XX Jubileuszowa-Krajowa, VIII Międzynarodowa Konferencja Naukowo - Techniczna
„ZAOPATRZENIE W WODĘ, JAKOŚĆ I OCHRONA WÓD"
XX-th Jubilee-National, VIII-th International Scientific And Technical Conference
„WATER SUPPLY AND WATER QUALITY"
Poland 15-18 June 2008

Ryszard BŁAŻEJEWSKI

Agricultural University,
Dept. of Hydraulic Engineering,
Poznań, Poland

PEAK DOMESTIC WATER USE IN INDIVIDUAL HOMES, APARTMENT BLOCKS AND VILLAGES

ZUŻYCIE WODY W POJEDYNCZYCH DOMACH, BLOKACH MIESZKALNYCH I NA OBSZARACH WIEJSKICH

The paper presents a short review of methods for calculation of peak domestic water use in individual homes (dwellings), apartment blocks and villages. A new formula for calculating maximum flows to and from settlings with a number of dwellings not greater than 1440 is developed. The values of the peaking factors are simultaneously related to an averaging over time and over ensemble (number of dwellings). The scope is limited to a cold indoor water consumption (excluding fire flows). A comparison of the proposed approach with existing methods of estimation of design flows for plumbing and water systems is also presented.

1. Introduction

Domestic water use has been explored for many years, mainly for design and operation purposes. It is frequently treated as a random variable, however in many cases it is at least partly determined and can be estimated using a deterministic approach. The domestic water use is shaped by multiple factors, namely, the number of users, their habits and individual demands, water pressure, water prices etc.

The unit (per equivalent person) consumption of water varies from 50 to 300 L/d EP. One may observe daily two or three peaks (morning, early afternoon and evening) in water demand in typical rural settlings (excluding industrial demands). From the beginning of nineties of the last century a decreasing trend in water use has been observed in Poland and in many other countries. The most important causes of that were: a broader application of water meters, higher water prices and technical possibilities to save water using e.g. the flush stop button at a water closet. In rural areas the low consumption of water and low sewage outflow have created problems with sewage conveying and treatment.

One can distinguish an instantaneous, hourly or daily peak demand. As a rule, the longer the averaging period the lower the peak flow. According to [2] the **instantane-**

ous peak demand is the maximum amount of water necessary to meet the peak short term demand rate which may occur several times a day, usually occurring during the peak hour period. It may last for several minutes [2], however in Polish literature it is considered as a flow lasting for one up to 10-15 seconds. It is used for sizing plumbing installations, water meters, storage tanks in hydro-pneumatic systems etc..

Maximum hourly demand is the greatest amount of water which will be used in any hour during the day. It is often used for sizing water mains, pumps etc.

Maximum daily demand is the greatest amount of water a system will use in one day. It is established on the base of 1-3 years, provided that the system had not changed significantly in the period. Small residential water systems typically have their daily maxima 1.5 to 2.0 greater than the average daily flow. The smaller the water system, the greater the ratio of the maximum to average daily demand. It is used for sizing water intakes and capacity of the water treatment facilities equipped with two-stage (the first in a well, the second – after water treatment) pump installations.

2. Review of calculation methods

There are several methods to size pluming installations and water systems. The basic problem at dimensioning is to establish a design flow. Approaches to solving the problem can be divided into three categories: empirical, rational (deterministic) and probabilistic (stochastic) methods. Sometimes economical aspects are also taken into account to establish an acceptable risk level.

For developing **empirical models** derived from experimental data one can use statistical regression techniques, time series analysis (e.g. ARIMA [9]), Kalman filtering, evolutionary strategies and artificial neural networks. Experimental data are based on measurements of water flows to typical users; e.g. Georgia Environmental Protection Division in its standards [2] gives typical values of instantaneous peak demand for residential communities in the range from 10 to 500 connections (table 1).

Tab. 1. Instantaneous (peak) demand for residential communities acc. to GEPD [2]

No. of connections, N_{ed}	10	30	50	70	100	200	300	500
$Q_{max\,i}$, L/min	151	220	363	435	530	776	965	1268

Zhang [18] found a power regression which describes the data in the form:

$$Q_{\max i} = 43.4\ N_{ed}^{0.54} \quad \text{[L/min]} \tag{1}$$

where N_{ed} – number of equivalent dwellings (connections).

The mean peak flow per one dwelling (connection or individual house) can be calculated dividing Eq. (1) by the number of dwellings

$$Q_{\max i} = 43.4\ N_{ed}^{-0.46} \quad \text{[L/min ED]} \tag{2}$$

A peaking factor is defined as the ratio of the maximum to a long-term average value. Dividing Eq. (1) by the mean yearly flow, expressed in L/min, Zhang obtained the following formula for the peaking factor [18]:

$$PF = \frac{Q_{\max i}}{Q_{aa}} = \frac{4.02}{\left(0.001\, N_{ep}\right)^{0.46}} \tag{3}$$

where N_{ep} – number of equivalent persons. The mean yearly flow Q_{aa} was calculated assuming 379 L/d EP (including indoor and outdoor water use) and 2.7 persons per connection (EP/ED).

Orłowska [6] used numerous domestic water demand measurements made by Koral [5] and herself in the years 2002-2004 to elaborate the following regression function for dwellings in two large Polish towns, similar to that given in the standard [7]:

$$Q_{\max i} = A\left(\sum q_n\right)^B + C \qquad \text{[L/s]} \tag{4}$$

where $Q_{max\, i}$ – instantaneous water use, A, B, C – constants, Σq_n – the sum of standard flows (loading units).

The value of the exponent C for dwellings with individual hot-water preparation is equal to 0.96, i.e. the function is almost linear. Eq. (4) is valid for the number of dwellings $20 \le N_{ed} \le 330$.

According to Polish standard PN-92/B-01706 [7] an instantaneous flow can be calculated as:

$$Q_{\max i} = 0.682\left(\sum q_n\right)^{0,45} - 0.14 \qquad \text{[L/s]} \tag{5}$$

where Σq_n – the sum of loading units. (Note that here $C = 0.45$ instead of 0.96).

A relevant peaking factor can be expressed in the form:

$$PF = \frac{0.682\left(\sum q_n\right)^{0,45} - 0.14}{N_{ed} N_{p/d} q_p} = \frac{0.682\left(\sum q_{n1}\right)^{0,45} - 0.14\, N_{ed}^{-0,45}}{N_{ed}^{0,55} N_{p/d} q_p} \tag{6}$$

where Σq_{n1} – the sum of discharge units in one dwelling, $N_{p/d}$ – number of persons per dwelling, q_p – daily water consumption by one person in L/s EP.

A design curve given in the new standard PN-EN 806-3 [8] can be approximated by Eq. (4) for $A = 0.1$, $B = 0.53$ and $C = 0.1$ L/s.

Rational methods incorporate a specific representation of the activities (scenarios) which result in water consumption at each residence. Predictions of water demand can then be made by modeling the expected changes in the number of these activities and the unit consumption for each of them [10].

Probabilistic approach treats the water use as a random variable with an assumed probability distribution. The most popular is so called fixture (discharge) unit method developed by Hunter [3]. It is based on assumption, that the number of simultaneously working fixtures has a binomial distribution. The guarantee value applied in his famous Hunter's curve was 99% (probability of exceedence $Pr = 1\%$). He introduced a notion of a discharge unit which was assigned to a typical tap. However, at his time the flow rate to a flush tank was 0.25 L/s and to a bathtub 0.5 L/s, and nowadays these values are twice lesser. A similar approach to that elaborated by Hunter was proposed later by Shopensky and Yurieva [11]. It is known and still used in Poland as "the new Soviet method".

For random variables the maximum can be theoretically infinite. In practice we observe a finite but very often not well established the highest value called *maximum maximorum*. In such a case one should consider a truncated probability distribution of the random variable. If the *maximum maximorum* and *minimum minimorum* occur very rarely, a theoretical probability distribution, like a normal or log-normal, can be applied

[12]. Then the maximum flow can be determined in terms of exceedence probability, typically in the form:

$$Q_{\max} = Q_{av} + t_{\Pr}\sigma_Q \tag{7}$$

where Q_{av} – average peak value, $t_{\Pr}$ – frequency factor, i.e. a function dependent on the exceedence probability level Pr for a given probability distribution, σ_Q – standard deviation.

Zaleski [16, 17] elaborated a simulation model of water supply for dwellings of different types which gave flows distributed according to the normal distribution and Tiukało [13] – to the beta distribution with four parameters. They used a notion of a characteristic (representative) flow to (from) a single dwelling, proportional to the total flow to (from) all dwellings under consideration. These theoretical schemes were verified mostly using data on hot water use, but they are rarely used in practice.

Buchberger and Wu [1] developed a model of indoor water use assuming that residential water demands occur as a non-homogeneous Poisson-rectangular-pulse process. Later on Zhang [18] described peaking factors of water demand using similar assumptions. They treated the maximum demand as a rare event with an assumption that for a longer averaging period, pulses with different starting times may overlap. Then, the total water use is the sum of the joint intensities from the coincident pulses. Finally, they obtain a general formula of the form:

$$PF_e = \frac{B}{\sqrt{N}} + C \tag{8}$$

where B – variability in water use at a typical dwelling, N – number of dwellings, C – a measure of the time weighted average total demand by a typical dwelling during the daily period of maximum water use,

It has occurred that the peak indoor water use follows a Gumbel Extreme Value Type I distribution. The above presented formulae (1-6 and 8) exemplify averaging over ensemble.

There are also formulae to calculate flow rates averaged over different time intervals. Jones [4] processed empirical data gathered during a research project conducted by USDA and Johns Hopkins University in 1964-65 on domestic water use in private and public water systems. He found the following correlations:

$$Q_\tau = \frac{B}{\tau^b} \quad \text{[L/min]} \tag{9}$$

where Q_τ - flow rate of peak demand in an individual home, τ - peak use period in minutes ($1 \le \tau \le 1440$ min). The values of parameters B and b are presented in table 2.

Tab. 2. Values of parameters in equation (9) [4]

Parameter in Eq. (9)	Flow rate			
	$Q_{max\tau}$ with probability of exceedence, *Pr*, %			Mean peak (daily)
	1.0	2.5	5.0	$Q_{a\tau}$
B	82.5	72.7	65.2	37.0
b	0.481	0.488	0.494	0.526

On the basis of data given by Jones [4], taking $B = Q_{am}$ and $b = 0.5$, one can estimate:

$$Q_{a\tau} \cong \frac{Q_{am}}{\sqrt{\tau^*_{av}}} \tag{10}$$

where $Q_{a\tau}$ – mean peak demand averaged over time period τ, Q_{am} – mean peak demand averaged over 1 minute, τ_{av}^* - number of minutes in averaging time period. For $\tau_{av}^* = 1440$ it gives $Q_{a\tau} = Q_{ad} = 0.026\ Q_{am}$.

Fig. 1 shows a good agreement between the formula (10) and measurements cited by Jones [4] for high occupancy homes (on average 4.6 EP/ED, using186 L/d EP). It also shows the regression function (2) which demonstrates the similar trend as Eq. (10).

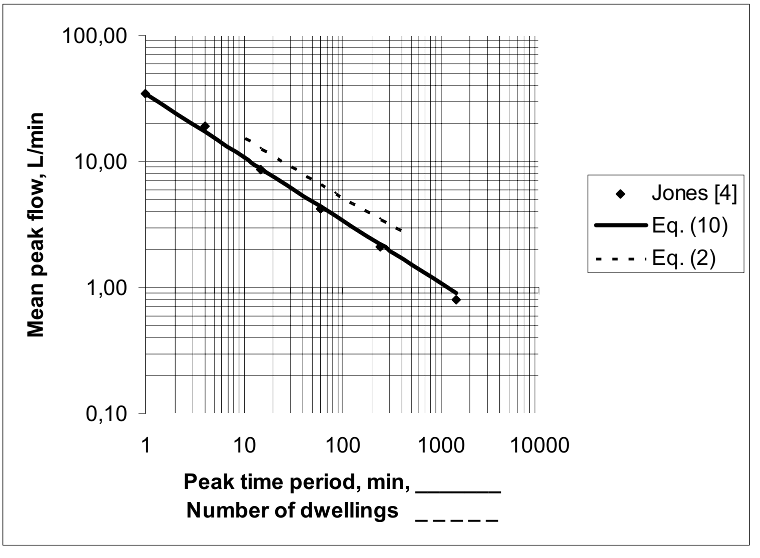

Fig. 1. Comparison of mean measured peak flows with those calculated using Eqs. (2) and (10) [4]

3. New approach

Assuming that the water flow is a random variable with a given probability distribution, its variability, as a function of averaging time duration, can be expressed using Eqs. (7) and (9) combined in the form:

$$PF_\tau = \frac{Q_{\max\tau}}{Q_{ad}} = \frac{Q_{a\tau} + t_{\mathrm{Pr}}\sigma_{Qa\tau}}{Q_{ad}} = \frac{Q_{a\tau}\left(1 + t_{\mathrm{Pr}}C_{v\tau}\right)\sqrt{1440}}{Q_{am}} = \left(1 + t_{\mathrm{Pr}}C_{vm}\right)\sqrt{\frac{1440}{\tau^*_{av}}} \tag{11}$$

where τ_{av}^* - number of minutes, $C_{v\tau} = \sigma_{Qa\tau}/Q_{a\tau}$ – coefficient of variability of flow (for a typical dwelling $C_{vm} = \sigma_{Qam}/Q_{am} = 0.2\text{-}0.4$ [4] at $\tau_{av} = 1.0$ min; $\tau_{av}^* = 1$).

The standard deviation of the mean flow ($\sigma_{Qa\tau}$) is inversely related to the square root of the sample size (i.e. $\sigma_{Qa\tau} = \sigma_{Qam} / \sqrt{\tau_{av}^*}$). However, the Eq. (10) shows that the same relationship can be applied to the mean peak values. It implies, that the coefficient of variability does not depend on the duration of the averaging time period, hence $C_{v\tau} \approx$ const.

One can notice that the structure of the above formula (10) is similar to that of Eq. (8). According to the Gibbs' principle of ergodicity, averaging over time is equivalent to the averaging over ensemble for a sufficiently large data set. The idea of simultaneous averaging over time and ensemble for our purposes is illustrated in Fig. 2. Both of the two samples consist of 3 x 5 = 15 measurements.

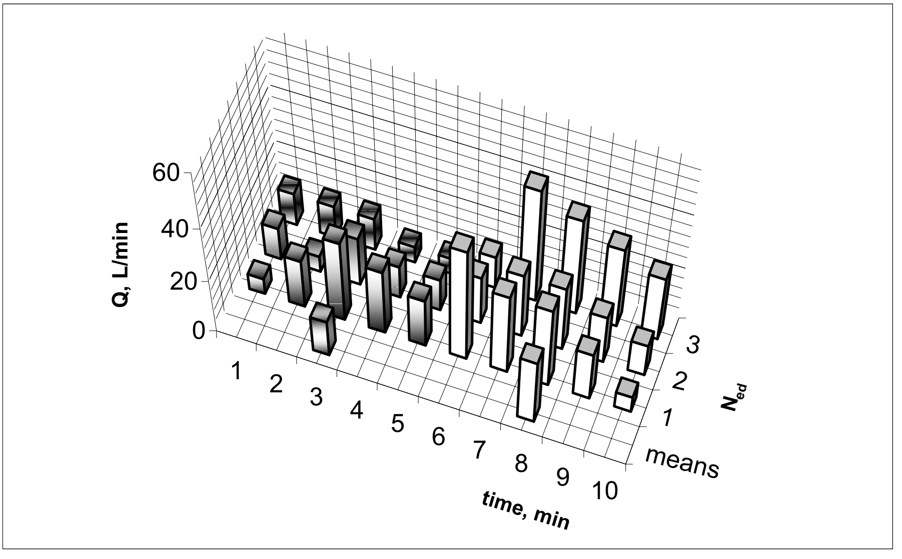

Fig. 2. Example of two samples taken from 3 dwellings over τ_{av} = 5 min (the means out of 15 measurements, equal to 13,6 and 24,4 L/min, are shown in the first row)

Assuming that the ergodicity principle can be applied to our problem, we may introduce both variability sources into one formula, as follows:

$$PF_{\tau\&e} = \frac{Q_{\max}}{Q_{ad}} = \frac{Q_{a\tau} + t_{\Pr}\sigma_{Qa\tau}}{Q_{ad}} = \left(1 + t_{\Pr} C_{vm}\right)\sqrt{\frac{1440}{\tau_{av}^* + N_{ed} - 1}} \qquad (12)$$

where Q_{ad} – mean daily flow, τ_{av}^* - number of minutes in averaging time period ($1 \le \tau_{av}^* \le 1440$), N_{ed} – number of dwelling units over which the total flow is averaged.

The equation (12) is valid for $\tau_{av}^* + N_{ed} \le 1441$.

Frequency factors (t_{Pr}) can be taken from statistical tables or approximately calculated using the following relationships:

a) for the normal distribution (approximation with an absolute error ≤ 0.003)

$$t_{\Pr N} \cong 1.238\,\mathrm{sgn}(\Pr - 0.5)\sqrt{-\ln[4\Pr(1-\Pr)]}\left\{1 + 0.0262\sqrt{-\ln[4\Pr(1-\Pr)]}\right\} \qquad (13)$$

where Pr – probability of exceedence in decimals, and

b) for the Gumbel Extreme Value Type I distribution

$$t_{\Pr G} \cong -\frac{\sqrt{6}}{\pi}\{0.5772 + \ln\ln[1/(1-\Pr)]\} \tag{14}$$

As can be seen in Fig. 3, for the same exceedence probability $Pr < 10\%$, the normal distribution provides lower t_{Pr} values than the Gumbel distribution ($t_{PrN} < t_{PrG}$), thus the latter one is more conservative.

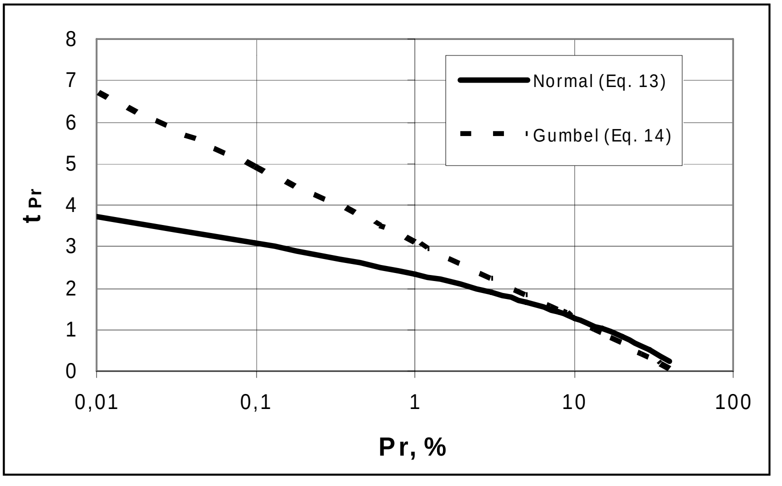

Fig.3. Comparison of frequency factors for normal and Gumbel distributions

4. Discussion

There is a problem, how to determine the smallest values of averaging units, both time and users. The shortest one is an instantaneous flow averaged over 0.1-1.0 s and the lowest number of users equals to unity (1 person). However, these values generate flows with very high variability and they are of less importance from the practical point of view. Dutch data gathered by Wijntjes [15] showed that the peak flows to single dwellings, averaged over 1.0 min were lower than those averaged over 1.0 s by 13% only. Thus, as a first approximation, the averaging time equaled to 1.0 min and a typical dwelling inhabited by 3 persons have been chosen. The number of persons in one dwelling unit and availability of fixtures for the users in the peak period can influence the variability of the peak water use.

The relationships (12) for $Pr = 1\%$ (t_{PrN}= 2,35) and C_{vm}= 0.3, (3) and (6) for $\sum q_{n1}$ = 3.0 are shown in Fig. 4.

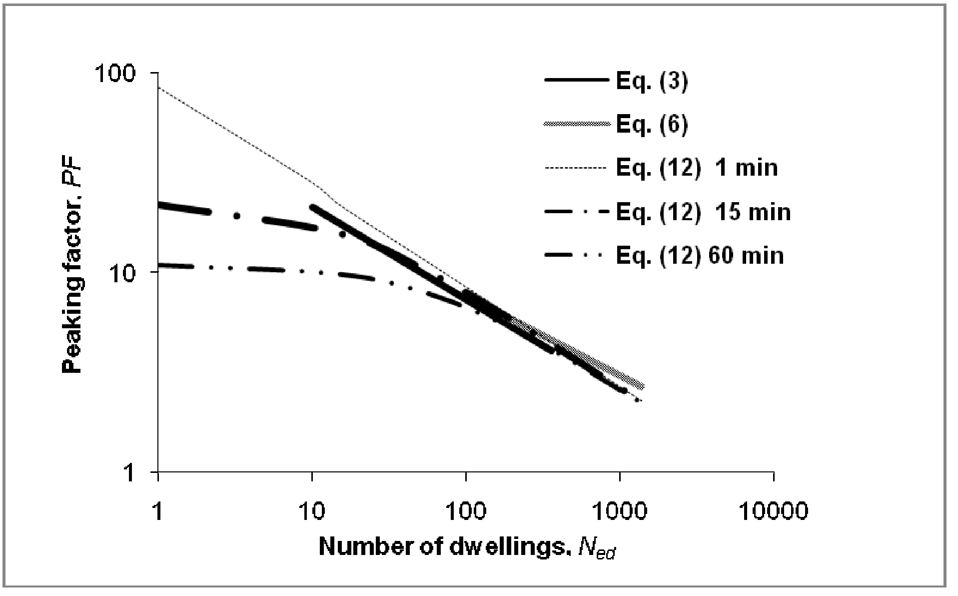

Fig. 4. Variability of average flows depending on averaging time and number of dwellings

Polish standard [7] has been recently criticized [5, 6, 14] that it gives too high values of design flows. Tuz and Dawidowicz [14] presented data on hourly water use in 11 apartment blocks inhabited by 48-169 PE in 20-90 dwellings. The unit water uses in these dwellings were relatively low, namely: 42-129 L/d PE. It does not necessarily mean that the total unit water consumption was so low; it depends also on the activities of the inhabitants (time spent in their dwellings, place of laundering etc.). The values of hourly peaking factors were very high (6.6-21.8), indicating that hourly flows were asymmetrically distributed. Unfortunately, the authors did not indicate the probabilities of exceedence of the Q_{maxh} values.

The relatively good agreement of the proposed formula (12) with empirical relationships is encouraging, however it has to be further validated using comprehensive empirical data.

5. Conclusions

Values of peaking factors diminish and converge over time as well as the number of identical dwellings to the value of coefficient of variability of the maximum flows from a single dwelling.

Application of the Gibbs ergodicity principle, to describe variability in water use, allows for estimation of maximum flows to and from individual houses, block apartments and villages in a wide range of averaging periods.

The values of effluent (wastewater flow) peaking factors are greater than those related to the indoor water supply due to retention tanks (bathtubs, toilet flush tanks and sinks) and relatively high discharge rates when emptying.

There is a need for further verification of the hypothesis about applicability of the Gibbs ergodicity principle to water use description, on the base of broader empirical material.

References

[1] Buchberger S. G., and Wu L. Model for instantaneous residential water demands. *J. Hydraul. Eng. Proc. ASCE*, 1995, 121 (3) 232-246

[2] Georgia Environmental Protection Division. Minimum standards for public water systems. Atlanta 2000 http://georgiaepd.com/Files_PDF/techguide/ wpb/standards.pdf 28. 01. 2008

[3] Hunter R. B. Methods of estimating loads in plumbing systems. Building Materials and Structures Report BMS65. Washington D. C. 1940

[4] Jones E. E. Domestic water use in individual homes and hydraulic loading of and discharge from septic tanks. Proc. of the *National Home Sewage Disposal Symposium*. ASAE, St. Joseph (Mi.), 1975, 89-103

[5] Koral W. Statystyczne metody doboru średnicy i oceny poprawności wskazań wodomierzy głównych instalowanych w budynkach wielorodzinnych. (Statistical methods of diameter choosing and readings' checking of main water meters installed in block of flats. *Instal*, 2005, 5 16-19

[6] Orłowska M. Wyznaczanie przepływów obliczeniowych przy doborze wodomierzy głównych i projektowaniu średnic instalacji wodociągowych w budynkach mieszkalnych wielorodzinnych (Estimation of design flows at main water meters choice and diameters of pipes in block compartments). *Gaz, Woda i Technika Sanitarna*, 6, 2006, 27-33

[7] PN-92/B-01706- Instalacje wodociągowe. Wymagania w projektowaniu. (Water plumbing. Design requirements. Polish standard) PKNMJ 1992

[8] PN-EN 806-3 Specifications for installations inside buildings conveying water for human consumption. Part 3; Pipe sizing – Simplified method. PKN Warszawa 2006

[9] Siwoń Z., Cieżak W., Cieżak J. Analiza i prognozowanie szeregów czasowych krótkotrwałego poboru wody. (Analysis and forecasting of water demand time series). Instal, 2, 2006, 44-49

[10] Power N. A., Volker R. E., Stark K. P. Deterministic models for predicting residential water consumption. Water Resources Bulletin. 1982.

[11] Shopensky L. A., Yurieva I. P. Priemy vychislenia raskhodov w setach vodoprovodov zdanij razlichnogo naznachenia i mikrorayonov (Design methods for flows in various building water nets and apartment blocks). *Vodosnabzhenie i Sanitarnaya Tekhnika*. 11

[12] Surendran S., Tanyimboh T. T., Tabesh M. Peaking demand factor-based reliability analysis of water distribution systems. *Advances in Eng. Software* 2005, 36, 789-796

[13] Tiukało A. Symulacja systemów zaopatrzenia budynków w wodę – podstawy i zastosowania. (Simulation of systems of water supply to buildings – principles and applications). *Prace Nauk. IICh Politech. Wrocław.*, 1987, 49 (M 27)

[14] Tuz P. K., Dawidowicz J. Problemy ustalania przepływu obliczeniowego do doboru wodomierzy (Problems of estimation a design flow for water meters' choice) I konf. *Instalacje wodociągowe i kanalizacyjne (Sanitary plumbing).* PW Warszawa-Dębe 2004, 59-69.

[15] Wijntjes W. C. Piekverbruik en watermeters (Peak demand and water meters) H_2O, 15 (No. 10) 1982, 232-238

[16] Zaleski J. Stochastyczne modelowanie procesów poboru wody w instalacjach wewnętrznych i jego zastosowanie. (Stochastic modeling of water demand processes in plumbing systems and its application). *Prace Nauk. IICh Politech. Wrocław.*, 1987, 48 (M 26)

[17] Zaleski J. Modele stochastyczne i symulacja komputerowa. Zastosowanie do systemów zaopatrzenia w wodę. (Stochastic models and computer simulation. Application to water supply systems). PWN, Warszawa, 2004

[18] Zhang X. Estimating peaking factors with Poisson rectangular pulse model and extreme value theory. M. Sc. thesis. Univ. of Cincinnati, 2005 http://www.ohiolink.edu/etd/send-pdf.cgi?ucin1123875661