2nd International Joint Conference on Water Distribution
Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14886

WATER CONSUMPTION ANALYSIS DURING NIGHT HOURS OF RESIDENTIAL CUSTOMERS

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Abstract

Managing and reducing water losses should be a primary concern to ensure the sustainability of a water utility. Among all the potential strategies, the design and construction of district meter areas (DMA) is probably one of the most widely used for water loss assessment and control. This is because partitioning a water network into smaller portions significantly facilitates the analysis procedures and improves the speed at which bursts and leaks are detected and located. This analysis is typically done by processing and evaluating the time series of the inflows into the DMA.

The Minimum Night Flow (MNF) represents the lowest flow into the DMA over a 24-h period. MNF typically occurs between 02:00 and 04:00 AM. During this period, most users do not intentionally use water and the inflows into the DMA are mainly composed of leakage at DMA pipes and private plumbing systems. Consequently, the analysis of the MNF allows for easy and accurate quantification of the magnitude of leakage in a particular DMA.

The main difficulty in applying this methodology appears when trying to disaggregate the night flows into its fundamental components: 1) Leakage in mains and connection pipes belonging to the distribution network 2) Leakage at customers' facilities, and 3) Intentional use of water by customers. The first two components correspond to continuous flows that, in most cases, remain constant during the night hours. The third component is inherently random and may vary in magnitude and duration.

In the proposed work, detailed data of one-year hourly readings from approximately 20,000 customers have been analyzed and disaggregated into leakage and intentional use. The aim is to improve the models that characterize the night consumption originated at the customers' facilities. Hence, the study's initial stage involves the development of algorithms that allow disaggregating the night consumption registered by the customers' water meters into a baseline consumption due to leakage and the component caused by the intentional use of water.

Probability function distributions of leakage flow rates at customers' plumbing systems have been obtained for various types of water users. Simplified probability distribution functions of intentional water use have also been developed to consider the duration of water consumption and the average flow of residential users. These probability functions allow the creation of synthetic consumption series that overlap with the baseline consumption caused by leakage inside the customers' premises.

The novelty of the proposed methodology is that the probability functions obtained have been derived from actual water consumption data of nearly 20,000 customers, monitored for one year. The night consumption model developed may enable the water utility to better estimate this parameter in those DMAs where the customers' water meters cannot be read hourly.

Keywords
Supply, Water, Probability, Leakage, Estimation.

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1 INTRODUCTION

Water scarcity has been growing around the world. Activities that influence these actions involve population growth, expanding industrial activities and urban areas, climate change, and water pollution. An estimated third of the population in the world has no access to clean water. One-fifth of the world's population lives in water scarcity areas where resources are insufficient to satisfy the demands. One-fourth of the population in the world lives having not filled their water demands because of the poor management supplies of authorities. (Narmilan et. al, 2020) [1].

According to the National Statistic Institute (INE) in Spain, "During 2018, approximated 4,236 cubic hectometres (hm3) of water were supplied to public urban supply networks. Approximately Three quarters (3,188 hm3) were volumes of registered water". The data shows that a quarter of the water supplied corresponds to unregistered volumes for which users do not pay. In a high proportion, these volumes correspond to leaked volumes in the distribution networks and the internal installations of the users.

Based on these concerns, the new Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020, concerning the quality of water intended for human consumption, member states will ensure that an assessment is made of the levels of water leakage in their territory and the potential for improvement in reducing water leakage. These actions are in line with the Sustainable Development Goals of the 2030 agenda. For this purpose, the Structural Leakage Index (SLE) classification method is usually used, joint with a vast knowledge of the network behavior and a set of management strategies and methodologies that allow operating in increasingly sustainable conditions over time.

As a strategy to fit the demands, water consumption patterns have always been present in supply management. These patterns can be well-defined or very sensitive depending on the population under study. In the past, obtaining these patterns was due to the incorporation of metering technology and the construction of metering district areas. This facilitated the definition of fairer tariffs for users and improved the operation of the supply. However, the installation of these devices is concentrated in population centers. At the same time, the ends of the network have fewer meter devices and those have daily interval resolution.

Usually, the relevant information for developing future planning is unavailable to take action at the correct time. For that reason, it is common to estimate them through methods that are fundamental for resilient network management. (Avni et. al, 2015) [2]. In districts with limited information, is often available general information and approximate. In many cases, the approximations are not very precise and outdated. This consequently reduces the operational management options and limits the capacity to adapt to the global consumption of the users. Knowing more specifically about the variation of the patterns offers a window of action in detecting leaks, analyzing atypical events, and the improvement of the potential efficiency of the network.

In managing leakage reduction, it is beneficial to study hourly consumption patterns at night. The analysis of the minimum nocturnal flow allows an easy and accurate quantification of the magnitude of leakage in a given sector. This is because, at that time, the flow transported was composed of two elements. Elements are mainly due to a continuous flow that can be leakage or storage elements and random but intentional water use.

Analyzing the consumption patterns during the hours of minimum night flow in sectors with actual measurements makes it possible to extrapolate these measurements to sectors without hourly readings. These readings can be used for consumption disaggregation. In this way, to establish in magnitude and frequency the range of the function of each element, the trend of the consumption data, and the influence they have on the overall consumption of the users.

2 DATA CHARACTERIZATION

This study analyses domestic consumption during night hours in a Mediterranean City. As expected, customers decrease their water-related activities at night, and most of them spend the time resting. This typical behavior of domestic customers facilitates the analysis. Considering this, the consumption during night hours can be classified into two types: 1) one originated by leaks and other continuous consumptions and 2) other intentional uses of water like, for example, flushing toilets, drinking a glass of water, washing hands, or taking baths and showers. Most of these intentional consumptions are produced at medium flow rates, close to 0.1 L/s or 0.2 L/s, and usually happens in randomly ways with changing magnitudes and durations.

Consolidated consumption patterns, those measured by the flow meters installed in the distribution network, show how people behave as a community. They can be considered a reflection of typical human activities during night hours and may identify how specific habits and events influence domestic water consumption. A Good example of this is how human behaviors change with respect to water consumption during weekends and holidays when it is common to appreciate higher flow and larger volumes delivered to customers at night time.

The Data provided by Global Omnium that have been used in this study are composed of daily and hourly volumetric measurements during one year (2019). After data cleansing, readings of more than 20 thousand customers across five network sectors are available for analysis. Costumers in these sectors are mainly domestic, although other commercial and industrial users are also present (Figure 1a). Figure 1b shows how customers are distributed per sector. However, due to the heterogeneity of non-domestic customers and the limited sizes of the available sample, the analysis presented has been restricted to domestic customers.

Water consumption measurements were taken from the water meters located at the customer's connections. Their normal size ranges from DN13 to DN100, although domestic meters DN13 and DN15 represented more than 99% of the meters. All these meters were less than five years old and had communications capabilities allowing water consumption data at one-hour intervals. A more detailed database with installation details such as users' location, demand type, users' code, and observations is available for further analysis.

The water utility provides hourly consumption data for one complete year from all meters installed in these sectors. Initially, the dataset was composed of 499 CVS files. These files were reorganized by a module of algorithms written in VBA language to build a single simplified database in Microsoft Access. However, due to MS Access size limitations, the simplified database only includes night consumption during night hours and the total daily water usage. In the next step. The data were checked and filtered to verify hourly reading availability and calculate the daily water consumption of each customer. This calculation was restricted to users having DN13 and DN15 meters. Finally, only users with more than 300 days of full records between 1:00 and 7:00 AM were considered for the analysis.

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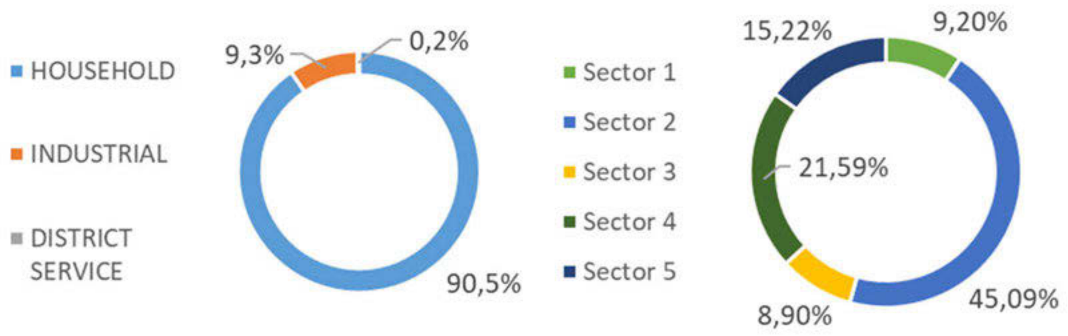

Figure 1. a) Customers distribution by users type b) Customers distribution by sectors.

At the end of this process, the database changes from 37,384 customers and 12,724,924 records to 19,145 customers and 6,883,340 records. This selection was a set point to start building up the methodology by disaggregating consumption at night.

3 ANALYSIS METHODOLOGY

The Night Flow is the lowest flow of the entire daily record. In many cases, this flow is steady, and usually, it is not modified by high consumption records. Sanitary devices' standard flows are indeed associated with those flows. For example, Figure 2 shows a night consumption that can notice a high flow during 2:00 AM and 7:00 AM. The rest of the time establishes a steady baseline of flow. Those high flows are similar to the waste of half-flush toilets.

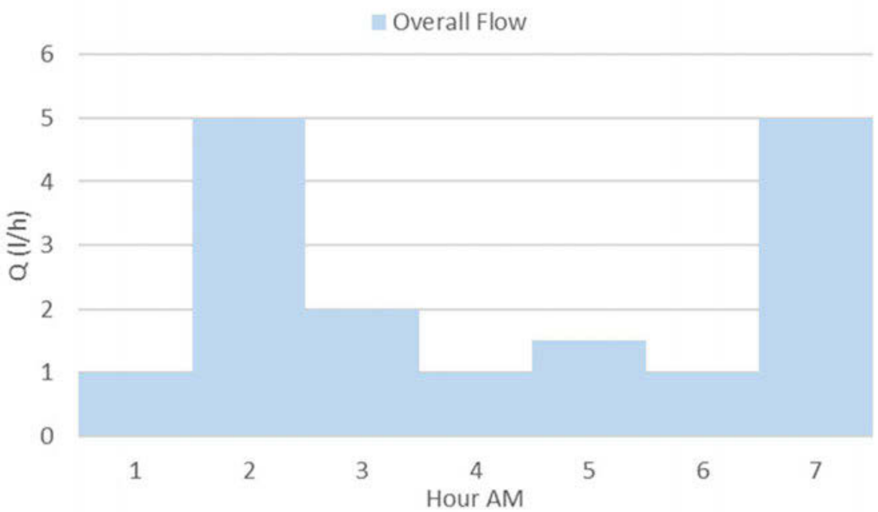

Figure 2. Example of consumption elements.

With the idea of applying a methodology to the entire database, the disaggregating of the consumption starts with evaluating the hourly measurements to identify which record is from intentional use or leakage. Therefore, it is necessary to reflect the steady behavior of leakage on statistic parameters to compare. The Median represents an excellent factor for establishing a range of evaluations. Because the high records have a low influence on the Median value, for that reason, the factor adopts the tendency of the data. The assessment compares the hourly Reading with the 10% increase in Median and, as the second conditional, The Median plus three units. These conditionals offer a range to express a minimum and maximum about the steady flow.

This first step identifies the flow caused by leakage between hours, but separating the leakage part on intentional use flow is the proper procedure to complete the disaggregating. For the second step, the PROFUGA factor was created. This factor is calculated only by the Mean of the hourly leakage consumption separated before, defining the magnitude in the daily record. The value of this parameter is removed from the intentional flow, so it notices the different flow types in every measurement. Figure 3 shows the final results applicated in the example before. This methodology can summarize the total volume of continuous/leakage flow and intentional flow over time.

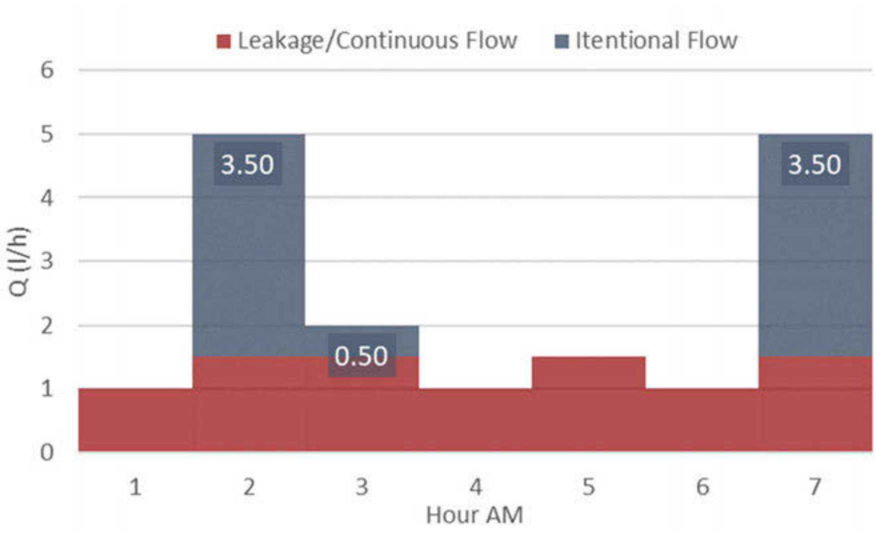

Figure 3. Example of disaggregated consumption.

Last of all, these procedures were applicated in the database by a module of algorithms written in VBA language. As a result, it is easy to see and manage the daily record decompose every hour, and make calculations as an independent data selection. This level of information gives a window of different scenarios and perspectives to manage the measurements. At this point, this work will focus on the analysis as follow in the next chapter.

4 DISCUSSION OF RESULTS

The new database comprises three information blocks: Overall consumption, leakage/continuous flow, and intentional flow. Therefore, each part must be analyzed, starting with Overall consumption. In this study, it is essential to know the tendency of the measurements, how it distributes and if there is atypical behavior.

4.1 Overall Consumption

Figures 4a and 4b show the consumption produced from 1:00 to 2:00 AM and 4:00 to 5:00 AM, respectively. A comparison between these two hours of consumption can show the contrast of values when there are the beginning of nighttime and the moment of minimum consumption. The Y-axis is the volume percentage occupied by each flow rate register compared with the total volume during 2019.

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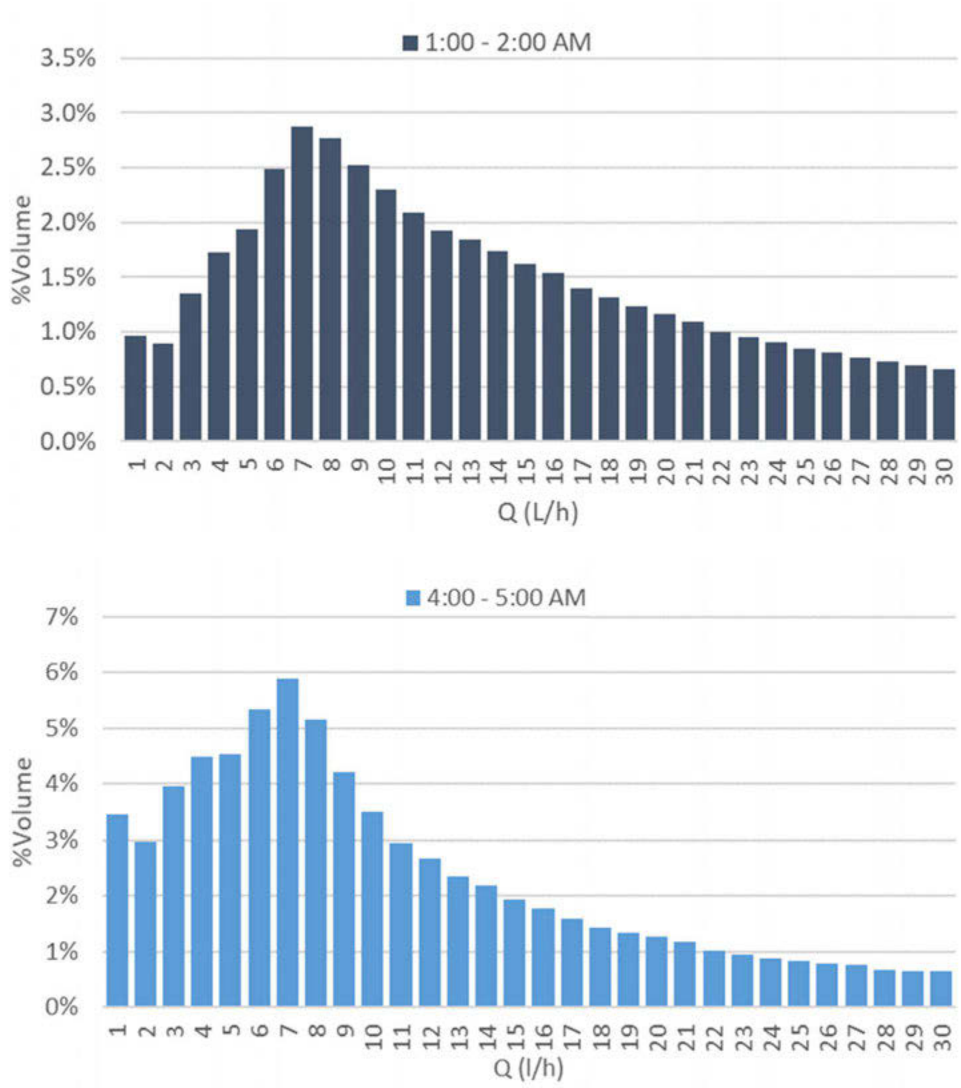

Figure 4. Distribution of flow rates in registers from a) 1:00 - 2:00 AM and b) 4:00 - 5:00 AM

At 4:00 AM, almost 6% of the total volume of his measurements is due to 7 L/h, while at 1:00 AM, only 2.9% of the total volume of his measurements is due to the same flow rate. In both cases, the flow rate with the highest volume percentage was 7 L/h. The data distribution is more concentrated at low flow rates and decreases drastically after 8 L/h. The volume percentage among the high flow rates decreases more steadily at 1:00 AM than at 4:00 AM but occupies a lower level of total volume percentage. In addition, the 4:00 AM histogram has higher volume percent records between 1 - 6 l/h due to the presence of baseline flow. At this hour is considered when it happens the minimum night flow occurs.

The following figures 5a and 5b show the consumption produced from 1:00 to 2:00 AM and from 4:00 to 5:00 AM as a rank. Also, in this figure, The secondary Y-axis is the frequency of occurrence percentage based on the total days registered at that time.

In general, low flow rate occurrence and volume are more frequent. At first seen, the highest range is not the same for both times. The rank between 31 and 70 L/h shows the maximum volume percentage at 1:00 AM, but the concurrency is also deficient. The most Frequency rate flow is in the field of 1 to 2 L/h. However, the lowest values of flow can be part of the rate error of the meters. The one that matches high values of volume and occurrence percentage in both figures is the range between 5 - 7 L/h and 8 - 12 L/h.

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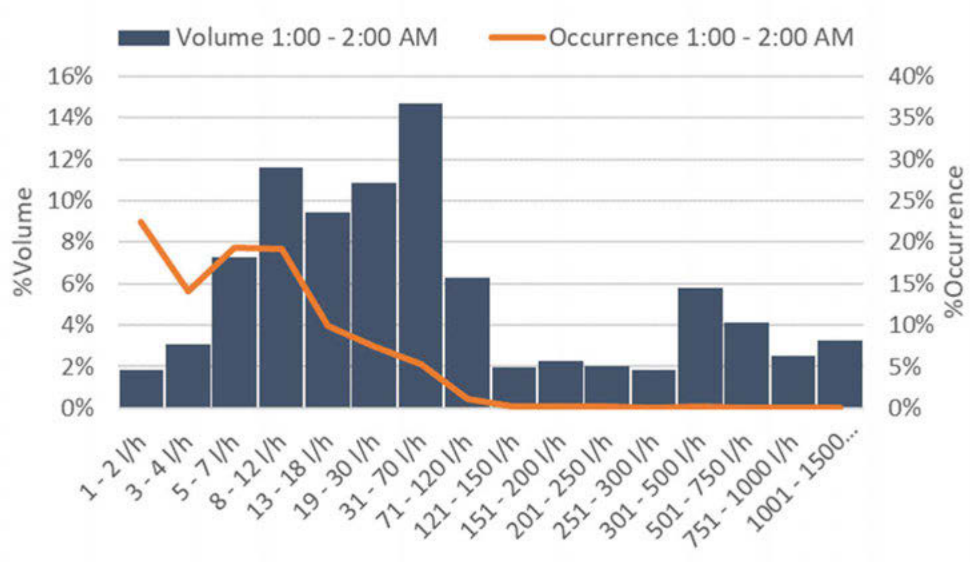

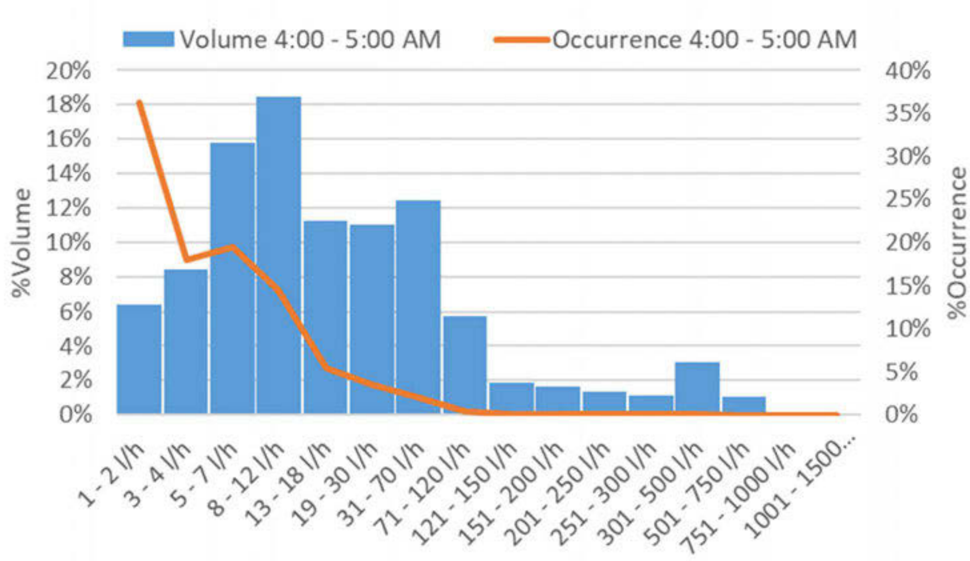

Figure 5. Distribution of flow in volume and occurrence percentages from a) 1:00 – 2:00 AM and b) 4:00 – 5:00 AM

Unifying all the hours over 4:00 AM measurements, as figure 6 shows. It was noticed a tendency in the measures except for the flow rate at 1:00 and 7:00 AM. Their values differ more in Volume and Occurrence than others and are more likely to register higher flow rates, which means they cannot be considered part of the minimum night flow. This figure could be associated with consumption patterns and reflect the influences of the values in every hour.

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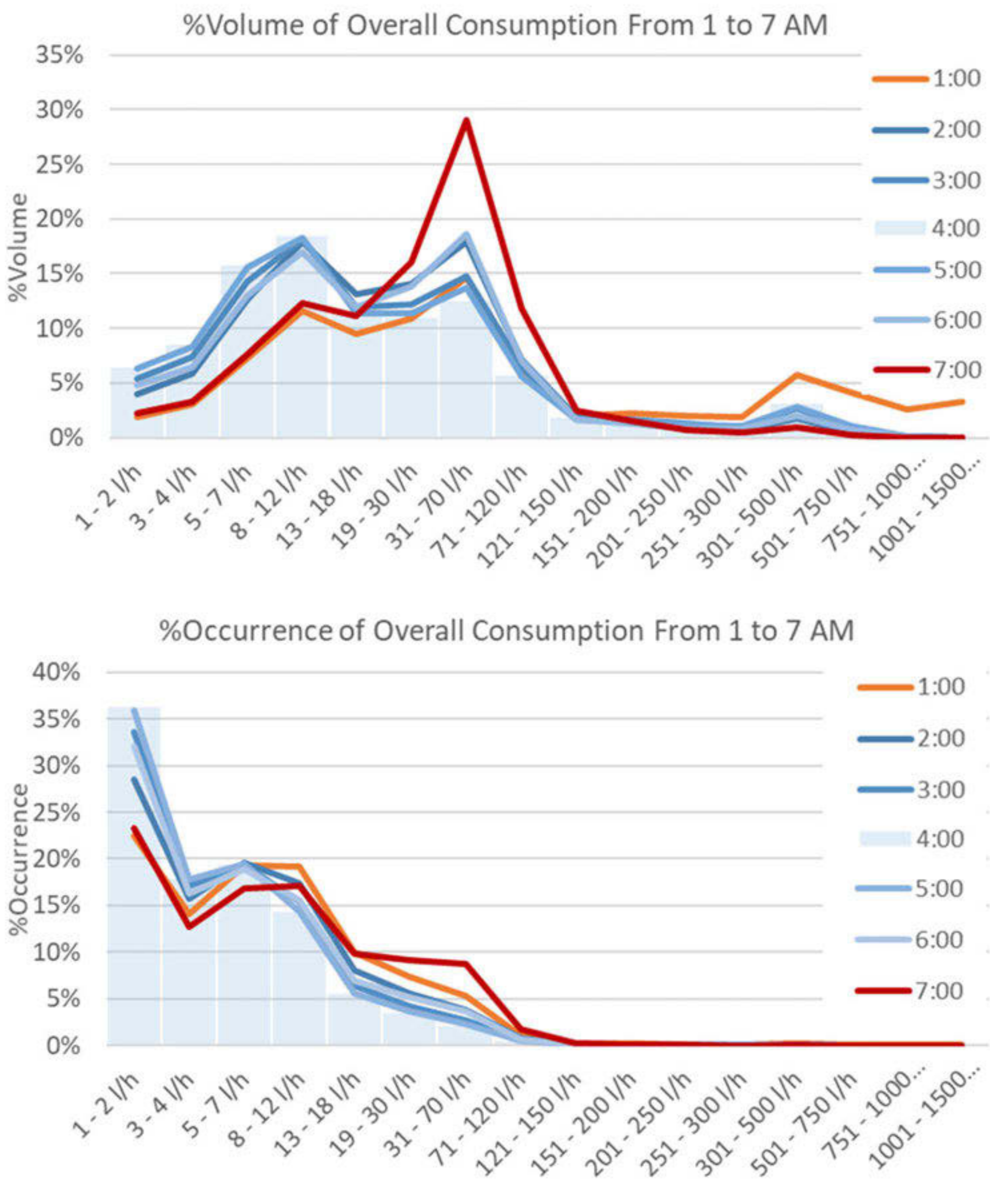

Figure 6. Distribution of Overall Consumption in a) %Volume and b) %Occurrence from 1:00 - 7:00 AM

4.2 Leakage/Continuous Flow

At the Leakage/Continuous flow data block, the flow rate was noticeable more steady. Figure 7 shows the volume and occurrence percentages of all hours compared. During the nighttime, the flow rate between hours is similar in volume and occurrence. The light blue color columns look almost the same, but dark blue color columns increase around lower ranges and then decrease at higher values. The occurrence is overlapped and higher around the lowest values. Approximately 25% to 23% of the time between 1:00 and 7:00 AM, a continuous nominal flow rate of 3 to 4 L/h occurs. The highest volume percentage is from 8 - 12 L/h, but low occurrence, as demonstrated in the figures before. Consequently, the leakage/continuous flow behavior is notoriously the same between 3:00 - 5:00 AM. Choosing any of these hours would fit the estimate of the rate flow at night.

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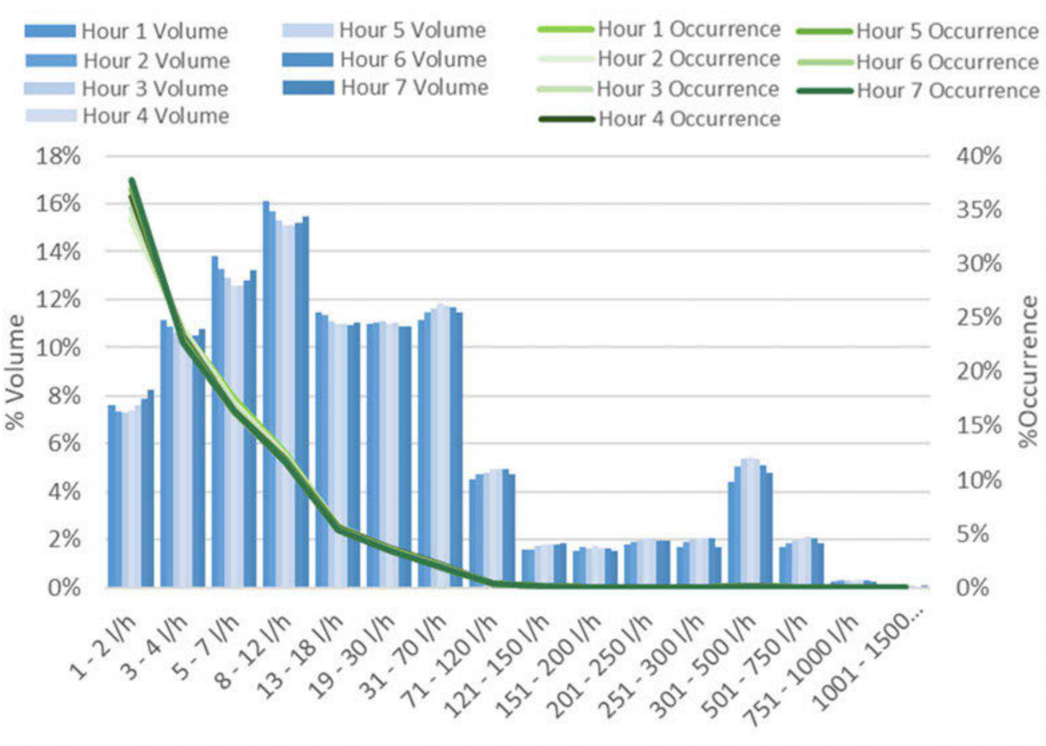

Figure 7. Distribution of Leakage/Continuous Flow by %Volume and %Occurrence from 1:00 - 7:00 AM

4.3 Intentional Flow

Intentional flow shows a solid relation to Overall consumption. Figure 8 indicates rates flow in the percentage of volume and occurrence, matching the highs and lows of Figure 6. Also, the contrast between 1:00 and 7:00 AM to the other hours clears and the tendency around 3:00 - 5:00 AM seems evident.

As a result, it is sure to say that the most common intentional consumption at night times and that occupied the most volume percentage is between 5 - 7 L/h and 8 - 12 L/h, which can be indeed associated with the action of haft-flush and full-flush toilets. Low flows as 1 - 2 L/h can be related to drinking, washing hands actions, or even an error factor of meters. All of this is reflected in Overall consumption as well. The first and last hours suffer a strong influence from other activities. Weekend consumption and morning routines increase the flow rate at these hours and separate from the night flow.

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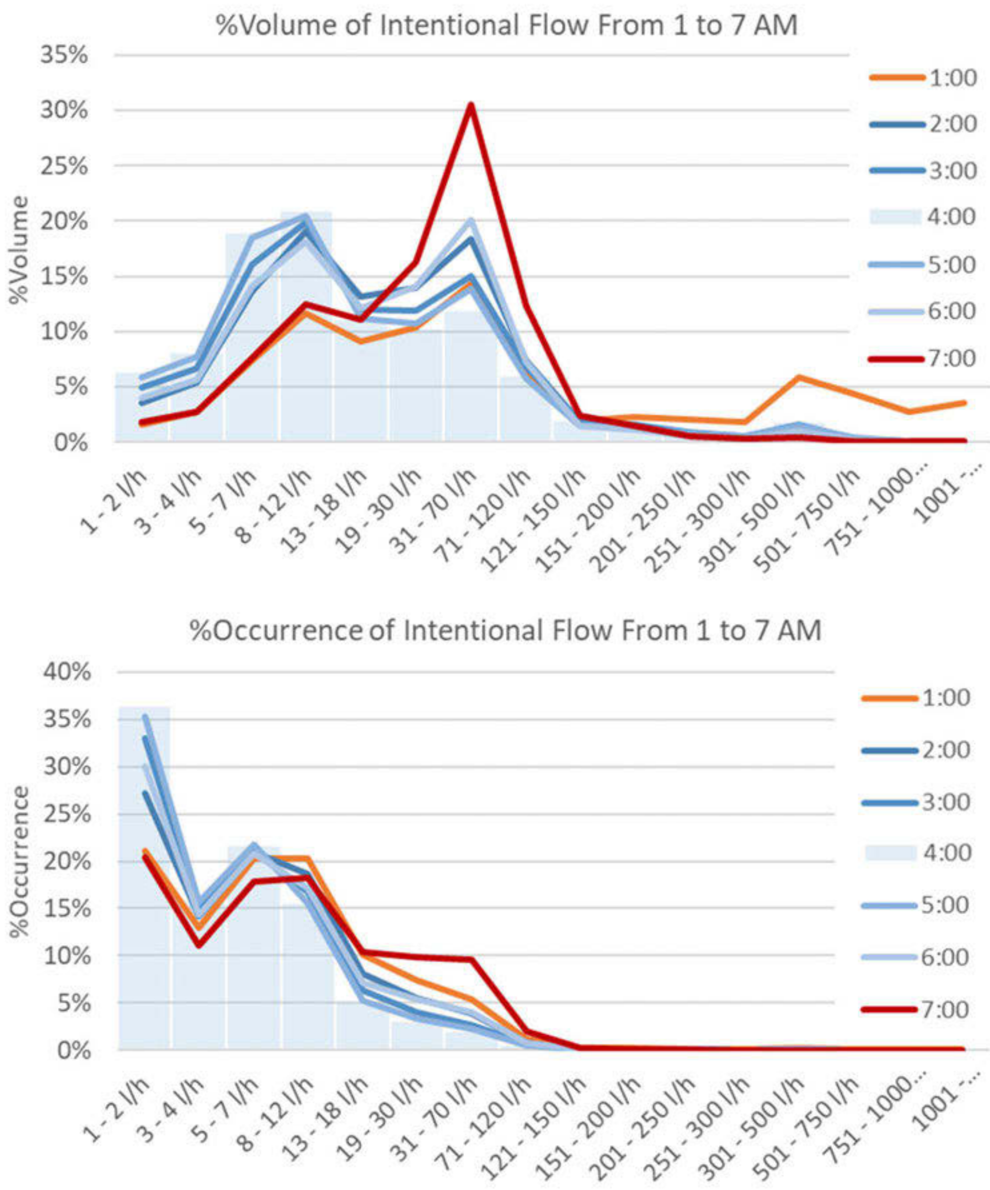

Figure 8. Distribution of Intentional Flow in a) %Volume and b) %Occurrence from 1:00 - 7:00 AM

4.4 Disaggregating Flow Rates

The disaggregating of consumption allows for defining the flow rate in three data blocks, as is shown in table 1. Also, table 2 shows filtered by sector.

Table 1. Flow estimation at Nighttime Minimums

Household Service	L/H/Customer	%TOTAL
Overall Consumption	1.50	100%
Leakage/Continuous Flow	0.53	36%
Intentional Flow	0.97	64%

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The Overall consumption at 4:00 AM is composed of 36% Leakage/Continuous flow and 64% Intentional flow. The baseline flow is steady at around 0.53 L/h/customer. This information represents a start point for managing the potential reduction of loss volume. It offers an upgraded and precise magnitude of the volume in the supply system installations and gives a reference to compare with itself and other supply systems. The partition is similar in the five sectors considered in the study, which means it could be the same in other sectors of Mediterranean City. Also, it shows through the method of minimum night flow that the leakage is hidden during the day activities while is highlighted at nighttime.

Table 2. Flow estimation at Nighttime Minimums by sectors

Sector 1	**L/H/Customer**
Overall Consumption	1.65
Leakage/Continuous Flow	0.63
Intentional Flow	1.02

Sector 2	**L/H/Customer**
Overall Consumption	1.55
Leakage/Continuous Flow	0.55
Intentional Flow	1.00

Sector 3	**L/H/Customer**
Overall Consumption	1.47
Leakage/Continuous Flow	0.47
Intentional Flow	1.00

Sector 4	**L/H/Customer**
Overall Consumption	1.40
Leakage/Continuous Flow	0.52
Intentional Flow	0.88

Sector 5	**L/H/Customer**
Overall Consumption	1.46
Leakage/Continuous Flow	0.50
Intentional Flow	0.96

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The objective of decomposing consumption into sectors was to analyze the influence of each sector on overall consumption. As a result, flow rate estimation is not way different between sectors. The baseline is evident even with a significant disparity in population and commercial activities.

4.5 Heat Maps

The heat maps show by color the intensity of the average night-hour flow every day in 2019. Figure 9 shows the heat maps for Overall Consumption, Leakage/Continuous Flow, and Intentional Flow. The color blocks are organized by a timeline and flagged by month. In addition, there is the number of customers registered on every date under the month layer to observe the information's weight and the variety of population in time.

The color contrast in the first map reflects changes in customers' consumption during the day, and observing the exact position of those blocks reveals patterns in this method. In general, the lowest values are in light blue blocks around 3:00 - 5:00 AM. Those blocks temporarily mismatch at weekends, showing darker colors at 2:00 - 3:00 AM and lighter at 6:00 AM. Also, values in March, May, and August lose the continuity of the patterns because of changes in the activities. Changes due to Holidays when people enjoy time with family or going out at night and Summer Vacations when people move out of the city for weeks.

Leakages/Continuous Flow present different distributions compared to the map before. The values adopt the form of lines on this map because of the steady behavior, but they change the tone slightly at 1:00 and 7:00 AM. The darkest blocks concentrate more over January, May, September, and December. Those months are related to high amounts of population and, for that reason, demand. Besides, this method can be applied in sectors to identify atypical events and locate the leakage origin.

Intentional Flow is similar to The Overall Consumption map. As seen before, the Intentional Flow is the one that can directly reflect customer consumption. The patterns are easily observed and have the same mismatch at weekends, holidays, and summer vacations but in lower values. The maximum value at the scale is similar while different from the minimum and the 50% quantile, which is lower.

Heat maps can also open a window to analyze the time evolution at a minimum night hour because they compile all the average daily records. In this way, figure 10 shows the consumption at 4:00 AM during 2019 in the three blocks of information. The three parts of the figure have a tendency that adopts a linear function and shows the equation of itself. The tendency gives a magnitude used for future references, showing precisely the flow rate of the leakage/continuous Flow that it wanted to estimate and how Intentional Flow and Overall Consumption overlap their form.

In Figure 11, the tendency equation of Leakage/Continuous Flow has an independent term that establishes at 0.53 L/h/customer while the Intentional Flow function establishes at 0.92 L/h/customer. Besides, this tool can be used in known sectors, relate their consumption to find patterns, and apply them in sectors without remote reading. This leakage flow rate creates a value for performance expectations or to compare the efficiency of other supply systems and even sectors of the same system.

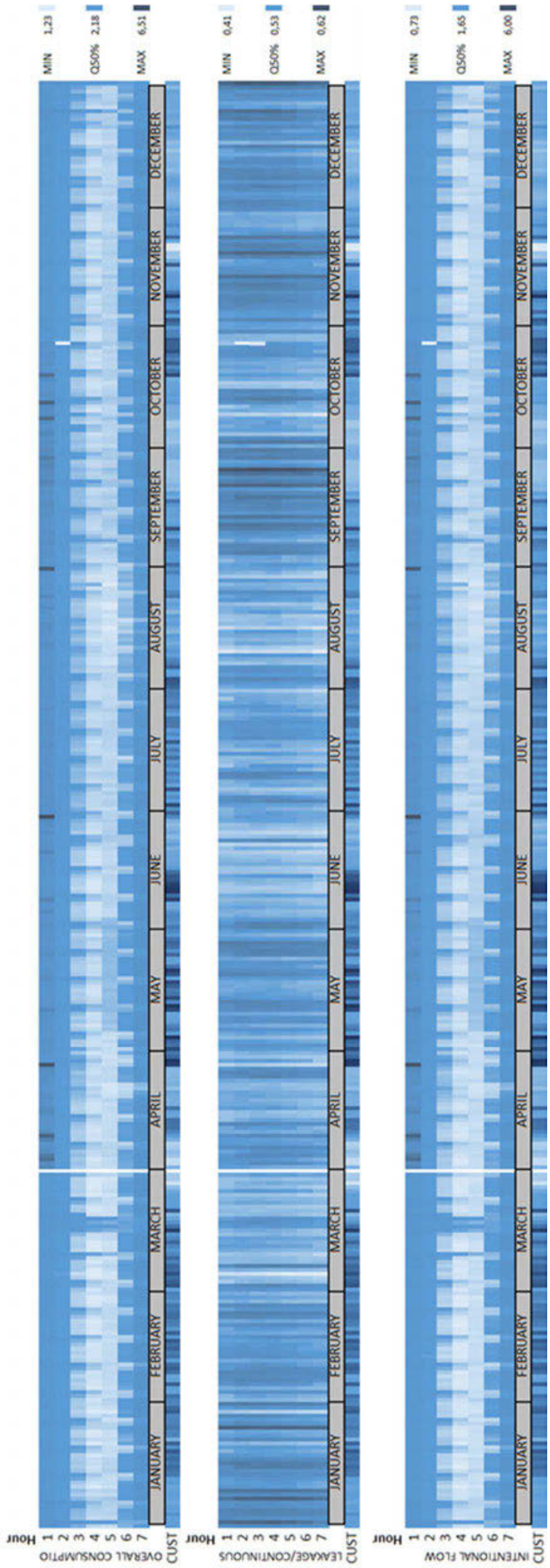

Figure 9. Heat Maps of a) Overall Consumption b) Leakage/Continuous Flow c) Intentional Flow

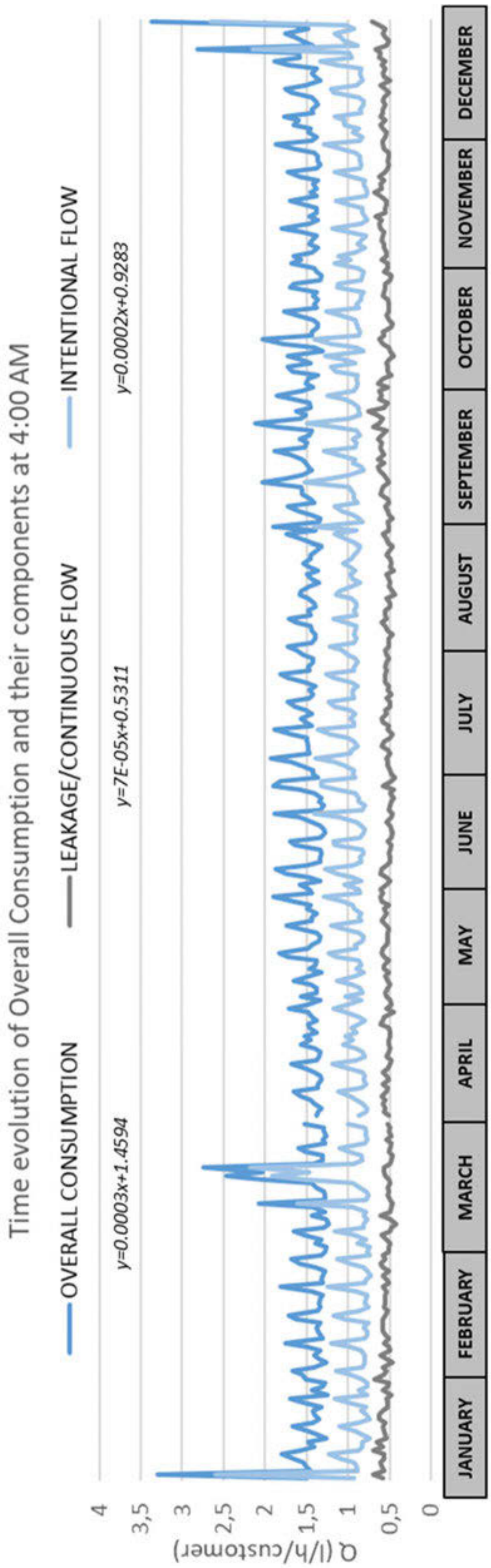

Figure 10. Time evolution of a) Overall Consumption b) Leakage/Continuous Flow c) Intentional Flow

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5 CONCLUSIONS

Analyzing consumption patterns is a helpful tool for understanding the demands and maximizing the system's efficiency through management decisions. This study focuses on analyzing water consumption by disaggregation of the overall consumption during night hours of residential customers. These are the conclusions:

The method of disaggregation makes it possible to evaluate each consumption element and analyze the flow rate that handles the demands. Due to the leakage indicator PROFUGA, extracting the Leakage/Continuous Flow portion in the Intentional Flow was possible. Because of that, this estimation can use extrapolated to all-day hours and gives another point of view.

It is a fact that exists a baseline flow of leakage or continuous flow in the supply system. During night hours consumption, this baseline is a flow rate of 0.53 L/h, representing 36% of the overall flow. Analyzing the five sectors, they all keep the portion of elements in the Overall Consumption. The consumption between 3:00 – 5:00 AM offers hours alternatives to estimate this value since the behavior is the same.

The intentional flow is associated with sanitary standards device flow at that hour. It is related because the range of more percentage of volume and occurrence are 5- 7 L/h and 8-12 L/h, which correspond to flow rates of half-flush and full-flush toilets, washing hands, and drinking water at night. During these hours, the distribution is occupied mainly by low flow rates. There are registers of punctual high values but with low occurrence. The consumption at 1:00 and 7:00 AM suffers highly influenced by weekend and morning routines. They are not considerate at the estimation of minimum night-hour flow.

Heat maps provide an easy way to identify patterns and variations over time. Changes in weekends, holidays, and vacation consumption are easy to observe. It also allows us to evaluate the months with the highest baseline flows and intentional spending to take the necessary precautions. The temporal evolution shows the difference in magnitude between the components and moments of high and low consumption values. Which offers a range of demands management.

These conclusions allow applicating in other sectors of the Mediterranean City, as they were in the five sectors mentioned before. The method allows for studying the consumption of the supply systems at level details, which represents a valuable tool to create bonds and parameters for being applicated beyond the network limits. By studying temporaries series and probability functions, this study can be developed at higher levels and make a difference in management operations.

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