Temporal and spatial aggregation in modeling residential water demand

R. Guercio, R. Magini & I. Pallavicini
Dipartimento di Idraulica, Trasporti e Strade,
Università di Roma 'La Sapienza', Italy

Abstract

A correct modeling of instantaneous water demand can be a powerful tool in the formulation of an optimal control policy of pressure heads aimed at the minimisation of physical losses in water distribution networks. The results of an annual monitoring campaign of instantaneous residential water consumption on 82 single-family residences, whose occupants belong to the same socio-economic status, are presented here. The parameters intensity, duration and frequency of water uses have been estimated, in the hypothesis that the instantaneous water demand can be described by a Poisson Rectangular Pulse (PRP) stochastic process. Their temporal and spatial variability has been analysed considering different temporal and spatial aggregation scales.

1 The use of instantaneous water demand models in the management of water distribution networks

Residential water demand is influenced by many factors among which the socio-economic level of users, the climate with its seasonal fluctuations and the water prices are the most representative. The residential water demand constitutes the predominant fraction of the total amount of water distributed by municipal aqueducts, reaching and overcoming in general 75% of the total. Beside this component, the quantity of resource lost from water distribution systems through ruptures and leaks must be also considered. It reaches and sometimes broadly overcomes, in a lot of Italian networks, the 30% of the volume introduced in the system.

In this paper we analyse data from measurements of instantaneous residential water consumption of 82 single-family residences. Why are we interested in

Transactions on Ecology and the Environment vol 61, © 2003 WIT Press, www.witpress.com, ISSN 1743-3541

describing and modeling instantaneous water demand? Actually, water demand can be analysed at different temporal scales and for each, specific forecasting models can be developed, each with a different field of application. In particular, according to the formulation of Billings and Jones [1], we are dealing with "long term" models when the temporal horizon taken into consideration is longer than 10 years. This kind of analysis of water demand is primarily finalised to water resources planning. "Middle term" models generally consider variations of water demand for time periods greater than 1–2 years but smaller than 10 years. They are employed both in the design of improvements of the distribution system and to define a correct price policy. When the temporal horizon of analysis is smaller than 1–2 years, "short term" models should be considered, which support water system operations as well as budgeting and financial management. The analysis of the water demand at the smallest time scale, which goes from 1 minute to 1 hour time, origins the so-called "instantaneous water demand models", whose field of application is mainly the real time management of distribution networks. Recently research has concentrated its efforts on a better characterisation of residential water demand, in particular defining its stochastic structure, in order to guarantee optimal conditions of service in term of quantity, pressure head, physical and qualitative features of the distributed resource, Buchberger et al. [2], [3], Clark et al. [4].

Our interest in instantaneous water demand modeling lies in the fact that they can be a powerful tool in the formulation of an optimal control policy of pressure heads aimed at the minimisation of physical losses. At this scope we interpret instantaneous demand models as a part of a wider control system which should also include:

- a methodology to maximise information from measurements of hydraulic parameters (pressures and flow discharges), for example through the interpolation of pressure heads based on geostatistical methods, Guercio et al. [8];
- a real time control system which supplies, under various conditions of water demand, "optimal" valves settings, that is the lowest pressures heads able to guarantee efficient service conditions, Guercio et al. [6];
- a suitable hydraulic network model.

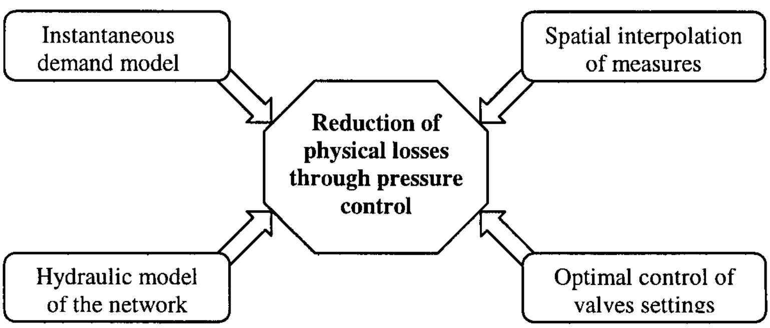

Figure 1: Schematic of a real time control of head pressure for leaks reduction.

Transactions on Ecology and the Environment vol 61, © 2003 WIT Press, www.witpress.com, ISSN 1743-3541

2 Modeling instantaneous water demand and parameters estimation

Water demand has been modeled as a Poisson Rectangular Pulse (PRP) process. Four parameters has been considered, namely Frequency λ, Duration ε, and Intensity with mean μ and variance σ^2, Guercio et al., [5].

Their estimation has been accomplished with the methods of moments equating four statistical properties (moments) of the observed data with their analytical expression. This system of equation is non-linear and has been solved with a non-linear least-squares algorithm.

Parameters estimation has been performed dividing each day in twenty-four hourly time intervals and assuming the stochastic process to remain stationary in the same time interval of the same day of the week of the same month. As a result the hourly variation of the parameters for each day of the week was found. Different parameter variations for each month were obtained.

3 The case-study

Water demand data of 82 single-family residences into four blocks of the same building in the city of Latina, 70 km south of Rome, were monitored for about one year by means of single-jet, turbine-type water meters equipped with a remote communication system emitting a pulse every 2.5 litres of water consumption. Actually, 85 water-meters were installed, but three of them are measuring common consumption. Housing data for the four monitored blocks are reported in Table 1.

Table 1: Housing data for the four blocks monitored.

Block	*1*	*2*	*3*	*4*	*TOTAL*
Families	31	12	27	12	82
Inhabitants	70	23	64	20	177

Water consumption was measured since December 2000 and the measurement campaign is still in progress now. Data analysed in this work are related to 8 complete months of 2001. For two of the four blocks (1 and 3) there is unfortunately a lack of data in the summer period, due to a data-loggers black-out. In Figures 2, 3 and 4 the monthly mean values of frequency, duration and intensity for water consumption both for each single block and for all block together, are reported. Parameters oscillate around their mean values without any peculiar trend. None of the parameters shows a course that could clearly mark monthly average consumption. The estimated parameters and demand, normalised in terms of their mean value at different time scales (hourly, daily and monthly), were compared. A comparison between the variances of the normalised parameters and the variance of the normalised demand has also been carried out.

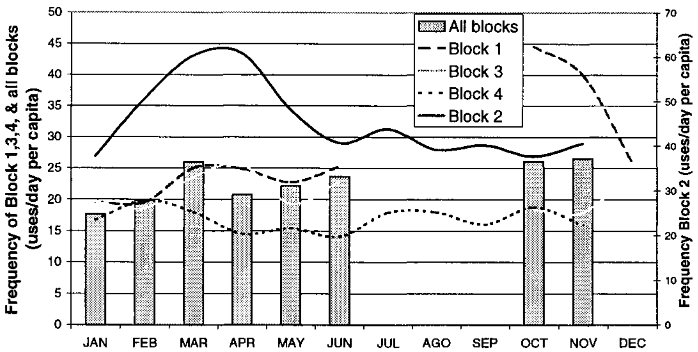

Figure 2: Mean monthly values of frequency.

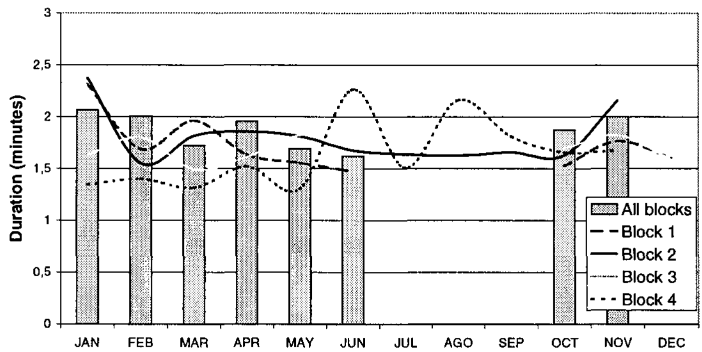

Figure 3: Mean monthly values of duration.

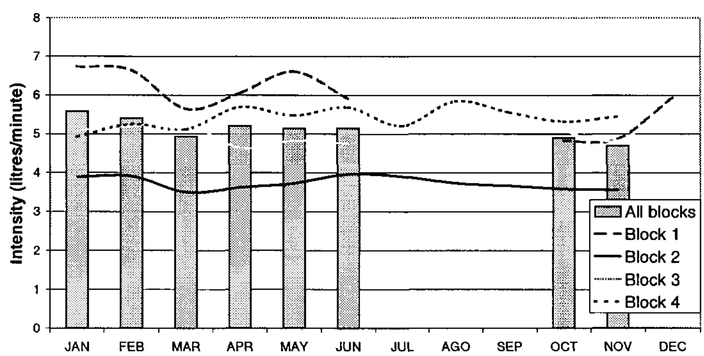

Figure 4: Mean monthly values of intensity.

At the monthly scale, the behaviour of all the parameters seems not to be strictly related to the demand one. In particular the frequency shows the main differences. Actually, in order to appreciate the monthly variation of the parameters and of water demand, a longer data set, covering a period of a few years, should be considered.

In Figure 5 the mean daily values of the frequency for each single block and for all the blocks together, are showed. The anomalous behaviour of Block 2, much higher than that of the others, can be noticed. This can be the sign of the presence of physical losses or of a non correspondence between the official and the real number of inhabitants.

Frequency shows a behaviour which is quite correlated to that of the demand, Guercio et al. [7], with a more consistent peak in the weekend and one less accented on Wednesday and Thursday (Figure 6).

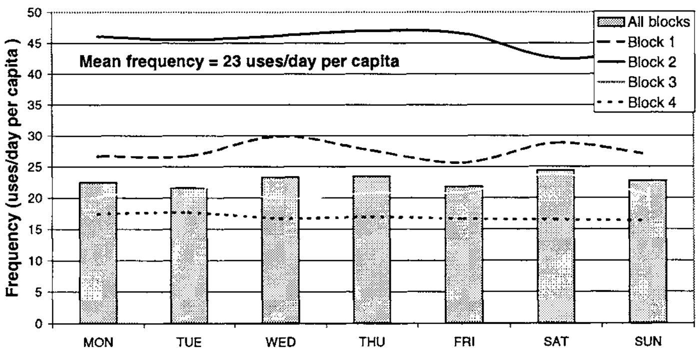

Figure 5: Mean daily values of frequency.

The comparison between frequency and demand has been carried out with the same procedure used for the monthly average consumption through the normalised values. Differently from the monthly scale, the frequency shows a better correlation to consumption. The estimated daily mean frequency is equal to 23 uses a day per capita. Buchberger and Wells [3] from water demand data of four households in Ohio, obtained a number of uses a day per capita in the range of 21–33 uses. It must be underlined that such result has been drawn using a completely different approach.

Transactions on Ecology and the Environment vol 61, © 2003 WIT Press, www.witpress.com, ISSN 1743-3541

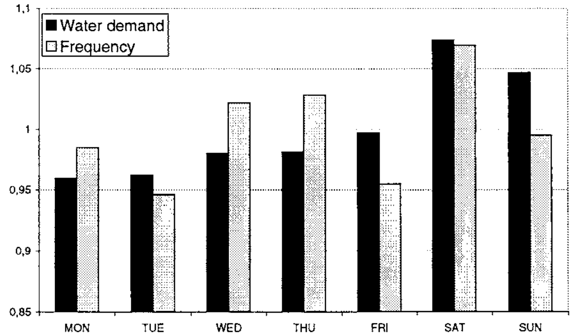

Figure 6: Comparison between mean daily normalized values of consumption and frequency.

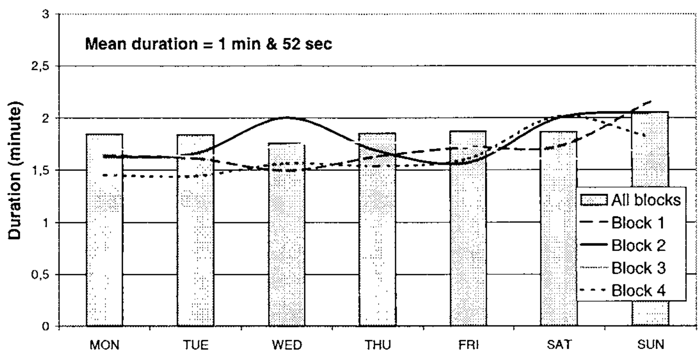

Figure 7: Average weekly behaviour of duration.

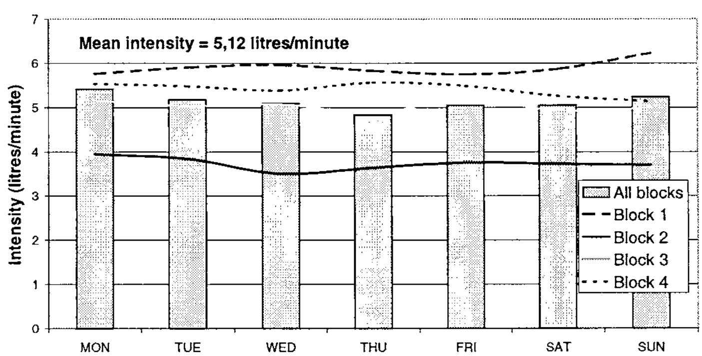

Figure 8: Average weekly behaviour of intensity.

Duration shows a weaker correlation to the consumption variation. The values remain almost constant around a mean value equal to 1 minute and 52 seconds (Figure 7), comparable to that estimated by Buchberger and Wells [3]. Intensity is the least varying parameter (Figure 8). Its value oscillates very little around the average of 5.12 litres/minute. Buchberger and Wells [3] in their work obtained values of duration in the range of 8.78–9.05 litres/minute. It must be underlined that Block 2 shows remarkably lower values of intensity than those of the other blocks, probably for the presence of losses that are interpreted by the model PRP as pulses of great frequency (Figure 5) and low intensity (Figure 8).

Finally the daily dimensionless behaviour of the estimated parameters has been reported (Figure 9, 10, 11, 12, 13). The day has been divided into time intervals, in some cases overlapped, as reported in Table 2.

Table 2: Time periods over the day.

Night	0–4
Early morning	5–6
Morning	6–9
Before lunch	10–12
After lunch	12–15
Afternoon	15–18
Evening	18–21
Late evening	21–24

The parameters estimated for Block 1, 3 and 4 and in the four blocks together show a typical behaviour, very different from that of Block 2, in which physical losses are supposed to take place. In particular frequency shows a peak located in the central hours of the day and maintains on elevated values up to evening. On the contrary this doesn't happen for the Block 2, (Figure 11), where frequency maintains on maximum values even at night time.

Duration shows a variation during the day characterised by a night time minimum and by two peaks in the morning and in the evening, while intensity shows the typical behaviour, as already underlined by Guercio et al. [5], with smaller values at night and larger during the daytime.

This peculiarity, well visible for the blocks more densely inhabited (Block 1 and 3) as well as for the 4 blocks together, is less evident for those blocks with a smaller number of inhabitants (Block 2 and 4), as they are much more sensitive to the randomness of the phenomenon of water demand.

Transactions on Ecology and the Environment vol 61, © 2003 WIT Press, www.witpress.com, ISSN 1743-3541

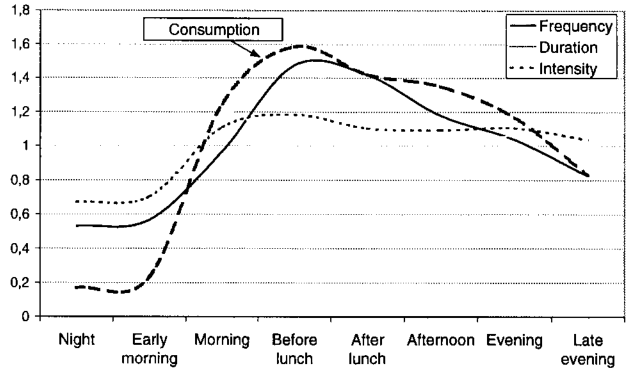

Figure 9: Average daily dimensionless parameters for all blocks together.

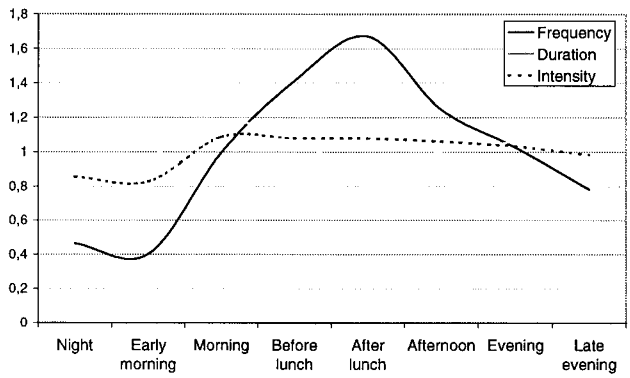

Figure 10: Average daily dimensionless parameters for the Block 1.

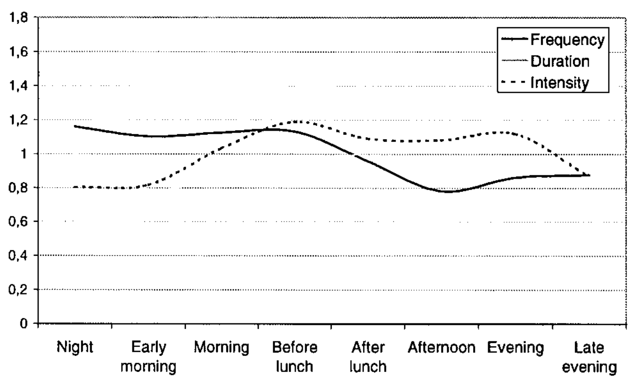

Figure 11: Average daily dimensionless parameters for the Block 2.

Transactions on Ecology and the Environment vol 61, © 2003 WIT Press, www.witpress.com, ISSN 1743-3541

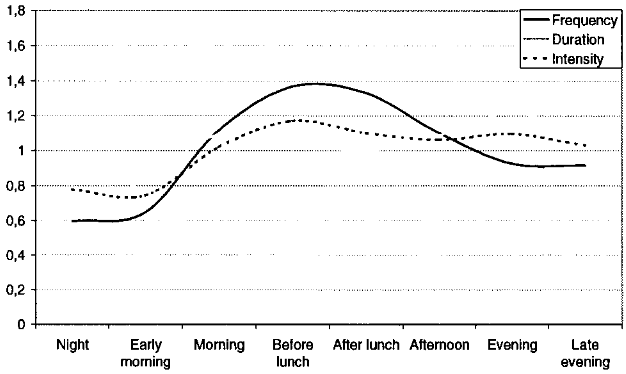

Figure 12: Average daily dimensionless parameters for the Block 3.

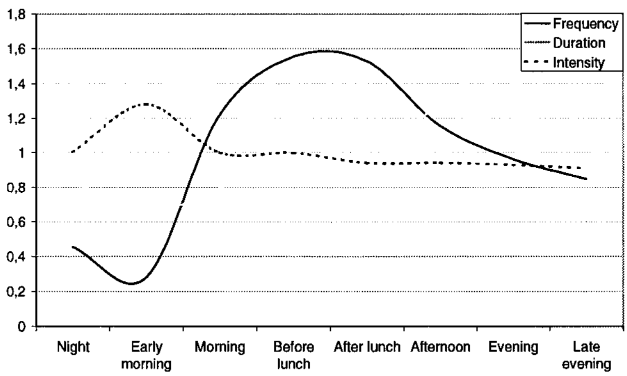

Figure 13: Average daily dimensionless parameters for the Block 4.

4 Conclusions

Instantaneous water consumption is described as a Poisson Rectangular Pulse stochastic process. The process is characterised by 3 main parameters: frequency, intensity and duration of each water use and from an additional parameter, the variance of the intensity.

Parameters have been estimated through the method of the moments applied on water consumption data of 82 single-family residences whose occupants belong to the same socio-economic level. Data are related to one year of observation. The mean value of frequency, intensity and duration are comparable with those determined by Buchberger and Wells [3], from measurements on four residential housing in the United States, carried out with a completely different estimation procedure. In particular in this work we obtained, for the whole

Transactions on Ecology and the Environment vol 61, © 2003 WIT Press, www.witpress.com, ISSN 1743-3541

number of the monitored families, a mean daily number of uses per-capita equal to 23, a mean duration of each use equal to1.52 minutes and a mean intensity of each use equal to 5.12 litres/min. For Block 1, 3 and 4 the mean values of frequency and duration do not differ substantially from these values. On the contrary for Block 2 the number of uses per capita increases to 45 and the mean intensity value is equal to 4 litres/min, sensibly smaller than that of the other three blocks equal to 5–6 litres/min. The anomalous behaviour of Block 2 could be caused to the presence of water losses or to a non correspondence between the official and the real number of inhabitants.

In general it can be observed that the results obtained considering spatial aggregations on a smaller number of families, can be often very different from the global mean values, as they are more sensitive to the peculiar habits of each single family.

The analysis of the parameters estimated in different hours of the day, in different days of the week and in different months of the year, underlines that, on an hourly scale, frequency (number of uses) and water demand variation well agree. The correlation between the number of uses and water demand is instead less evident at a daily scale, where the demand seems to correlate better with that of durations. Even weaker is the correlation at a monthly base, where only intensities variation show a weak correlation with that of consumption.

References

[1] Billings, R.B. & Jones, C.V., *Forecasting urban water demand.* AWWA: Denver, 1996.

[2] Buchberger, S.G. & Wu, L., A model for instantaneous residential water demands. *J. of Hydr. Engrg.* ASCE, 121(3), pp.232–246", 1995.

[3] Buchberger, S.G. & Wells, G.J., Intensity, duration, and frequency of residential water demands. *J. of Water Res. Plan. and Man., ASCE,* 122(1), pp.11–19, 1996.

[4] Clark, R.M., Grayman, W.M., Males, R.M. & Hess, A.F., Modeling contaminant Propagation in Drinking Water Distribution Systems. *J. of Envir. Engrg.*, ASCE, 119(2), pp.349–364, 1993.

[5] Guercio, R., Magini, R. & Pallavicini I., Instantaneous residential water demand as stochastic point process. Water Resources Management, Eds. Brebbia et al., WIT press, pp.129–138, 2001.

[6] Guercio, R., Magini, R. & Pallavicini I., Controllo delle perdite nelle reti di distribuzione idrica tramite il posizionamento ottimale di organi di sezionamento. *L'ACQUA*, I-2, Jan-Apr, pp.218–222, 2002.

[7] Guercio, R., Magini, R. & Pallavicini, I., Consumi idrici istantanei di utenze residenziali: monitoraggio, analisi dei dati e modellazione, *Atti Giornata di studio 'Evoluzione dei servizi idrici in Italia'*, CUEN, Naples, 2002.

[8] Guercio, R., Magini, R. & Pallavicini, I., Prediction of pressure heads in water distribution networks with cokriging, in *New Trends in Water and Environmental Engineering for Safety and Life*, Eds. Becciu et al., Essestampa s.r.l., 2002.