Assessment of Water Consumption Behavior in Single Households Using Smart Water Meters

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… ## Abstract

Smart water meters in households monitor hourly consumption patterns while mitigating the cost and inconvenience associated with traditional manual meters. This study comprehensively analyses 1871 households that previously used traditional manual water meters from the distribution point to the distribution area. All the households are equipped with smart water meters, and the collected data has been used for the analysis. According to the total estimated water consumption volume, 227 households were categorized as single households, further classified as single worker and nonworker households. The results indicate that single worker households peaked at 8:00, with 29 liters/h water consumption on weekdays. Consumption decreased during the day until late afternoon as households left for work. The consumption rate peaked again between 20:00 and 21:00 in the evening, averaging 32 liters/h. By contrast, in single nonworker households, the peak consumption was at 9:00 with 20 liters/h. No major changes in water consumption due to individual activities were observed throughout the afternoon. During evening times, the peak amount showed up between 19:00 and 20:00, with an average consumption of 19 liters/h. Moreover, worker single households peaked at 8:00 and 20:00 on weekdays, and at 9:00 and 19:00 on weekends. It was also revealed that worker households' weekend water consumption was 10% more than on weekdays and 262% more between 13:00 and 16:00 hours.

HIGHLIGHTS

1. Smart meters enable hourly water consumption monitoring and overcome traditional metering challenges.
2. Smart meter data allow understanding of daily water consumption behavior in single households.
3. Evaluate temporal variations in water consumption in single worker and nonworker households.
4. Comparison of water consumption in worker and nonworker households during weekdays and weekends.

1. INTRODUCTION

Water consumption has gained importance in urban areas in recent years due to efforts to conserve water resources (Farah and Shahrour 2017). Water meters are used to measure water consumption efficiently; however, manual meters require users to periodically travel and manually record water used, which can be costly and inconvenient (Depuru et al. 2011). This method contrasts with periodic metering, where daily water consumption is approximated for calculating consumption rates or planning purposes. Automated technology for monitoring and reviewing water consumption offers advantages to both water authorities and consumers (Stewart et al. 2010), as well as enables the implementation of various pricing strategies, such as time-based tariffs or seasonal pricing models (Cole et al. 2012; Parker and Wilby 2013). The widespread adoption of smart meters represents a notable research opportunity and management tool. These meters serve as visual cues for household water consumption, empower homeowners to take control of their water consumption, and facilitate implementing a wider array of pricing mechanisms, including seasonal tariffs (Clarke et al. 2009; Thumim et al. 2007). Extensive research has been undertaken to gain a deeper understanding of residential water consumption (Beal and Stewart 2011; Roberts 2005; Sivakumaran and Aramaki 2010). Research findings reveal significant variations in water consumption among households. It is imperative to consider this diversity in household water consumption to make precise water demand predictions and conduct effective assessments of supply and demand equilibrium across various geographical scales, particularly at the levels of single households and neighborhoods. According to (Deoreo and Mayer 2012), household water consumption has steadily increased over the past decade (Chen et al. 2012) examined trends, patterns, and statistical metrics related to water consumption and identified potential influencing factors, including housing types.

This research has laid the groundwork for the progress of smart water meter technology, allowing for the instant transmission of recorded data via real-time communication (Anandhavalli et al. 2018; Slaný et al. 2020). Furthermore, introducing smart water meters (Boyle et al. 2013; Cole et al. 2012) has empowered households to monitor their water consumption. These meters allow for the automatic capture, collection, and communication of real-time water consumption readings. Smart water meters, by offering high-resolution and frequent data on water consumption, can streamline billing processes by accurately measuring the volume of water used during a specific period of time (Stewart et al. 2018). Additionally, with IoTs rapidly advancing, numerous smart demand meters now monitor water consumption and other relevant parameters (Creaco et al. 2019). Smart water meters monitor water flow, distribution, and consumption, provide real-time access to water consumption data and billing, improve water efficiency, and detect leaks and fraud (Giurco et al. 2010). A comprehensive analysis identified 75 benefits associated with smart water meters, 57 of which benefit the water utilities, 40 benefit customers, and 22 are cross-benefits (Monks et al. 2019).

Indeed, most smart water meters are deployed in regions like North America, Europe, the Middle East, and Asia (Msamadya et al. 2022; JWRC 2016). Smart water meters are a vital strategy for water utilities to gain a comprehensive understanding of urban water consumption; they record water consumption data every 30 minutes (Homma and Iizuka 2018; March et al. 2017) track and analyze the behavioral household water consumption patterns during water events, revealing that households respond more strongly to the threat of water restrictions (Booysen et al. 2019).

Several factors are linked to domestic water consumption, as studies conducted over the past decade indicate. Previous research has established that the number of residents in a household influences water consumption (Zhang and Brown 2005; Domene and Saurí 2006; Harlan et al. 2009; House-Peters and Chang 2011; Ouyang et al. 2014). Among the studies examining water consumption, some have specifically considered the calendar factor (Antunes et al. 2018; Benítez et al. 2019; Maruyama and Yamamoto 2019; Niknam et al. 2022; Liu et al. 2023).

This study analyzes variations in water consumption across households, consumers, and time periods using smart water meters and influences water consumption patterns. In addition, it provides useful information for water utilities, and they can be more understandable in residential water consumption patterns.

This research focuses on the impact of water consumption within single households, with a particular focus on how smart water meters are integrated into the daily lives of households, how residents interact with these meters, and their impact on water consumption services at a broader scale. It offers empirical evidence that contributes significantly to the current policy discussions on digital water innovations. It also contributes to digital water consumption by supplying smart water meters to water distribution plants. The primary objective of this study is to assess water consumption based on smart water meter data to understand household water consumption behaviors.

2. METHODOLOGY

2.1 Study area

This study focused on the Chibata district in the northern part of Kosai City in Shizuka Prefecture, Japan. According to the report by the Japan Meteorological Agency, Kosai City's climate at the beginning of autumn in September has temperatures ranging from 22.9 to 29.8°C, averaging 25.9°C, signifying a moderately hot climate. While August is the warmest month with an average temperature of 32.3°C, January is the coolest month with an average temperature of 5.6°C. According to the 2019 census, Chibata district had a 5200-population spread across approximately 1900 households. However, the population declined by 4% between 2010 and 2019, decreasing the demand for water consumption. The Chibata water distribution plant boasts a capacity of 2000 m^3/day.

The water supply in this area was obtained by the amount of water used in each household every two months. After installing smart water meters, the water supply could be recorded hourly, providing data throughout the 24-hour period. Smart water meters were designed to collect and transmit data wirelessly, enabling efficient automatic monitoring in this area. The implementation of smart water meters in all households within the water distribution area of the Chibata district marks a pioneering initiative aimed at automating meter readings and proposing an efficient monitoring system for water consumption.

2.2 Data collection

The Chibata district water distribution plant provided 1871 households with data from smart water meters for this study, encompassing daily and hourly water readings for its service area. The data covered a monthly period from September 1 to 30, 2022. Furthermore, additional details, such as the ID numbers associated with each household, were shared, facilitating the analysis of smart water meter data and hourly water consumption volume; however, information on the number of occupant types per household is unavailable.

2.3 Data analysis

By analyzing the water consumption of households during particular periods of time, we can acquire insights into variations in water consumption among different households. These data are important for comprehending diverse water consumption patterns and behaviors exhibited by types of households. To evaluate water consumption, the techniques of one-way ANOVA, Tukey’s post-hoc test, and t-test analysis are used (Keselman et al. 1998; Beal et al. 2013). The probability (p) is compared by the following metrics: $p < 0.05$, $p < 0.01$, and $p < 0.001$. These ratings indicate whether consumption data are robust or highly significant.

3. RESULTS AND DISCUSSION

3.1. Temporal trend in water consumption among all households

Smart water meter data were chosen for three weeks (Monday through Sunday) in September 2022, which are the first week from the 5th to 11th, the second week from the 12th to 18th, and the third week from the 19th to 25th. Weekly water consumption as shown in Fig. 1 that Mondays has the highest consumption over three weeks at 1596 m^3/day. In contrast, Thursdays have the lowest consumption with 1436 m^3/day. A one-way ANOVA with Tukey's post-hos test was run over three weeks. The statistical test confirmed no significant difference in daily water consumption over three weeks ($F = 1.88$, $p = 0.53 > 0.05$).

Water consumption levels typically vary among households on weekdays, as seen in Fig. 2. Water consumption was monitored on Tuesdays, exhibiting a fluctuating pattern, often associated with users’ daily routines. The highest peak in water consumption was within an average of 36 liters/h from 7:00 to 9:00 in the morning hours. Typically, water consumption for 3 hours increases in the morning due to individual activities, as people often begin their day with general hydration by preparing breakfast, a common part of their daily routine. Water consumption decreases during the day until the late afternoon at 17:00, averaging 16 liters/h; consumption then starts to increase again due to individuals’ activities in the evening around 19:00–22:00 averaging 46 liters/h. The difference in the consumed water between the evening and morning hours was approximately 10 liters/h. The average daily water consumed over 24 hours was 587 liters/day. The highest peak of water consumption in the evening instead of the morning peaks is because daily activities, such as showering, cooking, and other routines, typically occur during evening hours. Additionally, the time spent consuming water in the morning is typically much shorter than in the evening hours. In the morning, households are usually busy getting ready for the day, which limits the available time for consumption. Additionally, many households engage in similar activities during this time, leading to almost concurrent water consumption. In contrast, various activities compete for water consumption during the evening, leading to longer and more staggered individual activities that consume water.

3.2. Categorization of single households by smart water meters data

According to the Tokyo Metropolitan Waterworks Bureau, a single person's daily water consumption in Japan in 2002 was 245 liters/day (TMWB 2001). Based on a report of Statista 2019 (Klein 2022), water consumption per person, including potable and nonpotable water, was 286 liters/day. A two-member household's average daily water consumption was calculated using 286 liters/day and doubled to 572 liters/day. To distinguish between single and two-member households, a threshold of 429 liters was used, calculated by averaging their respective average water consumption values. A ± 143 liters margin was applied to the average consumption to create an equitable range of water consumption. Consequently, for a single person, the minimum limit was 143 liters, the maximum was 429 liters, and for a household with two members, the minimum was 429 liters, and the maximum was 715 liters. Therefore, the selection method consisted of a few two-member households, from 143 to 429 liters/day, but most were single households. Water consumption was selected to differentiate between single households and total household data during the three weeks of September 2022. The smart water meter data were classified into five groups based on household water consumption: 0–143, 143–429, 429–715, 715–100l, and over 1001 liters/day, as seen in Fig. 3. This research exclusively concentrates on single households with a range of 143–429 liters/day. This categorization helped determine the number of households that selected the daily users based on their water consumption over three weeks.

The total average water consumption over the three weeks exhibited significant variation, as shown in Fig. 4. The lowest average consumption, totaling 1523 m^3/day with 1% of total water consumption, was observed among users in the 0–143 liters/day range, while the highest consumption reached 53392 m^3/day with 35%, and this was recorded for users consuming more than 1001 liters/day. By contrast, total water consumption in single households was 17728 m^3/day, 11% of total water consumption. These findings emphasized the substantial differences in water consumption patterns among users during the three weeks. However, when comparing the three weeks range of 143–429 liters/day water consumption, it was observed that some household IDs did not include all three weeks. To analyze the water consumption behavior of single households as shown in Fig. 5, the total number of single households and those that did not meet the target criteria during the observed weeks were depicted. In the dataset, three sections represent different weeks, each comprising a varying number of households. Across all three weeks, 317 households consistently participated. In the first section, consisting of 424 households, additional patterns emerged. In the second part, representing 409 households, 32 households were present in the first and second weeks but not in the third week. 25 households were absent during the first and third weeks and in the third part, which included all 425 households for the third week. Thirty-six households followed a similar pattern to those in the third week, and 37 households were present in the first and third weeks but not during the second week. Additionally, 36 households were present only in the third week. These patterns illustrate the varying levels of household participation across the three weeks of data collection. Therefore, 317 single households were selected from three weeks, all of which consistently consumed water within the range of 143–429 liters/day. We next narrowed down our selection to single households that exhibited this pattern over a maximum of three days from 5 days of the weekdays (Monday–Friday). Hence, by analyzing the single households during the weekdays (Mondays – Fridays) relative to all households, it was found that 227 households fell within the range of single households during the target weekdays.

To better understand the behaviors of single households' water consumption, consumption patterns during weekdays (Monday – Friday) and weekends (Saturday – Sunday) were examined. The variation in water consumption behaviors between weekdays and weekends are essential in water consumption behavior analysis. Tuesday was selected as representative of weekdays because average daily water consumption closely approximates the weekday average (Mondays – Fridays). Fewer people work on Saturdays because some companies are open on Saturdays in Japan; thus, Sundays were chosen to represent weekends. Hence, daily water consumption for each household was assessed over an extended timeframe, including four Tuesdays (the 6th, 13th, 20th, and 27th of weekdays) and four Sundays (the 4th, 11th, 18th, and 25th of weekends) in September 2022.

3.3 Analyzing water consumption and behavior differences between single households: Worker vs. nonworker

The variations in water consumption among 227 single households during weekdays are shown in Fig. 6. The highest peak occurred in the morning, around 8:00 to 9:00, with an average of 25 liters/h throughout the 2 hours. Thus, the consumption rate gradually declined until the late afternoon at 17:00, the rate was 9 liters/h. It then rises again until 22:00, peaking at 20 liters/h and the total daily average consumption for 24-hour periods was 295 liters/day during Tuesdays. Water consumption of single households was also examined. Identifying and focusing on households with stable and predictable consumption patterns made it possible to analyze and make decisions based on water consumption patterns and household types (single worker and nonworker households). Moreover, this categorization was done separately for weekdays and weekends to account for potential variations in water consumption patterns, and these categories were established by identifying patterns and characteristics that differentiate them. Indeed, during the week, single worker households typically consume water during specific hours, such as early morning and evenings when they are getting ready for work or returning home. Single nonworker households on weekdays consume water based on leisure time during the day. Hence, by investigating over 24 hours and applying for separation of single households, particularly on weekdays as outlined which afternoon hours were from 13:00 to 16:00 hours. During these hours, consumption is significantly lower, constituting less than 10% of the total daily water consumption on single worker households. The results of this categorization revealed that of 227 single households in the Chibata district, comparisons were conducted by monitoring on Tuesdays with the number of workers in the households ranging from 141 to 153. It was also observed that nonworker households consumed 10% more water in the afternoon than worker households. Single nonworker households included retirees, stay-at-home parents, and individuals not engaged in the workforce. These households' water consumption routines and daily schedules exhibited considerable diversity, influenced by their unique situations and circumstances. The water consumption pattern is observed in single worker and nonworker household types during weekdays, as shown in Fig. 7. These patterns exhibit notable variations throughout the day, reflecting the influence of workers' daily routines. Water consumption starts peaking at 7:00 a.m. with a consumption rate of 13 liters/h, and the highest peak during the morning is at 8:00 reaching 29 liters/day. In addition, initiates a discernible peak period at 7:00 to 10:00 in the morning, coinciding with the morning routine during these 4 hours, the average daily water consumption reaches 20 liters/h. These peaks could be attributed to activities such as breakfast preparation, and other personal tasks that typically occur before heading to work. As the workday progresses in single worker households, there is a significant decrease in water consumption, declining to the early afternoon at 13:00 averaging 2 liters/h. In contrast, a notable increase in water consumption appears again during the evening and night hours. These peaks begin at 19:00 and continue until 23:00, which are the evening and nightly peaks in consumption, with an average consumption of 26 liters/h. Notably, the highest peaks occur during the evening hours at 20:00–21:00, averaging 32 liters/day, primarily due to the resumption of household activities after work. These activities may include evening showers, dinner preparation, dishwashing, and other personal activities and domestic tasks. However, water consumption patterns of nonworker households exhibit a slightly delayed increase in consumption, commencing at 8:00 in the morning with a water consumption rate of 18 liters/h and the highest peak of morning times at 9:00 with 20 liters/day. Throughout the morning and into the early afternoon, water consumption in nonworker households remains relatively consistent due to the occupants being actively present at home during these hours, engaging in activities such as preparing lunch, using the toilet, and personal tasks. Nonworker households tend to spend more time at home during weekdays since they do not have professional commitments that require them to leave, contributing to increased water consumption during these daytime hours. The highest peaks during the evening times at 19:00 to 20:00 with an average rate of 19 liters/h. Interestingly, water consumption decreases during the evening time, from 21:00, with 13 liters/h. Conversely, their earlier bedtime habits contribute to reduced water consumption during the late evening hours. A t-test was run during the weekdays of worker and nonworker households. The statistical test confirmed that the afternoon from 13:00 to 16:00 ($t = 2.35$, $p = 0.002 < 0.01$) and the evening from 20:00 to 23:00 ($t = 1.71$, $p = 0.012 < 0.05$) were highly significant.

The water consumption patterns for single worker households on weekends and weekdays are shown in Fig. 8. On weekends, when residents dedicate more hours to being at home, water consumption increases by an average of 327 liters/day. Conversely, worker households with working individuals experience a lowering in daily water consumption during weekdays, averaging 296 liters/day. The factor behind this decline is the limited time spent outside of the home during working hours. The water consumption peak starts early around 7:00, with a consumption of 13 liters/h, and the highest peak occurs around 8:00 on weekdays. In contrast, during weekends, this peak is postponed until 9:00, whereas consumption remains relatively low throughout the afternoon times between 13:00 to 16:00 on both weekdays and weekends with an average of 2 liters/day and 9 liters/day respectively. However, water consumption on weekends during the evening hours as opposed to the morning hours starts early, around 18:00, with the highest peaks at 19:00 with 28 liters/h. On weekdays, peak consumption occurred at 20:00, averaging 33 liters/h. These variations highlight the significant differences in water consumption between weekdays and weekends, mainly due to daily routines, with peaks during the morning and evening times. A t-test between worker households on weekdays and weekends confirmed that the consumption were different between 13:00 and 16:00 hours ($t = 2.35$, $p = 0.00048 < 0.001$). Whereas insignificant differences were observed during the 24-hour period ($t = 1.71$, $p = 0.35 > 0.05$). Water consumption during the weekdays and weekends in nonworker households as seen in Fig. 9, on weekends consumption begins around 6:00 with an average of 7 liters/h. But, during the weekdays, it starts around 7:00 reaching 8 liters/h. Moreover, nonworker households constantly throughout the day consumed water during both weekdays and weekends with an average total daily water consumption of 294 liters/day and 291 liters/day respectively. A t-test was carried out to compare nonworker households during the weekdays and weekends confirming that differences were observed only from 13:00 to 16:00 hours ($t = 2.35$, $p = 0.02 < 0.05$). The total daily water consumption from observed results on weekends, divided by the weekdays households, is 110% as shown in Fig. 10. However, this percentage increased from 13:00 to 16:00 for both worker and nonworker households by around 361%. This percentage is lower than nonworker households, reaching 98% of daily water consumption and 59% during 13:00–16:00 hours. It was noted from the single worker households that the daily consumption on weekends increased by 31 liters/day compared to weekdays, while single nonworker households' water consumption experienced a decrease of 4 liters/day. The decrease in water consumption by nonworker households could be attributed to weekday consumption when household members tend to stay at home and consume water but during the target range; in contrast, on weekends, they may be outside the home or at work. Throughout the target period hours, worker households' water consumption increased by 27 liters from 13:00 to 16:00 hours, and nonworker water consumption decreased by 28 liters. This difference is because workers stayed at home during afternoon hours on the weekends. Even so, nonworkers decreased their water consumption due to individual activities. A t-test was done to check the difference in the percentage of consumption in workers' and nonworkers' households. The statistical test confirmed that the percentage during weekdays and weekends were the same ($t = 0.35$; $p = 0.35 > 0.05$), ($t = 0.1.71$; $p = 0.0.85 > 0.05$). However, from 13:00 to 16:00 hours, the percentages were found to be different ($t = 2.35$; $p = 0.0004 < 0.001$), ($t = 2.35$; $p = 0.023 < 0.05$). Hence, the research described in this manuscript provides valuable data and insights using smart water meters. These devices can provide accurate, real-time information about water consumption, contributing to our understanding of how households in similar regions use water. The data collected from smart water meters reveal consumption patterns that are vital for making informed decisions regarding water management and water resource management. Utilities and water providers can use this data to optimize operations and improve identification. For residents, the ability to monitor their own water consumption can lead to more conscious consumption and cost savings. In summary, the data collected through smart water meters have the potential to transform how water resources are managed, leading to more efficient and sustainable water consumption, and benefiting multiple stakeholders.

4. CONCLUSIONS

This paper presents an advanced methodology that uses data from smart water meters to calculate water consumption rates, enabling the identification of the number and types of households. The results revealed that on weekdays in single worker households, consumption peaks occurred in the morning hours at 8:00 with an average rate of 29 liters/h. In contrast, single nonworker households showed the peak 1 hour later at 9:00 with 20 liters/h. Consumption in worker households decreased until late afternoon due to residents being absent from the home for work. During this same period, nonworker households continued to consume water consistently. The peaks of worker households resumed in the evening with the peak around 20:00–21:00 at an average consumption of 32 liters/h. In contrast, single nonworker households had their peaks at 19:00–20:00 averaging 19 liters/h. However, compared to worker households daily, water consumption peaked at 8:00 and 20:00 on weekdays, while on weekends, water consumption peaked at 9:00 and 19:00. Moreover, compared to worker and nonworker households used water throughout the day, indicating that the change in water consumption was gradual. It was also found that worker households' water consumption on weekends increased by 10% compared to weekdays and 262% from 13:00 to 16:00 hours. These disparities indicate how household composition can influence water consumption patterns on different days of the week by smart water meters.

Declarations

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Ethical Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Authors’ Contributions

Conceptualization: T Inoue, K Yokota; Methodology: T Inoue, NM Ngoc, K Yokota; Formal analysis and investigation: S Obaid, K Hosoi; Writing - original draft preparation: S Obaid, K Hosoi; Writing - review and editing: T Inoue, NM Ngoc, S Obaid; Funding acquisition: T Inoue; Resources: T Inoue; Supervision: T Inoue.

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Competing Interests

There is no any competing interests between authors.

Availability of data and materials

All of data and materials are available in the manuscript.

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Figures

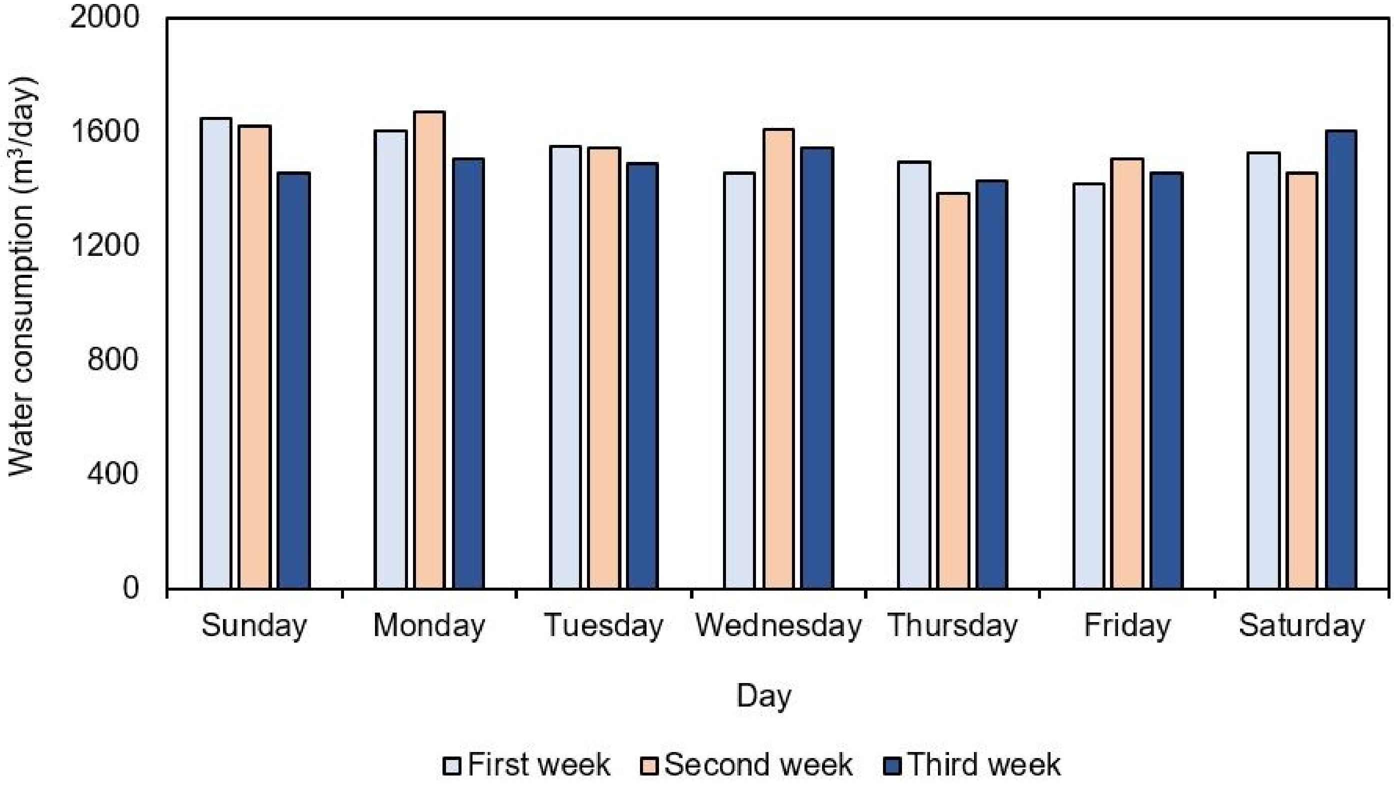

Figure 1

Total Weekly water consumption for the weeks of September 2022 in the Chibata district

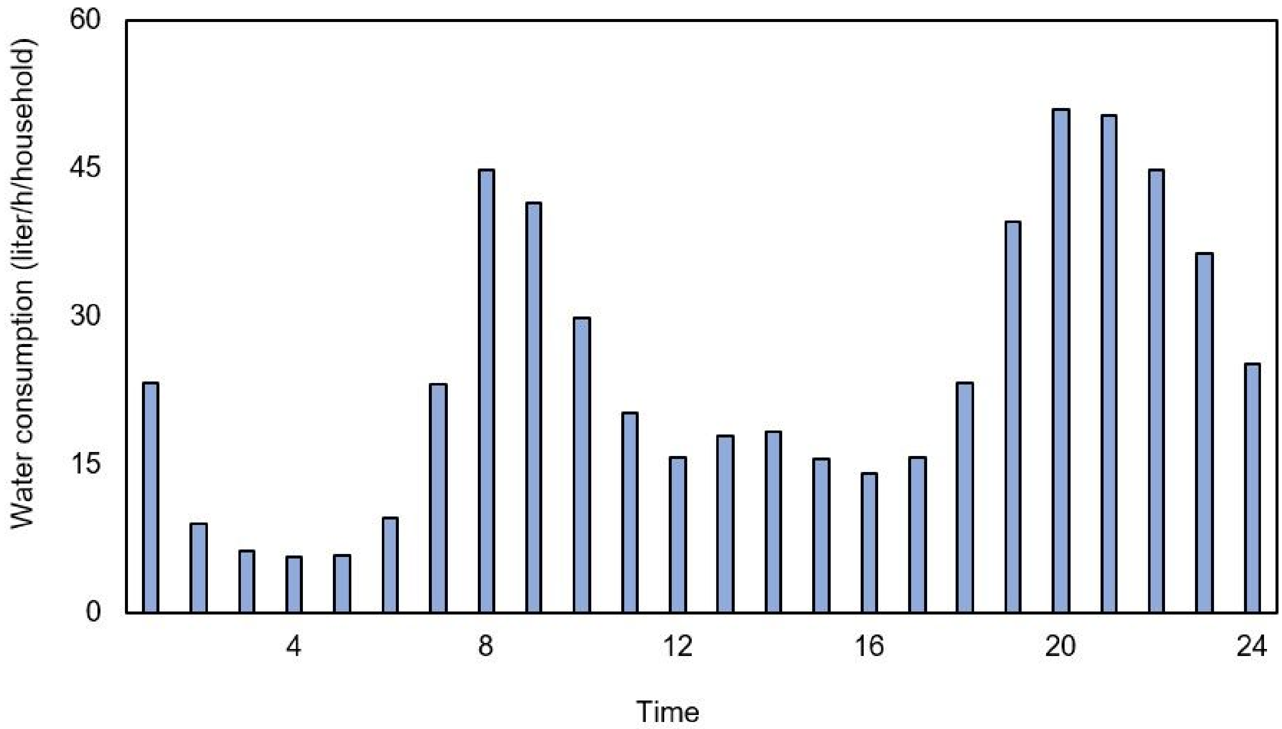

Figure 2

Water consumption in a total of 1871 households in the Chibata district on Weekdays

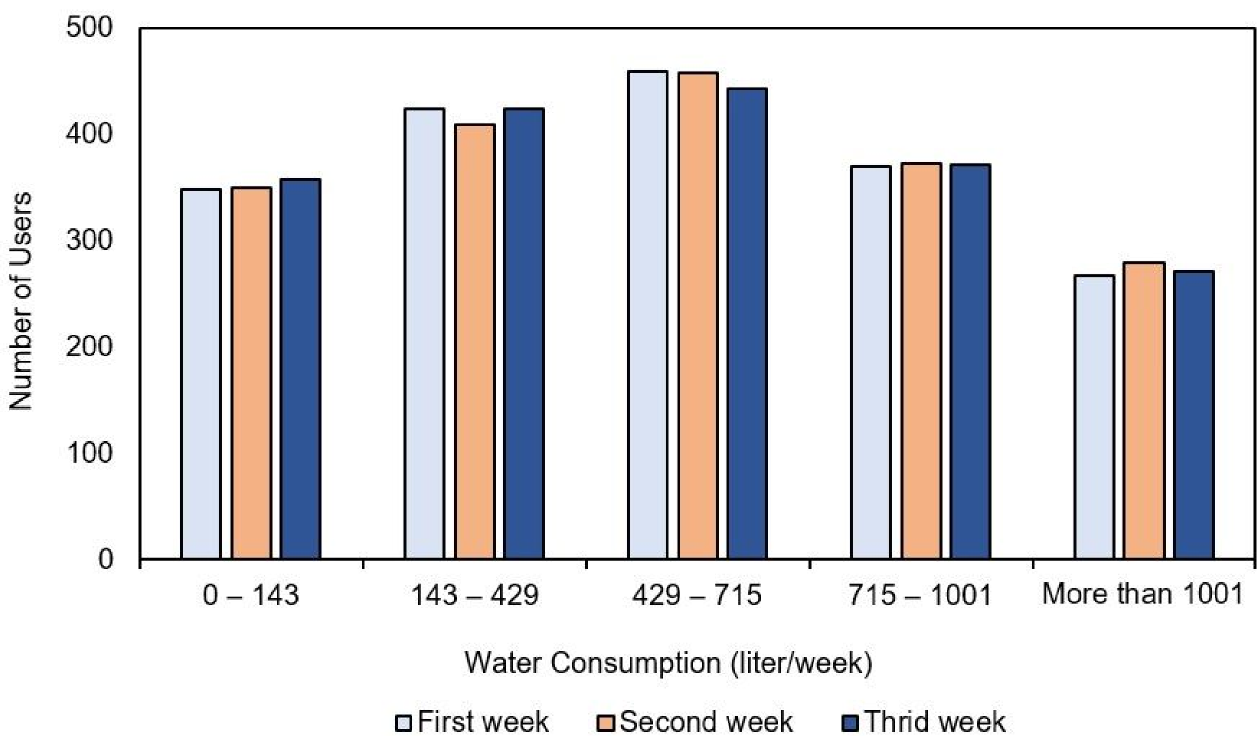

Figure 3

Numbers of users’ water consumption during the weeks

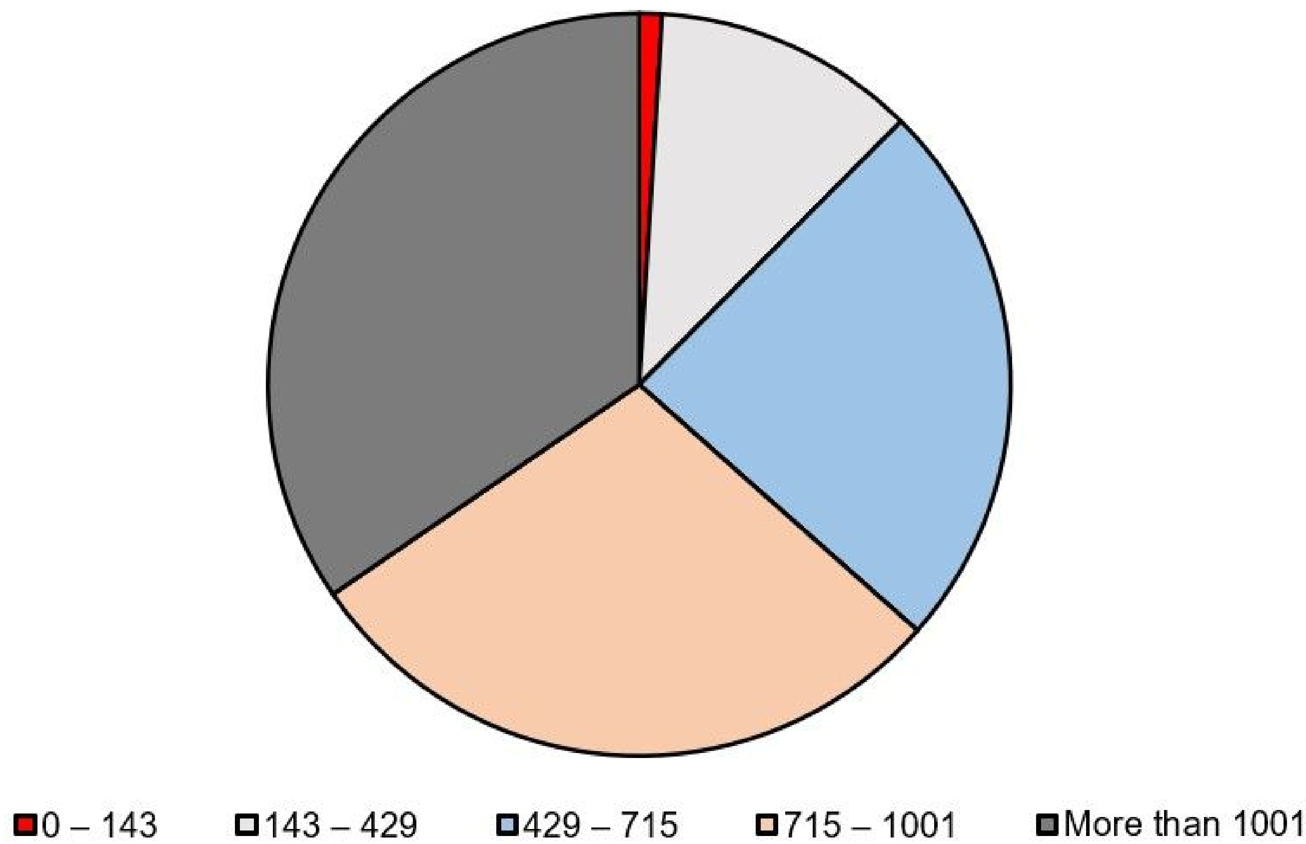

Figure 4

Total water consumption by users during the three weeks

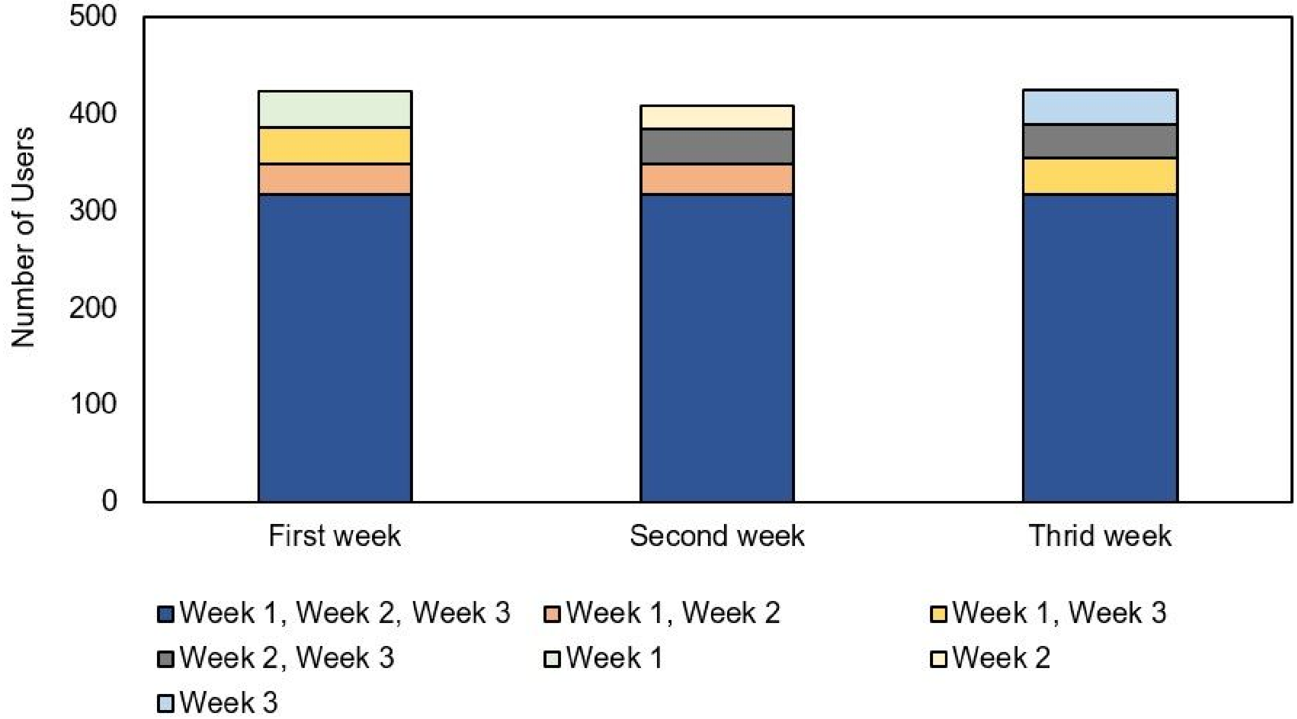

Figure 5

Number of users' water consumption between 143 and 429 liters/day

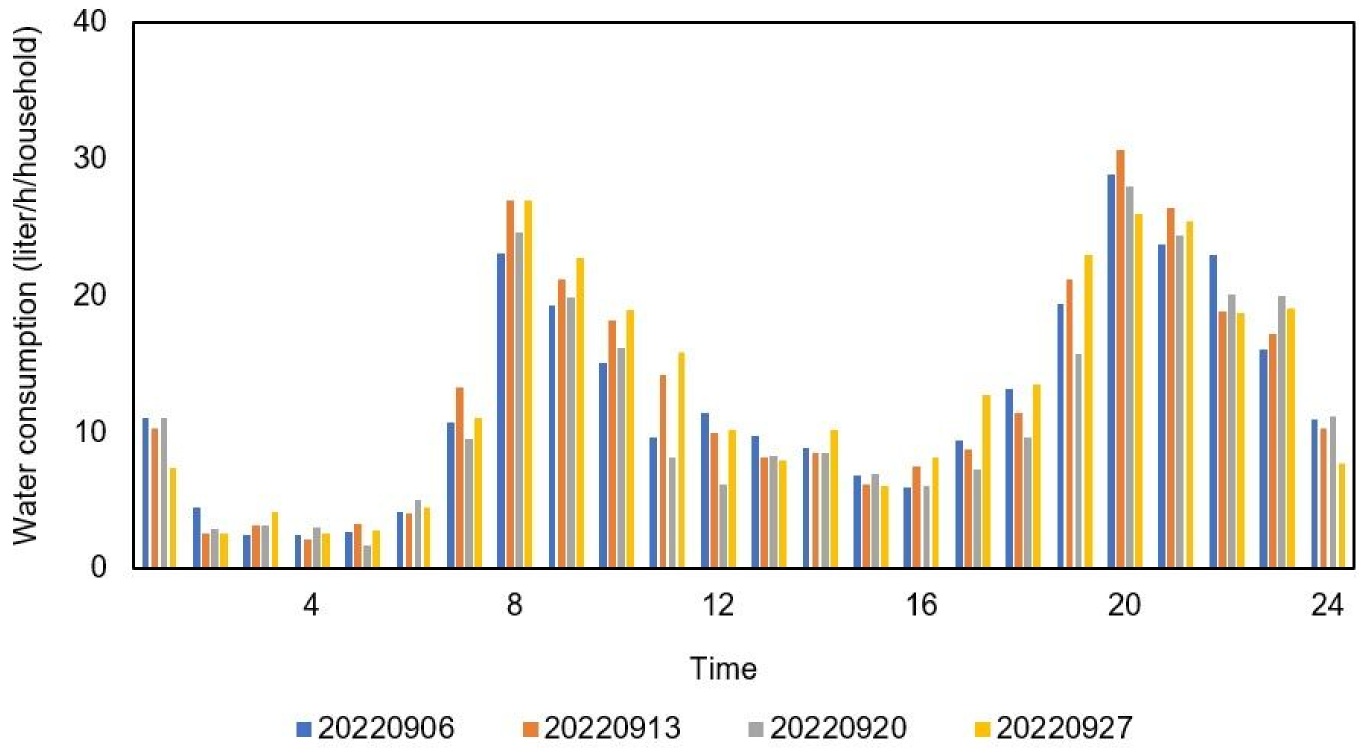

Figure 6

Water consumption among 227 single households on weekdays

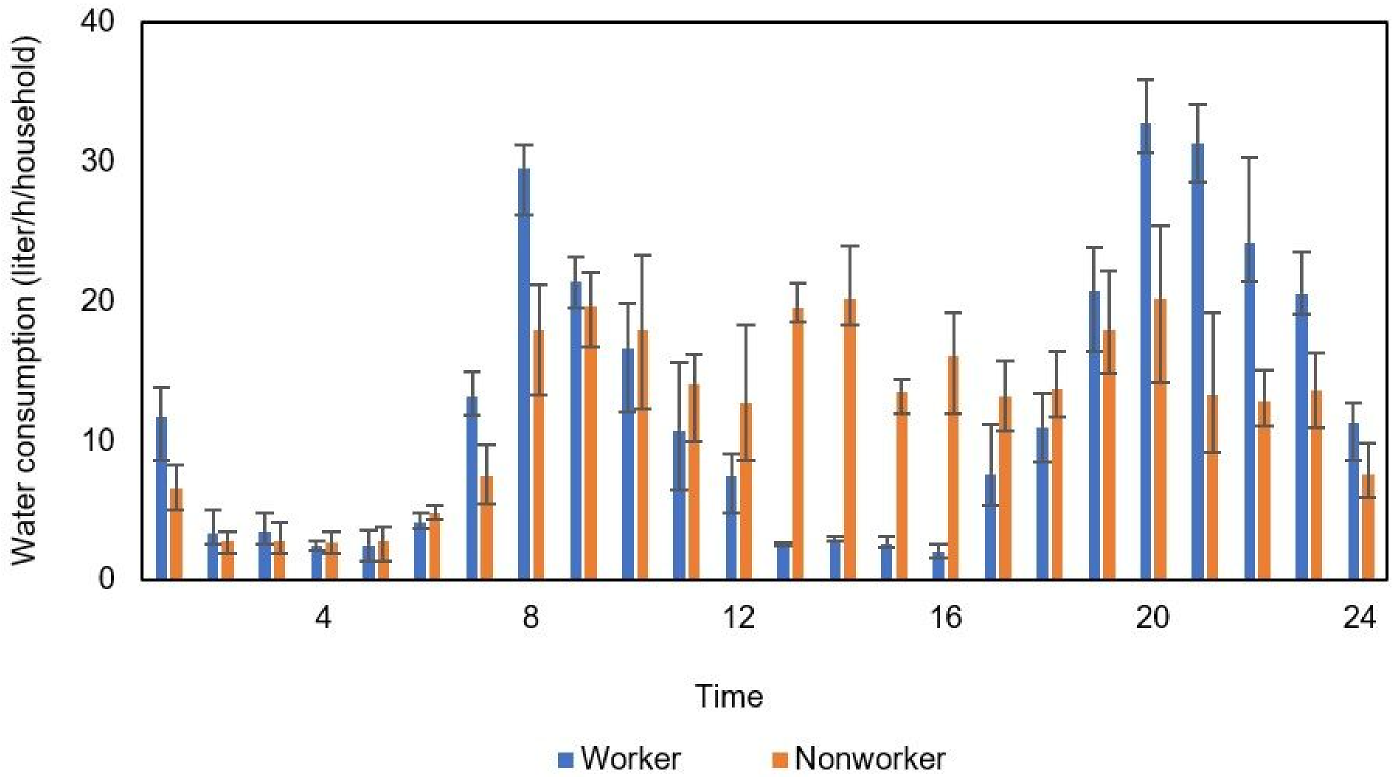

Figure 7

Comparing water consumption among single worker and nonworker households on weekdays

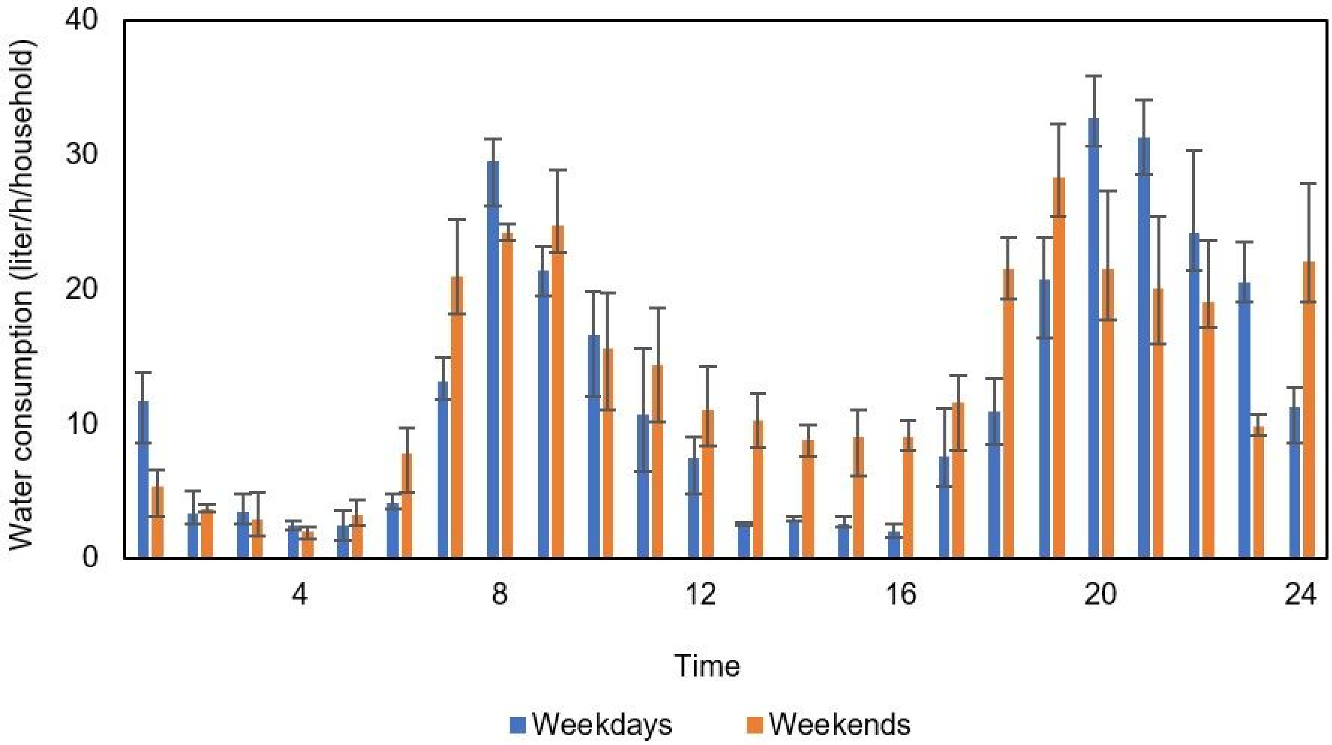

Figure 8

Comparing water consumption in single worker households on weekdays and weekends

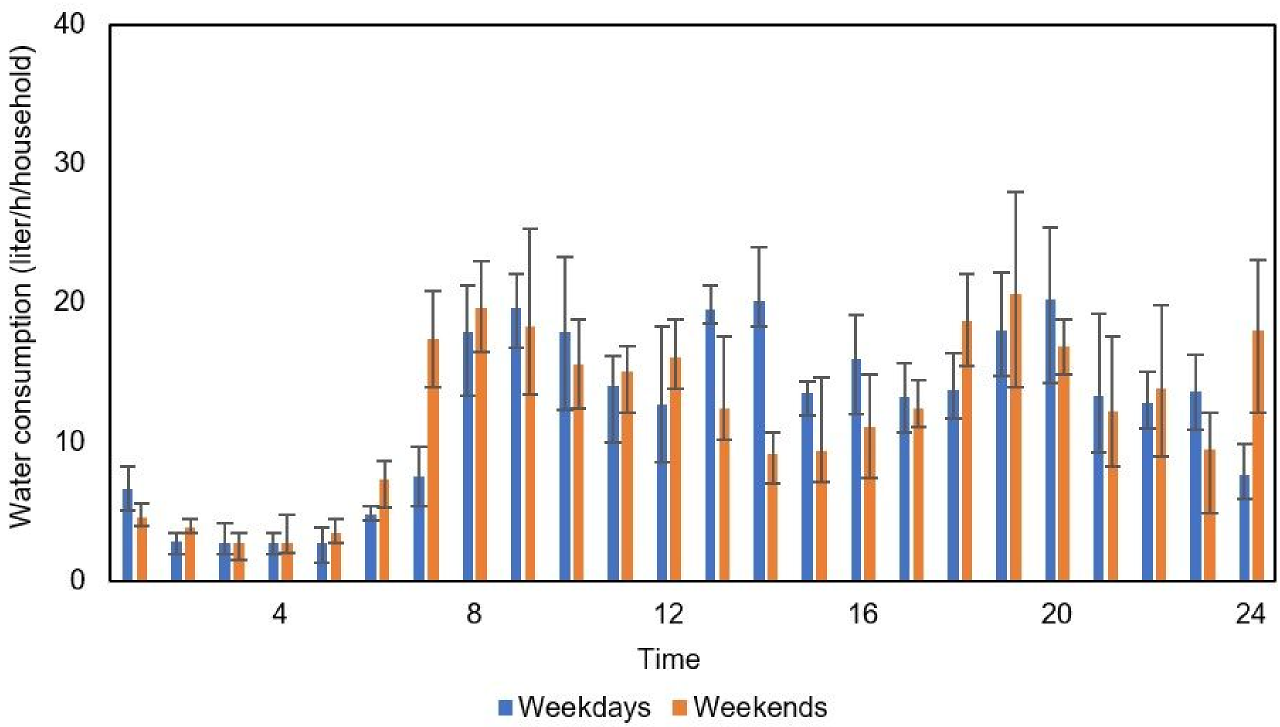

Figure 9

Comparing water consumption in single nonworker households on weekdays and weekends

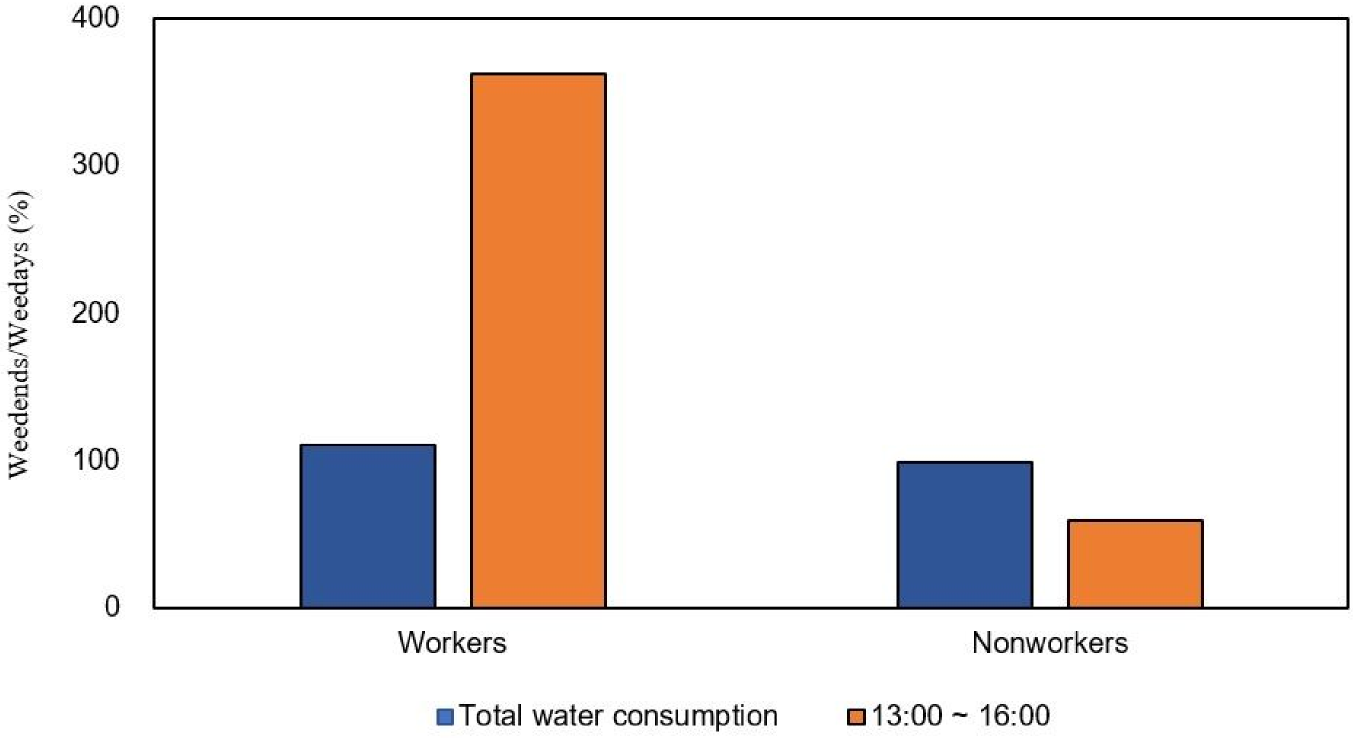

Figure 10

Percentage of water consumption during the weekends /weekdays