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Evaluation of Peak Water Demand Factors in Puglia (Southern Italy)

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Abstract: In the design of a water supply network, the use of traditional formulas of the peak factor may lead to over-dimensioning the network pipelines, especially in small towns. This discrepancy is probably due to changes in human habits as a consequence of a general improvement of living conditions. Starting from these considerations, and given the availability of a wide random sample data, an analysis of the water demand for several towns in Puglia was carried out, leading to the definition of a relationship between the above mentioned peak factor and the number of inhabitants, based on a stochastic approach. An interesting outcome of this study is that the design of water supply network is possible without considering the use of monthly and weekly peak factors, since the current water demands appear not specifically sensitive to these variations; moreover, the magnitude of the peak factor, as shown by measured data, is considerably lower compared to literature values, especially for small towns.

Keywords: peak factor; water demand; water distribution

1. Introduction

In the past century the improvement of living conditions and the large infrastructure investments of industrialized countries has led to a significant increase in water consumption. This process has started in Puglia (Southern Italy) in 1906 with the construction of the Acquedotto Pugliese (Puglia Aqueduct, AQP in the following lines) that conveys water from the spring of the Sele River in Campania to the most southeastern end of Italy (Figure 1).

AQP has the biggest water supply network in Italy and in Europe, and supplies the drinking needs of towns in Puglia deriving water from the Sele spring (superficial water and groundwater), located in the western hillslope of the Apennine watershed.

Actually, AQP manages a water network of 21,000 km (30 times the length of the Po River), including urban distribution networks, about 11,000 km of sewerage networks and 184 treatment plants. More than half of the network is rather old, built before 1970, and requires continuous maintenance and modernization. The need of expanding and renewing such networks is today very impelling and poses the problem of testing and/or updating with a critical approach, the design criteria that were used for their construction or dimension (e.g., [1,2]).

One of the principal factors in designing water distribution systems is the peak water demand. Water use is not constant in time; its variability can be observed at different time scales: yearly, seasonally, monthly, weekly, daily, hourly, and instantaneously. The maximum consumption peaks are usually higher in small communities than in large ones while in very large centers water demand

tends to be constant in time and close to its average. Several deterministic relationships and tables are available from technical literature for the design of water supply system accounting for the fluctuation in water demand. However, most of these relationships were provided more than fifty years ago and need to be updated by the light of different habits in social and economic contexts profoundly developed since then.

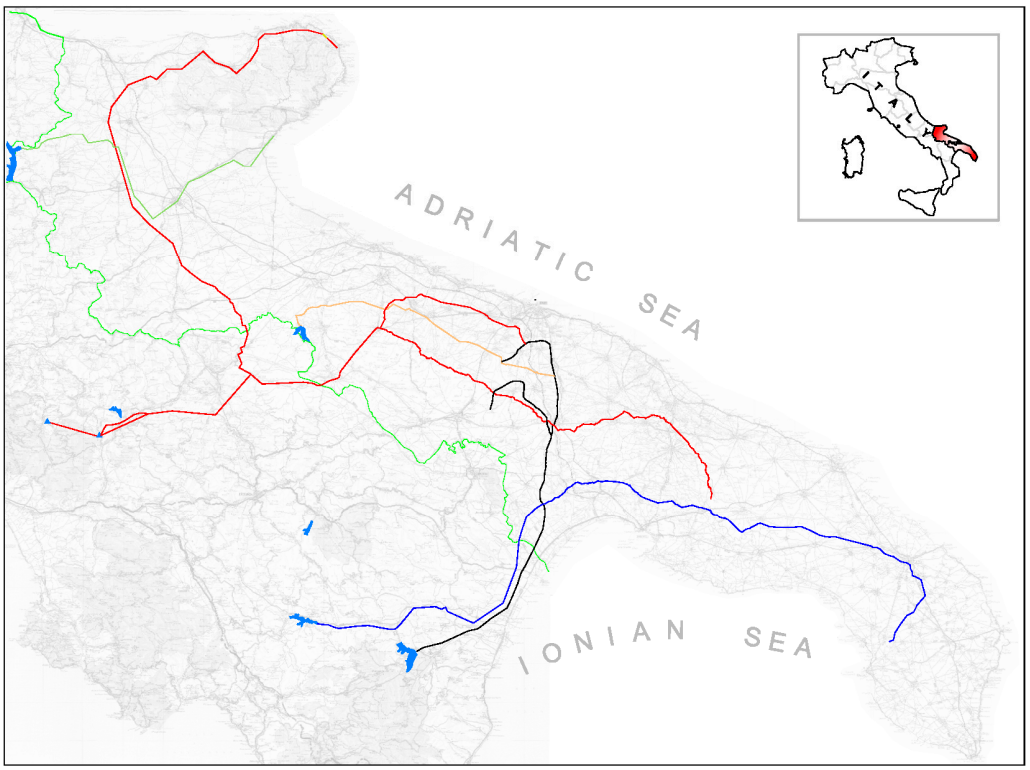


Figure 1. The AQP water supply network.

Based on data from an extensive field campaign carried out by AQP, we focus on the actual water usage and in particular on the magnitude of peak flow factors C_p, evaluated as the ratio, over a defined time period, between the maximum value and the average value of water consumption measured in several nodes of the AQP supply system.

2. Fluctuations in Demand: Literature Review

The peak water demand has an important role in water distribution system design because it represents one of the most onerous operating states of a network. Studies on drinking water distribution and consumption assume a certain importance in the international bibliography from the 1950s accordingly with the growth of urban distribution systems and the diffusion of more accurate measurement equipment.

Water consumption today is definitely not comparable to that of the early 1990s; therefore, the measures of water consumption and, consequently, the analysis about peak factors and discharge formulas of that period are not comparable with current ones.

Several recent studies have analyzed the influence of different parameters on water demand, for example Haque et al. [3] investigate how climate components and community intervention factors influence water demand. Gurung et al. [4] show that household peak water demand has a strong correlation with costly pipe network upgrades and this peak could be reduced through more efficient substitution strategies. Chang et al. [5] conducted a statistical analysis of seasonal water consumption,

including irrigation, from 1960 to 2013 in Portland and observe that climate and weather factors are the most influential parameters on water consumption.

Beal et al. [6], with the aim to identify hourly and daily peak demand for a range of water end-uses in households located in South East Queensland carried out an analysis on 18 months of household water consumption data obtained from high-resolution smart meters installed in 230 residential properties. While many literature studies are deepening knowledge about different behavior observed in climatic and societal types, still, in the absence of site-specific information, the main references useful for engineers to design water distribution systems are provided by general purpose formulas. Among these, Fair et al. [7], suggested, for the United States, a peak flow factor of about 2.0 for daily peak and a value of about 4.5 for the hourly peak. Al-Layla et al. [8], based on field experiences, found a peak flow value ranging from 1.2 to 2 for daily peak and a value ranging from 2 to 3 for the hourly peak. Barnes et al. [9] provided typical values for the peak flow factor depending by climate (Table 1). Adams [10] proposed the peak flow factors shown in Table 2 which are applicable to the UK and were derived from an investigation of areas in Liverpool. Linaweaver et al. [11] found that the peak hourly factor for domestic demand was about 2.6–2.8 for eastern states and 4.3–4.9 for western states of US. Gomella and Guerrée [12] suggested a peak factor constant value equal to 4 for the design of a water network.

Table 1. Peak flow factors computed at different time scales [9].

Peak Flow Factor	Climate			
	Temperate		Warm, Dry	
	Range	Typical	Range	Typical
Max hourly/average day *	2.0–4.0	2.5	3.0–6.0	3.5
Max daily/average day *	1.3–2.0	1.5	2.0–4.0	2.5
Max weekly/average day *	1.1–1.3	1.2	1.7–2.3	2.0

Notes: * Where the average day is the average annual consumption.

Table 2. Ratio of peak hourly flow to annual average flow [10].

Population	C_p
<500	2.9
500–5000	2.9–2.5
5000–50,000	2.5–2.1
50,000–500,000	2.1–1.9

The first relationships to recognize a dependence of the peak factor from population were proposed by Harmon [13]:

$$C_p = \frac{18 + \sqrt{P/1000}}{4 + \sqrt{P/1000}} \quad (1)$$

and Babbit [14]:

$$C_p = 20 \cdot P^{-0.2} \quad (2)$$

where P is population.

Both were originally developed to explain the variability of flow observation in sewer systems. In principle they can be used to calculate peak water flow rates in distribution systems assuming that all water used in the community is drained to the wastewater collection system.

Despite its age, the Harmon formula has been adopted in 2005 by the Australian ENVC (Department of Environment and Conservation) [15] in order to calculate peak flow rates for communities that do not have adequate measures of water consumption useful to calculate average day, maximum day and peak flow.

Also other relationships exploit a dependence of peak rates on population. Among these, Metcalf and Eddy [16] assume the peak factor is a constant value when the population is less than a fixed threshold, and decreases logarithmically when the population exceeds the same threshold:

$$C_p = \begin{cases} 4 & N \leq 5 \\ \frac{4.8}{N^{0.113}} & N > 5 \end{cases} \quad (3)$$

where N is population in thousands.

Johnson [17] proposed the following expression:

$$C_p = \frac{5.2}{N^{0.15}} \quad (4)$$

Using data from Metcalf and Eddy [16] and Johnson [17], Gifft [18] revised the Babbitt equation, suggesting the following expression:

$$C_p = \frac{5}{N^{0.167}} \quad (5)$$

Based on the Babbitt formula and exploiting daily water consumption observed for several Italian towns, Ippolito [19] proposed to adopt the values of hourly peak factor C_p reported in Table 3.

Table 3. Peak flow factor [19].

Population	C_p
<10,000	5–3
10,000–50,000	3–2.5
50,000–100,000	2.5–2
100,000–200,000	2–1.5

Within the Italian technical literature, after Ippolito [19], Milano [20], analyzing several studies conducted for Italian and German towns, provided an estimation of the peak flow factor, calculated as ratio between maximum hourly flow and average daily flow as a function of the population, as reported in Table 4.

Table 4. Peak flow factor [20].

Population	C_p
50,000–200,000	2.50
200,000–500,000	2.00
>1,000,000	1.70

Analyzing and comparing different values of peak factor extracted from the technical literature, it appears that conventional methods used for decades for estimating the peak factor are based on empirical deterministic expressions and engineering judgment [21].

A more recent literature proposes the use of a statistical approach to the definition of the peak factor. In particular De Marinis et al. [22] analyzed the water demand for a small town near Frosinone by monitoring continuously its system network. They agree that the classical literature relationships for estimating the peak factor lead to a significant overestimation compared to the real maximum water demand and proposed the use of a Gumbel distribution to describe the population of peak factors. Thus, starting from the relationship suggested by Babbitt [10], they found a relationship for the estimation of the peak flow factor, valid for a small town of about 6500 inhabitants, Piedimonte San Germano (Frosinone, Italy), characterized by the following expression:

$$C_P = 11 \cdot P^{-0.2} \quad (6)$$

Zhang et al. [21], proposed the application of a Poisson rectangular pulse (PRP) model for residential water use with principles from extreme value analysis to develop a theoretical reliability-based estimate of the peak factor. This kind of approach allows to incorporate in the peak factor evaluation several characteristics of the network system other than population. We followed their approach exploiting a theoretical expression of the instantaneous peak factor (*PF*) which is reported in Section 5, Equation (7).

So far, a few other studies have been developed starting from the consideration that the water demand pattern can be described by a PRP model [23]. Among these Blokker et al. [24] presented a water demand end-use model developed to predict water demand patterns with a small time scale (1 s) and residence spatial scale.

3. Field Campaign

3.1. Dataset Analysed

In this study sample measures of water consumption in 150 towns located in Puglia (Southern Italy) were exploited, a number representing about half of the municipalities served by AQP in the entire region. The towns' population ranges between 1900 and 190,000 inhabitants, although, 85% have less than 40,000 inhabitants. The flow data are related only to drinking water demand and to urban water consumption.

The flow data were collected during an extensive campaign aimed to the recovery and rationalization of distribution networks and reduction of water losses. The campaign lasted from 2008 to 2010 and provided sample measurements of flow and pressure, collected downstream of reservoirs at time steps of 3, 5, or 10 min. In each site measures were recorded continuously for a minimum period of about 14 days, lasting seven days before and seven days after some repair intervention in the downstream network.

3.2. Flow Data Definition

Data collected in the measurement campaign required some preliminary selection. In particular, only data collected after the repair intervention were used. Additionally, towns with significant touristic fluctuation and data characterized by abnormal water supply probably due to special regulation carried out by the managing authority or affected by instrumental measuring errors were excluded from these first analyses.

Thus the time series available after this pre-selection consist of continuous measurements sampled at 3, 5, or 10 min, recorded for about seven days, in 129 towns. The time series are recorded in a different month for each town. The total dataset includes measurements for each month of the year, except August, that, however, is a month considered not significant for the peak flow definition for residential water demand.

3.3. Effect of the Sampling Time Interval on the Peak Factor

In the technical literature the maximum water demand is usually related to the hour of the maximum demand. The peak coefficient is obtained as the volume of the water required at the peak hour over the average, hourly flow demand volume [25].

Adopting a time scale equal to 1 h the analysis of the sampling data could provide a lower estimation of water demand. The increase of the time scale leads to neglect major peaks that could arise during the time interval adopted. The effect of sampling interval has been investigated by Tricarico et al. [25] and de Marinis et al. [26] showing that 1 minute intervals can be considered to be a good compromise between 1 h and 1 s of sampling resolution, obtaining in this way a 20%–30% reduction of the peak factor. Gato et al. [27] using one set of flow data collected at 5 min intervals confirm this estimate even if, in some cases, with smaller reduction.

The effect of sampling resolution has been investigated in the present study. From a dataset of measures collected at 3, 5, or 10 min intervals, several further data sets have been derived like their multiples up to 1 h. For each of these the corresponding maximum C_p values have been estimated and results are shown in Figure 2 where, considering a 1-h time interval, instead of the smaller (3, 5, or 10 min), leads to an underestimation ranging from about 5% to 11%, smaller than those observed by de Marinis et al. [26] and Tricarico et al. [25].

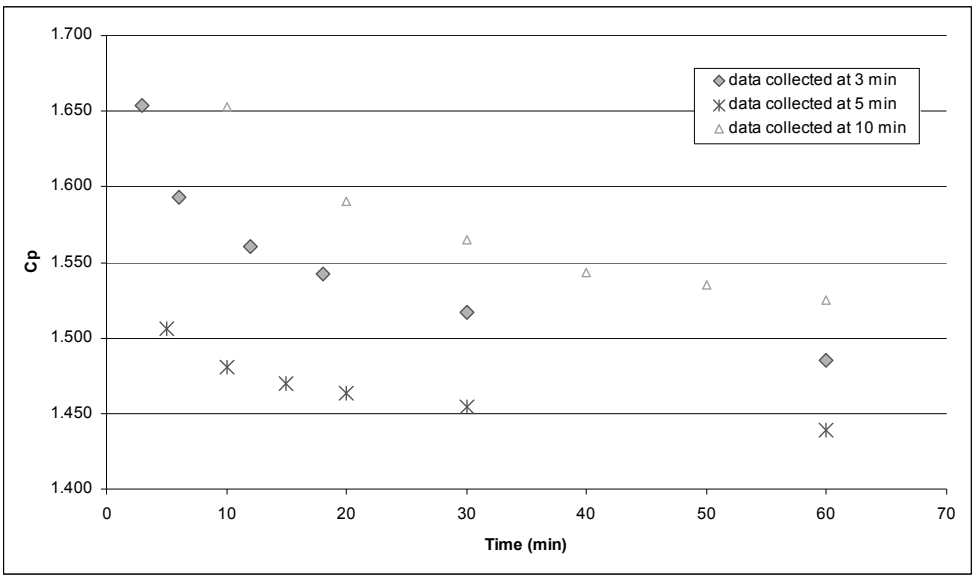


Figure 2. Effect of sampling interval (time) on peak factor.

The analyses here presented are focused on the peak flow factor evaluated as the ratio between the maximum value (evaluated using of the minimum available time of aggregation) and the average value of water daily consumption.

4. Analysis of Water Demand Variability

Figure 3 illustrates the typical daily demand pattern for one of the investigated towns (Crispiano). Observing this figure it is possible to recognize that the maximum water demand is reached early in the morning; other two peaks, although of lesser value, can be observed at midday and in the late afternoon. This trend reflects the classical pattern of an Italian residential area and confirms the behavior identified by Molino et al. [28], Alvisi et al. [29] and de Marinis et al. [30].

For each of the available time series and for each day of measurement a preliminary analysis was carried out by evaluating representative parameters of flow rate like maximum, daily average, minimum and secondary peaks, as well as the daily per capita water demand and the peak factor.

Data were then analyzed considering, for each municipality, the population served and the day of the week and the month of the first day of measurement campaign.

In fact, technical literature reports numerous data and experiences showing that water demand is influenced not only by hourly variation but also by a seasonal and weekly variability depending on climate and socio-economic conditions [19].

The analysis showed that water demand variability for different months and weekdays can be related in a more random way to water consumption with respect to the observed variability at daily, weekly or monthly scale. Figure 4 shows for example monthly variation of peak coefficient C_p for towns with less than 20,000 inhabitants: it is possible to observe the absence of a marked seasonal trend. Peak factors show a maximum value in correspondence of May, but also a strong random variability. The overall observation suggests that drinking water demand in Puglia is unaffected by

climate and temperature demonstrating, following Cole et al. [31] that indoor consumption mainly affects the nature of water use in this region.

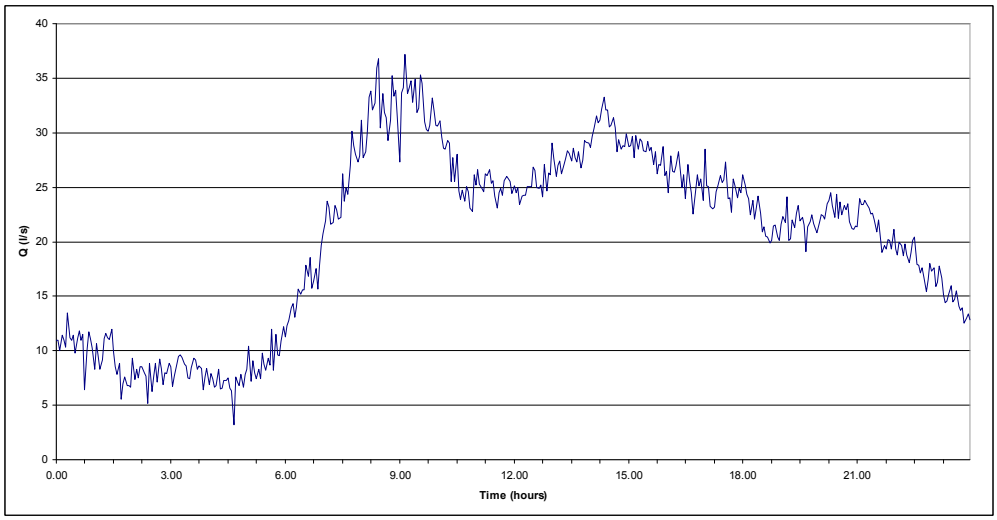


Figure 3. Example of daily water flow recorded during the measurement campaign (town: Crispiano).

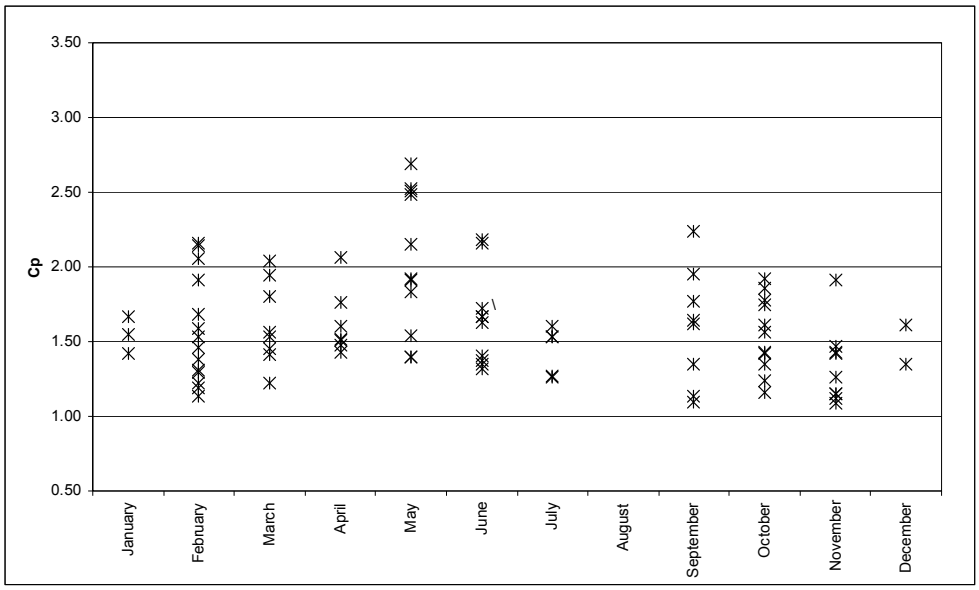


Figure 4. Peak coefficient: observed monthly variation.

The weekly variability of the peak coefficient is shown in Figure 5 and highlights a somehow large and homogeneous variability. Every line represents the daily peak coefficient during the monitoring campaign for a single town. It is not possible to identify a day of maximum consumption and not significant differences can be found between working days and the weekend. The results of this preliminary analysis lead to the conclusion that the maximum value of the peak flow factor C_p, computed as the maximum of the values for the different days of measurement, can be considered not affected by weekly and/or monthly variation.

Peak factors are usually assumed to increase when decreasing the number of consumers (e.g., [32]). The dependence on population of the measured (evaluated as maximum values on weekly temporal scale) peak factor C_p is shown in Figure 6, where a general decreasing trend can be observed. On the other hand, numerical values are significantly lower than those proposed by most of the empirical relationships just mentioned in Section 2. Observed values, except for two towns, Alezio and Sannicola,

do not exceed 2.50. A comparison among measured data and the empirical formulas of Harmon [13], Babbitt [14], Metcalf and Eddy [16], Johnson [17], Gifft [18] and De Marinis et al. [22] is illustrated in Figure 6. It can be observed that all the used literature formulas, except De Marinis et al. [22], tend to overestimate the value of the peak coefficient C_p. This is quite evident, in particular, for towns of less than 10,000 inhabitants where the overestimation reaches 150%. A different result is obtained, instead, using Equation (3) proposed by de Marinis et al. [22] that seems to represent well the average value of the measured data. On the other hand, this last formula is not sufficiently precautionary suggesting peak factors lower than the higher observed values.

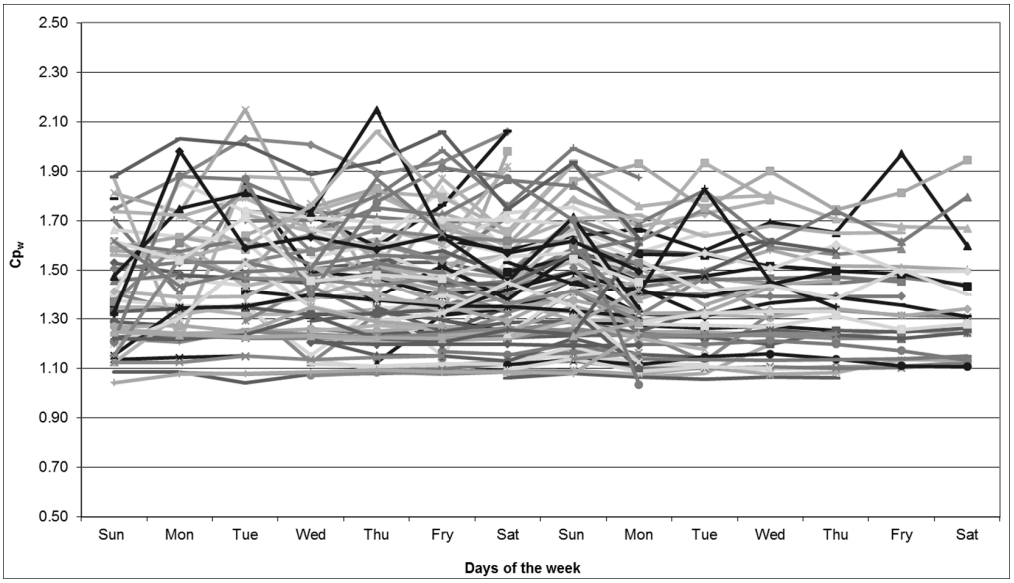


Figure 5. Weekly peak flow coefficient.

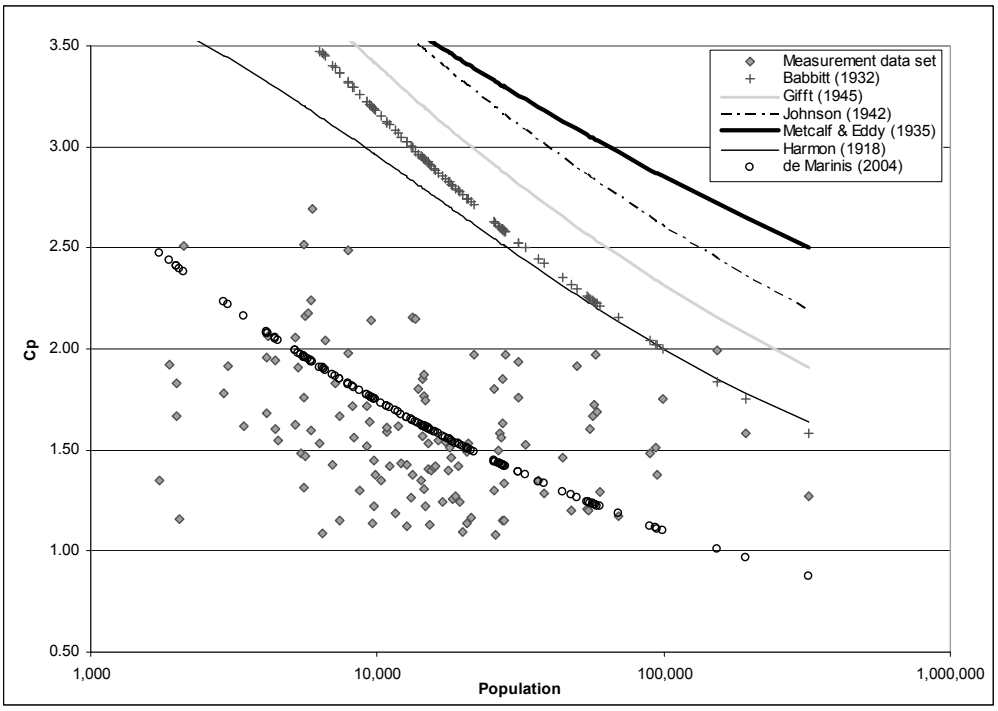


Figure 6. Comparison of experimental data and literature formulas for the corresponding population using a logarithmic scale.

The analysis of the data has shown that maximum values of the peak coefficient C_p can be represented as a function of the number of users, like most of the relationships provided by the technical literature and in particular the Harmon formula.

5. Theoretical Distribution of Peak Coefficient

Recent studies have shown how difficult it is to represent the water demand by adopting a deterministic approach because of its randomness or uncertainty [1]. That consideration can be confirmed observing sample data and their dispersion in Figure 6. In this context Zhang et al. [21], developed a theoretical reliability-based methodology for the estimation of an instantaneous peak factor (*PF*) for residential water use, using a probabilistic approach based on the PRP representation and leading to the extreme value Gumbel distribution of the maxima.

Following this approach, the instantaneous peak flow factor is evaluated as follows:

$$PF(N/p) = \psi^* \left(1 + \zeta_p \sqrt{\frac{1 + {\theta_q}^2}{\psi^* \, \rho \, N}} \right) \tag{7}$$

We exploited such a formulation, where N is the number of homes in the neighborhood evaluated considering that each home has 2.6 people on average in Italy; ψ^* is the dimensionless peak hourly demand factor assumed equal to 1.8, suitable to the Italian context (e.g., [19,20]); ξ_p is the pth percentile (frequency factor) of Gumbel distribution given by Chow et al. [33]:

$$\zeta_p = -\frac{\sqrt{6}}{\pi}[0.5772 + \ln\ln(1/p)] \tag{8}$$

Finally, ρ and θ_q are the daily average utilization factor for a single family home and a coefficient of variation of PRP indoor water demand pulse, respectively assumed equal to 0.045 and 0.55, as reported in Zhang et al. [21]. Using the above described parameters and considering the 99.9th percentile, and Equation (7) becomes:

$$PF(P) = 1.8 + \frac{1.8}{\sqrt{N}} \tag{9}$$

where N is the population in thousands. It is worth noting that, due to the structure of Equation (7), the dimensionless peak hourly demand factor also behaves as asymptotic value of the instantaneous peak factor for increasing N.

In Figure 7 comparison between the peak flow factors obtained using the above theoretical relationship and those extracted from the measurement campaign is reported; it is interesting to note that the above theoretical relationship is able to interpolate the maximum values of peak factors, providing a useful tool able to evaluate the maximum water demand using a precautionary approach considering also the typology of available data. Figure 8 shows a comparison between the theoretical curve in Equation (9) and values extracted from a previous study of the Politecnico di Bari in 1999 in the same region and data deduced from other Italian areas [29,34,35].

Equation (9) seems to be compatible with other data, ensuring, at the same time, an acceptable margin of safety for the design of a water supply.

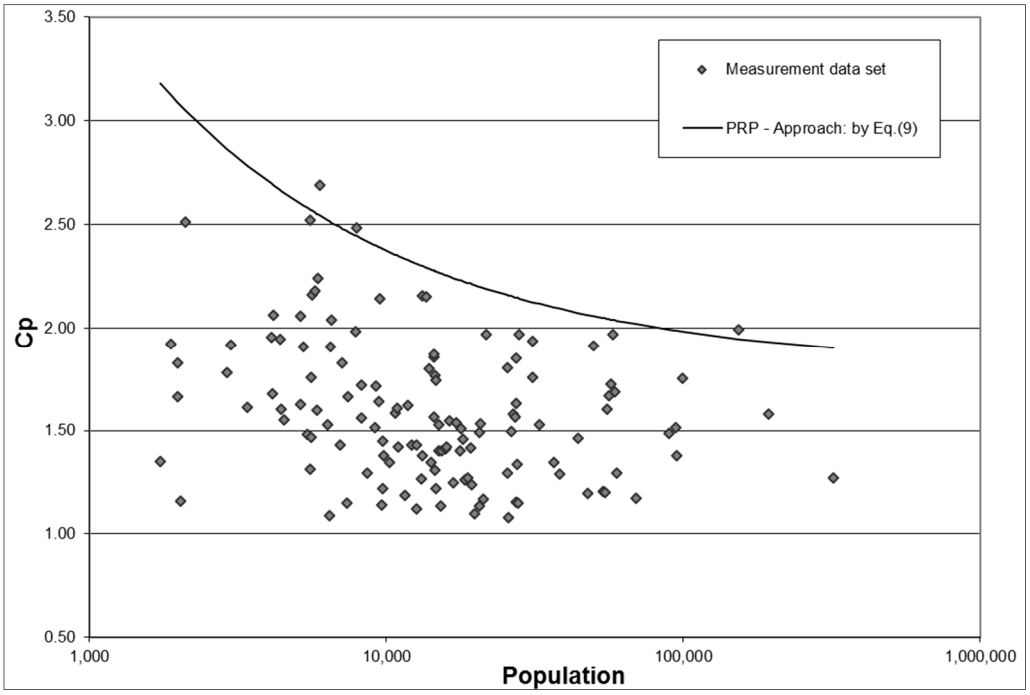


Figure 7. Theoretical relationship curve and measurement dataset depending on the population.

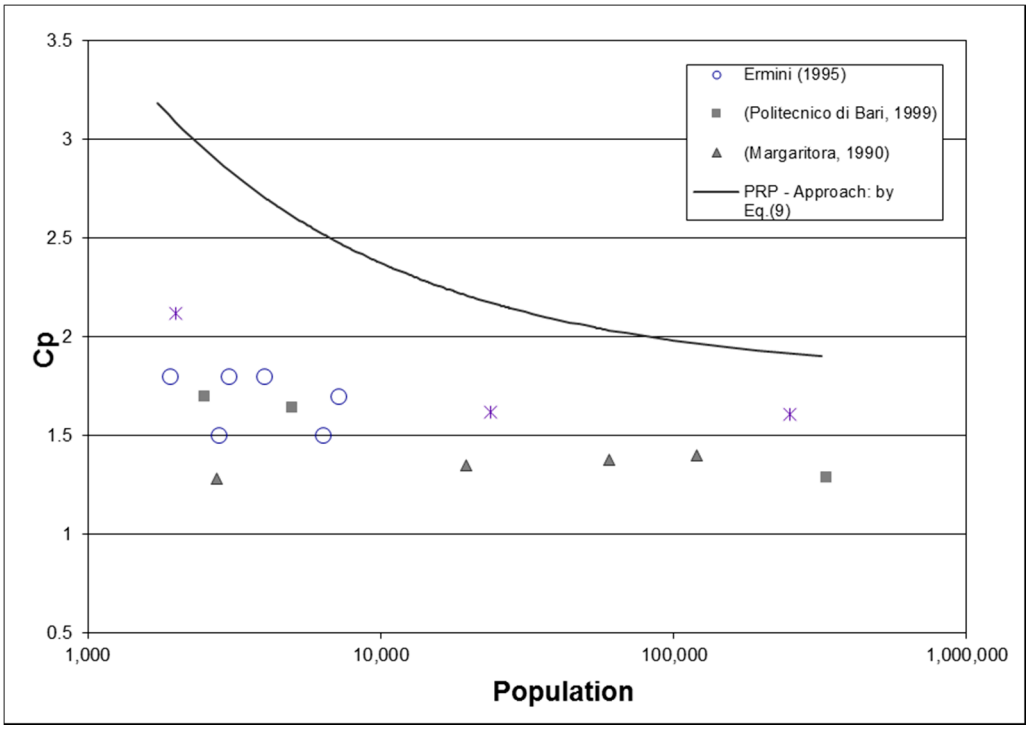


Figure 8. Theoretical relationship curve and measured data of others Italian studies using the logarithmic scale of population.

It is necessary to point out that the peak factors investigated in this research (whose values are reported in Figure 6), are the maximum values evaluated using a weekly observation interval placed in a random period of the year. Therefore, we used the theoretical approach proposed by Zhang et al. [21] for the analysis of the instantaneous *PFs*, in the hypothesis that the peak factors randomly sampled

during the field campaign belong to a statistically homogeneous population representing the base process of the Gumbel distribution of maxima. In order to test this hypothesis we investigated if the peak factors observed can be assumed exponentially distributed; by producing an exponential probability plot of the *PF* sampled variable (Figure 9). More in detail, assuming the *PF* random variable as exponentially distributed, its non-exceedance probability distribution, $p(PF)$ is:

$$p(PF) = 1 - e^{-PF \times \alpha} = 1 - e^{-\xi_e} \tag{10}$$

where ξ_e is the exponential distribution frequency factor and α is the scale parameter of the exponential distribution. Following the approach proposed by the Zhang et al. [21] the frequency factor of the Gumbel distribution, ξ_p, may be calculated using the Equation (7) as follows:

$$\xi_p = \frac{PF/\psi^* - 1}{\sqrt{\frac{1+\theta_q{}^2}{\psi^* \rho N}}} = \frac{PF}{\psi^* \sqrt{\frac{1+\theta_q{}^2}{\psi^* \rho N}}} - \frac{1}{\sqrt{\frac{1+\theta_q{}^2}{\psi^* \rho N}}} \tag{11}$$

where ξ_p can be written also $\xi_p = \alpha \times (PF - \mu)$ with α and μ parameters of the Gumbel distribution. On the other hand, the Gumbel distribution is the extreme value distribution of the annual maxima of a Poissonian number of independent and identically exponentially distributed random variables, with the scale (α) parameter of Gumbel distribution equal to the scale parameter of the exponential distribution [36]. Consequently, Equation (11) allows the evaluation of the α scale parameter of the exponential distribution hereafter reported:

$$\alpha = \frac{1}{\psi^* \sqrt{\frac{1+\theta_q{}^2}{\psi^* \rho N}}} \tag{12}$$

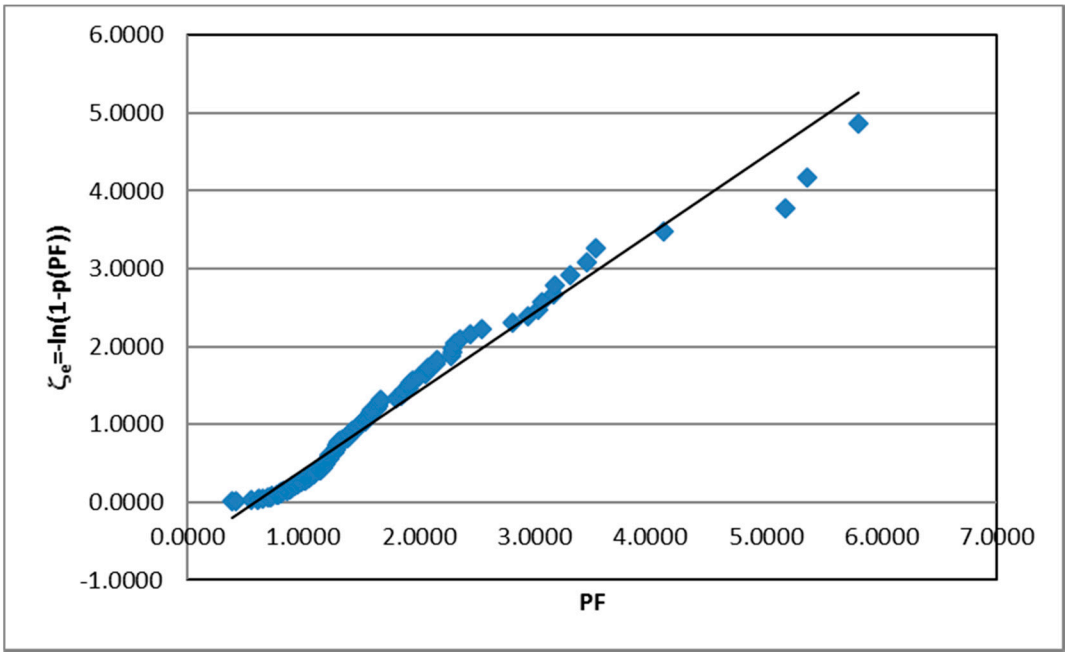


Figure 9. The exponential probability plot of the Peak Factor distribution (diamonds points) and the linear regression (black line).

Thus, using Equations (10) and (12), the frequency factor of the exponential distribution ξ_e is equal to:

$$-\ln(1-p(PF)) = \xi_e = \alpha \times PF = \frac{PF}{\psi^* \sqrt{\frac{1+{\theta_q}^2}{\psi^* \rho N}}} \quad (13)$$

Equation (13) allows for the evaluation of the PF probability distribution, $p(PF)$, by filtering the random variable from the influence of population. Looking at Figure 9, where the exponential probability plot of the peak factor data is reported, it is possible to confirm the assumption that the their distribution may be well represented by an exponential distribution. Apart from the visual assessment of Figure 9, the goodness of fit to the linear regression (black line in Figure 9) provides a coefficient of determination $R^2 = 0.97$. Thus, demonstrating that by filtering the effect of population of different towns, the randomly sampled peak factors can be ascribed to a unique regional exponential distribution.

6. Conclusions

In this study, a water demand of 129 towns located in Puglia region (Southern Italy) was investigated using the available flow data (characterized by time series of length about seven days) collected during a water loss campaign for the recovery and rationalization of distribution networks. In particular, the analysis was focused on the behavior of the peak flow factors extracted from the available time series respect to that investigated in recent papers. The analysis confirms what is suggested by Milano [20] and Alvisi et al. [29]: that there is a greater uniformity of the daily water consumption during the last fifty years; this may justify peak coefficient values rather low and, at the same time the poor representativeness of some literature expressions, normally suggested by technical manuals, that may lead to unnecessary oversizing of urban water networks supply.

The magnitude of peak factor, as shown by data exploited in this study, is considerably lower than literature values, especially for small towns. In detail, comparing peak factors measured with literature values it can be concluded that literature formulas overestimate the peak factor in 99% to 100% of the observed cases (Table 5). The same table shows also the average and maximum value of overestimation for each of the considered literature expressions. The magnitude of overestimation for the small towns amounts from 3.83 for Gifft formula to 3.09 for the Harmon formula with intermediate values for Babbit and Zhang formulas.

Table 5. Overestimation of peak hour factor using literature formulas.

	Babbitt	**Gifft**	**Harmon**	**Zhang**
Overestimated data	99.22%	100.00%	99.22%	100.00%
Average overestimation	1.98	2.13	1.84	2.07
Maximum overestimation	3.76	3.83	3.09	3.48

Available data allow the analysis of the daily, weekly, and seasonal variation of the peak coefficient for the Puglia region leading to a definition of a relationship between the number of inhabitants and the above mentioned peak factor. The proposed relationship is in agreement with recent Italian technical literature reporting measurements of flow data even if at the moment international literature does not report experimental analysis useful to test the validity of the proposed formula. An interesting outcome of this study is that the design of water supply network is possible without considering the use of monthly and weekly peak factors, since the current water demands appear no more sensitive to these variations.

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Author Contributions: Gabriella Balacco and Alberto Ferruccio Piccinni conceived the study. Antonio Carbonara provided data. Gabriella Balacco and Andrea Gioia did the computation. Gabriella Balacco, Antonio Carbonara, Andrea Gioia and Vito Iacobellis analyzed the data and performed the analysis. Gabriella Balacco and Andrea Gioia drafted the manuscript. Vito Iacobellis and Alberto Ferruccio Piccinni revised the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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