Future Implications of Past Domestic Water Usage Trends

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Civil Engineering

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Abstract

Residential water use typically constitutes a large proportion of total urban water consumption. Thus, its understanding is pivotal in water demand planning and management. However, in complex urban environments this task can be challenging since the heterogeneity in the household and housing characteristics may lead to considerable variations in water consumption. Many empirical studies have tried to evaluate the variation of water consumption across different housing types (e.g. separate house, apartment), consumer groups (e.g. different income groups) and seasons (i.e. summer and winter). However, they rarely achieved to thoroughly evaluate it because they generally relied on the small samples mainly due to the scarcity of disaggregated data. This study utilized a rich source of urban databases in Auckland, New Zealand, in order to develop a large sample of 60000 dwellings through integration of water consumption, property characteristics, water price, weather, and census microdata using geographic information system. Through data integration, this study fully evaluated the variation of water consumption and its determinants across different housing types, consumer groups and seasons both at the household scale and the aggregated scale (e.g. census area unit). The household scale analysis helped the study to understand the variation of responses to the determinants of water demand, practically water pricing and weather variables, among different group of customers (e.g. income groups). The aggregated analysis also made it possible to assess the determinants of spatial variation of water consumption across the city. Moreover, the understanding of water consumption across different housing types enabled this study to evaluate the effects of urban intensification (i.e.

transition from single houses to more intensified multi-unit houses such apartments) on residential water use. In Auckland, urban intensification is promoted by Auckland Council through Auckland Unitary Plan. The Auckland Unitary Plan proposes a compact city model through encouraging the increase of housing density in order to control the urban sprawl, due to its social, economic and environmental concerns. This study utilized regression methods specific to panel data to analysis residential water demand in Auckland from years 2008 to 2014. A panel data set contains repeated observations over the same units (e.g. households, census areas units), collected over a number of periods. The panel data models incorporate both the temporal and the spatial variations of water use in the modelling. Thus, they can generate better parameter estimates than traditional regression approaches. Through analysis of a large sample of housings, the study showed that the household water consumption was higher in the single houses (i.e. separate houses), in comparison with the low-rise (i.e. up to three-storey) and high-rise (four-storey and more) apartments. The higher household water consumption in the single houses can be attributed to the larger household size and more outdoor water use in this sector. However, on the basis of per capita water use, the water consumption was higher in the high-rise apartment since the small household size in this sector typically limits the efficient use of water (e.g. fully loaded watching machines, dishwashers, etc.). The study also showed that the spatial variation of water consumption across Auckland was mainly influenced by the household income. In general, consumers with higher per capita water consumption are mainly clustered in the wealthier areas in Auckland. This is because people in the higher income areas are more likely to use water for the outdoor usage such as garden and swimming pool. For the same reason, the seasonal variation of water consumption was more remarkable in the higher income areas, specifically across single houses with substantial outdoor usage. Generally, in the apartment sectors, specifically high-rise apartments, the seasonal and spatial variations of water demand are more limited since the indoor usage is predominant in it. Due to this characteristic, the water consumption in the high-rise apartments is not sensitive to the weather condition (e.g. temperature and rainfall). This study also showed that, under the current water price structure, the price elasticity of water demand in Auckland was very low across all income groups, housing types and seasons. The insensitivity of water demand to the price can be attributed to the flat rate pricing scheme and the low share of water price in the total household expenses in Auckland. Considering different growth scenarios, the study also showed that housing transition from single houses to more intensified multi-unit houses may not considerably affect per capita water consumption in Auckland. This is because the high per capita water consumption in the high-rise apartments would offset the effects of lower per capita water consumption in the low-rise apartments. However, the urban intensification may decrease the average per capita water consumption in the more affluent areas specifically on summers, through limiting the outdoor uses. This detailed knowledge of residential water consumption can help water managers and urban policy makers to more reliably plan water supply systems and design conservation programs in the complex urban environments.

Dedication

This thesis is dedicated to:

My parents

Mahin and Alireza

[*who taught me how to pursue beautiful dreams*]

My beloved wife

Fatemeh

[*who helped me to realise my dreams with her patience and immutable love*]

My lovely daughter

Melorin

[*who was born during this journey and gave us extra happiness and hope*]

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Table of contents

Lists of tables

Lists of figures

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Nature of contribution by PhD candidate	Lead author, conducted study and wrote the text
Extent of contribution by PhD candidate (%)	90%

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Name	Nature of Contribution
Asaad Y. Shamseldin	Supervision, Discussion, Technical Editing
Bruce W. Melville	Supervision, Discussion, Technical Editing

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
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Chapter 1

Introduction

This chapter provides a brief introduction of the background and motivation for this research. It also presents the main objectives of the thesis and its contribution to the field of residential water demand study. A brief review of determinates of water use and water demand models is provided. The thesis outline and a list of publication from this research are also presented in this chapter.

1.1. Background

Auckland is the largest city in New Zealand. Over the last decades Auckland has experienced a fast growth both in the population and housing stock (Goodyear and Fabian 2014; Statistics-NZ 2015). Since this trend is likely to continue in the future, it is essential to carefully plan for its water supply and treatment systems in order to meet the future need of residential sector, as the major water consumer group. To accomplish this, it is paramount to acquire a deep understanding of residential water consumption and its determinants. However, this task can be challenging in a complex urban environment like Auckland where the characteristics of housings and households vary significantly across the city and the transition from single houses to more intensified housings like apartments is an ongoing phenomenon.

In general, in order to fully understand water consumption and the determinants of its spatial and temporal variations across different groups of consumers, it is vital to have highly disaggregated information of water consumption, household and housing characteristics (i.e. household level information). However, the household level information is not typically available at the large scales such as metropolitan areas due to its high cost of data collection. Thus, the majority of the empirical studies of water demand either relied on the small sample of disaggregated data, which cannot assess the spatial variability of water use (Arbués et al. 2004; Arbués and Villanúa 2006; Pint 1999), or the aggregated data which cannot distinguish water consumption across different group of residential users (Chang et al. 2010; House-Peters et al. 2010; Wentz and Gober 2007).

Moreover, the disaggregated analysis of water demand can help to evaluate water consumption across different housing types. From urban and water planning perspective, this knowledge is vital since it can help to examine the effects of housing intensification (i.e.

housing transition from low-density single houses to the more intensified multi-unit housing such apartments) on water use. Housing intensification is a contemporary urban growth management strategy which promotes the use of higher density housings such as apartments in order to mitigate the social, economic and environmental consequences of uncontrolled low-density urban sprawl (Haarhoff et al. 2012; Randolph 2006). In Auckland, this strategy is outlined by the Auckland Unitary Plan (PAUP 2015). This plan proposes a quality compact city where urban growth is primarily focussed within the existing metropolitan area and concentrated within moderate walking distances from the city or local centres, rapid and frequent service network or within close proximity to urban facilities (Haarhoff et al. 2012; PAUP 2015).

Considering the importance of disaggregated analysis of water demand in the contemporary water demand management, this study proposed new approaches in data integration and multi-scale analysis of water demand. The data integration mainly involves combining the information of water consumption, land use, weather and demographic microdata. The multi-scale analysis approach includes the analysis of water demand at the household scale and the census area unit scale (i.e. the smallest geographic area for which the New Zealand census microdata is fully available). These proposed approaches can help to thoroughly evaluate the water consumption and its determinants across different housing types and consumer groups. The detailed knowledge of water consumption, obtained through the proposed approaches, can also help to evaluate the implication of housing intensification on water use. The use of data integration and multi-scale analysis of water demand is a new area in the field of water and urban planning and management. This thesis demonstrates how large scale data from a range of sources can be put together in order to help in the understanding of dynamic of water consumption in the complex urban environments. The next section at this chapter outlines the contribution of this research to the body of knowledge in the water demand study in more details.

1.2. Research contribution

This study proposed a new approach in data integration in order to overcome the issue of scarcity of data for the disaggregated analysis of water demand. Using geographic information system (GIS), the present study utilized a rich source of urban databases in Auckland in order to combine water consumption, land use (i.e. property characteristics), weather, water pricing and census microdata. Through data integration, the study developed a large sample of 60000 houses across 300 census area units in Auckland. The land use component of data enabled the study to distinguish three different housing types in Auckland (i.e. single houses, low-rise apartments and high-rise apartments). The census microdata also provided household information (e.g. household size and household income) for each sector. Using the developed disaggregated datasets, the study carried out a multi-scale analysis of water demand (i.e. household scale and the aggregated scale). The household-scale analysis helped the study to assess the variation of responses to the demand drivers specifically water price across different consumer groups (e.g. households with different income levels). The aggregated-scale analysis (i.e. analysis of water demand at the census area unit level) enabled the study to evaluate the determinants of spatial variation of water demand. This information not only can be used to plan water supply systems in an optimal manner, but also it can help to better target specific groups of consumers or urban areas (e.g. high water users) for conservation planning. In recent years, the data integration in water demand studies has become more plausible due to advances in database technology, data accessibility, computing power, and spatial tools (Dziedzic et al. 2015; Polebitski and Palmer 2010; Shandas and

Parandvash 2010). However, it has never been used to carry out disaggregated water demand analysis across different housing types in a large metropolitan area such as Auckland.

In this study, the acquired information of water demand across different housing types, urban areas and seasons was also combined with the Proposed Auckland Unitary Plan outlining the future housing composition over different areas in Auckland (PAUP 2015). This enabled the present study to answer some fundamental question regarding the effects of housing intensification on water use. Housing intensification is seen as a credible path for improving urban sustainability, reducing the use of urban resources and the needs for more infrastructures (Boon 2010; Haarhoff et al. 2012; Randolph 2006). However, in terms of water consumption there is no clear understanding of the benefits of higher density urban development. This study also can help to fill the gap in knowledge in this regard.

1.3. Objectives

In essence, the objectives of this study can be expressed as follows:

- Develop a new approach in data integration in order to make possible thorough evaluation of water consumption and its determinants in complex urban environments such as Auckland.
- Develop a new approach in multi-scale analysis of water demand (i.e. household scale and aggregated scale) in order to enable not only the evaluation of responses to water demand drivers such as water price across different group of consumers (i.e. household-scale analysis), but also enable the assessment of determinant of spatial variation of water demand across different housing types, urban areas and seasons (i.e. aggregated-scale analysis).
- Compare the water consumption and its spatial and seasonal variations across different housing type in order to evaluate the prospective implication of housing

intensification on residential water consumption in Auckland, under different growth scenarios.

1.4. Determinants of water use

Combining the information of water consumption, land use, water price, weather, and census microdata enabled the present study to quantify and test the effects of a wide range of variables on water use. The studied variables included:

- Household characteristics (e.g. household income, household size, age of residents),
- Housing characteristics (e.g. number of bedrooms, section size, swimming pool and garden),
- Climate factors (e.g. temperature, rainfall),
- Water price
- Housing density

All of these variables have been frequently reported as the influential factors on the empirical studies of water demand (House-Peters and Chang 2011). This section briefly reviews the findings of water demand studies regarding the effects of these five groups of factors on water consumption.

1.4.1. Household characteristics

Household characteristics include socioeconomic and demographic attributes of households which can reflect habits and tendencies of household members to use water facilities for different purposes (Ouyang et al. 2014). The three major household characteristics variables may include:

- Household income (Guhathakurta and Gober 2007; Harlan et al. 2009; Schleich and Hillenbrand 2009),
- Household size (Arbués et al. 2010; Domene and Saurí 2006; House-Peters et al. 2010), and
- Age distribution of household members (Nauges and Thomas 2000; Schleich and Hillenbrand 2009).

The income variable typically has a positive correlation with water consumption (Schleich and Hillenbrand 2009; Syme et al. 2004; Worthington and Hoffman 2008). This is because higher-income households are likely to own more water-using capital stock, such as larger lawns and gardens, and swimming pools which can increase household water use (Hoffmann et al. 2006; Mieno and Braden 2011; Schleich and Hillenbrand 2009). In general, the income variable mainly affects household outdoor water consumption. Thus, its effect is more remarkable at the houses with more outdoor space (i.e. single houses) specifically in summer months (Polebitski and Palmer 2010). Household water consumption also typically increases with household size because more people use more water (Corbella and Pujol 2009; Polebitski and Palmer 2010; Wentz and Gober 2007). However, water consumption increases more slowly than household size due to economies of scale (Arbués et al. 2003; Bradley 2004; Bruvold and Smith 1988; Clarke et al. 1997; Hummel and Lux 2007). The age distribution of residents may also affect household water demand, as people of different ages tend to have different water related behaviours at home. The previous studies of water demand revealed conflicting results regarding the effects of age distribution of residents on water use. For example, while Martínez-Espiñeira (2003); Martins and Fortunato (2007); Musolesi and Nosvelli (2007); Nauges and Thomas (2000) showed that there was a negative relationship between per capita water use and the share of elderly people living in households, some other studies such as Fox et al. (2009), Schleich and Hillenbrand (2009) and Rockaway et al. (2011) found that older people use more water. It is also demonstrated that households with children may have higher water demand as children are more likely to use lawns for play and recreation (Balling Jr. et al. 2008; Corbella and Pujol 2009; Hurd 2006), although children may use less water than adults for washing and hygiene (Schleich and Hillenbrand 2009).

1.4.2. Housing characteristics

The empirical studies of water demand also have found significant correlation between housing characteristics and water consumption. The major influential housing characteristics may include:

- Housing types (Domene and Saurí 2006; Fox et al. 2009; Loh et al. 2003; Rathnayaka et al. 2014; Russac et al. 1991; Troy and Holloway 2004; Zhang and Brown 2005),
- Age of dwelling (Chang et al. 2010; Harlan et al. 2009; Nauges and Thomas 2003),
- Number of bedrooms (Chang et al. 2010; Fox et al. 2009; Kenney et al. 2008),
- Lot size (Pint 1999; Renwick and Green 2000; Wentz and Gober 2007),
- Dwelling size (Domene and Saurí 2006; House-Peters et al. 2010),
- Property value (Arbués et al. 2004; Arbués et al. 2010), and
- Presence of swimming pool (Agthe and Billings 2002; Guhathakurta and Gober 2007; Harlan et al. 2009) and garden (Syme et al. 2004) in dwellings.

Water consumption may vary significantly across different housing types. In general, household water consumption in single houses is greater than multi-unit housings (e.g. apartments) mainly due to the larger household size and more outdoor uses in single houses (Domene and Saurí 2006; Fox et al. 2009; Loh et al. 2003; Russac et al. 1991; Zhang and Brown 2005). The studies also showed that variables which measure physical size of property such as number of bedrooms, lot size, dwelling size are positively related to residential water use (Fox et al. 2009; Guhathakurta and Gober 2007; Patterson and Wentz 2008; Polebitski and

Palmer 2010; Rockaway et al. 2011). Presence of swimming pool and garden also can substantially increase household water use specifically in summers (Mayer et al. 1999; Syme et al. 2004; Wentz and Gober 2007). Age of the dwelling can affect water use mainly because more recently built homes may have more efficient water fixtures and appliances (Billings and Jones 2008; Harlan et al. 2009). Property value, as a proxy of household income, also generally has a positive correlation with water use (Abrams et al. 2012; Arbués et al. 2004; Arbués et al. 2003).

1.4.3. Weather variables

The effects of weather variables, including air temperature and rainfall, on water use also been vastly investigated in the empirical studies of water demand (Arbués and Villanúa 2006; Fenrick and Getachew 2012; Kenney et al. 2008; Worthington et al. 2009). The studies showed that in general air temperature has a positive and rainfall has a negative correlation with water use (Arbués et al. 2003; Balling Jr. et al. 2008; Corbella and Pujol 2009; Polebitski and Palmer 2010). The precipitation may significantly reduce the outdoor water consumption (e.g. garden watering) while air temperature may affect both indoor and outdoor water use. For example, on a hot day water consumption may increase due to the need of more water for irrigation, swimming pools, and personal hygiene (Hoffmann et al. 2006; Ouyang et al. 2014). In general, the impact of weather variables on water use is more remarkable in the single house, rather higher density housing, due to the more outdoor use in this sector (Balling Jr. et al. 2008; Breyer and Chang 2014; Breyer et al. 2012).

1.4.4. Water price

Many empirical studies also have assessed the effects of water pricing on water consumption through quantifying the price elasticity of water demand (Arbués et al. 2003; Dalhuisen et al. 2003; Worthington and Hoffman 2008). Water price generally consists of two parts including fixed and volumetric charges. Customers typically pay fixed charges (i.e. the operational costs for providing water) irrespective of the amount of water consumption. Thus, the only effect of the fixed charge on water consumption would be through its effect on reducing household disposable income. Since water costs are a very small part of most household budgets, its effect is unlikely to be significant (Mieno and Braden 2011). In contrast, the volumetric charge is based on the volume of water households actually used (i.e. metered usage). Thus, an increase in the volumetric price should discourage the consumption (Arbués et al. 2003; Mieno and Braden 2011). Although water price typically has a negative correction with water use, the price elasticity of water demand has been found to be generally low (Arbués et al. 2003), implying that water pricing may have limited effects on regulating water use. In general, outdoor water consumption is more sensitive to water price, while the indoor water use (i.e. water for basic needs) is unlikely to exhibit high price sensitivity (Arbués et al. 2003; Corbella and Pujol 2009; Mieno and Braden 2011).

1.4.5. Housing density

Housing density, as a factor representing urban structure, may also influence residential water consumption. In general, the urban areas with lower density are likely to use more water (Balling Jr. et al. 2008; Chang et al. 2010; Polebitski and Palmer 2010; Shandas and Parandvash 2010). This is because with larger lot sizes, specifically in the affluent neighbourhoods, there are more opportunity for outdoor activities such as gardening and swimming pool (Patterson and Wentz 2008).

1.5. Water demand model

This study utilizes regression methods to evaluate the determinants of water demand in Auckland. Regression models have been widely used in the water demand studies (Arbués et al. 2003; Billings and Jones 2008; House-Peters and Chang 2011; Worthington and Hoffman 2008). Taking advantage of a strong statistical foundation, these models can include a wide range of variables together in the water demand modelling in order to explain the contribution of each of those factors on water use (Arbués et al. 2003; Worthington and Hoffman 2008).

Based on the type of data, the regression models may be classified into three major groups including time-series, cross-section and panel data models (Arbués et al. 2003; Worthington and Hoffman 2008). The time-series data is a collection of observations on a particular variable, such as water use or household income, over time. Although long time-series of data can be used to identify the water use trends (Jowitt and Xu 1992; Li and Huicheng 2010; Zhou et al. 2000), however models use merely time series data cannot consider spatial variations of water consumption (Billings and Jones 2008; House-Peters and Chang 2011). Cross-section data is the observations collected at the same period of time (e.g. recorded water use for each individual customer in a district for a single billing period or year). The cross-sectional models can capture the underlying functional relationships governing water usage across groups of consumers (Chang et al. 2010; House-Peters et al. 2010; Wentz and Gober 2007). However, since these models do not include temporal variations of data, they are not capable of evaluating the effects of trends in variables such of water price, weather, and household characteristics on the water use (Arbués et al. 2003; House-Peters and Chang 2011). The panel data is a combination of time-series and cross-sectional data (Arbués et al. 2003). This data consists of a number of individual customers or customer groups where their characteristics (e.g. water use, income, household size) are measured over time (e.g. months, or years) (Verbeek 2004). Panel data models are typically preferred in water demand studies to the time-series and cross-sectional models because they consider both spatial and temporal variations of data. Thus, they can provide more accurate parameter estimates (Arbués et al. 2003; Polebitski and Palmer 2010; Weber 1989). The increase in precision basically arises from the greater variation in the values of the independent variables and the larger sample size (Arbués et al. 2003; Billings and Jones 2008). This type of data also allows for the inclusion of variables that vary over time or over cross-sections, but that may not necessarily be varying over both dimensions (Hanke and de Mare 1982; Kenney et al. 2008; Polebitski and Palmer 2010).

This study utilized panel data models to evaluate the water demand. The developed panel data models included 6-years (i.e. 2008-2014) data of water consumption, water pricing, socioeconomic, and weather across different housing type and census area units in the water demand analysis. This study examined three common panel data methods (i.e. pooled, fixed effects, and random effects models) for water demand analysis. In the pooled method, the regression model has a single intercept (Hill et al. 2010). However, in the fixed effects and the random effects models the intercept is allowed to vary acros individual customers or customer groups (House-Peters et al. 2010; Kenney et al. 2008). Thus, fixed effects and random effects models are typically an improvement over pooled models since they can capture the variability among consumers using varying intercepts (Arbués et al. 2003; House-Peters et al. 2010; Kenney et al. 2008). The random effects model also has a useful feature over the fixed effects, when it can recover parameter estimates for time invariant variables as well (Fenrick and Getachew 2012). The statistical tests including partial F-test and Hausman test (Hill et al. 2010; Wooldridge 2012) were used to select the most appropriate panel data model for each dataset.

In recent years with increase in the data availability panel data models have been used more frequently (Arbués et al. 2004; Arbués et al. 2010; Fenrick and Getachew 2012; Kenney et al. 2008; Martinez-Espiñeira 2002; Nauges and Thomas 2000; Polebitski and Palmer 2010). However, none of the previous studies have used panel models for the multi-scale analysis of water demand across different housing types.

1.6. Thesis outline

This thesis has been written in the form of “thesis with publications”. It means that, expect the introduction and conclusions chapters, each of the five main chapters of the thesis are independent papers which either have been published as the journal articles or are under peer-review process. These papers sequentially address the objectives of the thesis. Thus, there is an appropriate coherence between the chapters.

In chapter 2, the water consumption and its determinants in single houses (i.e. separate houses), across different groups of consumers and urban areas, is fully investigated using data integration and multi-scale analysis approaches.

In chapter 3, the water consumption and its determinants in low-rise apartment (i.e. apartments up to three-storey), across different groups of consumers and urban areas, is fully investigated using data integration and multi-scale analysis approaches.

In chapter 4, the water consumption and its determinants in high-rise apartments (apartment with more than three-storey) are thoroughly evaluated using the data integration approach.

Chapter 5 thoroughly investigates the seasonal variations of water consumption across three different housing types in different urban areas (i.e. low and high income areas) in Auckland.

In chapter 6, all the acquired knowledge of water consumption across different housing types, urban areas and seasons, is combined with the Auckland Unitary Plan, outlining the future housing composition in Auckland, in order to examine the prospective effects of housing intensification on water use.

Finally, in chapter 7 as the conclusions, all the findings of this study are briefly outlined. At the end of this section the recommendations for future researches are also presented.

Since all the main chapters of this thesis are organised as the independent paper, some sections in each chapter have been repeated partially. However, these repeated sections generally have been carefully modified based on the data used in each chapter. Thus, the inclusion of them can help the readers to more easily follow the main discussions in the chapters.

1.7. Publications

Following is a list of publications based on the research presented in this thesis:

- Ghavidelfar, S., Shamseldin, A. Y., and Melville, B. W. (2016). "A multi-scale analysis of single-unit housing water demand through integration of water consumption, land use and demographic data." *(Under review)*.
- Ghavidelfar, S., Shamseldin, A. Y., and Melville, B. W. (2016). "A multi-scale analysis of low-rise apartment water demand through integration of water consumption, land use and demographic data." *Journal of the American Water Resources Association (JAWRA) 1-12. DOI: 10.1111/1752-1688.12430*.
- Ghavidelfar, S., Shamseldin, A. Y., and Melville, B. W. (2016). "Evaluating the determinants of high-rise apartment water demand through integration of water consumption, land use and demographic data." *(Under review)*.
- Ghavidelfar, S., Shamseldin, A. Y., and Melville, B. W. (2016). "Evaluating spatial and seasonal determinants of residential water demand across different housing types through data integration." *(Under review)*.
- Ghavidelfar, S., Shamseldin, A. Y., and Melville, B. W. (2016). "Future implications of urban intensification on residential water demand." *Journal of Environmental Planning and Management (Under revision)*.
- Ghavidelfar, S., Shamseldin, A. Y., and Melville, B. W. (2016). "Estimation of the effects of price on apartment water demand using cointegration and error correction techniques." *Applied Economics*, 48(6), 461-470.

Chapter 2

A multi-scale analysis of single-unit housing water demand through integration of water consumption, land use and demographic data

Abstract

Studies evaluating the determinants of water demand typically use household-scale data or aggregated data. The household-scale data basically is preferred since it allows investigating the variation of responses to the determinants of water demand, specifically watering price and weather variables, across different groups of consumers. However, the scarcity of household-scale data and its high data collection cost generally have limited the previous studies to rely on the small samples of household data. Thus, they failed to show the spatial variation of water demand. In contrast, the studies utilized the aggregated data have managed to assess the spatial variation of water use. However, they overlooked the variations across the households. This study proposed a new approach in data integration in order to enable the multi-scale analysis of water demand (i.e. household scale and aggregated scale). Using a rich source of GIS-based urban databases in Auckland, New Zealand, this study developed a large sample of 31000 single-unit housing through integration of household-level water use and property data with micro-scale household demographics information. In this way, the study first evaluated the effects of water pricing, property characteristics, and weather conditions on the water demand across different groups of households. Then, the data is aggregated into the census area unit level to include socioeconomic characteristics of households and evaluate the spatial variation of water demand. Panel data models were used in both scales to analysis water demand. This study showed that water consumption may vary significantly across different group of consumers with different income levels. The study also revealed that

household size was the most important determinant of single-housing water use in Auckland. However, water price, housing density and section size were found not to be important determinants of water demand. This detailed knowledge of water consumption can help water planners to more reliably plan water supply systems and manage consumption in the complex urban environments.

2.1. Introduction

Understanding the drivers of residential water use is pivotal in the water demand planning and management. However, in the complex urban environments this task can be challenging since the heterogeneity in characteristics of household and dwelling may lead to considerable variations in water demand and its determinants among different groups of consumers and across urban areas (Abrams et al. 2012; House-Peters and Chang 2011; Mieno and Braden 2011).

To address this variability, the studies of residential water demand typically use data at the household-scale or the aggregated-scale such as census area levels. In order to take into account the differences across consumer groups in the water demand analysis, the use of household-scale data is preferred, especially when econometric models are used and the estimation of price elasticity is desirable (Arbués et al. 2004; Arbués et al. 2010; Höglund 1999). However, in practice due to the unavailability of household-scale data or the high cost of obtaining such data the empirical studies mainly have relied on the small random samples of household data. In this way, this group of studies typically failed to show the spatial variation of water demand and the influence of neighbourhood characteristics on the water use (Arbués et al. 2004; Arbués and Villanúa 2006; Pint 1999). In contrast, the studies in which the aggregated data were used although have managed to address the spatial variations of water demand, they typically overlooked the variations across households (Chang et al. 2010; House-Peters et al. 2010; Wentz and Gober 2007).

In order to enable the multi-scale (i.e. household scale and aggregated scale) analysis of water demand, this study proposed a new approach in combining the water consumption, land use (i.e. property characteristics), weather, water price and demographic data. In this approach, using urban databases and the geographic information system (GIS), first the information of water consumption and property are linked together to build a large sample of household-scale data, theoretically as large as the number of all dwellings within a city. This large sample of household-scale data can be used to evaluate the effects of water pricing, property characteristics, and weather conditions across different customers groups. Afterward, the household-scale data is aggregated into an appropriate spatial scale such as census area unit in order to include the socioeconomic characteristics of households in the demand analysis and evaluate the spatial variation of demand over the urban areas. In this way, the study can take advantage from both individual-scale and aggregated data analysis.

This study uses the multi-scale analysis approach to evaluate the determinants of water demand in Auckland, New Zealand. Auckland is the largest city in New Zealand. Due to the heterogeneity in characteristics of household and housing in Auckland, the variation of water demand among different group of consumers and across suburbs is remarkable. Therefore, in this complex environment the proposed multi-scale approach would help to better understand the drivers of water demand.

Taking advantage from a rich source of GIS-based urban databases in Auckland the study developed a database containing the monthly water consumption and property information, including housing type, for all dwellings in Auckland. This chapter focuses on water use in the single-unit housing (i.e. single-family detached houses) in Auckland. Water consumption in the other housing types (i.e. low-rise and high-rise apartments) is investigated in the next chapters. This segregation helps the present study to fully evaluate the determinants of water use across different housing types and consumer groups. In general, water consumption may vary significantly in different housing types due to the socioeconomic characteristics of households and the level of outdoor usage (e.g. gardens and swimming pools) across them (Fox et al. 2009; Russac et al. 1991).

In this study, a random sample of more than 31000 separate housing over 291 census area units is used to quantify and test the effects of household socioeconomic (household income and household size), dwelling characteristics (number of bedrooms, section size, swimming pool), urban structure (housing density), weather (rainfall, temperature), and water pricing on water demand. All of these variables have been frequently reported as the influential factors on the empirical water demand studies (House-Peters and Chang 2011).

This study utilizes regression methods specific to panel data to evaluate the determinants of water use both the household level and the census area unit scale. A panel data set comprises repeated observations over the same units (e.g. households, census areas units), collected over a number of periods (Hill et al. 2010; Verbeek 2004). The panel data models incorporate both the temporal and the spatial variations of water use in the modelling. Thus, they can generate better parameter estimates than traditional regression approaches (e.g. time-series and cross-sectional models) (Arbués et al. 2003; Polebitski and Palmer 2010; Weber 1989). In recent years with improving the data availability, panel data models were used more frequently in demand studies both in individual level (Arbués et al. 2004; Arbués et al. 2010; Kenney et al. 2008) and aggregated level (Fenrick and Getachew 2012; Martinez-Espiñeira 2002; Nauges and Thomas 2000; Polebitski and Palmer 2010). In this study, the period of the analysis spans from July 2008 to July 2014. At the household scale, the study mainly focuses on the estimation of price elasticity of water demand among different group of consumers (i.e. low, middle, and high income households and houses with swimming pool). However, at the area unit level the understanding of drivers behind the spatial variability on water demand would be the main purpose.

The data integration in water demand studies has become more plausible in recent years due to advances in database technology, data accessibility, computing power, and spatial tools (Dziedzic et al. 2015; Polebitski and Palmer 2010). In an early attempt of data integration, as a pilot study, Troy and Holloway (2004) linked water demand and property information in 6 census area in Adelaide, Australia, to examines the water consumption patterns for different types of residential dwellings and areas. Shandas and Parandvash (2010) integrated water consumption, land use and demographic data to examine the relationship between land-use planning and water demand. Polebitski and Palmer (2010) integrated utility billing data with census demographic data, and property information in order to forecast residential use in Seattle, USA. In a recent study, Dziedzic et al. (2015) integrated water billing records, demographic census information, and property information in Ontario, Canada. Through this data integration and subsequent cluster analysis, they identified the pattern of water demand over different areas and groups of customers for the purpose of conservation planning. They emphasized the importance of data integration in order to use the full potential of rich data available with the organizations. In contrast, the multi-scale analysis of water demand has been relatively new in the domain of demand study. In a recent study, Ouyang et al. (2014) used water demand in three different scales (i.e. household, census tract and city scales) to identify the determinants of water demand and examine whether spatial scale may lead to ecological fallacy problems in residential water use research. They showed that the results of demand study on different scales are comparable.

This study pioneers an approach in combining data in order to enable analysis of water demand both at the household scale and the aggregated scale. The proposed method can help water planners to more reliably plan for conservation programs and infrastructure developments through fully understanding the water demand and its drivers across different group of customers and over different areas.

This article is organized in the following order. After the introduction, a review of study area is presented. Afterward, the data and the integration procedure are discussed. Then, the method of analysis is briefly discussed. Finally, the results and the conclusions are presented.

2.2. Study area

Auckland is the largest city in New Zealand. This city formerly was comprised from seven territorial authority areas. These areas were Rodney District, North Shore City, Waitakere City, Auckland City, Manukau City, Papakura District, and Franklin District. However, in 2010 these areas amalgamated to form a single authority known as the Auckland Council.

Auckland has experienced fast growth rates both in population and in the housing stock in the last decades. The population of Auckland has increased by 22% since 2001, reaching around 1.4 million people in 2013 (Statistics-NZ 2015). Under pressure of population growth, the city has experienced considerable changes in its urban structure. For example, the dwelling density increased in Auckland region between 2001 and 2013, from 86 to 102 dwellings per square kilometre (Goodyear and Fabian 2014). The section size of properties also decreased over the past decades (LINZ 2015). The trend in increasing the dwelling density is also boosted by Auckland council policy in compact city development. Based on the Auckland Unitary Plan the central areas with good access to high-frequency public transport and other facilities are targeted for higher density living (Goodyear and Fabian 2014).

The variations of household and housing characteristics in Auckland are remarkable. The average household size in Auckland is around three. However, this number increases to five people in some parts of southern Auckland where multifamily household (i.e. households in which two or more family nuclei reside in the same dwelling) is more common (Statistics-NZ 2015). The median age of population in Auckland is around 35 years. (Statistics-NZ 2015).

At the time of the 2013 Census, single-unit housing (i.e. separate dwelling) made up about three quarters of occupied private dwellings in Auckland while the percentage of private dwellings in Auckland that were joined (i.e. flats and apartments) was 25 percent (Goodyear and Fabian 2014).

In Auckland, there is a year-round precipitation. The average annual precipitation is around 1240 mm. The annual average air temperature is around 15 °C. The coldest month is usually July and the warmest month is usually January or February (NIWA 2015).

2.3. Data integration

This study combines the data of water consumption, dwelling, weather, water pricing, and census socioeconomic for the purpose of water demand analysis. The water consumption, dwelling, weather, water pricing information is available at both the household-scale and the census area unit level (i.e. after aggregating the data). However, the socioeconomic data only is available at the census area unit level.

In this study, the monthly water consumption data was provided by Watercare Services Limited, an Auckland Council Organization, on the monthly basis for all dwellings in Auckland for the period of 2008-2014. This data does not include Papakura District meters since the provision of retail water services in that district is franchised to a separate company. Thus, the Papakura district was excluded from this analysis. Up until July 2012, each former district of Auckland had different water recording span, varying from six months to bimonthly periods. From July 2012, the domestic accounts are read every two months by Watercare. To standardize the data all over Auckland, Watercare converted this data to the monthly period. In order to estimate the monthly water use for each individual meter, Watercare first estimates the average daily use during the reading period (i.e. the usage on the meter is divided by the number of days between the two readings). Then, this average use is allocated to each month according to the number of days corresponding to that month in that particular reading period. The water consumption database also includes the address of property and its geographical location, type of meter and its installation date for each individual meter.

The property information was obtained from the publicly available database at Auckland council (Auckland-Council 2015) and Land Information New Zealand (LINZ 2015). The property data is available in GIS format in which each property is represented by a polygon, reflecting the section size of property. In addition to the section size, for each property the information of housing type (i.e. single-unit, flats or apartments, etc.), assessed value of property, structure size of building (i.e. building footprint), impervious area, the issue dates of section (as a proxy of age of property), as well as the address of property were available.

The weather data, included monthly average air temperature and rainfall, was obtained from the New Zealand's National Climate Database (CliFlo 2015) for the periods of 2008 to 2014. This data came from 15 weather stations across Auckland and was interpolated in GIS to estimate average air temperature and rainfall over 291 census area units.

The water and wastewater charges for six districts of Auckland, from 2008 to 2014, were also provided by Watercare. The water tariff in Auckland consists of an annual fixed charge and volumetric charges for water and wastewater. Watercare calculates the volume of wastewater based on the water volume measured by the water meter. The water, wastewater and fixed charges have undergone substantial changes over the last few years in Auckland. Before 2010, the water and wastewater charges were determined by the local councils thus every district had its own tariff. However, after amalgamation of the Auckland councils in 2010, Watercare took over water sector in Auckland and gradually changed the water and wastewater tariffs all over the local councils to finally bring a unified tariff for all Auckland after July 2012. Watercare usually adjusts water and wastewater charges annually in July each year.

The socioeconomic information of households was obtained from Statistics New Zealand Data Lab (Statistics-NZ 2015) for census 2006 and 2013. The Data Lab provided access to the census microdata. From census microdata it is possible to estimate household and housing information (e.g. household income, household size, education level, number of bedrooms, etc.) for different types of housing. The census information was collected for separate housing at the census area unit level. Census area unit is the second smallest geographical unit that census information is available within. The smallest census unit is meshblock however in that level many variables would not be available in order to protect the information of residents.

In this study, the information of water consumption, land use, weather, water price and demographic microdata was combined using geographic information system (GIS). The water consumption and property data were arranged in GIS and linked together using the addresses and geographical coordinates. By this integration the information of water consumption and property for around 350000 housing including single-unit houses, low-rise and high-rise apartments became available for the water demand analysis.

This chapter thoroughly investigates water consumption and its determinants in the single-unit housing in Auckland. Around 75% of houses in Auckland are single-unit (i.e. separate house). After filtering the database based on the property type around 260000 single-unit houses remained for the rest of analysis. From this filtered data the houses with replaced meters (i.e. houses with more than one meter records) were excluded from the analysis. This is because in these houses the records from erroneous old meters usually overlap the new meters records for a period of time, thus they may cause error in the estimation of historical water consumption. After this data filtering around 130000 single-unit houses remained available for the final demand analysis.

This study selected a random sample of 31400 properties from the developed dataset in order to check the data for completeness and quality. Using high-resolution aerial images, this study visually inspected all the properties in the sample mainly to complete some unreported property characteristics such as presence of swimming pool in the dwellings. This random sample is large enough to reliably represent the total population of single-unit dwellings (i.e. there was no statistically significant difference between average water consumption estimated from the random sample and all meters) as well as fully cover all suburbs of Auckland to show the spatial variation of water use.

Using GIS the water pricing and weather information were also assigned to this random sample of single-units houses based on the geographical location of houses. This dataset is used to carry out the household-scale demand analysis. Then, the dataset is aggregated at the census area unit level to include the census socioeconomic variables on the demand study as well.

Using this data integration, the developed database provided a unique opportunity to investigate the determinant of water demand on the different scales.

2.4. Water demand models

This study applies regression methods specific to panel data to understand the determinants of water demand both in the household scale and the area unit scale in Auckland. A panel data set consists of a number of individual customers or customer groups where their characteristics (e.g. water use, income, household size) are measured over time (e.g. months, or years) (Verbeek 2004). In this study, the panel data included the repeated observations of water consumption, housing and household characteristics, water price, and weather variables for the single houses, collected over the period of 2008 to 2014. This study examined three common panel data methods including pooled model, fixed effects model, and random effects model. In the pooled model, the regression has a single intercept (Hill et al. 2010). However, in the fixed effects and the random effects models the intercept is allowed to vary between individual customers or customer groups (House-Peters et al. 2010; Kenney et al. 2008). Therefore, fixed effects and random effects models are typically an improvement over pooled models since they can capture the variability across consumers using varying intercepts. In panel data models, a pooling test (partial F-test) (Hill et al. 2010) is used to examine this improvement. The null hypothesis of this test is that all the intercepts between the individual customers or customer groups are equal. If the p-value associated with the test statists is below the range of accepting the null hypothesis (i.e. 0.05), it can be concluded that the panel estimators (i.e. fixed effects and random effects) are preferred to the pooled model. In order to choose an appropriate method between the fixed effects and the random affects models, a Hausman test is used (Hill et al. 2010; Wooldridge 2012). The null hypothesis of this test is that, if there are no omitted variables, the random effects model is more efficient (Polebitski and Palmer 2010). This means that if the null hypothesis of test does not reject the random effects model is preferred. The random effects model has a useful feature over the fixed effects, when it can recover parameter estimates for time invariant variables as well (Fenrick and Getachew 2012).

In this study, the panel data models are developed using the data available at the household and the census area unit scales. At household scale water demand analysis, the dependent variable is the average daily water consumption. To calculate this, the annual water consumption of household (calculated by adding monthly data) was divided by the number of days in each year for the individual dwellings. The developed dataset included water consumption of around 31400 individual houses over 6 years (i.e. August 2008 to July 2014). The water consumption data was estimated on the annual basis because the water price in Auckland changed annually (i.e. in July each year). Thus, it can better reflect the overall effects of changing in price across the years. The independent variables in the household-scale model are price of water, average air temperature, annual rainfall and housing characteristics.

This study investigates the effects of both volumetric and fixed charges of water and wastewater. Since in Auckland the wastewater price is calculated based on metered water use, this study summed up the charges of water and wastewater. This would help to evaluate the overall effect of volumetric and fixed charges.

Taking advantage of household-scale data, the study evaluated the effects of water pricing, as key instrument in managing water demand, across different groups of customers. In this way, the individual houses were clustered into different groups based on the housing value, as a proxy of household income, and water consumption. The k-means algorithm (Everitt et al. 2011) were used for the clustering. Using cluster analysis, 3 different groups of household were distinguished in Auckland (i.e. high income, middle income and low income). The price elasticity of water demand was also estimated in the houses with swimming pools to reveal the effects of water pricing on regulating water demand across this group of consumer with high water use.

At the level of census area unit, similar to the household level, the dependent variable is the average daily water use. In this level, three major census variables including household size, household income and number of bedrooms, were also added in the model. These census variables have been frequently reported as the influential factors in the water demand studies (House-Peters and Chang 2011). Variables such as age of residents and ownership of property were not included in the model because they were correlated with the household income. Thus, the income variables can present the effects of those variables in the model. In this study, a yearly estimate of census variables was used in the panel data analysis. Beside census variables, similar to household-scale models, water price (i.e. volumetric and fixed prices), average air temperature and annual rainfall were included in the model. Average section size of property, estimated from the household-scale data, and density of dwellings were also included in the models.

In order to better demonstrate the differences in water use across different groups of consumers at the census areas unit scale analysis, the k-means algorithm (Everitt et al. 2011) also was used to distinguish different census area units based on the housing value, as a proxy of household income, and water consumption. Using cluster analysis, three groups of census area units with the high income, middle income and low income were distinguished in Auckland. In order to consider this these cluster of consumers in the water demand model, two dummy variables, representing the low-income and high-income area units, were added into the panel data model. The middle income group dummy variable was omitted from the model in order to be used as reference group for the comparison purpose (Arbués et al. 2010; Hill et al. 2010; Wooldridge 2012). Using this approach, the significant dummy variables can reveal the significant differences across groups of consumers.

In the study also included two dummy variables representing the low income and high-income census area units in Auckland. The dummy variables were estimated through cluster analysis, where k-means method distinguished three different groups of consumers at the census are level based on the housing value, as proxy of income, and average daily water consumption.

Table 2.1 provides a list of variables which were used for demand analysis in the household and the census area unit scales. In this study the prices and income were deflated into real 2013 terms using the customer price index (CPI) (Statistics-NZ 2015).

Table 2.1. List of variables available for the multi-scale water demand analysis in single houses

Variables	Definition	Units	Scale of analysis
DWU	Daily water use	Litre/single-unit house/day	Household, Census area unit
HValue	Housing value in year 2013	NZ dollars	Household
BFootP	Building footprint (structure size)	m^2	Household
DumPool	Dummy variables representing houses with pool	N/A	Household
SecSize	Section size of property	m^2	Household, Census area unit
VPrice	Volumetric price of water and wastewater	NZ dollars/m^3 water	Household, Census area unit
FPrice	Annual fixed price of water and wastewater	NZ dollars/year	Household, Census area unit
Temp	Average air temperature	°C	Household, Census area unit
Rain	Total annual rainfall	mm	Household, Census area unit
Income	Household median income	NZ dollars/year	Census area unit
HhSize	Household size	People	Census area unit
BRooms	Number of bedrooms	Bedroom	Census area unit
Density	Total number of single-unit houses per square kilometre	Dwelling/km^2	Census area unit
DumLow	Dummy variables representing low-income areas	N/A	Census area unit
DumHigh	Dummy variables representing high-income areas	N/A	Census area unit

2.5. Results and discussion

2.5.1. Water demand models at household scale

At the household scale analysis, this study developed panel data models for different group of consumers (i.e. the low-income, middle-income, high-income households, and households with swimming pool). A panel data model also was developed using entire sample to show the overall effects of variables on water use. This study examined pooled, fixed effects and random effects models to select the best panel data method. For all developed models, the result of Partial-F test (pooling test) (Hill et al. 2010; Polebitski and Palmer 2010), shown in table 2.2, revealed that the panel models (i.e. fixed effects and random effects models) are an improvement over the pooled model (i.e. the null hypothesis of single intercept was rejected in the models). The results of Hausman test (Hill et al. 2010; Wooldridge 2012) in table 2.2 also revealed that random effects model is not valid on the household-scale datasets (i.e. the null hypothesis of the random effects model is more efficient was rejected). Thus, the fixed effect model is the best estimator which can produce consistent parameter estimates. One drawback of fixed effects model is that this model cannot provide parameter estimates for time-invariant variables such as housing characteristics (i.e. HValue, BFootP, DumPool, SecSize) which generally do not change over time. This feature of fixed effect models however does not mean that the model omitted the time-invariant variables. In fact, the fixed model controlled these variables, alongside with other unobserved household characteristics, to provide unbiased parameter estimates for the remaining variables (Kenney et al. 2004).

Table 2.2 shows the results of panel data models for the household scale water demand analysis. The time trend was included in all models to accommodate the nonlinearities in the underlying data. All the variables (except FPrice that contains zero values) were also transferred by natural logarithm thus the coefficients can be interpreted as the elasticity.

Table 2.2. Fixed effects water demand models for single houses at the household-scale

Variables	All households	Low-Income households	Mid-Income households	High-Income households	Households with pool
Const	5.61***	5.95***	5.08***	5.69***	5.30***
VPrice	-0.02***	-0.02***	-0.03***	-0.03***	-0.05***
FPrice	-1.1e-5*	3.5e-7	-9.0e-6	-1.7e-5	-2.5e-5
Temp	0.32***	0.25***	0.32***	0.43***	0.62***
Rain	-0.03***	-0.02***	-0.03***	-0.06***	-0.05***
time	0.008***	0.020***	-0.014***	0.012***	-0.02***
$time^2$	-0.004***	-0.005***	-0.001***	-0.004***	
Partial F-test	36.36***	13.66***	14.60***	22.33***	31.29***
Hausman test	617***	193.76***	185.34***	128.5***	77.27***
Number of studied houses	31404	13632	9468	8304	2067

Note: ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

The estimated coefficients for the variable VPrice in table 2.2 revealed that the price elasticity of water demand was negative and significant for all models, varying from -0.02 to -0.05. This result is within the range of values obtained by a number of previous studies (Abrams et al. 2012; Arbués et al. 2004; Arbués et al. 2003). The models showed that the pricing response within households with higher income and swimming pool is slightly greater than households with the low or middle-income. This difference can be attributed to the higher outdoor water use among households with higher income and swimming pool. In general, outdoor use is assumed to exhibit higher price sensitivity (Arbués et al. 2003; Polebitski and Palmer 2010).

Figure 2.1 shows the monthly variation of water demand among different groups of consumers (i.e. low-, middle-, high-income, pool owners). In this figure, the difference between summer (February) and winter (July) water consumption can be attributed to outdoor use for each group of users. Table 2.3 compares the water consumption and housing characteristics in the studied groups of consumers.

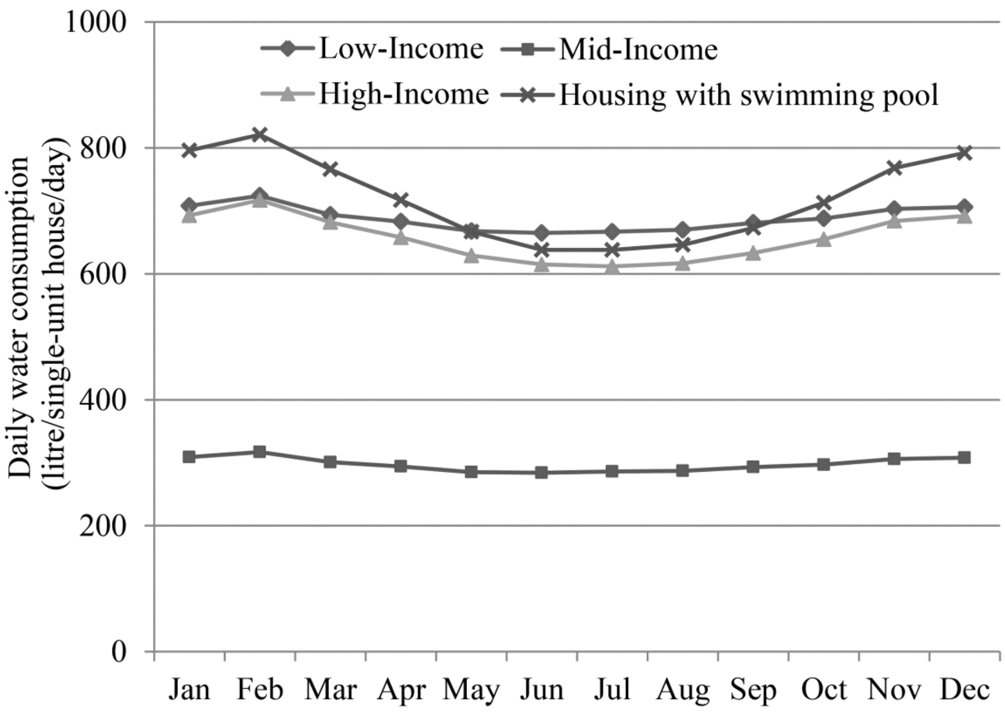

Figure 2.1. Monthly variation of water demand across four groups of consumers in single houses at the household scale (average of 6 years data)

Table 2.3. Water consumption and housing characteristics of different groups of consumers in single houses

Variables	Low-Income	Mid-Income	High-Income	Housing with swimming pool
DWU	687	298	656	716
HValue	423000	487000	1060000	1080000
SecSize	716	727	803	977
BFootP	183	175	215	232
Houses with pool (%)	4.1	2.5	15.3	100
Number studied houses	13632	9468	8304	2067

The estimated coefficient for the variables Temp and Rain in table 2.2 also showed that the households with higher income and swimming pool are more sensitive to the weather condition. In contrast, the low and middle-income households who have lower outdoor water consumption show a lower response to the weather variables. This finding is also in agreement with other studies (Balling Jr. et al. 2008).

The estimated coefficient for variable FPrice in table 2.2 also showed that the fixed price had very small and insignificant effect on water consumption in all models. In general, the only effect of the fixed charge on water consumption would be through its effect on reducing disposable income. Since the water costs usually comprises a small share of household expenditures it is not surprising that the effect of fixed price becomes insignificant (Mieno and Braden 2011).

The low magnitude of price elasticity estimated in this study (variable VPrice, table 2.2) revealed that the effects of water price is very limited across all groups of customers, under the current water price structure. This means, all group of consumers, including high water users (i.e. low-income, high-income and houses with pool) and low water users (mid-income), regardless of their water consumption levels and household and housing characteristics responded weakly to the pricing signal. The low price elasticity in Auckland can be mainly attributed to the fact that the water bill generally comprises a small share of total household expenditure. In addition, the current water/wastewater pricing scheme with flat volumetric rates may not provide enough incentive to reduce water consumption specifically among higher user groups.

Time trend also was negative and statistically significant in all models, representing a reduction trend in water use in all groups of consumers.

2.5.2. Water demand models at census area unit scale

Similar to household-scale analysis, the study examined pooled, fixed effects and random effects models to select the best panel data method. The result of pooling test, shown in table

2.4, revealed that the panel models are an improvement over the pooled model. The result of Hausman test, shown in table 2.4, also revealed that the random effect model is more efficient than fixed effect model and can better produce consistent parameter estimates. Table 2.4 shows the results of random effects model. The variables were transferred by natural logarithm thus the coefficients are elasticities.

Table 2.4. Random effects water demand model for single houses at the census area unit scale

Variables	Estimate
Const	4.61***
BRooms	0.31***
Income	0.03***
HhSize	0.36***
Density	-0.03***
SecSize	-0.01
VPrice	-0.03***
FPrice	-2.0e-5
Temp	0.38***
Rain	-0.03***
DumLow	0.15***
DumHigh	0.12***
time	0.013***
$time^2$	-0.004***
Partial F-test	18.21***
Hausman test	11.34
Number of area units	291

Note: ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

Similar to household-scale fixed effects models, the random effect model also provided satisfactory results where all variables were highly significant (except section size and fixed water charge) and had the expected sign. The coefficient of variation of the model (adjusted r^2) was also 0.77, implying the high explanatory power of the model.

In general, the census area unit model produced comparable results to the household-scale models for the water price and weather variables. The random effect model estimated a volumetric price elasticity of -0.03 (coefficient of variable VPrice in table 2.4), which was small but statistically significant. The fixed price was statistically insignificant. The model also showed that the temperature (Temp) positively and rainfall (Rain) negatively affect water demand. These results confirmed the finding of Ouyang et al. (2014), noting that scale of data does not significantly affect the outcomes of water demand models.

Beside the water price and weather variables, the model at the census area unit scale evaluated the effect of socioeconomic and urban structure on water demand.

The estimated coefficient for variable HhSize in table 2.4 also showed that household size has a positive impact on water consumption, where a 10% increase in the average number of people in a household would result in a 3.6% increase in household water consumption. This result is in agreement with many other water demand studies, where it was argued that due to economies of scale in the use of water, the increase in water consumption is less than proportional to the increase in household size (Arbués et al. 2004; Arbués et al. 2003; Hoffmann et al. 2006; Schleich and Hillenbrand 2009).

The income variable had a positive impact on water consumption. That is in line with many other demand studies (Kenney et al. 2008; Schleich and Hillenbrand 2009; Syme et al. 2004; Worthington and Hoffman 2008). In general, higher income household are associated with larger water consumption since they are likely to own more water-using capital stock, such as larger lawns and gardens, and swimming pools (Hoffmann et al. 2006; Mieno and Braden 2011; Schleich and Hillenbrand 2009).

The estimated coefficient of 0.31 for variable BRooms (table 2.4) also showed that the number of bedrooms in the property, as a proxy of size of dwelling, has a postive impact on household water consumtion. This is because increasing house size typically results in more bathrooms and higher chances of leaks (Polebitski and Palmer 2010).

This study also evaluated the effects of housing density and section size, as two important factors associated with the urban structure, on the water demand. These variables generally influence the amount of outdoor water use (Jorgensen et al. 2009). In general, dwelling density has a negative and section size, which is associated with smaller lot size and garden size, has a positive impact on water consumption (Balling Jr. et al. 2008; Chang et al. 2010; Domene and Saurí 2006; Polebitski and Palmer 2010; Shandas and Parandvash 2010). The estimated coefficient of -0.03 for the variable Density in table 2.4 showed that the dwelling density in Auckland had a statistically significant negative impact on water consumption. However, this impact was limited where the 10% increase in housing density only was associated with a -0.3% decrease in water consumption. The relationship between section size and water use also was insignificant. These results imply that the effects of compact development, through building higher density single-unit houses with smaller section size, would be limited on water demand in Auckland.

Finally, two dummy variables estimated through cluster analysis were highly significant, implying that water demand is different across low, middle and high-income suburbs. Figure 2.2 shows these three groups of census area units in Auckland. The first group is the low-income areas mainly clustered in Manukau City. The second group is the mid-income suburbs which were distributed all over Auckland and the third group included the high-income suburbs mainly clustered in Auckland City and North shore City.

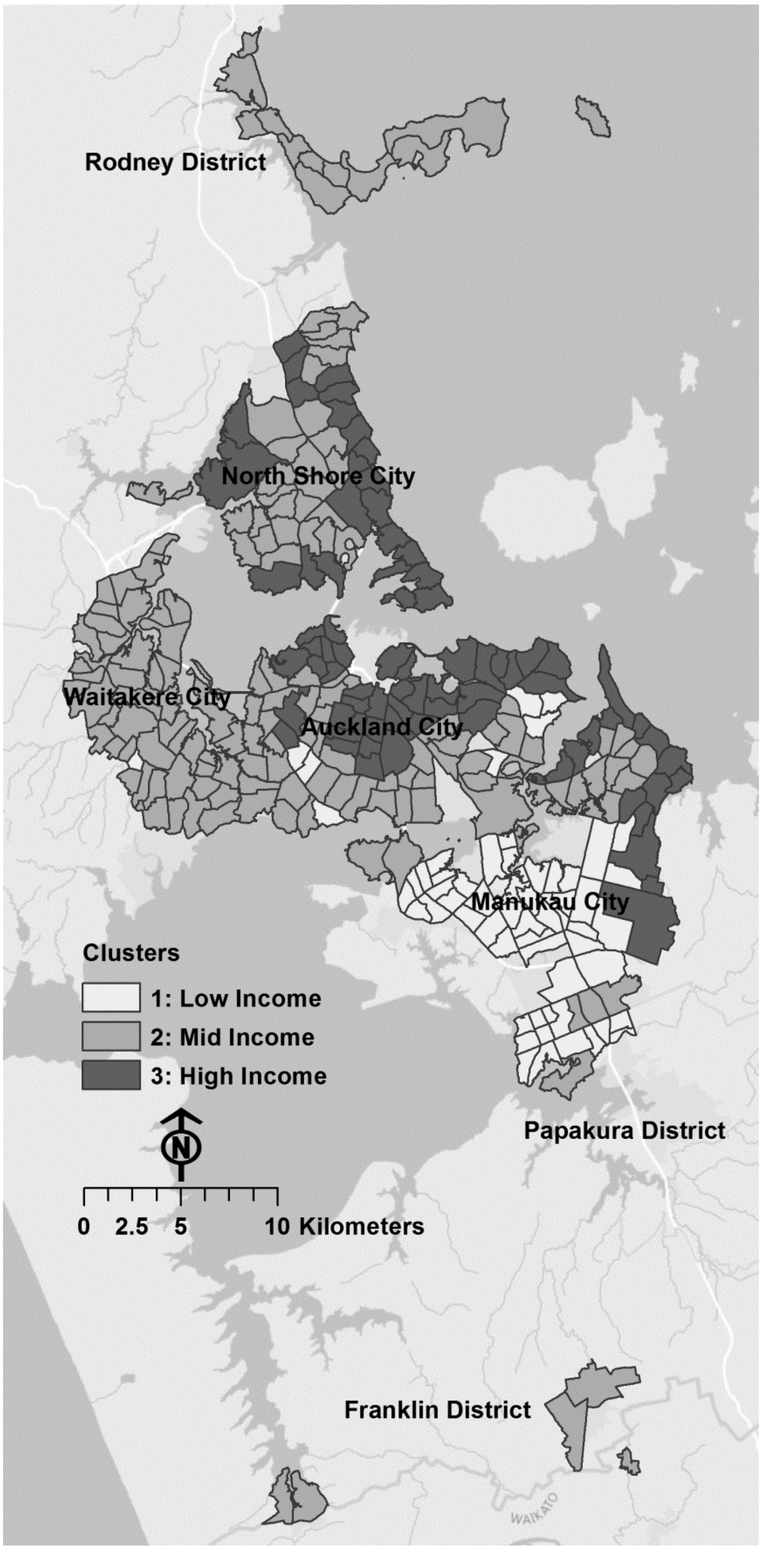

Figure 2.2. Three clusters of single houses in Auckland at the census area unit scale

Table 2.5 compares water consumption, housing and households characteristics across three groups of census area units.

Table 2.5. Water consumption, housing and households characteristics across different groups of consumers in single houses

Variables	Low-Income	Mid-Income	High-Income
DWU	669	517	607
HValue	345000	503000	1063000
SecSize	709	751	750
BFootP	188	180	205
Houses with pool (%)	2.1	4.8	13.4
BRooms	3.3	3.3	3.7
Income	69000	81000	126000
HhSize	4.1	3.1	3.1
Density	580	620	620
Number of area units	60	153	78
Per capita water use (litre/person/day)	163	167	196

Table 2.5 showed that, similar to the household-scale demand analysis, the low-income and the high-income suburbs had the higher per household water use (DWU) in comparison to the middle-income area units. This difference generally can be attributed into the higher outdoor water demand in the high-income suburbs (e.g. the percentage of houses with pool in the high-income areas is 13.4 in comparison to 4.8 in the middle-income areas), and higher indoor water use in the low-income area units (e.g. the household size in low-income areas is 4.1 where this number is 3.1 in the middle-income areas) in comparison to the middle-income areas.

Although the low-income suburbs had the highest per household water consumption, mainly due the larger household size, the amount of per capita water consumption among this group of consumers is as low as the mid-income area units (table 2.5). In contrast, the high-income area units had the highest per capita water consumption with an annual average of 196 litres per person per day. The seasonal variation of water demand is also considerable among the high-income suburbs where the water consumption increases by around 20% in the summers.

Figure 2.3 shows the seasonal variation of water demand across 3 groups of suburbs in terms of per capita water use.

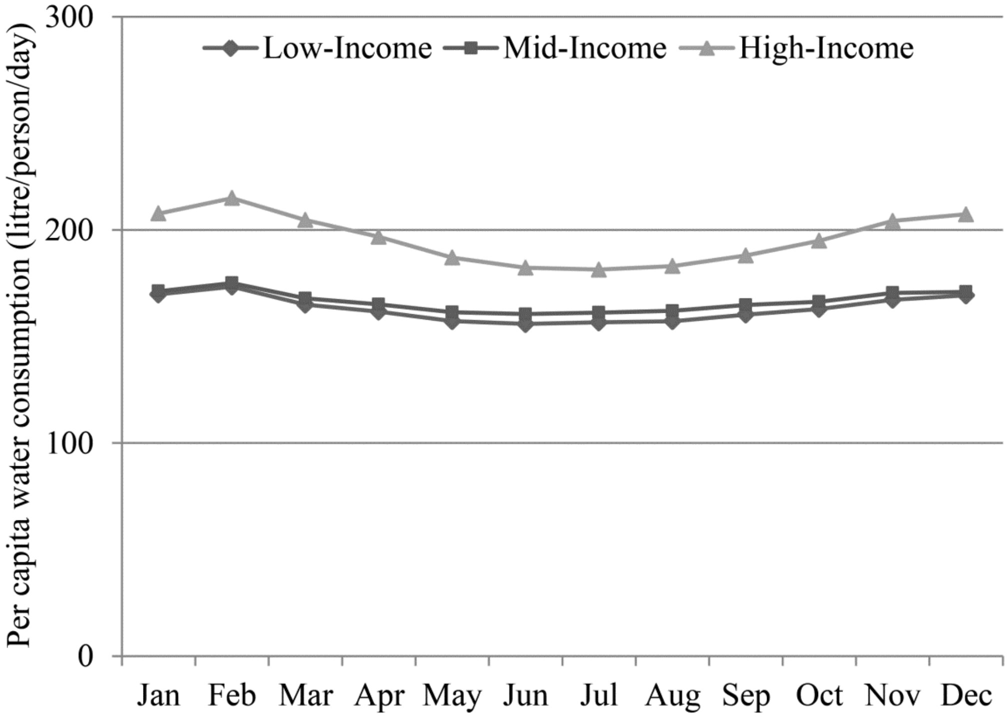

Figure 2.3. Monthly variation of per capita water consumption across three groups of consumers at the census area unit scale

Estimation of per capita water consumption is generally required by water utilities for the purpose of water planning and forecasting. Conduction a multi-scale analysis of water demand can help to not only understand the household water consumption, but also to estimate average per capita water use across different census area units through dividing the average per household water consumption by the average household size, obtain from the census data.

2.6. Conclusions

This study pioneered a new approach in multi-scale analysis of water demand through combining water consumption, land use and demographic data. Water demand studies typically use data at the household scale or the aggregated scale. The household-scale data is useful to evaluate the variation of responses to the determinants of water demand, practically water pricing, among different group of customers. However, the aggregated data can help to evaluate the spatial pattern of water consumption and the effects of urban density on demand. This study took advantages from both scales through carrying out the water demand analysis, using panel data models, both in household and census area unit scales. In this way, first the study integrated the water consumption and property data. Developing a large sample of more than 31000 individual houses, the study estimated the price and weather elasticities for low, middle, high-income households and houses with swimming pools. The results of study showed that the price elasticity of water demand for the groups of high users (i.e. household with high-income and swimming pool) is slightly higher. However, in general the price elasticity of water demand in Auckland was low for all groups of consumers, implying that the price of water would have limited effects on the water demand. The analysis also showed that the household with higher income and swimming pool are more sensitive to the weather conditions since they have more outdoor water use.

The household-level data was then aggregated (i.e. averaged out) at the census area unit level to include the census socioeconomic information. The study revealed that household income, household size and number of bedrooms positively correlated with the household water consumption. Dwelling density although had a negative correlation with the water use however its impact was limited. The section size of property also had an insignificant correlation with the water consumption. These results imply that the effect of compact developments would be limited on the water demand in Auckland. The results from aggregated model for water pricing and weather variables also were in agreement with the household-scale models.

With advances in database technology, data accessibility, computing power, and spatial GIS tools it is becoming more plausible to integrate disaggregated water consumption, land use and demographic data to make use the full potential of them in water demand studies. This data integration through multi-scale analysis allows the visualization and evaluation of demand information that was not previously possible. It provides planners with greater insights on the manner by which water is consumed spatially and how specific land use, demographics and weather impact consumption across space and time. This information can help water utilities to plan the water supply system in an optimal manner to meet demand and also better target a specific group of consumers or urban areas (e.g. high water users) for the conservation planning and demand management.

Chapter 3

A multi-scale analysis of low-rise apartment water demand through integration of water consumption, land use and demographic data

Abstract

Over the past decades, multi-unit housing developments (i.e. apartments) have been vastly expanded across urban areas around the world due to the population growth. In order to properly supply water to the apartment sector, it is essential to understand the determinants of its water use. However, this task has largely remained unexplored through the empirical study of water demand mainly due to the scarcity of data in the apartment sector. This study integrated apartment water consumption, property characteristics, weather, water pricing and census microdata to mitigate the issue of data scarcity in the apartment sector. Using a rich source of GIS-based urban databases in Auckland, New Zealand, the present study developed a large dataset containing the information of 18000 low-rise apartments in order to evaluate the determinants of water use both in the household scale and the aggregated scale. The household-scale water demand analysis enabled this study to assess the variation of responses to the demand drivers, specifically water price, across different consumer groups. The aggregated analysis also helped to understand the determinants behind the spatial variation of water demand at the census area unit level. This study revealed that the household size is the most important determinant of apartment water use in Auckland. However, the other socioeconomic factors, building features, water pricing were found to be insignificant determinants of water use. This knowledge of determinants of water demand can help water planners to better manage water demand in the compact urban environments.

3.1. Introduction

The rapid population growth in urban areas and the necessity of managing urban sprawl, due to its social, economic and environmental concerns, have promoted the development of multi-unit housing developments (i.e. apartments) in many cities around the world (Haarhoff et al. 2012; Randolph 2006). In general, multi-unit housing developments can help to build more compact cities (Haarhoff et al. 2012). In the contemporary urban planning, higher density living is seen as a credible path for improving urban sustainability (Boon 2010; Haarhoff et al. 2012). However, for a sustainable urban development it is also necessary to supply water for the fast growing multi-unit housing developments (Wentz et al. 2014). In order to properly supply water and manage consumption in the multi-unit housing sector, it is essential to understand the determinants of its water use. While many studies have investigated the factors affecting residential water use in the single-unit housing (e.g. separate houses) or as total (Chang et al. 2010; House-Peters et al. 2010; Polebitski and Palmer 2010; Rockaway et al. 2011; Schleich and Hillenbrand 2009; Wentz and Gober 2007), only few studies have evaluated the determinants of water use in the multi-unit housing developments. In the water demand studies, distinguishing multi-unit housing developments (i.e. apartment) from single-unit housing (i.e. separate houses) is necessary since the water use and its determinants may vary significantly across them (Domene and Saurí 2006; Fox et al. 2009; Russac et al. 1991). The distinction between these two housing types can be attributed to the differences in the socioeconomic characteristics of residents and the level of outdoor usage (e.g. gardens and swimming pools) on them (Fox et al. 2009; Russac et al. 1991).

The water consumption and its determinants also may vary considerably within each of these housing types based on the property characteristics. For example, the water consumption in the different types of multi-unit housing developments (e.g. high-rise apartments and low-rise apartments) can be significantly different (Domene and Saurí 2006; Fox et al. 2009; Loh et al. 2003; Russac et al. 1991; Troy and Holloway 2004; Zhang and Brown 2005). In general, smaller multi-unit housing developments with fewer housing units are more likely to show similar water habits to the single-unit housing (Wentz et al. 2014).

This chapter focuses on the understanding of water consumption and its determinants in low-rise apartments (i.e. up to three-storey buildings) in Auckland, New Zealand. The high-rise apartment water consumption (i.e. four or more storey buildings) will be discussed in the next chapter. The low-rise apartment, also known as flat, is the second common housing type in Auckland, making up around 21 percent of housing stock in this city (Statistics-NZ 2015).

In general, the empirical studies of water demand targeting multi-unit housing sector are very limited. In a study in Tucson, Arizona, Agthe and Billings (2002) developed regression models to explain the winter and summer water demand for 308 apartment complexes. They concluded that factors such as the value per bedroom, number of bedrooms, age of apartment, indoor water-saving devices, swimming pools, vacancy rates and water price were the principal determinants of apartment water use. Zhang and Brown (2005) evaluated the effects of household socioeconomics, water amenities and facilities, and attitude toward environmental concerns on apartment water use in Beijing and Tianjin, China. Using these variables they managed to explain around 10% to 55% of variation of water consumption in different types of apartment (i.e. high-rise, multi-storey, low-rise). Mayer et al. (2006) evaluated the apartment water demand across 13 cities in US with the main purpose of understanding the benefits of separate billing systems in the multi-unit housing sector. They showed that variables such as average number of bedrooms per unit, existence of cooling tower, fixture efficiency as well as submetering may significantly influence apartment water use. In a recent study, Wentz et al. (2014) used the design features of large apartment complexes to explain the variance in the high-rise apartment water use in Tempe, Arizona, USA. They found that the water consumption per bedroom increased with the pool area, dishwashers, and in-unit laundry facilities.

One of the main reasons that caused the study of apartment water demand to remain largely unexplored in comparison to the single-unit housing is the lack of readily available data in the apartment sector. In order to mitigate this data shortage, the present study used geographic information system (GIS) to combine water consumption, land-use (i.e. property characteristics) and census microdata associated with apartments. Through this data integration, the study developed a database containing the information of more than 18000 low-rise apartments over 201 census area units in Auckland. This large disaggregated dataset provides a unique opportunity to evaluate the determinants of water use both at the household scale and the aggregated scale (i.e. census area unit scale). In general, the household-scale data can be used to assess the variation of responses to the demand drivers specifically water price across different consumer groups (Arbués et al. 2004; Arbués et al. 2010; Höglund 1999). The aggregated scale also can help to evaluate the determinant behind the spatial variation of water demand (Chang et al. 2010; House-Peters et al. 2010; Polebitski and Palmer 2010; Wentz and Gober 2007).

This study firstly develops a household-scale dataset through linking the apartment water consumption data to the property information. Then, the dataset is aggregated at the census are unit scale in order to include the sociodemographics characteristics of households living at the apartments from census microdata. Census area unit is the smallest geographic area for which the New Zealand census microdata is fully available for the low-rise apartments (Statistics-NZ 2015). The information of water pricing and weather for different areas is also added into the both datasets in order to enable the evaluation of the effects of these variables on apartment water demand as well.

The proposed data integration (data combination) approach enabled the present study to evaluate the effects of a wide range of variables including household and housing characteristics, water price and weather on water consumption. In recent years, the data integration in water demand studies has become more plausible due to advances in database technology, data accessibility, computing power, and spatial tools (Dziedzic et al. 2015; Polebitski and Palmer 2010). In an early attempt of data integration, as a pilot study, Troy and Holloway (2004) linked water demand and property information in 6 census areas in Adelaide, Australia, in order to examines the water consumption patterns for different types of residential dwellings and areas. Shandas and Parandvash (2010) integrated water consumption, land use and demographic data in order to examine the relationship between land-use planning and water demand. Polebitski and Palmer (2010) integrated utility billing data with census demographic data, and property information in order to forecast residential use in Seattle, USA. In a recent study Dziedzic et al. (2015) integrated water billing records, demographic census information, and property information in Ontario, Canada. Through this data integration and subsequent cluster analysis, they identified the pattern of water demand over different areas and groups of customers for the purpose of conservation planning. They emphasized the importance of data integration in order to use the full potential of rich data available with the organizations. In contrast, the multi-scale analysis of water demand is relatively new in the domain of water demand study. In a recent study, Ouyang et al. (2014) evaluated water demand in the household scale, census area scale and city scale in order to identify the determinants of water demand and examine whether spatial scale may lead to ecological fallacy problems in a residential water use research. They showed that the results of water demand study on different scales are comparable. To the present knowledge of the author, the data integration and multi-scale analysis approaches never have been used for the evaluation of determinants of water demand in the multi-unit housing sector.

This study utilizes regression methods specific to panel data to analyse water demand in Auckland from years 2008 to 2014. A panel data set contains repeated observations over the same units (e.g. households, census areas units), collected over a number of periods (Hill et al. 2010; Verbeek 2004). The panel data models incorporate both the temporal and the spatial variations of water use in the modelling. Thus, they can generate better parameter estimates than traditional regression approaches (Arbués et al. 2003; Polebitski and Palmer 2010; Weber 1989). In recent years with increase in the data availability these models have been used more frequently (Arbués et al. 2004; Arbués et al. 2010; Fenrick and Getachew 2012; Kenney et al. 2008; Martinez-Espiñeira 2002; Nauges and Thomas 2000; Polebitski and Palmer 2010). However, to the present author’s knowledge, the panel data model has never been used for the water demand analysis in the apartment sector.

This chapter is organized in the following order. After the introduction, a review of study area is presented. Afterward, the data and the integration procedure are discussed. Then, the method of analysis is briefly discussed. Finally, the results and the conclusions are presented.

3.2. Study area

Auckland is the largest city in New Zealand. This city formerly was comprised from seven territorial authority areas. These areas were Rodney District, North Shore City, Waitakere City, Auckland City, Manukau City, Papakura District, and Franklin District. However, in 2010 these areas were amalgamated to form a single authority known as the Auckland Council.

Auckland has experienced fast growth rates both in population and housing stock over the last decades. The population of Auckland has increased by 22% since 2001, reaching around 1.4 million people in 2013 (Statistics-NZ 2015). Under pressure of this growth, the city has experienced considerable changes in its urban structure. Between 2001 and 2013 the dwelling density in Auckland has increased from 86 to 102 dwellings per square kilometre (Goodyear and Fabian 2014). In general, the increase of dwelling density has been due to the decrease of section size of single-unit housing and the increase of number of multi-unit dwellings (LINZ 2015; Statistics-NZ 2015).

The trend in increasing the dwelling density is also boosted by Auckland council policy aimed at a compact city development. Based on the Auckland Unitary Plan the central areas with good access to high-frequency public transport and other facilities are targeted for higher density living (Goodyear and Fabian 2014).

In Auckland the housing stock is dominated by the single-unit houses, which comprise around 75 percent of dwellings. However, in recent years the tendency towards apartment living has gradually increased. Between 2006 and 2013 the number of apartments in Auckland has increased by 11.3 percent, where single-unit housing has experienced an increase of 5.8 percent over this period (Statistics-NZ 2015).

The variation of household characteristics in Auckland also is remarkable. The average household size in low-rise apartments is around 2.5 people. However, this number can increase to five people in some parts of south Auckland where multifamily households (i.e. households in which two or more family nuclei reside in the same dwelling) is more common (Statistics-NZ 2015). The median age of people living in the Auckland low-rise apartments is around 36 years (Statistics-NZ 2015).

Auckland has a subtropical climate with a year-round precipitation. The average annual precipitation is around 1240 mm. The annual average air temperature is around 15 °C. The coldest month is usually July and the warmest month is usually January or February (NIWA 2015).

3.3. Data integration

This study combines the data of water consumption, property characteristics, weather, water pricing, and census microdata for the purpose of water demand analysis. The apartment water consumption, property, weather and water pricing information is available both at the household scale and the census area unit scale (i.e. after aggregating the data). However, the household socioeconomic data is only available at the census area unit level.

In this study, the monthly water consumption data was provided by Watercare Services Limited, an Auckland Council Organization, for the period of 2008-2014. This data does not include Papakura District meters since the provision of retail water services in that district is franchised to a separate company. Thus, the Papakura district was excluded from this study. Up until July 2012, each former district of Auckland had different water recording span, varying from six months to bimonthly periods. From July 2012, the domestic accounts are read every two months by Watercare. To standardize the data all over Auckland, Watercare converted this data to the monthly period. In order to estimate the monthly water use for each individual meter, Watercare first estimates the average daily use during the reading period. Then, this average use is allocated to each month according to the number of days corresponding to that month in that particular reading period. The water consumption database also includes the address of property and its geographical location, type of meter and its installation date for each individual meter.

The property information was obtained from the publicly available databases at Auckland council (Auckland-Council 2015) and Land Information New Zealand (LINZ 2015). The developed property dataset contains the information of housing type, assessed value of property, section size, structure size of building, impervious area, the issue dates of section (as a proxy of age of property), and the address of property. The garden size of property is also calculated by subtraction the sum of building footprint and impervious area from section size.

The weather data, included monthly average air temperature and rainfall, was obtained from the New Zealand's National Climate Database (CliFlo 2015) for the periods of 2008 to 2014. This data came from 15 weather stations across Auckland and was interpolated in GIS to estimate average air temperature and rainfall over different areas.

The water and wastewater charges for six districts of Auckland, from 2008 to 2014, were also provided by Watercare. The water tariff in Auckland consists of an annual fixed charge and the volumetric charges for water and wastewater. Watercare calculates the volume of wastewater based on the water volume measured by the water meter. The water, wastewater and fixed charges have undergone substantial changes over the last few years in Auckland. Before 2010, the water and wastewater charges were determined by the local councils thus every district had its own tariff. However, after amalgamation of the Auckland councils in 2010, Watercare took over water sector in Auckland and gradually changed the water and wastewater tariffs all over the local councils to finally bring a unified tariff for all Auckland after July 2012. Watercare usually adjusts water and wastewater charges annually in July each year.

The socioeconomic information of households was obtained from Statistics New Zealand Data Lab (Statistics-NZ 2015) for census 2006 and 2013. The Data Lab provided access to the microdata (i.e. data about specific people, households, or businesses). From the census microdata, it is possible to estimate household and housing information (e.g. household income, household size, education level, number of bedrooms, etc.) for different types of housing. For this study, the census information for households living in the low-rise apartments (i.e. joined dwellings with one-, two-, or three-storey) was collected at the census area unit level. Census area unit is the second smallest geographical unit in which the census information is available. The smallest census unit is meshblock however in that level many variables would not be available in order to protect the information of residents.

In this study, the information of water consumption, land use, weather, water price and demographic microdata was combined using geographic information system (GIS). The water consumption and property data were arranged in GIS and linked together using the addresses and geographical coordinates. By this data integration the information of water consumption and property for around 350000 housing including single-unit houses, low-rise and high-rise apartments became available for the demand analysis.

This chapter focuses on the evaluation of water demand in the low-rise apartments (i.e. apartments up to three-storey). Low-rise apartments made up around 21 percent of housing stock in Auckland. Thus, after filtering the database based on the property type around 70000 low-rise apartments remained for the rest of analysis. From this filtered dataset, the apartments with replaced meters (i.e. houses with more than one meter records) were excluded from the analysis. This is because in these apartments the records from erroneous old meters usually overlap the new meters records for a period of time, thus they may cause error in the estimation of historical water consumption. After this data filtering, the information of 40000 low-rise apartments remained available for the rest of study. In this dataset, the low-rise apartments may have joined or separate structures (e.g. two or more dwellings on a single block of land (section), but are not joined). Given that, the census information for apartment residents is available for the joined dwellings, the dataset was filtered by this criterion leaving around 18000 apartments with joined structures for the final demand analysis.

Using GIS, the water pricing and weather information were also included in the database in order to complete the household-scale dataset. This dataset can help to fully investigate the effects of water pricing, as the key factor in regulating water demand, and weather variables across different group of consumers (i.e. low, middle, and high income households). Afterward, the dataset is aggregated at the census area unit level in order to include census information to examine the determinants behind the spatial variation of water demand in Auckland.

3.4. Water demand models

This study applies regression methods specific to panel data to understand the determinants of water demand. A panel data set consists of a number of individual customers or customer groups where their characteristics (e.g. water use, income, household size) are measured over time (e.g. months, or years) (Verbeek 2004). In this study, the panel data included the repeated observations of water consumption, housing and household characteristics, water price, and weather variables for the low-rise apartments, collected over the period of 2008 to 2014. This study examined three common panel data models including pooled model, fixed effects model, and random effects model. In the pooled model, the regression has a single intercept (Hill et al. 2010). However, in the fixed effects and the random effects models the intercept is allowed to vary between individual customers or customer groups (House-Peters et al. 2010; Kenney et al. 2008). Therefore, fixed effects and random effects models are typically an improvement over pooled models since they can capture the variability across consumers using varying intercepts (Arbués et al. 2003; House-Peters et al. 2010; Kenney et al. 2008). In the panel data models, a pooling test (partial F-test) (Hill et al. 2010) is used to examine this improvement. The null hypothesis of this test is that all the intercepts between the individual customers or customer groups are equal. If the p-value associated with the test statists is below the range of accepting the null hypothesis (i.e. 0.05), it can be concluded that the panel estimators (i.e. fixed effects and random effects) are preferred to the pooled model. In order to choose an appropriate method between the fixed effects and the random affects models, a Hausman test is used (Hill et al. 2010; Wooldridge 2012). The null hypothesis of this test is that, if there are no omitted variables, the random effects model is more efficient (Polebitski and Palmer 2010). This means that if the null hypothesis of test does not reject the random effects model is preferred. The random effects model has a useful feature over the fixed effects, when it can recover parameter estimates for time invariant variables as well (Fenrick and Getachew 2012).

In this study, the panel data models are developed using both the household and census area unit scales data. At the household scale water demand analysis, the dependent variable is annual average daily water consumption over 6 years (i.e. August 2008 to July 2014). To calculate this, the annual water consumption of apartments with individual meters (calculated by adding monthly data) was divided by the number of days in each year. The water consumption data was estimated on the annual basis because the water price in Auckland changed annually (i.e. in July each year). Thus, it can better reflect the overall effects of changing in price across the years.

In Auckland, the majority of low-rise apartments are metred individually. However, there are few larger apartment buildings or complexes in which Watercare only measures the total water consumption using master meters and does not meter apartments individually (although the units may be sub-metered individually by the building managers). In this study, two thirds of studied apartments (around 12000 units) had individual meters (i.e. a single meter for each apartment), while around 6000 apartments, over around 360 apartment complexes, had master meters. In order to estimate average apartment water consumption in buildings with master meters, the total metered water consumption was divided by the number of apartments in each building.

In order to examine the difference in water use between apartments with and without individual meters, this study compared the average of water consumption in these two groups of apartments using a t-test (Field et al. 2012). The result of t-test, shown in table 3.1, revealed that there is no significant difference in water use between apartments with and without individual meters (The null hypothesis of no difference in water use between two groups was not rejected, $t = -1$, $p > 0.1$). However, since the main purpose of household-scale demand analysis is to reveal the response of different households to the pricing signals, this study used the sample of around 12000 apartments with individual meter for the demand analysis in order to make sure all households directly received the pricing signals. In contrast, for the census area unit level demand analysis, where the main purpose of study is to evaluate the spatial variation of water demand, the entire sample of apartments (i.e. data for more than 18000 apartments) is used since the census data included the information of both group of apartments (i.e. small and large low-rise apartment buildings, with or without meters).

Table 3.1. Comparison of water consumption in low-rise apartments with and without individual meters

Variables	Apartments with individual meter	Apartments without individual meter
Average daily water use (Litre/apartment/day)	369	376
Standard deviation	208	133
Sample size	11858	376 buildings (6752 apartments)
t-statistic	-1	
p-value (two-tailed)	0.32	

This study examines the effect of a wide range of variables including household and housing characteristics, water price and weather variables on apartment water use. Table 3.2 provides a list of variables which were used for water demand analysis in household and census area unit scales. All the studied variables have been frequently reported as the influential factors on the empirical water demand studies (Arbués et al. 2003; Chang et al. 2010; Fox et al. 2009; House-Peters et al. 2010; House-Peters and Chang 2011; Mieno and Braden 2011; Ouyang et al. 2014; Schleich and Hillenbrand 2009). This study investigates the effects of both volumetric and fixed charges of water and wastewater on the low-rise water consumption. Since the wastewater price in Auckland is calculated based on the metered water use, this study summed up the charges of water and wastewater. This would help to evaluate the overall effect of volumetric and fixed charges on low-rise apartment water consumption.

This study also evaluated the determinates of water use, specifically water price as a key instruments in managing water demand and weather variables, across different groups of consumers. The k-means algorithm (Everitt et al. 2011) was used to distinguish different groups based on the apartment value, as a proxy of household income, and water consumption. Using cluster analysis, three groups of consumers with the high income, middle income and low income were distinguished in Auckland. In order to examine the differences in water use across these groups, two dummy variables, representing the low-income and high-income area units, were added in the census areas unit scale model. The middle income group dummy variable was omitted from the model in order to be used as reference group for the comparison purpose (Arbués et al. 2010; Hill et al. 2010; Wooldridge 2012). Using this approach, the significant dummy variables can imply significant differences across groups of consumers.

In this study the price and income were deflated into real 2013 terms using the customer price index (CPI) (Statistics-NZ 2015).

Table 3.2. List of variables available for the multi-scale water demand analysis in the low-rise apartments in Auckland

Variables	Definition	Units	Scale of analysis
DWU	Daily water use	Litre/apartment/day	Household, Census area unit
AValue	Apartment value in year 2013	NZ dollars	Household, Census area unit
GardSize[a]	Garden size per apartment	m^2/apartment	Household, Census area unit
Units	Number of units in apartment buildings	apartments	Household, Census area unit
DumPool	Dummy variables representing apartment buildings with pool	N/A	Household
PercPool	Percentage of apartment buildings with swimming pool	%	Census area unit
VPrice	Volumetric price of water and wastewater	NZ dollars/m^3 water	Household, Census area unit
FPrice	Annual fixed price of water and wastewater	NZ dollars/year	Household, Census area unit
Temp	Average air temperature	°C	Household, Census area unit
Rain	Total annual rainfall	mm	Household, Census area unit
HhSize	Household size	People	Census area unit
BRooms	Number of bedrooms	Bedroom	Census area unit
Income	Household median income	NZ dollars/year	Census area unit
AgeUR	Median age of usual residents	years	Census area unit
DumLow	Dummy variables representing low-income areas	N/A	Census area unit
DumHigh	Dummy variables representing high-income areas	N/A	Census area unit

Note: [a] GardSize= garden size in each apartment building/number of apartments in the building

3.5. Results and discussion

3.5.1. Water demand models at household scale

At the household scale analysis, this study developed panel data models for different group of consumers (i.e. the low-income, middle-income, high-income households). A panel data model also was developed using entire sample to show the overall effects of variables on water use. This study examined pooled, fixed effects and random effects models to select the best panel data model. For all developed models, the result of partial F-test (pooling test) (Hill et al. 2010; Polebitski and Palmer 2010), shown in table 3.2, revealed that the panel models (i.e. fixed effects and random effects models) are an improvement on the pooled model (i.e. the null hypothesis of single intercept was rejected in the models). To choose between fixed effects and random effects models the Hausman test (Hill et al. 2010; Wooldridge 2012) were carried out for all datasets. The result of tests, shown in table 3.2, revealed that random effects model is not valid on the household-scale datasets (i.e. the null hypothesis of the random effects model is more efficient was rejected). Thus, the fixed effect model is the best estimator which can produce consistent parameter estimates. One drawback of fixed effects model is that this model cannot provide parameter estimates for the time-invariant variables such as housing characteristics (i.e. AValue, Garden, Units, DumPool) which generally do not change over time. This feature of fixed effect models however does not mean that the model omitted the time-invariant variables. In fact, the fixed model controlled these variables, alongside with other unobserved household characteristics, to provide unbiased parameter estimates for the remaining variables (Kenney et al. 2004).

Table 3.3 shows the results of panel data models for the household scale water demand analysis. The time trend was included in all models to accommodate the nonlinearities in the underlying data. All the variables (except FPrice that contains zero values) were also transferred by natural logarithm thus the coefficients can be interpreted as the elasticity.

Table 3.3. Fixed effects water demand models for low-rise apartments at the household-scale

Variables	All households	Low-Income households	Mid-Income households	High-Income households
Constant	5.31***	5.79***	4.89***	5.28***
VPrice	-0.02***	-0.01**	-0.03***	-0.02**
FPrice	0.00001	0.00003*	0.000007	0.00002
Temp	0.23***	0.11	0.14**	0.43***
Rain	-0.02***	-0.01	0.004	-0.06***
time	0.02***	0.041***	-0.016***	0.012**
$time^2$	-0.005***	-0.007***	–	-0.004***
Partial F-test	206.3***	10.13***	13.63***	21.21***
Hausman test	48.6***	38.3***	48.18***	18.44***
Number of studied apartments	11187	4677	3858	2652

Note: ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively; time represent time trend; $time^2$ represent quadratic time trend.

The estimated coefficients for the variable VPrice, in table 3.3, revelaed that the price elasticity of water demand was negative and significant for all models, varying from -0.01 to -0.03. The price elasticities estimated in this study are within the range of values obtained in a number of previous studies (Abrams et al. 2012; Arbués et al. 2004; Arbués et al. 2003). However, in general the price elasticity is very low, implying that water pricing has a limited impact on the low-rise apartment water demand in Auckland under current water pricing structure. The low price elasticity of apartment water demand can be attributed to the fact that in the apartment sector water is mainly used for the basic indoor needs (i.e. drinking, cooking, and sanitary needs) (Billings and Jones 2008; Zhang and Brown 2005). In general, the indoor water use is unlikely to exhibit a high price sensitivity (Arbués et al. 2003; Mieno and Braden 2011). In addition, in Auckland the water bill generally comprises a small share of total household expenditure and the current water/wastewater pricing scheme with flat volumetric rates may not provide enough incentive to reduce the water consumption.

The estimated coefficients for the variable FPrice, in table 3.3, also showed that the fixed price had very small and insignificant effect on water consumption in all models. In general, the only effect of the fixed charge on water consumption would be through its effect on reducing disposable income. Since the water costs usually comprises a small share of household expenditures, it is not surprising that the effect of fixed price becomes insignificant (Mieno and Braden 2011).

The weather variables in all models also had the expected positive signs for the temperature and the negative signs for the rainfall. However, the rainfall variable was only significant for the higher-income group. The temperature was significant for both the middle and high-income groups. This result was expected since the weather variables typically affect outdoor water demand rather than indoor (Arbués et al. 2003). In general, the higher income consumers are more likely to use water for the outdoor usage (e.g. irrigated landscaping and swimming pool) (Hoffmann et al. 2006; Mieno and Braden 2011; Schleich and Hillenbrand 2009). Table 3.4 compares the water consumption and housing characteristics among three different groups of consumers in Auckland. The results showed that the expensive apartments (i.e. higher-income group) in Auckland are more likely to have swimming pools (and perhaps the irrigated landscaping). Thus, it is not surprising that this group of consumer showed the greater response to the temperature and rainfall variables.

The time trend was also negative and statistically significant in all models, representing a reduction trend in water use for all groups of consumers over the study period.

Table 3.4. Water consumption and apartment characteristics for different groups of consumers in low-rise apartments

Variables	Low-Income	Mid-Income	High-Income
DWU	453	194	451
AValue	314000	350000	677000
GardSize	169	162	160
Units	2.7	2.7	2.5
Buildings with pool (%)	1.2	0.9	4.6
Number of studied apartments	4677	3858	2652

3.5.2. Water demand models at census area unit scale

Similar to the household-scale analysis, at the census areas unit scale this study examined pooled, fixed effects and random effects models to select the most appropriate panel data model. The result of pooling test (partial F-test), shown in table 3.5, revealed that the panel models are an improvement over the pooled model (the test result was not significant). The result of Hausman test, shown in table 3.5, also revealed that the random effect model is more efficient than fixed effect model and can better produce consistent parameter estimates in this dataset. Table 3.5 shows the results of random effects model. The variables were transferred by natural logarithm thus the coefficients are elasticities.

Table 3.5. Random effects water demand model for low-rise apartments at the census area unit scale

Variables	Estimate
Constant	5.51***
HhSize	0.44***
Income	-0.05
BRooms	-0.07
AgeUR	-0.02
Units	0.04
GardSize	0.01
PercPool	0.001
VPrice	-0.03***
FPrice	-0.000002
Temp	0.23***
Rain	-0.02
DumLow	0.21***
DumHigh	0.16***
time	0.012***
$time^2$	-0.003***
Partial F-test	20.78***
Hausman test	3.06
Number of area units	201

Note: ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively; time represent time trend; $time^2$ represent quadratic time trend.

Similar to the household-scale analysis, the random effect model provided satisfactory results as the estimated variables had the expected signs and significance. Moreover, the adjusted r^2-value of 0.58 is on the high end of the range presented in the past studies of apartment water demand (Agthe and Billings 2002; Mayer et al. 2006; Wentz et al. 2014; Zhang and Brown 2005).

In general, the census area unit model produced comparable results to the household-scale models for the water price and weather variables. The random effect model estimated a volumetric price elasticity of -0.03 (VPrice in table 3.5), which was low but statistically significant. The fixed price (FPrice in table 3.5) was statistically insignificant. The model also showed that the temperature positively and rainfall negatively affect water demand. These results confirmed the finding of Ouyang et al. (2014), noting that scale of data does not significantly affect the results of water demand models.

Besides the water price and weather variables, the model at the census area unit scale evaluated the effect of household socioeconomic and apartment physical characteristics on water demand. The estimated coefficient for variable HhSize, shown in table 3.5, revealed that household size is the most influential factor on the apartment water use. The estimated coefficient for the household size in the random effect model is 0.44, implying that a 10% increase in the household size would result in a 4.4% increase in the apartment water consumption. This result is in agreement with many other water demand studies, where it was argued that due to economies of scale in the use of water, the increase in water consumption is less than proportional to the increase in household size (Arbués et al. 2004; Arbués et al. 2003; Hoffmann et al. 2006; Schleich and Hillenbrand 2009).

The estimated coefficient of variable Income, in table 3.5, revealed that household income was not significantly correlated with the apartment water consumption. This result was expected in the case of Auckland apartments, where the majority of water consumption is in the form of indoor usage (i.e. water is used for the basic needs). In general, the income variable mainly affect household outdoor water consumption rather than indoor (Mieno and Braden 2011; Polebitski and Palmer 2010). The study also showed that the number of bedrooms and the age of resident were not significantly correlated with the apartment water use.

This study also evaluated the effects of apartment characteristics such as number of unit per building or complex, garden size, and swimming pools on the water demand. The result from table 3.5 reveals that the number of units in the buildings is not significantly correlated with the water demand (the variable Units was insignificant). This finding implies that the economies of scale for the shared water use (i.e. water is used for the building maintenance, cleaning, etc.) does not play a significant role in the average apartment water use. In addition, the variable garden size (GardSize) and swimming pools (PercPool), although had an expected positive sign, were not significantly correlated with the average apartment water use. These results were also expected, where a few numbers of apartment buildings in Auckland had swimming pools and the vegetated landscaping was limited to the planting of shrubs and trees which basically do not require much water. Moreover, the year-around precipitations in Auckland reduce the needs of irrigation for this type of landscaping.

Finally, two dummy variables estimated through cluster analysis were highly significant, implying that water demand is different across low, middle and high-income suburbs. Figure 3.1 shows these three groups of census area units in Auckland. The first group is the low-income areas mainly clustered in Manukau City. The second group is the mid-income suburbs which were distributed all over Auckland and the third group included the high-income suburbs mainly clustered in Auckland City and North shore City.

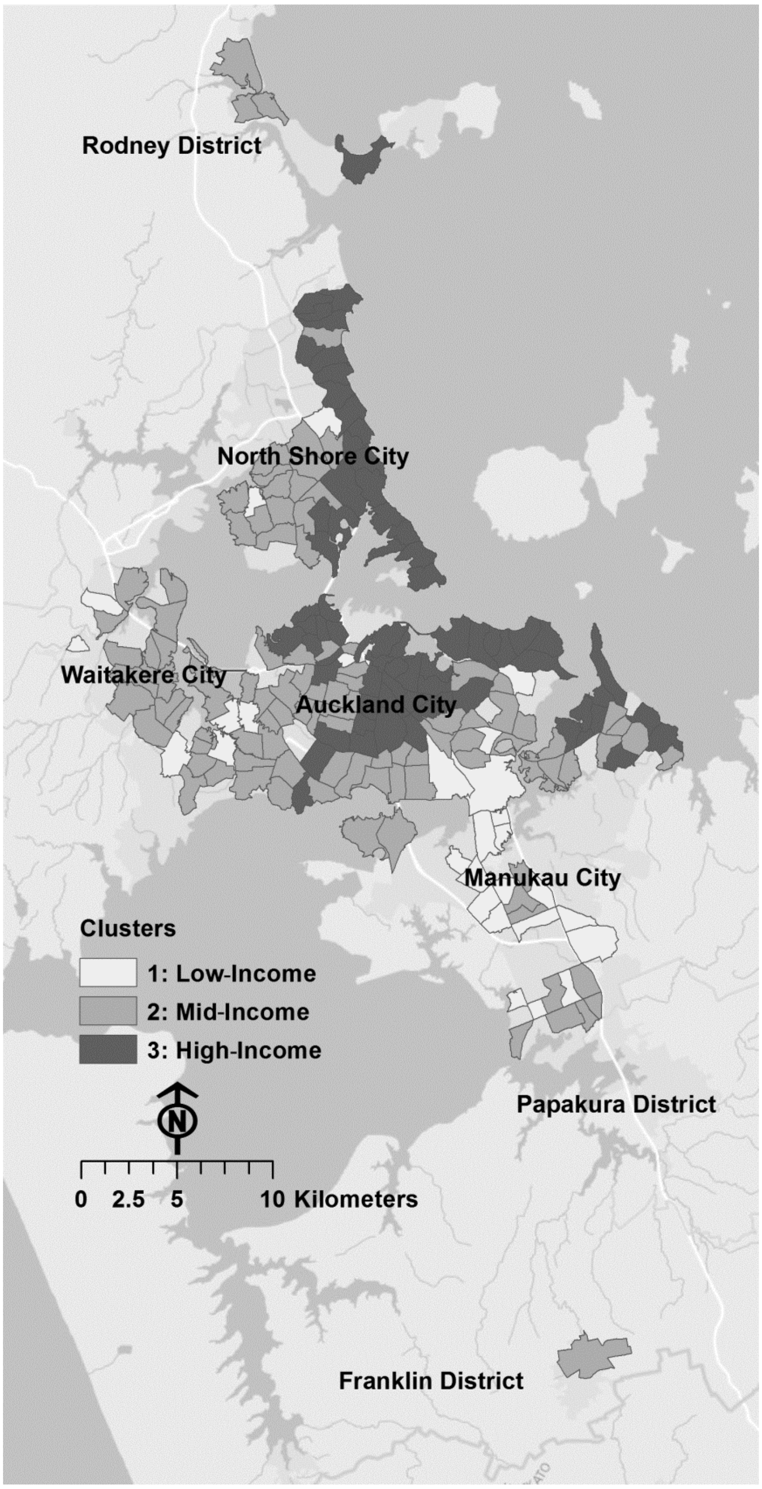

Figure 3.1. Three clusters of low-rise apartment in Auckland at the census area unit scale

Table 3.6 also compares water consumption, housing and household characteristics across three groups of census area units.

Table 3.6. Water consumption, housing and households characteristics across different groups of consumer in low-rise apartemnts

Variables	Low-Income	Mid-Income	High-Income
DWU	451	334	381
AValue	257000	328000	562000
GardSize	159	158	141
Units	5.1	4	4.7
PercPool	0.8	1.4	3.7
HhSize	2.8	2.3	2.2
Income	46300	48900	65900
BRooms	2.3	2.2	2.4
AgeUR	30	35	38
Number of area units	30	102	69
Per capita water use (litre/person/day)[a]	161	145	173

Note: Per capita water consumption was estimated through dividing the household daily water consumption by household size.

Similar to the household-scale water demand analysis, the results of census area unit scale analysis showed that the low-income and the high-income suburbs had the higher per household water use in comparison to the middle-income area units. This difference generally can be attributed into the higher outdoor water demand in the high-income suburbs (e.g. the percentage of houses with pool in the high-income areas is 3.7 in comparison to 1.4 in the middle-income areas), and higher indoor water use in the low-income area units (e.g. the household size in low-income areas is 2.8 where this number is 2.3 in the middle-income areas) in comparison to the middle-income areas.

Although the low-income suburbs had the highest per household water consumption, mainly due the larger household size, the amount of per capita water consumption in this group of consumers is lower than higher-income area units. The seasonal variation of water demand among the high-income suburbs is also higher than low and middle-income suburbs (Figure

3.2). However, in general the seasonal variation of apartment water consumption in Auckland is limited (less than 10 percent). This highlighted the fact that the indoor water use is the predominant usage at the Auckland apartments.

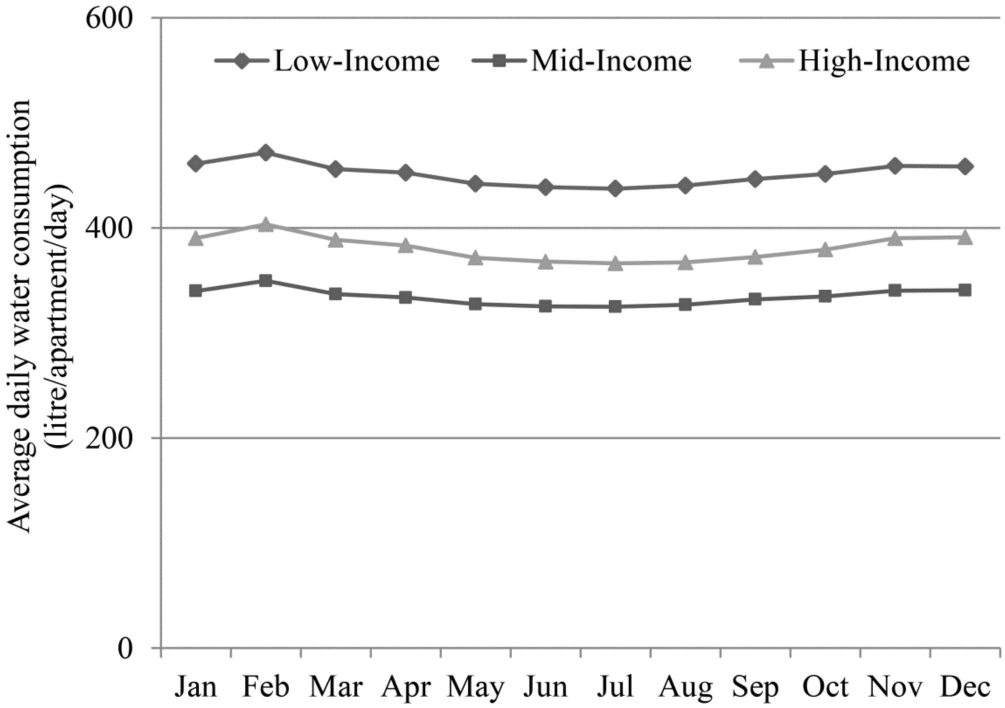

Figure 3.2. Monthly variation of low-rise apartment water consumption across three groups of consumers at the census area unit sacle

3.6. Management implications

This study thoroughly evaluated water demand in the low-rise apartments in Auckland. Since the multi-unit housings is a fast growing sector in many urban areas, a clear understanding of its water demand characteristics is pivotal in the contemporary water demand planning and management. In contrast to the single-unit housing which typically has substantial outdoor water use, in the multi-unit housing the indoor water use is a predominant usage. This means that in this sector the water is mainly used for the basic needs (i.e. drinking, cooking, and sanitary needs) thus the seasonal variation of water consumption is limited. This characteristic of apartment water consumption may limit the applicability of water pricing, as a key management instrument, in regulating water demand. This is because the water pricing is more effective where the water demand is mainly associated with the outdoor usage, rather than the basic indoor use.

This study also demonstrated how the data integration can be used to identify the pattern of water demand over different areas and groups of customers. This disaggregated water demand analysis can help water utilities to plan supply systems in a spatially oriented manner and more effectively carry out conservation planning by identifying the group of consumers with the higher water use. Through data integration and subsequent cluster analysis, this study showed that the higher income groups had a greater per capita water demand in Auckland. This group of consumer also was more sensitive to the weather condition since they generally have more outdoor water consumption. This study also showed that the apartment characteristics such as number of units in the building and presence of swimming pools and garden are not significantly correlated with the apartment water use. In contrast, the household size is the major determinant of water demand, stressing that the majority of water in the apartments is directly consumed by the residents for the basic needs. This findings imply that in cases where the water conservation would be required in this sector the conservation programs should concentrate on the methods associated to the regulating indoor use such as correcting the household water use habits, for example through running education campaigns, or by increasing the efficiency of water appliances.

3.7. Conclusions

This study proposed a new approach in multi-scale analysis of water demand through data integration (i.e. combining different data sources) in order to fully examine the determinants of low-rise apartment water demand in Auckland, New Zealand. This study utilized geographic information system to combine apartment water consumption data with the census microdata distinguishing sociodemographics characteristics of households living in the low-rise apartments, apartment physical characteristics, water pricing and weather variables. This rich dataset provided a unique opportunity to carry out a multi-scale demand analysis using both the household and census area unit scales data. The household-scale data is useful to evaluate the variation of responses to the determinants of water demand practically water pricing among different group of customers. Likewise, the aggregated data can be useful to evaluate the derivers behind the spatial variations of water demand. This knowledge can help to reliably consider the implication of fast growing apartment living on the future water and wastewater planning in Auckland.

This study applied panel data analysis in both scales, over a period of 6 years from 2008 to 2014. In the household-scale, the study showed that the price elasticity of water demand was negative and statistically significant for all groups of customers (i.e. low, middle, and high income households). However, the price elasticity was low for all groups, implying that the water pricing had a limited effect on apartment water demand in Auckland. This is mainly because, at the Auckland apartments most of the water is used for the basic needs (i.e. indoor use) and the outdoor usage, which is more sensitive to the price, generally comprises a negligible share of household water use. In addition, the water bill generally comprises a small share of total household expenditure and the current water pricing scheme with flat volumetric rates may not provide enough incentive to reduce water consumption. The analysis also showed that the household with higher income are more sensitive to the weather conditions since they are more likely to own outdoor water-using capital stock such as swimming pools.

In the census area unit scale, the study revealed that number of people in the household (i.e. household size) is the most important determinant of water demand in the Auckland apartments. Similar to household-scale models, the census area unit scale model showed that the water price had a negative but little effect on the apartment water demand. The air temperature also showed a positive impact on apartment water demand. The results also showed that other socioeconomic variables (i.e. household income, age of residents) and apartment physical characteristic (i.e. number of bedrooms, number of units in the building, garden size and swimming pools) had insignificant correlation with apartment water demand. That is because in apartments the majority of water consumption is in the form of indoor use (e.g. drinking, cooking, and sanitary needs) since the household size is the key determinants.

With advances in database technology, data accessibility, computing power, and spatial GIS tools it is becoming more plausible to integrate disaggregated water consumption, land use and demographic data to make use the full potential of them in water demand studies. This data integration through multi-scale analysis allows the visualization and evaluation of demand information that was not previously possible. It provides planners with greater insights on the manner by which water is consumed spatially and how specific land use, demographics and weather impact consumption across space and time. This information can help water utilities to plan the water supply system in an optimal manner to meet demand and also better target a specific group of consumers or urban areas (e.g. high water users) for the conservation planning and demand management.

Chapter 4

Evaluating the determinants of high-rise apartment water demand through integration of water use, land use and demographic data

Abstract

Over the past decades the rapid population growth in the urban areas has promoted the development of high-density housing such as high-rise apartments. In order to properly supply water to the high-rise apartment sector, it is essential to understand the determinants of its water use. However, this task has largely remained unexplored through the empirical study of water demand mainly due to the scarcity of data in the apartment sector. Using a rich source of GIS-based urban databases in Auckland, New Zealand, this study combined apartment water consumption, property characteristics, weather, water pricing and census microdata to overcome the issue of data scarcity for apartments. This study also compared the high-rise apartment water use and its determinants with the low-rise apartments. The present study utilized regression models specific to the panel data to analyse the high-rise apartment water demand in Auckland from 2008 to 2014. The results of this study revealed that, similar to the low-rise apartments, the household size is the most important determinant of high-rise apartment water use in Auckland. However, the other socioeconomic factors, building features, water pricing and weather variable were found to be insignificant determinants of water use. The study also showed that the per capita water consumption in the high-rise apartments in Auckland was higher than the low-rise apartments, challenging the assumption underlying much contemporary urban policy that densifying the central city areas can offer significant savings in water use. This knowledge can help water planners to more reliably plan water supply systems and manage consumption in compact urban environments.

4.1. Introduction

Compact developments as a contemporary urban growth management strategy has been used in many cities around the world in order to mitigate the social, the economical and the environmental consequences of uncontrolled low-density urban sprawl (Haarhoff et al. 2012; Randolph 2006). This strategy has promoted the use of intensive housing developments, mainly in the form of multi-unit housing (i.e. apartments), in and around existing urban centres (Haarhoff et al. 2012). In order to properly supply water and manage consumption in the multi-unit housing sector, it is vital to understand the determinants of its water use. While a vast amount of studies have investigated the factors affecting residential water use in the single-unit housing (e.g. separate houses) or as total (Chang et al. 2010; House-Peters et al. 2010; Polebitski and Palmer 2010; Rockaway et al. 2011; Schleich and Hillenbrand 2009; Wentz and Gober 2007), only few studies have evaluated the determinants of water use in the multi-unit housing developments. In the water demand studies, distinguishing multi-unit housing developments (i.e. apartment) from single-unit housing (i.e. separate houses) is necessary since the water use and its determinants may vary significantly across them (Domene and Saurí 2006; Fox et al. 2009; Russac et al. 1991). The distinction between these two housing types can be attributed to the differences in the socioeconomic characteristics of residents and the level of outdoor usage (e.g. gardens and swimming pools) on them (Fox et al. 2009; Russac et al. 1991).

The water consumption and its determinants also may vary considerably within each of these housing types based on the property characteristics. For example, the water consumption in the different types of multi-unit housing developments (i.e. high-rise and low-rise apartments) can be significantly different (Domene and Saurí 2006; Fox et al. 2009; Loh et al. 2003; Russac et al. 1991; Troy and Holloway 2004; Zhang and Brown 2005). In general, smaller multi-unit housing developments with fewer housing units are more likely to show similar water habits to single-unit housing (Wentz et al. 2014).

This chapter focuses on the understanding of water consumption and its determinants in high-rise apartments (i.e. buildings with four-storey or more) in Auckland, New Zealand. The high-rise apartment water consumption is also compared with the low-rise apartments (i.e. buildings with up to three-storey) water use in Auckland, discussed in the chapter 3. In Auckland, the majority of the high-rise apartments are concentrated in the central city, while the low-rise apartments are available across the city with a lower density. Thus, the comparison of water consumption across the high-rise and the low-rise apartments can help to reveal the effects of densifying central city areas on the urban water consumption in Auckland. In general, higher density living is seen as a credible path for improving urban sustainability through reducing the use of urban resources and the needs for more infrastructures (Boon 2010; Haarhoff et al. 2012; Randolph 2006). However, in terms of water consumption there is no clear understanding of the benefits of higher density urban development. This study, through fully examining the water consumption in the high-rise and the low-rise apartments, can help to fill the gap in knowledge regarding the effects of housing densification on water use.

In general, the empirical studies of water demand targeting multi-unit housing sector are very limited. In a study in Tucson, Arizona, Agthe and Billings (2002) developed regression models to explain the winter and summer water demand for 308 apartment complexes. They concluded that factors such as the value per bedroom, number of bedrooms, age of apartment, indoor water-saving devices, swimming pools, vacancy rates and water price were the principal determinants of apartment water use. Zhang and Brown (2005) evaluated the effects of household socioeconomics, water amenities and facilities, and attitude toward environmental concerns on apartment water use in Beijing and Tianjin, China. Using these variables they managed to explain around 10% to 55% of variation of water consumption in different types of apartment (i.e. high-rise, multi-storey, low-rise). Mayer et al. (2006) also evaluated the apartment water demand across 13 cities in US with the main purpose of understanding the benefits of separate billing systems in the multi-unit housing sector. They showed that variables such as average number of bedrooms per unit, existence of cooling tower, fixture efficiency as well as submetering may significantly influence apartment water use. In a recent study, Wentz et al. (2014) used the design features of large apartment complexes to explain the variance in apartment water use in Tempe, Arizona, USA They found that the water consumption per bedroom increased with the swimming pool area, dishwashers, and in-unit laundry facilities. However, to the present author's knowledge, none of these studies have fully evaluated the effects of all socioeconomic, property characteristics, weather and water pricing on the high-rise apartment water use and compared it with the low-rise apartments.

One of the main reasons that caused the study of apartment water demand to remain largely unexplored in comparison to the single-unit housing is the lack of readily available data in apartment sector. In order to mitigate this data shortage, the present study used geographic information system (GIS) to combine different sources of data associated with the apartments. In this way, the study firstly linked the apartment water consumption data to the property information. Then, the dataset was aggregated at the meshblock scale (i.e. the smallest geographical unit in which the census data are available for the high-rise apartments) in order to include sociodemographics characteristics of households living at the apartments from census microdata. Finally, the information of water pricing and weather for different areas were also added into the dataset in order to enable the evaluation of the effects of these variables on the apartment water demand as well.

In recent years, the data integration in water demand studies has become more plausible due to advances in database technology, data accessibility, computing power, and spatial tools (Dziedzic et al. 2015; Polebitski and Palmer 2010). In an early attempt of data integration, as a pilot study, Troy and Holloway (2004) linked water demand and property information in 6 census areas in Adelaide, Australia, in order to examines the water consumption patterns for different types of residential dwellings and areas. Shandas and Parandvash (2010) integrated water consumption, land use and demographic data in order to examine the relationship between land-use planning and water demand. Polebitski and Palmer (2010) integrated utility billing data with census demographic data and property information in order to forecast residential use in Seattle, USA. In a recent study Dziedzic et al. (2015) integrated water billing records, demographic census information, and property information in Ontario, Canada. Through this data integration and subsequent cluster analysis, they identified the pattern of water demand over different areas and groups of customers for the purpose of conservation planning. They emphasized the importance of data integration in order to use the full potential of rich data available with the organizations. However, none of these studies have applied the data integration in the multi-unit housing sector.

Through combining the different data sources, this study developed a database containing the information of 147 apartment buildings, with more than 11000 units, across 126 census meshblock units in Auckland in order to evaluated the effects of household socioeconomic (e.g. household income and household size), dwelling characteristics (e.g. number of bedrooms, lot size, swimming pool), weather (e.g. temperature), and water pricing on water demand. All of these variables have been frequently reported as the influential factors on the empirical water demand studies (House-Peters and Chang 2011).

In this study, the period of the analysis spans from July 2008 to July 2014. The study utilizes regression methods specific to panel data to evaluate the determinants of apartment water demand. A panel data set contains repeated observations over the same units (e.g. apartments or census meshblock units), collected over a number of periods (Hill et al. 2010; Verbeek 2004). The panel data models incorporate both temporal and spatial variations of water use in the modelling. Thus, they can generate better parameter estimates than traditional regression approaches (Arbués et al. 2003; Polebitski and Palmer 2010; Weber 1989). In recent years with increase in the data availability these models have been used more frequently (Arbués et al. 2004; Arbués et al. 2010; Fenrick and Getachew 2012; Kenney et al. 2008; Martinez-Espiñeira 2002; Nauges and Thomas 2000; Polebitski and Palmer 2010). However, in the present authors' knowledge, the panel models have never been used for the demand analysis in the apartment sector.

This chapter is organized in the following order. After the introduction, a review of study area is presented. Afterward, the data and the integration procedure are discussed. Then, the method of analysis is briefly discussed. Finally, the results and the conclusions are presented.

4.2. Study area

Auckland is the largest city in New Zealand with a population around 1.4 million. This city formerly was comprised from seven territorial authority areas. These areas included Rodney District, North Shore City, Waitakere City, Auckland City, Manukau City, Papakura District, and Franklin District. However, in 2010 these areas amalgamated to form a single authority known as the Auckland Council.

In Auckland the housing stock is generally dominated by the single-unit houses. At the time of the 2013 Census, single-unit housing (i.e. separate dwelling) made up about three quarters of occupied private dwellings in Auckland, while the percentage of multi-unit housing (i.e. joined dwelling) was around 25 percent (Goodyear and Fabian 2014; Statistics-NZ 2015).

High-rise apartments (i.e. apartment with four or more storey) comprise around 14 percent of the multi-unit housing stock in Auckland. Most of the high-rise apartments in Auckland (around 61 percent) are located within the Central Business District (CBD). Auckland CBD is the economic heart of the Auckland metropolitan area, where more than 75 percent of residential dwellings are high-rise apartments.

High-rise apartment living is a relatively new lifestyle choice for New Zealanders. By the 1970s a lack of people living in the Auckland CBD was seen as a problem (Boon 2010). However, since the early 1990's the interest towards apartment living has been gradually increased. Between 2006 and 2013, the number of people living in the high-rise apartments in Auckland almost has doubled, reaching around 30000 people in 2013 (Statistics-NZ 2015). The tendency toward apartment living in Auckland is also boosted by the Auckland Council policy in compact city development. Based on the Auckland Unitary Plan the central areas with good access to high-frequency public transport and other facilities are targeted for higher density living (Goodyear and Fabian 2014). Although extensive construction of apartments has promoted central city living, the quality of these developments has been under question. For example, the new developments in Auckland CBD generally were criticized for being too small and having insufficient outdoor space (Boon 2010; Carroll et al. 2011).

Inner city (CBD) apartments in Auckland are mainly occupied by younger people and students (Statistics-NZ 2010). There are several tertiary educational institutions within Auckland CBD. According to 2013 Census, around 30 percent of Auckland CBD residents are students. The median age of population in Auckland CBD is around 28 years. This number is substantially different for the out of CBD apartments, where the median age of usual residents is around 42 years. The average household size is about 2 people per household for both within and out of CBD apartments. In Auckland CBD around 80 percent of apartments are rental, where this number is around 50 percent for the out of CBD apartments (Statistics-NZ 2015).

Auckland has a subtropical climate with a year-round precipitation. The average annual precipitation is around 1240 mm. The annual average daily maximum air temperature is around 19 ºC. The coldest month is usually July and the warmest month is usually January or February (NIWA 2015).

4.3. Data integration

This study combines the data of water consumption, property, weather, water pricing, and census microdata to evaluate the determinants of high-rise apartment water use in Auckland.

In this study, the monthly water consumption data was provided by Watercare Services Limited, an Auckland Council Organization, for the period of 2008-2014. This data does not include Papakura District meters since the provision of retail water services in that district is franchised to a separate company. Thus, the Papakura district was excluded from this analysis. Up until July 2012, each former district of Auckland had different water recording span, varying from six months to bimonthly periods. From July 2012, the domestic accounts are read every two months by Watercare. To standardize the data across Auckland, Watercare converted this data to the monthly period. In order to estimate the monthly water use for each individual meter, Watercare first estimates the average daily use during the reading period. Then, this average use is allocated to each month according to the number of days corresponding to that month in that particular reading period. For each individual meter, the water consumption database also includes the address of property and its geographical location, type of meter (i.e. domestic, commercial, etc.) and its installation date. In contrast to single-unit housing, Watercare only measures the total water use in apartment buildings using master meters and does not meter apartments individually (although the units may be sub-metered individually by the building managers).

The property information was obtained from the publicly available databases at Auckland council (Auckland-Council 2015) and Land Information New Zealand (LINZ 2015). The developed property dataset contains the information of housing type, assessed value of property, structure size of building (i.e. building footprint), impervious area, the issue dates of section (as a proxy of age of property), and the address of property.

The weather data, included air temperature and rainfall, was obtained from the New Zealand's National Climate Database (CliFlo 2015) for the periods of 2008 to 2014. This data came from 15 weather stations across Auckland and was interpolated in GIS to estimate average air temperature and rainfall over different areas.

The water and wastewater charges for six districts of Auckland, from 2008 to 2014, were also provided by Watercare. The water tariff in Auckland consists of an annual fixed charge and the volumetric charges for water and wastewater. Watercare calculate the volume of wastewater based on the water volume measured by the water meter. The water, wastewater and fixed charges have undergone substantial changes over the last few years in Auckland. Before 2010, the water and wastewater charges were determined by the local councils thus every district had its own tariff. However, after amalgamation of the Auckland councils in 2010, Watercare took over water sector in Auckland and gradually changed the water and wastewater tariffs all over the local councils to finally bring a unified tariff for all Auckland after July 2012. Watercare usually adjusts water and wastewater charges annually in July each year.

The socioeconomic information of households was obtained from Statistics New Zealand Data Lab (Statistics-NZ 2015) for census 2006 and 2013. The Data Lab provided access to the microdata (i.e. data about specific people, households, or businesses). From the census microdata, it is possible to estimate household and housing information (e.g. household income, household size, education level, number of bedrooms, etc.) for different types of housing. For this study, the census information for households living in the high-rise apartments was collected at the meshblock level. Meshblock is the smallest geographical unit in which the census information for high-rise apartments is available.

In this study, the information of water consumption, land use, weather, water price and demographic microdata was combined using geographic information system (GIS). In this way, the water consumption and property data firstly were arranged in GIS and linked together using the addresses and geographical coordinates. By this data integration the information of water consumption and property for around 350000 housing including single-unit and multi-unit (i.e. low-rise and high-rise apartments) became available for the demand analysis.

This chapter focuses on the evaluation of water demand in the high-rise apartments (i.e. buildings with flour-storey or more) in Auckland. High-rise apartments made up around 4 percent of housing stock in Auckland (Statistics-NZ 2015). Thus, after filtering the database based on the property type around 15000 apartments from 190 high-rise residential apartment buildings remained for the rest of analysis. From this filtered dataset, the apartment buildings with missing water use records or shared meters with the commercial sector (i.e. non-residential customers such as restaurants and café) were excluded from the database, leavening 147 high-rise apartment buildings with 11832 units for the final demand analysis. Figure 4.1 shows the location of the studied apartments across Auckland.

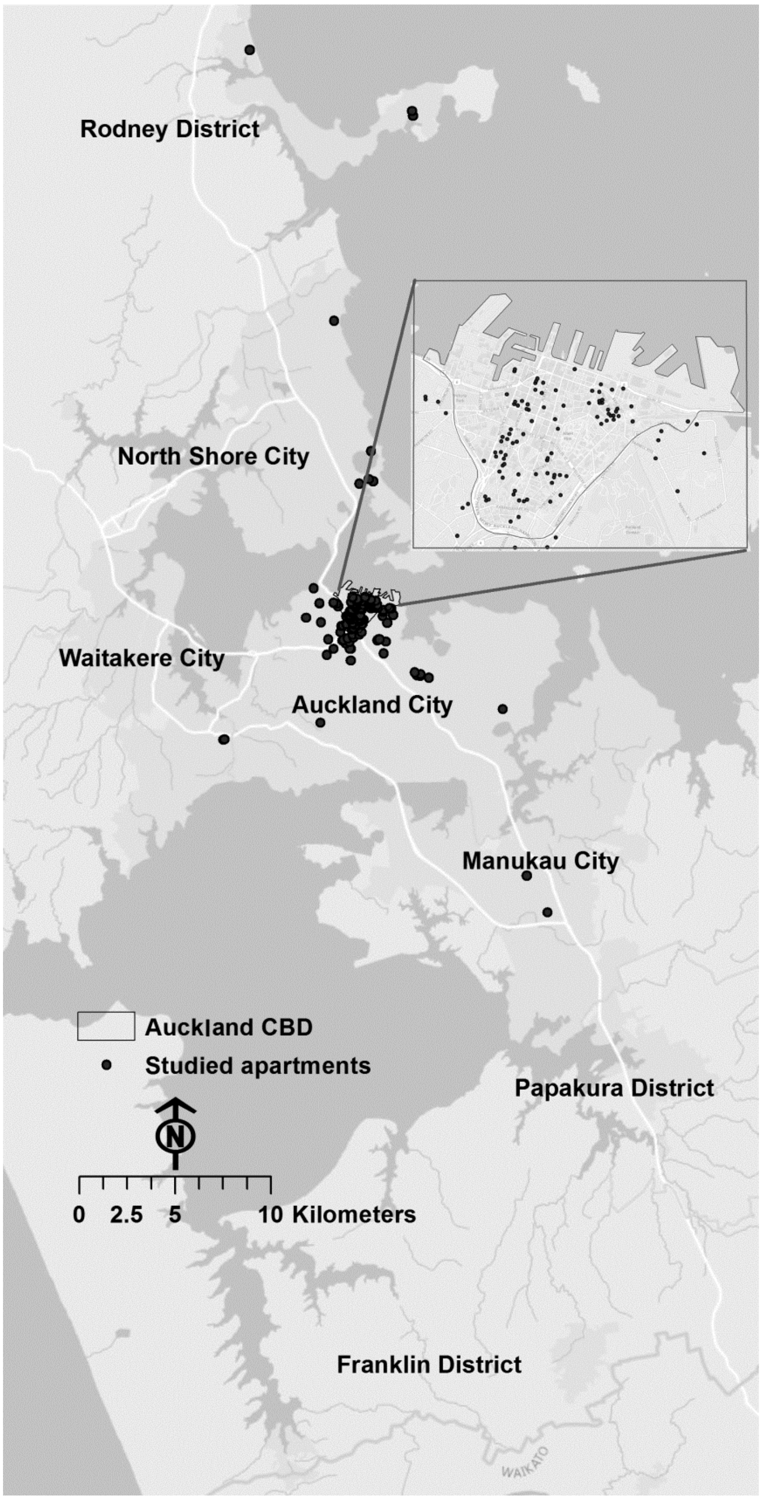

Figure 4.1. Studied high-rise apartments in Auckland

Through the first step of data integration the information such as average water consumption per apartments, number of units in each apartment building, age of buildings, lot size of buildings and presence of swimming pools and gardens in the buildings became available for the analysis. To estimate the average water use per apartment, the total water consumption of each apartment building was divided by the total number of apartment units in the building. The presence of garden and swimming pool in each apartment building also was also investigated using high-resolution aerial images through visual inspection. In the second step of data integration, the water consumption and property information was aggregated at the meshblock scale in order to add the socioeconomic characteristics of household living at the apartments into the dataset. By this data combination, information such as household size, household income, age of residents, and property ownership also became available for the water demand analysis. Finally, the water pricing and weather information was also assigned to each meshblock based on its geographical location in order to enable the understanding the effects of these variables on apartment water demand as well.

4.4. Water demand models

This study applies regression methods specific to panel data to understand the determinants of apartment water demand. A panel data set consists of a number of individual customers or customer groups where their characteristics (e.g. water use, income, household size) are measured over time (e.g. months, or years) (Verbeek 2004). In this study, the panel data included the repeated observations of water consumption, housing and household characteristics, water price, and weather variables for the high-rise apartments, collected over the period of 2008 to 2014. This study examined three common panel data methods models including pooled model, fixed effects model, and random effects model for the water demand analysis. In the pooled model, the regression has a single intercept (Hill et al. 2010). However, in the fixed effects and the random effects models the intercept is allowed to vary between individual customers or customer groups (Hill et al. 2010). Therefore, fixed effects and random effects models are typically an improvement over pooled models since they can capture the variability across consumers using varying intercepts (Arbués et al. 2003; House-Peters et al. 2010; Kenney et al. 2008). In the panel data models, a pooling test (partial F-test) (Hill et al. 2010) is used to examine this improvement. The null hypothesis of this test is that all the intercepts between the individual customers or customer groups are equal. If the p-value associated with the test statists is below the range of accepting the null hypothesis (i.e. 0.05), it can be concluded that the panel estimators (i.e. fixed effects and random effects) are preferred to the pooled model. In order to choose an appropriate method between the fixed effects and the random affects models a Hausman test is used (Hill et al. 2010; Wooldridge 2012). The null hypothesis of this test is that, if there are no omitted variables, the random effects model is more efficient (Polebitski and Palmer 2010). This means that if the null hypothesis of test does not reject the random effects model is preferred. The random effects model has a useful feature over the fixed effects, when it can recover parameter estimates for time invariant variables as well (Fenrick and Getachew 2012).

In this study, the dependent variable is the annual average daily water consumption per apartment at the meshblock level. In order to calculate this, the average annual apartment water use in each meshblock (calculated by adding average monthly consumption) was divided by the number of days in each year. The developed dataset of study included apartment average water consumption across 126 meshblock units over the 6 years (i.e. August 2008 to July 2014). The water consumption data was estimated on the annual basis because the water price in Auckland changed annually (i.e. in July each year). Thus, it can better reflect the overall effects of changing in price across the years.

This study examines the effect of a wide range of variables including household and housing characteristics, water price and weather variables on the apartment water use. Table 4.1 provides a list of variables used in this study. All of these variables have been frequently reported as the influential factors on water consumption in the literature of water demand

(Arbués et al. 2003; Chang et al. 2010; Fox et al. 2009; House-Peters et al. 2010; House-Peters and Chang 2011; Mieno and Braden 2011; Ouyang et al. 2014; Schleich and Hillenbrand 2009). In this study, the socioeconomic variables were estimated from censuses 2006 and 2013 microdata. A yearly estimate of census variables is used for the panel data analysis. The housing characteristics includes average number of units in apartment building, average number of bedrooms in apartments, age of building, lot size of building (i.e. section size of building excludes structure size) and two dummy variables representing the presence of outdoor swimming pool and garden in the buildings. In order to investigate the effects of water pricing both volumetric and fixed charges of water and wastewater were included in the model. Since the wastewater price in Auckland is calculated based on the metered water use, this study summed up the charges of water and wastewater. This would help to evaluate the overall effect of volumetric and fixed charges. A dummy variable distinguishing the within and out of CBD apartments also is included in the model in order to examine if the water consumption among these two groups of apartments is different.

In this study the prices and income were deflated into real 2013 terms using the customer price index (CPI) (Statistics-NZ 2015).

Table 4.1. Description, mean and standard deviation (SD) of the variables used in the high-rise water demand analysis

Variables	Definition	Mean	SD	Variable unit
DWU	Average daily water use	379	96	Litre/apartment/day
HhSize	Average household size	1.9	0.3	People
Income	Household median income	70600	33500	NZ dollars/year
AgeUR	Median age of usual residents	33.4	11.0	Year
Owner	Percentage of households owned the dwelling	33.3	18.9	%
BRooms	Average number of bedrooms	1.8	0.5	Bedrooms
Units	Average number of units in the apartment building	84	70	Apartments
AgeBld	Average age of apartment building in 2014	16	8	Year
LotSize	Average lot size of apartment building	855	1093	m^2
DumPool	Dummy variables representing the apartment building with pool	0.17	0.37	N/A
DumGarden	Dummy variables representing the apartment building with garden	0.16	0.36	N/A
Temp	Mean daily maximum air temperature	19.3	0.4	°C
VPrice	Average volumetric price of water and wastewater	4.1	0.8	NZ dollars/m3 water
FPrice	Average fixed price of water and wastewater	126	88	NZ dollars/year
DumCBD	Dummy variables representing houses within CBD	0.59	0.49	N/A

4.5. Results and discussion

This study examined pooled, fixed effects and random effects models to select the most appropriate panel data model for the water demand analysis. The result of partial F-test (pooling test) (Hill et al. 2010; Polebitski and Palmer 2010), shown in table 4.2, revealed that the panel models (i.e. fixed effects and random effects models) are an improvement over the pooled model (i.e. the null hypothesis of single intercept was rejected in the models). The result of Hausman test (Hill et al. 2010; Wooldridge 2012) in table 4.2 also showed that the random effects model is more efficient than the fixed effects model and can better produce consistent parameter estimates. The results of random effects model are shown in table 4.2. The time trend was included in the model in order to accommodate the nonlinearities in the underlying data. All the variables (except FPrice which contains zero values) were transferred by natural logarithm thus the coefficients can be interpreted as the elasticity.

Table 4.2. Random effects water demand model for the high-rise apartments

Variables	Estimate
Const	6.14***
HhSize	0.49***
Income	-0.03
AgeUR	-0.13
Owner	0.03
BRooms	0.12*
Units	-0.01
AgeBld	0.07
LotSize	-0.02
DumPool	0.02
DumGarden	0.07
Temp	-0.03
VPrice	0.02
FPrice	-0.00003
DumCBD	0.06
time	0.04***
$time^2$	-0.005***
Partial F-test	35.76***
Hausman test	15.36
Number of meshblock units	126
Overall adjusted-r^2	0.5

Note: ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

The random effects model provided satisfactory results as the estimated variables had the expected signs and significance. Moreover, the adjusted r^2-value of 0.50 is on the high end of the range presented in the past studies of apartment water demand (Agthe and Billings 2002; Mayer et al. 2006; Wentz et al. 2014; Zhang and Brown 2005).

The estimated coefficient for variable HhSize showed that household size is the most influential factor on the apartment water use. The estimated coefficient for the household size in the random effect model is around 0.5, implying that a 10% increase in the household size would result in a 5% increase in the apartment water consumption. This result is in agreement with many other water demand studies, where it was argued that due to economies of scale in the use of water, the increase in water consumption is less than proportional to the increase in household size (Arbués et al. 2004; Arbués et al. 2003; Hoffmann et al. 2006; Schleich and Hillenbrand 2009).

The estimated coefficient of variable Income, in table 4.2 also showed that the household income was not significantly correlated with the apartment water consumption. This result was expected in the case of Auckland high-rise apartments, where the majority of water consumption is in the form of indoor usage (i.e. water is used for the basic needs). In general, the income variable mainly influences the household outdoor water consumption in the single-unit housing. That is because, the higher income households are more likely to own water-using capital stock such as larger lawns and gardens, and swimming pools (Hoffmann et al. 2006; Mieno and Braden 2011; Schleich and Hillenbrand 2009).

Figure 4.2 shows the monthly variations of average apartment water use and the air temperature in Auckland. In general, in the residential sector the difference between summer and winter water consumption can be attributed to the outdoor use (Billings and Jones 2008). In the case of Auckland apartments, the variation of water use between summer (i.e. February) and winter (i.e. July) is very limited, implying that indoor water use is predominant at the apartments.

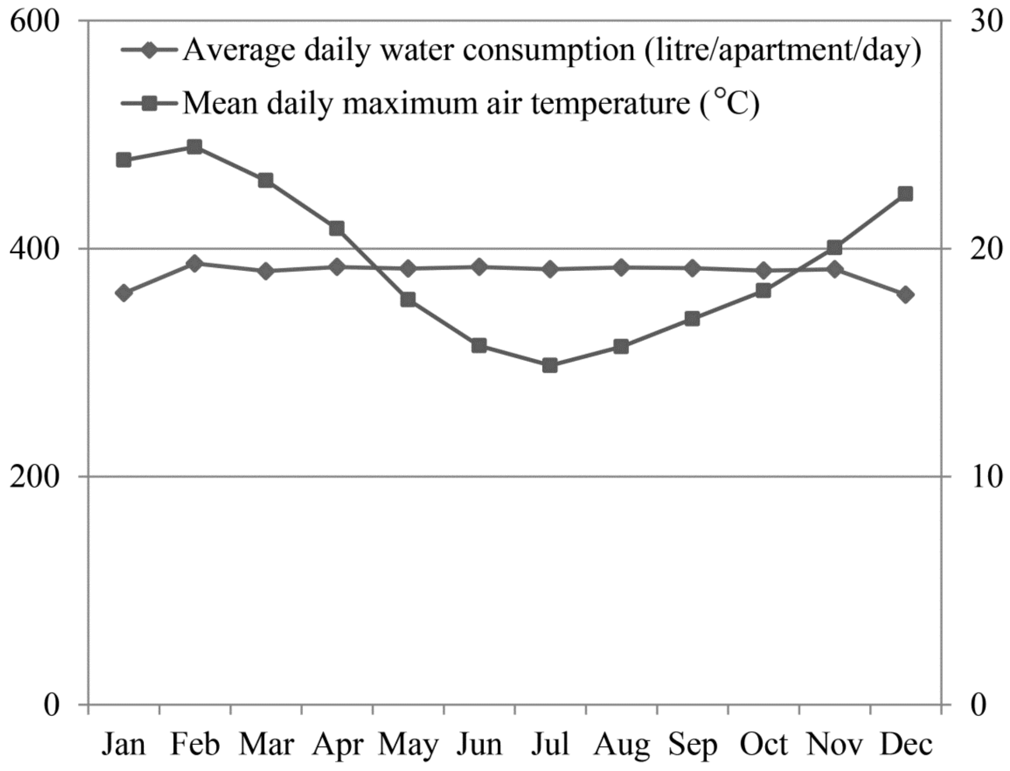

Figure 4.2. Monthly variations of high-rise apartment water consumption (left axis) and air temperature (right axis) in Auckland

Figure 4.2 also showed that in the summer the average apartment water consumption is relatively lower than the winter. This is in contrast to the common pattern of single-unit housing water use, where the consumption is typically higher in summers rather than winters (Billings and Jones 2008; Polebitski and Palmer 2010). In general, the higher summer water demand in the single-unit housings can be attributed to the higher water use arising from outdoor activities such as lawn watering, gardening and filling swimming pools (Billings and Jones 2008). Conversely, in the multi-unit housings, where the indoor usage is predominant, water use is likely to remain relatively stable across the different seasons (Domene and Saurí 2006). However, in the case of Auckland apartments the water consumption increases each year around end of February, stays relatively constant until November, and then declines (figure 4.2). This pattern closely follows the tertiary academic calendar in New Zealand rather than the usual summer and winter seasons. In a time-series study of apartment water demand, Ghavidelfar et al. (2016) showed that during the months of academic year the average water use of apartments in CBD increases around 10 percent. They attributed this increase to the more number of occupants in the apartments during the academic months.

As shown in table 4.2, the age of residents (AgeUR) and property ownership (Owner) were found to be insignificantly related to the apartment water use. This result was expected since these two variables had direct relationship with the household income (i.e. older residents, had higher income and subsequently higher chance of owning the property). Thus, similar to the income variable which did not significantly influence indoor water consumption, the effects of these two variables were also limited on the apartment water consumption.

The result from table 4.2 also showed that the lot size of apartment buildings (LotSize) and the presence of outdoor swimming pool (DumPool) and garden (DumGarden) did not significantly affect the average water consumption in the Auckland apartments (the estimated coefficient for these variables were not significant). This is because in general the outdoor space of apartment buildings in Auckland is limited and mainly used as the car parks. The size of gardens is also smalls and the vegetated landscaping is limited to the planting of shrubs and trees which basically do not require much water. Moreover, the year-around precipitations in Auckland reduce the needs of irrigation for this type of landscaping.

The estimated coefficient of variable BRooms, in table 4.2, also revealed that the number of bedrooms in aprments had a positive corelation with apartment water use. However, this variable was not statistically significant at the 0.05 level. In general, number of bedrooms is a proxy for the number of residents in aparments, having positive corelation with the water use (Agthe and Billings 2002; Mayer et al. 2006).

As shown in table 4.2, the number of units in the buildings (Units) was found to be insignificantly correlated with the apartment water consumption. This finding implies that the economies of scale for the shared water use (i.e. water is used for the building maintenance, cleaning, etc.) does not play a significant role in the average apartment water use.

The estimated coefficient for the variable AgeBld (age building) also showed that there was no statistically significant difference between the older and the newer apartment buildings in terms of water use. This finding was expected since the majority of apartment buildings in Auckland have been constructed in the last decade. In addition, the old buildings are likely to be renovated. This result is in contrast to the finding of Agthe and Billings (2002), who indicated that older apartments used more water than newer apartments, but is in agreement with the finding of Wentz et al. (2014).

The estimated coefficient for variable VPrice, shown in table 4.2, also revealed that the volumetric price of water had insignificant correlation with the apartment water consumption. This result is not surprising since the water generally is used for basic needs at the apartments. In general, the indoor water use is unlikely to exhibit a high price sensitivity (Arbués et al. 2003; Mieno and Braden 2011). The fixed price of water (FPrice) was also insignificantly related to the water consumption. In general, the only effect of the fixed charge on water consumption would be through its effect on reducing disposable income. Since the water costs usually comprises a small share of household expenditures it is expected that the effect of fixed price becomes insignificant (Mieno and Braden 2011).

The air temperature variable (Temp) was found to be insignificantly related to the apartment water use. This result was expected since the weather variables typically affect outdoor water demand rather than indoor (Arbués et al. 2003).

Finally, as shown in table 4.2 the estimated coefficient for variable DumCBD was statistically insignificant, implying that there is no difference between the within and out of CBD apartments in terms of water consumption, when controlling for all other variables.

4.6. Management implications

This study showed that the household size is the most influential determinant of high-rise apartment water consumption in Auckland, while the other socioeconomic factors, property characteristics, water pricing and weather variable were not significant determinants. This result is closely comparable with the findings of low-rise apartment water use, discussed in the chapter 3, with just few small differences. In the low-rise apartments the air temperature had a positive correlation with water consumption and the effect of water pricing, although very small, was statistically significant. These subtle differences can be attributed to this fact that in the low-rise apartments there is more opportunity for the outdoor water use (e.g. gardening and swimming pools) in comparison with the high-rise apartments. Therefore, the low-rise apartment sector showed more sensitivity to the weather variable and water pricing. In general, in the apartments the seasonal variation of water use is very limited (less than 10 percent), stressing that the indoor water use is the predominant usage in this sector. This result suggests that in cases where the water conservation would be required in this sector, the conservation programs should concentrate on the methods associated to the regulating indoor use such as correcting the household water use habits, for example through running education campaigns or by increasing the efficiency of water appliances, rather than more conventional methods such as water pricing.

From the perspective of urban planning and water management the findings of this study also can be important. Through comparison of water use in the low-rise and high-rise apartments, the study revealed that the densifying central city areas, through developing higher density housing, may not necessarily lead to the reduction of water use. The results of study showed that the average daily water use in the high-rise apartments is around 3 percent higher than the low-rise apartment (the average daily water consumptions in the high-rise and low-rise apartments were 379 and 367 litre per day, respectively). More interestingly, considering the average household size of 1.9 and 2.3 persons in the high-rise and the low-rise apartments respectively, on the per capita basis the water consumption in the high-rise apartments was around 24 percent higher than the low-rise apartments (i.e. per capita water consumptions in the high-rise and low-rise apartments were 199 and 160 litre per person per day, respectively). The higher per capita water consumption in the high-rise apartments can be mainly attributed to the smaller household size in this sector. In general, household size can exert an important effect on the per capita domestic water consumption (Domene and Saurí 2006). By decreasing the household size the per capita water consumption typically increases since the economies of scale cannot be accomplished in the smaller households (for instance, full loads in washing machines, dishwashers, etc.) (Arbués et al. 2003; Domene and Saurí 2006; Hummel and Lux 2007). These results imply that although housing intensification may have some social, financial and environmental benefits (Haarhoff et al. 2012; Randolph 2006), however in the respect of water consumption it may not substantially help to reduce water demand since the higher density housings may lead to the smaller household size where it can make more difficult the efficient use of water.

4.7. Conclusions

Over the past decade intensive housing development, in the form of multi-unit housing, has been extensively promoted in Auckland in order to mitigate the social, economic and environmental concerns arising from low density residential development, while addressing the increasing need of dwellings for the growing population.

In order to take into account the implication of increasing high-rise apartment living on the future water and wastewater planning in Auckland, this study thoroughly investigated water demand and its determinants in this sector. To accomplish this, the study utilized geographic information system to combine apartment water consumption data with the census microdata distinguishing sociodemographics characteristics of households living in the high-rise apartments, apartment physical characteristics, water pricing and weather variables. This rich dataset provided a unique opportunity to fully evaluate the effects of a wide range of variables on the apartment water use.

This study applied regression models specific to panel data to evaluate water demand in a sample of 11000 apartments, within 126 census meshblock units, over a period of 6 years. Through examining three common panel data methods (i.e. pooled, fixed effects and random effects), the study found that the random effects is the most appropriate model for the developed dataset. The random effects model was capable of evaluating the impacts of both time-varying (e.g. household sociodemographics, weather and water pricing) and time invariant (e.g. housing characteristics) variables on apartment water demand, while controlling for the heterogeneity among different apartments.

The study revealed that number of people in the household (i.e. household size) is the most important determinant of water demand in the Auckland apartments. The results showed that other socioeconomic variables such as household income, age of residents and property ownership did not have significant correlation with the apartment water use. This is because, at the Auckland apartments most of the water is used for the basic needs (i.e. indoor use) and the outdoor usage, which is more sensitive to the income related variables, generally comprises a negligible share of household water use. This characteristic of apartment water demand in Auckland also can explain the insignificant impact of property outdoor characteristics (i.e. lot size, garden and swimming pools), water pricing and weather condition on the water consumption. In general, all of these variables typically affect outdoor water use not indoor. The study also showed that the age of dwelling and numbers of apartment in the building did not have significant correlation with the apartment water consumption.

This study also compared the high-rise apartment water use and its determinants with the low-rise apartments. This enabled the study to examine the effects of housing densification in the central city areas on the water use where the higher density housings is considered as a sustainable urban form in the contemporary urban planning. The results of study showed that regarding the determinants of water use there is no considerable difference between the high-rise and low-rise apartments. In both sectors the household size was the major driver of water use and the effects of other socioeconomic variables, housing characteristics, weather and water pricing were marginal. The seasonal variation of water use was also limited in both sectors, implying that the majority of water is used for the basic needs (i.e. indoor use) in the apartments. The comparison also revealed that creating higher density housing in the central city areas may not lead to the reduction of water consumption. This is because in the higher density housings the size of household can be smaller. This may result in the less efficient use of water and subsequently the increase of per capita water consumption.

This study demonstrated how the data integration can help to fully evaluate water consumption in the apartments. This detailed knowledge of apartment water consumption and its determinants can help water planners to more reliably plan water supply and treatment systems in compact cities in order to help to create more sustainable urban environments.

Chapter 5

Evaluating spatial and seasonal determinants of residential water demand across different housing types through data integration

Abstract

Understanding the determinants of residential water consumption is pivotal in water demand planning and management. However, in complex urban environments this task can be challenging since the heterogeneity in characteristics of household and dwelling may lead to considerable variations in water consumption and its determinants across different housing types, urban areas and seasons. Many empirical studies have tried to thoroughly evaluate these variations but rarely achieved since they generally relied on the small samples mainly due to the scarcity of disaggregated data. This study utilized a rich source of urban databases in Auckland, New Zealand, in order to develop a large sample of 60000 dwellings through integration of water consumption, land use and census microdata using geographic information system. This enabled the study to fully evaluate the variation of responses to the determinants of water demand including housing and household characteristics, water price and weather variables across different groups of consumers. This study utilized regression models specific to panel data to analysis water demand in Auckland from 2008 to 2014. The result of study showed that the seasonal and spatial variations of water consumption were more remarkable in the single houses, in comparison to the low-rise and the high-rise apartments, due to the more outdoor water uses in this sector. The household size was the major determinant of water demand across all housing sectors, areas and seasons. However, the weather variables were more influential in the single houses and low-rise apartments. The effect of water pricing was also limited for all groups. This detailed information can help to plan water supply systems and conservation programs in an optimal manner.

5.1. Introduction

Understanding the determinants of residential water consumption is an integral component in water demand planning and management. However, in the complex urban environments this task can be challenging since the heterogeneity in characteristics of household and housing may lead to considerable variations in water consumption and its determinants across different housing types, urban areas and seasons (Abrams et al. 2012; Domene and Saurí 2006; House-Peters and Chang 2011; Mieno and Braden 2011).

In general, water consumption may vary significantly across different housing types due to the differences in sociodemographics characteristics of residents and the level of outdoor usage (e.g. gardens and swimming pools) (Domene and Saurí 2006; Fox et al. 2009; Loh et al. 2003; Rathnayaka et al. 2014; Russac et al. 1991; Troy and Holloway 2004; Zhang and Brown 2005). Even within each housing types, the water consumption may vary substantially across different urban areas (e.g. low and high income areas) and seasons (Balling Jr. et al. 2008; Chang et al. 2010; House-Peters and Chang 2011; Polebitski and Palmer 2010). The variation of water consumption across different groups of consumers may cause them to respond differently to the changes of determinants of residential water consumption such as water prices, weather conditions and household and housing characteristics (Abrams et al. 2012; Breyer and Chang 2014; Breyer et al. 2012; Domene and Saurí 2006; Mieno and Braden 2011; Renwick and Archibald 1998; Renwick and Green 2000). Many empirical studies have tried to understand the dynamic of residential water use (Arbués et al. 2003; Worthington and Hoffman 2008). However, the majority of these studies did not manage to fully consider the variations of water consumption across different housing types, urban areas (i.e. income groups) and seasons in the water demand analysis. This was mainly because most of the water demand studies were limited to rely on the small samples due to the scarcity of disaggregated data and its high cost of data collection.

In general, the empirical studies of water demand evaluated the variation of water consumption across different housing types remained very limited since the disaggregated data for different housing types is not usually readily available. In an early study in UK, Russac et al. (1991) investigated water demand in housings with different architectural types and concluded that water consumption of single houses is higher than intensified dwellings such as semi-detached and flats. Troy and Holloway (2004) also examined residential water consumption in different types of dwellings in Adelaide, Australia. They showed that water consumption varied between different types of residential dwellings and areas. Thus, the use of metropolitan area averages for water consumption of different types of dwelling can be misleading. In a study of determinants of water demand in Barcelona, Spain, Domene and Saurí (2006) investigated the effects of housing types, household characteristics and water price on seasonal water demand using a sample of 532 households. They showed that water consumption in low-density housings is higher than high-density housings, specifically in summers, mainly due to the outdoor uses. Fox et al. (2009) also classified properties in terms of their physical characteristics for the purpose of forecasting water demand. They concluded that water demand in the detached houses is higher than semi-detached and flats. However, none of these studies fully examined the spatial and temporal variations of water consumption and its determinants across different housing types.

In order to overcome the issue of scarcity of disaggregated data, the present study proposed a new approach in data integration (i.e. combining data) using geographic information systems (GIS). Utilizing a rich source of urban databases in Auckland, this study developed a large sample of 60000 dwellings, with different types, through combining water consumption, land use and demographic data. The land use information helped to distinguish different housing types and subsequently estimate water consumptions across them, where the census microdata provided household information (e.g. household size and household income) for different housing types (i.e. single house, low-rise and high-rise apartments). This highly disaggregated dataset enables the present study to evaluate water consumption and its determinants across different housing types (i.e. single house, low-rise and high-rise apartments), urban areas (i.e. low and high income areas) and seasons (i.e. summer and winter) in a large metropolitan area. This information can help water planners to more reliably plan for water supply and treatment systems and optimally design water pricing and conservation programs. This would be essential specifically for the fast growing cities like Auckland in which substantial changes in household and housing compositions (e.g. transition from single houses to more intensified apartments) are undergoing.

In recent years, the data integration in water demand studies has become more plausible due to advances in database technology, data accessibility, computing power, and spatial tools (Dziedzic et al. 2015; Polebitski and Palmer 2010). Troy and Holloway (2004) integrated water demand and property information for 6 census areas in Adelaide, Australia, in order to examine the water consumption patterns for different types of residential dwellings and areas. Shandas and Parandvash (2010) integrated water consumption, land use and demographic data to examine the relationship between land-use planning and water demand. Polebitski and Palmer (2010) integrated utility billing data with census demographic and property information in order to forecast single housing water use in Seattle, USA. In a recent study, Dziedzic et al. (2015) integrated water billing records, demographic census information, and property information in Ontario, Canada. Through this data integration and subsequent cluster analysis, they identified the pattern of water demand over different areas and groups of customers for the purpose of conservation planning. They emphasized the importance of data integration in order to use the full potential of rich data available with the organizations.

However, none of these studies utilized the data integration to fully evaluate seasonal and spatial water consumption across different housing types in a large metropolitan such as Auckland.

The study utilizes regression methods specific to panel data to evaluate the determinants of water demand across different housing types and income groups both in summer and winter seasons from years 2008 to 2014. A panel data set contains repeated observations over the same units (e.g. households, census areas units), collected over a number of periods (Hill et al. 2010; Verbeek 2004). The panel data models incorporate both the temporal and the spatial variations of water use in the modelling. Thus, they can generate better parameter estimates than traditional regression approaches (Arbués et al. 2003; Polebitski and Palmer 2010; Weber 1989). In recent years with increase in the data availability these models have been used more frequently (Arbués et al. 2004; Arbués et al. 2010; Fenrick and Getachew 2012; Kenney et al. 2008; Martinez-Espiñeira 2002; Nauges and Thomas 2000; Polebitski and Palmer 2010). However, to the present author's knowledge, the panel models have never been used for the demand analysis in such disaggregated datasets.

This chapter is organized in the following order. After the introduction, a review of study area is presented. Afterward, the data and the integration procedure are discussed. Then, the method of analysis is briefly discussed. Finally, the results and the conclusions are presented.

5.2. Study area

Auckland is the largest city in New Zealand. This city formerly was comprised from seven territorial authority areas. These areas were Rodney District, North Shore City, Waitakere City, Auckland City, Manukau City, Papakura District, and Franklin District. However, in 2010 these areas amalgamated to form a single authority known as the Auckland Council.

Auckland has experienced a fast growth both in population and housing stock over the last decades. The population of Auckland has increased by 22% since 2001, reaching around 1.4 million people in 2013 (Statistics-NZ 2015). This growth has led to a low-density urban expansion since the majority of dwellings in Auckland are single houses (i.e. around 75%). However, in recent years with decreasing section sizes of single houses and increasing number of multi-unit housings (i.e. low-rise and high-rise apartments) (LINZ 2015; Statistics-NZ 2015), the dwelling density in Auckland has increased, reaching from 86 to 102 dwellings per square kilometre between 2001 and 2013 (Goodyear and Fabian 2014). The trend in increasing the dwelling density is also boosted by Auckland council policy in compact city development. Based on the Proposed Auckland Unitary Plan the central areas with good access to high-frequency public transport and other facilities are targeted for higher density living (Goodyear and Fabian 2014; PAUP 2015). In general, higher density living is seen as a credible path for improving urban sustainability (Boon 2010; Haarhoff et al. 2012).

At the time of census 2013, the low-rise and high-rise apartments made up around 21% and 4% of housing stock in Auckland, respectively (Statistics-NZ 2015). The high-rise apartments are mainly within Auckland Central Business District (CBD) or at the adjacent suburbs, while the low-rise apartments have been constructed across the entire city.

In Auckland, the variations of household characteristics across different housing types and areas are remarkable. For instance, the average household size in the single houses is around 3.3. However, this number can increase to five people in some suburbs in the south of Auckland, where multifamily household (i.e. households in which two or more family nuclei reside in the same dwelling) is more common. In high-rise apartments the average household size is around 1.9, while the average number of people in low-rise apartments is about 2.3. In single houses, the median age of population is around 35 years, where in the low-rise and high-rise apartments the age of population are about 36 and 33 years, respectively (Statistics-NZ 2015).

Auckland has a subtropical climate with a year-round precipitation. The average annual precipitation is around 1240 mm. The annual average air temperature is around 15 °C. The coldest month is usually June or July and the warmest month is January or February (NIWA 2015).

5.3. Data integration

This study combines the data of water consumption, property characteristics, weather, water pricing and census microdata to evaluate water consumption and its determinants across different housing types, urban areas and seasons in Auckland.

In this study, the monthly water consumption data was provided by Watercare Services Limited, an Auckland Council Organization, for the period of 2008-2014. This data does not include Papakura District meters since the provision of retail water services in that district is franchised to a separate company. Thus, the Papakura district was excluded from this study. Up until July 2012, each former district of Auckland had different water recording span, varying from six months to bimonthly periods. From July 2012, the domestic accounts are read every two months by Watercare. To standardize the data all over Auckland, Watercare converted this data to the monthly period. In order to estimate the monthly water use for each individual meter, Watercare first estimates the average daily use during the reading period. Then, this average use is allocated to each month according to the number of days corresponding to that month in that particular reading period. For each individual meter, the water consumption database also includes the address of property and its geographical location, type of meter and its installation date. Watercare typically measures the water consumption of single houses and small multi-unit houses using individual meters. However, in the large low-rise apartment complexes and high-rise apartments Watercare only measures the total water use of buildings using master meters and does not meter apartments individually (although the units may be sub-metered individually by the building managers). In this study, where the individual meter data was not available, the housing average water consumption was estimated through dividing total metered water use by the number of units in the building.

The property information in this study was obtained from the publicly available databases at Auckland Council (Auckland-Council 2015) and Land Information New Zealand (LINZ 2015). The developed property dataset contains the information of housing type, assessed value of property, section size, structure size of building (i.e. building footprint), impervious area, the issue dates of section (as a proxy of age of property), and the address of property. The garden size of property is also calculated by subtraction the sum of building footprint and impervious area from section size.

The weather data, included monthly average air temperature and rainfall, was obtained by the New Zealand's National Climate Database (CliFlo 2015) for the periods of 2008 to 2014. This data came from 15 weather stations across Auckland and was interpolated in GIS to estimate average air temperature and rainfall over different areas.

The water and wastewater charges for six districts of Auckland, from 2008 to 2014, were also provided by Watercare. The water tariff in Auckland consists of an annual fixed charge and the volumetric charges for water and wastewater. Watercare calculates the volume of wastewater based on the water volume measured by the water meter. The water, wastewater and fixed charges have undergone substantial changes over the last few years in Auckland. Before 2010, the water and wastewater charges were determined by the local councils thus every district had its own tariff. However, after amalgamation of the Auckland councils in

2010, Watercare took over water sector in Auckland and gradually changed the water and wastewater tariffs all over the local councils to finally bring a unified tariff for all Auckland after July 2012. Watercare usually adjusts water and wastewater charges annually in July each year.

The socioeconomic information of households was obtained from Statistics New Zealand Data Lab (Statistics-NZ 2015) for census 2006 and 2013. The Data Lab provided access to the microdata (i.e. data about specific people, households, or businesses). From the census microdata, it is possible to estimate household and housing information (e.g. household income, household size, education level, number of bedrooms, etc.) for different types of housing across different areas. This study collected the census information of households living in the single house (i.e. separate house) and low-rise apartments (i.e. joined dwellings with one-, two-, or three-storey) at the census area unit level. The information of high-rise apartments (i.e. joined dwellings with four-storey or more) also was collected at the meshblock level. The meshblock and area unit are the first and second smallest geographical census units in New Zealand, respectively (Statistics-NZ 2015). For single houses and low-rise apartments the household information was collected at the area unit level because in these sectors, due to the low density of housing, many census variables were not available at the meshblock level in order to protect the confidential information of residents.

In this study, the information of water consumption, land use, weather, water price and demographic microdata was connected using geographic information system (GIS). In this way, the water consumption and property data firstly were arranged in GIS and linked together using the addresses and geographical coordinates. By this integration the information of water consumption and property for around 350000 housings including single-unit and multi-unit (i.e. low-rise and high-rise apartments) became available for the further investigation.

In order to evaluate water consumption and its determinants across three major housing types (i.e. single house, low-rise and high-rise apartments) in Auckland, the present study segregated the dataset based on the housing type. In Auckland, around 75% of houses are single-unit. Thus, through filtering the database based on the property type, around 260000 single houses were identified. From this filtered data the houses with replaced meters (i.e. houses with more than one meter records) were excluded from the analysis. This is because, in these houses the records from erroneous old meters usually overlap the new meters records for a period of time, thus they may cause error in the estimation of historical water consumption. After this data filtering, around 130000 single-unit houses remained available for the demand study. From this dataset, a random sample of 31000 single houses was selected in order to easier check the data for completeness and quality. Using high-resolution aerial images, this study visually inspected all the housings in the sample to make sure they are single houses and there is no missing data among them. This random sample is large enough to reliably represent the total population of single-unit dwellings (i.e. there was no statistically significant difference between average water consumption estimated from the random sample and entire single houses in Auckland) as well as fully cover all suburbs of Auckland to help to show the spatial variation of water use.

The same data filtering procedure was carried out to develop samples of low-rise and high-rise apartments. Low-rise apartments made up around 21% of housing stock in Auckland. Thus, through the filtering of dataset based on the property type, around 70000 low-rise apartments were identified. From this filtered data, the apartments with replaced meters were excluded from the analysis. After this data filtering, the information of 40000 low-rise apartments remained available for the rest of analysis. In this dataset, the multi-unit houses either may have joined structure or separate structure (e.g. two or more dwellings on a single block of land (section), but are not joined). Taking into account that the census information distinguished apartment as a dwelling with the joined structure, the dataset was filtered by this criterion leaving around 18000 low-rise apartments with the joined structures for the final water demand study in this sector.

The high-rise apartments also comprised around 4% of housing stock in Auckland. Thus, through the filtering of database based on the property type, around 15000 apartments from 190 residential apartment buildings were identified in Auckland. From this dataset, the high-rise apartment buildings with missing water use records, replaced meters or shared meters with the commercial sector (i.e. non-residential customers such as restaurants and café) were excluded from the database, leavening 147 apartment buildings with around 11000 units for the final water demand analysis. Similar to single houses data, both samples of low-rise and high-rise apartments were visually inspected using high-resolution aerial images, in order to make sure all the selected dwellings are within the correct category.

Using the proposed approach of data combination, this study managed to develop a large sample of 60000 dwelling to carry out a disaggregated analysis of water demand. In order to include census socioeconomic information to the housing data, the developed dataset was subsequently aggregated at the census area unit scale for single houses and low-rise apartments and meshblock scale for the high-rise apartments. Census area unit is the smallest geographic area for which the New Zealand census microdata is fully available for the single houses and the low-rise apartments. However, for the high-rise apartments, the meshblock is the smallest geographic area for which the census microdata is fully available.

5.4. Water demand models

This study applies regression methods specific to panel data to understand the determinants of water demand. A panel data set consists of a number of individual customers or customer groups where their characteristics (e.g. water use, income, household size) are measured over time (e.g. months, or years) (Verbeek 2004). In this study, the panel data included the repeated observations of water consumption, housing and household characteristics, water price, and weather variables for the single houses, the low-rise and the high-rise apartments in Auckland, collected over the period of 2008 to 2014. This study examined three common panel data models including pooled model, fixed effects model, and random effects model. In the pooled model, the regression has a single intercept (Hill et al. 2010). However, in the fixed effects and the random effects models the intercept is allowed to vary between individual customers or customer groups (House-Peters et al. 2010; Kenney et al. 2008). Therefore, fixed effects and random effects models are typically an improvement over pooled models since they can capture the variability across consumers using varying intercepts (Arbués et al. 2003; House-Peters et al. 2010; Kenney et al. 2008). In the panel data models, a pooling test (partial F-test) (Hill et al. 2010) is used to examine this improvement. The null hypothesis of this test is that all the intercepts between the individual customers or customer groups are equal. If the p-value associated with the test statists is below the range of accepting the null hypothesis (i.e. 0.05), it can be concluded that the panel estimators (i.e. fixed effects and random effects) are preferred to the pooled model. In order to choose an appropriate method between the fixed effects and the random affects models, a Hausman test is used (Hill et al. 2010; Wooldridge 2012). The null hypothesis of this test is that, if there are no omitted variables, the random effects model is more efficient (Polebitski and Palmer 2010). This means that if the null hypothesis of test does not reject the random effects model is preferred. The random effects model has a useful feature over the fixed effects, when it can recover parameter estimates for time invariant variables as well (Fenrick and Getachew 2012).

In this study, the dependent variable is the average daily water consumption in the winter and the summer. The average daily water consumption of June (the coldest month) was selected to represent the winter usage, while the February data (the warmest month) was used to represent the summer usage in the single houses and the low-rise apartments. However, in the high-rise apartments the January water consumption data was used to represent the summer usage since the February consumption was very similar to the July water use. In general, the seasonal variation of water consumption in the high-rise apartment is very limited.

This study examines the effect of a wide range of variables including household and housing characteristics, water price and weather variables on the water consumption. Table 5.1 provides a list of variables used in this study. All of these variables have been frequently reported as the influential factors on the empirical studies of water demand (Arbués et al. 2003; Chang et al. 2010; Fox et al. 2009; House-Peters et al. 2010; House-Peters and Chang 2011; Mieno and Braden 2011; Ouyang et al. 2014; Schleich and Hillenbrand 2009).

In this study, a yearly estimate of census variables (i.e. household income, household size, number of bedrooms, and ownership of property) was used in the panel data models. In the high-rise apartments the effects of swimming pool and garden were evaluated using dummy variables. In contrast, in the single houses and low-rise apartments the percentage of dwellings with pool and the average garden size was used to evaluate the variables. This is because, in the high-rise apartments swimming pools was typically shared between many units and the garden size was very limited. Thus, the use of dummy variables was more justifiable in the assessment of overall effects of pool and garden on average water consumption in the high-rise apartment.

In order to estimate the price elasticity of water demand, this study summed up the charges of water and wastewater. This is because, in Auckland the wastewater volume is calculated based on metered water use. This can help to evaluate the overall effect of pricing on water consumption. The prices and income were deflated into real 2013 terms using the customer price index (CPI) in this study (Statistics-NZ 2015).

Table 5.1. List of variables used for the seasonal water demand analysis

Variables	Definition	Variable unit
DWU	Average daily water use (in summer and winter)	Litre/dwelling/day
Income	Household median income	NZ dollars/year
HhSize	Average household size	People
BRooms	Average number of bedrooms	Bedrooms
Owner	Percentage of households owned the dwellings	%
PercPool	Percentage of houses with swimming pool (at area unit level for single houses and low-rise apartments)	%
PoolDum	Dummy variables representing meshblocks with high-rise apartment with swimming pool	N/A
GardSize	Average garden size (at area unit level for single houses and low-rise apartments)	m^2 or m^2/apartment[a]
GardDum	Dummy variables representing meshblocks with high-rise apartment with garden	N/A
Price	Sum of volumetric price of water and wastewater	NZ dollars/m^3 water
Temp	Average air temperature	°C
Rain	Total monthly rainfall	mm/month

Note: [a] garden size was measured by m^2 in single houses and m^2/apartment in low-rise apartments.

In order to fully investigate the variations water consumption and its determinants across different groups of consumers, this study clustered the Auckland census areas based on the average household income and per capita water consumption. Using k-means algorithm (Everitt et al. 2011), two groups of census areas with the low income and the high income were distinguished in Auckland. This clustering enabled the present study to evaluate water consumption across different housing types, income groups and seasons. Figure 5.1 shows two groups of low-income and high-income census areas in Auckland.

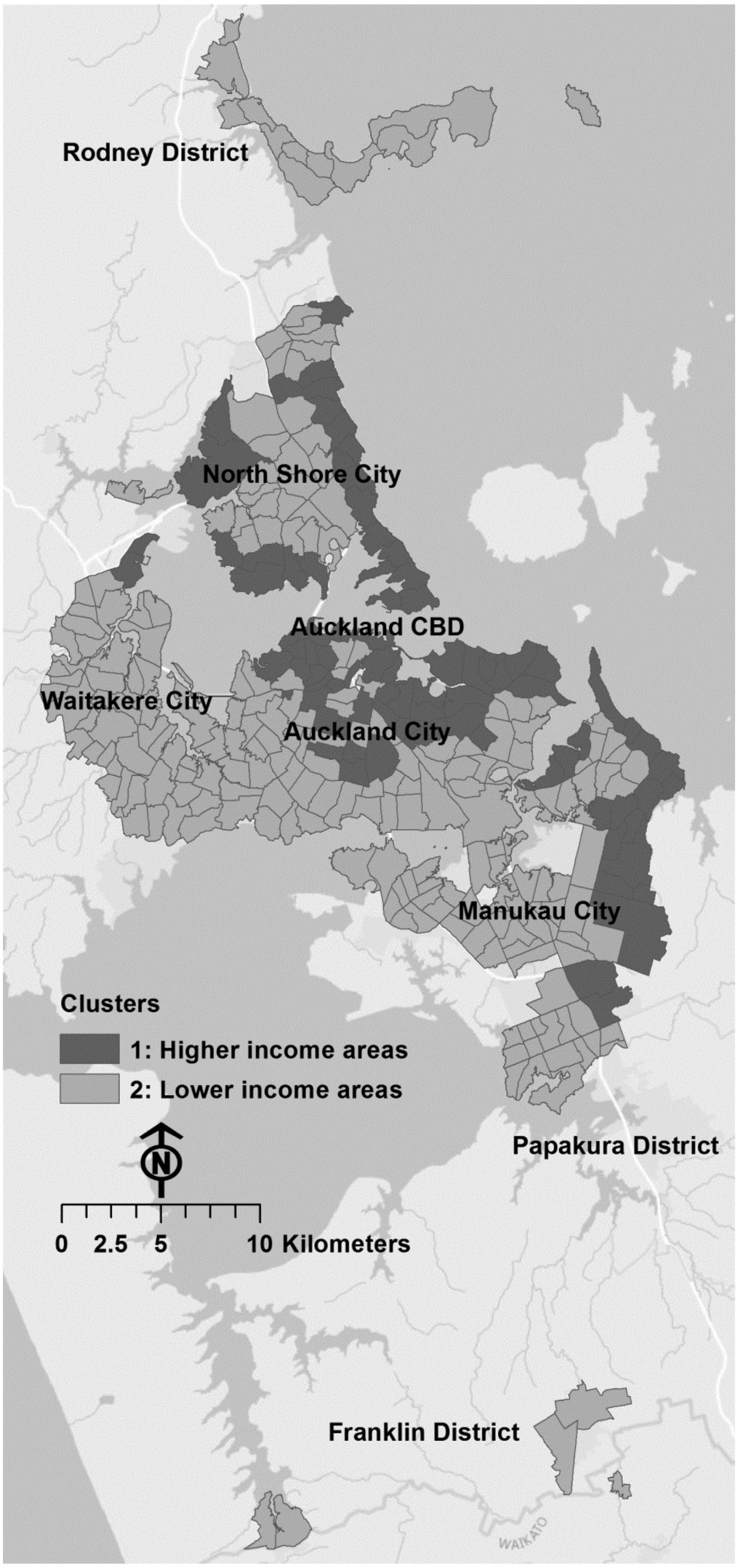

Figure 5.1. Two clusters of low-income and high-income census area units in Auckland

5.5. Results and discussion

The data disaggregation provided a unique opportunity for this study to fully examine residential water demand across different group of consumers. Table 5.2 shows the variations of water consumption, household size and household income (as two major sociodemographics variables) across different housing types, income groups and seasons in Auckland.

Table 5.2. Water consumption and household characteristics across different housing types, income groups and seasons in Auckland

Variables	Single houses		Low-rise apartments		High-rise apartments	
	L-income[c]	H-income[d]	L-income	H-income	L-income	H-income
DWUs[a]	588	655	380	389	360	366
DWUw[b]	538	561	356	357	386	383
Income	77800	123500	47600	69500	57300	95600
HhSize	3.4	3.1	2.4	2.2	2	1.9

Note: [a] average daily water consumption in summer (litre/dwelling/day); [b] average daily water consumption in winter (litre/dwelling/day); [c] cluster of higher income areas: [d] cluster of lower income areas.

The results from table 5.2 revealed that the average daily water consumption in the single houses in Auckland is significantly higher than the multi-unit houses (i.e. low-rise and high-rise apartments). This finding is in agreement with other water demand studies (Clarke et al. 1997; Domene and Saurí 2006; Fox et al. 2009; Russac et al. 1991; Troy and Holloway 2004). In general, the higher water consumption of single houses can be mainly attributed to the larger household size and the higher outdoor uses (garden and swimming pool) in this housing type (Domene and Saurí 2006; Fox et al. 2009; Russac et al. 1991). The outdoor water consumption generally can be estimated by subtracting the summer use form the winter use (Billings and Jones 2008). Estimating the outdoor water consumption from table 5.2, the study showed that in Auckland the outdoor water consumption is most remarkable in the single houses specifically in the high income areas where the water consumption may increase by 17% in summers. In contrast, the seasonal variation of water use in the low-rise and high-rise apartments is very limited, implying the indoor usage is predominant in these housing types. This result is in agreement with the other water demand studies (Domene and Saurí 2006; Polebitski et al. 2011). The results from table 5.2 also revealed that the spatial variation of water use (i.e. variation of water consumption across the high income and the low income areas) is more remarkable in the single houses. Examining the variable DWUs in the table 5.2 showed that in the single houses the summer water consumption in the high income areas is around 11% higher than the lower income neighbours. In general, people in the higher income areas consumed more water since they are likely to own more water-using appliances and amenities, and outdoor water facilities (Arbués et al. 2003; Billings and Jones 2008; Domene and Saurí 2006; Mieno and Braden 2011).

In order to identify the determinants of water consumption across different housing types, income groups and seasons, this study utilized panel data models. For each dataset three different panel data models including pooled, fixed effects and random effects were examined in order to select the most appropriate method for the water demand analysis. The result of partial F-test (pooling tests), shown in the tables 5.3, 5.4 and 5.5, revealed that the panel models (i.e. the fixed effects and the random effects models) were an improvement on the pooled model for all datasets. Subsequently, in order to choice between the fixed effect and the random effects models the Hausman test was carried out on all datasets. The result of Hausman tests, shown in the tables 5.3, 5.4 and 5.5, revealed that the random effects model was the best estimator in all datasets except for the low income areas of the single houses dataset. Thus, for this latter dataset the fixed effect model was chosen to produce the consistent parameter estimates. One drawback of fixed effects model is that this model cannot provide parameter estimates for the time-invariant variables such as housing characteristics (i.e. PercPool and GardSize) which were constant over time on the studied sample. This feature of fixed effect models however does not mean that the model omitted the time-invariant variables. In fact, the fixed model controlled these variables, alongside with other unobserved housing and household characteristics, to provide unbiased parameter estimates for the remaining variables (Kenney et al. 2004).

Tables 5.3, 5.4 and 5.5 show the results of panel data models for three housing types. All the variables (except PercPool, PoolDum and GardenDum which contains zero values) were transferred by the natural logarithm thus the coefficients can be interpreted as the elasticity. The time variable also was added in the models in order to capture the underlying trend in the water consumption data.

Table 5.3. Seasonal water demand models for single houses

Variables	Low income areas		High income areas	
	Summer	Winter	Summer	Winter
Constant	4.16***	5.42***	5.82***	4.64***
HhSize	0.52**	0.23*	0.31*	0.92***
Income	0.02	0.02	0.002	0.03*
BRooms	0.32	0.20	0.19	0.02
Owner	0.22**	-0.01	0.29**	0.13
PercPool	–	–	0.008***	0.005***
GardSize	–	–	-0.10**	-0.08**
Price	-0.01	-0.02***	-0.02***	-0.04***
Temp	0.07	0.11***	-0.18	0.17***
Rain	-0.01***	-0.01**	-0.03***	-0.03***
time[a]	-0.01***	-0.02***	-0.01***	-0.04***
$time^2$	–	–	–	0.002**
Partial F-test	13.91***	14.86***	17.28***	12.42***
Hausman test	31.46***	21.50***	8.17	7.31
Panel data model	FE[b]	FE	RE[c]	RE
Overall adjusted-r^2	0.38	0.62	0.51	0.66
Number of area units	210	210	82	82

Note: [a] time trend; [b] fixed effects model; [c] random effects model; ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

Table 5.4. Seasonal water demand models for low-rise apartments

Variables	Low income areas		High income areas	
	Summer	Winter	Summer	Winter
Constant	6.15***	5.88***	5.41***	6.22***
HhSize	0.61***	0.56***	0.45**	0.13
Income	-0.12**	-0.03	-0.02	-0.03
BRooms	0.08	0.07	0.09	0.55**
Owner	-0.04	-0.05	0.03	-0.10
PercPool	-0.003	-0.005	0.01**	0.01
GardSize	-0.01	-0.02	-0.04	-0.08**
Price	-0.02**	-0.03***	-0.04***	-0.04***
Temp	0.23*	0.10***	0.19	0.17***
Rain	-0.001	-0.01	-0.01*	-0.03**
time[a]	-0.01***	-0.02***	-0.01**	-0.02***
Partial F-test	19.03***	24.64***	13.39***	17.98***
Hausman test	14.27	12.68	7.54	9.13
Panel data model	RE[b]	RE	RE	RE
Overall adjusted-r^2	0.35	0.34	0.26	0.30
Number of area units	138	138	63	63

Note: [a] time trend; [b] random effects model; ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

Table 5.5. Seasonal water demand models for high-rise apartments

Variables	Low income areas		High income areas	
	Summer	Winter	Summer	Winter
Constant	4.98***	5.74***	5.06***	7.11***
HhSize	0.74***	0.39***	0.86***	0.89***
Income	-0.02	-0.03	-0.02	-0.16*
BRooms	0.14	0.26**	-0.22	-0.17
Owner	0.06	-0.04	0.05	0.08
PoolDum	-0.11	-0.13	0.09	0.06
GardDum	0.01	-0.01	0.02	-0.03
Price	0.04	0.04	0.09	0.04
Temp	0.08	0.24***	0.11	0.003
Rain	-0.003	-0.08***	-0.01	-0.03
time[a]	0.04***	-0.01*	–	–
$time^2$	-0.01***	–	–	–
Partial F-test	14.17***	17.16***	16.35***	20.18***
Hausman test	5.72	6.67	3.63	4.56
Panel data model	RE[b]	RE	RE	RE
Overall adjusted-r^2	0.49	0.46	0.17	0.22
Number of meshblocks	83	83	43	43

Note: [a] time trend; [b] random effects model; ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

All the developed models provided satisfactory results as the estimated variables generally had the expected signs and significance. The overall fit (adjusted r^2-value) of models was also acceptable and consistent with the prior studies in which panel data models were used on the micro datasets (Kenney et al. 2004; Pint 1999; Renwick and Archibald 1998).

The estimated coefficients for variable HhSize in tables 5.3, 5.4 and 5.5 showed that household size had a significant positive correlation with the water consumption almost across all consumer groups. The coefficient of household size varied between 0.13 to 0.92 across different housing types, income groups and seasons with an average of 0.55, implying that on average a 10% increase in the number of people in a household would result in a 5.5%

increase in household water consumption. This result is in agreement with many other water demand studies, where it was noted that due to economies of scale in the use of water, the increase in water consumption is less than proportional to the increase in household size (Arbués et al. 2004; Arbués et al. 2003; Hoffmann et al. 2006; Schleich and Hillenbrand 2009).

The income coefficients (Income) in tables 5.3, 5.4 and 5.5 were small and mainly insignificant across different groups. The insignificance of income elasticity can be attributed to the lack of variability of this variable within each dataset. This is because the datasets were developed through cluster analysis based on the household income (i.e. areas with similar incomes were clustered in the same groups). In addition, in the apartment sectors where the indoor water use is predominant the impact of income is typically limited. In general, the income variable mainly influences the household outdoor water consumption since the higher income households are more likely to own water-using capital stock such as larger lawns and gardens, and swimming pools (Hoffmann et al. 2006; Mieno and Braden 2011; Schleich and Hillenbrand 2009).

The estimated coefficients for variable BRooms in tables 5.3, 5.4 and 5.5 also showed that the number of bedrooms in the property, execpt for two models in the apartment sector, did not have a significant correlationship with the household water consumtion. In generall, number of bedrooms is more likely to apper significant in the apartment sector becaue it can be a proxy for the number of residents (Agthe and Billings 2002; Mayer et al. 2006).

The ownership of property, as shown by variable Owner in the tbales 5.3, 5.4, 5.5, only had a significant correlation with the summer water consumption in the single houses manily due to its poitive corretaion with household income, however the variable was insingnificant on the other models.

Tables 5.3, 5.4, 5.5 also revealed that presence of garden did not significantly affect the average water consumption neither in single houses nor in apartments. The variables coefficients were small and insignificant in most models. In few models the coefficients were negative and significant, implying that household with larger garden did not necessarily consume more water. This is mainly because in the Auckland houses the vegetated landscaping is limited to the planting of native grass, shrubs and trees which basically do not require much water. Moreover, the year-around precipitations in Auckland reduce the needs of irrigation for this type of landscaping. In contrast, the swimming pools were found to be significantly related to water use specifically in summers at the high income areas. These results imply that swimming pools is the main source of outdoor water consumption in Auckland.

One important advantage of disaggregated water demand analysis is to understand the variations of responses to the changes in the water price and weather across different groups of consumers. The estimated coefficients for variable Price in tables 5.3, 5.4 and 5.5 revealed that the volumetric price of water had insignificant correlation with the high-rise apartment water consumption. This result is not surprising since the water mainly is used for basic needs at the apartments. In general, the indoor water use is unlikely to exhibit a high price sensitivity (Arbués et al. 2003; Mieno and Braden 2011). In contrast, in the low-rise apartments and single houses where outdoor water use is more remarkable the price elasticity was statistically significant, varying from -0.01 to -0.04. This result is in agreement with the prior studies concluded that outdoor was consumption is more sensitive to water price (Arbués et al. 2003). However, this study did not found any significant difference in the price responsiveness across income groups as it was noted in some literatures (Mieno and Braden 2011; Renwick and Archibald 1998).

The price elasticity of demand estimated in Auckland is within the range of values obtained by a number of previous studies (Abrams et al. 2012; Arbués et al. 2004; Arbués et al. 2003). However, in general it is very limited. The low price elasticity of water demand can be attributed to the fact in Auckland the water bill generally comprises a small share of total household expenditure. In addition, the current water/wastewater pricing scheme with flat volumetric rates may not provide enough incentive to reduce water consumption, specifically among group of consumers with high water use.

Finally, the weather variables Temp and Rain in tables 5.3, 5.4, 5.5 showed the expected positive signs for the temperature and the negative signs for the rainfall almost for all models. However, the weather variables were mostly significant for the lower density housing. This result implies that the impact of weather variables is more remarkable in the single house and low-rise apartments. This finding is also in agreement with other studies noted that the sensitivity of water demand to the weather condition would diminish with the increase of housing density due the decrease in the outdoor water consumption (Balling Jr. et al. 2008; Breyer and Chang 2014; Breyer et al. 2012).

5.6. Conclusions

This study evaluated the determinants of residential water consumption in Auckland metropolitan area. The heterogeneity in housing and household characteristics has caused water consumption to vary substantially across different housing types, income groups and seasons in Auckland. In order to fully evaluate the variations of water consumption and the determinants of it across different groups of customers basically a large set of disaggregated data distinguishing different housing types is required. This study utilized geographic information system in order to combine urban databases to develop a large sample of 60000 dwellings in Auckland. The integration of water consumption, land-use and census microdata enabled this study to thoroughly evaluate water consumption across different housing types (i.e. single house, low-rise and high-rise apartments), socioeconomic groups (i.e. low and high income groups) and seasons (i.e. summer and winter). Taking advantage of highly disaggregate datasets, this study also evaluated the heterogeneity in response to the water pricing and weather variables across different groups of consumers. Evaluating water consumption across different housing types can help water planners and policy makers to better understand the implication of urban densification (i.e. transition from single houses to more intensified multi-unit houses) on water demand which is an undergoing phenomenon in many large cities including Auckland. In addition, recognizing the variation of water consumption across different areas and understanding customer responses to the water pricing and weather can help water utilities to plan for water supply and treatment systems in a spatially-oriented manner and optimally design conservation programs.

Through disaggregated water demand analysis, this study showed the average daily water consumption in the single houses is significantly higher than the multi-unit housings (i.e. low-rise and high-rise apartments). The higher water consumption of single houses can be mainly attributed to the larger household size and higher outdoor uses in this sector. This study also showed that the seasonal and spatial variations of water use are more remarkable in the single houses, where the water consumption may increase considerably in the higher income areas specifically in summers due to the outdoor water uses. In contrast, in the high-rise and low-rise apartments the household water consumption and its seasonal and spatial variations are more limited since the indoor usage is predominant in these sectors.

Using panel data analysis, the study revealed that the household size is the major determinants of water consumption across different housing types, seasons and income groups, where other variables such as number of bedrooms and ownership of property did have significant correlation with water consumption. The study also showed that in the single houses the swimming pool is the main source of outdoor usage where the garden size had limited effects on water use. The estimated price elasticity of water demand also revealed that none of group of consumers considerably response to the water pricing in Auckland. This result implies that under the current pricing scheme (i.e. flat volumetric rates) the water pricing cannot be used as an effective management instrument to regulate water demand specifically across group of consumers with high water use. Finally, the study showed that lower density housing, with more outdoor usage, is more sensitive to weather condition. This result highlighted the fact that in the future by increasing the number of apartments the effects of weather and subsequently the seasonal variation of water consumption may be less significant.

This study demonstrated how the data integration can be used in the contemporary water demand study to fully address the complexity of water demand in the urban environments. In recent years, with advances in database technology, data accessibility, computing power, and spatial GIS tools it is becoming more plausible to integrate disaggregated water consumption, land use and demographic data to make use the full potential of them in water demand studies. This data integration allows the visualization and evaluation of demand information that was not previously possible. It provides planners with greater insights on the manner by which water is consumed across different kinds of development, urban areas and over different seasons. This information can help water utilities to plan the water supply system in an optimal manner to meet future water demand.

Chapter 6

Future implications of urban intensification on residential water demand

Abstract

Over the past decades Auckland, New Zealand, metropolitan area has vastly expanded as a result of rapid population growth and low-density housing developments. In order to manage the uncontrolled low-density urban sprawl, Auckland Council proposed a compact city model through promoting higher density housing developments. In order to understand the implications of this transition on future residential water demand, this study firstly evaluated water consumption in three major housing types in Auckland including single houses, low-rise and high-rise apartments. Geographic information system was used to estimate water consumption from a large sample of 60000 dwellings across Auckland. The water consumption information was subsequently combined with the Proposed Auckland Unitary Plan outlining the future housing composition over different areas in Auckland. Different growth scenarios were developed to examine the implications of housing intensification on water use in Auckland. This study showed that the housing transition from single houses to more intensified multi-unit houses may help to reduce the per capita water consumption in the affluent areas, specifically in summers, through limiting the outdoor uses. However, in general it cannot considerably affect the average per capita water consumption in Auckland. This information can help water planners to more reliably plan for the future water supply and treatment systems in Auckland.

6.1. Introduction

Over the past decades Auckland has experienced a vast expansion of urban areas due to the rapid population growth and low-density housing developments. In order to mitigate the social, economic and environmental concerns arising from the low-density urban sprawl (Domene and Saurí 2006), Auckland Council proposed a compact city model through the Auckland Unitary Plan (PAUP 2015). This plan proposes a quality compact city where urban growth is primarily focussed within the existing metropolitan area and concentrated within moderate walking distances from the city or local centres, rapid and frequent service network or within close proximity to urban facilities (Haarhoff et al. 2012; PAUP 2015).

Zoning is one of the key areas under the Proposed Auckland Unitary Plan. It determines where certain types of development can occur so that Auckland's future growth can be managed in a way that creates a higher quality and more compact city (PAUP 2015). Unitary Plan encourages greater intensification through relaxing the height and density controls for the housing developments in Auckland. This plan rezones many residential areas with traditional single houses (i.e. one house on one block of land) to the mixed housing zones (i.e. where construction of low-rise apartments with less than 4 storeys is allowed) or more intensified terrace housing and apartment zones (i.e. where construction of high-rise apartments with 4 or more storeys is allowed). In general, higher density living is seen as a credible path for improving urban sustainability (Boon 2010; Haarhoff et al. 2012).

According to the proposed Unitary Plan, around 30 percent of residential areas in Auckland would continue to be part of single housing zones. However, over 60 percent of residential areas would turn into the mixed housing zones with the low-rise apartments. Around 6 percent of residential areas in Auckland also include the terrace housing and apartment zones where the construction of high-rise apartments is allowed. This can lead to enormous changes, where currently more than 75 percent of housings in Auckland are single houses.

This fundamental reformation of housing composition may significantly affect the future residential water demand in Auckland. This is because, water demand across different housing types can be substantially different due to the sociodemographics characteristics of residents and the level of outdoor usage (e.g. gardens and swimming pools) on them (Domene and Saurí 2006; Fox et al. 2009; Loh et al. 2003; Russac et al. 1991; Troy and Holloway 2004; Wentz et al. 2014; Zhang and Brown 2005).

In order to assess the implications of urban intensification on the residential water demand in Auckland, this study firstly evaluates the water consumption across different housing types (i.e. single house, low-rise and high-rise apartments), socioeconomic groups (i.e. low and high income groups) and seasons (i.e. summer and winter). This is inherently a challenging task since the disaggregated data for different housing types is not usually readily available. This is one of the main reasons caused the empirical studies comparing water demand in different housing types to remain very limited. In an early study in UK, Russac et al. (1991) investigated water demand in housings with different architectural types and concluded that water consumption of single houses is higher than more intensified dwellings such as semi-detached and flats. Troy and Holloway (2004) also examined residential water consumption in different types of dwellings in Adelaide, Australia. They showed that although water consumption varied significantly across different housing types, the per capita water consumption is almost same across them. In a study of determinants of water demand in Barcelona, Spain, Domene and Saurí (2006) investigated the effects of housing types on water demand and showed that water consumption in low-density housings is higher than high-density housings manly due to the outdoor uses. Fox et al. (2009) also classified residential properties in terms of their physical characteristics for the purpose of forecasting water demand. They concluded that water demand in detached houses is higher than semi-detached and flats. However, none of these studies considered the spatial variation of water demand across different housing types since they generally relied on the small samples of household data. In general, the residential water demand can wary significantly over urban areas mainly due to heterogeneity in the sociodemographics characteristics of households (e.g. household size and income) and housing features (e.g. size of housing, swimming pool and garden) (House-Peters and Chang 2011; Polebitski and Palmer 2010).

In order to overcome the issue of scarcity of disaggregated data, this study utilized a rich source of GIS-based urban databases in Auckland to develop a large sample of 60000 houses with different types through data integration (i.e. combining different data sources). In recent years, the data integration in water demand studies has become more plausible due to the advances in database technology, data accessibility, computing power, and spatial tools (Dziedzic et al. 2015; Polebitski and Palmer 2010). Troy and Holloway (2004) integrated water demand and property information for 6 census areas in Adelaide, Australia, in order to examine the water consumption patterns for different types of residential dwellings and areas. Shandas and Parandvash (2010) integrated water consumption, land use and demographic data to examine the relationship between land-use planning and water demand. Polebitski and Palmer (2010) integrated utility billing data with the census demographic and property data in order to forecast single housing water use in Seattle, Washington. In a recent study, Dziedzic et al. (2015) integrated water billing records, demographic census information, and property information in Ontario, Canada. Through this data integration and subsequent cluster analysis, they identified the pattern of water demand over different areas and groups of customers for the purpose of conservation planning. They emphasized the importance of data integration in order to use the full potential of rich data available with the organizations.

However, none of these studies have utilized the data integration to evaluate water demand in different housing types over a large metropolitan scale like Auckland.

Using geographical information system (GIS), this study combines residential water consumption, land use and census microdata for all dwellings in Auckland. The land use information in the integrated dataset can help to distinguish different housing types and subsequently estimate water consumptions across them. In addition, the census microdata can provide household information (e.g. household size and household income) for different housing types (i.e. single house, low-rise and high-rise apartments). This enabled to estimate per capita water consumption in each of housing groups across 300 census area units in Auckland. This study uses six years monthly water consumption data (i.e. 2008-2014) and two census microdata (i.e. census 2006 and 2013) for the water demand analysis.

After estimating the water consumption for different housing types across Auckland, this information is combined with the Proposed Auckland Unitary Plan outlining the future housing composition over different areas in Auckland. Through developing different urban growth scenarios, this study examines the prospective impacts of housing intensification on the residential water demand. This information can help water planners to more reliably plan for the future water supply and treatment systems in Auckland. To the present author's knowledge, this important subject has never been investigated in the literature of water demand in this extent.

This chapter is organized in the following order. After the introduction, a review of study area is presented. Afterward, the data and the integration procedure are discussed. Then, the water consumption and its seasonal and spatial variations across different housing types are demonstrated. Finally, the implications of urban intensification under different growth scenarios and conclusions are presented.

6.2. Study area

Auckland is the largest city in New Zealand. This city formerly was comprised from seven territorial authority areas. These areas were Rodney District, North Shore City, Waitakere City, Auckland City, Manukau City, Papakura District, and Franklin District). However, in 2010 these areas amalgamated to form a single authority known as the Auckland Council.

Auckland has experienced a fast growth both in population and housing stock over the last decades. The population of Auckland has increased by 22 percent since 2001, reaching around 1.4 million people in 2013 (Statistics-NZ 2015). This growth has led to a low-density urban expansion since the majority of dwellings in Auckland are single houses (i.e. around 75 percent). However, in recent years with decreasing section sizes of single houses and increasing number of multi-unit housings (i.e. low-rise and high-rise apartments) (LINZ 2015; Statistics-NZ 2015), the dwelling density in Auckland has increased, reaching from 86 to 102 dwellings per square kilometre between 2001 and 2013 (Goodyear and Fabian 2014).

At the time of census 2013, the low-rise and high-rise apartments made up around 21 percent and 4 percent of housing stock in Auckland, respectively (Statistics-NZ 2015). The high-rise apartments are mainly within Auckland Central Business District (CBD) or at the adjacent suburbs, while the low-rise apartments have been constructed across the entire city.

In Auckland, the variations of household characteristics across different housing types and areas are remarkable. For instance, the average household size in the single houses is around 3.3. However, this number can increase to five people in some suburbs in the south of Auckland, where multifamily household (i.e. households in which two or more family nuclei reside in the same dwelling) is more common. In high-rise apartments the average household size is around 1.9, while the average number of people in low-rise apartments is about 2.3. In single houses, the median age of population is around 35 years, where in the low-rise and high-rise apartments the age of population are about 36 and 33 years, respectively (Statistics-NZ 2015).

Auckland has a subtropical climate with a year-round precipitation. The average annual precipitation is around 1240 mm. The annual average air temperature is around 15 °C. The coldest month is usually June or July and the warmest month is January or February (NIWA 2015).

6.3. Data integration

This study combines the water consumption, property information and census microdata to estimate per housing and per capita water consumption in different housing types across Auckland.

In this study, the monthly water consumption data was provided by Watercare Services Limited, an Auckland Council Organization, for the period of 2008-2014. This data does not include Papakura District meters since the provision of retail water services in that district is franchised to a separate company. Thus, the Papakura district was excluded from this study. Up until July 2012, each former district of Auckland had different water recording span, varying from six months to bimonthly periods. From July 2012, the domestic accounts are read every two months by Watercare. To standardize the data all over Auckland, Watercare converted this data to the monthly period. In order to estimate the monthly water use for each individual meter, Watercare first estimates the average daily use during the reading period (i.e. the usage on the meter is divided by the number of days between the two readings). Then, this average use is allocated to each month according to the number of days corresponding to that month in that particular reading period. For each individual meter, the water consumption database also includes the address of property and its geographical location, type of meter and its installation date. Watercare typically measures the water consumption of single houses and small multi-unit houses using individual meters. However, in the large low-rise apartment complexes and high-rise apartments Watercare only measures the total water use of buildings using master meters and does not meter apartments individually (although the units may be sub-metered individually by the building managers). In this study, where the individual meter data was not available, the housing average water consumption was estimated through dividing total metered water use by the number of units in the building.

The property information in this study was obtained from the publicly available databases at Auckland Council (Auckland-Council 2015) and Land Information New Zealand (LINZ 2015). The developed property dataset contains the information of housing type (i.e. single house, flats or apartments, etc.), assessed value of property, section size, structure size of building (i.e. building footprint), impervious area, the issue dates of section (as a proxy of age of property), and the address of property.

The socioeconomic information of households was obtained from Statistics New Zealand Data Lab (Statistics-NZ 2015) for census 2006 and 2013. The Data Lab provided access to the microdata (i.e. data about specific people, households, or businesses). From the census microdata, it is possible to estimate household and housing information (e.g. household income, household size, education level, number of bedrooms, etc.) for different types of housing across different areas. This study collected the census information of households living in the single house (i.e. separate house), low-rise apartments (i.e. joined dwellings with one-, two-, or three-storey), and high-rise apartments (i.e. joined dwellings with four-storey or more) at the census area unit level. Census area unit is the second smallest geographical unit in which the census information is available. The smallest unit is meshblock however in that level many variables would not be available in order to protect the information of residents.

In this study, the data combination was carried out using geographical information systems (GIS). The water consumption and property data firstly were arranged in GIS and linked together using the addresses and geographical coordinates. By this data integration the information of water consumption and property for around 350000 housings including single houses, low-rise and high-rise apartments became available for the further investigation.

In order to estimate the water consumption in three major housing types (i.e. single house, low-rise and high-rise apartments) in Auckland, the present study segregated the dataset based on the housing type. In Auckland, around 75 percent of houses are single-unit. Thus, through filtering the database based on the property type, around 260000 single houses were identified. From this filtered dataset, the houses with replaced meters (i.e. houses with more than one meter records) were excluded from the analysis. This is because, in these houses the records from erroneous old meters usually overlap the new meters records for a period of time, thus they may cause error in the estimation of historical water consumption. After this data filtering, around 130000 single-unit houses remained available for the demand study. From this dataset, a random sample of 31000 single houses was selected in order to easier check the data for completeness and quality. Using high-resolution aerial images, this study visually inspected all the housings in the sample to make sure they are single houses and there is no missing data among them. This random sample is large enough to reliably represent the total population of single-unit dwellings (i.e. there was no statistically significant difference between average water consumption estimated from the random sample and entire single houses in Auckland) as well as fully cover all suburbs of Auckland to help to show the spatial variation of water use.

The same data filtering procedure was carried out to develop samples of the low-rise and the high-rise apartments. The low-rise apartments made up around 21 percent of housing stock in Auckland. Thus, through the filtering of dataset based on the property type, around 70000 low-rise apartments were identified. From this filtered data, the houses with replaced meters were excluded from the analysis. After this data filtering, the information of 40000 low-rise apartments remained available for the rest of analysis. In this dataset, the multi-unit houses either may have joined structure or separate structure (e.g. two or more dwellings on a single block of land (section), but are not joined). Given that the census information recognizes apartment as a dwelling with the joined structure, the dataset was filtered by this criterion leaving around 18000 low-rise apartments with the joined structures for the final water demand study in this sector.

The high-rise apartments also comprised around 4 percent of housing stock in Auckland. Thus, through the filtering of database based on the property type, around 15000 apartments from 190 residential apartment buildings were identified in Auckland. From this filtered dataset, the apartment buildings with missing water use records, replaced meters or shared meters with the commercial sector (i.e. non-residential customers such as restaurants and café) were excluded from the database, leavening 147 apartment buildings with around 11000 units for the final water demand analysis. Similar to single houses data, both samples of the low-rise and the high-rise apartments were visually inspected using high-resolution aerial images, in order to make sure all the selected dwellings are within the correct category.

Through the data integration, a large sample of 60000 dwelling was developed in this study. This enables the study to fully investigate the variation water demand across different housing types, urban areas and seasons in Auckland. This dataset was subsequently aggregated at the census area unit scale in order to add census socioeconomic information, specifically household size, for each housing types. The household size information at the census unit level can help to estimate average per capita water use, for each housing types, at a fine spatial scale. The average per capita water use can be estimated through dividing the average per housing water use by the associated household size in each housing category.

In order to reveal the effects of housing transition on the future water demand in Auckland, the water consumption information was joined with the Auckland Unitary Plan data. The data of proposed Auckland Unitary Plan was obtained from the publicly available database at the Auckland Council (PAUP 2015). This dataset shows the zoning information (i.e. permitted housing types in each section) for all properties in Auckland.

6.4. Results and discussion

6.4.1. Water consumption

Developing a large sample of housings through data integration provided a unique opportunity for this study to thoroughly evaluate the variations of water consumption across different housing types, seasons, and urban areas. Table 6.1 shows the average water consumption across three housing types in Auckland. Using the household size information, the per capita water consumption for different housing types also was estimated. The results from table 6.1 revealed that the average water consumption in the single-unit housings is significantly higher than the multi-unit housings (i.e. low-rise and high-rise apartments). This results is in agreement with other water demand studies (Clarke et al. 1997; Domene and Saurí 2006; Fox et al. 2009; Russac et al. 1991; Troy and Holloway 2004). In general, the higher water consumption of single houses can be attributed to the higher outdoor uses (garden and swimming pool), larger household size and more water appliances (due to greater space) in this sector (Domene and Saurí 2006; Fox et al. 2009; Russac et al. 1991).

Table 6.1. Water consumption across different housing types in Auckland

Housing types	Household water consumption (litre/household/day)	Household size	Per capita water consumption (litre/person/day)
Single house	572	3.3	173
Low-rise apartments	367	2.3	160
High-rise apartments	375	1.9	197

The estimated water consumption, shown in table 6.1, also revealed that the average per capita water use in the single houses is higher than the low-rise apartments, but lower than the high-rise apartments. In general, people living in single houses have a greater opportunity to use water such as external use on gardens and swimming pools and in multiple toilets and/or bathrooms (Domene and Saurí 2006; Fox et al. 2009; Randolph and Troy 2008). Despite having more opportunities to use water, on an average per capita basis, residents in the single houses did not use more water than those living in the high-rise apartments. The higher per capita water consumption in the high-rise apartments can be attributed to the small household size, lack of individual meters and high percentage of rental properties in this sector. In general, household size can exert an important effect on per capita domestic water consumption. By decreasing the household size the per capita water consumption typically increases since the economies of scale cannot be accomplished in the smaller households (for instance, full loads in washing machines, dishwashers, etc.) (Arbués et al. 2003; Domene and Saurí 2006; Hummel and Lux 2007). Empirical studies of water demand also showed that individual metering can significantly reduce water demand (Inman and Jeffrey 2006; Mayer et al. 2006). In general, individual metering allows water to be billed based on the consumption, and hence increases both awareness of the water used and the financial incentives for water conservation (Nauges and Thomas 2000). Finally, the high per capita water use in the high-rise apartment may have been influenced by the low level of property ownership in this sector (around 68 percent of high-rise apartments in Auckland are rental).

In general, tenants usually have little or no control over the homes and are not in a position to undertake substantial refitting or buying new appliances, which can assist in lowering water consumption (Randolph and Troy 2008).

In addition to the average water consumption, the seasonal variation of water use may also be significantly different across housing types (Figure 6.1).

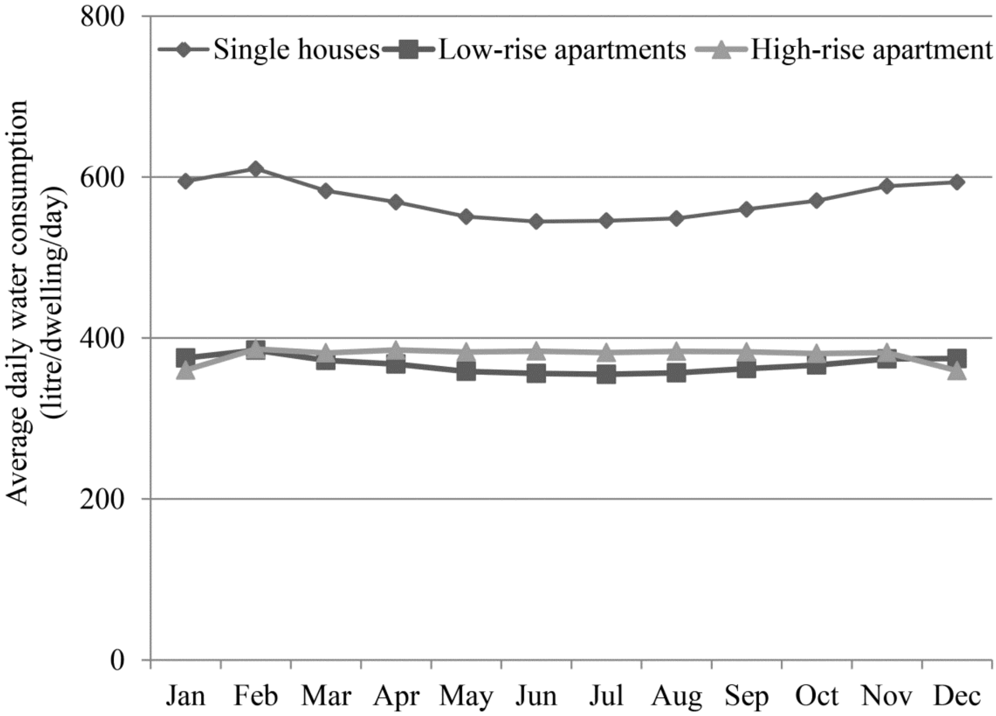

Figure 6.1. Seasonal variation of water consumption across different housing types in Auckland

As shown in figure 6.1, the seasonal variation of water use in the single houses is more remarkable, stressing the importance of outdoor water usage in this sector. In contrast, in the apartment sectors, where the indoor usage is predominant, the seasonal variation of water use is more limited. This result is in agreement with the other water demand studies (Domene and Saurí 2006). In Auckland, although the seasonal variation of low-rise apartments is limited, the pattern of it still is influenced by the local climate (i.e. water use is higher in the summer and lower in the winter). This is because, in general the low-rise apartments have greater outdoor water use opportunity than the high-rise apartments, thus are more likely to show similar water habits to single houses (Domene and Saurí 2006; Wentz et al. 2014). However, in the high-rise apartments in Auckland the seasonal variation of water use does not follow the local climate (i.e. winter water consumption is slightly higher than summer water consumption). Ghavidelfar et al. (2016) showed that the seasonal pattern of water use in Auckland high-rise apartments more closely follows the tertiary education calendar in New Zealand, rather than usual summer and winter seasons. This is due to a large student population living in the Auckland CBD high-rise apartments. They attributed the higher winter water use to the more number of occupants during academic months.

Water consumption may also vary substantially across different urban areas mainly due to the heterogeneity in the socioeconomic characteristics of households, specifically income. In general, the more affluent suburbs are more likely to show higher water consumption (Chang et al. 2010; House-Peters et al. 2010; Polebitski and Palmer 2010). This because the larger income usually increase the standard of living expressed in the presence of more water-using appliances and amenities, and outdoor water facilities (Arbués et al. 2003; Billings and Jones 2008; Domene and Saurí 2006; Mieno and Braden 2011). In order to investigate water consumption across different income groups in Auckland, this study applied cluster analysis to group urban areas. Using K-means algorithm (Everitt et al. 2011), two different groups of census area units were distinguished in Auckland based on the per capita water use and household income. The first cluster encompassed the affluent areas with higher per capita water demand, while the second cluster included the lower income areas with lower per capita water use. Figure 6.2 shows two clusters of census areas in Auckland.

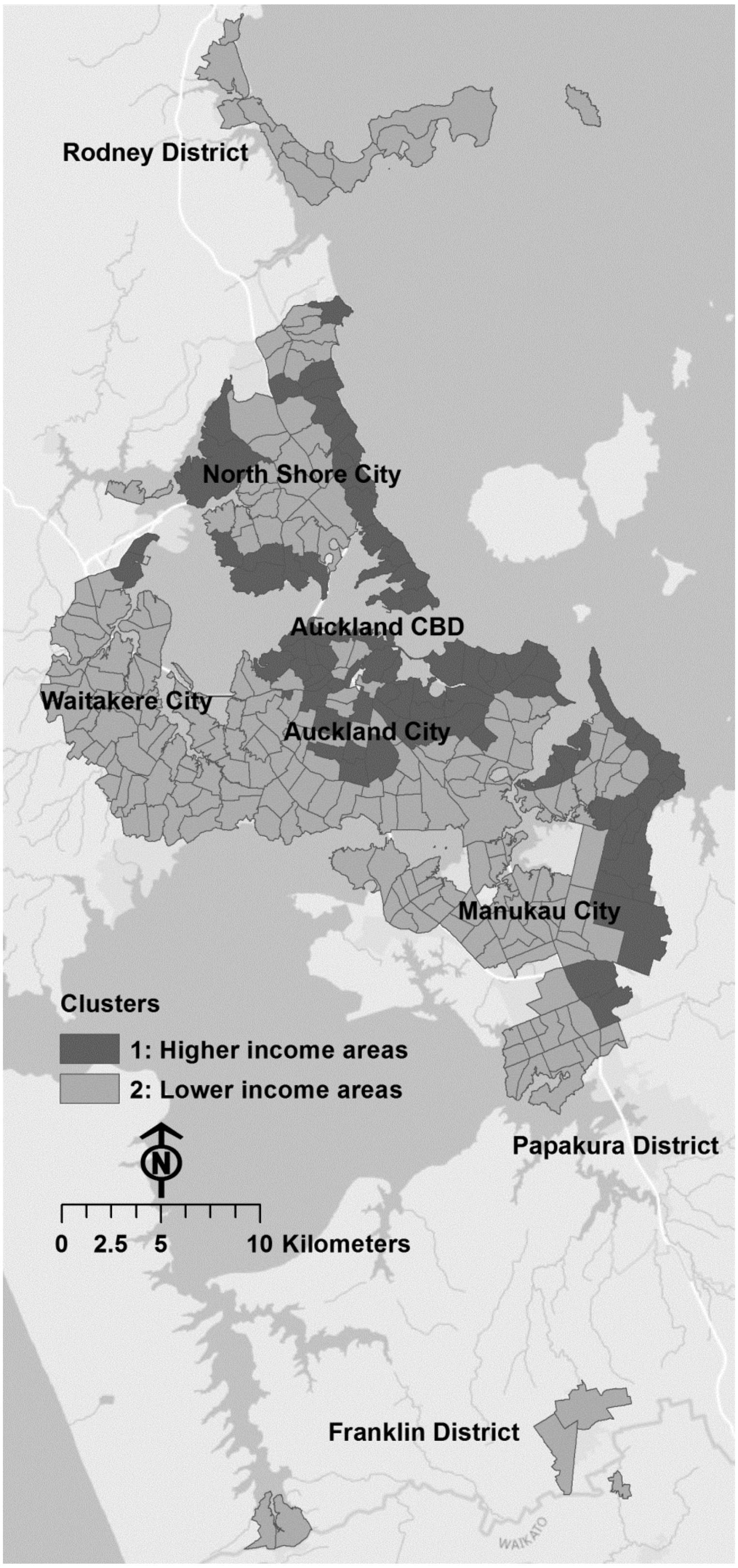

Figure 6.2. Two clusters of census area units in Auckland, distinguished based on the per capita water use and household income

Table 6.2 shows the average per capita water consumptions and the sociodemographics characteristics of household living in three housing types across these two clusters.

Table 6.2. Water consumption and households characteristics of different housing types across different areas

Variables	Single houses		Low-rise apartments		High-rise apartments	
	L-income[g]	H-income[h]	L-income[g]	H-income[h]	L-income[g]	H-income[h]
PCCa[a]	165	194	154	172	195	200
PCCs[b]	172	212	160	182	196	208
PCCw[c]	158	181	150	167	198	203
Income[d]	77800	123500	47600	69500	57300	95600
HhSize[e]	3.4	3.1	2.4	2.2	2	1.9
AreaUnits[f]	210	81	138	63	15	15

Note: [a] annual average per capita water consumption (litre/person/day); [b] summer average per capita water consumption (litre/person/day); [c] winter average per capita water consumption (litre/person/day); [d] average household income (NZ dollars); [e] average household size (people); [f] number of area units with specific housing types in each cluster; [g] cluster of higher income areas: [h] cluster of lower income areas.

As shown in table 6.2, in the affluent areas the per capita water consumptions were higher for all housing groups. However, this difference was more remarkable in the single houses, where the average per capita water consumption was around 18 per cent higher than lower income neighbours. This was in contrast to 12 percent and 3 percent of water consumption variation across two clusters for the low-rise and the high-rise apartments, respectively. In addition, the seasonal variations of water consumption were also more remarkable for the single houses in the wealthy areas. In the high-income areas, the average per capita water consumption increased by around 17 percent in summers. The high seasonal variation of water use in the single house at the affluent areas represents the high level of outdoor water usage in these areas.

This water consumption information across different housing types, socioeconomic groups and seasons is combined with the Unitary Plan data in order to reveal the effects of housing intensification in Auckland.

6.4.2. Urban intensification

In order to investigate the effects of urban intensification on the future residential water demand in Auckland, this study developed 3 different growth scenarios. These scenarios considered the low, moderate and high levels of transition in the housing types. In the first scenario it was assumed that all rezoned single houses would change into the multi-unit housings with the minimum density (i.e. minimum number of units per building). In this scenario, it was assumed that the low-rise apartments would have two units, where the high high-rise apartment would build by four units. In contrast, for the high intensification scenario, it was assumed that the low-rise apartments would have 4 units per building. This is the average number of units currently is available in the Auckland low-rise apartments. For the high high-rise apartments, it was assumed that each building would have 50 units. This is the average number of units currently is available in the out of Auckland CBD high-rise apartments. The moderate intensification scenarios would also consider a middle position between the low and high intensifications. Table 6.3 outlines the three developed scenarios.

Table 6.3. Developed scenarios for future intensification in Auckland

Urban growth scenarios	Average number of units in low-rise apartments	Average number of units in high-rise apartment
Scenario 1: low intensification	2	4
Scenario 2: moderate intensification	3	25
Scenario 3: high intensification	4	50

These urban growth scenarios were combined with the water consumption and Unitary Plan information in order to estimate the prospective water consumption across different areas in Auckland. In this way, firstly the total daily water consumption across different areas units was estimated. The total water consumption was the sum of water use in each housing types, calculated through multiplying the annual average per capita water consumption by the total population in each housing group. Afterward, the average per capita daily water consumption (i.e. combined per capita water use included all housing types) was estimated for each area, through dividing the total daily water consumption by the associated total population. Table 6.4 shows the average per capita water consumption across all areas units in Auckland. The per capita water use in two clusters of the low-income and the high-income areas units under current housing composition (i.e. base scenario) was also shown in table 6.4. As shown in the table 6.4, the average per capita water consumption in Auckland is around 170 litres per person per day, varies between 163 and 190 across different areas.

The same procedure was also carried out to estimate the average per capita water consumption under different growth scenarios. In this way, firstly the number of dwellings in each housing type, across different area units, was estimated under different growth scenarios. This was calculated through multiplying the total number of dwellings in each housing type, based on the Unitary Plan, by the assumed number of units on it under each intensification scenarios. Afterward, the population in each housing types was estimated through multiplying the dwelling numbers by the household size in each groups. For this estimation, it was assumed that the current household size in each housing types remains constant at the current level. This is justifiable assumption since the household size typically changes very slowly over time (Statistics-NZ 2015). Then, the estimated population was multiplied by the per capita water consumption in order to estimate total water consumption in each groups. The total water consumption of different housing groups was subsequently aggregated in order to make total water consumption in each area. Combined total water consumption then divided by the total population to estimate average per capita water consumption for each scenario. Table 6.4 also shows the estimated per capita water demand under three different intensification scenarios. Under all scenarios, through transition of single houses to the higher density multi-unit housings, the total number of dwellings would increase. This increase would lead to the population increase and subsequently the total water consumption. However, in terms of per capita water consumption, on average, the changes due to the urban intensification would not be significant. This is mainly because by increasing the number of low-rise apartments the average per capita water demand may reduce slightly (i.e. per capita water demand in the low-rise apartments is slightly lower than single houses). However, the increase of high-rise apartments, having higher per capita water demand, would offset its effects. Thus, on average, the effects of transition of housing types (i.e. urban intensification) would be limited on the residential water use.

Table 6.4. Prospective water consumption under different intensification scenarios across different areas

Urban growth scenarios	Total number of dwellings	Total population	Total water consumption (m^3/day)	PCCac All areas[a]	PCCac L-income[b]	PCCac H-income[c]
Base	374000	1116000	190000	170	163	190
Scenario 1	560000	1351000	225000	167	162	180
Scenario 2	1136000	2534000	434000	171	166	180
Scenario 3	1785000	3860000	664000	172	167	180

Note: [a] annual average combined per capita water consumption (i.e. for all housing types) for entire Auckland (litre/person/day); [b] annual average combined per capita water consumption over lower income areas (litre/person/day); [c] annual average combined per capita water consumption over higher income areas (litre/person/day).

However, the results from table 6.4 also showed that the impacts of urban intensification on water use can be more remarkable in the wealthy areas, where the water consumption may decrease by around 5.5 percent. This is because in the high-income areas the outdoor water use (i.e. swimming pools, gardening, etc.) can make up a considerable share of single houses usage. Thus, transition to the apartments can limit the outdoor uses and subsequently reduce per capita water consumption for this group of users with high summer water consumption. In contrast, the transition in the housing types may increase the per capita water consumption by around 2 percent in the lower income areas, where the indoor water use is predominant.

In order to better understand the effects of urban intensification on seasonal variation of water demand, this study estimated the average per capita water demand for the summer (February) and winter (June) months under different growth scenarios (table 6.5). The estimated water use, shown in table 6.5, revealed that in the summer the per capita water consumption may decrease by around 7 percent in the high-income areas. However, in the lower income areas, where the outdoor water demand is limited, the changes in summer per capita water use were not significant. In contrast, in the winter, when the majority of water used indoor, the per capita water consumption may only decrease by 3 percent in the higher income areas, while in the lower income areas the water consumption may increase by 4 percent.

Table 6.5. Prospective seasonal variation of water consumption under different intensification scenarios across different areas

Urban growth scenarios	PCCsc[a] (Summer)			PCCwc[b] (Winter)		
	All areas[c]	L-income[d]	H-income[e]	All areas[c]	L-income[d]	H-income[e]
Base	180	170	205	163	157	179
Scenario 1	175	168	191	161	157	172
Scenario 2	177	171	191	165	162	174
Scenario 3	177	173	190	167	164	174

Note: [a] summer average combined per capita water consumption (i.e. for all housing types) (litre/person/day); [b] winter average combined per capita water consumption (litre/person/day); [c] all urban areas; [d] lower income areas; [e] higher income areas.

From the tables 6.4 and 6.5, it can be concluded that, in general, the urban intensification cannot considerably influence the water demand and its effects would be limited to the reducing water demand in the high-income areas specifically in the summer. This result generally supports the findings of Troy and Holloway (2004), where they challenged a contemporary urban policy assumption that housing form can offer significant savings in consumption of water and may lower levels of investment in urban water services.

The finding of this study provided a comprehensive vision about the prospective effects of urban intensification on water demand. This can help urban planners and policy makers to more reliably plan the water supply systems and assess the effects of urban planning on water consumption.

6.5. Conclusions

This study examined the prospective implications of urban intensification on the residential water consumption in Auckland. Urban intensification is considered as an effective urban growth management strategy helping to mitigate the social, economic and environmental concerns arising from the low density urban sprawl. This strategy promotes the use of intensive housing development, mainly in the form of multi-unit houses in and around existing urban centres. Although the social, economic and environmental consequences of compact city developments have been widely recognized, its consequence on residential water demand has not been clearly understood. This study evaluated the impacts of urban intensification on residential water demand in Auckland through the integration of water consumption, land-use and census microdata. Utilizing GIS-based urban databases in Auckland, this study developed a large sample of 60000 dwellings through data integration in order to evaluate water consumption across different housing types (i.e. single house, low-rise and high-rise apartments), socioeconomic groups (i.e. low and high income groups) and seasons (i.e. summer and winter). This information, subsequently, was joined with the Proposed Auckland Unitary Plan, outlining the future housing composition in Auckland, in order to estimate the future water demand in the city under different growth scenarios.

The results of this study showed that the water consumption varies between different types of residential dwellings, where the single houses had the highest household water consumption. The highest household water consumption in the single houses can be mainly attributed to the more outdoor uses (garden and swimming pool) and larger household in this sector. However, in terms of per capita, the high-rise apartments had the highest water consumption. The higher per capita water consumption in the high-rise apartments can be mainly attributed to the small household size in this sector, liming the effects of economies of scale in water use (for instance, full loads in washing machines, dishwashers, etc.). The low-rise apartments had the lowest water consumption in terms of both per household and per capita water consumption. This study also showed that the seasonal variation of water use is more remarkable in the single houses, specifically in the higher income areas, where the outdoor water uses are considerable. In contrast, in both high-rise and low-rise apartment the seasonal and variations of water demand is more limited since the indoor usage is predominant in these sectors.

In order to examine the effects of housing intensification on water use, this study combined the water consumption and Auckland Unitary Plan information under different growth scenarios. This study showed that in general housing transition from single houses to more intensified multi-unit houses cannot considerably affect per capita water consumption in Auckland. This is because the high per capita water consumption in the high-rise apartments would offset the effects of lower per capita water consumption in the low-rise apartments. Nevertheless, the urban intensification can decrease the average per capita water consumption up to 7 percent in the more affluent areas on summers, through limiting the outdoor uses. These findings can provide urban planners and policy makers with a comprehensive vision about the effects of urban intensification on water demand, where it can help them to more reliably plan for the future water supply systems.

This study introduced the data integration as an effective instrument to assess the effects of urban planning on water consumption. In recent years, with advances in database technology, data accessibility, computing power, and spatial GIS tools it is becoming more plausible to integrate disaggregated water consumption, land use and demographic data to make use the full potential of them in water demand studies. This data integration allows the visualization and evaluation of demand information that was not previously possible. It provides planners with greater insights on the manner by which water is consumed across different kinds of development, urban areas and over different seasons. This information can help water utilities to plan the water supply system in an optimal manner to meet future water demand.

Chapter 7

Conclusions and recommendations

This chapter outlines the major findings of this research. At the end of chapter, limitations of the study and recommendations for future researches are also presented.

7.1. Conclusions

This study proposed new approaches in data integration (i.e. combining data) and multi-scale analysis of water demand (i.e. household scale and census area scale). Using a rich source of urban databases in Auckland, this study utilized geographic information system to combine water consumption data with property characteristics, weather, water price and census microdata. The employed data integration technique helped the present study to develop a large sample of 60000 dwellings across Auckland metropolitan area. This sample included the information of around 31000 single houses, 18000 low-rise apartments and 11000 high-rise apartments. These large datasets enabled the study to fully evaluate water consumption across different housing types, urban areas and seasons in Auckland. It also enabled the present study to assess the spatial pattern of water consumption and the effects of urban density on the water consumption. In addition, by using the proposed multi-scale analysis approach, this study accomplished to evaluate the variation of responses to the determinants of water demand, including water price and weather variables, across different group of customers. This detailed information of water consumption was subsequently used to evaluate the prospective implication of housing intensification, promoted by the Proposed Auckland Unitary Plan, on the residential water use in Auckland.

This study demonstrated how the data integration can be used in the contemporary water demand study to fully address the complexity of water demand in the urban environments. In recent years, with advances in database technology, data accessibility, computing power, and spatial GIS tools it is becoming more plausible to combine disaggregated water consumption, land use and demographic data. The data integration can help to make use of the full potential of data in the water demand studies. It allows the visualization and evaluation of demand information that was not previously possible. It also provides planners with greater insights on the manner by which water is consumed across different kinds of development, urban areas and seasons. In addition, combining the water consumption data with the land use and demographic information can help to provide a reliable perspective regarding how urban development policy may affect future water consumption. This knowledge can help the optimal planning for water supply and treatment systems in order to meet the future water demand in the complex urban environments.

The following sections outline the major findings of this study.

7.1.1. Water consumption across different housing types

Through disaggregated analysis of water demand, this study showed that the residential water consumption in Auckland varies significantly across different housing types, customer groups, urban areas, and seasons. The study revealed that single houses had the highest per household water use. On average, the daily water consumption in the single houses was around 54 percent higher than the apartments. The higher household water consumption in the single houses can be mainly attributed to the more outdoor uses (garden and swimming pool) and larger household size in this sector. In Auckland, the household water consumption in the high-rise and the low-rise apartments was more comparable. On average, the daily water use in the high-rise apartments was only around 2 percent higher than the low-rise apartments.

However, in terms of per capita water consumption the study revealed that the high-rise apartments had the highest usage. On average, the per capita water consumption in the high-rise apartment was around 14 and 23 percent higher than the single houses and the low-rise apartments, respectively. The higher per capita water consumption in the high-rise apartments can be mainly attributed to the small household size in this sector. In general, household size can exert an important effect on per capita water consumption. By decreasing the household size the per capita water consumption typically increases since the economies of scale cannot be accomplished in the smaller households (e.g. full loads in washing machines, dishwashers, etc.).

This study also showed that, regardless of housing types, the residential water consumption varied significantly across different group of consumers and urban areas based on the income levels. In general, people in the higher income areas consumed more water, on the per capita basis, since they are more likely to own water-using capital stock such as swimming pools. In Auckland, the variation of water consumption across different income groups was more remarkable in the single houses. On average, the per capita water consumption in the higher income areas was around 18 per cent higher than the lower income neighbours. This was in contrast to 12 percent and 3 percent of water consumption variation across low and high incomes areas for the low-rise and high-rise apartments, respectively.

The seasonal variations of water consumption were also more remarkable in the single houses, specifically in the wealthy areas, where in summers the per capita water consumption increased by around 17 percent. The high seasonal variation of single houses water use in the affluent areas can represent the high level of outdoor water usage in these areas. In contrast, the seasonal variation of water consumption in the apartment sectors were more limited (around 5 percent on average), meaning that the indoor usage is predominant in these sectors.

7.1.2. Determinants of water consumption across different housing types

Using the data integration and the multi-scale analysis approaches, this study examined the effects of a wide range of variable (i.e. household and housing characteristics, weather and water price) on residential water use across different housing types, urban areas and seasons in Auckland. The study utilizes regression methods specific to panel data to evaluate the determinants of water demand. A panel data set consists of a number of individual customers or customer groups where their characteristics (e.g. water use, income, household size) are measured over time (e.g. months, or years). The panel data models incorporate both temporal and spatial variations of water use in the modelling. Thus, they can generate better parameter estimates than traditional regression approaches.

The results of present study revealed that household size was the most important determinant of apartment water use in Auckland. In all housing types, the household water consumption increased with the household size. However, the increase of household water was less than proportional to the increase in household size due to economies of scale. The studies also revealed that the effect of household income on water use was more remarkable in the single houses. This is because higher income households living in the single houses were more likely to use water for the outdoor activities. In Auckland, the main source of outdoor water use is swimming pools. The study showed that summer water consumptions, specifically in the single houses at the high income areas, was significantly correlated with the percentage of houses with swimming pools in those areas. In contrast, the presence of garden in the house was found to be insignificantly correlated with water use. This is because in Auckland the majority of houses typically plant native grass, shrubs and trees in the gardens, which basically do not require much water. Moreover, the year-around precipitations in Auckland reduce the needs of irrigation for this type of landscaping. This study also revealed that other household and housing characteristics such as age of residents, property ownership, section size, and density of single houses generally were not significantly corrected with household water use.

Through disaggregated multi-scale analysis approaches, this study also evaluated the variation of responses to the water price and weather across different consumers groups. Through estimation of price elasticity of water demand across different groups, the study showed that in general none of group of consumers considerably response to the water price in Auckland under the current price structure. The low price elasticity of water demand in Auckland can be attributed to the flat-rate pricing scheme and the small share of water bill in total expenditure of households. The study also showed that in the low density housings (i.e. single houses and low-rise apartments) water consumption was more significantly affected by the weather condition, where the higher temperature and lower rainfall increased the water use. However, in the high-rise apartments the correlation between water use and weather variables was insignificant. This is because single houses and low-rise apartment had a higher outdoor water use, in comparison to the high-rise apartment. Thus, they showed more sensitivity to the weather changes.

7.1.3. The effects of housing intensification on water consumption

Through combining the water consumption data with the Auckland Unitary Plan outlining the future housing composition in Auckland, this study examined the prospective implication of housing intensification. This study developed three different growth scenarios including low, moderate and high levels of housing transition in Auckland. In the first scenario, it was assumed that all the single houses would turn into the multi-unit housings with the minimum density (i.e. low-rise apartments with two units and high high-rise apartments with four units). In contrast, for the high intensification scenario, it was assumed that the low-rise apartment would have 4 units per building (i.e. the average number of units currently is available in the Auckland low-rise apartments). The high-rise apartments would also include 50 units per building (i.e. the average number of units currently is available in the out of Auckland CBD high-rise apartments). The moderate intensification scenarios also considered a middle position between the low and high intensifications.

The study showed that through transition of single houses to the higher density multi-unit housings, in all scenarios the total number of dwellings would increase. This increase would lead to the population increase and subsequently the total water consumption. However, in terms of per capita water use, on average, the consumption changes due to the urban intensification would not be significant. This is mainly because by increasing the number of low-rise apartments the average per capita water demand may reduce slightly (i.e. per capita water demand in the low-rise apartments is slightly lower than single houses). However, the increase of high-rise apartments, having higher per capita water demand, would offset its effects. Thus, on average, the effects of transition of housing types (i.e. urban intensification) would be limited on the residential water use.

However, the results also showed that the impacts of urban intensification can be more remarkable in the wealthy areas, where the water consumption may decrease by around 5.5 percent. This is because in the high-income areas the outdoor water use (i.e. swimming pools, gardening, etc.) can make up a considerable share of single houses usage. Thus, transition to the apartments can limit the outdoor uses and subsequently reduce per capita water consumption for this group of users with high summer water consumption. In contrast, the transition in the housing types may increase the per capita water consumption by around 2 percent in the lower income areas, where the indoor water use is predominant.

Moreover, the housing intensification can affect the seasonal variation of water demand. The results of study showed that due to the intensification the per capita water consumption, in the summers, may decrease by around 7 percent in the high-income areas. However, in the lower income areas, where the outdoor water demand is limited, the changes in summer per capita water use were not significant. In contrast, in the winter, when the majority of water used indoor, the per capita water consumption may only decrease by 3 percent in the higher income areas, while in the lower income areas the water consumption may increase by 4 percent.

From these results it can be concluded that, in general, the urban intensification cannot considerably influence the water demand and its effects would be limited to the reducing water demand in the high-income areas specifically in the summer. This result can challenge the contemporary urban policy assumption that housing form can offer significant savings in consumption of water and may lower levels of investment in urban water services. The finding can help urban planners and policy makers to more reliably plan the future water supply systems and assess the effects of urban planning on water consumption.

7.2. Limitations

This study combined GIS data from different resources to evaluate residential water demand in Auckland. Using the data integration techniques, this study managed to evaluate the effects of a wide range of variables including household and housing characteristics, water price and weather on water use. However, the effects of household water use attitudes and water use efficiency did not consider in this study since the information of those variables was not available.

7.3. Recommendations for future researches

Using the proposed approaches in data integration and multi-scale analysis of water demand, this study managed to provide valuable knowledge regarding the variation of water consumption across different group of consumers and the effects of housing intensification in Auckland. However, there are still few unexplored domains for which more detail investigation can be carry out in order to better understand the water consumption in Auckland.

Following is a list of recommendation for the further research.

- This study can be companied with a household survey in order to evaluate the effects of household water use attitudes and water use efficiency which did not considered in this study since the employed data of property characteristics and census microdata was able to capture those effects.
- This study also can be enriched by a more detailed study of high-rise apartment water demand using household survey to fully understand the main reasons behind the high per capita water consumption in this sector and perhaps propose some initiatives to regulate that.
- Since the swimming pool is the major determinate of high water use in Auckland, a separate study also can target this group of costumer in order to find out the best practices for regulating water demand across this group of high water user.

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