Factors Influencing Residential Water Consumption in Wallonia, Belgium

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Abstract

Studies on residential water determinants often considered a limited number of possible factors due to lacking data, especially at micro-levels. This study aims to address the simultaneous effects of (1) household characteristics, (2) alternative sources of water, (3) dwelling properties, (4) water appliances, (5) attitudes, and (6) urban form on household water use in Wallonia (Belgium). Results emphasize the importance of household characteristics, use of alternative water sources, and dwelling properties. When compared to these variables, the influence of urban density appears very limited. Accordingly, the often-observed location factors are mainly related to the shared household characteristics, such as composition, income, lot area, or the practice of using rainwater.

Keywords: residential water demand; households; spatial variability

1 Introduction

Measuring and, more importantly, accurately forecasting demand have become essential than ever for water utilities and city planners to ensure financial, ecological, and social sustainability. Even in temperate regions such as Wallonia (Belgium), where water shortage is often not a problem, understanding the trends and drivers in water use is still crucial. Since

1996, despite the rise in both the numbers of connections and population, the total potable water sold in various municipalities in Wallonia has declined continually, with an average rate of - 0.9% a year (Westhoff and Dewals, 2015). Efficient water use technologies, active conservation programs, and changes in people's perceptions and behavior are among the commonly identified drivers behind this phenomenon (Franczyk and Chang, 2009). Besides the undisputable conservation benefit, water utilities' revenue is declining due to this trend, while infrastructure repair and replacement costs still must be met (Beecher and Chesnutt, 2012). Meeting the cost while still encouraging conservation efforts and maintaining water accessibility for everyone is a conundrum question for both utilities and policymakers. Hence, accurate water demand prediction based on location- or country-specific knowledge of water use determinants would be the first step in solving this question (Bich-Ngoc and Teller, 2018).

In recent years, the literature on water demand has included several potential factors such as economic, sociodemographic, physical properties, technological, climatic, and spatial drivers (Bich-Ngoc and Teller, 2018; House-Peters and Chang, 2011). All these determinants produce a very complex picture with many possible interrelationships and feedback loops. Lack of data, especially at the household level, is often the main challenge for researchers to study all these variables simultaneously (House-Peters and Chang, 2011). The choice of explanatory variables for water demand is highly subjective to forecast horizons and study locations. Seasonal variables such as rainfall and temperature often influence short-to-medium water use (Maidment et al., 1985; Wong et al., 2010). However, socio-economic factors, climate, and land-use changes show significant power in predicting long-term demand (Donkor et al., 2014; Polebitski et al., 2011).

Another factor influencing water use that has recently gained more and more attention in the literature is the spatial effect (Bich-Ngoc and Teller, 2018). Wentz and Gober (2007) suggested that households tend to consume water at a comparable level to their neighbors, irrespective of their demographic and economic characteristics. Additionally, using the metropolitan area of Barcelona as a case study, March and Saurí (2010) linked regions having high net population density with lower average water consumption; while Kulinkina et al. (2016) found a positive association between distances (m) to the nearest alternative water source and piped water consumption in their study in Ghana. Despite the increasing number of papers including spatial variables as an explanatory factor for residential water demand, these studies often employed data at aggregated spatial levels such as multi-family residential buildings (Kontokosta and Jain, 2015), census tracts (Polebitski and Palmer, 2010), and counties (Franczyk and Chang, 2009). This common practice innately neglects the spatial variability resulting from natural and social processes among individual users. Hence, random- and mixed-effects models have been considered in several studies to analyze both the within variations of water use among households in the same spatial entity and the between spatial units variations (Duerr et al., 2018; Mini et al., 2015). While better capturing the household-level variation, only a limited number of covariates were included in these studies due to the lack of data at the same detail level.

By combining actual water consumption with questionnaire data containing potential explanatory factors at the household level of more than 2,000 households in Wallonia, this study aims to answer the following research questions: (1) What are the determinants of residential water consumption in Wallonia? (2) Whether the spatial variation of water consumption exists beyond these predictors? Furthermore, if yes, (3) what are the possible explanations for spatial variability in water use in Wallonia?

2 Methods

2.1 Data collection and processing

2.1.1 Study region

Wallonia is the predominantly French-speaking region of Belgium, which comprises 55% of Belgium's physical territory and around 32% of its population. The Walloon population mainly concentrates in the northern areas following the 19th-century industrial axis, running from east (Liege) to west (Mons). Administratively, the region consists of 20 administrative arrondissements dividing into 262 municipalities. Wallonia, as well as Belgium as a whole, has an oceanic temperate climate that generally features mild summers and cool winters. Although Wallonia has a typically reliable and constant precipitation level throughout the entire year, together with a large part of Europe, the region recently experienced anomalous droughts in the summers of 2018 and 2019 (Buras et al., 2020).

The region has been the water reservoir of Belgium, with a long history of water export to the Brussels-Capital and Flemish regions. Even though aquifer accounts for 75% to 84% of total distribution water, the water exploitation index plus (WEI+) of Wallonia is often less than 8%, i.e., water is not scarce in Wallonia (European Environment Agency, 2019). Water production and distribution in Wallonia are provided entirely by public companies brought together by the Professional Union of Public Water Cycle Operators (Aquawal). The average water consumption in Wallonia reported for 2016 was 118.6 L per inhabitant per day. However, when only residential use was considered, the average consumption was estimated at around 90 L per inhabitant per day (Aquawal, 2017). With this level of consumption, Wallonia is among the regions with the lowest residential water consumption in Europe (EurEau, 2017). Similar to most places in the developed world, Wallonia is currently experiencing a constant decline in water consumption, which can be up to 2% per year in some municipalities, in both terms of total and per capita consumptions (Vallès-Casas et al., 2017; Westhoff and Dewals, 2015).

Following the European principles of full-cost recovery, a single water tariff structure (Appendix A), which covers the cost of both water production and sanitation, is imposed for all Wallonia families. Despite a recent rise in water tariff, in 2014, the annual water cost for a family in Wallonia is averaged at about EUR 380, which is around the median of European countries and, in most cases, accounts for less than 3% of household disposable income (Aquawal and CEHD, 2015; EurEau, 2017).

2.1.2 Utility survey

Predictors of water consumption at the household level employed in this study were obtained from the Water and Energy Utilization Survey data in the Household and Cost 2015 (Utility Survey in short). It was carried out by Aquawal (The Union of Public Water Cycle Operators) and CEHD (Centre d'Etudes en Habitat Durable de Wallonie) in two waves in early 2015. A database with meter identifications and addresses of 1.5 million households was created using customer databases of all major water providers in Wallonia. In the first wave, 15,000 homes were randomly selected from the database and contacted by post-mail. The contacted households could complete the survey either by Paper and Pencil (with pre-stamped envelope) or Computer Assisted Web. Due to a high number of non-responses, a second wave was carried out at the end of April 2015 by sending the same questionnaires to another randomly selected 15,000 households in the region with an addition of phone survey mode. The representativeness of the final 2,763 obtained responses was checked using the Walloon population's actual distributions by province, reference person's age, housing tenure, and dwelling type and age. Post-stratification weights were then calculated and employed in all later analyses to correct for sampling bias. Doubled and uncompleted responses (abandoning before question number 10) were eliminated. Households who also used distribution water for professional purposes at home were excluded.

The Utility Survey contained a broad range of questions about water and energy consumption, dwelling characteristics, household composition, water use devices, and consumption habits and preferences. After removing the variables with a high proportion of missing, 48 potential explanatory factors were identified and classified into five groups: (1) household characteristics, (2) alternative sources of water, (3) dwelling properties, (4) water appliances, and (5) attitudes (Bich-Ngoc and Teller, 2018). Since cross-sectional data were used in this study, commonly studied variables such as price (Marzano et al., 2018), air temperature, and rainfall (Gato et al., 2007) were excluded because they have modest or no variation during the study period. A complete list of considered variables and summary statistics is included in Appendix B and discussed further in 3.1.

Information regarding household characteristics obtained from the survey includes the number of inhabitants and their ages; reported household income (nine categories); reference person's gender, job, and educational level; water affordability (annual water bills as a percentage of reported income); and whether the family had difficulties in paying their water bill or received support from the Social Water Fund (Fonds Social de l'Eau). Since several previous studies suggested that the amount of consumed water depends on the age of inhabitants (Nauges and Whittington, 2009), instead of the total number of members in each household, we considered the number of children (< 14 years old) and the number of adults (≥ 14 years old). The number of adults was recentered at the value one so that the intercepts of regression models can represent the average consumption of single-member households. Additionally, coefficients were used to adjust for the duration they stayed in the studied dwelling per week. As for income, to better represent the buying power of the participated households, income per equivalent adult was used instead of household income. This variable was calculated using the mid-points of recorded household income categories and the OECD-modified equivalence scales. Per capita income was then categorized as precarious-, modest-, average-, and higher-income using the cut-off values suggested by the Walloon Housing Association (Société Wallonne du Lodgement) with average-income as the reference level.

Information regarding alternative water sources was obtained by asking the respondents to indicate whether they use any alternative sources (well, rainwater, bottled water, and others) for a specific purpose such as drinking or cooking, toilet flushing, garden irrigation, pool filling. The survey provided a total of 48 binary variables (4 alternative sources × 12 purposes). New nominal variables were created with four levels (no use, use for indoor purposes only, use for outdoor purposes only, and use for both indoor and outdoor purposes) for each type of alternative water source to reduce the number of dimensions in later analyses. "No use for any purposes" was chosen as the reference level for all the alternative water source variables.

Examples of dwelling property variables are year built, housing tenure, dwelling type, living area, number of rooms, and the presence of (a) bathtub(s), garden(s), or pool(s). The living area was scaled to have zero mean and unit variance. The presence of a garden was derived from whether the households used water for irrigation purposes. Two binary variables for the presence of (a) permanent pool(s) and inflatable pool(s) were considered.

As for water appliances, both water use appliances (washing machine, dishwasher) and water-saving appliances (water-efficient toilet, low-flow showerhead) were considered. The households were asked whether they had these appliances and whether they had recently replaced them after 2009. Hence a total of eight binary variables were included in the analysis. No house visits or home water audits were carried out.

The survey only provided limited information regarding people's attitudes toward water use. Two variables were included in this study to represent people's attitudes indirectly. The first one is people's confidence in tap water quality recorded in six categories (confident, rather confident, neither confident nor suspicious, rather suspicious, suspicious, and no opinion). The second one is whether the water bill depends on the usage volume or not because some families rent their dwellings from the private sector and pay for water through their landlords.

2.1.3 *Urban form*

Besides household-level determinants, the effect of urban form was addressed by population and building densities. Since most municipalities consist of a populated central urban area and low-density suburbs, both densities were calculated at the statistical-unit level, corresponding to neighborhoods in urban areas or large depopulated zones in rural areas. There are 9,876 statistical units whose areas range from 1.3 ha to 5,834 ha in Wallonia. The gross population density was calculated by the total registered population per square kilometer. Building density was defined by the percentage of area covered by buildings in each statistical unit. Raw data regarding total population, total area, and cadastral maps for all statistical units were obtained from the Belgian Statistical Office[1] and Federal Public Service Finance[2] websites. Provided addresses of participating households in the Utility Survey were used for mapping and connecting with data at other spatial aggregation levels.

2.1.4 *Water consumption*

Our dependent variable is the water consumption (m^3) in 2014 recorded by water utilities at the household level. However, different households recorded their meter at different moments during the year. Hence, to standardize the data, we assumed an average daily water use during

[1] https://statbel.fgov.be/en/open-data?category=209

[2] https://finances.belgium.be/fr/particuliers/habitation/cadastre/plan-cadastral/lambert-72

each recording period (e.g., March 2013 – March 2014 and March 2014 – March 2015). These numbers will then be multiplied by the respective actual number of days belonging to 2014 to estimate the total consumption of 2014. This method was adapted from Ghavidelfar et al. (2017). Extreme value removal was based on expert advice (> 300 m^3/year) and outlier analyses (further discussed in 2.2). Water meters' identifications were used to connect the previously described survey data and recorded household water consumption in 2014.

2.2 Multiple regression

A vast number of possible covariates in the Utility Survey dataset increase the variable selection process's difficulty and the risk of multicollinearity due to correlation among explanatory variables. Hence, a parsimonious and well-performing linear regression model was first developed to provide a baseline for the more complex ones with spatial regressors to follow. Both categorical and continuous covariates were considered in the model $y_k = \boldsymbol{x}_k^T\boldsymbol{\beta} + \varepsilon_k$, where y_k is the total water use of household k in 2014, $\boldsymbol{x}_k$ is the vector of considered household-specific factors and their possible polynomial and interaction terms, $\boldsymbol{\beta}$ is the vector of regression coefficients, and ε_k is the error terms. In this study, a core model including explanatory factors with a high level of consensus in the literature was first fitted (Bich-Ngoc and Teller, 2018). Partial residual plots were used to identify other important factors and their possible relation with household water consumption. Variables were only added to the model if they significantly improved the model’s goodness of fit (p-value of likelihood ratio test < 0.05). Competitive models were then assessed using k-fold cross-validation (with k = 100). Mean squared prediction errors (MSPE) from each run were averaged to produce a single estimate for each model. The final model is the model with the highest predictive power, i.e., the smallest MSPE. The potential of adding or removing several variables at once was also tested using Likelihood-ratio tests. Outliers or influential observations were identified using

MM Estimation and several single-case diagnostics such as DFFITS, DFBETAS, and Cook's distance (Ayinde et al., 2015). Variance inflation factor (VIF) and standardized residual plots were used to check for violations of regression assumptions.

2.3 Spatial variation analyses

Two approaches, namely fixed effects regression with spatial predictors and mixed-effects regression with spatial random intercepts, were employed to study the spatial patterns of water consumption. The final baseline model resulted from the previous analysis was updated with spatially varying factors such as population or building density. The model equation becomes $y_{jk} = \boldsymbol{x}_{jk}^T\boldsymbol{\beta} + \beta_1 d_j + \beta_2 d_j^2 + \varepsilon_{jk}$ with d_j is either population density or building density of statistical unit j, while β_1 and β_2 are respectively regression coefficients of linear and quadratic terms. These models assume that the spatial pattern of water use depends on the variation in densities. Additionally, random intercept at the municipality level (u_i) was added (Verbeke and Molenberghs, 2009) to capture the effects of other possible unobserved spatially varying factors and allow different base water consumptions for different municipalities. The model formula is then $Y_{ijk} = \boldsymbol{x}_{ijk}^T\boldsymbol{\beta} + \beta_1 d_{ij} + \beta_2 d_{ij}^2 + u_i + \varepsilon_{ijk}$. Random effects u_i, which can also be interpreted as municipality-specific deviance from the global mean of water use, is assumed to follow a normal distribution $N(0, \sigma_u^2)$. This model also assumes that the effects of household-specific predictors $\boldsymbol{x}_{ijk}$ on water consumption remain constant from one municipality to another.

2.4 Software

All data processing and statistical modeling were performed using R-4.0.0 (R Core Team, 2020) with the aid of lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), and MuMIn packages (Barton, 2020). The scripts are available upon request from the first author.

3 Results and discussions

3.1 Data exploration

On average, a household in our sample consumed around 69.4 m^3 potable water in 2014, with a considerable variation among households (SD = 44.4 m^3). The average daily water consumption per person was 85.2 L (SD = 50.8 L), close to the 90 L/p/d reported by Aquawal (2017) and is modest compared to reported numbers from other European countries, as discussed in 2.1. Bivariate Pearson correlations in Figure 1 suggest positive relationships between household water use and household size and living area. Water consumption is also negatively correlated with the reference person's age. It can be explained by the fact that, in Wallonia, older people often live separately from their grown-up children and generally consume less water than families with young children.

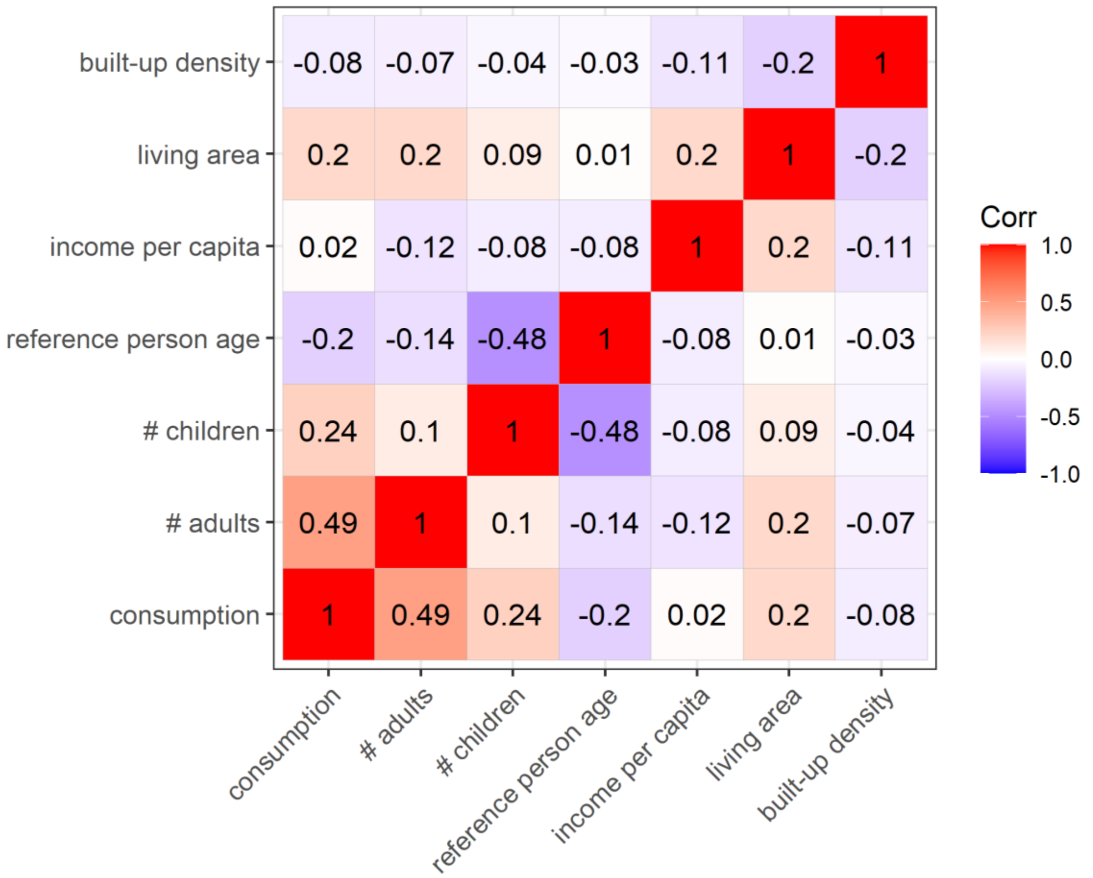

Figure 1. Correlation matrix of primary quantitative variables

Sociodemographic characteristics of the families participating in the Utility Survey were somewhat comparable with the population data in 2014. The average household size in the sample was 2.4, which is slightly higher than the 2.3 value of Belgium in 2014 (Anfrie et al., 2017). The proportion of single-member families, families with children, and couples without children in the data are 23%, 22%, and 41%, respectively. Even though the average household size in Belgium was relatively stable since 2010, rises in the proportions of single-member and single-parent households were predicted (Anfrie et al., 2017). This trend might reduce the efficiency in water use resulting from the economies of scale (Bich-Ngoc and Teller, 2018).

Rainwater is the primary alternative source of water in Wallonia, with about 48% of respondents reported using rainwater for at least one purpose. Additionally, nearly 5% of the participants answered that they used private well water. Aside from bottled one, tap water is much safer than other sources of water in Wallonia. Hence other water sources such as rainfall are mainly used for outdoor purposes and some specific indoor purposes such as toilet flushing and cleaning (Figure 2).

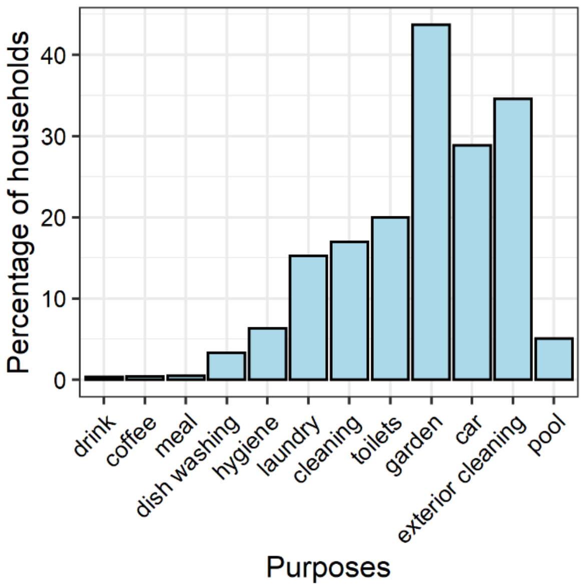

Figure 2. The proportion of families in the Utility Survey using rainwater for different outdoor and indoor purposes

Generally speaking, single-family houses built before 1990 and with medium living areas made up a large part of housing stock in Belgium (Anfrie et al., 2017). The average living area (without considering garden and outdoor space) in the Utility Survey was 128 m^2. It is positively correlated with income, though slightly (Figure 1). Although there was no recorded data regarding lot size or garden size in the dataset, nearly 80% of the families reported using distribution water for garden irrigation. While studies employing data from Australia or the US often show higher consumption during summer months due to garden irrigation and pool filling (Gato et al., 2007), the opposite seasonal pattern with lower summer consumption and higher winter water use was observed in Wallonia (Bich-Ngoc and Teller, 2020). A general cool and wet climate, moderate garden sizes, and high outbound travel activities during the summer months might be the reasons behind this (Bich-Ngoc and Teller, 2020).

Together with other countries in West Europe, the saturation of the water use appliances market in Belgium was very high, with 92% of the families having a washing machine, and two-third of them owning a dishwasher (Pakula and Stamminger, 2010; Richter and Stamminger, 2012).

Additionally, 72% of the families claimed that they had either (a) dual-flush or low-flush toilet(s). Nearly 40% of the participants also reported using low-flow showerheads. Hence, the variation in appliance ownership in the data was relatively modest.

Very few questions regarding people's attitudes and water use habits were included in the Utility Survey. In general, people in Wallonia expressed high confidence in tap water quality, with 78% of the respondents said they are confident or rather confident. Since water meters were fitted for all individual households in Wallonia, even in multi-family buildings, most families had direct contracts with water utilities and followed the general tariff scheme as described in Appendix A. Only 1.5% of the surveyed participants who rented their dwelling in the private sector had their water bill as a fixed amount included in their rent.

In this study, population and building densities at the statistical unit level were used as urban form indicators. Units with high overall population density or building density are often core city areas, while units with lower overall densities have a higher share of unpopulated agricultural land or forest. The summary statistics of these two variables are reported in Table 1. Both population and building densities show significant negative correlations with water consumption, though slightly. The boxplots in Figure 3 also suggest slightly higher consumptions in peri-urban areas (medium built-up density) than in core city centers (high density) or rural areas (low density).

Table 1. Summary statistics of population density and building density

Variable	**Unit**	**Mean**	**SD**	**Pearson's correlation with water consumption**
Population density	People/km^2	2147	2033	-0.0506 *
Building density	%	11.6	8.75	-0.0758 **

Note. * and **: p-value < 0.05 and < 0.01 respectively

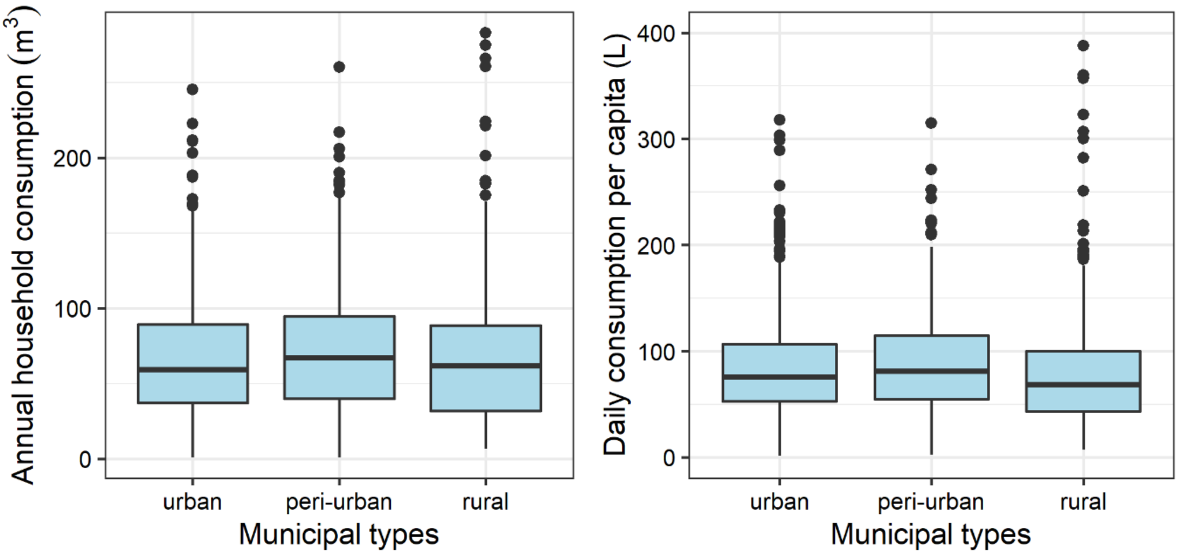

Figure 3. Boxplots of annual household water consumption (Left) and daily consumption per capita (Right) by municipal types

Besides correlations with built-up density and other variations, spatial autocorrelation in water consumption was also suggested by Moran's I statistic (p-value = 0.0216) in the data. As previously mentioned, a family in the dataset consumed about 70 m^3 of water in 2014. However, these average values vary among municipalities (Figure 4). Municipalities in the northwest of Wallonia generally have a significantly lower average water consumption (blue-colored), while a higher average of water use can be observed in the southeast area of the region (red-colored).

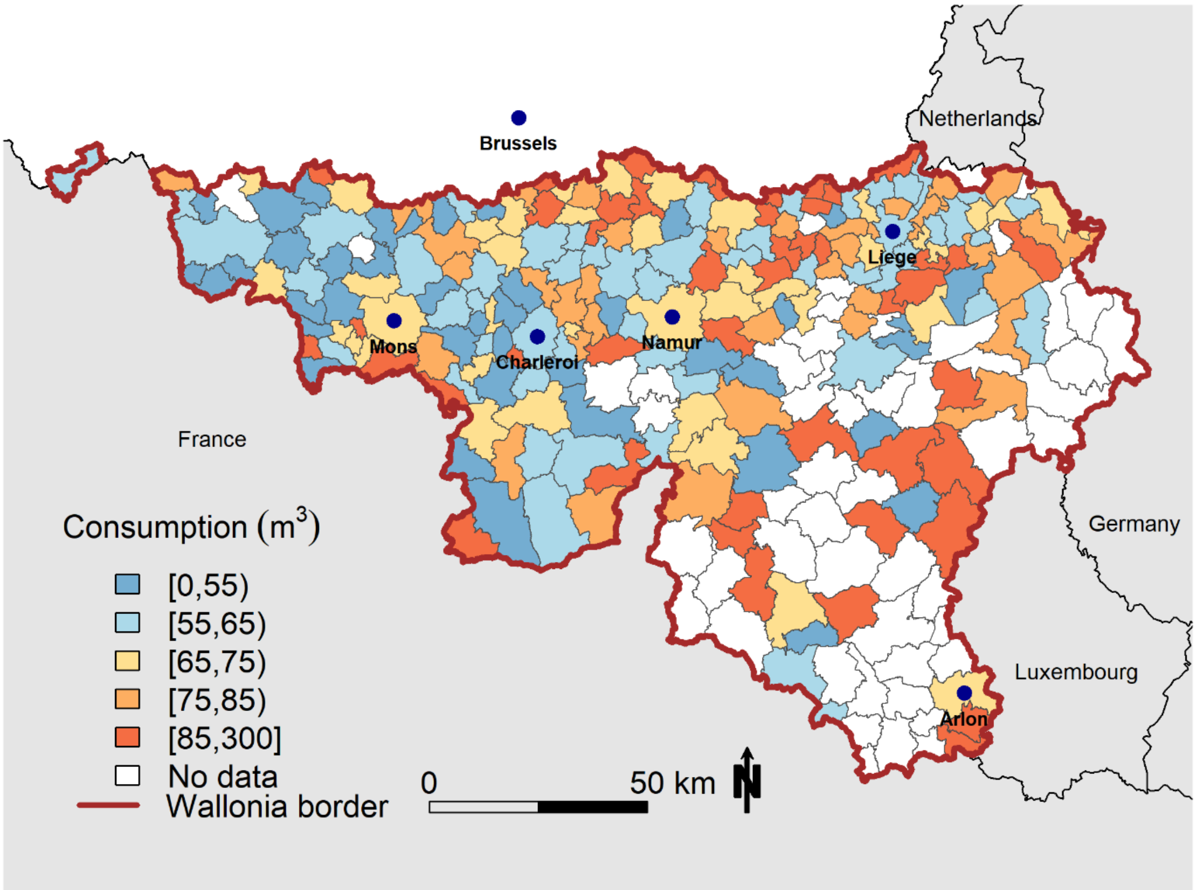

Figure 4. The variation of average water consumption per household in 2014 by municipalities (Mean = 70 m^3/household, SD = 27.11 m^3/household)

Besides water consumption, several predictors in the data also express spatial variations and correlations with built-up density. In Wallonia, high-density areas often have a higher share of lower-income and smaller living area families (Figure 1). Additionally, significant negative correlations were also observed between built-up density and the proportions of households with (a) rainwater tank(s) (Pearson's r = -0.2169, p-value 0.0015) and garden(s) (Pearson's r = -0.2692, p-value < 0.001) at the municipality level. Results from Moran's I test also suggested spatial dependencies of household income per capita (p-value 0.0085), household size (p-value = 0.0312), and the proportion of households with rainwater use (p-value < 0.001).

3.2 Multiple regression

Results from the final regression models were reported in Table 2. The VIFs did not suggest multicollinearity problems in the models. Additionally, linearity assumptions were checked visually by partial residual plots, while homoscedasticity and normality assumptions were checked using scatter and Q-Q plots of standardized residuals. Sensitivity analysis with and without the outliers showed that the model estimates are stable despite different model fitting or outliers identification techniques (Table 2). The adjusted-R^2 of all final models range from 0.404–0.413, belonging to the high end of the range presented in past studies that have utilized household-level data. For example, the adjusted R-square in Pint's study (1999) regressing water use data of 599 single-family households in California on dwelling characteristics and weather is 0.25. More recent studies using household-level data, such as Basani et al. (2008) and Kenney et al. (2008), obtained adjusted-R^2 of 0.374 and 0.400, respectively.

Table 2. Estimated effects of predictors on total household water use and their p-value using different modeling methods

	Baseline		Baseline + population density		Baseline + building density		Baseline + building density + random intercepts	
	β	p-value	β	p-value	β	p-value	β	p-value
Intercept	38.60	<0.001	39.38	<0.001	39.66	<0.001	39.88	<0.001
Number of adults	23.89	<0.001	23.89	<0.001	23.87	<0.001	23.77	<0.001
Number of children	10.89	<0.001	10.95	<0.001	10.94	<0.001	10.96	<0.001

Income-precarious	-5.15	0.0562	-4.74	0.0792	-4.48	0.0969	-4.67	0.0848
Income-modest	0.69	0.7333	0.71	0.7233	0.80	0.6925	0.81	0.6886
Income-higher	5.55	0.0371	5.77	0.0303	5.96	0.0248	5.61	0.0348
Rainwater-outdoor	-3.50	0.1058	-3.88	0.0743	-4.07	0.0603	-3.80	0.0804
Rainwater-indoor	-15.13	0.0811	-15.39	0.0757	-15.44	0.0744	-14.34	0.0969
Rainwater-both	-25.81	<0.001	-26.40	<0.001	-26.58	<0.001	-26.48	<0.001
Living area	2.85	0.0024	2.62	0.0053	2.49	0.0080	2.77	0.0034
Bathtub	5.76	0.0022	5.56	0.0031	5.59	0.0029	5.83	0.0020
Garden	7.04	<0.001	6.49	0.0023	6.16	0.0038	6.02	0.0047
Pool	24.39	<0.001	23.99	<0.001	23.70	<0.001	22.75	<0.001
Population density	*na*	*na*	-1.48	0.0454	*na*	*na*	*na*	*na*
Built-up density	*na*	*na*	*na*	*na*	-2.50	0.0015	-2.31	0.0056
Adjusted R^2	0.4039		0.4050		0.4073		0.4162†	

Note. †: likelihood-ratio based pseudo-R-Squared calculated using package 'MuMIn' (Barton, 2020), *na*: not applicable

The final baseline model contains linear effects of the number of adults (centered at 1), the number of children, categorized income per equivalent adult, rainwater use, scaled total living area in square meters, and the presence of (a) bathtub(s), garden(s), and permanent pool(s) (Figure 5). "Average" was set as the reference level of income per equivalent adult, while the reference level of rainwater use is "no use". None of the interactions or quadratic terms of independent variables significantly improves the predictive power of the model. Variables that were not included in the final models (due to having a low-significant level or leading to models with higher MSPE) are not reported in this figure but will be discussed further later.

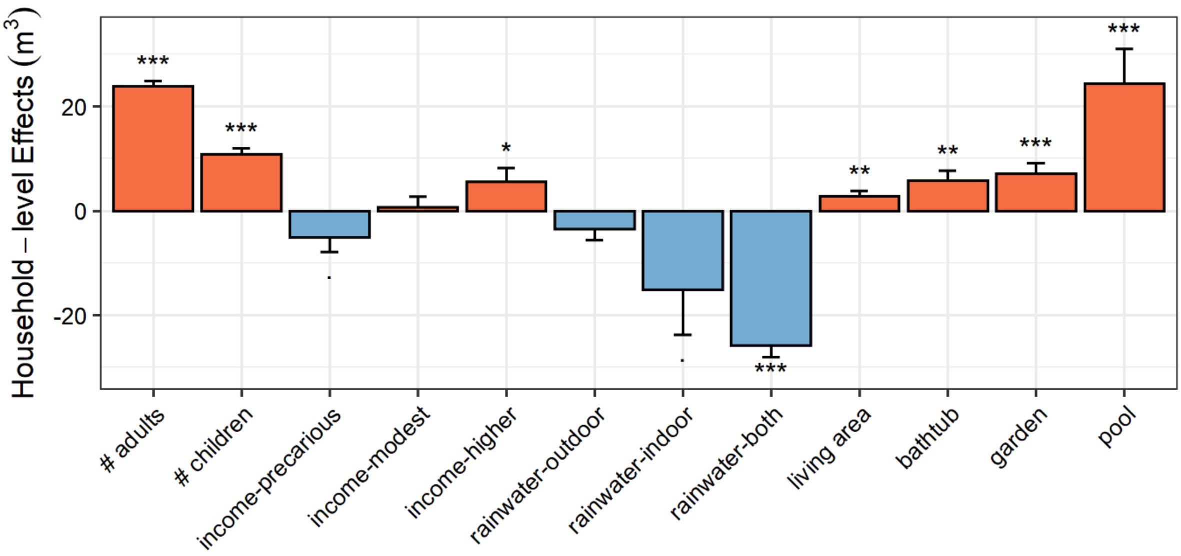

Figure 5. Estimated effects of predictors on total household water use, their standard deviation, and their significant level (p-value < 0.05: *, < 0.01: **, < 0.001: ***) for the baseline model

When a group of variables is last added to the model, changes in R-square represent the unique variance which that particular group explains above and beyond the other variables in the model. Hence, it can be used to compare the importance of different predictor groups in the final models. Sociodemographic factors (household size and income) are the most prominent since it increases the R-square by 0.2737; the alternative source of water and dwelling properties only raise the R-square by 0.0534 and 0.0212, respectively (Table 3).

Table 3. Added explained variation by each group of predictors when it was added last

Variable	Socio-demographics	Rainwater use	Dwelling characteristics	Spatial factors
Increase R^2	0.2737	0.0534	0.0212	0.0010-0.0123

3.2.1 Household characteristics

Household composition is the most important explanatory variable in our model since it improves the percentage of explained variance by nearly 27%, while effects for all other important variables are controlled. Although the quadratic effects of the number of adults and the number of children are not statistically significant, the economies of scale in water use are still observed in the dataset. While single-member families consumed, on average, 40 m^3/year, the estimated increase in water use for every additional adult is 24 m^3. The estimated value for each added child is even lower (11 m^3). The calculated equivalence scales for water consumption using this data are 0.6 and 0.3, respectively, for each additional adult and child. These values are close to the OECD-modified equivalence scales of needs which are 0.5 to each additional adult member and 0.3 to each child (OECD, 2011). Hence, it is advisable for water use per capita to be calculated using equivalence scales rather than the total number of inhabitants as is common practice (Billings and Jones, 2008).

The positive effect of income was widely accepted and empirically demonstrated in the literature (Corbella and Pujol, 2009; Kenney et al., 2008). A statistically significant effect of income was also found in this study. Higher-income families consume on average 5–6 m^3 a year more than the average families, while precarious families consume 4–5 m^3 less. Water demand literature often explained the effect of income on the quantity of water consumption by the direct upsurge caused by lifestyle or indirect increase through having dishwashers, gardens, or pools (Schleich and Hillenbrand, 2009). Since the effects of water use equipment were not significant and the effects of dwelling characteristics and rainwater use were controlled (and discussed below), the effect of income in this analysis may solely be explained by the household's capacity to buy more water, which can be traced to habit and living standards.

Information of reference people such as gender, job, and educational level are all not statistically significant. Jorgensen et al. (2014) have argued that while individual factors such as job and educational level influence water use of single-member households, these variables do not necessarily represent the characteristics of the whole family in larger households.

3.2.2 Alternative water sources

In this study, drinking, making meals, dishwashing, personal hygiene, clothes washing, house cleaning, and toilet flushing were considered indoor purposes; garden irrigation, car washing, external cleaning, and permanent or inflatable pool filling were treated as outdoor use. Figure 5 shows a substantial decrease in piped water demand for families using rainwater for indoor purposes (for indoor-only as well as both indoor and outdoor). Since indoor purposes such as laundry and toilet flushing account for more than half of household total water use in Western Europe (Lallana et al., 2001; Pakula and Stamminger, 2015), it is logical that less piped water is saved when rainwater is only used outdoor. Even though the effect of rainwater on distribution water demand is promising, further studies should be considered. Neither the actual amount of rainwater used by the households nor potential rebound effects could be assessed in this study.

3.2.3 Dwelling properties

Dwelling characteristics (e.g., year built, total living area, and the number of rooms) are often considered important factors in water demand literature (Fox et al., 2009; Wentz and Gober, 2007). Besides having strong predictive power, this information is often the only available data for newly developed unoccupied housing areas. One concern in including both household size and living area is their natural correlation. The VIFs of the final models did not signal any problem with multicollinearity, even though a significant positive Pearson correlation of 0.233 was observed.

When controlling for other factors, a significant but marginal effect of the total living area was found. It can be interpreted as the average increase in water use with every additional unit of living area when keeping other factors such as household size unchanged. The presences of (a) bathtub(s), garden(s), and pool(s) also induce a significant increase in water consumption. It is an expected result since there has been an amount of supporting evidence in the literature (Fox et al., 2009; Wentz and Gober, 2007). Although previous studies have suggested the seasonal pattern in water use for gardening and pool filling (Corbella and Pujol, 2009), it was not possible to address this fluctuation in our study since household water consumption in Wallonia is habitually recorded and billed once per year.

The non-significant effects of dwelling type and year built contradict findings in the literature (Fox et al., 2009; Stoker and Rothfeder, 2014). House-Peters et al. (2010) have successfully linked higher water consumption with newer properties. Their explanation for this effect is that new houses are often bigger and have higher values. However, Harlan et al. (2009) expected that newer homes would consume less water due to the higher presence of rainwater tanks or water-efficient equipment. In Wallonia, around 60 % of houses built after 1990 have rainwater tank(s) for domestic use while that number for older homes is less than 40 %. However, since household income, living area, presence of (a) pool(s), and rainwater use have been controlled in our models, the unique parts of the year-built and house type effects become trivial.

3.2.4 Water appliance and people attitudes

Water appliance ownerships and people's opinions regarding water quality were found to be not significant in explaining household water use in this data. Lack of details and variations in these variables might be the primary explanation. Previous studies often emphasized the role of behaviors in influencing water use/saving devices' effects. For example, when people know that their showerhead is low-flow, they tend to take longer showers (Campbell et al., 2004). The study of Richter (2010) also suggested that the amount of water consumed for dishwashing depends more on people's habits (e.g., pre-rinsing the dishes, program selection) than the mere presence of a dishwasher. Since actual water use habits were not asked in the Utility Survey, other studies are needed to deepen the knowledge of people's customs in Wallonia and their effects on total water demand.

3.3 Spatial variation in residential water consumption

Since Moran's I statistic suggests spatial autocorrelation in household water consumption, two approaches discussed in 2.3 were employed to model the spatial effects on water use. Moran's I test (p-value = 0.9509) for error terms of the most complicated final model (i.e., the model with both random intercepts at the municipality level and building density at the statistical unit level) suggests that the model has well captured the spatial variation in the data. Detailed results of these models are discussed below.

Although boxplots in Figure 3 show lower water demand in both high-density urban areas and low-density rural areas than average-density peri-urban areas, both quadric terms of population and building densities did not prove to be necessary. The population density estimate suggests a decrease of -1.48 m^3 (p-value = 0.0454) in average annual household consumption when population density increase by one standard deviation (Table 2). The negative effect of building density (-2.50 m^3) has a higher significant level (p-value = 0.0015). Since the registered population used for population density calculation might differ from the actual residential population, building density might be a better indicator of urban form, thus explaining water use slightly better. In contrast to March and Saurí (2010), who found urban density is the most critical variable to explain water consumption, the effects of density in this study, though significant, hardly improve the adjusted R-square of the model (Table 2). Previous studies often found that higher urban density reduces water demand mainly through smaller lot sizes (Fox et al., 2009; Villar-Navascués and Pérez-Morales, 2018). Even though lot size was not available in this study, after controlling for similar factors such as living area and the presence of (a) pool(s) or garden(s), the remaining effect of densities becomes marginal.

Additionally, to accommodate the potential unobserved effects of other municipality characteristics besides density, random intercepts at the municipality level were introduced into the model. It also allowed to separately estimate the within and between municipality variations of household water use. Although the significant random effects of municipalities (p-value = 0.0354) implied an unexplained spatial heterogeneity in average water consumption, based on R-square values in Table 2, its contribution to model improvement is much less than those of household-level factors, as discussed in section 3.2.

Even though both fixed effects of densities and random effects of municipalities are significant, all models with spatial factors showed limited improvements compared to the baseline model (Table 2). A potential explanation for this phenomenon is that the spatial variation in water consumption has already partly been explained by other predictors in the baseline model, especially since most of them also express spatial heterogeneity (see section 3.1). In other words, families living in the same area often share similar characteristics in socio-economic status, water use habits, and the presence of water use facilities — thus consume a comparable amount of water.

4 Conclusions

By combining the data from the Utility Survey and historical water consumption, this study has addressed the effects of (1) household characteristics, (2) alternative sources of water, (3) dwelling properties, (4) water appliances, (5) attitudes, and (6) urban form on household water uses in Wallonia. Since this is a cross-sectional study, time-varying variables such as prices, weather, or the general trend in water demand could not be studied.

The result has confirmed the importance of household size in explaining single-family water use from previous studies. Data from Wallonia suggests an equivalence scale of water use with a value of 1 for the first adult, 0.6 for every additional adult member, and 0.3 for any added child. From the demand point of view, the result from this study also supports a substantial saving (20%–35%) in piped water consumption when rainwater is used as an alternative source, especially for indoor purposes. However, from a financial perspective, it might reduce even more water utilities' revenue and lead to difficulties in service operation and new energy-efficient systems investment. The general belief that the amount of household water use depends partly on where they live seems to be explained solely by the fact that households in the same area often share similar characteristics such as household composition, income, lot area, the practice of using rainwater, and having (a) garden(s) or pool(s). After controlling for these factors, the spatial effect on water consumption becomes almost negligible.

Besides contributing to the understanding of household water use determinants, this study also suggests further consideration of several current water policies. Since the effect of household location is almost negligible after controlling for household characteristics, policymaking could occur at a regional scale, particularly for territories with uneven water availability, such as Wallonia. Additionally, the effect of household income is modest, especially compared to household size, which calls into question the ability to meet the equity objective of progressive tariffs based on water consumption at the connection level. As previous studies have recognized (Donkor, 2010; Whittington and Nauges, 2020), without considering household size, poorer households with more members often faced higher average water prices when increasing-block tariffs are applied.

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Data statement

The statistical unit and population data used in this study can be obtained via the websites of the Belgian Statistical Office (https://statbel.fgov.be/en/open-data?category=209) and Federal Public Service Finance (https://finances.belgium.be/fr/particuliers/habitation/cadastre/plan-cadastral/lambert-72). The survey and water consumption data were kindly provided by Aquawal and CEHD under the approval of the Service Public de Wallonie via confidential agreements and thus are not accessible to the public or research community. Interested parties may directly contact Aquawal (www.aquawal.be) and CEHD (https://www.cehd.be/) to request the data.

Appendix A: Water tariff in Wallonia

Following the European principles of full cost recovery, a single water tariff structure covering both the cost of water production (CVD) and wastewater treatment (CVA) is imposed for all families in Wallonia. The final bill contains a fixed subscription fee, a three-block volumetric charge, and a contribution to social fund following the formulas in Table A1.

Table A1. Water tariff structure in Wallonia

Tariff parts	**Formula**
Fixed subscription fee	20*CVD + 30*CVA (per household)
Volumetric charge	
From 0 to 30 m^3	0.5*CVD (per m^3)
From 30 to 500 m^3	CVD + CVA (per m^3)
Above 500 m^3	0.9*CVD + CVA (per m^3)
Social Water Fund contribution	0.0125 € (per m^3)
Value-added tax	6 % of the total bill

The CVD is recalculated each year by water companies following a standardized accounting plan set by the Walloon government. Any increase in CVD requires opinions from Water Control Committee and approval from the Federal Public Service Economy. On the other hand, a single CVA is set for the whole Walloon region by the Société Publique de Gestion de l'Eau (SPGE) each year. Figure A1 presents the recent evolution in CVA and CVDs of the four primary distributers. The total bills calculated for families consuming at an average level of 70 m^3/year showed a constant increase of about 5 % each year (Figure A1).

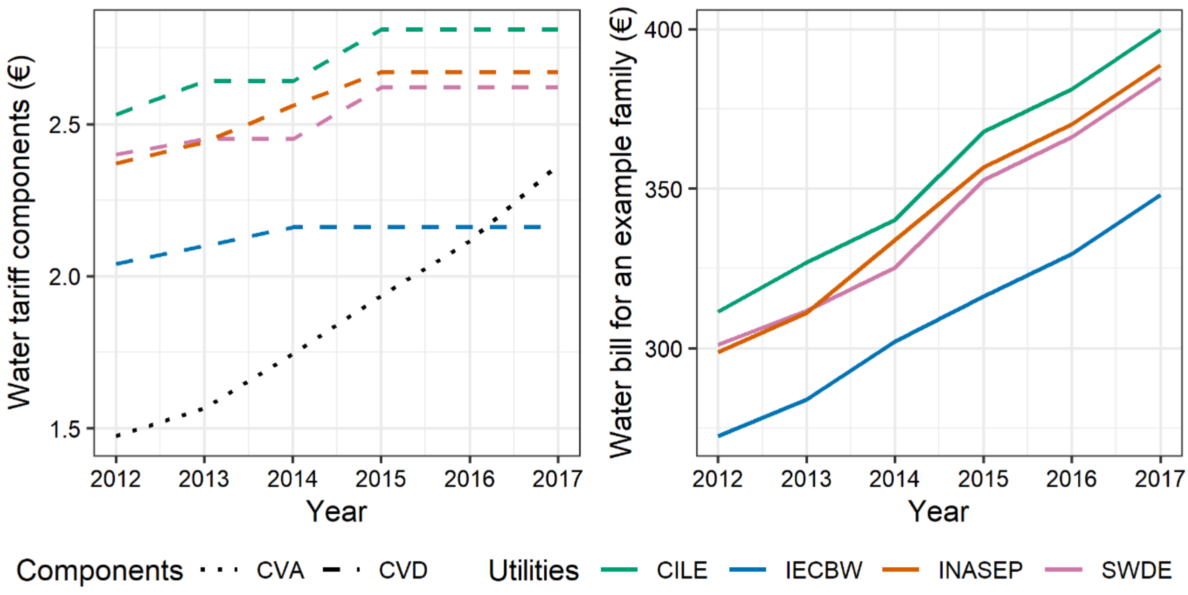

Figure A1. A plot of increasing CVD and CVA in recent years (Left) and a plot of example annual water bills for an average family who consumes 70 m^3/year (Right).

Appendix B: Variables' summary statistics

Table B1. Summary statistics of all numerical factors

Variable	**Unit**	**Mean**	**SD**	**Min**	**Max**	**Missing**
Verified consumption	m^3/year	69.31	44.39	0	523.95	156
Consumption per capita per day	L/p/d	85.20	50.80	0	717.74	287
Water bill 2014	€	347.96	207.38	110.55	2,445.09	20
Number of adults		2.06	0.92	0	3	141
Number of children		0.35	0.77	0	4	141
Household size		2.4	1.32	1	9	141
Reference person's age		52.15	16.35	19	95	141
Household income	€/month	2,461	1,191	125	5,250	109
Income per equivalent adult	€/year	18,613	7,624	750	57,000	254
Water affordability	%	1.40	1.04	0.21	13.10	124
Total living area	m^2	128.22	58.52	20	400	22

Table B2. Summary statistics of all categorical factors

Variable	**Levels**	**Count**	**Percentage**
Using water from private well	no	2018	95.23
	outdoor-only	40	1.89
	indoor-only	6	0.28
	both	55	2.60
Using rainwater	no	1111	52.43
	outdoor-only	465	21.94
	indoor-only	24	1.13
	both	519	24.49
Province	Walloon Brabant	278	13.12
	Hainaut	738	34.83
	Liège	603	28.46
	Luxembourg	114	5.38
	Namur	246	11.61
	missing	140	6.61
Distributor	AIEM	1	0.05
	CILE	329	15.53
	IECBW	169	7.98
	INASEP	44	2.08
	SWDE	1558	73.53

	Communal organizations	9	0.42
	missing	9	0.42
Reference person gender	Female	581	27.42
	Male	1369	64.61
	missing	169	7.98
Reference person job	(pre)retired	814	38.41
	freelancer	25	1.18
	housewife/husband	27	1.27
	incapable	64	3.02
	independent	75	3.54
	manager	88	4.15
	other	39	1.84
	private sector	278	13.12
	state employee	282	13.31
	student	8	0.38
	unemployed	75	3.54
	worker	167	7.88
	missing	177	8.35
Reference person educational level	before high-school	268	12.65
	high-school	326	15.38
	professional	158	7.46
	technique	203	9.58
	higher not university	564	26.62
	university	323	15.24
	missing	277	13.07
Receive help from the Social Water Fund	yes	4	0.19
Financially difficult for water paying	yes	143	6.75
Housing tenure	owner - mortgage loan	729	34.40
	owner	1029	48.56
	renter - private sector	224	10.57
	renter - social or public	101	4.77
	missing	36	1.70
Dwelling type	4 facades	964	45.49
	3 facades	434	20.48
	2 facades	541	25.53
	apartment/studio	172	8.12
	missing	8	0.38
Year built	Before 1945	743	35.06
	1946-1970	479	22.61
	1971-1990	486	22.94
	1991-2000	161	7.60
	2001 and after	244	11.51
	missing	6	0.28

Number of kitchens	0	19	0.90
	1	2063	97.36
	2	30	1.42
	3 or more	4	0.19
	missing	3	0.14
Number of living rooms	0	24	1.13
	1	1817	85.75
	2	246	11.61
	3 or more	29	1.37
	missing	3	0.14
Number of bedrooms	0	33	1.56
	1	227	10.71
	2	573	27.04
	3 or more	1281	60.45
	missing	5	0.24
Number of bathrooms	0	31	1.46
	1	1741	82.16
	2	309	14.58
	3 or more	35	1.65
	missing	3	0.14
Number of toilets	0	79	3.73
	1	1202	56.72
	2	720	33.98
	3 or more	115	5.43
	missing	3	0.14
Using distribution water for pool filling	yes	149	7.03
Presence of permanent pool	yes	46	2.17
Recent replacement of permanent pool	yes	14	0.66
Presence of inflatable pool	yes	113	5.33
Recent replacement of inflatable pool	yes	37	1.75
Using distribution water for garden irrigation	yes	1615	76.22
Presence of dishwasher	yes	1413	66.68
Recent replacement of dishwasher	yes	605	28.55
Presence of washing machine	yes	1950	92.02
Recent replacement of washing machine	yes	776	36.62
Presence of rainwater tank	yes	849	40.07
Recent replacement of rainwater tank	yes	86	4.06
Presence of bathtub or shower	none	176	8.31
	shower	387	18.26
	bathtub	845	39.88
	both	711	33.55

Presence of efficient showerhead	yes	830	39.17
Recent replacement of efficient showerhead	yes	394	18.59
Presence of efficient toilet	yes	1533	72.35
Recent replacement of efficient toilet	yes	511	24.12
Presence of dried toilet	yes	27	1.27
Recent replacement of dried toilet	yes	16	0.76
Government subsidies for rainwater tank	yes	5	0.24
Confidence in piped water quality	confident	1055	49.79
	rather confident	591	27.89
	neither confident nor suspicious	240	11.33
	rather suspicious	96	4.53
	suspicious	50	2.36
	no opinion	67	3.16
	missing	20	0.94
Pay per volume use	yes	2088	98.54
	missing	1	0.05
Budget water meter	yes	3	0.14
Limited water meter	yes	1	0.05

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