



The role of climate variability in convergence of residential water consumption across Chilean localities

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Abstract

This paper analyses the existence of convergence in residential water consumption across geographical regions using econometric methods taken from the economic growth literature and a panel of water consumption of 348 Chilean localities from 2010 to 2015. Convergence was found, and the main causes were factors related to economic and climate variables.

Keywords Climate variability · Economic development · Latin America · Water management

JEL Classification Q25 · Q56

1 Introduction

Climate change is reducing rainfall and increasing temperatures in the most populated regions of Chile (CONAMA 2007). The reduction in rainfall, which affects water supply, together with higher temperatures have been associated with an

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increase in water demand for residential and non-residential uses (Nauges and Thomas 2003; Gaudin 2006; Hanemann and Nauges 2006). In other words, residential water demand is highly sensitive to seasonal variables. Water demand increases in the summer, because there are more outside uses such as watering gardens, filling swimming pools, and washing cars, and inside uses such as more frequent showers. In addition, social drivers such as the increase in per capita income associated with the process of economic development, is allowing households to rise their consumption of goods and services, including water. The two stylised facts suggest that the distribution of water consumption might be changing across time.

Chile is among the longest north–south countries in the world. Its territory is long and narrow, stretching over 4300 km (2670 mi) from north to south, while its narrowest and widest points are only 90 km (60 mi) and 445 km (276 mi), respectively. The country comprises a wide range of climate zones across its large territory. It has a desert climate in the north, mediterranean climate in central Chile, and oceanic and tundra climate in the south. Chile is experiencing the effects of climate change. A study conducted by CONAMA (2007) showed that, since the decade of the 1970s, there is a decreasing trend in rainfall in Central, Southern, and Austral Chile, while temperatures have remained stable. The study predicts increases in the zero isotherm and temperatures in all regions of the country, while rainfall will increase in the north and decrease in the Central, Southern and Austral zones of Chile.

Although Chile is not considered a developed country, it is the most prosperous nation of South America and it is considered a high-income economy by the World Bank. The country is one of the 35 members of the OECD and, together with Argentina, is the only Latin American nations in the group of Very High Human Development countries (UNDP 2016). Therefore, we believe that Chile, an emerging country with distinctive geographic characteristics, is an interesting place to study the dynamics of water consumption and their relationship with climate variability and economic development.

This paper studies the process of convergence of residential water consumption in Chilean localities that is the process of equalisation of water consumption levels across geographic units. We want to answer two questions: (1) is there convergence in residential water consumption across Chilean localities? and, (2) which are the causes of convergence or divergence? As suggested before, if there were convergence, two main factors would seem to be the causes: the change in climate variables across the country and the increase in per capita income. To answer these questions, econometric models taken from the literature of economic growth were used to analyse a panel database of 348 Chilean localities from 2010 to 2015, containing data about water consumption levels, water prices, socioeconomic variables, and weather.

Water consumption convergence and its determinants are important because, if localities with low levels of water consumption were converging to the levels of localities with high levels of water consumption—which it seems to be the case—total water demand will increase, putting pressure on water utilities which have to supply water, and it will cause a rapid increase in water prices that could seriously affect the water consumption of the households. To effectively address this problem, it is necessary to understand the causes of such convergence.

Chile has localities with increasing and decreasing water consumption levels, but most of them are increasing their water consumption. Thus, the overall average is increasing, and this trend might continue in the future due to climate change and the rising living standards. However, convergence in water consumption across geographic regions might not occur with certainty, especially in the case of Chile, given that the country has a distinctive structural characteristic: its climate variability; so, it is not clear that water consumption levels of arid and rainy localities would be similar in the long run.

The remainder of the paper is organised as follows. Section 2 presents a brief review of the literature about economic convergence and water demand. Section 3 describes the data used in our research. Section 4 details the econometric approach used to analyse the data. Section 5 discusses the results of the analysis. Section 6 summarises the main results and conclusions of the study.

2 Overview of the convergence and water demand literature

2.1 Convergence

Economic convergence of income is the hypothesis that economies with low levels of per capita income will tend to grow faster than richer economies; so, in the long run all economies will converge in terms of per capita income [for useful literature reviews see Chatterji (1992), Barro and Sala-i-Martin (1995). Canova and Marcet (1995), Galor (1996), Sala-i-Martin (1996a), de la Fuente (1997), Martin and Sunley (1998)]. Convergence is an implication of the neoclassical growth model of Solow (1956) and Swan (1956): the diminishing returns to capital in the production function imply that the rate of return to capital (and, therefore, its growth rate) is very large when the stock of capital is small, and vice versa. Therefore, if the only difference across countries is their initial levels of capital, countries with little capital will be poor and will grow faster than rich countries.

According to Sala-i-Martin (1996a), there are two types of convergence. Absolute β -convergence exists in a cross-section of economies when we find a negative relation between the growth rate of per capita income and the initial level of income. In other words, there is absolute β -convergence when poor economies tend to grow faster than wealthy ones. On the other hand, there is σ -convergence when the dispersion of per capita income across economies tends to decrease over time. These concepts are related since β -convergence is a necessary, but not a sufficient condition for σ -convergence.

Absolute β -convergence is predicted by the neoclassical model when the assumption that the only difference across countries is their initial levels of capital holds; however, economies may differ in their structural characteristics. Thus, if economies have different initial parameters, they will have different steady states and absolute β -convergence might not be found. In this context, a third concept arises: conditional β -convergence, which means that economies converge but to their own steady states. To test the hypothesis of conditional convergence the steady state of each economy must be constant, for example, by conditioning on a set of variables that

holds constant the steady state [see, for example, Sala-i-Martin (1996a), Barro and Sala-i-Martin (1992), Mankiw et al. (1992)].

Sala-i-Martin (1996a) analysed convergence in a variety of data sets, including a large cross-section of 110 countries, the OECD countries, the states of US, the prefectures of Japan, and regions within several European countries. He found absolute β -convergence and σ -convergence in all cases except for the large cross-section, which exhibits conditional β -convergence and σ -divergence. Sala-i-Martin (1996b) found empirical evidence of regional income convergence across the United States, Japan, and five European nations. He also found that the estimated speeds of convergence were surprisingly similar across data sets, about 2% per year, which means that the half-life of convergence is around 35 years.¹ Barro and Sala-i-Martin (1995) found that the speed of regional convergence in the United States, Europe, and Japan has varied over time, and they found divergence in regional per capita income in some periods. Coulombe and Lee (1995) found evidence of convergence across Canadian localities between 1961 and 1991, according to six different measures of per capita income and output.

A speed of convergence of 2% per year is too slow to be consistent with the theoretical model. To address this problem, Mankiw et al. (1992) interpreted these empirical results within the framework of an augmented Solow growth model—which incorporates human capital as a factor of production—explaining that the slow rate of convergence indicates that the production technology exhibits almost constant returns to scale. By contrast, authors such as Canova and Marcet (1995), Islam (1995) and Caselli et al. (1996) estimated rates of convergence ranging between 4.3 and 12% using a panel data specification with fixed country effects. However, these results are not consistent with the Solow model, since the estimated speeds of convergence are too fast. These estimates imply that the diminishing returns to capital are not enough to explain convergence, so additional convergence mechanisms must be considered, for example, technological diffusion and reallocation of resources across regions.

Regarding water analysis, Portnov and Meir (2008) found β -convergence of residential water consumption in Israel, and β -divergence in water consumption of the non-residential sector. They explained that the convergence trend in the residential sector stems from two main factors: (1) the saturation of water consumption in wealthy localities, and (2) the rising standards of living in poor localities, which enable them to consume more water for household use. However, it must be remarked that the main climates of Israel are Mediterranean, semi-arid, and desert; thus, the limited climate variability could help to make convergence possible, since Israel localities are similar in their structural characteristics, a condition that does not hold in Chile. On the other hand, the econometric specification used in that paper is not compelling enough, as the authors omitted some important determinants of water consumption in their analysis, such as water tariffs. In addition, we believe that the

¹ According to Martin and Sunley (1998), the half-life, or time required for one-half of the initial deviation of relative regional per capita income from its steady state value to be eliminated, is given by $H = \ln 2 / -\ln(1 - \beta)$.

authors identified the determinants of water consumption growth, but not the determinants of convergence.

2.2 Residential water demand

The research in residential water demand focuses mainly in providing suitable methods to estimate price and income elasticities (Vásquez-Lavín et al. 2017). In this section, we briefly review some important aspects of the literature. For useful and complete literature reviews see Arbúes et al. (2003) and Worthington and Hoffman (2008).

The literature of water demand uses a typical econometric model of the form $Q_D = f(P, Z)$, where Q_D is the quantity of residential water consumed, P is some measure of price, and Z is a set of other variables affecting residential water demand, such as income, and sociodemographic and climate variables. Regarding prices, Worthington and Hoffman (2008) indicate that prices are characterised by three features: (1) metering (individual or collective); (2) price structure (fixed charge plus variable prices); and (3) billing frequency. The price structure can be complex, including a fixed charge, which is independent of the level of consumption, and a variable price that depends on the amount of consumption. The variable price can be non-linear if the price per additional consumption unit varies when consumption reaches certain thresholds that define different marginal prices for different consumption blocks. For example, increasing block pricing means that a higher marginal price is charged for consumption beyond a certain threshold (Dahan and Nisan 2007; Olmstead et al. 2007; Yates et al. 2013; Schoengold and Zilberman 2014).

Water is a commodity with few substitutes, so it is price-inelastic. When there are consumption blocks, price is determined simultaneously with the quantity demanded, thus it is endogenous. To address this issue, a widespread solution uses a variable—known as the Nordin's difference—that reflects the income effect imposed by decreasing or increasing price structures in the water demand equations (Taylor 1975; Nordin 1976). This specification has been the subject of much controversy, with some authors recognising its importance (Espey et al. 1997), and others finding it unnecessary (Shin 1985; Chicoine et al. 1986; Nieswiadomy and Molina 1991; Arbúes et al. 2003). The price specification is diverse across literature: while some authors use marginal prices, others use Nordin's specification, the average price, or other variants; however, in most studies, price elasticity is estimated to be in the range 0.25–0.75.

Income elasticity of water demand has been found to be positive and inelastic, and small in magnitude, because water bills are typically a small percentage of the income of the households, especially in the case of high-income households (Arbúes et al. 2003). However, some authors argue that the effect of income on consumption could be negative, since greater levels of income—through its correlation with education—would be capturing the effect of water conservation measures taken by the households (Worthington and Hoffman 2008).

Most importantly to our goals, residential water demand is highly sensitive to seasonal variables. It increases in summer months, because there are more outside uses

such as watering gardens, filling swimming pools, and washing cars, and inside uses such as more frequent showers. These seasonal factors can be measured in many ways, through temperature (Griffin and Chang 1990), minutes of sunshine, accumulated rainfall, the number of rainy days and evapotranspiration (Billings and Agthe 1980, Nieswiadomy and Molina 1991; Hewitt and Hanemann 1995).

Furthermore, households' characteristics are important determinants of water demand. For example, Nauges and Thomas (2000) argued that water consumption in areas with a high proportion of young person is likely to be high due to less careful use, more frequent laundering and use of water-intensive outdoor activities. Similarly, Martinez-Espineira (2003) argued that areas with a high proportion of old persons are prone to consume more due to more gardening activity. On the other hand, if the dependent variable is water consumption per household, the household size is positively related to water consumption (Arbúes et al. 2003).

Arbúes et al. (2003) indicated that housing characteristics are also important determinants of water demand. For instance, the proportion of secondary residences in a locality helps to identify areas where seasonal uses are important. In addition, the proportion of individual houses in a locality is a proxy of the average size of gardens. Finally, housing features such as the number of bathrooms and the stock of appliances could help to distinguish between short run and long run effects of water demand.

3 Data

3.1 Variables

The database is a monthly panel of 348 Chilean localities from 2010 to 2015 ($N=348$, $T=72$ months). Water consumption and price data were collected from the regulatory agency, SISS (*Superintendencia de Servicios Sanitarios*), for 30 water utilities.

Water consumption data were complemented with socioeconomic and demographic data taken from the CASEN survey, a national household survey, available for years 2009, 2011, 2013 and 2015. Data for years 2010, 2012, and 2014 was imputed by interpolation. The database has climate data from the DMC (*Dirección Meteorológica de Chile*) and DGA (*Dirección General de Aguas*), assembled by the Center of Climate Science and Resilience (CR2). Missing climate data were imputed using the nearest-neighbour method.

Residential water consumption is the water consumed by households living in urban areas. The dependent variable is the average residential water consumption in a month. Our data includes the total monthly consumption (m^3/month) in each locality of the country. We divided this figure by the total number of households in the corresponding locality to obtain the average households' monthly consumption.

The rest of the variables are three categories of water consumption determinants: (1) economic variables (water price and income of the households); (2) sociodemographic variables (household and dwelling characteristics); and (3) climate variables (accumulated rainfall and average temperature).

Regarding water prices, in Chile each water utility has its own rate structure, and only some of them use incremental block pricing, that is a two-block structure which is valid only during summer months, the “peak period” from December to March, while during the rest of the year consumers face a uniform marginal rate. The limit between the two blocks of water consumption is 40 m³ of water, which is greater than the actual consumption of most of the households; so, only a few households consume in the second block of consumption.

Despite the price structure, our relevant price measure is the average price of water, since there is evidence that consumers do not devote much effort to study the structure of changes in intramarginal rates because of information costs (Billings and Agthe 1980; Bacharach and Vaughan 1994). As a result, they use the average price to decide how much water they consume. Several research has shown that consumers tend to respond to average prices for water demand rather than marginal prices (Foster and Beattie 1979, 1981; Griffin and Chang 1990; Martinez-Espineira 2003; Gaudin 2006), and for electricity demand (Shin 1985; van Helden et al. 1987).

The average price was calculated by dividing the monthly total spending in water by total consumption in m³, so we obtained the average price in monetary units per m³ (Gaudin et al. 2001; Gaudin 2006).²

Income is the monthly per capita income of the household, averaged by locality. Per capita income of the household was calculated by dividing the total monthly income by the number of people in the household. Total income is the sum of monetary earnings from labour, capital, and transfers from the State, including subsidies to water consumption³ and the imputed rent of the house (given that house owners do not have to pay rent, they have more disposable income to consume).⁴

Two variables were used to control for household characteristics: (1) the number of people in the household (average by locality), as more numerous households should consume more water (Arbúes et al. 2003); and (2) the number of youngsters in the household, where youngsters are below 15 years old, since households with more youngsters may consume more water (Nauges and Thomas 2000).

To control for differences in dwellings characteristics, two variables were used: the number of bedrooms and the number of bathrooms in the dwelling. These variables are positively related to water consumption, since it should be higher the larger the dwelling, as they may be proxies of the number of household members (Barkatullah 1996; Hewitt and Hanemann 1995).

Climate variables also drive water consumption, since consumption is higher in warm and dry localities. Two variables were used to control for climate factors: the monthly accumulated rainfall; and the monthly average temperature by locality.

² Price and income are used in real terms, deflated by the Consumer Price Index (CPI).

³ The state finances between the 25 and 100% of the first 15 m³ of water consumption depending on the socioeconomic condition of the household, which has to pay the difference.

⁴ We also used other measures of income: (1) the income from labor, (2) the income from labor and capital, and (3) the income from labor and capital plus transfers from the State. We obtained similar results with all variables, but the best ones in terms of statistical significance were achieved with total income.

Table 1 Summary of descriptive statistics

Variable	<i>n</i>	Mean	SD	CV	Min	Max
Consumption (m ³ /month)	24,750	13.71	8.67	0.63	1.33	88.70
Price (CLP/m ³)	24,332	975.07	391.65	0.40	80.10	2208.46
Income (CLP/month)	24,906	251,397	170,537	0.68	91,854	1,602,867
Number of people	24,906	3.33	0.28	0.09	2.13	4.39
Number of youngsters	24,906	0.71	0.15	0.21	0.17	1.57
Number of bedrooms	24,906	2.74	0.23	0.09	1.95	4.71
Number of bathrooms	24,906	1.08	0.31	0.28	0.20	2.99
Rainfall (mm ³ /month)	22,507	54.03	78.35	1.45	0.00	806.40
Temperature (°C)	22,083	12.95	4.47	0.35	−7.93	23.51

SD standard deviation, *CV* coefficient of variation

Table 2 Water consumption (m³/month) by quintiles of income (2010) between 2010–2015

Quintiles	Mean 2010	Mean 2015	Change (%)
All	13.85	14.07	1.6
1	10.13	10.96	8.2
5	18.24	17.62	−3.4%

Finally, there is a set of dummies for the natural regions of Chile, which are five territorial units defined on the basis of geographic and economic criteria. The regions are ordered from north to south, and each has its own natural characteristics. The Far North has mainly a desert climate, the Near North has a semi-arid climate, Central Chile has a Mediterranean climate, the Southern Zone has a temperate oceanic climate, and the Austral Zone has a subpolar oceanic climate. The limits between the natural regions are the parallels 27, 33, 37 and 42 (°S). In this research, we used data of localities located throughout 34 degrees in latitude, from Arica to Porvenir, which are separated by 3871 km (2405 mi) from north to south.

3.2 Descriptive statistics

Table 1 shows the summary of descriptive statistics. The average water consumption during the period of analysis was around 13.71 m³/month, while the median was 11.77 m³/month. The average price was around 975 CLP/m³ (1.4 USD/m³).

The average income was around 251,000 CLP/month (362 USD/month), while the median income was 210,565 (303 USD/month). Chile is one of the most unequal countries in the world; however, income inequality is decreasing according to a study published by UNDP (2017) that reports a decrease in income inequality in Chile during the last years. Appendix 1 shows a set of income inequality indicators for the period 1990–2015 presented by UNDP (2017). There has been an improvement in all income inequality indicators since 2000, while the poverty rate has decreased every year since 1990. During the period 2009–2015, a span

Table 3 Climate statistics by natural region

	Localities	Rainfall (mm ³ /month)		Temperature (°C)	
		Average	Change (%) ^a	Average	Change (%) ^a
Far North	10	0.59	1712	17.15	8
Near North	57	12.28	−23	13.43	−18
Central Chile	177	37.41	8	13.85	3
Southern Zone	86	108.98	0	11.53	8
Austral Zone	18	95.00	−17	8.36	11

^aPercentage change between 2010 and 2015

Table 4 Mean and SD of water consumption [ln(m³/month)] by year

Year	Mean	SD
2010	2.4810	0.4363
2011	2.4942	0.4208
2012	2.5182	0.4137
2013	2.5226	0.4055
2014	2.5262	0.4018
2015	2.5404	0.3898

of time similar to the one analysed in this study, the Gini index decreased from 50 to 47.6%, the Palma index decreased from 3.2 to 2.8%, and the ratio $Q1/Q5$ decreased from 12.8 to 10.8%. On the other hand, the poverty rate decreased from 25.3 to 11.7%.

Table 2 shows the water consumption levels and growth rates between 2010 and 2015 of localities belonging to the first and fifth quintile of income in 2010. The poorest localities increased their water consumption, while the wealthiest decreased it, a situation that suggests that the rising standards of living of poor localities might be a cause of convergence.

Regarding other characteristics of the households, the average number of people in the household was around three, of which one was a youngster. On the other hand, the average dwelling had around three bedrooms and one bathroom.

The average monthly accumulated rainfall was around 54 mm³; however, this variable showed a great dispersion across localities, since some localities averaged 0.00 mm³/month, while others averaged 806 mm³/month. The average temperature was around 13 °C. Table 3 shows the summary statistics of climate variables by natural region. It may be seen that the temperature tends to decrease from north to south, whereas accumulated rainfall tends to increase from north to south. During the period of analysis, rainfall decreased in the Near North and Austral Zone, while temperature increased in most regions except for the Near North.

Table 4 shows the mean and standard deviation (SD) of water consumption (ln) by year. There was an increase in consumption and a decrease in standard deviation in every year. The decrease in SD implies that there was σ -convergence and,

Table 5 Means between 2010 and 2015 by groups of localities

Localities	Variable	Mean 2010	Mean 2015	Change (%)
All $n = 348$	Consumption (m ³ /month)	13.11	13.51	3.05
	Income (CLP/month)	241,728	270,462	11.89
	Rainfall (mm ³ /month)	53.34	53.11	-0.42
NG localities $n = 99$	Consumption (m ³ /month)	16.36	15.06	-7.94
	Income (CLP/month)	321,882	353,325	9.77
	Rainfall (mm ³ /month)	39.29	42.58	8.38
PG localities $n = 249$	Consumption (m ³ /month)	11.82	12.92	9.26
	Income (CLP/month)	210,048	238,967	13.77
	Rainfall (mm ³ /month)	58.89	57.12	-3.02

NG localities, negative growth of water consumption; PG localities, positive growth of water consumption

therefore, there was (absolute) β -convergence, since β -convergence is a necessary condition for σ -convergence (Sala-i-Martin 1996a).

The average water consumption has increased over time; however, some localities have increased their consumption during the period while others decreased it. A total of 249 localities have increased their water consumption level, while 99 decreased it. Hereinafter, localities with Positive Growth in water consumption are referred to as PG localities, while localities with Negative Growth in water consumption are referred to as NG localities. Table 5 compares the average level of consumption, income, and rainfall of the full sample, with the levels of PG and NG localities during the period 2010–2015.

The average water consumption of NG localities was higher than the one of PG localities. The growth rate in both groups of localities was similar in absolute value; so, the greater number of PG localities explain the upward trend in water consumption. NG localities had a higher income than PG localities. Income increased in both type of localities, but it increased the most in PG localities. On the other hand, accumulated rainfall increased in NG localities, while it decreased in PG localities. Consequently, we hypothesise that these are the variables that appear to be explaining the process of convergence during the period 2010–2015, as the effect of the changes in income and rainfall seems to be explaining the increasing consumption in PG localities, which is converging to higher levels. A similar argument is valid for NG localities, which are reducing their consumption, converging to lower levels as accumulated rainfall increases in these areas.

4 Methodology

Following the explanation of Caselli et al. (1996), to analyse if there is absolute β -convergence, the following growth equation is estimated:

$$\ln(C_{i,t}) - \ln(C_{i,t-\tau}) = \alpha + \beta \ln(C_{i,t-\tau}) + \epsilon_{i,t} \quad (1)$$

where $C_{i,t}$ is the water consumption of locality i in period t ; $C_{i,t-\tau}$ is the water consumption of locality i in period $t - \tau$, where τ could vary depending on the period in which convergence is analysed (see below for more details); α is a constant; β is the coefficient on lagged water consumption, which is the speed of convergence; and $\epsilon_{i,t}$ is an error term. If β is significant and negative, then there is absolute β -convergence, since localities close to their steady state consumption level will experience a deceleration in consumption growth.

On the other hand, to analyse if there is conditional β -convergence, the following growth equation is estimated:

$$\ln(C_{i,t}) - \ln(C_{i,t-\tau}) = \alpha + \beta \ln(C_{i,t-\tau}) + W_{i,t-\tau}\delta + \eta_i + \xi_t + \epsilon_{i,t} \quad (2)$$

where $W_{i,t-\tau}$ is a row vector of determinants of water consumption; η_i is a fixed-individual-effect by locality, and ξ_t is a fixed-time-effect by year. These variables are proxies for the steady state level of consumption to which the locality is converging.

The list of variables included in $W_{i,t-\tau}$ are the determinants of water consumption that could explain the consumption level in the long run, while η_i captures the effect of other determinants that are not included in $W_{i,t-\tau}$.

On the other hand, τ could vary depending on the period in which convergence is analysed. There could be convergence for the whole period, but not for some sub-periods. In this paper different values for τ were tested, so the dependent variable was the growth rate of water consumption between $(t - \tau)$ and t . Control variables ($W_{i,t-\tau}$) are the initial levels of water determinants in each period that characterised the corresponding initial conditions.

Caselli et al. (1996) pointed out that Eq. (2) could be rewritten as:

$$\ln(C_{i,t}) = \alpha + \tilde{\beta} \ln(C_{i,t-\tau}) + W_{i,t-\tau}\delta + \eta_i + \xi_t + \epsilon_{i,t} \quad (3)$$

where $\tilde{\beta} = (1 + \beta)$, so there is convergence if $\tilde{\beta} < 1$. Equation (3) makes it clear that estimating (2) is equivalent to estimating a dynamic equation with a lagged dependent variable in the right-hand side.

Caselli et al. (1996) showed that in a dynamic equation the fixed-locality-effects are correlated with the other right-hand side variables, so the standard cross-section estimators are inconsistent, an error that explains the small coefficients found in most of the convergence literature. A second criticism has to do with the frequently disregarded issue of endogeneity, given that is clear that some of the variables in $W_{i,t-\tau}$ are endogenous. Caselli, Esquivel and Lefort addressed these two issues using the GMM estimator proposed by Holtz-Eakin et al. (1988), and Arellano and Bond (1991). This estimator, called the Arellano-Bond estimator, estimates a first-difference transformation of the equation that eliminates the individual effects and uses past values of the explanatory variables as instruments to control for endogeneity. We used the Arellano-Bond estimator to estimate Eq. (3), and all variables were previously transformed into deviations from monthly means, so the time effects are also eliminated.

In the case of water consumption, at least two variables are endogenous, water price and income. However, given that initial values of the determinants were used as regressors, all variables were treated as exogenous, except for price and income that were treated as predetermined (weakly exogenous). The model specification

was tested for autocorrelation and overidentifying restrictions using the tests proposed by Arellano and Bond (1991).

Next, the sources of convergence were analysed using a methodology proposed by De La Fuente (2002). The purpose was to decompose the measure of β -convergence into a series of additive factors that capture the effect of water demand determinants on the evolution of the cross-sectional distribution of consumption.

As De La Fuente (2002) explained, let y_i and x_i , with $i = 1, \dots, n$ be two series, where y_i can be written as the sum of its k components, $y_i = \sum_k y_{ik}$. Then, if we regress y_i and each of its components on x_i , the coefficients of these regressions are related by $b = \sum_k b_k$, where b_k is the coefficient of the k th component regression and b is the coefficient of the “total” regression of y_i on x_i . In this analysis y_i is the average water consumption growth by locality and x_i is their initial consumption, b is the convergence coefficient (β), which can be decomposed as the sum of the b_k —the partial convergence coefficients—obtained by regressing each of the components of average consumption growth on initial water consumption.

To be more precise, the components of water consumption growth, y_{ik} , are the contributions of each water demand determinant to average water consumption growth. To estimate the value of these components, in the first place the average growth rates of all variables during the sample period were computed, and then the following equation was estimated:⁵

$$\Delta \ln (C_{i,t}) = \alpha + \Delta \ln (W_{i,t})\delta + \epsilon_{i,t} \tag{4}$$

Where the average growth rate of water consumption, $\Delta \ln (C_{i,t}) = \left(\frac{1}{\tau}\right) (\ln (C_{i,t}) - \ln (C_{i,t-\tau}))$, with $\tau = 60$, depends on the average growth of the water demand determinants.⁶ Likewise, $\Delta \ln (W_{i,t}) = \left(\frac{1}{\tau}\right) (\ln (W_{i,t}) - \ln (W_{i,t-\tau}))$ is the vector of average growth rates of water determinants. Then, the components of water consumption growth are estimated by the expression $\hat{\delta}_k \Delta \ln (w_{i,t,k})$, where $\Delta \ln (w_{i,t,k})$ is the k th component of the vector of determinants $\Delta \ln (W_{i,t})$, and $\hat{\delta}_k$ is the corresponding estimated coefficient.⁷

The speed of convergence, β , is estimated using Eq. (5):

$$\Delta \ln (C_{i,t}) = \alpha + \beta \ln (C_{i,t-\tau}) + u_{i,t} \tag{5}$$

While the k regressions of the components of water consumption growth are:

$$\hat{\delta}_k \Delta \ln (w_{i,t,k}) = c + \beta_k \ln (C_{i,t-\tau}) + \epsilon_{i,t,k} \tag{6}$$

⁵ Let $Q_D = f(X)$ be a water demand equation. We can take logs and differences in both sides of the equation to obtain $\Delta \ln (Q_D) = f(\Delta \ln (X))$.

⁶ We chose $\tau = 60$ to have at least one measure of average growth for each month of the year ($T = 72$) with the aim of capturing the effect of weather variables on the seasonal pattern of consumption.

⁷ You should note that $\hat{\alpha} + \hat{\delta}_k \Delta \ln (W_{i,t})$ is the prediction of Eq. (4), which is equal to the sum of the k components, $\hat{\delta}_k \Delta \ln (w_{i,t,k})$, plus $\hat{\alpha}$.

Table 6 Estimates of β -convergence

Panel A	(1)	(2)	(3)	(4)	(5)	(6)
β	-0.3290***	-0.2552***	-0.3177**	-0.3345**	-0.3260***	-0.3619***
p value	0.000	0.009	0.014	0.012	0.009	0.005
R^2	0.1690	0.1632	0.2131	0.2465	0.2456	0.3059
N	24,283	20,510	16,451	12,314	8179	4122
τ	1	12	24	36	48	60
Panel B	(1)	(2)	(3)	(4)	(5)	
β	-0.3279***	-0.3365***	-0.3361***	-0.3351***	-0.3154***	
p value	0.000	0.001	0.004	0.001	0.000	
R^2	0.1686	0.1734	0.1708	0.1723	0.1635	
N	23,575	20,350	12,019	18,183	23,005	
Excl. region	Far North	Near North	Central Z.	South Zone	Austral Z.	
Panel C	(1)	(2)	(3)	(4)	(5)	(6)
β	-0.3339***	-0.3143***	-0.3484***	-0.3309***	-0.5203***	-0.5812***
p value	0.005	0.001	0.000	0.000	0.000	0.000
R^2	0.1717	0.1619	0.1779	0.1696	0.9539	0.9162
N	17,475	22,297	22,992	23,323	23,817	18,383
Excluded	Extr. rain	Extr. heat	Outliers C	Outliers Y	-	-
Specification	-	-	-	-	FE	FE + WD

Panel A, absolute β -convergence for different values of τ . Panel B, robustness analysis by excluding a natural region of the estimation, $\tau=1$. Panel C, 1–4: robustness analysis by excluding extreme localities, $\tau=1$. Panel C, 5–6: Arellano–Bond estimator; FE: controls are only fixed effects, $\tau=1$; FE + WD: controls are fixed effects plus water determinants, $\tau=1$

p values in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Thus, β can be decomposed as the sum of the β_k . Finally, it should be noted that, to obtain a sum of components equal to the actual β , the residuals of the estimation of Eq. (4), $\hat{\epsilon}_{i,t}$, should be considered as an additional component of water consumption growth, which is the part of average growth not explained by the evolution of the water demand determinants.

5 Results

A modified version of Eq. (1) was estimated using the within estimator for different values of τ :

$$\ln(C_{i,t}) - \ln(C_{i,t-\tau}) = \alpha_i + \beta \ln(C_{i,t-\tau}) + \epsilon_{i,t} \tag{7}$$

In this equation α_i are fixed-individual effects; so, we estimated a conditional convergence coefficient. Clustered robust standard errors by natural region were used for inference. The results are shown in Table 6, panel A.

Convergence was found for all values of τ . The result for $\tau = 1$, our preferred specification—since it is a more demanding test for convergence than using larger values of τ , and the results are comparable to the ones obtained using the Arellano–Bond estimator—an estimated speed of convergence of 0.3290, implies a “half-life” of about 1.7 years.

Then, a robustness analysis of the results was performed. In columns (1) to (5) in Table 6, panel B, all the localities belonging to a specific natural region were excluded from one of the estimations (with $\tau = 1$). The results were similar to the ones obtained using the complete sample: β -convergence was found in every case.

In columns (1) and (2) in Table 6, panel C, the localities belonging to the most extreme natural regions in terms of accumulated rainfall (Far North and Southern zone) and temperature (Far North and Austral zone) were excluded, respectively, while in column (3) the localities identified as outliers in water consumption distribution in 2010 were excluded. In addition, in column (4) the localities identified as outliers in income distribution in 2010 were excluded. Significant β -convergence was found in every case, showing that the results do not depend on the group of localities or the type of climate of the regions in the sample.

Equation (3) was estimated using the Arellano–Bond estimator. The results are in columns (5) and (6) in Table 6, panel C. In column (5) we controlled for the different steady states using only fixed effects, whereas in column (6) the determinants of water demand were added as additional control variables.⁸ The estimated speeds of convergence, 0.5203 and 0.5812, imply a half-life of about 0.9 and 0.8 years, respectively. For comparison, it is mentioned that Portnov and Meir (2008) found a speed of conditional β -convergence equal to 0.1550 for residential water consumption in Israel, which implies a half-life of 4.1 years.

Table 7 shows the results of the analysis of the sources of convergence. The first row of each panel is the estimate of Eq. (5), while the following rows show the results of the k th version of Eq. (6). A significant negative beta means that the corresponding variable is a source of convergence, while a significant positive beta indicates a source of divergence. The percentage (%) column shows the normalised values of the convergence coefficients, where the “total” beta coefficient is set to 100.

Table 7, panel A shows the results of the estimations using the full sample. We found five variables that are significant sources of convergence: income, price, temperature, rainfall, and the number of youngsters in the household; while one variable was a significant source of divergence: the number of bathrooms in the dwelling. Hence, two groups of variables seem to be the most influential in the process of convergence: economic and climate variables, as we hypothesised above. Among the identified sources of convergence, price seems to be the most important, followed by rainfall, temperature, income, and number of youngsters. On the other hand, the number of bathrooms was identified as a source of divergence. This is a variable that has been described as a proxy of the number of household members (Barkatullah 1996; Hewitt and Hanemann 1995).

⁸ The complete results of this estimation are presented in Appendix 2.

Table 7 Sources of convergence

Panel A	Beta	%	<i>p</i>	<i>R</i> ²
	−0.0058***	100.00	0.000	0.3220
Income	−0.0001***	0.89	0.000	0.0085
Price	−0.0002***	3.37	0.000	0.0125
Number of people	1.11E−05	−0.19	0.569	0.0002
Number of youngsters	−3.88E−05***	0.67	0.000	0.0074
Number of bedrooms	3.62E−06	−0.06	0.100	0.0014
Number of bathrooms	2.61E−05***	−0.45	0.000	0.0090
Temperature	−0.0001**	1.21	0.015	0.0030
Rainfall	−0.0001***	1.35	0.004	0.0042
Residual	−0.0054***	93.22	0.000	0.2987
Panel B	Beta	%	<i>p</i>	<i>R</i> ²
	−0.0044***	100.00	(0.000)	0.2681
Income	−0.0001***	1.26	(0.000)	0.0116
Price	−0.0001***	3.10	(0.000)	0.0106
Number of people	1.13E−05	−0.25	(0.312)	0.0008
Number of youngsters	−0.0001***	1.34	(0.000)	0.0123
Number of bedrooms	−4.80E−06	0.11	(0.277)	0.0009
Number of bathrooms	2.37E−05***	−0.53	(0.000)	0.0163
Temperature	−1.25E−05	0.28	(0.447)	0.0004
Rainfall	−3.97E−05*	0.90	(0.086)	0.0022
Residual	−0.0042***	93.80	(0.000)	0.2469
Panel C	Beta	%	<i>p</i>	<i>R</i> ²
	−0.0104***	100.00	(0.000)	0.5061
Income	−6.03E−06	0.06	(0.777)	0.0001
Price	−0.0004***	4.27	(0.000)	0.0252
Number of people	−3.46E−05	0.33	(0.650)	0.0003
Number of youngsters	8.39E−08	0.00	(0.995)	0.0000
Number of bedrooms	1.10E−05	−0.11	(0.537)	0.0006
Number of bathrooms	9.26E−06	−0.09	(0.446)	0.0009
Temperature	−0.0002**	1.72	(0.035)	0.0068
Rainfall	−0.0001	0.56	(0.205)	0.0024
Residual	−0.0097***	93.26	(0.000)	0.4810

Panel A, full sample. Panel B, localities with negative growth in water consumption. Panel C, localities with positive growth in water consumption

p values in parenthesis. **p* < 0.1, ***p* < 0.05, ****p* < 0.01

Panels B and C in Table 7 show the results of the analysis of the sources of convergence in localities with only negative or positive growth in water consumption, respectively. We found relevant to study whether there are different sets of sources of convergence for these localities, given that NG localities would be converging to

lower levels of consumption, while PG localities would converge to higher levels of consumption. The results show that there is convergence in both groups of localities—which is another proof of the robustness of the results—and that the speed of convergence is faster in localities with positive growth in water consumption.

Panel B in Table 7 shows that income, price, the number of youngsters, and rainfall are sources of convergence in NG localities, while the number of bathrooms is a source of divergence. We believe that income affect convergence by increasing the rate at which water consumption decrease in localities with high levels of consumption. In other words, the effect of income on water consumption in these localities is negative, since it would be capturing the effect of water conservation measures taken by the households (Worthington and Hoffman 2008). On the other hand, panel C in Table 7 shows that the only relevant variables explaining convergence in PG localities are prices and temperature.

Although we find some significant sources of convergence, its contribution to the total speed of convergence is marginal or moderate, as the most important source of convergence in all estimations is the residual. This means that there are other variables in the residual explaining convergence, in addition to the variables we just identified. This is a first attempt to find variables that could explain the tendency of households' water consumption to converge to a long run level. However, we believe that this part of the work must be improved in future research by analysing the role of additional variables in the convergence process. For instance, there are other water consumption determinants that may affect convergence, such as the number of dwellings per locality, age of the dwellings, percentage of homes that are owner-occupied, property value, population density, number of tourists, the presence of swimming pools, type of yard vegetation, lawn size, the evaporation rate, the amount of rainfall in summer months, the number of rainy and warm days, minutes of sunshine, etc. In addition, there may be non-linear effects of water consumption determinants on convergence.

It is important to bear in mind that the determinants of water demand may not be the same determinants of convergence. So, another set of variables from the convergence literature may play a role, for instance, the rate of unemployment, total employment, the net stock of privately held physical capital, technology and knowledge diffusion across regions, the level of education of the population, the reallocation of resources across economic sectors, the effect of economic reforms, construction activity, the level of trade, cultural and institutional differences, competitiveness indicators, migration patterns, and economic development variables such as health, poverty and inequality indicators. If these factors affect convergence of income, they may well explain convergence in consumption too, as consumption depends on income.

6 Conclusions

We found evidence of β -convergence in per household water consumption in Chile, given that a negative relationship between the growth rate and the initial level of water consumption was found, which means that localities with small

initial levels of water consumption tend to increase their consumption faster than localities with higher initial levels of consumption (and vice versa). For the period 2010–2015, the estimated speed of convergence has been around 33% by month. We also found evidence of σ -convergence, which means that the dispersion of per household water consumption distribution is decreasing over time; so, water consumption distribution has been becoming less unequal.

Previous research identified the effect of economic development on convergence, as the rising living standards of poor localities appear to explain their increasing water consumption levels, which were converging to the levels of wealthy localities in Israel (Portnov and Meir 2008). We focused this article on analysing the effect of climate variability on convergence, as the distinctive geographic characteristics of Chile allowed it. We showed that climate variables—accumulated rainfall and temperature—were significant sources of convergence in Chile during the period 2010–2015. We also remark that rainfall was an important source of convergence in localities with negative growth of consumption, while temperature was a significant factor explaining convergence in localities with positive growth of consumption.

A positive aspect of water consumption convergence is that water demand will grow at a decreasing rate, and the future consumption level could be predicted. However, overall water demand is increasing, which is undesirable from the point of view of sustainable development. On the other hand, the decreasing rainfall levels will affect water supply, increasing the cost of water and, consequently, causing a rapid increase in water prices that could seriously affect the consumption level of households, especially in the case of the poor.

These findings are useful to plan measures to manage water consumption in a better way. Water conservation measures might be encouraged in risky localities, such as those with decreasing rainfall levels, increasing water consumption or high levels of current consumption. However, some policies may have unexpected effects. For instance, Ward and Pulido-Velazquez (2008) show that policy measures that encourage adoption of water-conserving irrigation technologies, such as water conservation subsidies, are unlikely to reduce water use under conditions that occur in many river basins. The authors show that the adoption of more efficient irrigation technologies reduces valuable return flows and limits aquifer recharge. Thus, these policies can actually increase water depletions.

In contrast, we propose the implementation of norm-based programs, which use behavioural nudges to induce voluntary reductions in water consumption. This type of programs has had significant impacts in the localities where they have been implemented, and they are also cost-effective (Ferraro et al. 2011; Ferraro and Price 2013; Bernedo et al. 2014).

A more detailed analysis of the sources of convergence is an important area for future study. In this paper we focused in the role of water consumption determinants, especially economic and climate variables. However, we omitted many other variables of the analysis, which could better explain the process of convergence.

Appendix 1: Income statistics

Income inequality from 1990 to 2015

Source: UNDP (2017)

Year	Gini	Palma	Q5/Q1	% Poverty
1990	52.1	3.6	14.8	68.0
1996	52.2	3.6	15.2	42.1
2000	54.9	4.2	17.5	36.0
2003	52.8	3.7	15.3	35.4
2006	50.4	3.3	13.3	29.1
2009	50.0	3.2	12.8	25.3
2011	49.1	3.0	12.2	22.4
2013	48.8	3.0	11.6	14.4
2015	47.6	2.8	10.8	11.7

Gini index ranges from 0 to 100, with 0 representing perfect equality and 100 representing perfect inequality. The Palma ratio is the income of the richest 10% of the population divided by the income of the poorest 40%. The Quintiles ratio is the average income of the richest 20% of the population divided by the average income of the poorest 20%. The poverty rate is the percentage of households whose income is under the line of poverty.

Appendix 2: Equation (3) estimates

Variables	Coefficients
Consumption ($\tilde{\beta}$)	0.4188*** (0.000)
Income	-0.0163 (0.996)
Price	0.0571 (0.174)
Number of people	-0.0668 (0.862)
Number of youngsters	0.0051 (0.997)
Number of bedrooms	-0.0051 (0.989)
Number of bathrooms	-0.0292(0.988)
Temperature	0.0057 (0.444)
Rainfall	-0.0001 (0.427)
Constant	-0.0216 (0.369)
Beta (β) ^a	-0.5812***
p value	(0.000)
R^2	0.9595
N	18,383

p values in parenthesis * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

$$a\beta = 1 - \tilde{\beta}$$

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