000 PCS: NZTM2000	Land Information New Zealand (LINZ) www.linz.govt.nz

Table 13 (continued): Data sources and metadata

Dataset	**Description**	**Spatial Extent**	**Format**	**Coordinate System**[1]	**Source**
Populated Places	Populated places in New Zealand as at 16 June 2011	New Zealand	Shapefile (.shp) (polygon)	GCS: NZGD2000 PCS: NZTM2000	Peter Scott via https://koordinates.com
Study Area	Study area defined for the thesis	1789000-1810000 E 5808000 - 5826000 N (21km x 18km)	n/a	GCS: NZGD2000 PCS: NZTM2000	n/a

[1] For further details on geographic (GCS) and projected (PCS) coordinate systems see section 3.2.2.

Appendix 2: Supervised Classification Band Scatterplots

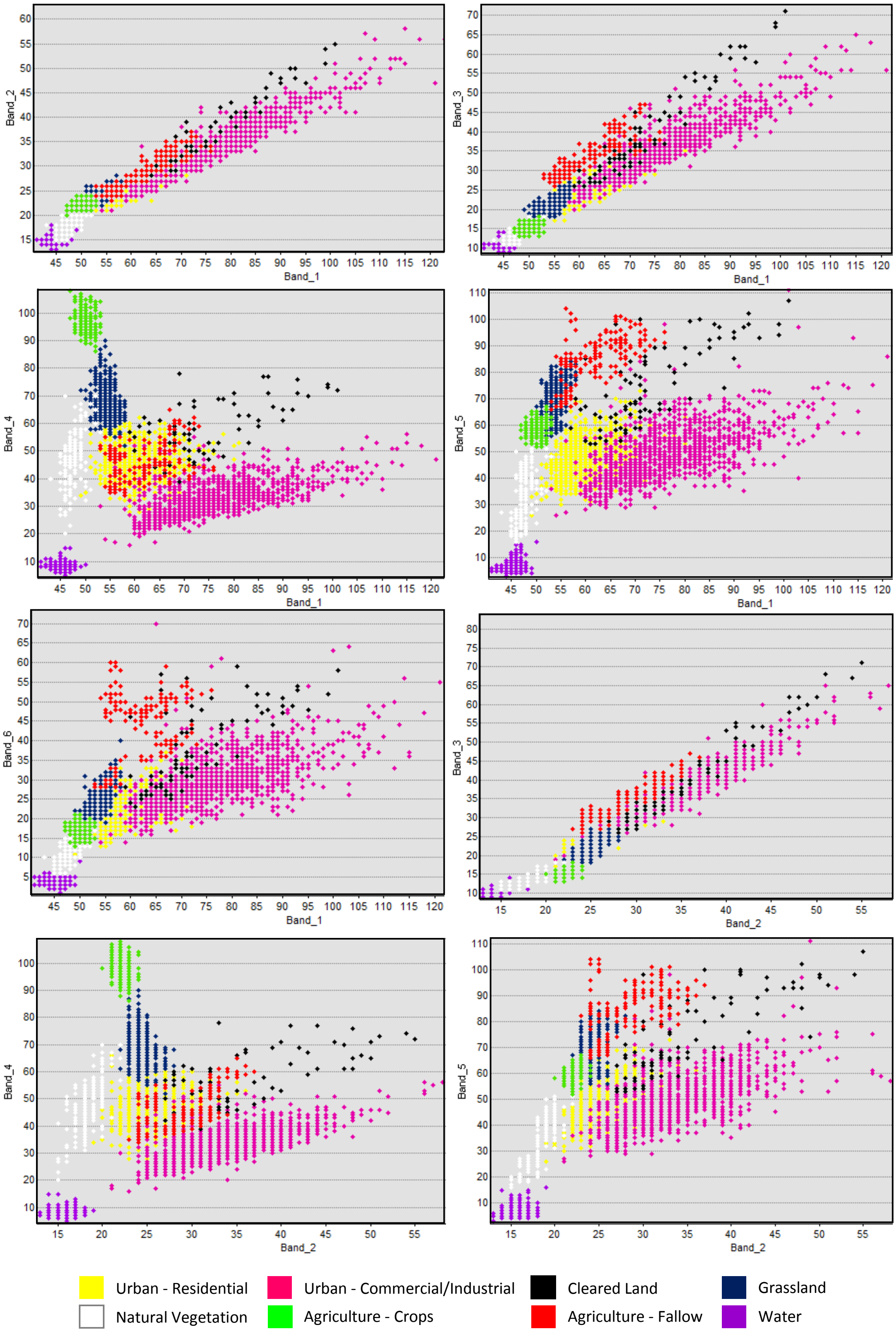


Figure 17: Band scatterplots used to assess training sample separability (1990).

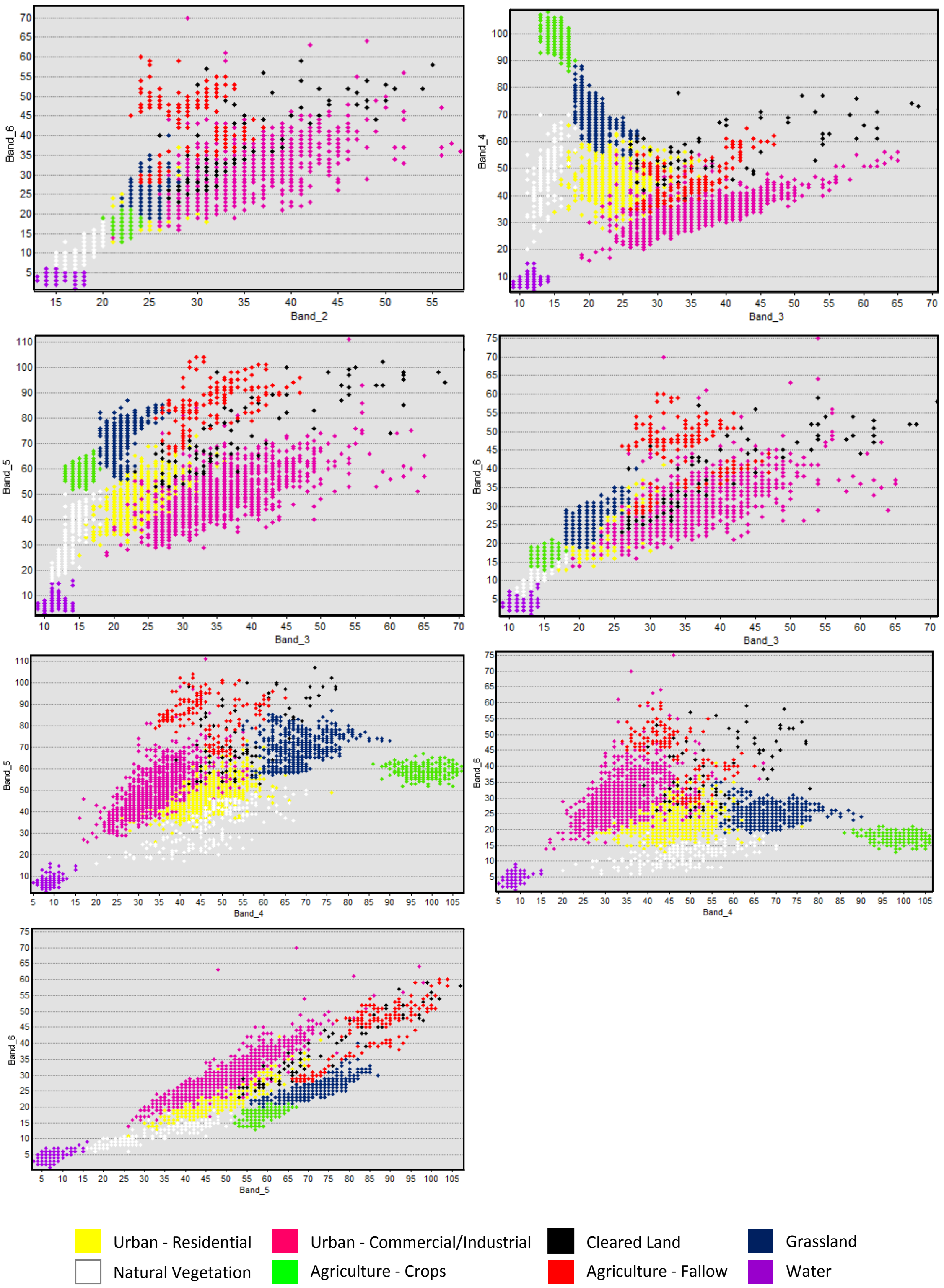


Figure 17 (continued): Band scatterplots used to assess training sample separability (1990).

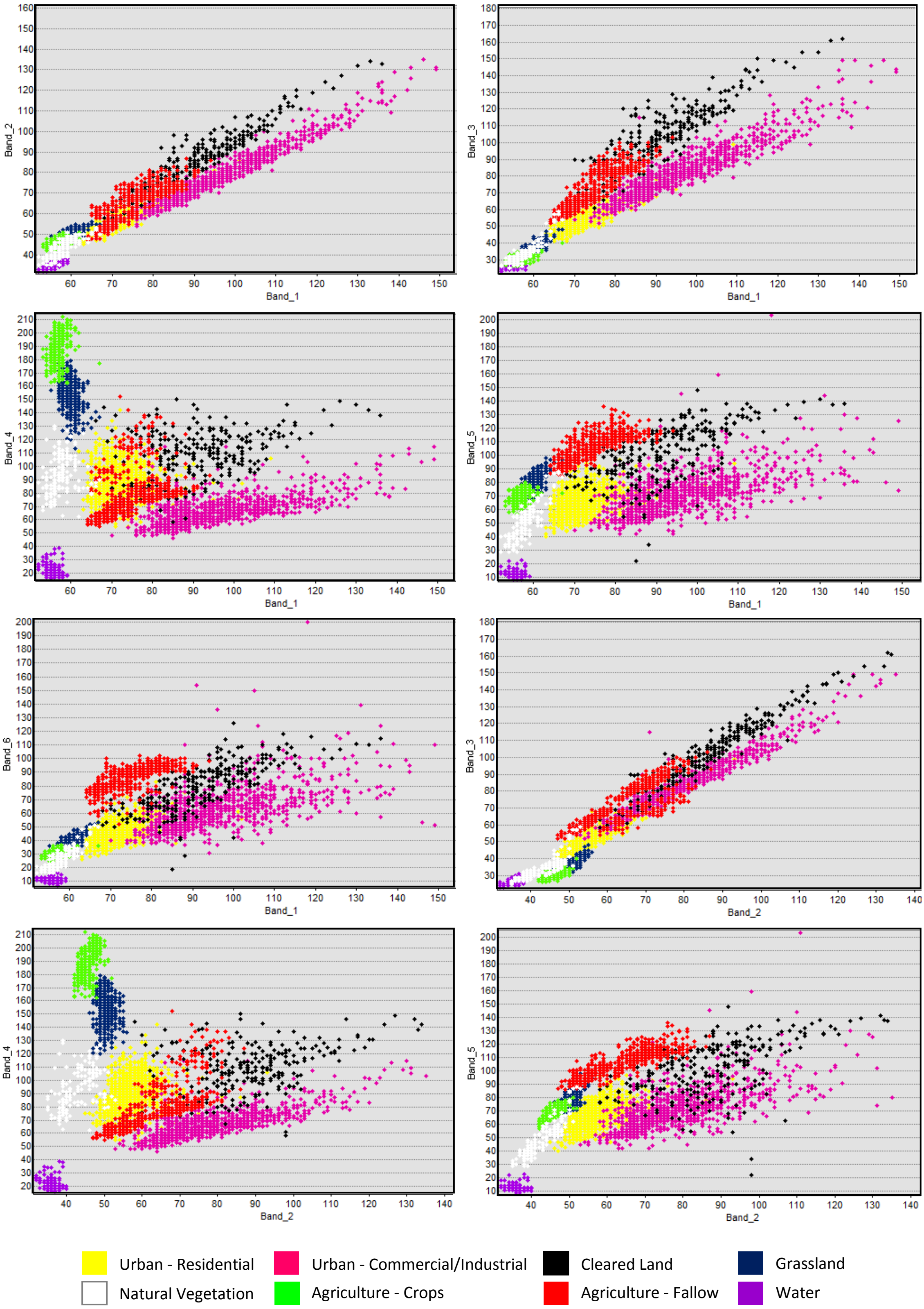


Figure 18: Band scatterplots used to assess training sample separability (2001).

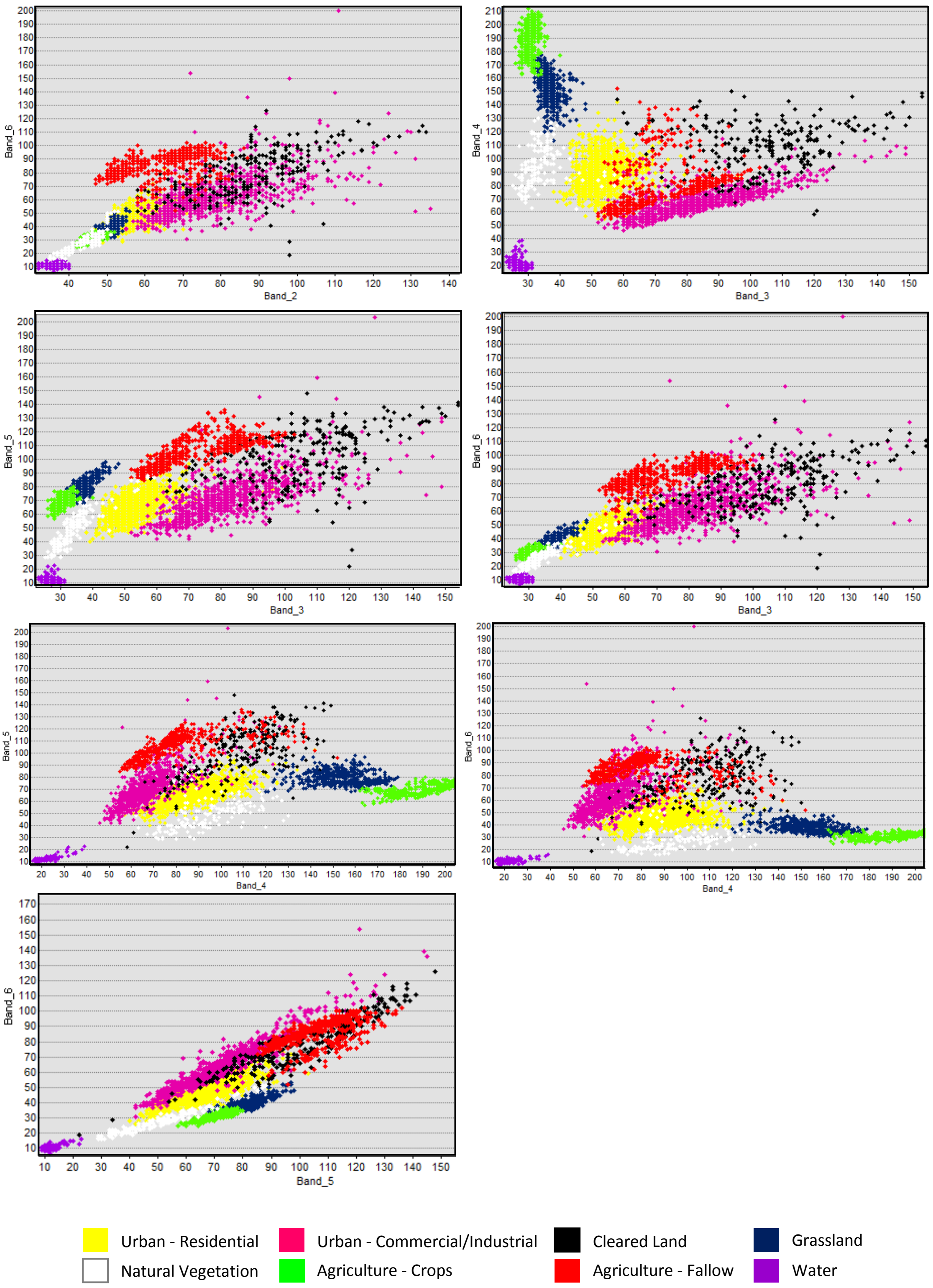


Figure 18 (continued): Band scatterplots used to assess training sample separability (2001).

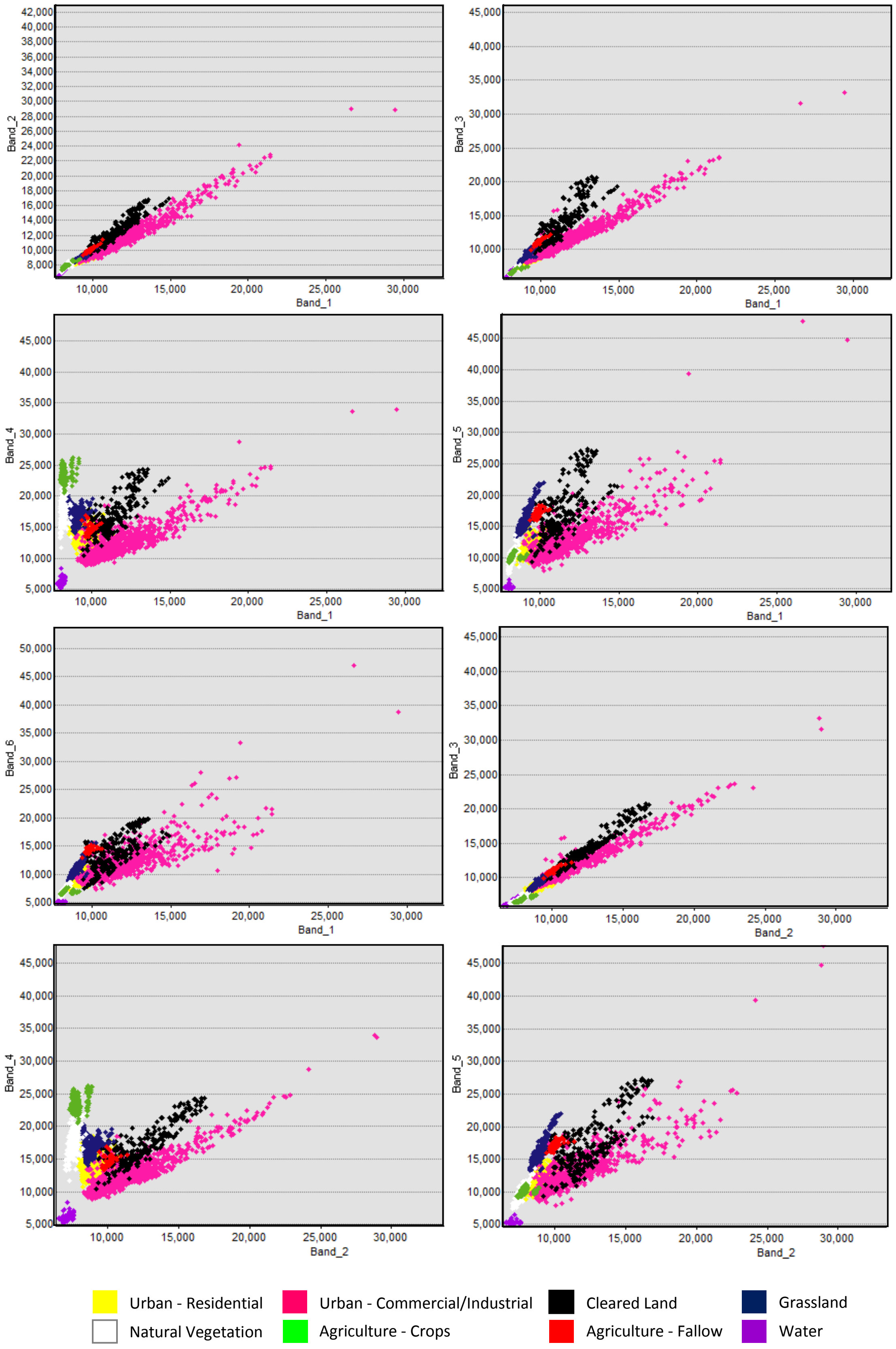


Figure 19: Band scatterplots used to assess training sample separability (2014).

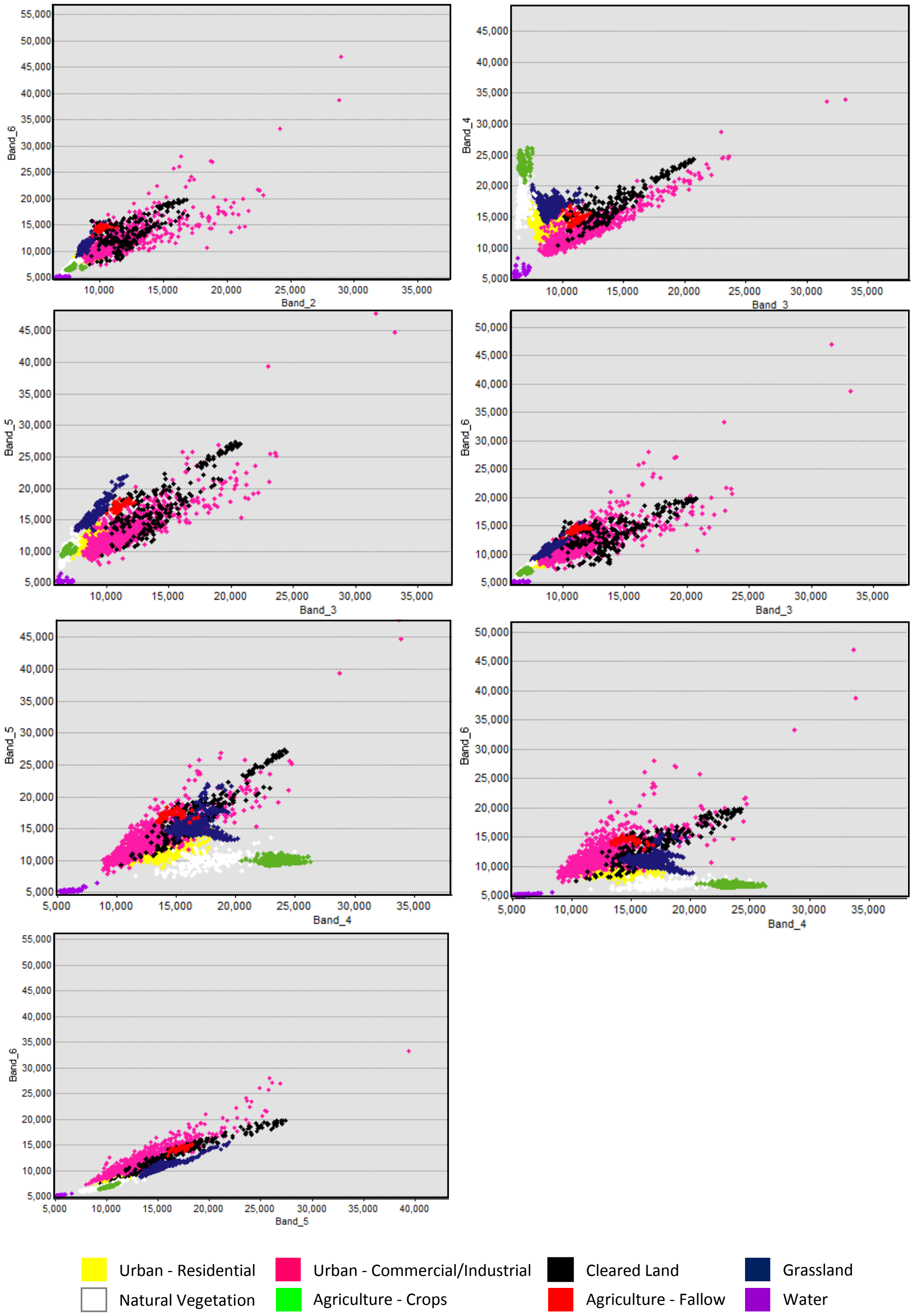
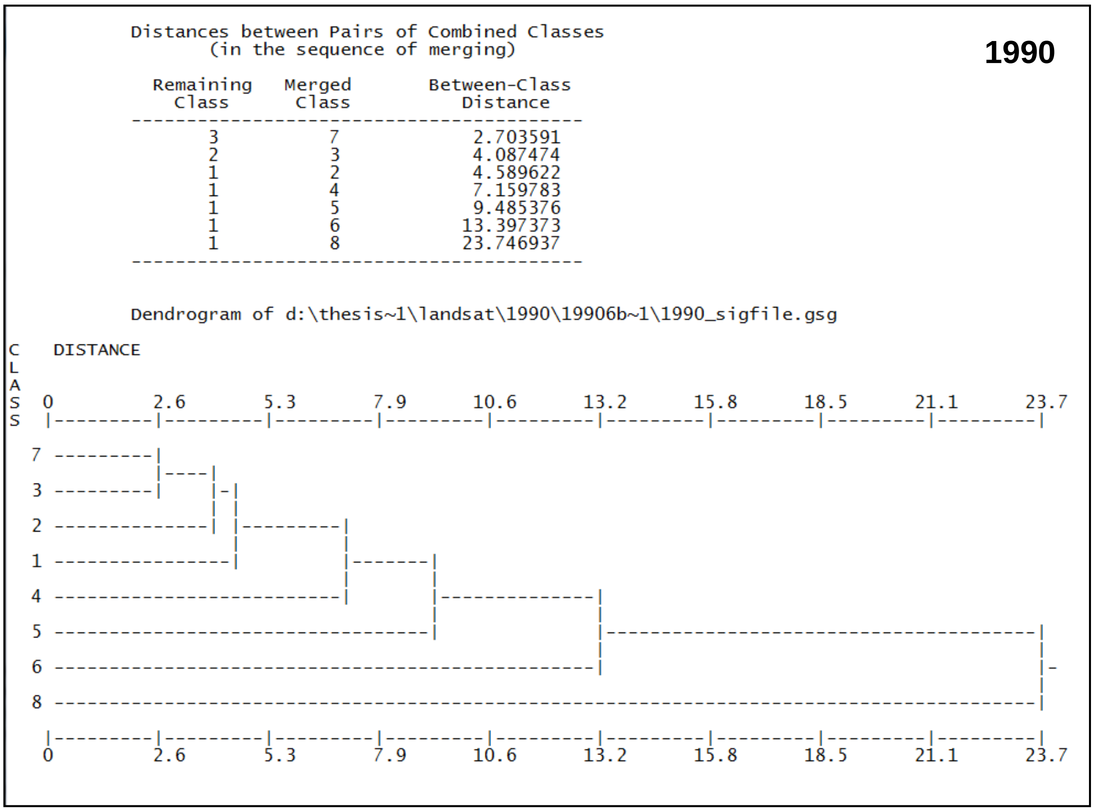
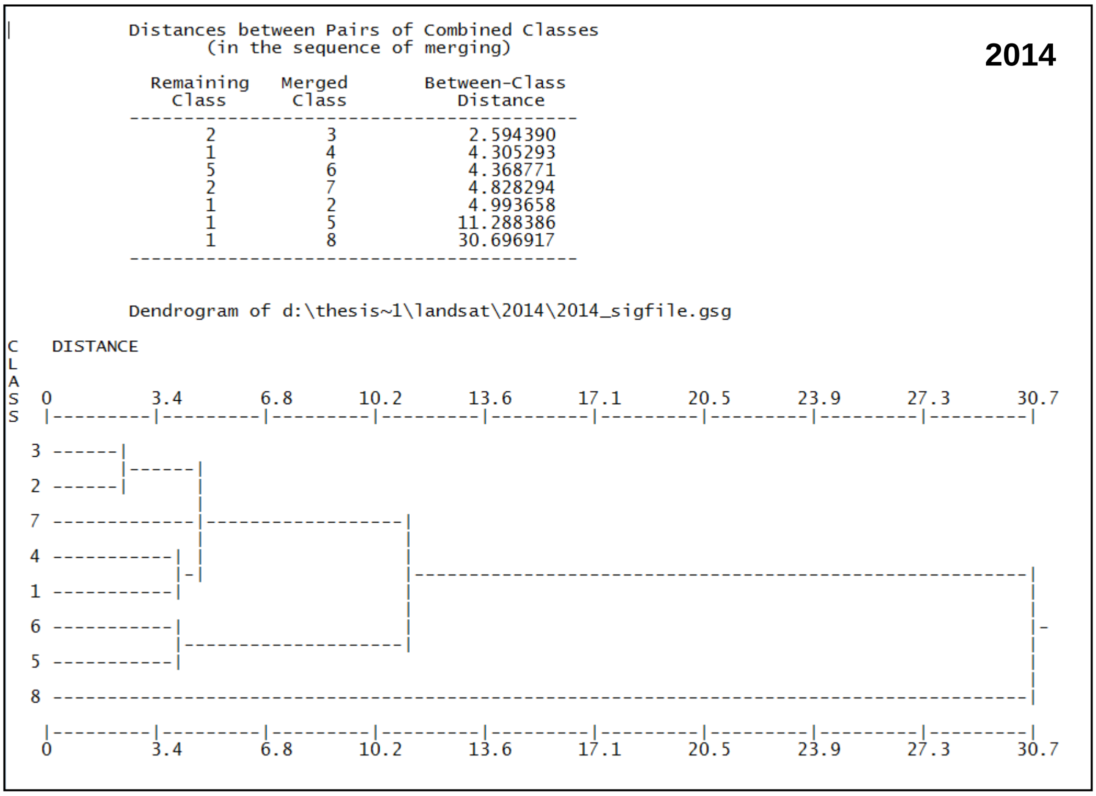


Figure 19 (continued): Band scatterplots used to assess training sample separability (2014).

Appendix 3: Supervised Classification Dendrograms



```
           Distances between Pairs of Combined Classes
                  (in the sequence of merging)

             Remaining   Merged       Between-Class
               Class       Class         Distance
           -----------------------------------------
                  3          7            2.703591
                  2          3            4.087474
                  1          2            4.589622
                  1          4            7.159783
                  1          5            9.485376
                  1          6           13.397373
                  1          8           23.746937
           -----------------------------------------


           Dendrogram of d:\thesis~1\landsat\1990\19906b~1\1990_sigfile.gsg

C   DISTANCE
L
A
S  0         2.6       5.3       7.9      10.6      13.2      15.8      18.5      21.1      23.7
S  |---------|---------|---------|---------|---------|---------|---------|---------|---------|

  7 ---------|
             |----|
  3 ---------|    |-|
                  | |
  2 --------------| |---------|
                    |         |
  1 ----------------|         |-------|
                              |       |
  4 --------------------------|       |--------------|
                                      |              |
  5 ----------------------------------|              |---------------------------------------|
                                                     |                                       |
  6 -------------------------------------------------|                                       |-
                                                                                             |
  8 -----------------------------------------------------------------------------------------|

   |---------|---------|---------|---------|---------|---------|---------|---------|---------|
   0         2.6       5.3       7.9      10.6      13.2      15.8      18.5      21.1      23.7
```



```
|          Distances between Pairs of Combined Classes
                  (in the sequence of merging)

             Remaining   Merged       Between-Class
               Class       Class         Distance
           -----------------------------------------
                  2          3            2.594390
                  1          4            4.305293
                  5          6            4.368771
                  2          7            4.828294
                  1          2            4.993658
                  1          5           11.288386
                  1          8           30.696917
           -----------------------------------------


           Dendrogram of d:\thesis~1\landsat\2014\2014_sigfile.gsg

C   DISTANCE
L
A
S  0         3.4       6.8      10.2      13.6      17.1      20.5      23.9      27.3      30.7
S  |---------|---------|---------|---------|---------|---------|---------|---------|---------|

  3 ------|
          |------|
  2 ------|      |
                 |
  7 -------------|------------------|
                 |                  |
  4 -----------| |                  |
               |-|                  |--------------------------------------------------------|
  1 -----------|                    |                                                        |
                                    |                                                        |
  6 -----------|                    |                                                        |-
               |--------------------|                                                        |
  5 -----------|                                                                             |
                                                                                             |
  8 -----------------------------------------------------------------------------------------|

   |---------|---------|---------|---------|---------|---------|---------|---------|---------|
   0         3.4       6.8      10.2      13.6      17.1      20.5      23.9      27.3      30.7
```

Figure 20: Dendrograms of signature files for the 1990 and 2014 classifications.

Appendix 4: Supervised Classification Accuracy Assessments

Table 14: Supervised classification 1990 error matrix and accuracy assessment

ERROR MATRIX

		Ground Truth			
	Class	Urban	Non-Urban	Water	TOTAL
Supervised Classification	Urban	100	2	0	102
	Non-Urban	0	98	13	111
	Water	0	0	37	37
	TOTAL	100	100	50	250

ACCURACY ASSESSMENT

	Urban	Non-Urban	Water	Total
No. of Correctly Mapped Points (A)	100	98	37	235
No. of Ground Truth Points (B)	100	100	50	
No. of Mapped Points (C)	102	111	37	
B x C	10200	11100	1850	23150
Total Number of Points (N)				250

Overall Accuracy / Total Accuracy = ΣA / N				94.0%
User / Object Accuracy = A / C	98%	88%	100%	
Producer / Classification Accuracy = A / B	100%	98%	74%	
Mean Accuracy = (2xA)/(B+C)	99%	93%	85%	
Areal Difference = (C-B)/B	2%	11%	-26%	
Kappa Estimation (For Each Class) = ((NxA)-(BxC)) / ((NxB)-(BxC))	100%	96%	69%	
Kappa Estimation (Overall) = ((NxΣA)-Σ(BxC)) / (N^2-Σ(BxC))				90%

Table 15: Supervised classification 2001 error matrix and accuracy assessment

ERROR MATRIX

		Ground Truth			
	Class	Urban	Non-Urban	Water	TOTAL
Supervised Classification	Urban	100	2	1	103
	Non-Urban	0	98	4	102
	Water	0	0	45	45
	TOTAL	100	100	50	250

ACCURACY ASSESSMENT

	Urban	Non-Urban	Water	Total
No. of Correctly Mapped Points (A)	100	98	45	243
No. of Ground Truth Points (B)	100	100	50	
No. of Mapped Points (C)	103	102	45	
B x C	10300	10200	2250	22750
Total Number of Points (N)				250

Overall Accuracy / Total Accuracy = ΣA / N				97.2%
User / Object Accuracy = A / C	97%	96%	100%	
Producer / Classification Accuracy = A / B	100%	98%	90%	
Mean Accuracy = (2xA)/(B+C)	99%	97%	95%	
Areal Difference = (C-B)/B	3%	2%	-10%	
Kappa Estimation (For Each Class) = ((NxA)-(BxC)) / ((NxB)-(BxC))	100%	97%	88%	
Kappa Estimation (Overall) = ((NxΣA)-Σ(BxC)) / (N^2-Σ(BxC))				96%

Table 16: Supervised classification 2014 error matrix and accuracy assessment

ERROR MATRIX

		Ground Truth			
	Class	Urban	Non-Urban	Water	TOTAL
Supervised Classification	Urban	100	3	8	111
	Non-Urban	0	97	3	100
	Water	0	0	39	39
	TOTAL	100	100	50	250

ACCURACY ASSESSMENT

	Urban	Non-Urban	Water	Total
No. of Correctly Mapped Points (A)	100	97	39	236
No. of Ground Truth Points (B)	100	100	50	
No. of Mapped Points (C)	111	100	39	
B x C	11100	10000	1950	23050
Total Number of Points (N)				250

	Urban	Non-Urban	Water	Total
Overall Accuracy / Total Accuracy = ΣA / N				94.4%
User / Object Accuracy = A / C	90%	97%	100%	
Producer / Classification Accuracy = A / B	100%	97%	78%	
Mean Accuracy = (2xA)/(B+C)	95%	97%	88%	
Areal Difference = (C-B)/B	11%	0%	-22%	
Kappa Estimation (For Each Class) = ((NxA)-(BxC)) / ((NxB)-(BxC))	100%	95%	74%	
Kappa Estimation (Overall) = ((NxΣA)-Σ(BxC)) / (N^2-Σ(BxC))				91%

Appendix 5: Neighbourhood Land Use, Dwelling and Street Network Data

Table 17: Neighbourhood land use and total dwelling count

Neighbourhood	Land Use (m^2)						Total Dwellings 2013 Census
	Single-Residential	Multi-Residential	Commercial	Industrial	Community Facilities	Open Space	
OLD							
Bader	752,514	224,418	9,955	2,331	32,308	471,067	1,548
Beerescourt	727,893	203,374	32,436	5,183	63,788	82,254	1,332
Bryant	1,289,877	258,229	11,752	35,251	102,327	618,082	2,223
Chartwell	670,312	120,871	4,068	0	251,333	181,374	957
Chedworth	1,005,746	28,329	66,596	0	67,211	133,635	1,278
Clarkin	630,113	160,004	13,739	0	160,395	117,861	1,149
Claudelands	382,121	186,401	32,478	1,073	315,513	81,406	1,122
Crawshaw	407,179	163,863	0	0	20,830	97,552	966
Dinsdale North	892,319	117,616	22,284	19,541	20,352	87,424	1,467
Dinsdale South	737,703	207,297	41,799	6,567	13,238	177,152	1,491
Enderley	682,421	257,155	34,427	21,326	183,912	49,740	1,614
Fairview Downs	740,021	45,021	1,419	0	0	68,915	1,158
Glenview	1,268,538	208,407	16,027	1,589	50,517	431,783	1,950
Grandview	488,935	144,950	5,440	18,454	38,897	40,987	1,128
Hamilton East	368,815	281,837	105,067	0	182,638	297,102	1,476
Hamilton Lake	628,765	294,901	34,793	521,566	295,010	727,871	1,641
Hillcrest West	715,447	119,198	15,748	0	4,940	77,405	1,290
Insoll	482,473	70,620	2,254	0	52,838	1,295	798
Maeroa	630,603	256,843	5,802	14,594	56,441	173,406	1,479
Melville	998,918	148,435	17,811	37,385	237,319	137,536	1,701
Nawton	857,108	234,949	13,235	33,853	130,123	145,117	1,701
Naylor	717,579	285,108	34,072	0	23,295	783,604	1,875
Peachgrove	378,926	196,988	36,565	121,711	335,979	110,366	1,398
Porritt	366,434	53,001	7,104	0	249,622	220,642	633
Pukete	591,668	32,284	0	0	22,866	118,639	843
Pukete West	451,502	37,760	3,582	52	21,215	147,289	702
Queenwood	934,987	94,309	3,655	0	2,019	403,992	1,191
Riverlea	707,633	110,196	13,934	268,571	111,254	227,502	1,005
Silverdale	538,686	84,787	3,183	0	124,309	189,573	930
Swarbrick	562,724	349,578	3,706	65,468	116,009	153,299	1,893
University	476,326	239,964	31,970	0	761,673	65,711	1,776
NEW							
Brymer	628,065	16,539	0	0	0	76,385	885
Flagstaff	957,456	182,769	14,845	0	6,627	202,833	1,551
Horsham Downs	1,636,432	2,013	0	0	93,272	23,982	1,545
Huntington	1,959,854	79,285	99,746	0	88,812	458,420	2,685
Rototuna	757,203	41,972	26,689	0	10,909	316,757	1,176
Sylvester	1,034,676	0	0	1,780	5,138	168,907	666

Table 18: Neighbourhood street intersections and cul-de-sacs

Neighbourhood	Intersections	Cul-De-Sacs
OLD		
Bader	45	25
Beerescourt	50	19
Bryant	74	31
Chartwell	40	21
Chedworth	58	22
Clarkin	42	17
Claudelands	32	7
Crawshaw	33	18
Dinsdale North	61	36
Dinsdale South	48	29
Enderley	59	22
Fairview Downs	48	24
Glenview	60	32
Grandview	43	25
Hamilton East	48	11
Hamilton Lake	62	20
Hillcrest West	40	21
Insoll	32	10
Maeroa	56	18
Melville	51	32
Nawton	59	28
Naylor	56	19
Peachgrove	46	18
Porritt	29	11
Pukete	36	20
Pukete West	25	15
Queenwood	44	19
Riverlea	42	26
Silverdale	33	11
Swarbrick	68	19
University	54	27
NEW		
Brymer	48	35
Flagstaff	72	48
Horsham Downs	84	65
Huntington	138	107
Rototuna	57	49
Sylvester	77	61

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