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Daily water demand

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ABSTRACT

This paper develops a model to characterize the demand for domestic water based on its end users' usage habits. The use of individual residential appliances (bathroom sink, toilet, shower, bath, etc.) is interpreted using a probabilistic approach. The paper also applies the model to the distribution network of the municipality of Sparanise, a small city in the province of Caserta, Italy. The results of this application are compared to the real output of the city's actual water reservoir. Flow variability during the day was successfully modelled. A comparison of the simulated and recorded data on a daily level indicates the proper adjustment of the volume distribution; the peak flow rates were also comparable. The model could be a useful tool for analyzing domestic water consumption, especially in the design and management of water distribution networks. Use of the model would particularly aid the Integrated Urban Water Management Operator both in optimizing the operating pressures in the various districts' networks and in predicting domestic water consumption when drafting its water balance documents.

Keywords: domestic appliances, management, probabilistic model, water demand, water distribution network.

Demanda hídrica diária

RESUMO

No artigo é proposto um modelo para caracterizar a demanda hídrica doméstica a partir dos hábitos de utilização dos usuários finais de água. O uso dos equipamentos domésticos (bidê, pia, chuveiro, banheira, lava-roupas, etc.) é analisado com o uso de abordagem probabilística. Também é descrita a aplicação do modelo na rede de distribuição do município de Sparanise na Província de Caserta (Itália) e a consequente verificação dos resultados obtidos com aqueles registrados diretamente na saída para o reservatório da cidade. A comparação entre os dados registrados mostrou um bom ajuste do volume distribuído diariamente, os volumes de pico também se mostraram compatíveis. O modelo se mostrou como instrumento útil para análise do consumo doméstico com grande potencial de aplicação no projeto e na gestão das redes de

distribuição. Em particular a utilização do modelo poderia auxiliar o Órgão de Gestão Integrada de Recursos Hídricos na otimização das pressões operacionais nas redes subdivididas em distritos e para prever o consumo de água doméstico quando da elaboração de relatórios de balanço hídrico.

Palavras-chave: demanda hídrica, equipamentos domésticos, gestão, modelo probabilístico, rede de distribuição hídrica.

1. INTRODUCTION

Integrated Urban Water Management (IUWM) consists of all public services relating to water management, such as catchment, conveyance and distribution of water for civil uses, and sewage and wastewater treatment.

Current Italian regulations require that IUWM is managed with respect to the principles of efficiency, effectiveness and affordability. The achievement of the above principles must necessarily also comprise knowledge of the complex infrastructure system, its current performance levels, the volumes collected and distributed, and the flows collected in the final receptors of the sewer system.

In an urban center, the variability of the water demand over time describes its functional range and is also a useful tool for its managing institutions in order to correctly manage the service.

Civil consumption of water depends on a variety of uses which can be related to multiple components. Civil consumption is generally separated into two components: domestic consumption and collective consumption.

Domestic consumption is intended as the water demand of dwelling occupants; collective consumption is instead usually considered consumption by public and commercial activities.

Public consumption takes into account all civil consumption, which is not generated by the residential users. When industrial consumption is restrained, it is counted as collective consumption.

Experimental investigations carried out in ten municipalities located in Southern Italy showed a baseline consumption value which remained more or less constant throughout the day (Silvagni et al., 2004).

This value also considers the presence of losses - a physiological component which is always present in distribution networks - and the collective consumption component (Figure 1 and 2).

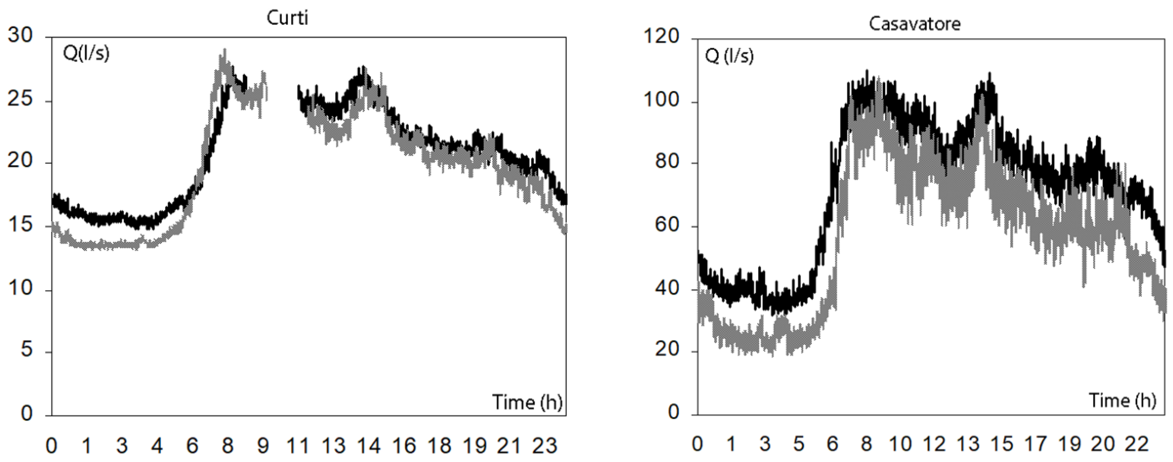

Figure 1. Plots of city reservoir output flows.

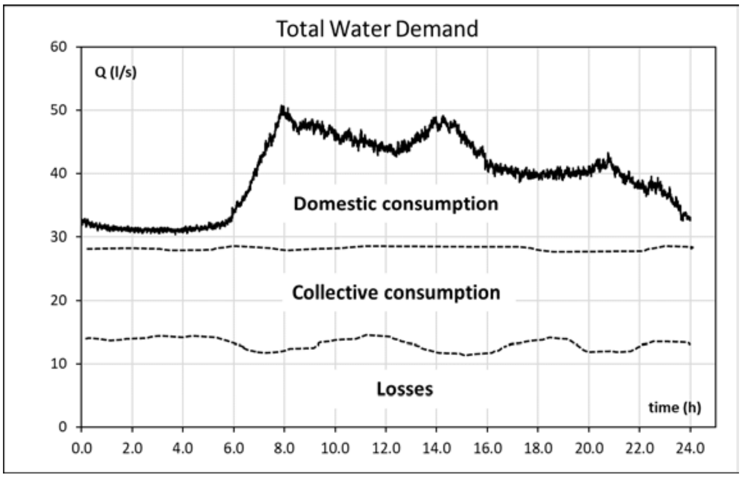

Figure 2. Plot indicating the division of consumption based on flow – time.

Therefore, the output flow Q_L [l/s] in Figure 1 can be expressed as the sum of domestic flow Q_D [l/s], collective flow Q_C [l/s] and losses Q_P [l/s] (Equation 1).

$$Q_L = Q_D + Q_C + Q_P \text{ [l/s]} \quad (1)$$

The estimation of network losses is basic to correct IUWM operator management, as it is a fundamental aspect of the water balance; indeed, the detection, estimation and resolution of the losses allow the managing institutions to optimize service with direct, positive repercussions on administrative aspects.

Estimating losses is a complex task based on the comparative analysis of the daily volumes delivered by the distribution network, the volumes invoiced to users and the volumes delivered to collective users. In technical literature, some models have been proposed for estimating the vulnerability and incidence of the losses (Infrastructure Leakage Index – ILI), which are based on a network's topography, type and working pressures (Lambert et al., 1999; Lambert, 2000; Thornton and Lambert, 2006).

Collective consumption depends on the type of town planning and the socio-economic services present in the area; they are generally identified with special water supply contracts. Detailed knowledge of the system and its users allows for the direct estimation of the amounts of water delivered in the provision of services to citizens and production systems.

Domestic consumption is directly correlated to the number of inhabitants and their daily habits; it varies from urban center to urban center within the geographic areas considered (Silvagni et al., 2004), and within the various water districts relating to town planning types.

The model described in this paper makes it possible to estimate domestic demand based on domestic appliances and users' daily habits.

The characterization of users' water demand together with the estimates of collective volumes and respective losses therefore makes it possible to create a diagram indicating the daily water demand required by each urban center analyzed.

The model can be applied to the entire urban center, as well as to the different, homogeneous water districts within the same center. The result is a snapshot of water use over space and time, with obvious benefits for monitoring and managing the water supply system.

The technical literature on the analysis of users' water demand has essentially targeted the estimation of per capita daily water volume. These studies often reveal a weakness in the system: they highlight that the daily drinking water demand is higher than the available amount of natural water, also as a consequence of climate changes (Fox et al., 2009; Schleich and Hillenbrand, 2009; Arbués et al., 2003; Levallois et al., 1998).

Other studies have focused more on characterizing the demand within a broader context of reducing losses to reduce use of the available amount of water (e.g. Makropoulos and Butler, 2007; Bertola et al., 2014; Parker and Wilby, 2013).

A recent study (Gargano et al., 2016) presented a probabilistic model that allows for users' demand to be estimated based on residential meter readings.

The proposed methodology for defining domestic water demand is based on the experiences carried out in the sewage networks and in particular on the analysis of domestic users' waste (Butler, 1991; 1993; Butler and Graham, 1995). The aim of this study is to link demand to the number and type of appliances existing inside a home and their use during a typical day.

Therefore, the estimation of each appliance’s usage times and frequency is necessary, as well as the volume and variability of the water used.

Butler and Graham (1995) developed a probabilistic model for a sewage network to simulate the spatial and temporal variation of domestic wastewater in dry weather conditions.

The discharged wastewater was considered equivalent to the volume of water delivered to users.

Water demand is the result of the random use of domestic appliances, each one with its own characteristics (i.e. usage volume and variability, assumed as randomly variable within certain ranges) and with usage frequency related to defined hourly periods of the day. These flows have an intermittent nature and are used for limited durations (in the range of 10-15 s).

The probability p that an appliance will be used in time interval T_a is given by Equation 2:

$$p = \frac{t_{a1}}{T_a} < 1 \tag{2}$$

where t_{a1} is the total observed time during which the hydro-sanitary device delivers water.

The probability of having r appliances out of a total N appliances which are simultaneously in use can be determined with a binomial distribution expressed by the following relationship Equation 3:

$$p(r) = \frac{N!}{r!(N-r)!} p^r (1-p)^{N-r} \tag{3}$$

The binomial distribution makes it possible to determine the expected amount of simultaneous uses *E(r)* in a generic moment in time as the product of N appliances and probability *p(r)*.

The resulting flow $E_q(r)$ relating to the simultaneous use of multiple appliances is determined (Butler and Graham, 1995) by the product of the expected number of simultaneous uses *E(r)* and the initial flow q of the single appliance considered (Equation 4).

$$E_q(r) = E(r) \cdot q \tag{4}$$

Butler and Graham (1995) also indicate the possibility of extending their theory to define a mean or expected flow value generated by intermittent demand to estimate the flow variability around its mean value.

This transposition is possible through the use of the standard deviation σ (Equation 5) of the simultaneous demand expressed by means of normal distribution (Shaw, 1963), and the calculated flow variability.

$$\sigma = \sqrt{Np(1-p)} \tag{5}$$

The amount of simultaneous demand $E^{\alpha}(r)$ and the resulting flow $Eq^{\alpha}(r)$ are related to a fixed level of confidence α (confidence coefficient Z^{α}) (Equation 6).

$$E^{\propto}(r) = Np \pm Z^{\propto}\sigma \rightarrow E_q^{\propto}(r) \cdot q \quad (6)$$

Butler and Graham (1995) applied this probabilistic model to the English sewer system of Edenbridge, obtaining an excellent correspondence between recorded and simulated flood hydrographs.

The approach used, which starts with a typical distribution of equipment and home appliances, allows for both a characterization of domestic demand in existing networks and the estimate of demand charts for project design. In fact, domestic water demand can be estimated starting with the data available from regulations based on town planning type, the number and type of apartments and the maximum number of occupants.

An important aspect highlighted by Butler (1991; 1993) is the variability of the parameters depending on geographical areas (northern or southern Europe) or lifestyle (lower class, upper class); previous studies have already highlighted this variability in some distribution networks in Southern Italy (Silvagni et al., 2004). The domestic demand charts for certain towns in the Campania Region have shown trends and parameters of the harmonic functions which depict them as being comparable with one another (Figure 3).

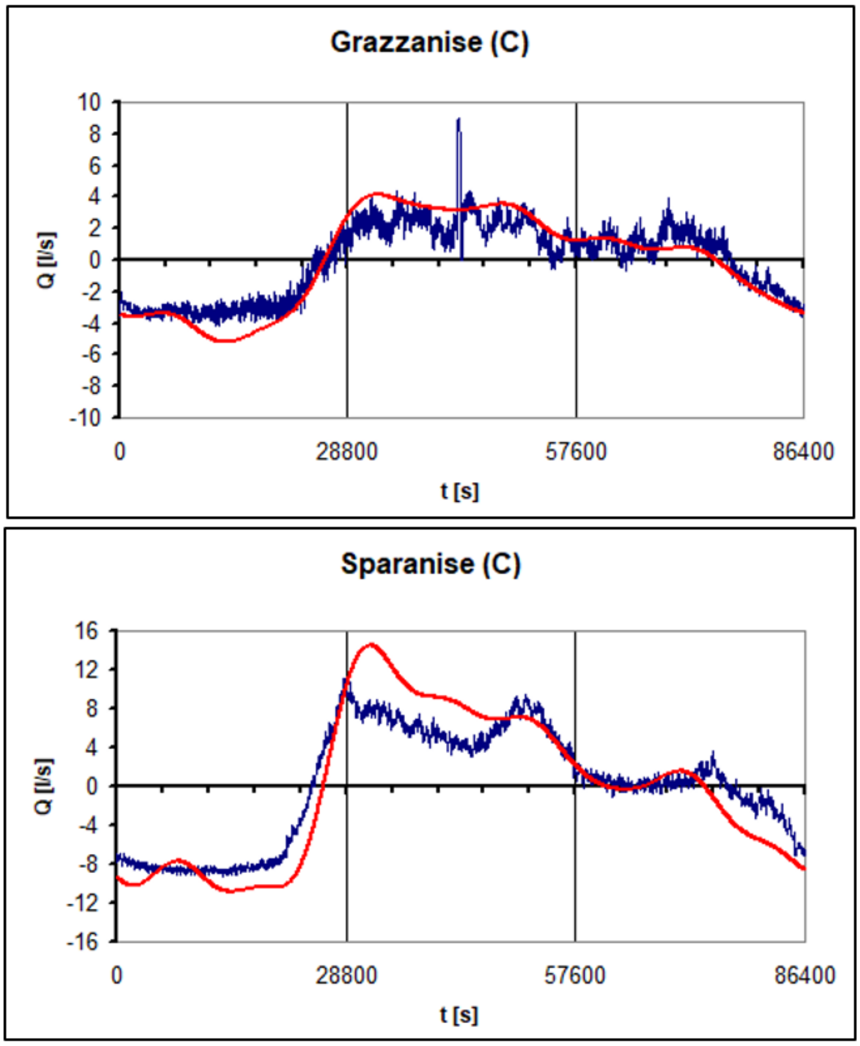

Figure 3. Charts recorded vs. reconstructed sinusoidal signals (Silvagni et al., 2004).

2. MATERIALS AND METHODS

In this first stage, the proposed model considers middle-class users without any specifications regarding age, profession or economic-cultural conditions.

The daily use of appliances by a typical user was set in reference to a standard domestic environment.

The individual appliances were characterized using four parameters:

1. Average daily frequency of use [uses/day];
2. Start time of use during the day [h];
3. Average duration of appliance use [minutes/use];
4. Volume of water required [litres/use].

For domestic appliances, a probabilistic process must be applied by estimating the standard deviation (σ) compared to the mean value.

In particular, and in agreement with Butler and Graham (1995), a normal distribution around the mean value μ was assumed.

This assumption makes it possible to consider the habits, lifestyles and different needs of users, which can cause significant variability in the manner and frequency of use.

The daily demand hydrograph of users is strongly influenced by σ; an experimental investigation with flow-demand measurements and users' daily usage reports is the most effective tool for correctly estimating the standard deviations.

In this first development phase of the probabilistic model, the σ values for the various types of appliances tested were assumed equal to Butler's experimentally estimated values (1991, 1993), suitably adjusted according to the estimated habits and lifestyles of the population which was subsequently studied in this paper.

The probability density function of the normal distribution *pdf* is expressed by the following (Equation 7), as a function of the average value μ and the standard deviation σ:

$$f(t, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma\sigma}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} \tag{7}$$

With a daily number of users greater than one, the effects due to the single *pdf(t)* must be combined.

Figure 4 shows the Probability Density Functions (*Pdf*) for the start time of using the sink.

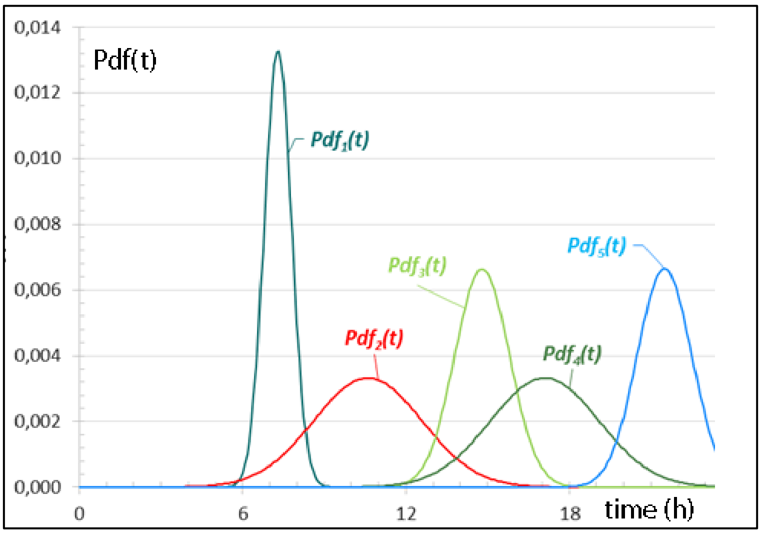

Figure 4. Use start time – Pdf.

A random process makes it possible to estimate the start time, duration and volume of use throughout the day for the appliance in question. Figure 5 shows the daily chart for a sink.

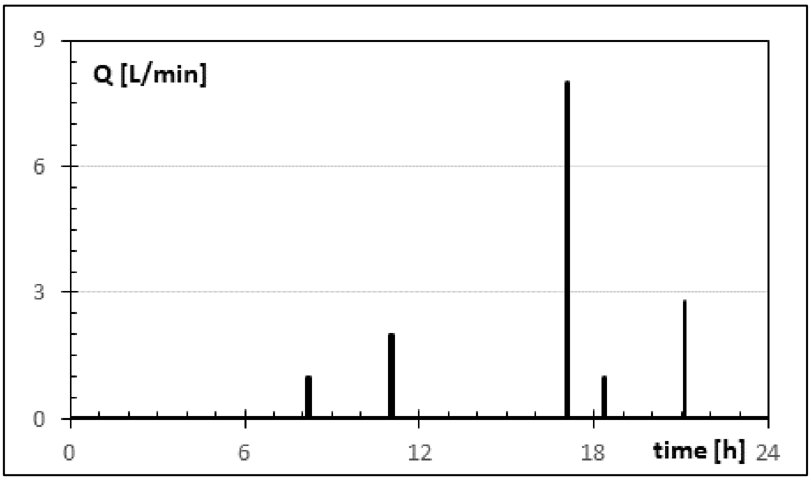

Figure 5. Sink – Estimated daily demand.

The chart in Figure 6 shows the water demand considering a number of users (*N*) equal to 20 and considering other domestic appliances (kitchen sink, shower, bathtub, toilet, washing machine, dishwasher, etc.) in addition to the bathroom sink.

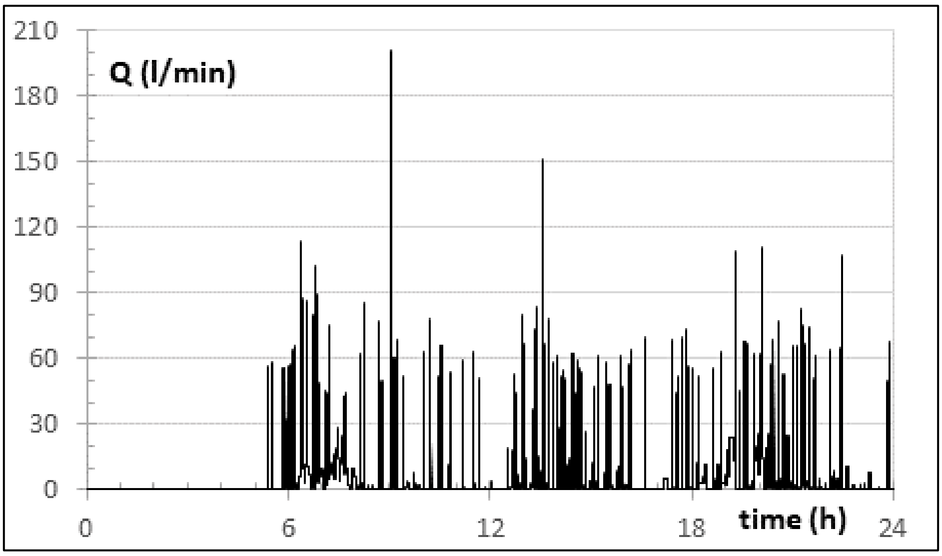

Figure 6. Typical user - Estimated daily demand - *N* = 20

This model was applied and adjusted to the municipality of Sparanise in the province of Caserta (Italy).

3. RESULTS AND DISCUSSION

The monitoring system of Sparanise water distribution network provided daily demand data for a study characterizing water consumption (Silvagni et al., 2002).

The municipality of Sparanise has about 7,000 inhabitants and is predominantly residential.

The diagrams in Figure 7 show the recorded city reservoir output data, both as recorded (a) and as filtered data (b), linked to traditional uses (collective) and the net losses deducted from the overnight time range (t = 0÷6 h, Figure 7a).

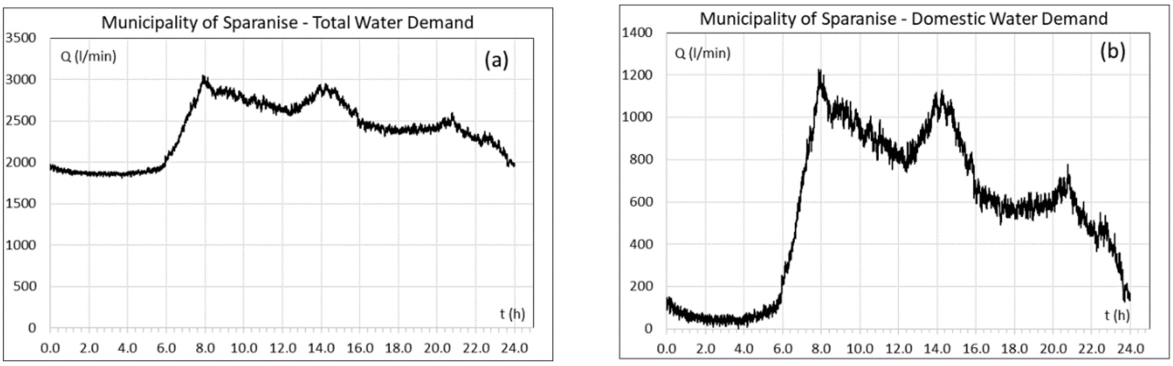

Figure 7. Municipality of Sparanise – Water Demand (April 1995).

Table 1 shows the model parameter values, mean value (μ) and standard deviation (σ), estimated for Sparanise using data from the literature (Butler 1991; 1993; Blokker et al., 2006; 2010; Buchberger and Wu, 1995), which is based on the town planning type, average living standards and mostly residential water use.

The average use duration and mean volume are fixed and use the experimental results Butler obtained for wastewater (Butler, 1991), considering the flows that the appliances are able to distribute, also in reference to the existing technical standards (UNI, 2014).

A middle-class household was considered for the type of appliances examined: a household composed of three people with a single bathroom with a shower and bathtub, a kitchen with a dishwasher and a washing machine.

The shower and bathtub are considered as not generally being used simultaneously. The model assumes an average bathtub use of once per week. Therefore, considering that the user area consists of N typical users, the use of the bathtub on the reference date is by N/7 users; the remaining 6N/7 users use the shower.

A similar consideration was made for the washing machine and dishwasher.

The hypothesis also includes the consideration that a single appliance is shared by three users. This hypothesis can be explained by considering the daily use of a family comprised of three people on average, or the appliance's use every three days on average by each individual user in question.

The average use frequency and times were set based on user behavior and by analyzing the consumption shown in Figure 7, which indicates three flow peaks at 8:00, 14:00 and 21:00.

Figure 8 depicts the first results of the model's application to the municipality of Sparanise. The model produced an optimal estimation of the peak demand values and overall, the demand trends obtained in the chart are quite in line with the chart of recorded data.

The results obtained for the time period from 9:00 to 12:30 underestimate the recorded flow data; although less marked, a similar trend emerges in the time period from 15:30 to 19:30.

The highlighted time periods both include the opening of commercial activities with the addition, between 9:00 and 12:30, of activities in the citizen services and public facilities sectors.

The above-mentioned activities are not considered within the proposed probabilistic method, which is aimed at domestic users. Therefore, the underestimation is certainly influenced by the initial assumption of removing a constant amount from the recorded values due to non-domestic users.

The time period deviation of the volume distributed to users between the probabilistic model and the recorded data has no significant effect on the overall daily volumes delivered. In fact, the daily water allocation estimated by the model (equivalent to 136 litres per inhabitant) is almost identical to the per capita available water supply recorded (134.7 litres per inhabitant).

Table 1. Probabilistic model input.

Domestic Appliances		Bathroom Sink	Toilet	Bidet	Shower	Bathtub	Kitchen sink	Dishwasher	Washing Machine
Use duration	μ_d [min/use]	1.0	1.5	0.6	4.0	6.0	1.0	0.7	5.0
	σ_d [min/use]	1.5	1.0	1.0	1.0	0.5	1.5	0.3	0.5
Volume	μ_v [l/use]	3.0	7.0	3.5	25.0	35.0	4.5	4.0	30.0
	σ_v [l/use]	1.7	1.0	1.7	20.0	20.0	2.0	1.3	10.0
Use frequency	f [use/day]	4.0	4.0	2.0	2.0	1.0	3.0	3.0	2.0
Start time use	μ_1 [h]	8.0	7.3	7.5	8.0	14.0	9.0	21.3	14.0
	σ_1 [h]	1.5	1.5	1.5	1.5	1.0	1.5	8.0	12.0
	μ_2 [h]	13.5	17.0	21.0	14.0	--	14.0	22.0	14.5
	σ_2 [h]	1.0	2.0	1.5	1.5	--	1.5	8.0	12.0
	μ_3 [h]	17.1	20.5	--	--	--	21.0	22.2	--
	σ_3 [h]	2.0	1.0	--	--	--	1.5	8.0	--
	μ_4 [h]	21.5	23.0	--	--	--	--	--	--
	σ_4 [h]	1.0	2.0	--	--	--	--	--	--

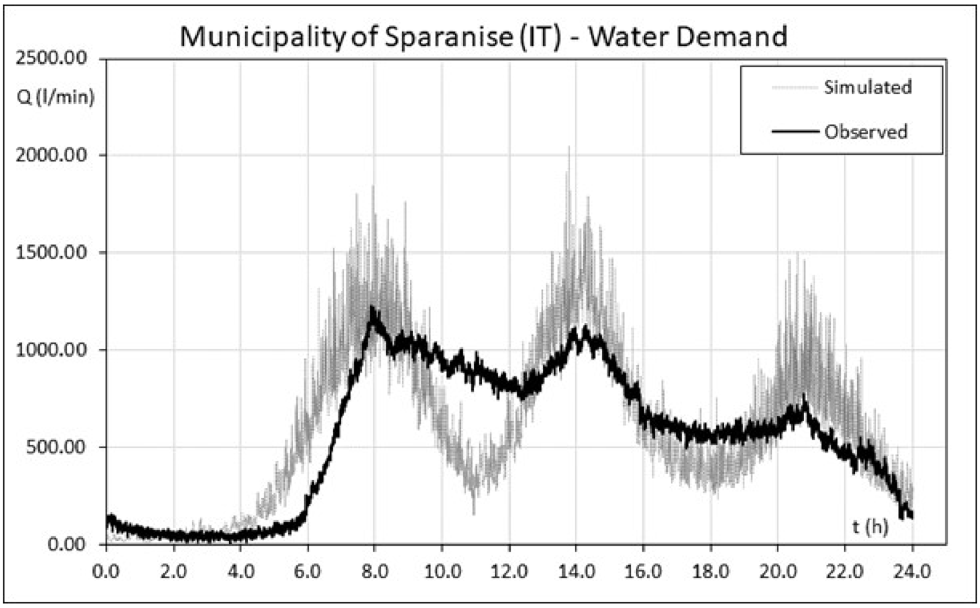

Figure 8. Model application – Results.

4. CONCLUSIONS

The variability of an urban center's water demand over time is directly related to its citizens' use of residential equipment. The probabilistic model proposed makes it possible to estimate users' hourly consumption, starting from the single residential unit.

In this first phase, the model was tested on Sparanise users which are predominantly residential, with commercial activities and public services for the community.

The results demonstrate that the proposed model can be effective for managing distribution networks, as it is able to temporally place and estimate peak flow values.

This aspect, especially in networks which are subdivided into districts, allows for the management of pressures in order to optimize the networks' operation and ensure the expected service level to users.

The results obtained in the estimation of the user volume demand for domestic use show how the model can be used to define an urban centre's water balance, especially considering how this water balance consists of domestic consumption, collective consumption and losses. Further investigations and applications of the model are underway in order to confirm and thereby also generalize both the method and the results obtained from it.

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