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A MULTI-SCALE ANALYSIS OF LOW-RISE APARTMENT WATER DEMAND THROUGH INTEGRATION OF WATER CONSUMPTION, LAND USE, AND DEMOGRAPHIC DATA[1]

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ABSTRACT: Over the past decades, multi-unit housing developments have been vastly expanded across urban areas due to the population growth. To properly supply water to this growing 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 this sector. This study integrated apartment water consumption, property characteristics, weather, water pricing, and census microdata to overcome this issue. Using a rich source of GIS-based urban databases in Auckland, New Zealand, the study developed a large dataset containing the information of 18,000 low-rise apartments to evaluate the determinants of water use both in the household scale and aggregated scale. The household-scale demand analysis helped to assess the heterogeneity in responses to the demand drivers specifically water price across different consumer groups, whereas the aggregated analysis revealed the determinants behind the spatial variation in water demand at the census area unit level. Through applying panel data models, the study revealed the household size as the most important determinant of apartment water use in Auckland, where other socioeconomic factors, building features, and water pricing were not significant determinants. This knowledge of determinants of water demand can help water planners to better manage water demand in the compact urban environments.

(KEY TERMS: water use; planning; geographic information system (GIS); apartments; data integration; price elasticity; panel data model.)

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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 multiunit housing (e.g., apartments, flats, etc.) in many cities around the world (Randolph, 2006; Haarhoff *et al.*, 2012). To properly supply water and manage consumption in this fast growing sector, it is essential to understand the determinants of its water use. Although many studies have investigated the factors affecting residential water use in the single-unit housing (e.g., separate houses) or as total (Wentz and Gober, 2007; Schleich and Hillenbrand, 2009; Chang *et al.*, 2010; House-Peters *et al.*, 2010; Polebitski and Palmer, 2010; Rockaway *et al.*, 2011), only few studies have evaluated the determinants of water use in the multiunit housing. This segregation is necessary as there

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may be substantial differences in the determinants of water use across the single-unit and the multi-unit houses. This distinction can be attributed to the differences in the socioeconomic characteristics of residents and the level of outdoor usage (e.g., gardens and swimming pools) between these two housing types (Russac *et al.*, 1991; Fox *et al.*, 2009).

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

This study focuses on the understanding of water consumption and its determinants in low-rise apartments (i.e., one-storey to three-storey buildings) in Auckland, New Zealand. The low-rise apartment, also known as flat, is the second common housing type in Auckland, making up around 21% of housing stock in this city.

In general, the empirical studies of water demand targeting multi-unit housing 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 10-55% of variation in water consumption in different types of apartment (i.e., high rise, multi-storey, low rise). Mayer *et al.* (2006) also evaluated apartment water demand across 13 cities in the United States (U.S.) 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. By examining some of the indoor and the outdoor features of buildings through regression analysis, they concluded that the per bedroom water use increased with the pool area, dishwashers, and in-unit laundry facilities.

One of the main reasons that caused the study of apartment water demand remains largely unexplored in comparison to the single-unit housing is the lack of readily available data in this sector. To mitigate this data shortage, this study utilized geographic information system (GIS) to integrate 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 18,000 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 in the household scale and the aggregated scale. In general, the household-scale data can be used to assess the heterogeneity in responses to the demand drivers specifically water price across different consumer groups (Höglund, 1999; Arbués *et al.*, 2004, 2010), whereas the aggregated data can help to evaluate the determinant behind the spatial variation in water demand (Wentz and Gober, 2007; Chang *et al.*, 2010; House-Peters *et al.*, 2010; Polebitski and Palmer, 2010).

For the multi-scale water demand analysis, 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 to include the sociodemographics characteristics of households living at the apartments from census microdata. The information of water pricing and weather for different areas is also added into both the datasets to enable the evaluation of the effects of these variables on apartment water demand as well.

Using the developed datasets, the study evaluates the effects of household socioeconomics (e.g., household income, household size, age of residents), dwelling characteristics (e.g., number of bedrooms, garden size, swimming pool), weather (e.g., air temperature and rainfall), and water pricing on apartment water use. All of these variables have been frequently reported as the influential factors on the empirical water demand studies (House-Peters and Chang, 2011).

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 (Polebitski and Palmer, 2010; Dziedzic *et al.*, 2015). In an early attempt of data integration, as a pilot study, Troy and Holloway (2004) linked water demand and property information in six census areas in Adelaide, Australia, 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 in parcel level to examine the relationship between land-use planning and water demand. Polebitski and Palmer (2010) integrated utility billing data with census demographic and property appraisal data in census track level to forecast residential 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 to use the full potential of rich data available with the organizations. In contrast, multi-scale analysis of water demand has been relatively new in the domain of water demand study. In a recent study, Ouyang *et al.* (2014) evaluated 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 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 authors, 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 analyze water demand both at the household and census area unit levels. The period of the analysis spans from July 2008 to July 2014. Panel data models are typically preferred to the time-series and cross-sectional models because they include the advantages of both models and can provide more accurate parameter estimates (Arbués *et al.*, 2003; Polebitski and Palmer, 2010). In recent years with increase in the data availability these models have been used more frequently (Nauges and Thomas, 2000; Martinez-Espiñeira, 2002; Arbués *et al.*, 2004, 2010; Kenney *et al.*, 2008; Polebitski and Palmer, 2010; Fenrick and Getachew, 2012). However, to the knowledge of the authors, the panel data model never has been used for the water demand analysis in the apartment sector.

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.

STUDY AREA

Auckland is the largest city in New Zealand. This city formerly was comprised from seven territorial authority areas (i.e., 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 unitary authority 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 the urban structure. Between 2001 and 2013 the dwelling density in Auckland has increased from 86 to 102 dwellings per square kilometer (Goodyear and Fabian, 2014). In general, the increase in dwelling density has been due to the decrease in section size of single-unit housing and the increase in number of multi-unit dwellings (LINZ, 2015; Statistics-NZ, 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). In general, higher density living is seen as a credible path for improving urban sustainability (Boon, 2010; Haarhoff *et al.*, 2012).

Although in Auckland the housing stock is dominated by the single-unit houses (75% of dwellings are single unit), in recent years the tendency toward apartment living has gradually increased. Between 2006 and 2013 the number of apartments in Auckland has increased by 11.3%, whereas single-unit housing has experienced an increase of 5.8% over this period (Statistics-NZ, 2015).

The variation in 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 5 people in some parts of south Auckland where multi-family household is more common. 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 1,240 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).

DATA INTEGRATION

This study integrates 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 are available both at the household scale and the census area unit scale (i.e., after aggregating the data). However, the household socioeconomic data are only available at the census area unit level.

In this study, the water consumption data were 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 as 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 a 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 into the monthly period. 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 the property and its geographical location (i.e., X and Y coordinates), type of meter (i.e., domestic, commercial, etc.), and the 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 information such as housing type (i.e., single unit, 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 garden size of property is also calculated by subtracting the sum of building footprint and impervious area from section size.

The weather data, including monthly average air temperature and rainfall, were provided by the New Zealand's National Climate Database (CliFlo, 2015) for the periods of 2008-2014. This data came from 15 weather stations across Auckland and were 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 local councils in 2010, Watercare took over the 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 collected 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 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 stories) was collected at the census area unit level. Census area unit is the second smallest geographical unit that census information is available within (the smallest unit is meshblock; however, in that level many variables would not be available to protect the information of residents).

In this study, the data integration was carried out using 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 350,000 housing units including single-unit and multi-unit (i.e., low-rise and high-rise apartments) became available for the demand analysis.

This article only focuses on the evaluation of water demand in the low-rise apartments. Low-rise apartments made up around 21% of housing stock in Auckland. Thus, after filtering the database based on the property type around 70,000 apartments remained for the rest of analysis. From this 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, the information of 40,000 low-rise apartments remained available for the rest of the study. In this dataset, the multi-unit houses 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 18,000 apartments with joined structures for the final demand analysis.

Using GIS, the water pricing and weather information were also included in the database to complete the household-scale dataset. This dataset is used to investigate mainly the price elasticity of water demand among different groups of consumers (i.e., low-, middle-, and high-income households). Afterward, the dataset is aggregated at the census area unit level to include census information to examine the determinants behind the spatial variation in water demand in Auckland.

WATER DEMAND MODELS

This study applies regression methods specific to panel data to understand the determinants of water demand both in the household and area unit scales. A panel of data is the repeated observations for specifics subjects over multiple time periods (Hill *et al.*, 2010). In this study, the subjects are individual apartments in the household scale and census area units in the aggregated scale analysis. The repeated observations are changes in water consumption, water pricing, socioeconomic, and weather within houses or census area units over six years. This study examined three common panel data methods (i.e., pooled, fixed, and random effects models). In the pooled method, the regression model has a single intercept. However, in fixed effects and random effects models the intercept is allowed to vary between subjects (Hill *et al.*, 2010). Therefore, fixed effects and random effects models are typically an improvement over pooled models as they can capture the variability among subjects using varying intercepts. In panel data models, a pooling test (partial F-test) is used to examine this improvement (Hill *et al.*, 2010). The null hypothesis of this test is that all intercepts between subjects are equal. If the *p*-value associated with the test statistics is below the range of accepting the null hypothesis (i.e., 0.05), it can be concluded that the panel estimators (i.e., fixed and random effects) are preferred to the pooled model.

To choose an appropriate method between fixed effects and random effects 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, the dependent variable is annual average daily water consumption over six years (i.e., August 2008 to July 2014). To calculate this, the annul 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 were 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 metered 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 submetered individually by the building managers). In this study, two-thirds of studied apartments (around 12,000 units) had individual meters (i.e., a single meter for each apartment), whereas around 6,000 apartments, over around 360 apartment complexes, had master meters. 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.

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 showed that there is no significant difference in water use between apartments with and without individual meters ($t = -1$, $p > 0.1$). 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 12,000 apartments with individual meters for the demand analysis 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 in water demand, the entire sample of apartments (i.e., data for 18,000 apartments) is used as the census data included the information of both groups of apartments (i.e., small and large low-rise apartment buildings, with or without meters).

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. As the wastewater price in Auckland is calculated based on the metered water use, the study summed up the charges of water and wastewater. This helps to evaluate the overall effect of volumetric and fixed charges.

Using the household-scale data, this study evaluated the effects of water pricing, along with other variables, across different groups of customers. In this way, the individual apartments were clustered into different groups based on the apartment value, as a proxy of household income and water consumption. The k-means algorithm (Everitt *et al.*, 2011) was used for the clustering. Using cluster analysis, three different groups of households were distinguished in Auckland (i.e., high income, middle income, and low income).

At the level of census area unit, similar to the household level, the dependent variable is the annual average daily water use. In this level, in addition to property characteristics, weather variables, and water price, census variables including household size, household income, age of residents, and number of bedrooms were also added in the model. A yearly estimate of census variables was used for the panel data analysis.

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 a level based on the apartment value, as proxy of income, and average daily water consumption. Based on the pseudo F-statistic, this is the optimal number of clusters which can maximize both within-group similarity and between-group difference. Table 1 provides a list of variables which were used for demand analysis in household and census area unit scales. In this study the prices and income were deflated into real 2013 terms using the customer price index (Statistics-NZ, 2015).

TABLE 1. List of Variables Available for the Multi-Scale Demand Analysis.

Variables	Definition	Units	Scale of Analysis
DWU	Daily water use	Liter/apartment/day	Household, Census area unit
AValue	Apartment value in year 2013	NZ dollars	Household, Census area unit
GardSize[1]	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

[1]GardSize = garden size in each apartment building/number of apartments in the building.

RESULTS AND DISCUSSION

Water Demand Models at Household Scale

This study developed four panel data models at the household scale. The first model used entire sample of apartments with individual meter, whereas the models 2, 3, and 4 used the grouped data for the low-, middle-, and high-income households, respectively.

The study examined pooled, fixed, and random effects models to select the best panel data method. For all four models the result of pooling tests showed that the panel models (i.e., fixed and random effects models) are an improvement on the pooled model. To choose between fixed and random effects models the

TABLE 2. Fixed Effects Water Demand Models 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***
Number of studied apartments	11,187	4,677	3,858	2,652

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

Hausman test was carried out for all datasets. The result of tests revealed that random effects model is not valid on the household-scale datasets, thus the fixed effects 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 effects 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 shows the results of household-scale models. 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.

The results of the study showed that the price elasticity of water demand was negative and significant for all models, varying from −0.01 to −0.03. The price elasticities obtained in this study are within the range of values obtained by a number of previous studies (Arbués *et al.*, 2003, 2004; Abrams *et al.*, 2012). 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. The low price elasticity of apartment water demand can be attributed to the fact that in this sector water is mainly used for the basic indoor needs (i.e., drinking, cooking, and sanitary needs) (Zhang and Brown, 2005; Billings and Jones, 2008). 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 study 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. As the water costs usually comprise 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, whereas the temperature was significant for both the middle- and high-income groups. This result was expected as 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; Schleich and Hillenbrand, 2009; Mieno and Braden, 2011). Table 3 compares the water consumption and housing characteristics among three different groups of consumers in Auckland. The results showed that the expensive

TABLE 3. Water Consumption and Apartment Characteristics for Different Groups of Consumers.

Variables	Low Income	Mid Income	High Income
DWU	453	194	451
AValue	314,000	350,000	677,000
GardSize	169	162	160
Units	2.7	2.7	2.5
Buildings with pool (%)	1.2	0.9	4.6
Number of studied apartments	4,677	3,858	2,652

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 consumers 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.

Water Demand Models at Census Area Unit Scale

Similar to the household-scale analysis, this study examined pooled, fixed, and random effects models to select the most appropriate panel data method for the aggregated dataset. The result of pooling test showed that the panel models are an improvement over the pooled model. The Hausman test also revealed that the random effects model is more efficient than fixed effects model and can better produce consistent parameter estimates in this dataset. Table 4 shows the results of random effects model. The variables were transferred by natural logarithm, thus the coefficients are elasticities.

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

TABLE 4. Random Effects Water Demand Model at 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***
Number of area units	201

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

In general, the census area unit model produced comparable results to the household-scale models for the water price and weather variables. The random effects model estimated a volumetric price elasticity of −0.03, which was low but statistically significant. The fixed price 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 results of this study showed that household size is the most influential factor on the apartment water use. The estimated coefficient for the household size in the random effects 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.*, 2003, 2004; Hoffmann *et al.*, 2006; Schleich and Hillenbrand, 2009).

The study 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 affects household outdoor water consumption rather than indoor (Polebitski and Palmer, 2010; Mieno and Braden, 2011). 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 units per building or complex, garden size, and swimming pools on the water demand. The study showed that the number of units in the buildings is not significantly correlated with the water demand. This result 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 study revealed that garden size and swimming pools, 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-round precipitation in Auckland reduces the need 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 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.

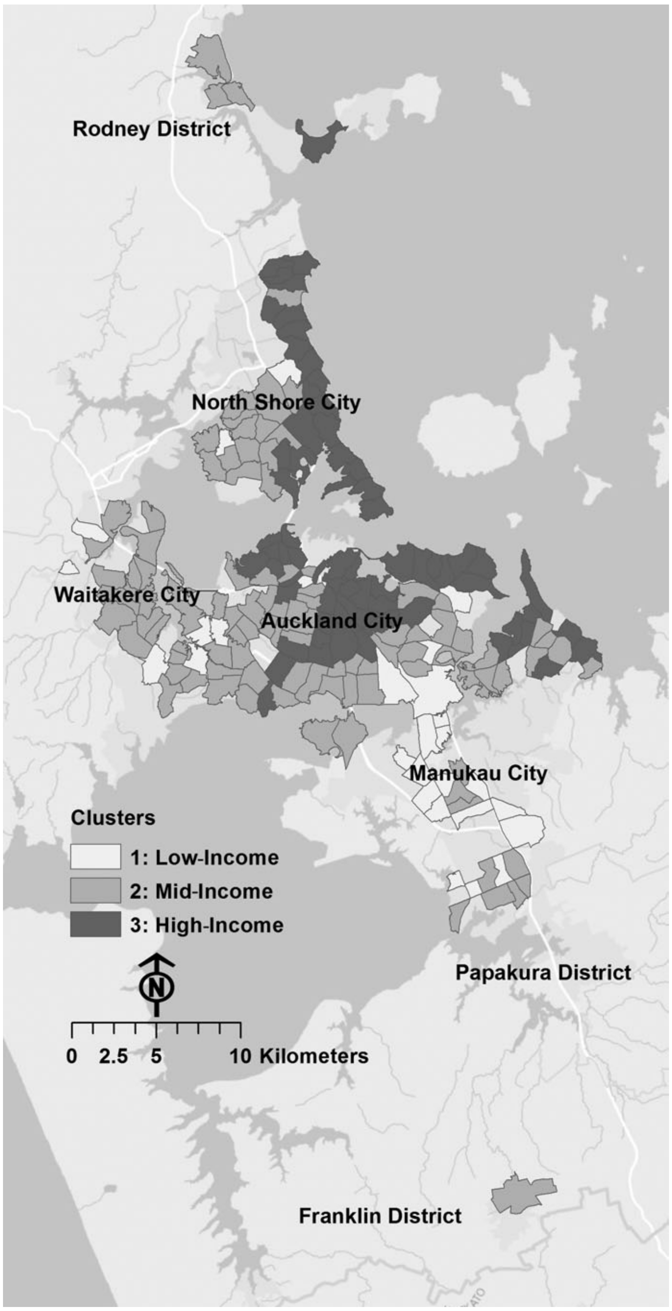

FIGURE 1. Three Clusters of Census Area Units in Auckland.

Table 5 compares water consumption, housing, and household characteristics across three groups of census area units.

Similar to the household-scale demand analysis, the results of this study 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 to 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 in water demand among the high-income suburbs is also higher than low- and middle-income suburbs (Figure 2). However, in general the seasonal variation in apartment water consumption in Auckland is limited (less than 10%). This highlighted the fact that the indoor water use is the predominant usage at the Auckland apartments.

Management Implications

This study thoroughly evaluated water demand in the low-rise apartments in Auckland. As the multi-unit

TABLE 5. Water Consumption, Housing, and Household Characteristics across Different Groups.

Variables	Low Income	Mid Income	High Income
DWU	451	334	381
AValue	257,000	328,000	562,000
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	46,300	48,900	65,900
BRooms	2.3	2.2	2.4
AgeUR	30	35	38
Number of area units	30	102	69
Per capita water use (liter/person/day)[1]	161	145	173

[1]Per capita water consumption was estimated through dividing the household daily water consumption by household size.

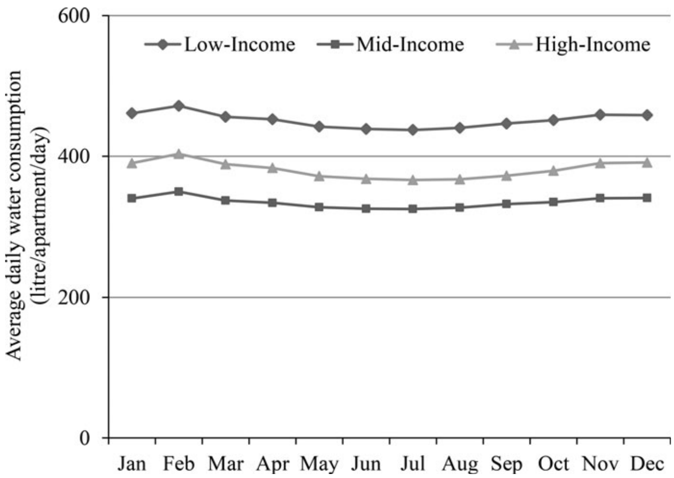

FIGURE 2. Monthly Variation in Apartment Water Consumption across Three Groups of Census Area Units.

housing 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 in 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 consumers also was more sensitive to the weather condition as 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. These 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.

CONCLUSIONS

This study proposed a multi-scale analysis approach to thoroughly evaluate the determinants of low-rise apartment water demand in Auckland, New Zealand. This knowledge would help to reliably consider the implication of fast growing apartment living on the future water and wastewater planning in Auckland.

This study utilized GIS to integrate 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 analysis can help to evaluate the heterogeneity of responses to the determinants of water demand, practically water price, across different groups of customers, while the aggregated data analysis can help to assess the determinants behind the spatial variations of water consumption.

This study applied panel data analysis in both scales, over a period of six years. 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 households with higher income are more sensitive to the weather conditions as 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 the 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 aggregated 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 characteristics (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) as 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 of the full potential of them in water demand studies. This data integration through multiscale 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.

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