THESIS

CHARACTERIZATION OF URBAN WATER USE AND PERFORMANCE EVALUATION OF CONSERVATION PRACTICES USING THE INTEGRATED URBAN WATER MODEL IN SÃO PAULO, BRAZIL

Submitted by

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ABSTRACT

CHARACTERIZATION OF URBAN WATER USE AND PERFORMANCE EVALUATION OF CONSERVATION PRACTICES USING THE INTEGRATED URBAN WATER MODEL IN SÃO PAULO, BRAZIL

Increasing urban population around the globe has intensified the need for water, food and energy. The residential sector is responsible for the highest water use in urban settings. Understanding the factors affecting water use helps to improve management strategies, incentivize conservation practices, develop public educational events, feed demand forecasting models and support policy creation.

Modelling urban water demand in the long-term is a complex process because of incorporation of multiple dynamic components in the urban-environment system. The Integrated Urban Water Model – IUWM – offers capabilities of long-term modelling by using a mass-balance approach for urban water demand predictions and potential demand reductions assessment.

A combination of climate anomalies, water resources management practices over the years and watershed conservation contributed to the water shortage in Southeastern Brazil in 2014-2015. In the city of São Paulo, the shortage was worsened by drops in reservoir levels, rise in water use patterns and in number of inhabitants, and the historical tendency to neglect local water sources. Residential water demand, which accounts for 84% of the total water use, faced compulsory reductions through behavioral changes and reuse of graywater and roof runoff harvesting.

The goals of this study are to apply IUWM to the city of São Paulo to quantify savings produced by graywater and roof runoff use and to evaluate the potential of conservation practices for demand reduction. The first part of the study focuses on exploring differences in water demand patterns under shortage conditions using a water use time-series from 2013-2017. In this part, IWUM is trained to estimate indoor and outdoor demand through calibration procedures. Determinants of water demand are also investigated through a multiple linear regression, which identified household size and socioeconomic variables as having a significant effect in water use.

The second portion focuses on applying IUWM to evaluate reductions during the shortage and performance of graywater, stormwater, roof runoff harvesting and effluent reuse for potable and non-potable purposes. Climate change was added to assess shifts in performances of conservation practices due to future reductions in precipitation. Lastly, a comparison of maximum potential and benefits of fit-for-purpose technology adoption is done using a cost-benefit matrix. The matrix was adapted for required treatment representing cost and percentage reductions in water demand as benefit.

The results of this work support decision-making with respect to conservation practices adoption by enhancing the list of options to manage water demand, especially during shortage conditions. Ultimately, these results can encourage development of water reuse policies in Brazil.

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Chapter 1 - Introduction

Urban sprawl over the past decades has caused researchers, governments, society and environmentalists to dedicate special attention to the impacts of unplanned growth on the population and the available resources. According to the World Bank (2018), in 2014, urban population was estimated to be almost 3.9 billion people, increasing the demand for basic needs such as water, housing, food and energy.

Despite the abundance of water on Earth, its unequal availability for consumption poses a challenge for major urban cities in terms of reliability, quality, and costs. In addition, population growth and climate change are also expected to impact the water supply and demand in highly urbanized areas, not to mention the natural competition with other uses such as agricultural, industrial, power generation, and ecological uses. Even in regions where water availability per person is reasonable, it is not possible to guarantee this condition will persist in the long-run.

The diversity of water use within urban areas is worth attention due to the substantial number of ongoing activities. The main uses for water in urban areas are residential, commercial, industrial and institutional.

The residential sector is responsible for the largest use of urban water. Factors that account for household water demand variations are climate, time of the year, family behavior and habits, number of persons living in the house, persons in the household during the day, persons employed and working outside of home, number of children and teenagers, income, education, cost of water and wastewater, quantity and quality of fixtures and appliances and parcel size (DeOreo et al., 2016).

Understanding the factors that affect water use helps to improve water management strategies and recommend conservation practices to promote demand reduction, especially in more vulnerable regions due to extreme climatic events or growing population. In addition, this understanding enables the development of public outreach and educational events, and the feeding of demand forecasting models (Makki et al., 2013).

Demand forecasting models based on water supply and demand assessment are an asset to enhance actions of water managers and urban planners (House-Peters and Chang, 2011; Cominola et al., 2015). Urban water can be modeled for short and long terms using different types of models. Short-term demand forecast analysis is useful for adjusting water supply operations and management, whereas long-term demand forecasting is important in the decision-making process for planning and infrastructure design. Therefore, long-term forecasting models are more complex, because they can incorporate dynamic components of climate, behavioral factors, and possible water conservation and reuse scenarios (Bougadis et al., 2005; Sharvelle et al., 2017).

Regression and time-series analyses, along with Artificial Neural Networks (ANN), have been used to forecast short-term demand. Santos (2014) compared the use of ANN's against a multiple linear regression (MLR) method in the Metropolitan Region of São Paulo, Brazil. The study focused on supply from the Cantareira distribution system through application of water use, meteorological, and socio-environmental variables. Results showed forecast feasibility of up to 12 hours in advance when using ANNs for the Cantareira system which performed better than MLR. Bougadis et al. (2005) investigated the applicability of ANNs, regression and time-series analysis for short-term forecasting in the city of Ottawa, Canada. Both studies agree regarding better performance of ANNs compared to other methods.

Urban water models have advanced over time as the availability of data and technological support have risen, thus allowing for long-term modelling and more sophisticated analysis at several spatial scales (House-Peters and Chang, 2011). Modelling urban water based on an integration concept leads to three key points, as explained by Bach et al. (2014): (1) modelling is made using multiple components and interactions among them, (2) long term modelling timeframe considers impacts in water quality and quantity, (3) better oriented support for strategic management through consideration of local and global perspectives of the urban-environment system. Therefore, long-term urban water modelling can support the adoption of the Integrated Urban Water Management approach.

The Integrated Urban Water Management approach – also known as one water approach – embraces the triple bottom line of sustainability while combining numerous factors of long-term water demand predictions. The approach acknowledges the role of natural system and built infrastructure on urban water and vice-versa and seeks to augment economic and social strength as results of a holistic view of the urban water components: water supply, sanitation and drainage (Whitler and Warner, 2014). As described by Mitchel (2006), Integrated Urban Water Management emphasizes both demand and supply aspects including the use of nontraditional water resources, fit-for-purpose water and decentralization to reduce demand. In addition, land use and landscaping policies, economics and urban development, regulations, legislations, community education and participation are part of the approach. The main goal is to maximize system efficiency while minimizing adverse impacts.

Most efforts towards one water approach and applications of urban water models have been done in the United States and Australia where extensive studies and surveys on various water subjects like water availability, water demand patterns, and end uses of water can feed the models and enhance results. Undeveloped countries struggle with implementation and improvement of sanitation infrastructure and urban drainage systems, enforcement of regulations for land use and occupation and income concentration. These factors hinder advancement of data collection and further studies on water consumption patterns.

According to the United Nations (2016), in 2016 of 31 megacities – (more than 10 million inhabitants) – 24 were in Africa, Latin America and undeveloped countries of Asia, including the Middle East. Shanghai and Beijing in China, Delhi and Mumbai in India, Mexico City in Mexico, Cairo in Egypt and São Paulo in Brazil were part of the top ten megacities list located in the “global South” in 2016. Water management, water supply, and water availability in these megacities clash with the same reality – the greater the population gets, these cities are at more risk of not meeting demand either because of quality concerns, poor management or water scarcity.

China is the most populous and one of the most polluted nations worldwide. These factors may negatively impact economic development, public health, food production, social well-being and environmental aspects that compromise both surface and groundwater. Urban water use per capita was near 212 liters per day – 55.9 gallons per day (Cheng et al., 2009). This value reached a peak in 2013 since 2005 and started to decline in the following years (Udimal et al., 2017). Water reuse and non-conventional sources have the potential to overcome the differences in supply and demand even though quality is still a factor to be considered (Udimal et al., 2017). Non-conventional water sources and practices performed in China are rainwater harvesting, seawater utilization, precipitation enhancement and wastewater reuse. Beijing stands out as a city performing wastewater reclamation (Wang et al., 2017). In addition, the Chinese government has put in place policies to incentivize the use of water efficient devices in agricultural irrigation, industrial facilities and urban centers (Cheng et al., 2009).

In India, water supply is intermittent and nearly 30% of households do not have access to tap water (Wankhade et al., 2014). Service efficiency is poor, and most cities receive only 69 liters per capita per day. The amount is lower than the required Indian national standards of 135 to 150 liters per capita per day causing households to seek and rely on multiple sources of water. These figures contrast with water use in the United States that is about 222 liters per capita per day – 58.6 gallons per capita per day (DeOreo et al., 2016). Slums and periphery zones are also vulnerable. In Mumbai, 54% of inhabitants live in slums, but use only about 5% of the supplied water (Wankhade et al., 2014). Delhi and Mumbai depend mostly on surface water from very distance sources implying energy costs and greater possibility of losses which should be reasons to encourage local conservation (McDonald and Shemie, 2014; Wankhade et al., 2014).

Over 90% of the population is offered potable water through municipal utilities in the Valley of Mexico where Mexico City is located. However, for part of this population the supply is still intermittent (World Bank, 2013). The main water source for the urban portion is local aquifers that are intensely exploited, but less than 35% of the treated water per year is reused (World Bank, 2013). In addition, almost 40% of urban use is losses that may be attributed to domestic or system leaks, irregular connections and deficient infrastructure or even metering errors. According to the World Bank (2013), another aggravating factor is the unsustainable economic and financial systems of tariffs and taxes for both the user and the service provider which prevents the application of price tools for limiting demand and discourages use control. This situation causes the provider to be constantly dependent on government support, deepening the service inefficiency.

The largest population density in Egypt is concentrated in the Nile Delta, where Cairo and Alexandria are located. The Nile River is the largest renewable water supply source, but groundwater from renewable and non-renewable sources is also available (World Bank, 2005). A demand management intervention caused by economic and social development resulted in non-conventional sources to be adopted such as wastewater reuse, agricultural drainage reuse, sea and brackish water desalination and rain harvesting. These practices demand more attention regarding water quality, given that only approximately 52% of urban population has access to wastewater collection and treatment (World Bank, 2005; Abdel-Dayem, 2011).

The distribution of water in Brazil is unequal with respect to population density across regions. Agricultural irrigation is ranked first in consumptive use of water and municipal use follows (ANA, 2017). Potable water serves 100% of the urban population in São Paulo, while the water loss index is one of the lowest in Brazil, around 30% (SNIS, 2015). Provided by two watersheds – the Piracicaba, Capivari and Jundiai (PCJ) Basin and the Upper Tiete Basin –

surface water is the main water source to the city. The Metropolitan Integrated System (MIS) is made up of nine producer systems consisting of 24 reservoirs distributed in these watersheds. The system is managed and controlled by the same state water utility that also treat and distribute water for 35 municipalities in the Metropolitan Region of São Paulo (MRSP) (Sabesp, 2015; Borges et al., 2017). From a mass-balance perspective, the volume of wastewater generated is greater than the installed capacity of wastewater treatment plants and tend to increase as new diversions into the MIS are expected with the objective to increase water security (Hespanhol, 2008). This difference in volume that is beyond treatment capacity could allow for a potential reuse and conservation in the MRSP. However, guidelines and water quality regulations for indirect and direct potable reuse do not yet exist in Brazil. Hence, conservation practices are not widely implemented (Hespanhol, 2015).

Poor water services, unsustainable use, temporal and spatial water availability, and pollution are the main causes for lack of efficiency of management. Most of the cities exemplified present these issues even though alternative and non-conventional sources are employed in certain cases. As climate change becomes more evident and population growth is a reality, other cities around the globe are also susceptible to increased water scarcity. Cape Town, in South Africa, has faced a serious drought since 2015 with price and non-price restrictions imposed for agriculture and residential use, limiting a maximum of 50 liters per day per person – 13 gallons per day per person. According to the City of Cape Town (2018), this condition required the water sources portfolio to be expanded, thus working towards implementing programs and infrastructure to facilitate adoption of alternative sources. Desalination, water reclamation, water transfer and groundwater use are planned to grow until 2022. The main immediate measures to avoid complete lack of water are graywater reuse and behavioral changes.

Inefficient management practices also curb the employment of survey tools for thorough quantification of water use habits, end uses of water, realistic capacity of reuse possibilities, and identification of system strengths and weaknesses. Lack of knowledge to support decision-making can worsen management abilities. A cycle breaker is essential to create a clear picture of the necessities and opportunities for better understanding of the details and system components. This comprehension aids the proposal of management solutions, guidelines considerations, and regulation and policy creation.

Rising population and climate change have also been compelling enhanced water management practices associated with conservation programs that can be price or non-price based. Olmstead and Stavins (2007) state that non-price tools, such as education, public information and appliance retrofit (Michelsen et al., 1999), can contribute anywhere from no water savings whatsoever to significant water savings, but they are closely related to human behavior towards water. This might explain why voluntary policies and educational programs have weaker effects than mandatory ones. This issue requires an intense campaign of education and outreach about water topics to impact behavior. In addition, policies that originate from solid knowledge and established supervision are more likely to be effective.

Given that urban areas will continuously grow, and authorities must be able to provide safe water to meet basic population needs and support economic development, urban water models are important tools for planning and management. The dynamism and abilities for a systemic analysis of the urban water components, with alternatives evaluation of non-conventional sources and reuse strategies as well as identifying key factors affecting demand are extremely useful. An integrated approach enables better management practices while offering ways to a one-water proposal, therefore, minimizing effects of shortages, decreasing water supply vulnerability and expanding quality of services and community engagement.

Motivation

The motivation for this study arose from the concern of water security in São Paulo and the MRSP, especially after the water crisis of 2014-2015. The exploration of components that drove demand during the time-series enables the understanding of the variation in water use and demand across shortage conditions. The assessment of system capacity for adoption of conservation practices to enlarge the alternatives portfolio for demand reduction is relevant to maximize potential and benefits should another shortage occur in the future. In addition, estimating the gains from application of technologies that support fit-for-purpose can contribute to decision-making and cost savings.

A supplementary motivation arose from the interest in diversifying the study areas where the Integrated Urban Water Model (IUWM) is applied to assess its flexibility and enhance its applicability as a long-term demand projection tool.

Objectives

This work includes two main objectives:

1. Comprehensively characterize urban water demand and use in the city of São Paulo, Brazil, through the application of the Integrated Urban Water Model focusing on residential demand. More specifically, this characterization comprises the:
    1.1 Investigation of factors affecting water demand.
    1.2 Exploration of differences in water use patterns under shortage conditions;
2. Evaluate the demand reduction potential of conservation practices by:
    2.1 Assessing performance of practices and potential to maximize savings and fit-for-purpose benefits;
    2.2 Exploring impacts of climate change in performance of practices.

Chapter 2 - Characterization of Residential Urban Water Demand Under Pre-Shortage, Shortage and Post-Shortage Conditions

Introduction

The start of the hydrologic year of 2013-2014 in Southeastern Brazil was severely affected by climatic anomalies that prevented summer rainfall from reaching water supply reservoirs (Marengo and Alves, 2015). In São Paulo city and state, the water crisis in the years of 2014 and 2015 was a result of climatic conditions, water resources management practices over the past years, watershed conservations efforts, and public awareness based on press releases (Rodrigues and Villela, 2015). At distinct levels, these factors contributed to the reality faced by the people in a few municipalities in the state of São Paulo.

In the city of São Paulo, a combination of drops in reservoir levels aggravated by the number of inhabitants, rise in water use patterns and the historical tendency to neglect local sources led to the shortage period (Cesar Neto, 2015; Custodio, 2015; Rodrigues and Villella, 2015).

The city was founded next to two main rivers: the Tamanduateí and the Anhangabaú Valley. Over the years, public policies prioritized channelization and rectification of water bodies that modified the landscape of most streams and rivers crossing the city, especially the Tietê and Pinheiros Rivers. Historically, urban development and economic growth caused water supply to be prioritized over wastewater and stormwater infrastructure (Custodio, 2015).

Water quality of local sources has been repudiated by the public since the 18th century. The water was also polluted because of mining exploration, early urban settlements, river bank excavation and raw effluent discharge (Custodio, 2015). The practice of importing water from distant basins started in the late 19th century, but the political, institutional, operational and environmental problems of this practice have been exacerbated in the past years by increase in population and demand for different uses. Climate change has further imposed increasing pressures on water supplies. In addition, local watercourses pollution and the gap between water supply and sewage treatment are still bottlenecks to be overcome in São Paulo (Hespanhol, 2008).

Residential water use accounts for approximately 84% of the total use in the city (Sabesp, 2017). Water use per capita fluctuates depending on the region's climate, culture, social development, public policies, public awareness, household income, cost, and availability (Hafner, 2007). Detailed studies about the residential demand profile are still scarce in Brazil, especially ones that describe differences in indoor and outdoor uses. Santos (2011) identified that the average water demand follows the cyclic annual trend of temperature and precipitation and points out that habits – laundry, car washing, cleaning after floods – after long rainy periods tend to increase water use.

Despite the recent shortage, there is still an absence of studies that detail residential water use in São Paulo in a comprehensive manner during the shortage using a district and regional approach. Moreover, future projections of water demand in São Paulo are still limited to short-term forecasting in a portion of the city (Santos, 2011) and do not include a broader view of the urban water elements as proposed in the One Water concept. The application of the Integrated Urban Water Model (IUWM) to aid characterizing water demand in the city is relevant in order to expand knowledge of conservation efforts potential along with explaining the factors playing roles in demand.

Objectives

The goal of this chapter is to comprehensively characterize residential urban water demand in the city of São Paulo while applying the Integrated Urban Water Model to support the analysis of the next chapter. More specifically, this chapter aims to:

1. Evaluate the applicability of IUWM in predicting residential water demand by the estimation of parameters under pre-shortage, shortage, and post-shortage conditions;

2. Investigate factors affecting water demand during the shortage condition.

Research Questions

The main research questions to be answered in this chapter are:

1. How is the water demand pattern across regions in São Paulo?
2. How did the shortage condition affect water demand?
3. What are the main contributors to variations in water demand in the city during the time-series?

Study area – City of São Paulo

Geography and Demographics

The municipality of São Paulo is located in the southeastern region of Brazil and is the most populous city nationwide. São Paulo and other 38 municipalities form the Metropolitan Region of São Paulo (MRSP), the largest urban agglomeration in South America and the fifth worldwide (United Nations, 2015). The MRSP corresponds to about 18% of the Brazilian Gross Domestic Product and concentrates approximately 21.5 million people (Emplasa, 2018).

In 1992, São Paulo was geographically divided into 96 districts that became territorial reference for the municipal government (São Paulo, 1992). In 2002, administration boroughs were established to bring the decisions and management from the municipal government to local levels, having their territorial boundaries based on socioeconomic characteristics. In 2013, there were 32 boroughs (São Paulo, 2002; 2013). In addition, five macro-regions (regions) (figure 1) are also denoted for geographic reference, as detailed on appendix I.

According to the Brazilian Institute of Geography and Statistics (IBGE), the annual rate of population growth in the city was lower when compared to the national and state rates and has decreased over the decades from 1.16, in 1980 to 1991, to 0.76, in 2000 to 2010 (Infocidades, 2017).

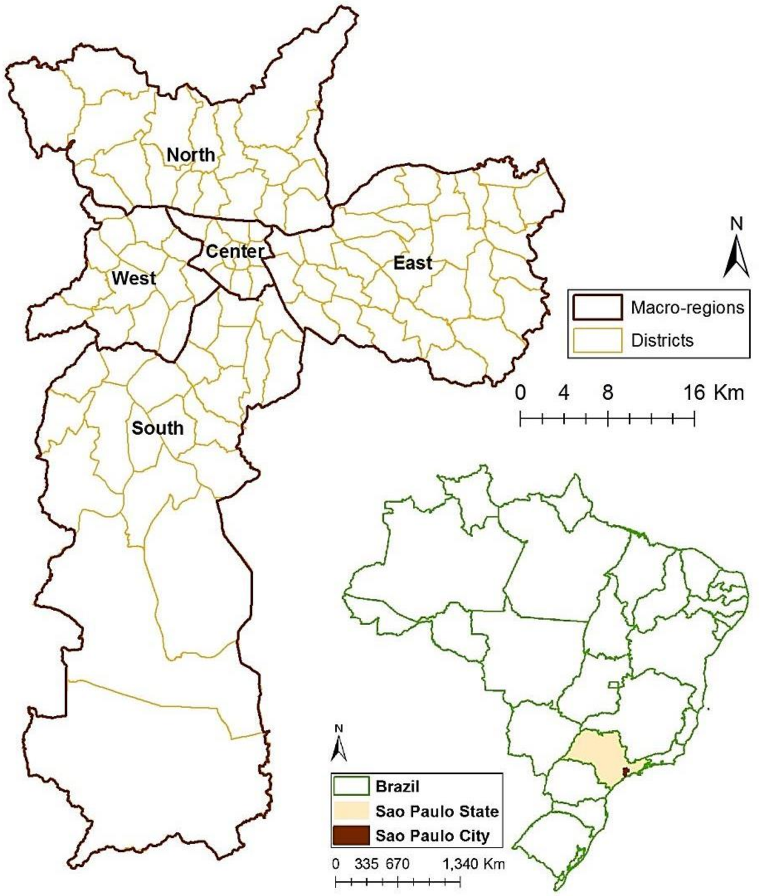


Figure 1. São Paulo location, macro-regions and districts (Shape sources: Geosampa/NEREUS-USP)

Population estimates calculated by the State System Foundation of Data Analysis (SEADE) project that the number of inhabitants will surpass 12 million by 2025 and slower growth rates are expected until 2050. Most characteristics of the MRSP can be used to describe São Paulo. However, this study will address the particularities of the city alone.

From SEADE's projections for the year of 2015, population and household densities display similar spatial distribution across regions and districts (Figure 2). Population and household densities are greater in districts of the Center and South and the periphery of the East.

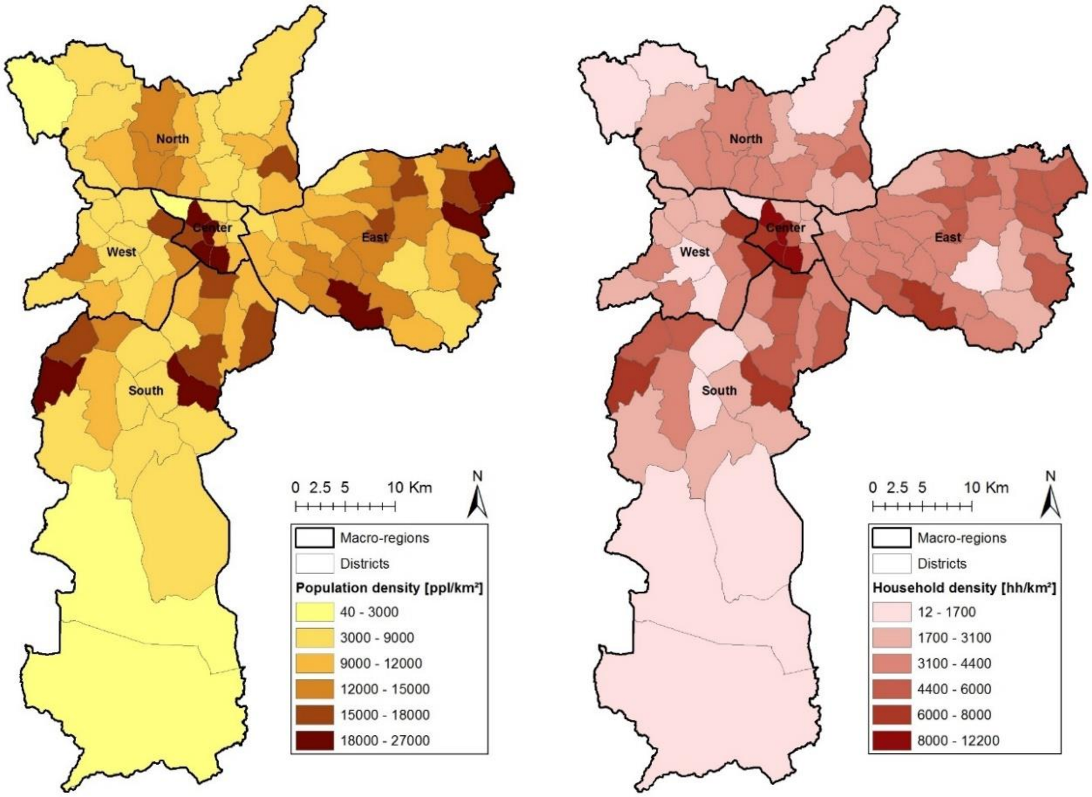


Figure 2. Demographic distributions in São Paulo in 2015 – Population density (left) and household density (right)

Climate

Koppen classification for the city is the *Cwa* characterized by warm temperate climate with dry winter ($P_{winter_{min}} < P_{summer_{min}}$ and $P_{summer_{max}} > 10P_{winter_{min}}$) and hot summer (maximum temperature equal or greater than 22°C) (Kottek et al., 2006). Figure 3 shows the historic climate pattern using the climate data from the IAG-USP station. According to the hydrologic year, wet and dry seasons are from October to March and April to September, respectively.

The hotter and cooler months also follow the latter cycle. The driest month is August and the wettest is January. The coldest month is July and the hottest is February.

The temperature variability is greater in the winter months, while the precipitation variability is greater during summer months. The variance in the temperature data ranges from

4.1°C in February to 11.4°C in September. For the precipitation data, the variance goes from 970 millimeters in August to 10,746 millimeters in January.

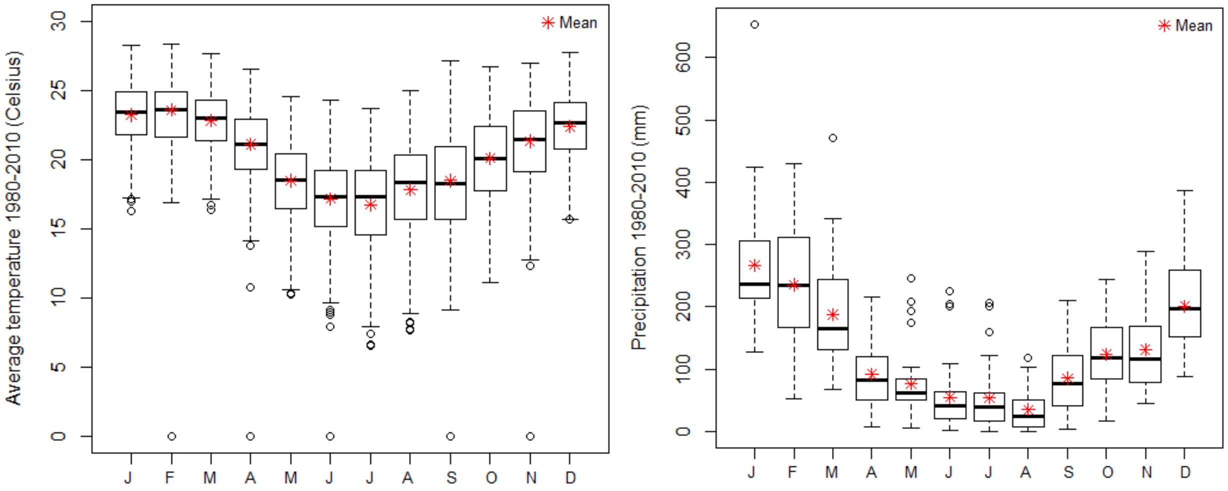


Figure 3. São Paulo historical climate pattern from 1980 to 2010 – average daily temperature (left) and total monthly precipitation (right) (Source: IAG-USP)

Land use and urbanization

Founded in 1554, São Paulo experienced an industrial development boom in the 20th century. The arrival of migrants from other parts of the country demanded land for housing and infrastructure that contributed to a disorderly growth in the urban area (Sporl and Seabra, 1997).

The urban area in São Paulo is very diverse. It contrasts luxury apartment complexes to slums, known as “favelas”, irregular settlements in the most peripheral lines of the city and middle-class households. Residential, commercial and industrial activities are spread across the city. The population density in 2017 is almost 8,000 inhabitants per square kilometer (Emplasa, 2018), with the largest density in the Center. Likewise, districts in western Center and surrounding districts have the strongest presence of multi-family homes, explaining higher population and household densities in these areas (figure 4).

Large ratios of imperviousness are also present in the urban area, aggravating heat islands, increasing runoff and contributing to inland flooding. Ratio of impervious to pervious is inversely proportional to vegetation cover. The largest vegetation cover occurs in the South and

North, as remaining of the Atlantic Rainforest. The Center and the West have the largest portion of impervious area with less vegetation cover (Rede Nossa São Paulo, 2013).

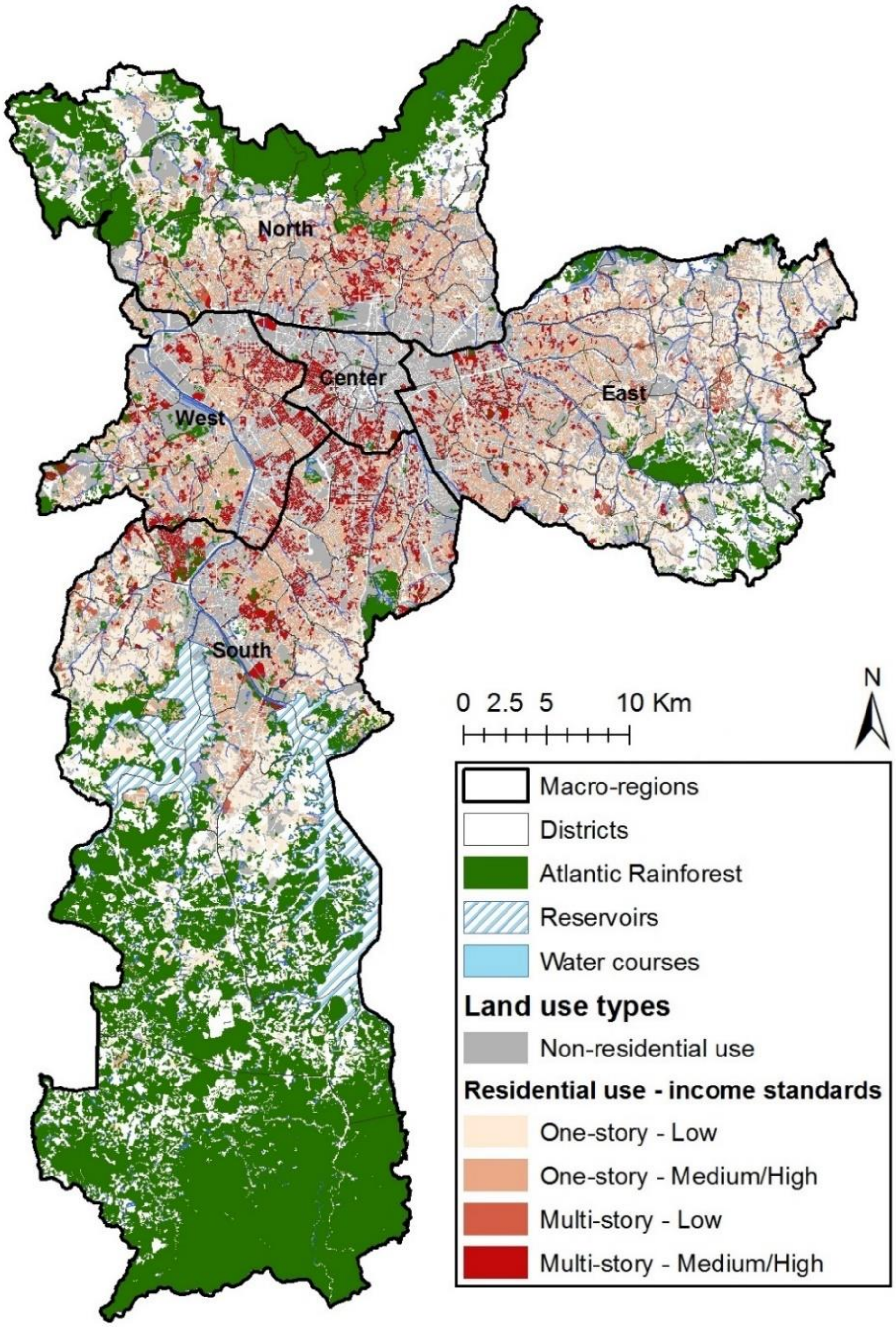


Figure 4. Residential use spatial distribution and land use in São Paulo (Source: GeoSampa shapefiles)

Income and socioeconomics

Although São Paulo is the economic and business center in Brazil, the high social inequality across districts is still striking. The Map of Inequality from the Our São Paulo Network for the year of 2017 shows several indicators among districts. According to the report, slums and shanty towns are distributed in the outskirts of all regions, with the lowest percentages in the Center and the highest percentages in the South, compared to the total number of households in each district. In addition, in 2015, five out of ten top average wages were registered in the West, and the lowest average wages occurred in the East.

Corroborating this report, figure 5 shows household income distribution across districts contrasting with household size. Estimations were made using a weighted average from the income data of the 2010 Census household projections from the SEADE foundation. From the maps, it is possible to notice the opposition between higher income households in the West and South districts and their lower household size.

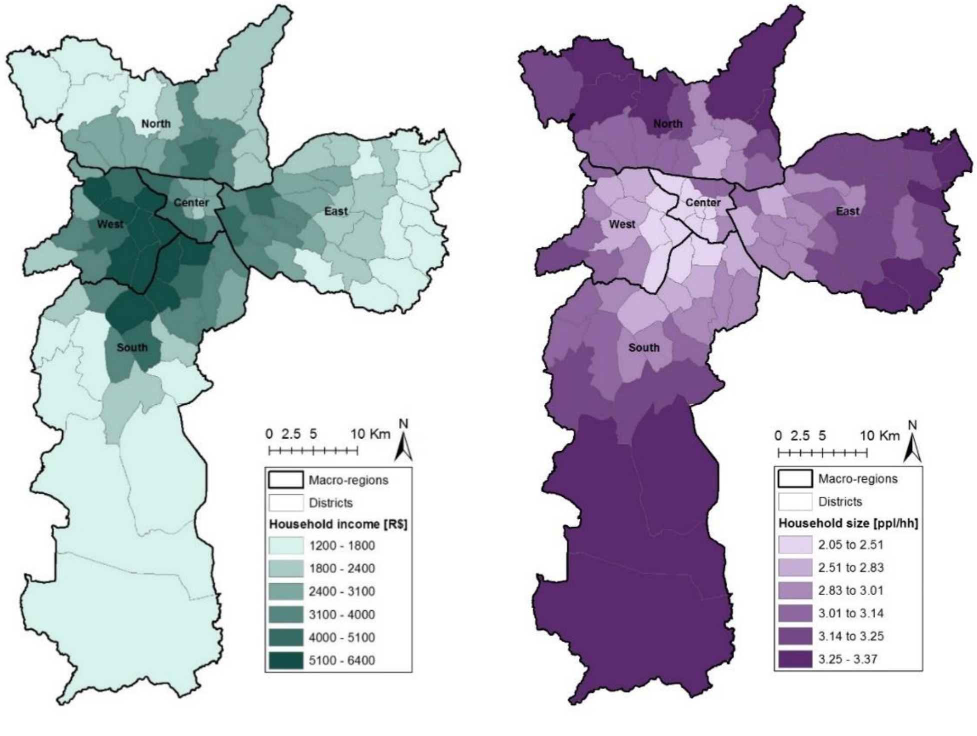


Figure 5. Household socioeconomic spatial configuration (2015) – Household income (left) and household size (right)

Water resources

The Brazilian National Basic Sanitation Policy (Brasil, 2007) defines basic sanitation as the infrastructure, services and operations of potable water supply, wastewater collection and treatment, drainage and stormwater management and urban solid waste management. Currently, the Basic Sanitation Company of the State of São Paulo (Sabesp) provides sanitation services of water treatment and supply and wastewater collection and treatment for 35 out of 39 municipalities of the MRSP including São Paulo. Sabesp is a public-held, mixed capital company 50.3% owned by the State and 49.7% as shares in the stock market (Sabesp, 2016). Sabesp owns the grants of right of use of the water in the reservoirs for public supply but does not perform reservoir management, which is under responsibility of the state and/or federal water management authorities. Four major producer systems in the MIS supply water to São Paulo (São Paulo, 2010), as described on appendix II.

The Cantareira system, the largest of all producer systems, is the only one located in the Piracicaba, Capivari and Jundiai (PCJ) Basin. The PCJ is mainly an industrial and agricultural basin. This basin is very critical because the second largest urban and industrial agglomeration in the state, the Metropolitan Region of Campinas, partially depends on the basin's production capacity as well. In the end of 2013, this system provided water for about 65% of the municipality of São Paulo (Sabesp, 2015). The Upper Tiete Basin is a primary urban and industrial basin (São Paulo, 2013) and comprises the other systems, including Guarapiranga, the second largest water supplier to São Paulo city. Table 1 provides a few characteristics within the city's service area.

During the 2014-2015 shortage, the Cantareira System had the most critical levels. The largest reservoir in the system, the Jaguari-Jacarei, had its levels dropped below operational levels of 820.8 m above sea level, considered the minimum level for transfer to the next reservoir in the system (Sabesp, 2014). Figure 6 presents observed water use in São Paulo from 2013 to June of 2017 and levels of the Jaguari-Jacarei reservoir.

Table 1. Service area characteristics

Area (km^2) (2010)	1,521.11[a]
Population (2010)	11,253,503[a]
Households (2010)	3,608,581[a]
Average daily per capita demand (gpcd) (1995-2005-2015)	62 – 42 - 38.5[b]
% Urban population served with water supply (2015)	100[b]
Water loss index	30.46%[b]
Average annual precipitation (1980-2010) [mm]	1543.7[c]
Average annual temperature (1980-2010) [°C]	20.3 [c]

Source: [a] Infocidade/IBGE, 2010; [b] SNIS, 2015; [c] IAG-USP, 2017

From figure 6, the reservoir level began to decline after the end of the rainy season in the month of March of 2013 and start of colder and drier months. Reservoir went below operational levels around June of 2014 and remained under until January of 2016, when summer rainfalls started replenishment and recovery. The lowest level recorded was about 810 meters above sea level in October of 2015, which is 10 meters below minimum level and 25 meters below levels of early 2013.

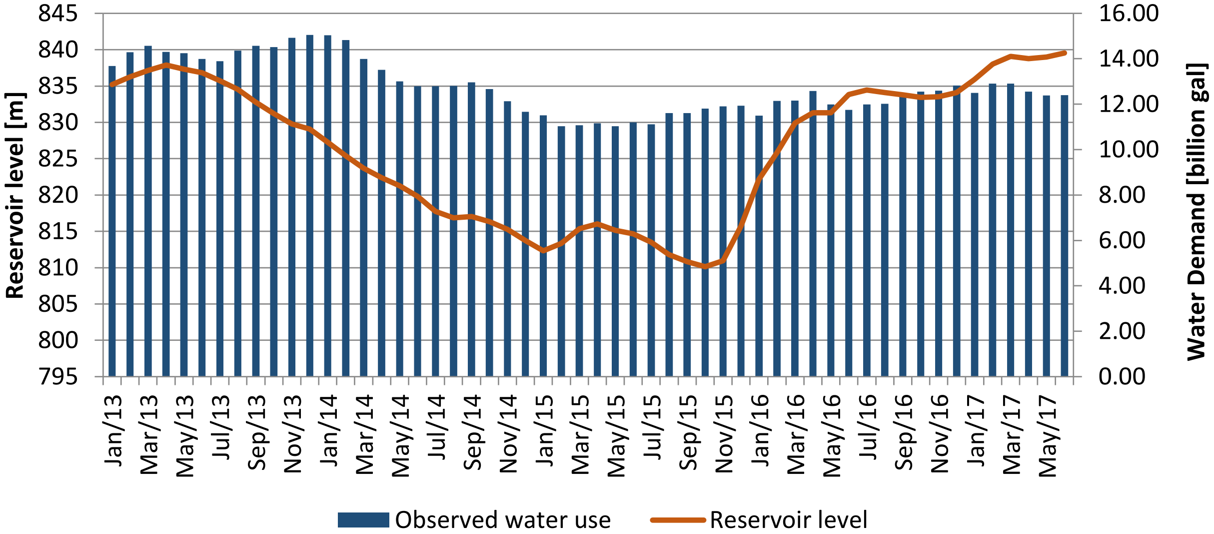


Figure 6. Water use in São Paulo and Jaguari-Jacarei monthly levels

Water use fluctuated down and up following temperature variations until early 2014, when it started to decline. The lowest use was observed in May of 2015, about 11 billion gallons, contrasting with the highest use observed in the time-series of about 15 billion gallons in December of 2013. As reservoir level started to recover, water use also showed a slight increase, but it did not reach use observed previously to the shortage.

As a mean to address the shortage and avoid water rationing, Sabesp developed a contingency plan based on three strategies: economic tools to incentivize demand reduction through application of discounts and penalty fees; replace areas supplied by the Cantareira System with water transfers from other systems, and intensify actions to prevent and fix leaks, implying infrastructure improvements and investments (Sabesp, 2015).

The economic tools directly impacted the residential group of consumers. The program started in March of 2014 offering a 30% discount in the total bill price (water and wastewater) for users that reduced their monthly water use by 20% compared to their average use from February of 2013 until January of 2014. It was applied only in the areas of MRSP that were supplied by the Cantareira System, (Sabesp, 2015a). In April 2014, the discounts were expanded to all households in the MRSP supplied by other producer systems.

In October of 2014, ranges of discounts were created for levels of reductions achieved to encourage customers who had been decreasing use but were still exempt from the discounts. In January of 2015, a penalty fee over water use was created for customers who increased use in comparison to their average consumption from February of 2013 until January of 2014. The fee was implemented because about 24% of users still showed increase in use (Arsesp, 2015). Table 2 presents the ranges of discounts and fees for changes in use.

Customers who used the monthly minimum of 10 cubic meters (m^3) – 2641 gallons – or below were exempted from the fee. The program was officially ended in March of 2016 and stopped being applied on the bills in the month of May of that year (Arsesp, 2016; Arsesp, 2016a).

Souza (2016) concluded that the application of the discounts had a strong correlation with demand reduction and performed better than the penalty fee. Income also had a significant influence in demand reduction; in higher income households the reduction was greater. However, the author mentions that in these households the use is higher which gives margin to greater reductions.

Table 2. Discounts and fees ranges

Discounts*		Penalties**	
% discount	% reduction	% fee	% increase
30	20 or more	40	up to 20
20	15-20	100	20 or more
10	10-15		

*over total bill price; **over water bill price
(Source: adapted from Sabesp, 2015)

Water Use

According to the Aquastat Database from the Food and Agriculture Organization of the United Nations (2018), the largest total renewable water resources volume worldwide is in Brazil with 8647×10^9 m^3 per year. The same source also shows that the total water withdraws per inhabitant in 2010 was 369.7 m^3 – 97.7 thousand gallons – per year in the country.

The United Nations (UN) classifies that the water availability for a region is acceptable when ranging between 2,500 and 20,000 cubic meters – 66 thousand to 5 MG – per year per capita. The water availability in the Upper Tiete Basin is 130.68 m^3 – 34.5 thousand gallons – per year per capita. This is the lowest value for all basins in the state of São Paulo and is intensified by the large population (FABHAT, 2016). In the PCJ Basin, the water availability per capita varies from 49.6 to 116.8 m^3 – 13.1 thousand to 30.9 thousand – per year per capita for the portion directed to supply the population of the MRSP. During times of most availability, it rounds to the highest end which is still classified in the “critical” range by the UN (Sabesp, 2016a; Sabesp, 2018).

Few studies were performed to describe the end water uses patterns in Brazilian cities and most of them had a small sample size. In the residential sector, Almeida (2007) studied the end use of water in Feira de Santana. The city is the second most populous in the state of Bahia with about 556 thousand inhabitants (IBGE Cidades, 2010). Located in the semi-arid portion of the country, measurements were collected from five households. In the findings, the author notes that the habit of having lunch at home could be an indicator of large kitchen faucet use, and that the toilet water use depends on the type of flush and household habits as well as use proportion to other uses. Studies conducted in the United States in 1999 and 2016 showed that toilet water was responsible for the largest use with shower use outranking clothes washing in 2016 in second place (DeOreo et al, 2016).

The socioeconomic factor is also a relevant consideration. Hafner (2007) acknowledged the several variations in different regions of Brazil and the difficulties in creating a standard of end use categories. For example, in the absence of a dishwasher that is an extraordinary appliance for Brazilian families, the kitchen faucet use is increased and both uses must be aggregated. Bathtubs are also not common in Brazilian homes accounting for only 6% of one-story single-family and 4% of multi-family households in São Paulo (Sanchez, 2007), thus their use should also be aggregated with shower use. Considering studies made in Brazil only, Hafner (2007) established their average as a standard residential profile for Brazilian cities.

Barreto (2008) conducted a study in a residential sample of seven households monitored for seven days with an average household size of three persons per household in western São Paulo city to measure the residential water use profile and the end uses of water. The author clarified that the other uses classification comprises gardening, patio, driveway and garage washing, general outdoor uses and invisible leaks, and were points that could not be measured separately (personal communication).

The Program of Rational Water Use of the University of São Paulo (PURA-USP) was structured in six large-scale projects with the objective to reduce on campus demand and improve local water management (Silva and Goncalves, 2005). PURA-USP was applied to the university main campus in the city of São Paulo, also located in the Western region. By mapping the water connections and measuring the flow in the buildings, the program was able to quantify demand by end uses and users in different buildings and departments including student apartments to promote significant reduction in demand (Tamaki, 2003; Hafner, 2007).

Rocha and Barreto (1999) performed an end use study in one single family home located in an apartment complex in the city of São Paulo. The studies end-uses are summarized on table 3.

Table 3. End uses of water from Brazilian studies

	% of total household use				
Category	**Feira de Santana**[a]	**Average Brazilian studies**[b]	**Western São Paulo City**[c]	**USP**[d]	**Single family home**[e]
Kitchen faucet	33	18	12.0	17	18
Faucet	10	7	4.2	6	8
Shower	28	37	13.9	28	55
Laundry sink faucet	5	4	5.4	6	3
Toilet	8	22	5.5*	29	5
Clothes Washer	12	9	10.9	9	11
Top loading washing machine	-	-	9.2	-	-
Clothes washer + sink	-	-	8.3	-	-
Gardening/Car and patio washing	-	3	-	-	-
Outdoor faucet	3	-	-	-	-
Other uses	-	-	30.6	-	-
Dishwasher	-	-	-	5	-

Source: [a] Almeida, 2007; [b] Hafner, 2007; [c] Barreto, 2008; [d] *apud* Goncalves, 2006; [e] Rocha and Barreto, 1999
*Close coupled toilets

The constraints of these studies are related to the measure of outdoor use of water. Due to socio-cultural and climatic characteristics, irrigation is not performed within household levels. The City of São Paulo, through the Parks Division, and some irrigation system design companies stated that the urban population in the city does not apply automatic irrigation techniques. In addition, park landscaping is made using species of low water requirements and easy planting that rely mostly on rainfall or receive manual watering as needed (personal communication).

Outdoor water uses in São Paulo are mostly for patio, driveway, garage and sidewalk washing and cleaning (floor washing), car washing and leisure – swimming pools. Watering cans or hoses are used for small flower or vegetable gardens as needed. In the analysis made by Almeida (2007), the questions related to outdoor use (irrigated area, frequency of irrigation using equipment, presence of swimming pools, washing and cleaning and number of pets) had no correlation with water use, being little representative of outdoor use in those particular homes.

Methodology

The development of this work demanded extensively data collection, which was used for statistical analysis and model input. The focus was residential water use and demand and its components, such as indoor and outdoor demand. Local features also drove specific model features to be adapted.

This methodology section details the data used, considerations and assumptions, calculations and model modifications to achieve the proposed objectives. In *Data Description*, all information used in this work was explained, including their original aggregation, sources and considerations for use. The following section – *Water use influencing factors* – describes the multiple linear regression tools and variables adopted to identify determinants of water use during the time-series available. Lastly, the Integrated Urban Water Model (IUWM) is presented, following by its customization to fit São Paulo's regional and socio-cultural characteristics and details about its training procedures and parameter selection.

Data description

In this section, water use, demographics, land use, climate and socioeconomic datasets are detailed regarding their sources, aggregation and preparation for use. Further explanation on use and assumptions are described within the respective section.

São Paulo datasets required as input for IUWM were often readily available online mainly through governmental agencies databases or were requested. These databases are periodically updated depending on the frequency of measurements. The geographic level of information can also be classified into districts (96), administration boroughs (32), regions (5) or city level.

Water Use

Sabesp's administrative model is based on watersheds with a decentralized administration composed by the Boards and Business Units (BU). Within the Metropolitan Board, the BU's are divided according to the slopes and river beds of sub-basins in the Upper Tiete Basin (São Paulo, 2010). The BU's do not necessarily correspond to the district limits.

Observed water use provided dataset was split into the Center, East, North, West and South BU's. The data was aggregated in a monthly basis starting in January of 2013 through June of 2017 totalizing 54 months in four years and a half of observed water use. It provided monthly volume consumed by category of use (commercial, industrial, public, residential, mixed use, total), and the number of accounts. This study focused on the residential category of use.

One account is defined as a building or its subdivisions with independent occupation that uses one single water and/or sewer main connection (Sabesp, 2017a). The mixed-use category does not specify the types of categories nor the number of accounts included in the measurements, preventing the precise estimation of residential, commercial, industrial and institutional (CII) portions from it. Therefore, its 2% contribution to the total water demand was excluded from this study. It is not specified in the dataset the end uses of water for any category.

Demographics

The Brazilian Institute of Geography and Statistics (IBGE) conducts the census survey for demographics characterization every 10 years throughout the country. The last Census year was 2010. The Municipal Department of Urbanism and Licensing of the City of São Paulo compiles demographic data in different geographic scales based on the Census results. In addition, the State System Foundation of Data Analysis (SEADE) makes projections of demographics down to the district scale.

In order to match the time series of the water use dataset, population and household counts were collected from SEADE's projections for the years of 2013, 2014, 2015, 2016 and 2017. The projections were available at the district level.

Land use and residential outdoor area

Data of vegetation cover for the year of 2013 is available online from the Rede Nossa São Paulo (Our São Paulo Network) at the boroughs level, based on indicators from the Municipal Department of Green and Environment of the City of São Paulo, the São Paulo State Bureau of Environment and the IBGE. Estimates of impervious area were calculated from vegetation cover, building area and total borough area followed by proportional distribution into district areas. It is assumed constant from 2013 to 2017.

For the residential type of use, outdoor areas can be patios, driveways, porches, pathways and decks. From the Territorial, Building, Conservational and Cleaning (TPCL) registry, total plot size and total constructed area were available by district and land cover type – residential, single or multi-family, low, middle, high income standards. Because the constructed area has a real estate taxation purpose, the types of property influence on how this area is presented. In São Paulo City, the TPCL registry bases property market value on gross constructed area bounded by walls and columns, except for multi-family residential buildings (São Paulo, 1986; São Paulo, 2018). The difference between plot size and constructed area in the residential land cover type was interpreted as non-constructed area, thus, outdoor area.

In single-family homes, constructed area was considered as presented with a straight-forward subtraction for outdoor area. Constructed area in multi-family homes was defined by the occupation coefficient of the plot that is defined by municipal urban regulations. Occupation coefficient (OC) is the relationship between the projected horizontal building area and the plot size, the former interpreted as the gross constructed area (São Paulo, 2014). This approach using OC was applied due to the total constructed area in multi-family homes be larger than the total plot size.

Occupation coefficients are different for plot sizes in every urban zone of development defined by the City, i.e. Transformation, Qualification, Preservation (São Paulo, 2016). Most of the urban area is inserted in the Qualification zone with OC varying from 0.5 to 0.85. Thus, considering the OC in the high end, at least 15% of the total plot size would be non-constructed in multi-family residential land cover and might be subjected to some type of outdoor use in the form of washing. The TPCL registry was available for estimation by districts and the estimation was later aggregated by regions. All areas were also assumed the same for all years.

Over this study, constructed area is denoted as developed area as well as non-constructed area is referred as both undeveloped area and outdoor area. The latter does not necessarily represent impervious or non-impervious surfaces, but it is assumed to be subjected to some type of outdoor use of water that will be described in the following sections.

Climate

The Santana Observatory and the IAG-USP Station are the two main meteorological stations. They are located in the northern and the southeastern parts of the city and are operated by the National Meteorological Institute (INMET) and the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG) from the University of São Paulo (USP), respectively. Dataset from the IAG-USP station was provided under request and was used in this study from 1980 to 2017 due to its completeness. The variables considered are precipitation and temperature (maximum, minimum and average).

Socioeconomics

Socioeconomic data was available from the 2010 Census for every district and was assumed constant throughout the time-series. The dataset presented the number of households containing in a range of income, quantified in minimum wages per month – up tp ½, more than ½ to 1, more than 1 to 2, more than 2 to 5, more than 5 to 10, more than 10 to 20, more than 20. Minimum wage in 2010 was 510 reais – Brazilian currency. A weighted average in each range was computed and multiplied by the number of households. The sum of all ranges of income produced the total district income, which could be normalized by both number of households (permanent private) and population from SEADE's projections for the time-series years. Regional variability of household income is presented on figure 7.

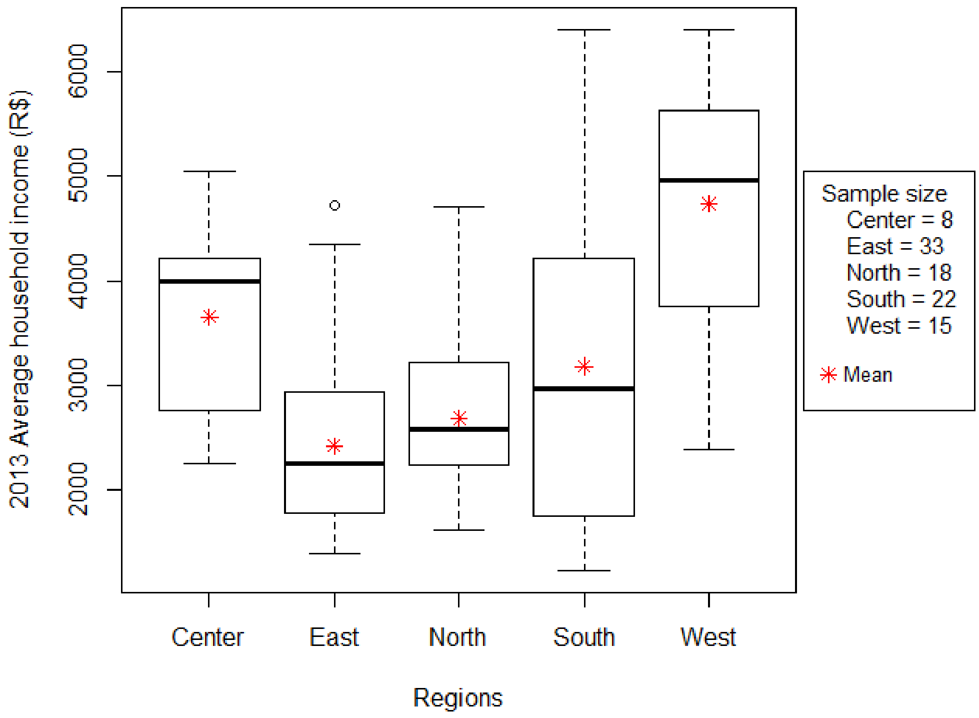


Figure 7. Boxplot of regional income per household in 2013

Water use influencing factors – Multiple linear regression

To better explore the determinants of water use during the time-series available and understand the key factors driving the unusual consumption pattern observed, a regression model was applied. Using observed water use dataset, a multiple linear regression including several explanatory variables was performed to investigate what factors had a significant effect on residential water use.

The regression was normalized by household, this way monthly household observed water use was defined as the response variable and the predictor variables were both qualitative and quantitative. The qualitative variables were region and the economic tools applied by the water company. The quantitative variables were household size, areas – residential developed and undeveloped – temperature, precipitation and income per capita (table 4). The variables included geographical, meteorological, demographical and socioeconomic aspects that are featured within regions in the city.

Table 4. Regression variable labels and categories

Variable	*Labels*	*Categories*
Household water use (gal per month)	USE	-
Region	REG	Center (1), East (2), North (3), South (4), West (5)
Household size (pop/hh)	SIZE	-
Area [developed, undeveloped] (acres)	DEV, UNDEV	-
Temperature [min. and max.] (°C)	Tmin, Tmax	-
Precipitation (mm)	PREC	-
Average household income (R$/month)	INC	
Economic incentive	ECON	No incentives (1), Discounts (2), Discounts + penalty fee (3)

The multiple linear regression model is represented in equation (1).

$$USE = \beta_0 + \beta_{Rg}REG + \beta_{Sz}SIZE + \beta_{A_d}DEV + \beta_{A_u}UNDEV + \beta_{T_{max}}T_{max} + \beta_{T_{min}}T_{min} + \beta_{Pr}PREC + \beta_I INC + \beta_E ECON + \varepsilon \quad (1)$$

For analysis of the city variables, the time-series had a total of 54 months for each region from January of 2013 to June of 2017, totalizing 270 months of realizations from all regions. R statistical software was used for the calculations. Using the *cor* function, a correlation matrix was computed for all explanatory variables using the Pearson correlation coefficient method. Descriptive statistics was also calculated for the mean, standard deviation, minimum and maximum values for each of the quantitative variables.

The multi-linear regression fit was executed using the *lm* function in R using all nine explanatory variables, denoting the full model. Akaike information criterion (AIC) was used to select the model containing the most relevant explanatory variables with the *stepAIC* function in both directions. The model with the lowest AIC was considered the reduced model and another multi-linear regression was executed using the most relevant variables.

Another regression was executed using the same functions for each region separately to find the variables most influential in each. The total number of realizations was 54 and the categorical variable REG was dismissed. The ECON monthly classification was kept the same for all regions.

The significance levels evaluated were 95% ($\alpha=0.05$), 99% ($\alpha=0.01$) and 99.999% ($\alpha=0.001$). For regional analysis, a significance level of 90% ($\alpha=0.1$) was also added.

Integrated Urban Water Model – IUWM

The Integrated Urban Water Model - IUWM - is a web tool, cloud-based, mass balance approach for urban water demand prediction and potential savings assessment. IUWM allows for projections of water management scenarios (Sharvelle et al., 2017). Main input datasets are population and households, land use and climate with a selection of a service area to mark a geographic boundary. In the United States, the input datasets are readily available through the U.S. Census Bureau, the Multi-Resolution Land Characteristics Consortium (National Land Cover Dataset - NLCD), and PRISM Climate Group which makes the model flexible enough for application in any area nationwide. The application of IUWM outside of the U.S demands data gathering of the main inputs in order to meet the model's basic requirements. For further details on IUWM and its parameters, refer to Sharvelle et al. (2017).

IUWM customization for São Paulo

São Paulo is the first location outside of the United States in which IUWM is being applied. Therefore, the model flexibility for creation of not yet established boundaries and boundaries outside of the American national dataset ranges ensures the application of it anywhere through the upload of geospatial features (shapefiles) and dataset feeding. Due to diverse land use, water use and demand characteristics, climate and cultural features in São

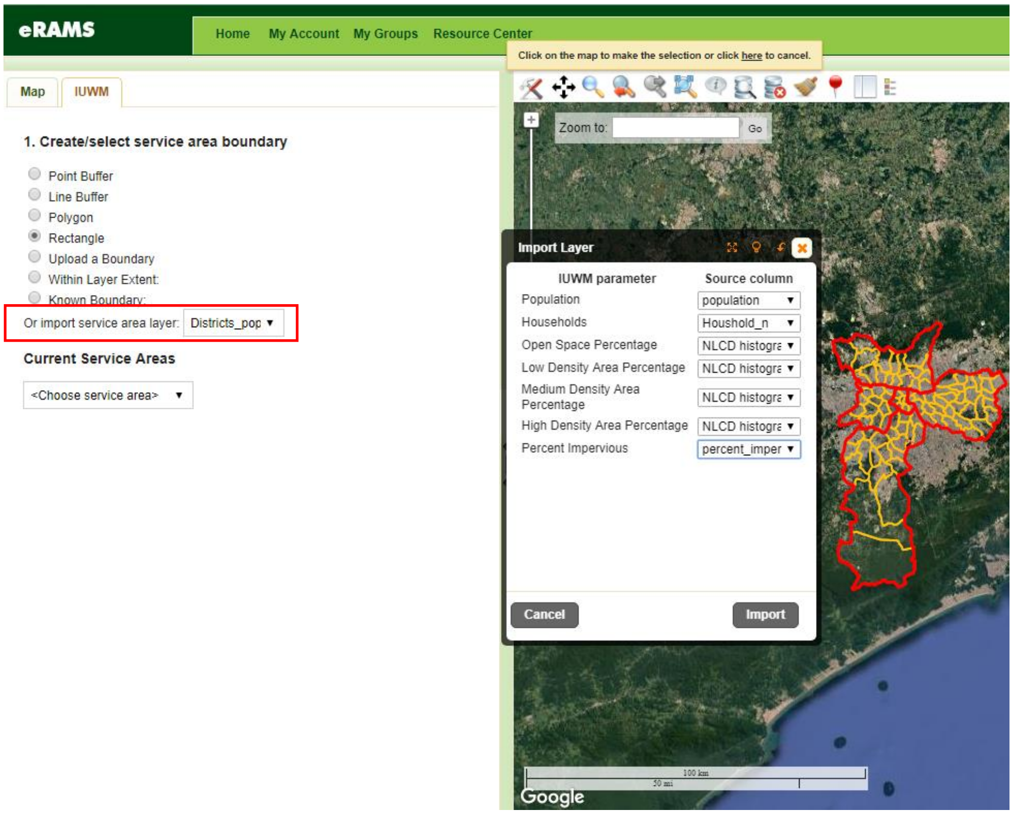
Paulo compared to the United States, prompted adaptations and assumptions to improve model suitability for the city.

Basic input data and land use shapefiles were gathered for descriptive and model calibration purposes. Modifications were mainly focused on the core Python code in which IUWM runs, but also included an addition on the web interface. This addition addressed land use features within the intended service area, enabling the user to upload GIS shapefiles and specify land use attributes to match those to the NLCD classification. The option was named *import service area layer* (figure 8) and is helpful in areas where landscape irrigation is the primary outdoor use, which is strictly associated with land use in IWUM. The main barrier to continue using the NLCD classification in São Paulo was the absence of irrigation, that is a local socio-cultural habit supported by climatic conditions.

To address this specific habit in São Paulo households, two main adaptations were created in the Python core code, in which IUWM is written. The first one was the incorporation of the residential land use definition, based on developed and undeveloped areas, as previously described. The second was a creation of a customized code for outdoor demand, based on these areas, activity frequency and volume per unit area.

Originally, IUWM allows the calculation of open space, low, medium and high-density development using from a land use shapefile using GIS tools or the NLCD database. These variables are used to estimate the outdoor demand for irrigation which is not applicable to this study.

As an alternative, a customized function in Python was created and incorporated into the core of IUWM to calculate residential washing demand in outdoor areas. The estimation of outdoor water use for floor washing was based on the engineering parameters suggested by Tomaz (2009), as shown on table 5, and outdoor area. The residential area was split into developed and undeveloped area, equivalent to constructed and non-constructed areas, respectively. Frequency of washing was selected as once a week – 4 times a month.



1. Create/select service area boundary

○ Point Buffer
○ Line Buffer
○ Polygon
● Rectangle
○ Upload a Boundary
○ Within Layer Extent:
○ Known Boundary:

Or import service area layer: Districts_pop

Current Service Areas

<Choose service area>

IUWM parameter	Source column
Population	population
Households	Houshold_n
Open Space Percentage	NLCD histogra
Low Density Area Percentage	NLCD histogra
Medium Density Area Percentage	NLCD histogra
High Density Area Percentage	NLCD histogra
Percent Impervious	percent_imper

Figure 8. IUWM interface when importing the service area layer already uploaded by the user

Table 5. Engineering parameters for outdoor use estimation (Tomaz, 2009)

Regular garden watering	2 L/m^2.day
Patio/Floor washing	2 L/m^2.day
Frequency	2x/week or 1x/week or once every 15 days

Residential end-uses of water

The definition of the most accurate demand profile for São Paulo considered only the studies performed by Barreto (2008) and PURA-USP (*apud* Goncalves, 2006). The two studies were performed in São Paulo city and presented larger sample size compared to other studies. In IUWM, the end-use percentages of indoor residential demand are based on the Residential End Uses of Water – REUWS (DeOreo et al., 2016).

“Dish” (kitchen faucet), “faucets”, “shower” and “toilet” were the average of values from both studies. “Clothes” was aggregated values of the averages of clothes washer and laundry sinks. “Bath” was not separately measured in any study. For other uses – evaporative cooling, humidification, water softening and other unclassified uses – the value from the REUWS 2016 was adopted, and the difference was attributed to leaks, because none of the studies in São Paulo accounted for these types of use. Dishwasher portion from the USP study was not included because it is not representative of the entire city population.

The combination of Barreto (2008) and PURA-USP are the adopted indoor demand profile for São Paulo and is summarized on table 6.

Table 6. Demand profiles for São Paulo based on Barreto (2008) and USP (*apud* Goncalves, 2006)

Categories	% of total household use
Bath	0
Clothes	20.25
Dish	17
Faucet	5.1
Leak	15.65
Other uses	3.8
Shower	20.95
Toilet	17.25

Training and testing

The City of Fort Collins, Colorado, was used for IUWM original validation. A few modifications were needed in order to adapt it to be representative of São Paulo, particularly regarding outdoor water demand. The water use dataset provided by Sabesp was applied for estimation of outdoor washing demand and calibration procedures of indoor parameters. The water use dataset was comprised of 54 months and a total of 1642 days. Because the patterns of water use during 2014-2015 shifted drastically, the dataset was divided into three distinct conditions of pre-shortage, shortage and post-shortage.

The observed month to month water use slopes were in accordance with the months in which the economic incentives were in place. Therefore, the three conditions were defined accordingly and deemed representative of each period. The conditions were then defined as:

1. Pre-shortage: from January of 2013 to February of 2014, totalizing 424 days in 14 months; the predominant year is 2013;
2. Shortage: from March 2014 to January 2016, totalizing 702 days in 23 months; the predominant year is 2015;
3. Post-shortage: from February 2016 to June 2017, totalizing 516 days in 17 months; the predominant year is 2016.

The predominant year was used in the calibration procedures in each condition. The median in the shortage is the lowest, at the same time this condition holds the greater variability (figure 9). This shortage is also the longest condition in the time-series. A one-way ANOVA was used to test whether there was a significant difference in the means of the three conditions.

The regions – Center, East, North, South and West - were selected as service areas for calibration having districts as subunits. Because the geographic division of BU's does not match the district boundaries, the full district areas were considered into the BU in which their largest area was inserted (São Paulo, 2010). The district of Itaim Bibi and Capão Redondo had significant portions of their areas in different BU's and for practical purposes they were placed into the BU where the largest portions of their boroughs are located. The water use dataset was disaggregated by household for the districts in each BU and then the districts were gathered in their belonging region for calibration.

Calibration procedures were performed using Python. Generation of parameter sets was made using a Monte Carlo method for 1500 simulations. The calibration process aimed the selection of the optimal α and β parameters that describe average daily household indoor water usage over time, according to the mathematical model developed by DeOreo et al., (2016). In a simplistic form, this model may be represented by equation 2, in which *gphd* is gallons per household per day, H is the household size, represented by the average number of people per household, and α and β are the estimated indoor parameters.

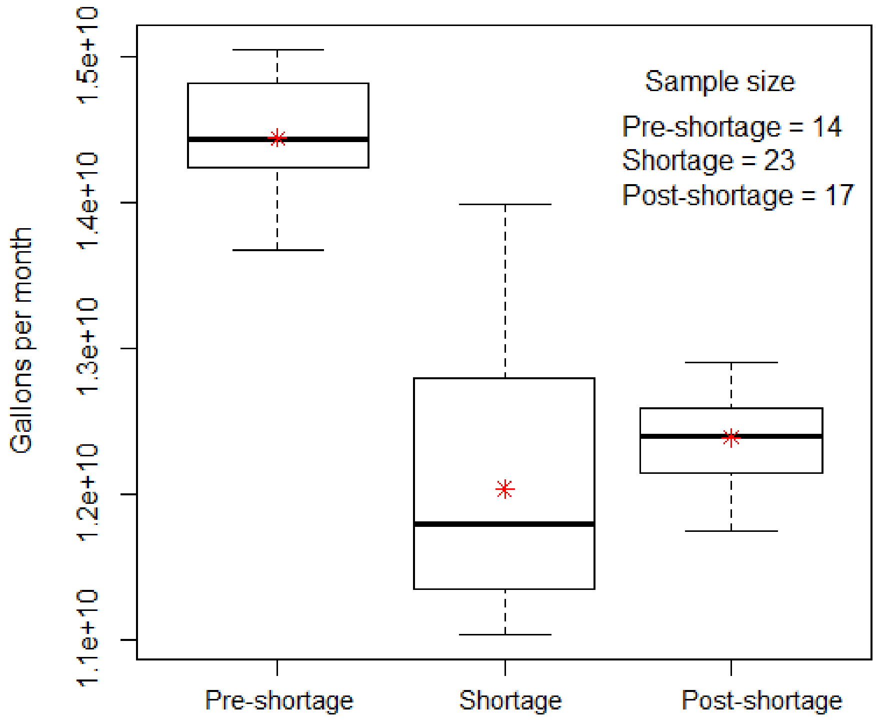


Figure 9. Boxplots of total monthly water use in the pre, shortage and post-shortage conditions in São Paulo

$$gphd = \alpha H^{\beta} \tag{2}$$

$$gphd_{i,p} = \alpha_{i,p} H^{\beta_{i,p}} + Fw_i; i = 1,2,3,4,5; p = 1,2,3 \tag{3}$$

$$Fw_i = A_{ud_i} * V * t \tag{4}$$

In this mathematical model, i corresponds to each region – Center, East, North, South, West, p corresponds to the period – pre-shortage, shortage or post-shortage, α and β are calibrated parameters, H is household size – number of people per household, and Fw is the floor washing demand, which is calculated using equation 4 from the region undeveloped area (A_{ud}), the volume of water used (V), and the washing frequency (t). In this estimation, V and t had assumed values as previously described.

Based on the described approach, the model inputs previously detailed for a service area – end-uses, population, households, climate, residential land use – are the variables accounted in IUWM. Table 7 presents the parameters applied for estimation of indoor use and will be used for scenarios projections in the next chapter.

Table 7. Parameters used during calibration

Parameter	Realistic value or range
α	35 - 90
β	0.30 - 0.90
% precipitation runoff	90[a]
Faucet % graywater	33.3[a]
Leak % blackwater	50[a]
Indoor % consumed	10[a]
Total Population (2013 - 2017)	11,446,275 – 11,696,088
Total Households (2013 - 2017)	3,737,441 – 3,951,074

Source: [a]Sharvelle et al, 2017.

Parameters selection was performed based on the maximum likelihood and mean relative errors. Fifteen sets of parameters α and β were selected and applied in the regions for the conditions through Python simulations, resulting in monthly demands of indoor in all shortage conditions.

The customized code for outdoor projections was run during calibration simulations to separate the indoor portion to be calibrated from the observed use. Model performance was evaluated using Percent BIAS fraction and Nash-Sutcliffe coefficient of efficiency on simulated and observed monthly household demand for 270 realizations in the time-series – 54 from each region –, using the functions *nse* and p*bias* in the R software.

The version of IUWM code used for calibrations was 3.1.2. Testing of the model using the selected parameters was not performed on different temporal or spatial scales.

Analysis of variance - ANOVA

A monthly calibration for pre and post-shortage was also performed to examine specific trends such as seasonality within these conditions. The best monthly regional parameter was selected based on the mean relative error (MRE) and percent bias fraction error statistics for each month in each region. Pre and post-shortage monthly demand simulations was normalized by household to obtain gphd and then by sum of gphd for each condition for ANOVA calculations.

An analysis of variance (ANOVA) was performed in all regions using the *aov* function in the R statistical software to investigate seasonality. Sample size was 14 and 17 in the pre and post-shortage, respectively. Regional gphd was the response variable in a linear regression with different groups as predictor variables. The groups were split in calendar seasons (summer, fall, winter, spring) with 3 months of each year; wet, moist and dry conditions (WMD), ranked by the amount of precipitation, with 4 months of each year; and wet and dry (WD) months, based on the hydrologic calendar with 6 months of each year (table 8). A statistical difference in the means can indicate a seasonal pattern over the months. Significance levels of 90% (α=0.1) and 95% (α=0.05) were evaluated in this analysis.

Table 8. Groups used in the ANOVA and its corresponding months of the year

Month	*Seasons*	*WMD*	*WD*
Jan	Summer	Wet	Wet
Feb	Summer	Wet	Wet
Mar	Fall	Wet	Wet
Apr	Fall	Moist	Dry
May	Fall	Dry	Dry
Jun	Winter	Dry	Dry
Jul	Winter	Dry	Dry
Aug	Winter	Dry	Dry
Sep	Spring	Moist	Dry
Oct	Spring	Moist	Wet
Nov	Spring	Moist	Wet
Dec	Summer	Wet	Wet

Results and Discussion

Multi-linear regression and residential water use influencing factors

The regression was performed using pertinent variables for the three shortage conditions. The four spatial scale variables were - region (REG), developed or constructed residential area (DEV) and residential undeveloped or outdoor area (UNDEV). Demographics variables were household size (SIZE). The meteorological variables were minimum and maximum temperature (Tmin, Tmax) and precipitation (PREC). The socioeconomics variables were – average household income (INC) and presence or not of economic tools (ECON).

All variables considered are known to have effects in residential water demand and were key-factors during the shortage periods. Table 9 shows a summary of the descriptive statistics of the data used from 270 realizations. The two qualitative variables – REG and ECON – were not included.

Table 9. Descriptive statistics of MLR variables

Variable	*Mean*	*Standard deviation*	*Min.*	*Max.*
USE [gph]	3399.1	392.2	2778.3	4351.5
REG		-		
SIZE [people/hh]	2.86	0.32	2.29	3.20
DEV [acre]	9451.9	5188.8	1155.3	16045.8
UNDEV [acre]	5392.0	3684.2	201.4	9986.5
Tmin [ºC]	15.8	2.7	10.2	19.6
Tmax [ºC]	26.3	2.8	21.3	31.8
PREC [mm]	133.0	88.5	2.8	368.2
INC [R$/mo]	3197	924	2148	4810
ECON		-		

Pearson correlation coefficients were calculated for all variables and the correlation matrix is presented on table 10. High correlations were considered equal or above 0.800 and medium correlations were in the interval of 0.600 and 0.799. USE was not highly or medium correlated to any of the variables.

Variables REG, PREC, INC and ECON were not highly correlated with any variable, however PREC had medium positive correlation with Tmin and INC had a medium negative correlation with SIZE, DEV and UNDEV. High positive correlations are present between SIZE and spatial variables of residential areas. The absence of stronger correlations of USE across the city could be due to the shortage and change of water patterns occurring during the time-series.

Table 10. Pearson correlation coefficient matrix

Variable	*USE*	*REG*	*SIZE*	*DEV*	*UNDEV*
USE	1.000	-0.092	-0.257	-0.313	-0.282
REG	-0.092	1.000	0.262	0.249	0.236
SIZE	-0.257	0.262	1.000	**0.900**	**0.833**
DEV	-0.313	0.249	**0.900**	1.000	**0.956**
UNDEV	-0.282	0.236	**0.833**	**0.956**	1.000
Tmin	0.027	0.000	-0.008	0.000	0.000
Tmax	0.010	0.000	-0.009	0.000	0.000
PREC	-0.114	0.000	-0.016	0.000	0.000
INC	0.278	0.365	-0.751	-0.712	-0.737
ECON	-0.570	0.000	-0.014	0.000	0.000

Variable	*Tmin*	*Tmax*	*PREC*	*INC*	*ECON*
USE	0.027	0.010	-0.114	0.278	-0.570
REG	0.000	0.000	0.000	0.365	0.000
SIZE	-0.008	-0.009	-0.016	-0.751	-0.014
DEV	0.000	0.000	0.000	-0.712	0.000
UNDEV	0.000	0.000	0.000	-0.737	0.000
Tmin	1.000	**0.866**	0.660	-0.005	0.190
Tmax	**0.866**	1.000	0.474	-0.006	0.215
PREC	0.660	0.474	1.000	-0.010	0.067
INC	-0.005	-0.006	-0.010	1.000	-0.010
ECON	0.190	0.215	0.067	-0.010	1.000

High correlation: > ± 0.800, medium correlation: 0.600 - 0.799

The MLR with USE as response variable was fit with a full and a reduced model. The latter was defined based on AIC values. The results are presented on table 11. AIC values from both models have a minimum difference. From all nine variables in the full model, only Tmax did not have a significant effect in USE at a minimum of 95% confidence level, being the only variable removed in the reduced model. All other variables had a significant effect in USE at a 99.999% confidence level.

REG, DEV, PREC and ECON showed a strong negative effect on USE in the full and reduced models, while UNDEV, Tmin, Tmax and INC showed a strong positive effect on USE. SIZE showed a positive effect in the full model and a negative one in the reduced model.

With lower AIC, the reduced model does not contain the non-significant variables from the full model. Even though the estimates for the variables may slightly change, their effect strength remains at the same confidence level from the full to the reduced model.

Table 11. Full and reduced models result for São Paulo

	Full model			*Reduced model*		
	Estimate	**t-value**	**p-value**	**Estimate**	**t-value**	**p-value**
Interc.	-13280	-20.04	2.00E-16	-13120	-20.187	2.00E-16
REG	-737.3	-25.547	2.00E-16	-734.3	-20.187	2.00E-16
SIZE	4601	25.017	2.00E-16	4581	-20.187	2.00E-16
DEV	-0.2943	-24.13	2.00E-16	-0.2932	-20.187	2.00E-16
UNDEV	0.4422	24.379	2.00E-16	0.4404	24.334	2.00E-16
Tmin	32.72	4.002	8.21E-05	41.04	8.997	2.00E-16
Tmax	8.363	1.225	0.222		x	
PREC	-0.6678	-4.641	5.50E-06	-0.7144	-5.144	5.28E-07
INC	1.839	26.062	2.00E-16	1.831	26.028	2.00E-16
ECON	-236.3	-21.64	2.00E-16	-235.3	-21.587	2.00E-16
AIC		2710.51			2710.06	

The socioeconomic variables in both models had a strong effect on USE. The positive relationship between INC and USE suggests that water use is greater where household income is higher. The ECON variable effect, which is a qualitative variable denoting the months in which the economic tools were applied, corroborates the findings of Souza (2016), proving the effectiveness of the discounts and penalty fees in reducing demand.

Similarly, a multiple linear regression performed by region with 54 realizations in each corresponding to the months in the time-series identifies the most significant variables by region. Using the same approach of a full and a reduced model based on AIC values, tables 12 and 13 present the results showing whether the variables produces a positive or negative effect within the region and the significance level in which it occurs. The variable REG was dismissed in this analysis.

In the full model, Tmin had no effects whatsoever in the USE of any region, whereas it had a positive effect only in the East in the reduced model. The demographic and socioeconomic variables of SIZE, INC and ECON had effects in the USE of all regions in both models. SIZE showed negative effects in all regions, except for the East. Likewise, INC had a positive effect in all regions, except for the East. ECON had a negative effect in all regions. Tmax and PREC had positive and negative effects, respectively, in both models.

Table 12. Significant variables from full model by region and corresponding significance

	Full					
	SIZE	Tmin	Tmax	PREC	INC	ECON
Center	[-] 0.01	-	-	[-] 0.05	[+] 0.001	[-] 0.01
East	[+] 0.001	-	-	-	[-] 0.001	[-] 0.001
North	[-] 0.001	-	[+] 0.1	[-] 0.1	[+] 0.001	[-] 0.001
South	[-] 0.001	-	[+] 0.1	[-] 0.05	[+] 0.001	[-]0.001
West	[-] 0.001	-	-	[-] 0.05	[+] 0.001	[-] 0.01

Significance levels: α = 0.001, 99.9%; α = 0.01, 99%; α = 0.05, 95%

Table 13. Significant variables from reduced model by region and corresponding significance

	Reduced					
	SIZE	Tmin	Tmax	PREC	INC	ECON
Center	[-] 0.001	-	[+] 0.01	[-] 0.05	[+] 0.001	[-] 0.01
East	[+] 0.001	[+] 0.001	-	[-] 0.05	[-] 0.001	[-] 0.001
North	[-] 0.001	-	[+] 0.001	-	[+] 0.001	[-] 0.01
South	[-] 0.001	-	[+] 0.001	[-] 0.05	[+] 0.001	[-] 0.001
West	[-] 0.001	-	[+] 0.001	[-] 0.05	[+] 0.001	[-] 0.01

Significance levels: α = 0.001, 99.9%; α = 0.01, 99%; α = 0.05, 95%

The socioeconomic variables of INC agree with other studies for having an overall positive effect on water use (Ruijs et al., 2008; Willis et al., 2011; Makki et al., 2013; Romano et al., 2014). Although, this is not true for the East, possibly because this region holds the lowest household income, which could make these households more mindful of their expenses. At different levels, all regions reduced water consumption during the shortage, proving the negative effect of the ECON variable.

Shortage Impacts in Water Demand Pattern – IUWM testing

The evolution pattern of water use along the time series – January 2013 to June 2017 - was very unusual because it comprehends the beginning and end of the 2014-2015 shortage during which compulsory changes in demand were needed. In order to have a full understanding of the water demand patterns in São Paulo the water use dataset was split into pre-shortage, shortage and post-shortage conditions.

The customized code created to estimate outdoor demand applied to floor washing was based on the non-constructed residential area according to urban regulations and real estate taxation. Engineering parameters were used to approximate the volume of water consumed and it was established that the frequency of washing happened once a week – four times a month. This estimation aimed at the minimum outdoor washing demand, because it considers maximum occupation coefficient in the parcel and only one washing per week. Other reasons and habits, such as presence of pets in the household and dust control, may increase the washing frequency as well as lower occupation coefficients and larger outdoor areas.

It was assumed that the outdoor area was constant during the time series and, therefore the water demand for washing was also constant. The estimated volume of outdoor washing demand was embedded in the calibration procedure of behavioral indoor parameters, α and β. Outdoor washing demand accounted for only 2% of the total residential demand. Due to its lower estimated outdoor use, the calibrated indoor parameters represented a reasonable estimation close to the total residential demand in each region for different conditions.

As a result of calibration and validation procedures, table 14 presents the selected parameters sets that best describe indoor household water demand in each region of São Paulo under different conditions.

Model performance was checked using the Nash-Sutcliffe (NSCE) coefficient of efficiency and the Percent BIAS fraction (BIAS). NSCE varies from $-\infty$ to 1, indicating how well the plot of observed versus simulated values fits the 1:1 line, in which 1 is the optimal value. BIAS indicate whether the model average tendency is to predict smaller or greater values than the observed one, with the optimal value being zero, positive values indicating underestimation bias and negative values indicating overestimation bias (Moriasi et al., 2007).

Table 14. Regional parameters selected for the shortage conditions

	Pre-shortage		*Shortage*		*Post-shortage*	
	α	***β***	***α***	***β***	***α***	***β***
Center	88.42	0.53	50.33	0.89	58.44	0.81
East	80.63	0.36	55.01	0.47	69.24	0.34
North	87.77	0.32	44.86	0.66	46.90	0.70
South	47.76	0.86	43.03	0.74	48.62	0.72
West	75.63	0.55	59.36	0.52	55.44	0.67

Both calculations were made using the values presented on figure 10, containing 270 realizations and the monthly household indoor and outdoor demands. NSCE was 0.703, indicating a very good model fit, and BIAS was -1, indicating an overall tendency of overestimation. On figure 10, monthly household demand by region is plotted with the regression line and 95% tolerance intervals for future observations – prediction intervals. The upper cluster of points represents the pre-shortage condition. Shortage and post-shortage values are blended among regions but show a clear separation with respect to the pre-shortage. It is possible to notice the variation in demand across regions, with the Center presenting largest demands and the East, the lowest. Further explanations are presented in the next section.

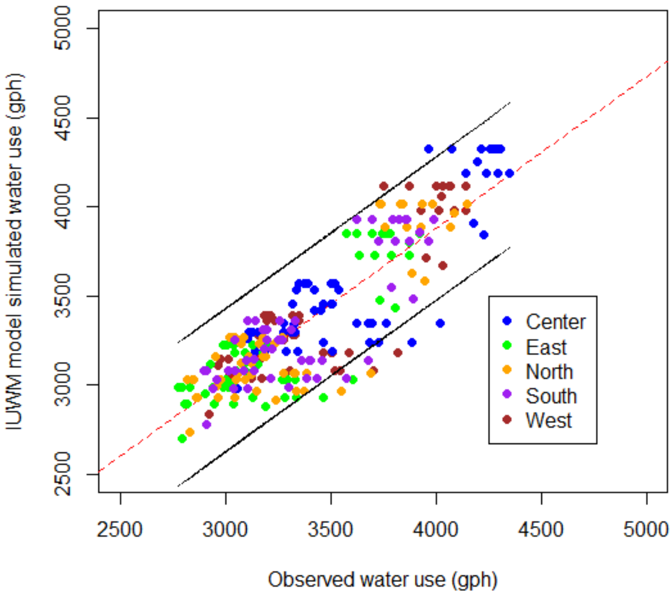


Figure 10. Monthly household demand for the time-series – 2013-2017. Red dotted-line is the regression line and black lines are the 95% prediction intervals

Daily Household Indoor Water Usage

Using the simplified equation developed by DeOreo et al., (2016) and applying the selected parameter sets, average daily household indoor demand projections was calculated in each shortage condition for all the regions to explore regional differences in household water demand. The Residential End Use (REU) studies from 1999 and 2016 developed based on North-American household usage were added for comparison purposes (DeOreo et al., 2016). In addition, the Home Efficiency study (HE) from 2011 is also projected. This study explores baseline water uses for new and high-efficient homes through intense application of the best available technology for high-efficiency fixtures and appliances (DeOreo, 2011).

During the pre-shortage, household water demand was greater when compared to the other two conditions. At the regional level, household demand also varied across conditions, but more importantly, varied across regions. Figure 11 presents the projections of average daily household water use in each region from selected parameters for the pre-shortage.

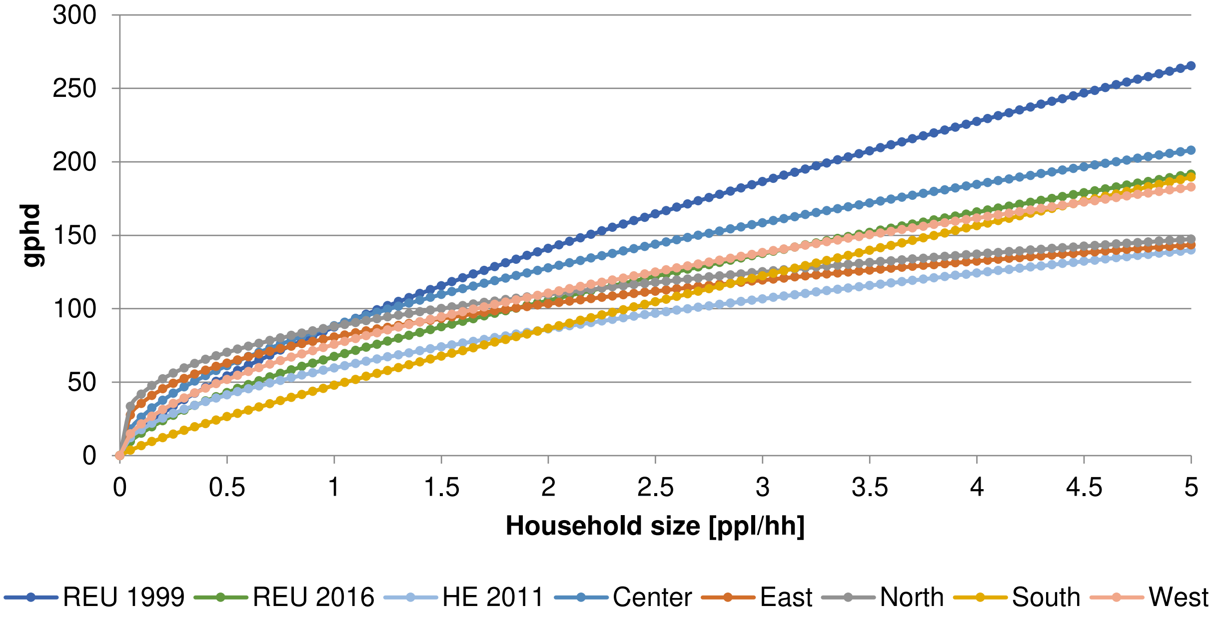


Figure 11. Daily Household Usage during the Pre-shortage

Considering the city average household size of three persons per household in 2013, the Center had the highest daily household usage, which was also greater than the REU 2016. This study shows about the same household demand for the West with 3 ppl/hh. East and North are also very close in daily household usage for all household sizes, being the lowest uses for households greater than the average. Table 15 shows the household sizes for the predominant year in the pre-shortage with its respective household daily water usage.

Table 15. Household size and gphd during the Pre-shortage

Region	Household Size (2013)	gphd
Center	2.4	139.5
West	2.7	130.9
South	3.1	124.5
North	3.2	127.4
East	3.2	122.2

From the table, the two regions with lowest household sizes, Center and West, have gphd greater than the East, which has the largest household size. This observation suggests that on a per capita basis, the water use in the households in the East is lower than in the Center and the West. This is also an indication of different features across regions that influence household demand.

Figure 12 presents daily household usage for the shortage. All curves shifted downward and the Center fell below REU 2016 in household sizes smaller than 3.5 persons. All other regions are either below – East, North, South – or about the same as the HE study – West.

Considering the household demand for average regional household sizes, as it happened in the pre-shortage, the regions with largest household sizes are the ones with lowest gphd. During the shortage, all demands were reduced to below 100 gphd, except in the Center (table 16).

In the post-shortage, it is possible to notice a little upward shift in the regions again (figure 13). The West and the South moved above the HE study curve, while the increase in demand in the Northern household brought this curve to HE values.

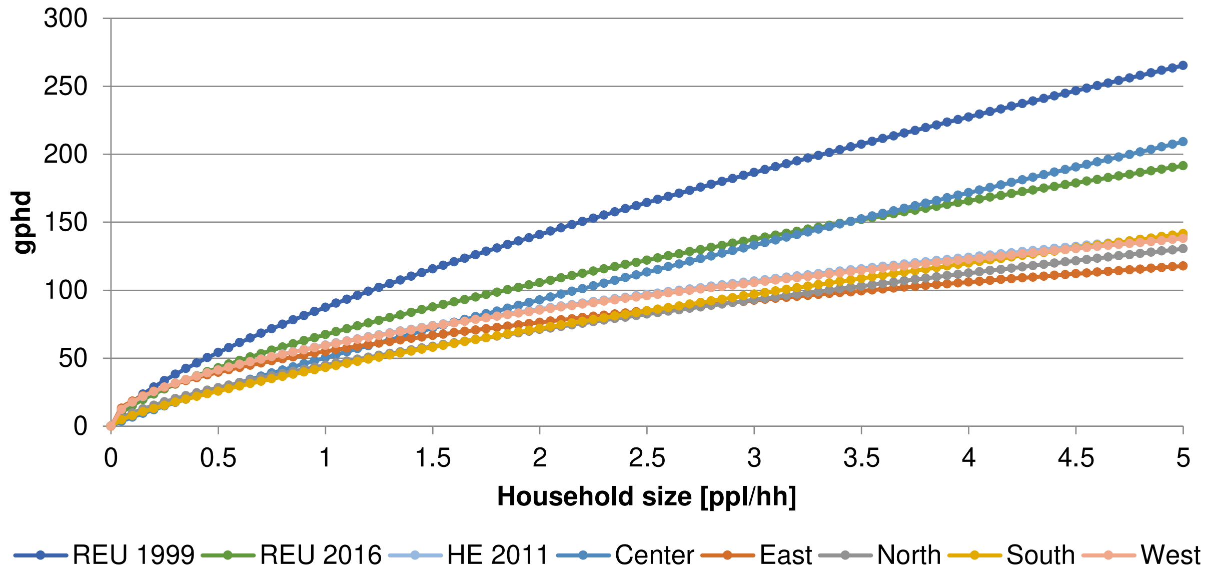


Figure 12. Daily Household Usage during the Shortage

Table 16. Household size and gphd during the Shortage

Region	Household Size (2015)	gphd
Center	2.3	106.0
West	2.7	99.5
South	3.0	97.0
North	3.1	95.9
East	3.1	94.5

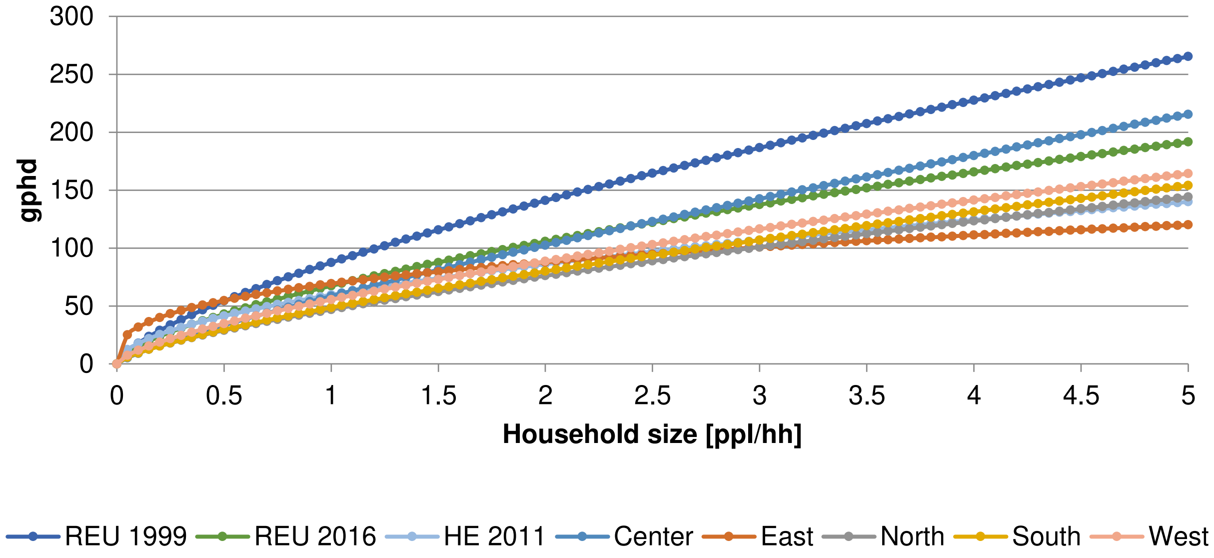


Figure 13. Daily Household Usage during the Post-shortage

Considering that household size did not change from the shortage to the post-shortage, the increase in demand suggests that other factors caused this rebound from one condition to the other (table 17).

Table 17. Household size and gphd during the Post-shortage

Region	Household Size (2016)	gphd
Center	2.3	115.2
West	2.7	107.5
South	3.0	106.3
North	3.1	103.4
East	3.1	102.0

Furthermore, the pattern of water use varies across regions depending on its characteristics. Overall, a few explanations are raised that may help understand the overall drop in water use from the pre-shortage to the shortage condition.

1. Quicker showers
2. Use of washing machine water to clean patio and sidewalks (graywater use)
3. Rainwater/roof runoff harvesting
4. Decrease in car washing frequency
5. Sidewalk/patio sweeping instead of washing
6. Attempt to not refill swimming pools
7. Mindful use of faucets during tooth brushing, dish washing, hand washing and shaving
8. Less water use for recreation

These hypotheses are essentially associated with behavioral changes applied by the population according to their awareness, capabilities and willingness. In addition, as demonstrated by Souza (2016) and the previous section, the economic incentives also played a meaningful role in decreasing demand.

In all conditions, household sizes in the Center and the West are always the lowest whereas water uses are the greatest. Associating findings from previous sections and studies, these regions are examples of socioeconomics having a positive significant impact on water use. In addition, residential land use follows household income patterns, showing that homes of medium and high-income standards are most found in districts with progressively higher incomes. The large concentration of multi-family homes in these districts also suggests a possible preference of that higher income families to live in multi-family buildings. This practice could be related to greater feeling of safety provided by these buildings compared to single family homes. On the other hand, as experienced by Sanchez (2007), the possibility of leaks and losses in these types of buildings is also greater, which would increase water use in these districts.

Seasonality investigation using ANOVA

As previously explained, several factors influence residential water demand. From the MLR in the previous section, temperature and precipitation also have significant effect on demand. A seasonal analysis was performed to explore the presence of patterns of water use in the pre and post-shortage. For the latter condition, the objective was to examine whether this pattern, if existent, returned despite acquired habits during the shortage that were motivated by the need to comply with reduction.

The following boxplots of daily household demand (figure 14) show that the medians during the pre-shortage months were greater than during the post-shortage months. From this observation, the rebound effect did not occur when comparing these two conditions. A slightly visual monthly variation that follows the weather cycles of precipitation and average temperatures is more perceivable in the pre-shortage than in the post-shortage.

Water demand is expected to be higher during summer months due to higher temperatures and demand is increased due to more shower use, recreational use, clothes washing and drinking. Summer months also have higher precipitation indices. Santos (2011) noticed an increase in water demand after long rainy periods, because population would wash cars, clothes, and shoes and take advantage of following sunny days to let them dry.

The school summer break also occurs from mid-December until mid-February. January is when families usually travel on vacation and that can contribute to lower water demands. On the other hand, the presence of more individuals at home during the break may contribute to increase demand. The winter months of June, July and August are expected to have the lowest water demand. However, the low air relative humidity in the month of August may increase demand (Santos, 2011).

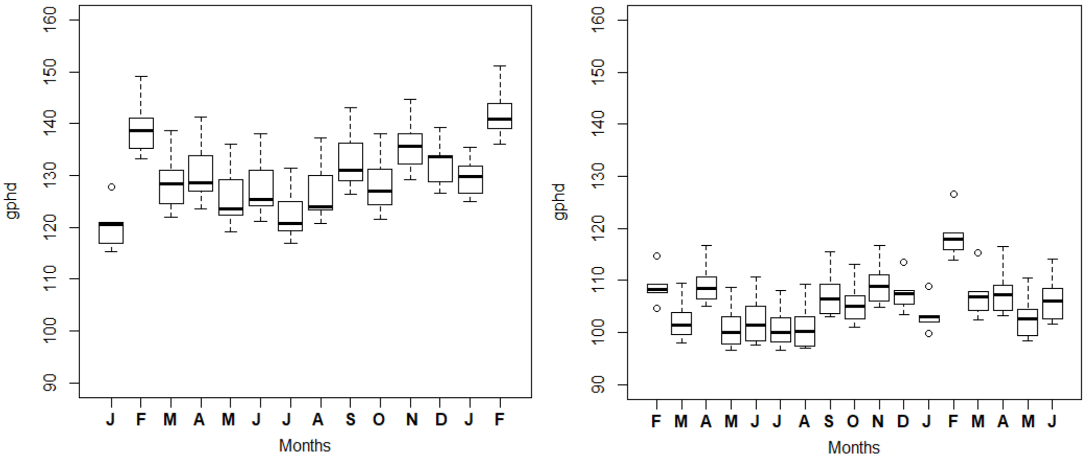


Figure 14. Pre and post-shortage gphd from monthly simulations by IUWM

The ANOVA method was applied to check whether the differences in the mean of gphd over the months are statistically significant and can prove a seasonality effect. According to the results on table 18, at a significance level of 95% (α=0.05), a statistically significant difference in the monthly means occur only in the wet/dry condition, or every six months, in the North only. The wet set of months goes from October to March, and the dry set goes from April to September. This classification was based on the hydrologic year, in which the wet months are also the hottest, and the dry months are also the coldest months.

Table 18. ANOVA results for the Pre-shortage

Region	**Season**		**WDM**		**WD**		**Sample size**
	F-test	p-value	F-test	p-value	F-test	p-value	
Center	0.544	0.663	1.047	0.384	0.598	0.454	14
East	1.451	0.286	2.001	0.181	2.561	0.136	
North	2.240	0.146	3.504	0.067	4.760	0.049	
South	1.119	0.387	1.641	0.238	1.890	0.197	
West	0.669	0.590	1.152	0.351	0.758	0.401	

Significance level: 90%– Dotted line; 95% – continuous line

At a 90% significance level (α=0.1), the North also has a statistically significant difference in the WDM condition. This condition adds moderate levels of temperature and precipitation. In this case, the seasonality effect would happen every four months.

The ANOVA results for the post-shortage (table 19) show that the North is the region with statistically significant difference in the means of the months in all monthly groups at a significance level of 95% (α=0.05). That being said, it is possible to notice a seasonality effect in the North every three months, according to the calendar season. The East and the South also present a significant difference under the WDM group at the same significance level of 95%.

At a 90% significance level (α=0.1), the Center and West also show a significant difference in the monthly means in the WDM group. The East show significant differences in the season and WD group, meaning that at this level, seasonality is noticeable starting at every three months. The South shows statistically significant differences at the same level in the WD group as well.

Table 19. ANOVA results for the Post-shortage

Region	Season		WDM		WD		Sample size
	F-test	p-value	F-test	p-value	F-test	p-value	
Center	1.133	0.372	2.927	0.087	1.380	0.258	17
East	2.666	0.091	4.723	0.027	3.363	0.087	
North	3.695	0.040	5.881	0.014	5.016	0.041	
South	2.437	0.111	4.304	0.035	3.394	0.085	
West	1.328	0.308	2.870	0.090	1.509	0.238	

Significance level: 90%– Dotted line; 95% – continuous line

It is important to remark that the sample size in the post-shortage is 3 months larger than in the pre-shortage. From these findings, it is possible to note a seasonal pattern happening every four months in the post-shortage in all regions at a 90% significance level, which did not occur in the pre-shortage. Because the WDM group was based on precipitation volumes and temperature, it is likely that after the shortage, people were more aware and concerned about rainfall levels and it may have had an impact in monthly water demand.

Conclusion

The shortage in the city of São Paulo caused compulsory demand reduction in the residential sector, which accounts for 84% of total water use in the city. Understanding changes in demand that occurred during the time-series of 2013 to mid-2017.

Water demand pattern across regions varies depending on their features. Determinants of demand are different in each region. The economic tools during the shortage was a common factor that contributed to demand reductions in all regions. High correlations of water use with other variables were not found, probably because of the changing patterns due to the shortage. All variables analyzed had a significant effect on water use ($\alpha = 0.001$) in São Paulo, except for maximum temperature. Income and the economic incentives also had a very high effect on demand in all regions.

The calibrations of IUWM for indoor demand predictions enabled a high NSCE, proving a very good fit of the model for to project water demand in São Paulo under different shortage conditions. Furthermore, the method used to estimate outdoor demand during calibrations caused a very close approximation of indoor demand to total use due to a 2% outdoor use contribution. Average household sizes in each region show that households in the Center consume more water than all other regions, while households in the East consume less of all. Average household sizes shifting along the shortage did not change this pattern.

There was a demand reduction of over 12% from the pre to the post-shortage. This was achieved by behavioral changes and reuse practices emergently implemented drove by the need to reduce demand. An observed seasonality of at least four months was found in the post-shortage for all regions at a 90% confidence level. The shortage also reduced average daily household demand in all regions, with the demand in the East, North and South inferior than values projected in the High Efficiency study done in the United States.

IWUM testing in this chapter supports the analysis in the next part of this study.

Chapter 3 – Evaluation of Conservation Practices for Potential and Benefits Maximization

Introduction

Hespanhol (2008) advocates for water reuse initiatives and water conservation in São Paulo as a form to alleviate the overflow of non-treated sewage discharged into water bodies and avoid inter-basin water transfers into the MRSP. A survey conducted by Sanchez (2007) in the city of São Paulo found that residents in over 90% of the interviewed households think saving water is important, but only 61 to 71% of the households allegedly save water somehow. The survey also revealed that almost half of these households save water by rational use and less than 30% of all single-family residential units (two-story plus single-family households) reuse water for some purpose. These results suggest that in addition to public acceptance and awareness, further incentives and support are needed for the implementation of alternative water sources succeed.

Conservation strategies have the potential to reduce potable demand for a variety of purposes, i.e. toilet flushing, floor washing, irrigation, cleaning of vehicles, civil construction, dust control and groundwater recharge (Hespanhol, 2002). Graywater reuse, stormwater use, effluent use and roof runoff harvesting are alternatives to promote reuse and conservation that can be applied from household scale up to neighborhood or larger spatial scales. However, the purpose of reuse will define the water quality to be met, the best type of treatment and the costs of operation and maintenance.

The fit-for-purpose concept is ideal to prevent overtreatment and under-treatment of reclaimed water and save energy, resources and costs during the process. The level of treatment can be defined for the appropriate water quality and is based on the end use of reclaimed water (Chhipi-Shrestha et al., 2017).

In Brazil, the Ministry of Health established standards for potable use through the Ordinance 2914 (Brasil, 2011). However, the lack of specific regulations for non-potable reuse of water is an obstacle for the development of large scale decentralized non-potable water systems. The reuse of water in single-residence homes, such as laundry graywater for toilet flushing or floor washing, poses fewer risk to the residents in the household due to a closed cycle, in which the pathogens load in this water proceed from and involve the same residents (Sharvelle et al., 2017a). In this case, the need for treatment and the risk of exposure are minimal. The same does not apply to graywater collection and distribution from and to multiple residences or commercial buildings. Hence, the influent quality must also be considered when applying fit-for-purpose technologies in large-scale systems to safeguard public health.

During the 2014-2015 shortage, change of habits was adopted by the population to promote demand reduction. Lafloufa (2016) describes that people decreased shower duration and frequency, car washing frequency and used less water for tooth-brushing as well. The uses of roof runoff and graywater were also embraced in both rudimentary and sophisticated manners for non-potable reuses, such as floor washing, toilet flushing and plant watering (Sousa, 2015; Veja, 2015; G1, 2016; Akatu, 2018).

Albeit the shortage proved the potential for water reuse and conservation in São Paulo, it was deepened by climatic abnormalities in the Southeastern region of the country that was considered an extreme climatic event (Marengo and Alves, 2015). Extreme events of precipitation and temperature are projected to intensify until the end of the century and are likely to adversely impact large urban agglomeration as São Paulo, posing risks to economy, public health, community welfare and water resources (Nobre, 2011). A hot and dry scenario is projected with an addition in maximum temperatures of up to 9°C by the end of this century in the RCP 8.5 scenario and annual precipitation reduction between 40 to 45% in São Paulo (Lyra et al., 2017).

A reduction in precipitation implies increasing supply vulnerability and the possibility of recurring water shortages. Furthermore, less precipitation level can also compromise performance of roof runoff and stormwater use, reducing conservation reliability of these two practices. In order to ensure water for basic needs, it is crucial to explore the potential of conservations strategies to maximize savings while reducing sole dependency on reservoir withdraws.

Objectives

This chapter aims to investigate the potential of conservation strategies for water demand reduction. More specifically, the objectives are to:

1. Evaluate savings of graywater reuse and roof runoff that contributed to residential demand reduction from pre to post-shortage;
2. Assess residential demand reduction potential of conservation practices of graywater reuse, stormwater use, roof runoff harvesting, and wastewater reuse;
3. Project maximum potential and benefits that can be gained by adoption of technologies for fit-for-purpose water and estimate the how climate change influences performance of conservation strategies.

Research questions

Over this chapter, the following research questions will be answered:

1. How much saving was possible using graywater and roof runoff from pre to post-shortage?
2. What are the maximum savings that can be achieved through the application of conservation practices?
3. What are the cost-benefit tradeoffs of each scenario and climate change implications in practice performance?

Methods

Conservation strategies evaluation

The Integrated Urban Water Model has the ability to estimate the conservation potential of alternative sources to meet potable and non-potable demand. The available strategies in the model include indoor conservation using more efficient fixtures, landscape irrigation conservation, and use of graywater, stormwater and treated wastewater (Sharvelle et al., 2017).

As previously described, the use of graywater and roof runoff to meet a portion of non-potable demand in households was applied during the shortage period. The potential of these two strategies are here compared against the pre and post-shortages to evaluate their contributions to demand reduction during that time.

Furthermore, in order to enlarge the portfolio of conservation options two more alternatives – stormwater and effluent reuse - were analyzed along with graywater and roof runoff harvesting under three scenarios. All four practices can be applied to meet potable and non-potable demand, depending on quality required and the level of treatment available.

Conservation savings during shortage

The Technological Research Institute (IPT) published a manual for emergency roof runoff harvest, storage and use in early 2015, and a manual for emergency graywater collection, storage and reuse a year later (Zanella, 2015; Alves et al., 2016). The scope of the manuals did not include plumbing and structural building adaptations. Instead, both manuals aimed to instruct and inform consumers on water quality and ways to handle graywater and roof runoff given that these types of reuse became widespread during the shortage.

Roof runoff harvesting, according to the manual (Zanella, 2015), can be used in normal conditions for gardening, car and floor washing and toilet flushing. In abnormal or extreme cases, roof runoff can be used for shower, dish washing, clothes washing and drinking, only if followed the instructions provided to ensure acceptable quality for these purposes. Graywater can be used for toilet flushing, wall, floor and car washing, watering of trees, bushes, grasslands and flower gardens; it is not recommended for vegetable gardens and sports fields (Alves et al., 2016).

Using the regional α and β parameters from table 14 for pre and post-shortage, adoption calibrations of graywater and roof runoff adoptions were performed to examine the adoption that met demand reduction during the shortage condition in all regions. Calibration procedures were again conducted using IUWM Python code, and estimated uses for floor washing and toilet flushing, both non-potable uses. The practices were evaluated separately with 1500 simulations using a Monte Carlo method as in Chapter 2.

Selecting percentages of adoption by the maximum likelihood method, different storages were set to evaluate the conservation potential of the practices. The Brazilian Standard (NBR) 5626/98 establishes the requirements for design, execution and maintenance of cold water plumbing for domestic use, residential or not, including specifications of water storage in a building. Contrary to many developed countries, the water supply to Brazilian households consists of indirect supply – the water is delivered into a head storage tank that is connected to the water fixtures in the house. In some households, there may be fixtures connected directly to the public supply in addition to the storage tank (Sanchez, 2007).

According to the NBR, the storage tank used for indirect potable supply must be designed taking into account the patterns of water use in the building and the stored volume must be, at least, enough for 24 hours of use in case of supply interruptions. For small households, the minimum volume recommended is 132 gallons – 500 liters. Therefore, selected storage volumes for evaluation were 33 gal, 66 gal and 132 gal – 125, 250 and 500 liters. Emphasizing that the non-potable plumbing structures must be separated from potable ones, this storage volume selection aims to not surpass the already existing potable storage.

The comparison was made between practice performance with different storages and pre and post-shortage conditions through bar charts and percentage reductions.

Conservation practices potential to decrease potable demand

The potential reduction with application of conservation practices of graywater, stormwater, effluent reuse and roof runoff harvesting was assessed to meet both potable and non-potable demand. The pre-shortage condition was set as the benchmark for comparison using the set of regional α and β parameters from Chapter 2 for conservation projection. In the pre-shortage, it is assumed that no reuse is being done and water demand uses raw water from the supply system for all household end uses.

Three scenarios were evaluated for each practice – a combination of potable (includes toilet flushing) and floor washing demands (Pot+FW), combination of floor washing and toilet flushing demands (FW+TF), and floor washing demand alone (FW). Table 20 specifies the adoption and storages selected for the evaluation.

Table 20. Level of adoption and storage volumes for scenarios evaluation

	Adoption (%)	*Storage (gallons (liters))*
Graywater	85	132 (500)
Stormwater	85	3000 (11370)
Roof runoff	85	132 (500)
Effluent	85	no storage

For all scenarios, 85% of the service area would adopt the practices whereas 15% would not adopt any practice whatsoever. This selection aimed an aggressive approach, but still gives margins for more savings.

Storage volumes for all scenarios were selected aiming practicality and feasibility. Graywater and roof runoff practices allows for building scale storage (single or multi-family homes). Stormwater is projected to be collected from a neighborhood or larger spatial scales – i.e. districts, thus requiring larger storage. Effluent reuse is considered with the implementation of a dual-system distribution with minimum or system storage.

Graywater production is calculated based on the end uses of water from faucets (except kitchen), shower and clothes washing. Stormwater is estimated from precipitation depth, runoff coefficient and impervious area in the spatial subunit. Roof area and precipitation are used to calculate roof runoff for harvesting at a building scale. At last, effluent potential is calculated based on produced blackwater (toilet and kitchen faucets).

The projections were made for each region and the average period demand – 14 months in the pre-shortage – were added up to project the demand for the city and compare reductions. Reuse to meet potable demand requires a minimum mixing fraction with raw water, here selected as 60%. All practices had 100% of availability to be used to meet residential demand.

After scenarios evaluation, a cost-benefit matrix was created, having level of treatment represented as cost and percentage reductions represented as benefit. The levels of treatment are very low, low, medium, high and very high with very low treatment level being the best-case scenario. All potable reuses require high or very treatment level, depending on the source. Table 21 presents the reduction ranges and table 22 the level of treatment needed for each scenario. This classification enables matching the concept of fit-for-purpose when choosing the most appropriate conservation scenario.

Combinations of treatment level and percentage reductions were classified into four categories to facilitate selection of the most adequate scenario from 25 possible combinations (table 23). The ideal scenario would combine very low treatment levels and yield very high reductions in demand, whereas the worst possible scenario would be the exact opposite.

Table 21. Classification of % reductions ranges

	% reduction range
Very low	0 - 5
Low	5 - 10
Medium	10 - 15
High	15 - 25
Very high	> 25

Table 22. Scenarios and level of treatment required

Scenario	*ID*	*Treatment level required*
Graywater for floor washing	GW-FW	Medium
Graywater for floor washing and toilet flushing	GW-FW+TF	Medium
Graywater for potable uses and floor washing	GW-Pot+FW	Very high
Stormwater for floor washing	SW-FW	Medium
Stormwater for floor washing and toilet flushing	SW-FW+TF	Medium
Stormwater for potable uses and floor washing	SW-Pot+FW	High
Roof runoff for floor washing	RR-FW	Very low
Roof runoff for floor washing and toilet flushing	RR-FW+TF	Very low
Roof runoff for potable uses and floor washing	RR-Pot+FW	High
Effluent reuse for floor washing	Eff-FW	High
Effluent reuse for floor washing and toilet flushing	Eff-FW+TF	High
Effluent reuse for potable uses and floor washing	Eff-Pot-FW	Very high

Table 23. Possible combinations of treatment levels and reductions

	Required treatment	*Reduction*
Preferred	Very low	Very high
	Very low	High
	Low	Very high
	Low	High
Acceptable	Very low	Medium
	Low	Medium
	Medium	Very high
	Medium	High
	Medium	Medium
	High	Very high
	High	High
	Very high	Very high
	Very high	High
Undesirable	Very low	Low
	Low	Low
	High	Medium
	Very high	Medium
	Very low	Very low
	Low	Very low
	Medium	Very low
	Medium	Low
Not acceptable	Very high	Very low
	Very high	Low
	High	Low
	High	Very low

All categories are ranked by treatment levels but prioritize reduction targets. The preferred category describes the ideal combinations of low or very low treatment and high or very high reductions in potable demand. This category highlights best choices for both items. Because treatment required is minimum, this situation could be applied under normal conditions to incentivize savings but when shortage is not an imminent concern. In this case, shortage events would be delayed, and water supply could be preserved.

The acceptable condition presents varying treatment focusing on very high to medium reductions. Under this category reduction in potable demand is of primary concern, allowing maximizing treatment levels to enable very high or high reductions. When ranking the options, treatment levels are still the criteria. This category could be applied during the threat or start of another shortage when higher reductions are still a target to reduce and delay aggravated shortage effects, especially when uncertainties around its duration exist. However, water managers and government agencies must strategically plan the implementation of higher treatment levels due to time constraints and financial investments.

The undesirable category scenarios would be needed in case of deepened shortage. In this category, tradeoffs for treatment levels and possible reductions are debatable depending on how much reductions are expected – medium reductions are still possible – and the availability of investments to support them. At last, the not acceptable category does not appear to have a realistic application feasibility.

Climate change impact on scenario performance of roof runoff and stormwater

The selection of a conservation scenario that contributes to reducing demand is a long-term application. The performance achieved through demand reductions must be sustained over time, especially if investments are required and tradeoffs between multiple options are considered. That being said, the practices of stormwater and roof runoff harvesting could face diminished reductions if climate change decreases precipitation.

To assess the impact of climate change in these two practices, a brief climate analysis of the precipitation and temperature variables was executed to check the behavior of the projections until the end of the century. Downscaled climate projections for precipitation and temperature until 2099 were provided by the National Institute of Space Research (INPE). This dataset supported the research published by Lyra et al. (2017). The spatial scale of daily data was 5 kilometers and was downscaled from the HadGEM2-ES model for Representative Concentration Pathways (RCP) 4.5 and 8.5.

The closest latitude and longitude of the IAG-USP meteorological station in São Paulo was selected for analysis. Time slices of 31 years – 2007-2037, 2038-2068, 2069-2099 – were taken of precipitation, minimum and maximum temperature.

Decrease in precipitation due to climate change may decrease volume of rainfall to be stored in these two practices, reducing their performance and increasing raw water demand from the system. Adoption of these practices and reduction in their performances could be seen as a form of rebound, since it would be increasing demand after a period of decrease.

The assessment of climate change impacts in practice performance was made with IUWM running scenarios of all scenarios with climate data for RCP 8.5 for two intervals, one for mid-century (2038-2068) and one for the end of the century (2069-2099). The RCP was chosen due to its extreme case that presents the most intensive greenhouse gas concentration level in the atmosphere.

In addition, several studies indicate the impact of higher air temperature in affecting water demand (Bougadis et al., 2005; Adamowski, 2008; Santos, 2011). Lyra et al. (2017) also indicate the potential increase in maximum temperatures in the MRSP of about 9°C in the end of the century. For these reasons, a discussion is made around the importance of higher temperature in water use and demand.

Results and Discussion

Conservation during shortage

From the pre to the post-shortage condition, several factors contributed to reducing water consumption. Reuse practices became widespread with practices of graywater and roof runoff harvesting. The investigation of the potential of these two strategies from one condition to the other was pertinent to quantify this reuse potential. Separate analysis was made for each strategy.

A calibration of percentage of graywater adoption of was performed for pre and post-shortage. This calibration aimed to estimate the optimal adoption of graywater to be used for outdoor floor washing and toilet flushing, the two most common non-potable reuses that happened during the shortage. The adoption that met demand reduction in the pre-shortage was about zero, agreeing with the previous assumptions that no reuse was performed during this condition. The adoption in the post-shortage varied, as shown on table 24.

Table 24. Optimal graywater adoption in Pre and Post-shortage

Region	Period	Adoption (%)
Center	Pre-shortage	0.1
	Post-shortage	94.3
East	Pre-shortage	0.2
	Post-shortage	83.4
North	Pre-shortage	0.1
	Post-shortage	97.0
South	Pre-shortage	0.1
	Post-shortage	66.2
West	Pre-shortage	0.15
	Post-shortage	90.4

In the post-shortage, the adoptions that met demand reduction varied by region. Largest adoption would have occurred in the North and lowest adoption would have occurred in the South. The adoptions were run with three storage volumes: 132, 66 and 33 gallons – 500, 250 and 125 liters. The variation in storage volume allows accounting for different household realities. In addition, the sizes are practicable, with accessible cost and not larger than the minimum recommended by the NBR 5626/98 for potable indirect supply storage.

The evaluation of percentage adoption of graywater, associated with storage, intended to provide an estimation of the capacity of savings allowed by the adoption of graywater from one period to another, should this practice had been exclusively adopted (figure 15).

The reduction in potable demand using graywater is the same regardless the storage selected. This can be explained by the difference in supply and demand. Floor washing and toilet flushing account for about 19.25% of household demand, which was about 25 and 20.6 gallons in the pre and post-shortage conditions, respectively. In this case, demand for these end-uses is less than the minimum storage defined of 33 gal. Therefore, despite the 41% of graywater production within the household, larger storage would not cause further reductions. In this case, production larger than storage would cause excess to spill and not be used.

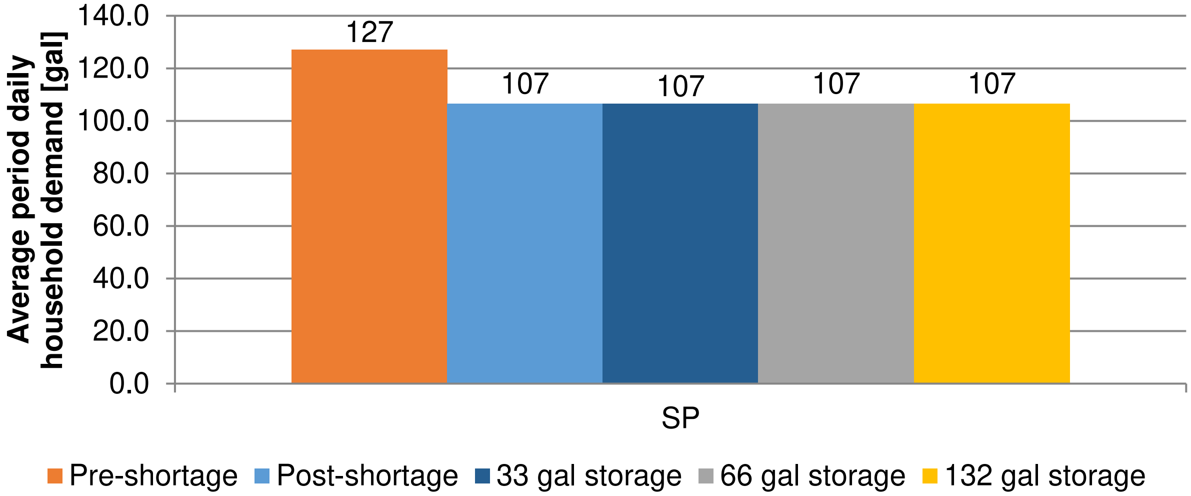


Figure 15. Potential reduction achieved with graywater adoption in São Paulo with difference storages

The reduction from pre to post-shortage from IUWM simulations was approximately 12.55%, while the reduction from pre-shortage to a post-shortage with graywater adoption was 12.53%. The difference in volume that graywater did not meet was approximately 2.3 million gallons, which accounts for about 0.02% of the average post-shortage demand. With such small difference, it is possible to perceive that if graywater reuse was the only practice contributing to reducing demand from pre to post-shortage, the adoptions on table 24 could represent the contributions from each region.

Likewise, the same approach was used for roof runoff. This practice was not combined with graywater reuse. A calibration for adoption that met demand reduction from the pre to post-shortage conditions was performed and the values were used to run IUWM with three storage volumes of 132, 66 and 33 gallons. Table 25 shows the calibrated adoptions for roof runoff.

Table 25. Optimal roof runoff adoption in pre and post-shortage

Region	Period	Adoption (%)
Center	Pre-shortage	5.8
	Post-shortage	99.95
East	Pre-shortage	7.2
	Post-shortage	99.95
North	Pre-shortage	10.1
	Post-shortage	99.95
South	Pre-shortage	8.0
	Post-shortage	96.8
West	Pre-shortage	6.01
	Post-shortage	99.95

In the pre-shortage, the adoptions are low but above zero, meaning that some small adoption of roof runoff harvesting could have been performed under this condition. In the post-shortage, the adoptions are very high near 100%. The reductions produced by different storage volumes are shown on figure 16.

Different from graywater, varying storage capacity changes the demand reduction potential up to 4% when going from 33 to 132 gal and 2% from 33 to 66 gal. However, savings provided only by roof runoff harvesting were not sufficient to meet the reduction achieved in the post-shortage even at 132 gal storage capacity. The difference between demand with maximum storage – 132 gal – and post-shortage demand is almost 700 million gallons, corresponding to about 6% of the average total demand in the post-shortage. Nonetheless, the reduction achieved from pre-shortage to post-shortage with roof runoff adoption was about 8% with storage of 132 gal.

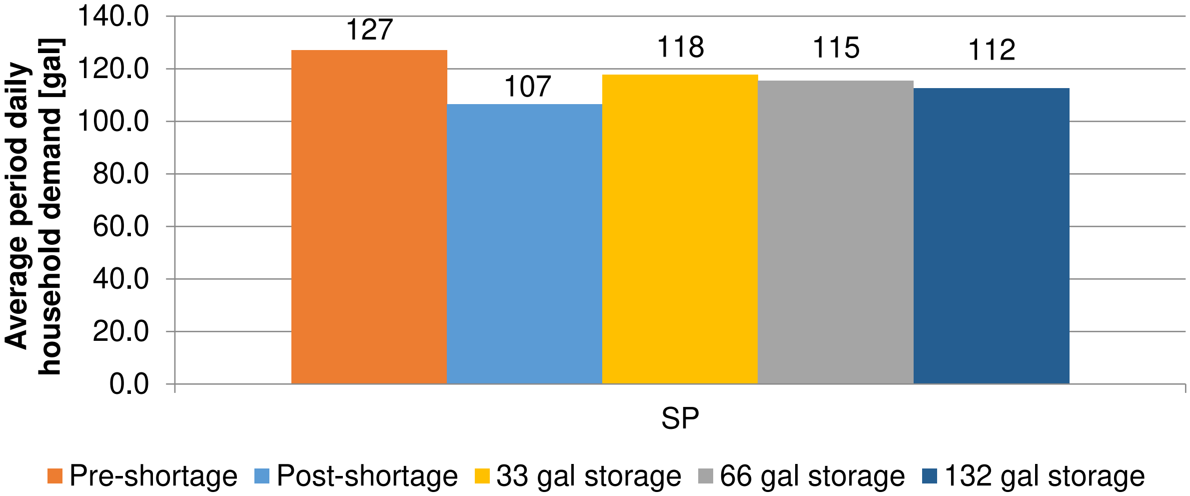


Figure 16. Potential reduction achieved with roof runoff adoption in São Paulo with different storages

Considering that adoptions are at their maximum values, demand reduction from one condition to the other could have been achieved with larger storages. However, at the household level larger storages may not be viable in terms of costs or space required.

The potential of graywater reuse is larger than roof runoff. The steady production of graywater guarantees it is constantly available, according to the habits of water use within the household. However, in this analysis, non-potable demand was less graywater supply. The average annual graywater supply is also greater than roof runoff supply, which depends on the amount of rainfall that changes over the months and is not as reliable as graywater.

Both graywater and roof runoff practices contributed to reduce demand during the shortage and were used in combination in many homes. The greater potential of both strategies can be unfolded if potable reuse becomes available, institutional support is established and proper treatment is executed. An aggressive approach to evaluate maximization of potential and benefits is performed as follows.

Conservation alternatives potential and fit-for-purpose benefit maximization

Three conservation scenarios were evaluated in order to explore the savings and conservation options available – combined potable and floor washing (Pot + FW); combined floor washing and toilet flushing (FW + TF), and floor washing alone (FW).

The combination of potable use and floor washing comprises indoor and outdoor uses. Potable uses are mainly indoor uses, such as drinking water, shower, laundry and faucets, in which there is human contact and exposure in all forms - absorption, ingestion and inhalation. For this reason, it is crucial to prevent health hazards by ensuring adequate level of treatment.

Non-potable uses pose less health-risk, but yet require some degree of treatment that can be determined by the source and the end-use to match the fit-for-purpose context. Within homes, non-potable uses are irrigation and floor washing, car washing and toilet flushing.

Enlarging the portfolio of water sources available for both potable and non-potable allows for greater reduction, but at the same time, demands investments in treatment options. However, conservation that increases efficiency in water use through the urban water mass balance avoids compulsory changes in behavior.

Figure 17 presents the impact in average period demand – pre-shortage – from all conservation practices in the combined Pot + FW, FW+TF and FW scenarios, projected with storages and adoptions from table 20. IUWM simulations of pre and post-shortage without conservation are also present for comparison. Standard errors are also shown. The demands are shown for the city of São Paulo from aggregation of all regional simulations.

The combination of Pot + FW is the scenario that provides largest reductions because all uses within the household are being considered for reuse. In the combined Pot + FW scenario, graywater, stormwater and effluent use promote greater savings than roof runoff when compared to the pre-shortage. Compared to post-shortage, these three alternatives had the potential to further contribute to reduce demand beyond what was actually achieved, except for roof runoff, which would have promoted as much savings as reached in post-shortage use.

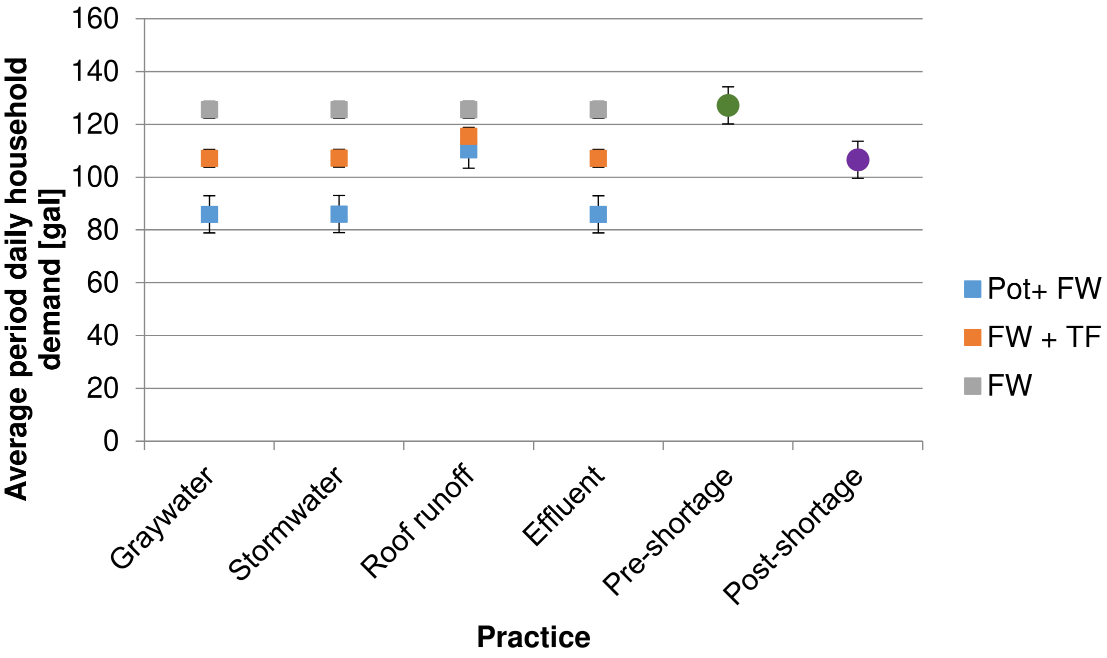


Figure 17. Average period household demand with application of conservation practices for Pot + FW, FW + TF and FW demands in the pre-shortage

The scenario of non-potable reuse, FW + TF, produced medium reductions overall, with roof runoff still showing the lowest reductions. The scenario of FW produced the lowest reductions. This can be explained by the low demand that this scenario supplies. In this last scenario, all practices were not able to achieve reductions from the pre to post-shortage conditions.

Percentage reductions are consistent across regions, except for the Center, where reductions decrease slightly for roof runoff savings in Pot+FW and FW+TF. Roof runoff shows the lowest percentage reduction in all regions (table 26).

The end-use and the source of the water determine the most adequate treatment, security criteria, and costs of installation, operation and maintenance (Hespanhol, 2002). For example, graywater and effluent reuse must achieve equal quality for the same end-use, but their different sources characteristics may require more or less treatment to reach the desired quality. Nevertheless, potable uses require a higher level of treatment than non-potable uses despite of the source.

Table 26. Regional reductions from scenarios application

		Center	*East*	*North*	*South*	*West*	*SP*
Graywater	**FW**	0.2%	1.4%	1.4%	1.6%	1.3%	1.3%
	FW+TF	14.8%	15.8%	15.8%	16.0%	15.7%	15.8%
	Pot+FW	31.7%	32.5%	32.5%	32.6%	32.4%	32.5%
Stormwater	**FW**	0.2%	1.4%	1.3%	1.6%	1.3%	1.3%
	FW+TF	14.8%	15.8%	15.7%	16.0%	15.7%	15.7%
	Pot+FW	31.7%	32.4%	32.4%	32.5%	32.3%	32.4%
Roof runoff	**FW**	0.2%	1.3%	1.3%	1.5%	1.3%	1.%
	FW+TF	7.4%	9.5%	9.4%	9.1%	9.6%	9.2%
	Pot+FW	9.7%	13.6%	13.5%	12.7%	14.3%	13.2%
Effluent	**FW**	0.2%	1.4%	1.3%	1.6%	1.3%	1.3%
	FW+TF	14.8%	15.8%	15.8%	16.0%	15.7%	15.8%
	Pot+FW	31.7%	32.5%	32.5%	32.6%	32.4%	32.5%

The types of treatment available can be natural or biological processes – settling/septic tank, anaerobic filter/sludge blanket, packed bed filter, trickling filter, activated sludge, wetlands, sand filters, treatment ponds -, physical processes by filtration – sand filters, membranes, cartridge/bag filter, dual media filter with coagulant - and disinfection processes – chlorination, UV radiation, oxidation, pasteurization. These processes can remove chemical components or pathogens, the latter can be inactivated by interception, predation, adsorption, settling and die-off (Sharvelle et al, 2017a). Processes can also be more or less energy intensive, with easy or hard operation and maintenance, demand more or less sophisticated facilities or structures, among other requirements. The selection of the treatment technology and its impacts can be evaluated through a life-cycle assessment (Carre et al., 2017).

The choice of the scenario that best achieve water demand reductions while needing low treatment can be made using a cost-benefit matrix model, with adaptations to present treatment versus percentage reduction in demand. Using this matrix, it is possible to visualize the scenarios that can maximize benefits – more demand reduction – and minimize costs – lower treatment levels.

Despite the high percentage reductions for Pot+FW, the potable end-uses require very high or high level of treatment. The use of effluent for any scenario also demands very high or high level of treatment due to high concentration of pathogens. Using the combinations on table 23, figure 18 shows no preferred scenario. A summary of the alternatives is presented on table 27.

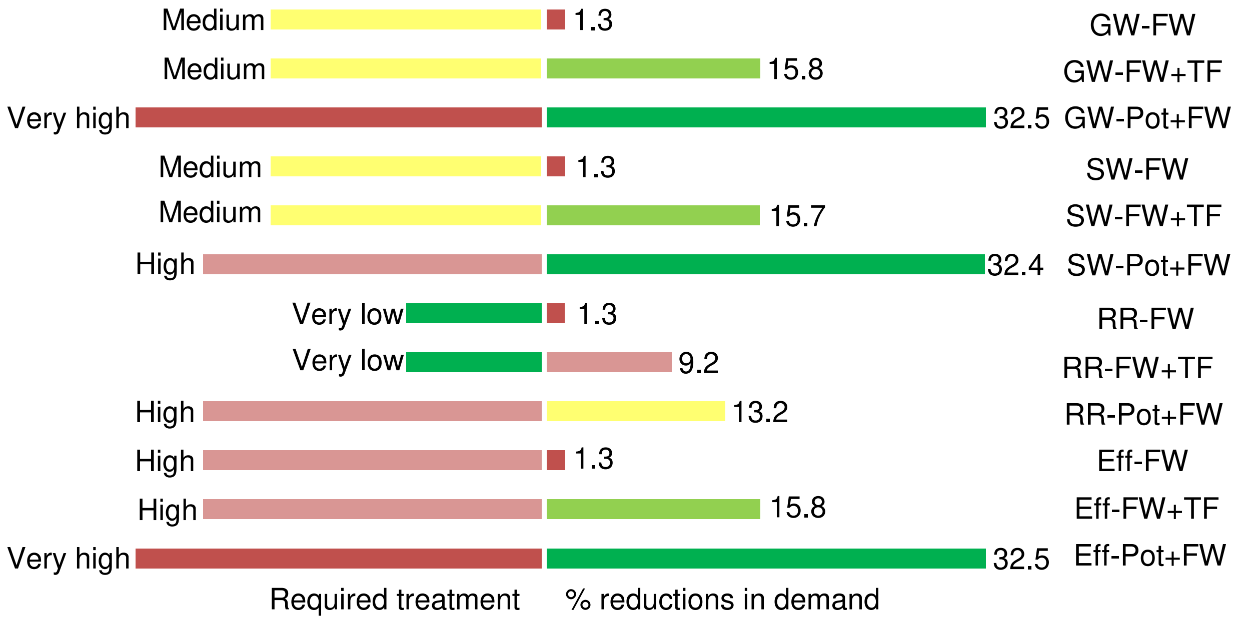


Figure 18. Treatment-reduction matrix with percentage reductions for São Paulo projected based on the pre-shortage condition

Table 27. Scenarios classification according to practicable categories

Preferred	-		
Acceptable	GW-FW-TF GW-Pot+FW	SW-FW+TF SW-Pot+FW	Eff-FW+TF Eff-Pot-FW
Undesirable	RR-FW+TF GW-FW	RR-Pot+FW SW-FW	 RR-FW
Not acceptable	Eff-FW		

From the matrix, the priority for overall demand reduction would be adoption of practices for non-potable demands, in this case FW+TF. From the fit-for-purpose point of view, this finding was expected because non-potable reuses require inferior water quality that can be achieved with medium level of treatment, except for effluent reuse, which requires at least high treatment level for non-potable uses. The options from the acceptable category produce very high or high reductions for potable and non-potable reuses, respectively.

The undesirable category is a trade-off between higher treatment levels for medium reductions or medium treatment level for lower reductions. Roof runoff harvesting is the practice with lowest performance but would require high level of treatment if used for potable purposes. Undesirable scenarios could be adopted in case of aggravated long-term shortages. The not acceptable category is an investment in high treatment levels for a use that is dismissible in critical shortage situations.

When selecting the most appropriate technology and scenario, it is also relevant taking into account the spatial level of reuse – building, neighborhood or larger scales – for treatment facilities and infrastructure development.

Climate assessment and impact on roof runoff and stormwater practices

As shown in the previous section, the acceptable scenarios are for non-potable uses of FW+TF using graywater, stormwater and effluent. Even though roof runoff promotes up to medium savings, this practice, as well as stormwater, depend on the amount of rainfall (precipitation depth), along with impervious or roof area and runoff coefficient. The adoption of these practices may have its performance diminished by less precipitation volumes caused by climate change. This analysis aimed to look at the effects of less precipitation in scenarios performance and does not consider decrease in supply which is assumed the same over time.

The dataset provided by INPE that supported the findings of Lyra et al. (2017) was divided into 31-year intervals for trend examination in both RCP 4.5 and 8.5 along with the historical dataset. Figure 19 shows the trends of maximum temperature and precipitation for each time interval in both RCP’s 4.5 and 8.5. Figure 20 shows yearly values for both variables.

In both RCP, there is a tendency of hotter and drier scenarios as described by Lyra et al. (2017).

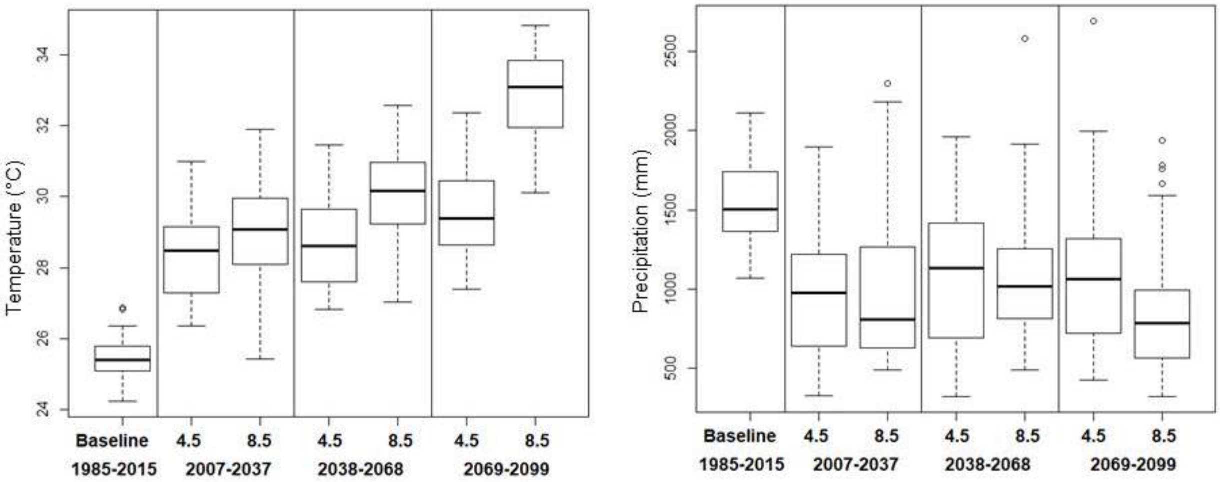


Figure 19. Annual average maximum temperature (left) and total annual precipitation (right) for RCP 4.5 and 8.5

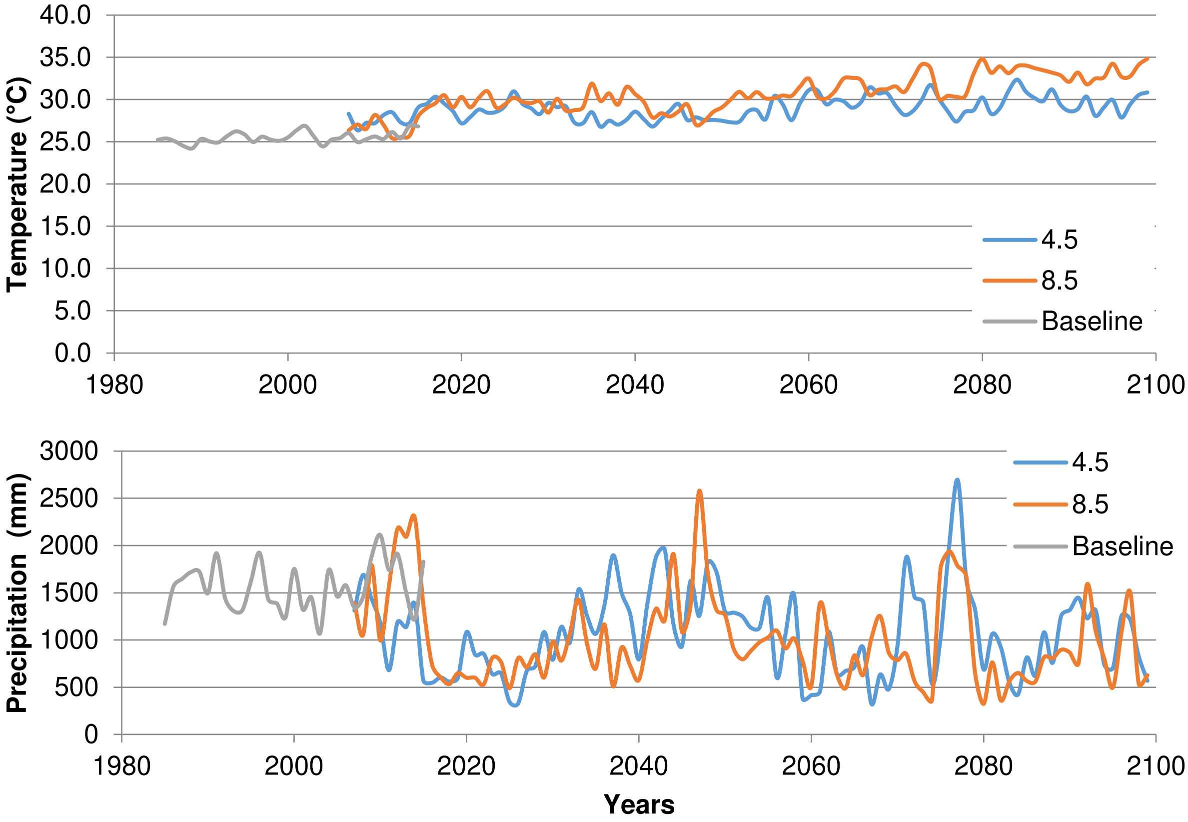


Figure 20. Average annual maximum temperature (top) and total annual precipitation (bottom) of historic data (1985-2015) and projected RCP's 4.5 and 8.5 (2007-2099)

In scenarios of less precipitation, the treatment-reduction matrixes show lower reductions for roof runoff harvesting and stormwater use scenarios compared to current conditions (figure 21). Variations between mid-century and end-of-century conditions are very small, being potentially more perceptible regarding roof runoff for potable and non-potable demands. Roof runoff scenarios also show greater differences in reductions when compared to current conditions and end-of-the-century simulations (figure 22).

The reductions provided using roof runoff for Pot+FW in the future fall into low savings with less than 10% demand reduction, while in current conditions this saving was classified as medium (10-15%). This decrease shifts this scenario to the not acceptable category, for requiring high level of treatment and yielding low savings. All other scenario combinations of roof runoff remain the same as current conditions. Future simulations for stormwater scenarios remained within the same classifications as current conditions, and therefore, are still acceptable (SW-Pot+FW, SW-FW+TF) and undesirable (SW-FW) for demand reductions.

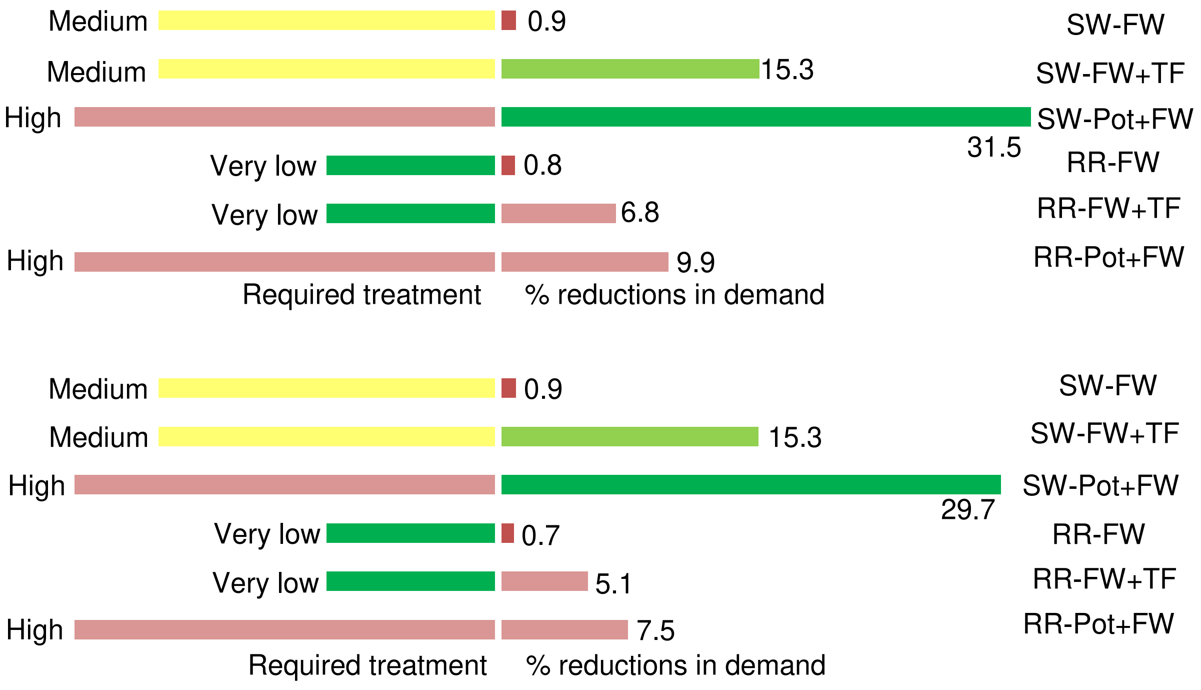


Figure 21. Treatment-reduction matrix for changes in stormwater and roof runoff harvesting in mid-century (top) and end-of-century (bottom)

In the roof runoff for Pot-FW in the end of the century, the percentage reductions from 13.2% to 7.5% are significantly different. Adopting this scenario should be carefully considered, but since this strategy falls under the undesirable category, it is not a priority in selection.

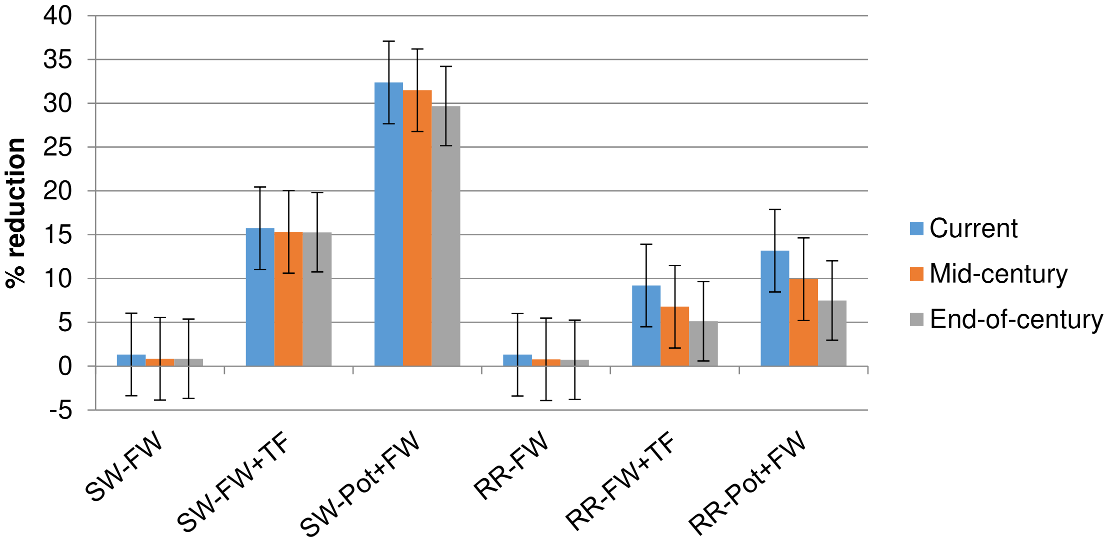


Figure 22. Differences in reduction in stormwater and roof runoff scenarios for the three climatic conditions

In this analysis, it is also important to ponder that all scenarios account for floor washing demand. This demand was estimated based on the minimal outdoor area and, thus, might be larger in reality, leading to higher water demand. In this case, lower amounts of precipitation would not be able to meet higher demands and the impact in mid and end-of-century performances could be even bigger and possibly statistically different from the current condition regarding other strategies presented, such as RR-FW+TF and SW-Pot+FW.

The variations in graywater and blackwater availability resulting from the climatic interference in the habits and water uses are not considered in this analysis and are assumed to have a steady performance over time. Nonetheless, habits and lifestyle could face changes should the climate get hotter and drier, shifting the demand profile and defined percentages of end-use of water. That being said, produced graywater and blackwater could also vary the performance of graywater and effluent reuse practices.

In a hotter scenario, the following habits could be affected:

- + water for drinking, that can lead to
- + toilet flushing, increasing
- + hand-washing and faucet use;
- + shower frequency;
- + recreational activities;
- + clothes washing;
- + water for air-conditioning.

Less precipitation could increase floor washing for cleaning impulses and dust control and increase use of water in humidifiers to improve breathing, in case of lower air relative humidity. Practice not affected by changes in temperature or precipitation is consumptive use for cooking. Clothes, shower and toilet are the largest end-uses in households (table 6). Should climate change increase water demand from these end-uses, with no conservation practice in place, supply faces even greater vulnerability.

Conclusion

The adoption of conservation practices for potable and non-potable reuse in São Paulo proves to have up to 32% capacity of demand reduction in residential water use. The reduction promoted during the shortage could be maximized had potable reuse been implemented with proper treatment. However, it is important to notice that outdoor demand in this study was assumed to be minimal, based on the smallest undeveloped area and small washing frequency. Higher outdoor demand could enhance demand reduction even further using non-potable reuse.

Savings achieved during the shortage for non-potable reuses of floor washing and toilet flushing through the adoption of graywater reuse alone had the potential to promote the real reduction from the pre to the post-shortage period, assuming that the adoptions in each region corresponded to the estimated ones to meet reduction. On the other hand, roof runoff harvesting alone could not have promoted the achieved reduction even with 132-gallon storage, which was the maximum volume considered. One possible explanation was that rainfall events did not occur constantly, whereas non-potable use did. This causes the storage to be used up quicker than it is replenished, demanding raw water to supply the difference.

The conservation potential of graywater, stormwater and effluent reuse is higher than roof runoff in all regions and scenarios evaluated. The scenario of potable plus floor washing achieved the largest reductions of about 32% from graywater, stormwater and effluent reuse each compared to the pre-shortage, with an average reduction beyond 4.5 billion gallons per month. The practices were not assessed in combination. Reduction in precipitation from climate change did not changed stormwater and roof runoff performance significantly.

The tradeoffs involved in choosing the most adequate scenario and practice is associated with required treatment for reuse. The source and the end-use determines the water quality to be achieved, which is defined by treatment. Primarily, non-potable reuses of floor washing, and toilet-flushing are recommended and deemed acceptable. Potable reuses would require higher levels of treatment despite of promoting the highest observed reductions.

The analysis provided in this chapter can support long-term decision-making for conservation practices adoption and encourage development of water reuse policies.

Closing remarks

The present study was based and motivated by the shortage faced by the Brazilian Southeastern population, more specifically the city of São Paulo. The shortage was caused and aggravated by climatic conditions, deficient water management over the years, lack of proper environmental management within watersheds and increasing population and water demand.

The use of urban water models for demand projection allows for improved management practices in various temporal and spatial scales. Integrated modelling also aids with paving the way for a one water approach in urban areas, by supporting a systematic view of the urban water components. The mass balance approach of IUWM and the model flexibility enable its use in any service area worldwide as long as adequate data is available. Its capabilities of projecting conservations scenarios are an asset in terms of planning and management to promote demand reduction in residential and CII water use.

The application of IUWM in São Paulo during the shortage condition sought to quantify savings that occurred during this condition while exploring the potential for even further demand reductions through additional conservation practices. This study contributed to the scientific expansion of urban water knowledge in São Paulo and described not shortage causes or behavioral changes, but realistic potential solutions to improve water use in the city.

The regional approach for analysis was valuable to promote decentralization and to evaluate variations occurring within the same city and management style. While attempting to focus in smaller spatial scales, this study was able to provide a broad view over the whole city. It made possible to classify regions with the highest and lowest household demands and prove that water use differ across regions.

The exploration of determinants of water demand that significantly drove residential demand during the period considered – 2013-2017 – enhanced understanding and enabled identification of the most significant variables influencing water use and demand in the regions. Even though not all regions were supplied by the Cantareira system, the chain of events caused a systemic response and the economic incentive was a significant variable affecting monthly use in all regions.

Associating the determinants of water demand provided in Chapter 2 improves the potential for reuse strategies adoption analyzed in Chapter 3. In this case, decisions concerning reuse in each region should not only take into account scenario performance but also what relevant factors can favor one scenario over the other. For example, adopting a scenario at the household level might be easily accepted at higher income household if the treatment level to be installed is more sophisticated, while at lower income households, families might be more reluctant and willing to prefer the second best alternative if it is more affordable. Other types of economic analysis may be required in this case.

The reuse potential in the city has been broadcasted but was not yet widely implemented. As emergency measures during the shortage, graywater reuse and roof runoff harvesting were adopted and contributed to demand reduction. The examination of the possible practices and scenarios and the categorization approach for scenario selection have the potential to support decision-making with respect to conservation practices adoption and can serve to encourage the development of water quality regulations for reuse. In addition, further studies based on the quality of the water source and the end use, associated costs and surveys of public acceptance of water reuse practices can support guidelines for treatment options in different spatial scales, incentivize institutional support and intensify society's engagement in water issues.

During the development of this study, the main hurdle was the quantification of outdoor demand. The method used based on constructed and non-constructed area generalized for a minimum non-constructed area due to lack of more detailed data at smaller spatial scales. In addition, the inexistence of water end-use studies with larger and more representative sample sizes of a region or at city level was also a challenge to overcome. End-use studies are extremely helpful in understanding the consumption within households or other buildings. They would also contribute to define a demand profile accounting for outdoor uses and that is faithful to regional features and habits.

Further work to enrich the knowledge on urban water demand in São Paulo could include a thorough assessment of outdoor use of water and its quantification to enhance the prediction of conservation strategies through end-use studies surveying; characterization of water supply and wastewater treatment from a bird-eye view, including another mass-balance approach and possibly the impacts in supply and wastewater production from adoption of conservation strategies; exploration of the possibilities and requirements for effluent reuse and the economic implications of this strategy. Studies focused on commercial, industrial and institutional uses of water are also suggested in order to enable projections of demand reduction through conservation scenarios. Longer time series of water use data could also support evaluation of rebound and post-shortage effects.

Additional studies taking into account impact of climate change in surface water supply and demand forecast based on demographics change over time would also contribute to quantifying supply vulnerability, allowing management authorities to seek solutions to prevent future shortages.

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Appendices

Appendix I: São Paulo Districts, City Boroughs and Macro Regions

Macro region	Regional administration	Districts
Center	Sé	Bela Vista Bom Retiro Cambuci Consolação Liberdade República Santa Cecília Sé
East	Aricanduva/Formosa/Carrão	Aricanduva Carrão Vila Formosa
	Cidade Tiradentes	Cidade Tiradentes
	Ermelino Matarazzo	Ermelino Matarazzo Ponte Rasa
	Guaianases	Guaianases Lajeado
	Itaim Paulista	Itaim Paulista Vila Curuçá
	Itaquera	Cidade Líder Itaquera José Bonifácio Parque do Carmo
	Mooca	Água Rasa Belém Brás Moóca Pari Tatuapé
	Penha	Artur Alvim Cangaíba Penha Vila Matilde
	São Mateus	Iguatemi

		São Mateus
		São Rafael
	São Miguel	Jardim Helena
		São Miguel
		Vila Jacuí
	Sapopemba	Sapopemba
	Vila Prudente	São Lucas
		Vila Prudente
North	Casa Verde/Cachoeirinha	Cachoeirinha
		Casa Verde
		Limão
	Freguesia/Brasilândia	Brasilândia
		Freguesia do Ó
	Jaçanã/Tremembé	Jaçanã
		Tremembé
	Perus	Anhanguera
		Perus
	Pirituba	Jaraguá
		Pirituba
		São Domingos
	Santana/Tucuruvi	Mandaqui
		Santana
		Tucuruvi
	Vila Maria/Vila Guilherme	Vila Guilherme
		Vila Maria
		Vila Medeiros
West	Butantã	Butantã
		Morumbi
		Raposo Tavares
		Rio Pequeno
		Vila Sônia
	Lapa	Barra Funda
		Jaguara
		Jaguaré
		Lapa
		Perdizes
		Vila Leopoldina
	Pinheiros	Alto de Pinheiros
		Itaim Bibi

		Jardim Paulista
		Pinheiros
South	Campo Limpo	Campo Limpo
		Capão Redondo
		Vila Andrade
	Capela do Socorro	Cidade Dutra
		Grajaú
		Socorro
	Cidade Ademar	Cidade Ademar
		Pedreira
	Ipiranga	Cursino
		Ipiranga
		Sacomã
	Jabaquara	Jabaquara
	M'Boi Mirim	Jardim Ângela
		Jardim São Luís
	Parelheiros	Marsilac
		Parelheiros
	Santo Amaro	Campo Belo
		Campo Grande
		Santo Amaro
	Vila Mariana	Moema
		Saúde
		Vila Mariana

Source: Infocidade, 2016

Appendix II: Reservoirs for São Paulo Water Supply

	Cantareira	Guarapiranga	Upper Tiete	Rio Claro
Basin	PCJ	Upper Tiete	Upper Tiete	Upper Tiete
Production capacity (m^3/s)	33	16	15	4
Reservoirs	5	1 + diversions	1	1
Treatment Plant	Guarau	ABV	Taiacupeba	Casa Grande

Source: São Paulo, 2010; Sabesp, 2017b

LIST OF ABREVIATIONS AND ACRONYMS

ANA	National Water Agency (Brazil)
ANN	Artificial Neural Network
BU	Business Unit (Sabesp)
CII	Commercial, Industrial and Institutional
eRAMS	environmental Resources Assessment and Management System
GIS	Geographic Information System
gpcd	gallons per capita per day
gphd	gallons per household per day
IAG-USP	Institute of Astronomy, Geophysics and Atmospheric Sciences from the University of São Paulo
IBGE	Brazilian Institute of Geography and Statistics
INMET	National Meteorological Institute (Brazil)
INPE	National Institute of Space Research (Brazil)
IPT	Technological Research Institute (Brazil)
IUWM	Integrated Urban Water Model
MG	Million gallons
MIS	Metropolitan Integrated System
MLR	Multiple linear regression
MRE	Mean relative error
MRSP	Metropolitan Region of São Paulo
NBR	Brazilian Standards
NLCD	National Land Cover Database (United States)
OC	Occupation coefficient
PCJ	Piracicaba, Capivari and Jundiai Rivers
PURA-USP	Program of Rational Water Use of the University of São Paulo
REUWS/REU	Residential End Uses of Water
Sabesp	Basic Sanitation Company of the State of São Paulo
SEADE	State System Foundation of Data Analysis

SNIS	National Information System of Sanitation (Brazil)
TPCL	Territorial, Building, Conservational and Cleaning registry
UN	United Nations