Peak residential water demand

C. Tricarico PhD, G. de Marinis PhD, R. Gargano PhD and A. Leopardi PhD

Residential water consumption has been analysed by monitoring a water distribution system in a small town of about 1200 inhabitants, Piedimonte San Germano, in southern Italy. The design of a water distribution system is usually undertaken with reference to the maximum water required by customers—one of the most onerous operating conditions to which an hydraulic network is exposed. The aim of the present work has been to contribute to the characterisation of the peak water demand through statistical inferences on a large data sample collected from the system under consideration. Specifically, the data have been analysed for the effect of resampling the raw data with respect to time interval on the estimate of peak demand factor. Formulae are suggested to estimate the maximum flow demand for small towns, in relation to the number of users. In addition, statistical inferences have shown that the stochastic, maximum flow demand is described by the log-normal and Gumbel models. With reference to small residential areas, the parameters of such statistical distributions have been estimated. These have shown that the coefficient of variation (CV) of the peak water demand is a function of the number of users. Although these results are only directly applicable to the specific context from which they have been obtained, the comparison with the sparse data available in the technical literature leads to the belief that the proposed relationships could be extended to other small residential areas.

1. INTRODUCTION

The maximum residential water requirement assumes a noteworthy importance in the study of water distribution systems (WDSs) because the peak flow demand represents one of the most onerous operating conditions of the network. The maximum residential demand is therefore taken into account when designing or rehabilitating hydraulic networks.

Diverse and complex factors influence water consumption; therefore, some researchers (e.g. Garcia et al., Buchberger and Wells, Alvisi et al. and de Marinis et al.) have studied these using experimental approaches. Indeed, through statistical inference on data samples, these researchers have proposed some models to represent residential water demand.

In the technical literature, copious relationships exist to evaluate the peak phenomenon (e.g. Babbit and Rich) but they are usually with reference to residential areas with a minimum of 5000–10 000 inhabitants. Less attention is given to the case of a small number of users for which, moreover, the peak phenomenon is often more important if compared with the average flow requirement.

In addition, it should be noted that the study of small town hydraulic networks has relevance in the case of larger conurbations. In these cases, indeed, the larger network may be seen as being segregated into smaller sections, of which each single node will supply a small number of inhabitants.

With the aim of contributing to the characterisation of water demand models, a WDS of a small town in southern Italy, Piedimonte San Germano (PSG), has been monitored. The redundancy of this system allows the consideration of the flow measurements being equal to the water demand required by users. Even if this study refers to the specific small town analysed, the results obtained are in agreement with those obtained from the study of similar real-life WDS (Alvisi et al. and LATibi).

The study of maximum water demand has been undertaken considering both a deterministic approach and a more accurate, probabilistic approach. Several researchers, indeed, have highlighted the need to tackle flow demand with a specific probabilistic approach as a stochastic variable (e.g. Bao and Mays and Gargano and Pianese). Some formulae to describe the maximum flow demand are suggested.

Probabilistic models to describe the peak flow requested and the relative parameters (mean and standard deviation) have been obtained through statistical inferences on experimental data collected from the network under consideration. These results could be useful in a probabilistic approach to generate homogeneous data samples of the maximum flow demand using a sampling technique such as the Monte Carlo method.

2. THE PIEDIMONTE SAN GERMANO HYDRAULIC NETWORK

In order to obtain realistic demand data, a monitoring system has been installed on a real hydraulic network. The WDS under consideration here comprises a section of the PSG hydraulic network. The network topology is composed of 45 pipes (comprising 12 loops), 33 junction nodes and a reservoir (node 0), as illustrated in Fig. 1.
All of the existing pipes are cast iron, with the exception of two newer branch lines (43 and 45) which are high-density polyethylene (HDPE). The measurement system consists of four pressure loggers and four bidirectional electromagnetic flow meters, each connected to a data logger. The location of the meters is shown in Fig. 1. The measurements could thus be taken continuously with an acquisition frequency of up to 1 Hz. An example of data collected by one of the meters in a day is illustrated in Fig. 2.

In addition to obtaining a detailed knowledge of the physical system, a census of consumers was undertaken with the aim of determining the principal characteristics of the users and their sanitary fittings. The portion of the hydraulic network considered supplies 400 customers (i.e. properties) under contract, with around 1220 inhabitants. The dominant contract type for this section, accounting for some 96.8% of contracts, is for domestic usage.

Using these data, it was further possible to estimate accurately the exact number of properties \( N_e \) and consequently the number of people \( N_{ab} \) that can be considered to be supplied from each measurement point (Table 1). Through the use of mass balance equations, it has been possible to investigate the water demand not only at the measurement points but also for other numbers of inhabitants derived from the flows taken at the measurement points, as shown in the last two rows of Table 1.

The study of water demand, using flow data collected from a real-life WDS, cannot ignore leakage estimation. Neglecting this could lead to the consideration of water demand higher than reality. In the case of small towns, the minimum night flow datum could be interpreted as the value of possible leakage,\(^{12-15}\) This approach has been used to estimate the leakage value for the data analysed herein. The resulting values have been compared with

```plaintext
Table 1. Number of properties and inhabitants supplied at each measurement point

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>( N_e )</th>
<th>( N_{ab} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>400</td>
<td>1220</td>
</tr>
<tr>
<td>7</td>
<td>320</td>
<td>981</td>
</tr>
<tr>
<td>8</td>
<td>48</td>
<td>144</td>
</tr>
<tr>
<td>22b</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>7–(8 + 22b)</td>
<td>252</td>
<td>777</td>
</tr>
<tr>
<td>3a–7</td>
<td>80</td>
<td>239</td>
</tr>
</tbody>
</table>
```

Fig. 1. Topology and monitoring arrangements of the PSG hydraulic network

Fig. 2. Demand data collected over 24 h from meter 7 (data collected each second and averaged over 1 min intervals)
3. PEAK DEMAND COEFFICIENT

Data collected by the PSG monitoring system over a period of almost two years show that the average flow does not change significantly with seasons and years. This is owing mainly to two factors. First, in the PSG network the type of usage is especially indoor water use. Second, the number of inhabitants supplied is constant throughout the year because the seasonal fluctuation is balanced. The seasonal component, moreover, being strictly dependent on the specific characteristics of the WDS under consideration, cannot be generalised and its analysis could lead to results that can be considered as being valid only in the specific context in which they have been obtained. These considerations meant that the focus of the study was on the daily demand variation, neglecting the seasonal component.

Figure 2 illustrates the typical daily demand pattern of a small Italian residential area (e.g. Molino Alvisi et al.17 and Alvisi et al.3), in which the maximum value of water demand is reached early in the morning and two further peaks of lower intensity are present, corresponding with lunch and dinner time. Fig. 3 shows the same daily pattern but takes into account three different measurement sections with a different number of users. The flow required by users has been represented dimensionlessly (Cd) considering the mean demand requested by users every 15 min of the day over the daily average flow, μq. Results show that the daily Cd pattern does not vary its shape during the day with the number of users supplied.11

A dimensionless expression of the maximum water required is thus given by the peak demand coefficient, Cp, a ratio of the maximum flow, Qm, against daily average flow, μq:

\[ C_p = \frac{Q_m}{\mu_q} \]

Results obtained for one of the measurement sections (termed ‘3a’) have been estimated. For each of these, the corresponding maximum Cp values (MCp) have been estimated. Results obtained for one of the measurement sections (termed ‘3a’) are shown in Fig. 4, from which it can be seen that when considering Δt = 1 h, instead of 1 min, leads to an underestimation of about 28% of demand during the peak.

The residential water requirement is a function of multiple factors, many of them specific to the conurbation under consideration. This explains the numerous relations and tables available in the technical literature, which suggest means for estimating the maximum water consumption (e.g. Babbitt5 and Rich6). These relations can often lead to extremely different estimates of the peak factor and, usually, they do not take into consideration the random nature of the peak water demand. A common element to most of them, however, is the expression of the peak factor as a function of the number of inhabitants NAb, as for example suggested by Babbitt5 in the relationship

\[ C_p = 5 \left( \frac{N_{Ab}}{1000} \right)^{-0.2} \geq 20 \cdot N_{Ab}^{0.2} \]

Even if equation (2) originally refers to Cp evaluation for sewer systems, it has been widely applied in the peak drinking water studies for conurbations with at least 5000–10 000 inhabitants.

Table 2, referring to some of the well-established relations and tables in the technical literature, shows the Cp values obtained when considering a number of users similar to the case study presented in the current research.

### Table 2. Peak coefficient for small residential areas

<table>
<thead>
<tr>
<th>Number of inhabitants</th>
<th>100</th>
<th>250</th>
<th>750</th>
<th>1000</th>
<th>1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babbitt5</td>
<td>7.9</td>
<td>6.6</td>
<td>5.3</td>
<td>5.0</td>
<td>4.8</td>
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<tr>
<td>Funel18</td>
<td>9.8</td>
<td>—</td>
<td>—</td>
<td>4.4</td>
<td>—</td>
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<tr>
<td>Fair and Geyer19</td>
<td>5.2</td>
<td>5.1</td>
<td>4.9</td>
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<td>4.7</td>
</tr>
<tr>
<td>Rich6</td>
<td>7.3</td>
<td>6.3</td>
<td>5.3</td>
<td>5.0</td>
<td>4.8</td>
</tr>
</tbody>
</table>

4. EFFECT OF THE SAMPLING INTERVAL ON THE PEAK FACTOR

In the technical literature, the maximum water demand is usually related to the hour of the maximum demand. Equation (1) could be obtained as the volume of water required at the peak hour over the average, hourly flow demand volume.

Assuming a time interval of 1 h could result in a lower estimation of demand than is correct. Indeed, taking the average may neglect major peaks that could arise during the peak hour.4 On the other hand, considering finer time scales (e.g. 1 s) would produce more information than can be justified by the quality of the hydraulic models, which operate at coarser time intervals, and could lead to the over-fitting of the model.20 Researchers de Marinis et al.4 demonstrated that 1 min intervals can be considered to be a good compromise.

The effect of sampling resolution has been investigated in the present study. From one set of flow data collected at 1 min intervals, several further data sets have been derived \( \Delta t \in \{ 1', 2', 5', 10', 20', 30', 60' \} \). For each of these, the corresponding maximum Cp values (MCp) have been estimated. Results obtained for one of the measurement sections (termed ‘3a’) are shown in Fig. 4, from which it can be seen that when considering \( \Delta t = 1 \text{ h} \), instead of 1 min, leads to an underestimation of about 28% of demand during the peak.
Consequently, this analysis of demand has been undertaken using 1 min interval data.

5. PEAK FLOW DATA ANALYSIS

The analysis has been performed taking into account weekly data, collected over a period of almost two years. The data collected show that on weekdays the peak phenomenon is more marked than for weekends. Indeed, the average daily water volume supplied on Saturdays or Sundays is greater than the average daily water volume supplied on a weekday (Monday–Friday).

Analysis of the data has shown that the maximum water requirement can be represented as a function of the number of users. Fig. 5 illustrates the regression curve of maximum values of mean $C_p$, that are fitted by the curve following the relationship in equation (3).

\[ C_p = 11N_{Ab}^{0.2} \]

This expression can thus allow the estimation of the maximum flow required using a deterministic approach.

It should be noted that just the outlier point (▲) in Fig. 5 is not fitted by the curve. This point relates to the measurement point 8 of the network and may be explained considering that in the branched pipes downstream of point 8, the users are equipped with small tanks with pumps. This results in the truncation of the water demand during the peak requirement, reducing its effective value. The presence of pumps is testament to the inadequacy of the private links to the hydraulic network as the measured pressures at the corresponding node are fully satisfactory.

The proposed expression (3) is similar to that related by Babbitt,5 equation (2), that refers to $C_p$ evaluation for sewer systems, but with a lower coefficient. If this expression represents a useful relationship for estimating the maximum flow demand with a deterministic approach, the description of a stochastic variable—such as the water demand—should be studied with a probabilistic approach (e.g. Bao and Mays6 and Gargano and Pianese7). From this point of view, it is more appropriate to define confidence intervals of $C_p$ with a predefined failure probability, than to use a specific value. In Fig. 6, the experimental points (●) refer to average values of $C_p$ estimation, $\mu_{C_p}(N_{Ab})$, and the relative confidence intervals of 90%, 95%, 98% and 99% are plotted. In addition, the mean peak demand values have been fitted by a curve with a power relationship as follows

\[ \mu_{C_p} = 8N_{Ab}^{0.2} \]

The plot in Fig. 6 has been prepared considering standard deviation as being variable with respect to the number of inhabitants. Reducing the number of users leads to an increase of the confidence intervals. The trend of the coefficient of variation $CV(\sigma/\mu)$ when varying the number of inhabitants is shown in Fig. 7.

\[ CV = 0.1 + \frac{2}{[1 + (N_{Ab}/0.4)]^{1/4}} \]

The relationship proposed in equation (5) shows a good fit with the data collected from the monitoring system and could be assumed valid for a range of inhabitants from 60 to 1220. When decreasing the number of users, however, this relationship gives results comparable with some existing studies based on field data (e.g. Buchberger and Wells5). For a greater number of customers the $CV$, according to its expression, tends to 0.1—the value largely used in the literature for large networks (e.g. Kapelan et al.21 and
to employ wide precautions in estimating the demand is an uncertain variable might have induced practitioners. It is probable that, in the past, the knowledge that the water demand for other case studies. Nevertheless, it would also be mentioned relations could be used to study the maximum flow concentrations. The results could therefore be generalized and the above-mentioned relations could be used to study the maximum flow demands for other case studies. Nevertheless, it would also be convenient to use other experimental data relating to other real WDS in order to validate these relationships further.

6. MAXIMUM WATER DEMAND MODELS

Probabilistic models have been studied in this paper to describe the maximum water demand. Optimal rehabilitation/design and reliability studies on WDS use probabilistic models to generate data samples of the maximum flow demand. This is usually done through the application of the Monte Carlo sampling scheme or a similar sampling approach, for example Latin hypercube (McKay et al.21), modelling the demand with the normal probability density function. In the case of a small number of users, it has been seen that other models could be better suited to representing the maximum water requirement. Statistical inferences on a wide range of data samples, indeed, have shown (Fig. 8) that both log-normal and Gumbel models represent well the peak requirement for a small number of users. Both distributions satisfy the Kolmogorov–Smirnov test. The parameters required for the presented models are the mean value, \( \mu \), and the standard deviation, \( \sigma \). These have both been estimated from the data collected and their values are shown in Fig. 8 in relation to the number of users.

7. CONCLUSIONS

A better knowledge of the maximum water demand allows for the more effective design or management of a WDS. With the water demand being a random variable, in the technical literature there is a general agreement to tackle WDS studies with a probabilistic approach. The lack of empirical research on the topic, however, means that there are few practical applications. The present work, therefore, has had the aim of contributing to a deeper knowledge of the maximum water demand. Indeed, new formulae to estimate the peak flow demand for a small number of users have been proposed. This has been achieved through analysing data collected from a real WDS. Gumbel and log-normal distributions represent well the peak water requirement—at least for the range of users investigated here. Moreover, in relation to the number of users, the parameters of the models have been estimated and it has subsequently been shown that the CV decreases, with the increasing number of inhabitants. The above-mentioned models and the corresponding relations for the estimation of the parameters (e.g. \( \mu \), \( \sigma \)) can be used for generating random demand data and, thus, could allow the application of probabilistic approaches.

For a better data analysis, the effect of the resolution for resampling the collected data, with respect to the time interval, on the peak rate estimation has been investigated. The results obtained show that a more accurate estimation of water demand at the peak can be achieved by using 1 min interval data. Moreover, it has been highlighted that the classical relations available in the technical literature lead to an overestimation of the maximum water demand and consequently to an over-design of the WDS components. The results obtained are, however, in

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**Table 3. Peak demand coefficient**

<table>
<thead>
<tr>
<th>Number of inhabitants</th>
<th>Deterministic approach</th>
<th>Probabilistic approach</th>
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</thead>
<tbody>
<tr>
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<td>250</td>
</tr>
<tr>
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<td>4</td>
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<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**Table 4. Peak demand coefficient in similar experimental research**

<table>
<thead>
<tr>
<th>Inhabitants</th>
<th>( C_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alvisi et al.2</td>
<td>( 600–2000 )</td>
</tr>
<tr>
<td>LATibi7</td>
<td>( 2805 )</td>
</tr>
</tbody>
</table>

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![Fig. 7. Variation of CV in relation to the number of users](image-url)
agreement with the few available studies based on experimental data.

The useful information obtained by this analysis of the PSG network could encourage the installation of new monitoring systems, which could then lead to the verification of the relationships suggested and result in an increased availability of usable data for future studies.

REFERENCES


7. LATibi. *Bilancio Idrico e Affidabilità dei Sistemi e delle Reti Idriche*. See http://www.latibi.unibas.it/prodotti/rapporti/02rapp01/02.html


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