Future implications of urban intensification on residential water demand

Saeed Ghavidelfar, Asaad Y. Shamseldin & Bruce W. Melville

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Future implications of urban intensification on residential water demand

Saeed Ghavidelfar *, Asaad Y. Shamseldin and Bruce W. Melville

Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand

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Over recent 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 first evaluated water consumption in three major housing types in Auckland including single houses, low-rise and high-rise apartments. Using the geographic information system, the water consumption information, estimated from a large sample of 60,000 dwellings across Auckland, was subsequently integrated with the Proposed Auckland Unitary Plan outlining the future housing composition over different areas in Auckland. Through developing different growth scenarios, the study showed that the housing transition from single houses to more intensified multi-unit houses cannot considerably affect the average per capita water consumption in Auckland.

Keywords: residential water use; housing types; urban intensification; data integration; geographic information system (GIS)

1. Introduction

Over recent decades, Auckland has experienced a vast expansion of urban areas due to rapid population growth and low-density housing developments. In order to mitigate the social, economic and environmental concerns arising from 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 (PAUP 2015; Haarhoff *et al*. 2012).

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). The Unitary Plan encourages greater intensification by 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 mixed housing zones (i.e. where construction of low-rise apartments with less than four

*Corresponding author. Email: sgha885@aucklanduni.ac.nz

storeys is allowed) or more intensified terraced housing and apartment zones (i.e. where construction of high-rise apartments with four 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 per cent of residential areas in Auckland would continue to be part of single housing zones. However, over 60 per cent of residential areas would turn into mixed housing zones with low-rise apartments. Around 6 per cent of residential areas in Auckland also include terraced housing and apartment zones where the construction of high-rise apartments is allowed. This can lead to enormous changes, where currently more than 75 per cent of housing in Auckland is 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 sociodemographic characteristics of residents and the level of outdoor usage (e.g. gardens and swimming pools) by them (Fox, McIntosh, and Jeffrey 2009; Wentz *et al*. 2014; Domene and Saurí 2006; Loh, Coghlan, and Australia 2003; Zhang and Brown 2005; Russac, Rushton, and Simpson 1991; Troy and Holloway 2004).

In order to assess the implications of urban intensification on the residential water demand in Auckland, this study first 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 are not usually readily available. This is one of the main reasons why the empirical studies comparing water demand in different housing types remain very limited. In an early study in the United Kingdom, Russac, Rushton, and Simpson (1991) investigated water demand in housing of different architectural types and concluded that water consumption for single houses is higher than more intensified dwellings such as semi-detached houses 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 the 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 housing is higher than high-density housing mainly due to outdoor uses. Fox, McIntosh, and Jeffrey (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 in semi-detached houses 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 vary significantly over urban areas mainly due to heterogeneity in the sociodemographic characteristics of households (e.g. household size and income) and housing features (e.g. size of housing, presence of a 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 geographic information system (GIS)-based urban databases in Auckland to develop a large sample of 60,000 houses of different types, through data integration. 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 at parcel level 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 appraisal data at census track level 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 on a large metropolitan scale such as Auckland.

Using 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 consumption 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 us to estimate per capita water consumption in each housing group across 300 census area units in Auckland. This study uses 6 years of monthly water consumption data (i.e. 2008–2014) and 2 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. By 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 future water supply and treatment systems in Auckland. To the current authors' knowledge, this important subject has never been investigated in the literature on water demand to this extent.

This article is organized in the following order. After the introduction, a review of the study area is presented. Afterwards, 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.

2. Study area

Auckland is the largest city in New Zealand. This city was formerly comprised of 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 single authority known as the Auckland Council.

Auckland has experienced a fast growth, both in population and housing stock, over recent decades. The population of Auckland has increased by 22 per cent since 2001, reaching around 1.4 million people in 2013 (Statistics-NZ 2015). This growth has led to low-density urban expansion, since the majority of dwellings in Auckland are single houses (i.e. around 75 per cent). However, in recent years with decreasing section sizes for single houses and an 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, to reach 86 to 102 dwellings per square kilometre between 2001 and 2013 (Goodyear and Fabian 2014).

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

In Auckland, the variations in 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 multi-family 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 the population is around 35 years, whereas in the low-rise and high-rise apartments the age of the population is 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 1,240 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).

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 were provided by Watercare Services Limited, an Auckland Council Organization, for the period of 2008–2014. These data do 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 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 these 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 (i.e. X and Y coordinates), type of meter (i.e. domestic, commercial, etc.) 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 submetered individually by the building managers). In this study, where the individual meter data were not available, the housing average water consumption was estimated by 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 data-set contains information on 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 for the section (as a proxy for the age of the property) and the address of the property.

The socioeconomic information on households was obtained from Statistics New Zealand Data Lab (Statistics-NZ 2015) for the 2006 and 2013 census. 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. The census area unit is the second smallest geographical unit in which the census information is available. The smallest unit is meshblock, however at that level many variables would not be available in order to protect the information of residents.

In this study, the data integration was carried out using GIS. The water consumption and property data were first arranged in GIS and linked together using the addresses and geographical coordinates. With this data integration, the information on water consumption and property for around 350,000 housings including single houses, low-rise and high-rise apartments became available for 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 data-set based on the housing type. In Auckland, around 75 per cent of houses are single-unit. Thus, by filtering the database based on the property type, around 260,000 single houses were identified. From this filtered data-set, the houses with replaced meters (i.e. houses with more than one meter record) were excluded from the analysis. This is because in these houses the records from erroneous old meters usually overlap the new meter records for a period of time, thus they may create errors in the estimation of historical water consumption. After this data filtering, around 130,000 single-unit houses remained available for the demand study. From this data-set, a random sample of 31,000 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 houses 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 show the spatial variation in 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 per cent of housing stock in Auckland. Thus, by filtering the data-set based on the property type, around 70,000 low-rise apartments were identified. From these filtered data, the houses with replaced meters were excluded from the analysis. After this data filtering, information on 40,000 low-rise apartments remained available for the rest of the analysis.

In this data-set, the multi-unit houses may either have a joined structure or a 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 apartments as a dwelling with a joined structure, the data-set was filtered by this criterion leaving around 18,000 low-rise apartments with joined structures for the final water demand study in this sector.

The high-rise apartments also comprised around 4 per cent of housing stock in Auckland. Thus, by filtering the database based on the property type, around 15,000 apartments from 190 residential apartment buildings were identified in Auckland. From this filtered data-set, 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 cafés) were excluded from the database, leaving 147 apartment buildings with around 11,000 units for the final water demand analysis. Similar to single house 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 60,000 dwelling was developed in this study. This enables the study to fully investigate the variation in water demand across different housing types, urban areas and seasons in Auckland. The developed data-set was subsequently aggregated at the census area unit scale in order to add census socioeconomic information, specifically household size, for each housing type. The household size information at the census unit level can help to estimate average per capita water use, for each housing type, at a fine spatial scale. The average per capita water use can be estimated by 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 future water demand in Auckland, the water consumption information was joined with the Auckland Unitary Plan data. The data for the proposed Auckland Unitary Plan were obtained from the publicly available database at the Auckland Council (PAUP 2015). This data-set shows the zoning information (i.e. permitted housing types in each section) for all property in Auckland.

4. Results and discussion

4.1. Water consumption

Developing a large sample of housing through data integration provided a unique opportunity for this study to thoroughly evaluate the variations in water consumption across different housing types, seasons and urban areas. Table 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 was also

Table 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

estimated. The results from Table 1 revealed that the average water consumption in the single-unit housing is significantly higher than for multi-unit housing (i.e. low-rise and high-rise apartments). These results are in agreement with other water demand studies (Fox, McIntosh, and Jeffrey 2009; Clarke *et al*. 1997; Domene and Saurí 2006; Russac, Rushton, and Simpson 1991; Troy and Holloway 2004). In general, the higher water consumption of single houses can be attributed to higher outdoor usage (garden and swimming pool), larger household size and more water appliances (due to greater space) in this sector (Fox, McIntosh, and Jeffrey 2009; Domene and Saurí 2006; Russac, Rushton, and Simpson 1991).

The estimated water consumption, shown in Table 1, also revealed the average per capita water consumption 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, for example, on gardens and swimming pools or in multiple toilets and bathrooms (Domene and Saurí 2006; Randolph and Troy 2008; Fox, McIntosh, and Jeffrey 2009). 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 economies of scale cannot be achieved in smaller households (for instance, full loads in washing machines, dishwashers, etc.) (Domene and Saurí 2006; Hummel and Lux 2007; Arbués, García-Valiñas, and Martínez-Espiñeira 2003). 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 per cent of high-rise apartments in Auckland are rental). In general, tenants usually have little or no control over their 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 in water use may also be significantly different across housing types (Figure 1).

As shown in Figure 1, the seasonal variation in 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 indoor usage is predominant, the seasonal variation in water use is more limited. This result is in agreement with other water demand studies (Domene and Saurí 2006). In Auckland, although the seasonal variation for low-rise apartments is limited, the pattern of it is still 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 in water use does not follow the local climate (i.e. winter water consumption is slightly higher than summer water consumption). Ghavidelfar, Shamseldin, and Melville (2016) showed that the seasonal pattern in water use in Auckland high-rise apartments more closely follows the tertiary education calendar in New Zealand, rather than usual summer

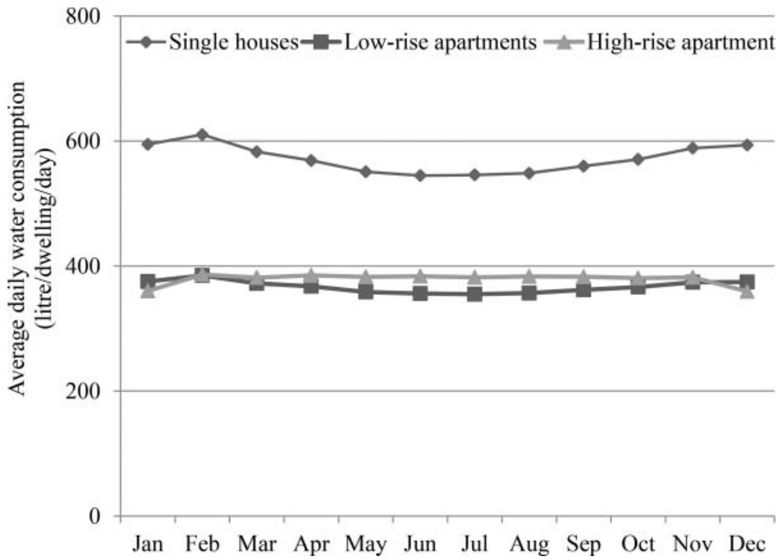

Figure 1. Seasonal variation in water consumption across different housing types in Auckland.

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 higher 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, Parandvash, and Shandas 2010; House-Peters, Pratt, and Chang 2010; Polebitski and Palmer 2010). This is because a larger income usually increases the standard of living, expressed in the presence of more water-using appliances and amenities, and outdoor water facilities (Domene and Saurí 2006; Billings and Jones 2008; Mieno and Braden 2011; Arbués, García-Valiñas, and Martínez-Espiñeira 2003). In order to investigate water consumption across different income groups in Auckland, this study applied cluster analysis to group urban areas in relation to per capita water use and household income. 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. Based on the pseudo F-statistic, this is the optimal number of clusters which can maximise both within-group similarity and between-group difference. Figure 2 shows two clusters of census areas in Auckland.

Table 2 shows the average per capita water consumption and the sociodemographic characteristics of household living in three housing types across these two clusters.

As shown in Table 2, in the affluent areas, the per capita water consumption was 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 per cent and 3 per cent of water consumption variation across two clusters for the low-rise and the high-rise apartments, respectively. In addition, the seasonal variations in water consumption were

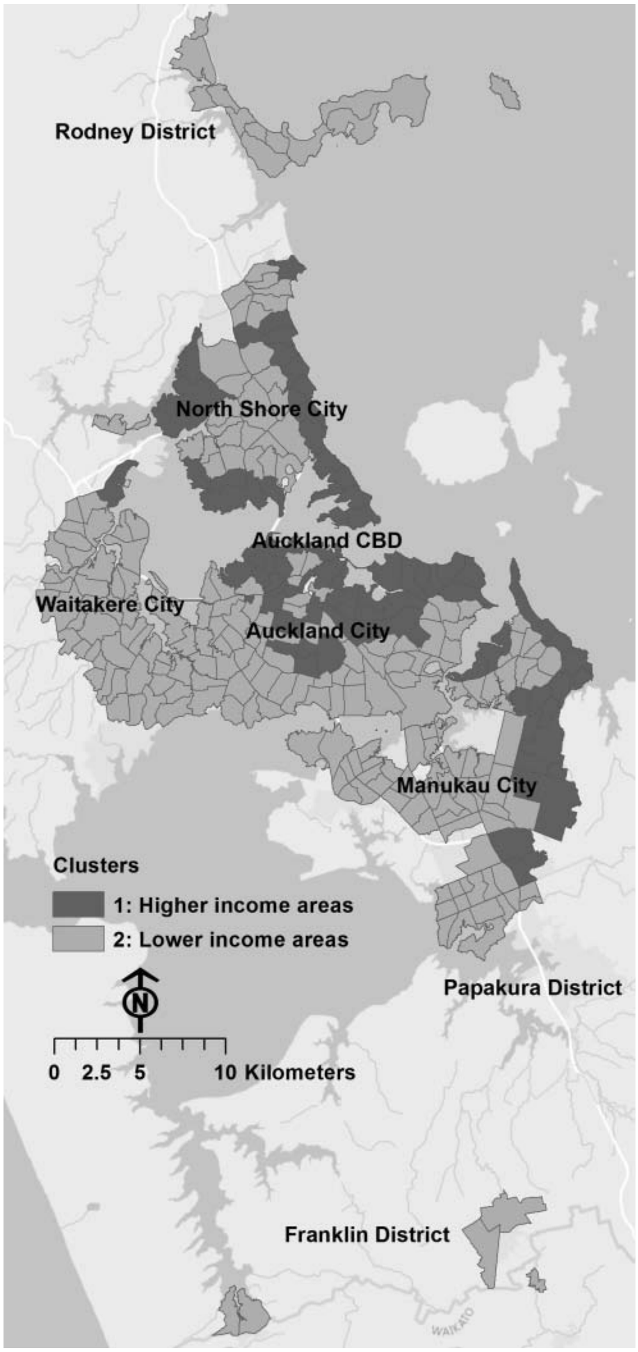

Figure 2. Two clusters of census area units in Auckland.

Table 2. Water consumption and household characteristics for different housing types across different areas.

	Single houses		Low-rise apartments		High-rise apartments	
Variables	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]	77,800	123,500	47,600	69,500	57,300	95,600
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.

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 per cent in summer. The high seasonal variation in water use in the single houses in 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 was subsequently combined with the Unitary Plan data in order to reveal the effects of housing intensification in Auckland.

4.2. Urban intensification

In order to investigate the effects of urban intensification on the future residential water demand in Auckland, this study developed three 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 re-zoned single houses would change into multi-unit housing 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-rise apartments would have four units per building. In contrast, for the high intensification scenario, it was assumed that the low-rise apartments would have four units per building. This is the average number of units in the existing out of Auckland CBD high-rise apartments. For the high-rise apartments, it was assumed that each building would have 50 units. This is the average number of units currently 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 3 outlines the three developed scenarios.

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, first the total daily water consumption across different area units was estimated. The total water consumption was the sum of water use in each housing type, calculated by multiplying the annual average per capita water consumption by the total population in each housing group. Afterwards, the average per capita daily water consumption (i.e. combined per capita water use including all housing types) was estimated for each area, by dividing the total daily water consumption by the

Table 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 apartments
Scenario 1: low intensification	2	4
Scenario 2: moderate intensification	3	25
Scenario 3: high intensification	4	50

associated total population. Table 4 shows the average per capita water consumption across all area units in Auckland. The per capita water use in two clusters in the low-income and the high income area units under current housing composition (i.e. base scenario) was also shown in Table 4. As shown in Table 4, the average per capita water consumption in Auckland is around 170 litres per person per day, and 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, first the number of dwellings in each housing type, across different area units, was estimated under different growth scenarios. This was calculated by 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 scenario. Afterwards, the population in each housing type was estimated by multiplying the dwelling numbers by the household size in each group. For this estimation, it was assumed that the current household size in each housing type remains constant at the current level. This is a 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 group. The total water consumption for different housing groups was subsequently aggregated in order to calculate total water consumption in each area. Combined total water consumption was then divided by the total population to estimate average water consumption per capita for each scenario. Table 4 also shows the estimated per capita water demand under three different intensification scenarios. Under all scenarios, through transition of single houses to higher density multi-unit housing, the total number of dwellings would increase. This would lead to a population increase and subsequently a rise in total water consumption. However, the changes in per capita water

Table 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	374,000	1,116,000	190,000	170	163	190
Scenario 1	560,000	1,351,000	225,000	167	162	180
Scenario 2	1,136,000	2,534,000	434,000	171	166	180
Scenario 3	1,785,000	3,860,000	664,000	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).

Table 5. Prospective seasonal variation of water consumption under different intensification scenarios across different areas.

	PCCsc[a] (summer)			PCCwc[b] (winter)		
Urban growth scenarios	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.

consumption would not be significant. This is because, by increasing the number of low-rise apartments the average per capita water demand may reduce slightly (i.e. the per capita water demand in the low-rise apartments is slightly lower than single houses). However, the increase in high-rise apartments, which have higher per capita water demand, would offset its effects. Thus, on average, the effects of transition of housing types (i.e. urban intensification) on residential water use would be limited.

However, the results from Table 4 also showed that the impacts of urban intensification on water use can be more remarkable in the wealthy areas, where water consumption may decrease by around 5.5 per cent. This is because, in the high-income areas, 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 outdoor usage 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 per cent in the lower income areas, where indoor water use is predominant.

In order to better understand the effects of urban intensification on seasonal variation in water demand, this study estimated the average per capita water demand for the summer (February) and winter (June) months under different growth scenarios (Table 5). The estimated water use, shown in Table 5, revealed that, in the summer, the per capita water consumption may decrease by around 7 per cent 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 was used indoor, the per capita water consumption may only decrease by 3 per cent in the higher income areas, while in the lower income areas the water consumption may increase by 4 per cent.

From these findings it can be concluded that, in general, urban intensification cannot considerably influence the water demand and its effects would be limited to 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 from 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.

4.3. Policy implications

In contemporary urban policy and planning, a compact city is promoted as a sustainable urban form. This type of urban form may provide considerable advantages in regard to energy conservation, environmental protection and social welfare in comparison with the dispersed city (Ewing and Rong 2008; Anderson, Kanaroglou, and Miller 1996; Banister, Watson, and Wood 1997; Brownstone and Golob 2009; Norman, MacLean, and Kennedy 2006). While the benefit of the compact city in terms of energy conservation has been studied extensively, its impact on the residential water use has largely remained unexplored. The efficient use of water is a key factor for sustainable living (Wentz *et al*. 2014). Thus, it is pivotal for urban planners to have a comprehensive understanding of the implications of compact development on water use.

By combining the water consumption information for different housing types with the urban intensification scenarios, this study revealed that the intensification of urban land uses would not result in a noticeable reduction in overall water consumption. This is because transition from single houses to higher density multi-unit housing may lead to smaller household size. Smaller household size generally results in higher per capita water use since economies of scale cannot be easily achieved in small households. Nevertheless, the urban planner can still benefit from the compact development in terms of water conservation, since in the wealthier areas, specifically during summer, there is considerable potential for saving water by limiting outdoor usage (i.e. gardening and swimming pools).

The policy implication of the study is that residential water consumption is largely determined by the sociodemographic characteristics of households (i.e. household size and income) rather than urban form (i.e. dwelling type, urban density). Thus, it is essential to develop spatially-oriented planning to achieve greater water conservation in the residential sector. For instance, in the urban areas with compact development the conservation programs should concentrate more on the methods associated with regulating indoor use, such as correcting household water use habits by running education campaigns or by increasing the efficiency of water appliances. In contrast, in the urban areas with more single houses, where outdoor usage is substantial, the conservation programs should focus more on regulating outdoor usage. This approach in water conservation can produce better results that help promote a sustainable urban environment.

5. Conclusions

This study examined the prospective implications of urban intensification on residential water consumption in Auckland. Urban intensification is considered as an effective urban growth management strategy in helping to mitigate the social, economic and environmental concerns arising from 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, their 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 60,000 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 combined 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 water consumption varies between different types of residential dwellings, where single houses had the highest household water consumption. The highest household water consumption in the single houses can be mainly attributed to greater outdoor usage (gardens and swimming pools) and larger households in this sector. However, in per capita terms, 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, limiting 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 in water use is more remarkable in single houses, specifically in the higher income areas, where outdoor water usage is considerable. In contrast, in both high-rise and low-rise apartments the seasonal variations in water demand are more limited, since 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, urban intensification can reduce average per capita water consumption by up to 7 per cent in the more affluent areas in summer, by limiting the outdoor usage. 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 future water supply systems.

This study introduced 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 of their full potential 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 into 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.

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ORCID

Saeed Ghavidelfar http://orcid.org/0000-0003-2726-6637

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