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Analysis of the Structure of Water Demand with the Example of Selected Buildings †

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Abstract: The basis for the designing of water supply devices is knowledge of the distribution of water demand. The only practical tool that utility companies can use to measure water consumption is water meters. The literature part of the article compares the guidelines for the devices contained in the following directives: EEC (European Economic Community—withdrawn) and Measuring Instruments Directive—MID (applicable at present). The methodology of selecting water meters in accordance with previous and current regulations was also presented. The main purpose of this work was to determine the structure of water demand for selected building objects. Differences between real and literature values of water flows and water demand were determined. It was found that the average consumption in the analyzed buildings was higher then the consumption in Polish Regulation and in the town of Dabrowa Gornicza. The highest level of demand was in the buildings, which were equipped with automatic watering systems. The maximum momentary volumetric flows are also shown. Based on the obtained data, the accuracy of the water meters selection was checked. The calculated daily and hourly peak factors were compared with the values from the literature. The analysis was performed based on current legal acts, technical literature and data obtained from Dabrowskie Wodociagi Sp. z o.o. in Dabrowa Gornicza, Poland.

Keywords: water demand; momentary volumetric flow; peak factor; water meters

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1. Introduction

The key issue in the design and operation of water supply networks and systems is to evaluate the volume of water supplied, which represents the basis for the calculation of such systems. Water meters are mainly used as devices for measuring volumetric flow. The optimum choice for a water meter is not simple. There is no easy and effective method that would allow for correct measurements of the service connection. This is due to the following factors influencing the structure of water distribution:

- Differentiation of consumers in terms of water demand and the resulting varied volumetric water streams over time: Residential buildings, hotels, restaurants, schools, industrial plants, shops, etc.,
- A constant reduction in water consumption by consumers, due to the introduction of modern and more efficient equipment and fittings, as well as for economic reasons,
- The impact of weather and climate changes on water demand,
- The large variety of types and sizes of measuring devices [1–5].

Measurements of water consumption performed in order to enable settlements between water suppliers and consumers require the use of water meters. They are designed for the automatic measurement and registration of the volume of flowing water. Properly designed and chosen measurement equipment installed in the water supply system should guarantee the reliability of measurements and ensure water supply for all consumers without any breaks and with appropriate pressure. The reliability of a water supply system depends on the reliability of its individual components, including water meters [6]. Water meters have to meet increasingly high metrological requirements and work over wide measurement ranges. This is necessary due to the substantial variation of water volume streams resulting from the variability in water demand, e.g., taking into account the demand for fire-fighting purposes [7,8]. For this reason, the correct calibration of devices is very important. It should reflect the actual volatility of the demand [9]. Determining the service life of devices is also an important issue, after which it is necessary to replace them. The new devices are most often installed after a certain time or after measuring a given volume of water. Increasingly both these factors are taken into account together, as well as other parameters, e.g., water pressure at which the water meter works, the risk of occurrence of damage or consideration of the life cycle cost (LCC) [10–12].

Water use is not constant in meeting the needs of the population, there occurs daily and hourly flow variability. These values are directly related to the way that people use water, their lifestyle (sleep, working hours, meal preparation, washing, etc.). Variability of the water flow is determined by the peak factors: Daily N_d and hourly N_h, determined according to the following mathematical expressions:

$$N_d = Q_{dmax}/Q_{dśr},$$

$$N_h = Q_{hmax}/Q_{hśr}.$$

The emergence on the market of smart water meters allows for better knowledge of the average daily demand for water and the maximum daily and hourly water demand. Smart meters are a crucial infrastructural feature of a modernizing water network and fit into a wide range of smart home technologies. They enable the observation of dynamic water flow rates. These kinds of meters are attached to a device that allows higher frequency meter reading, storage, display and the ability to transfer all data in real time. Smart water meters can be used to identify water loss through leakages and, hence, determine the potential water savings, if remedial actions are taken. Their usage can also influence behavioral change among water consumers towards better water conservation practices too. We can see, e.g., on mirrors, current water consumption in real time, which limits the amount of water we use. We can calculate the daily and hourly peak factors and on the basis of the flow variability we can choose the optimal water meter for a particular customer [13–16].

Directive 2014/32/EU MID (Measuring Instruments Directive) [17] is the current legal act that covers measuring devices, including water meters, within the European Union. It replaces the previous documents: Council Directive 75/33/EEC and Directive 79/830/EEC. Since January 2018, measuring devices, including water meters, can be placed on the public market only after the assessment of conformity with the MID Directive. The Polish standard—PN-EN14154, which applies to currently manufactured devices, was developed based on the above regulation [18].

Similar solutions to those applied in the European Union are contained in OIML R 49-1 and OIML R 49-2—internationally recognized standards for the pattern approval of water meters. These standards are developed by the International Organization of Legal Metrology (OIML). In Australia, the modified versions of these standards are NMI R 49-2 and NMI R 49-2 respectively. Water volumetric flow rates Q_1, Q_2, Q_3 and Q_4 for water meters are determined in the same way [19–22]. Table 1 shows a comparison of the determination of water volumetric flow rates for water meters used in the previous and current legislation. It should be noted that the previously applicable nominal volumetric flow rate does not correspond to the current flow rate value of Q_3.

Table 1. Comparison of volumetric flow rates for water meters manufactured according to the EEC and Measuring Instruments Directive (MID) directives.

EEC Directives (Withdrawn)	MID Directive (Applicable at Present)
$\mathbf{Q_{min}}$—minimum volumetric flow rate at which the water meter readings meet the requirements for the maximum permissible error of ±5%	$\mathbf{Q_1}$—minimum volumetric flow rate at which the water meter readings meet the requirements for the maximum permissible error of ±5%
$\mathbf{Q_t}$—intermediate volumetric flow rate, maximum permissible error changes value to ±2%	$\mathbf{Q_2}$—intermediate volumetric flow rate that divides the measurement load range into upper and lower range, at which the maximum permissible error changes the value to ±2%, $Q_2 = 1.6 \times Q_1$
$\mathbf{Q_n}$—nominal volumetric flow rate, at which the correct operation of the water meter is required under normal conditions of use, i.e., at continuous and/or intermittent flow	$\mathbf{Q_3}$—continuous volumetric flow rate, the highest value at rated operating conditions, at which the water meter can operate at either continuous or intermittent flow
$\mathbf{Q_{max}}$—maximum volumetric flow rate, at which correct operation of the water meter is required for a short period of time without damages, $Q_{max} = 2 \times Q_n$	$\mathbf{Q_4}$—overload volumetric flow rate, maximum flow rate at which the water meter can operate for a short period of time, $Q_4 = 1.25 \times Q_3$

After the withdrawal of the PN-92 B-01706 standard "Water supply systems: Requirements in design" by the Polish Committee for Standardization, which was used to choose diameters of water meters, and due to the lack of its replacement with another standard, there are currently no legal regulations concerning the choice of the above mentioned measurement devices [23]. The PN-92 B-01706 standard is referred to in the Regulation of the Minister of Infrastructure "Technical conditions to be met by buildings and their location", but only in terms of the design flow [24].

Calculation methods resulting from Polish Standards can be used to determine water flow for choosing a water meter, but this is voluntary (not obligatory). The data obtained by recording actual water flow rates can also be used. However, the method of monitoring real water flow rates can only be employed for current facilities equipped with measuring devices. The data obtained from this method can be used to correct, if needed, the choice of the water meter already in use, with specific metrological parameters.

Furthermore, the only legal act in which unit daily water demand is stipulated is the regulation of the Minister of Infrastructure of 14 January 2002 on the determination of average standards for water consumption () [25].

2. The Aim and Scope of the Study

The aim of this study was to determine the structure of water distribution for single-family buildings. The differences between the actual and literature values of maximum water flow rates and water demand per unit of time were determined. The analysis allowed for the determination of actual peak factors of water distribution to individual objects. These values were used to choose optimal measuring devices.

The scope of the study covered the comparison of the withdrawn legal acts relating to water meters with those currently in force. The previously applied methodology of choosing the measuring devices and recommendations of manufacturers of water meters introduced on the market in accordance with the MID Directive were presented. The results of measurements of variability of water flow in single-family buildings located in the city of Dabrowa Gornicza were discussed.

The analysis was performed based on current legal acts, technical literature and data made available by Dabrowskie Wodociagi Sp. z o.o. in Dabrowa Gornicza, Poland. Two types of water meters were used for data recording: The electromagnetic iPerl meter and volumetric type 640 (SENSUS) meter. The water meters were equipped with integrated digital recorders and radio modules for remote data transmission.

3. Comparison of the Methodology of the Choice of Water Meters According to Previous and New Legal Regulations

Due to the withdrawal of the PN-92 B-1706 standard by the Polish Committee for Standardization [23], there are currently no standards or other legal acts regulating the choice of the water meter diameters. Proper size of the water meter is determined by obtaining a measurement with the smallest possible error, thus allowing for minimal losses. When choosing a water meter, it should be noted that an excessively large water meter will increase the investment costs, and, in the case of a small flow, it will show low measurement accuracy. Its indications will be lower than the actual water flow rates, which will cause problems with balancing of the amount of water supplied and used, leading to losses for the supplier. On the other hand, too small a water meter will be overloaded at a high water flow rate, which will result in the quick destruction of its moving parts and high pressure losses. Therefore, in order for the water meter to operate properly within its measuring range and within the permissible errors, it is necessary to properly determine the individual characteristic values.

The withdrawn Polish Standard [23] considered the choice of the water meter to be correct if the following condition was met:

$$q \leq 0.5\ Q_{max},\ m^3/h,$$

where:

q—actual water flow through the water meter (design flow),
Q_{max}—maximum volumetric flow rate for the water meter.

At the same time, in the technical literature, higher values were accepted as design flow at the given maximum flow rate for the device of $q \leq 0.6\ Q_{max}$ m^3/h, according to Sosnowski [26] or $q \leq 0.7\ Q_{max}$ m^3/h, according to Chudzicki [7].

Currently, the essence of choosing water meters, due to its metrology, is to choose such a size and type that the measuring range Q_1—Q_3 (according to MID) covers as much as possible the entire water demand curve at the service connection. Individual manufacturers of devices (e.g., BMeters, Apator) and service departments give their own recommendations on the methodology of choice. Most often it is assumed that the ratio of the design flow rate or actual q to the water meter flow rate Q_3 should range from 0.45 to 0.6, with a maximum of 0.7 (Sensus guidelines). It should be noted that the volumetric flow rate Q_3 is defined based on Q_4 as equal to 0.8 Q_4. The value of q calculated based on this value will therefore be either lower than the value determined using the withdrawn Polish Standard i.e., $0.36\ Q_4 < q < 0.48\ Q_4$ (first range of values) or slightly higher, $q < 0.56\ Q_4$ (Sensus guidelines) for the same maximum (overload) flow rate. Furthermore, previous literature guidelines recommended higher flow rates [25,26].

In order to present the choice of water meters in accordance with the current directive and manufacturers' recommendations, the case of a water meter with a DN 20 diameter was analyzed. Table 2 compares the values of volumetric flow rates for the water meter DN 20 according to the withdrawn and current regulations. For this water meter, according to the MID Directive, the value of Q_3 is 4 m^3/h, whereas according to the EEC Directive, it was equal to 2.5 m^3/h. The design flow rate q according to the current manufacturer's recommendations should range from 1.8 to 2.4 m^3/h. These are flow rates lower than the maximum permissible value calculated according to the Polish Standard (the design flow rates could not be higher than 2.5 m^3/h). On the other hand, in light of the Sensus' guidelines, the flow rate is 2.8 m^3/h, which is slightly higher than that recommended by PN. Furthermore, both Sosnowski and Chudzicki had previously recommended higher flow rates. This leads to the conclusion that the water meter loads recommended today by manufacturers are lower than the loads according to the previous water meter marking contained in the literature, but comparable to the guidelines contained in the Polish Standard.

Table 2. Comparison of volumetric water flow rates for the water meter DN 20 mm.

Symbols According to the EEC Directive		**Recommended Flow Rates q**		
Q_n 2.5 m^3/h	Q_{max} 5.0 m^3/h	PN ≤2.5 m^3/h	According to Sosnowski ≤3.0 m^3/h	According to Chudzicki 3.5 m^3/h
Symbols According to the MID Directive		**Recommended Flow Rates q**		
Q_3 4.0 m^3/h	Q_4 5.0 m^3/h	Manufacturers and service departments (1.8–) 2.4 m^3/h		Sensus ≤2.8 m^3/h

4. Methods of the Research

The research was conducted in the area of the city of Dabrowa Gornicza (Silesian region). There were 116,916 inhabitants registered for permanent residency at the end of 2016 in the town. The average daily water consumption in Dabrowa Gornicza was q = 83 dm^3/(inhabitant * day).

The analysis of water consumption included 10 single-family houses and was carried out in the 2017 and 2018 year. Water consumption and maximum volume flows for every house were recorded in the hourly interval. The duration of the measurement in individual building objects ranged from two to six months. The measurement period was dependent on the type of device, the number of programmed parameters and the time of installation of a water meter. The metrological parameters of installed water meters are shown in Table 3.

Table 3. The metrological parameters of installed and planned to be installed water meters.

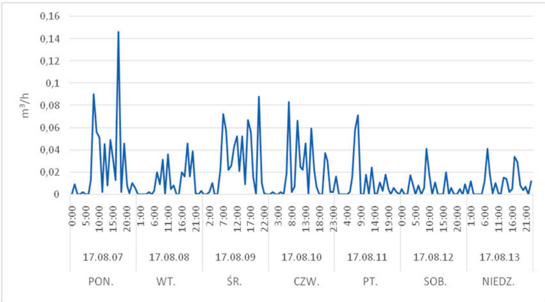
Type	**Diameter mm**	**Q_1 dm^3/h**	**Q_2 dm^3/h**	**Q_3 m^3/h**	**Q_4 m^3/h**	**R**
640	15	6.3	10	2.5	3.125	400
iPerl	15	3.13	5	2.5	3.125	800
640	20	10	16	4	5	400
iPerl	20	5	8	4	5	800

Markings Q_1, Q_2, Q_3, Q_4 and R in accordance with the Measuring Instruments Directive 2014/32/EU [17].

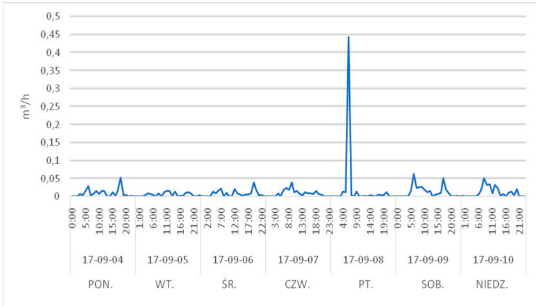
The number of inhabitants, the total water consumption during the year and water demand per unit was determined for each building. The following graphs (Figure 1) present hourly water consumption for four selected buildings, for weekly periods in which the maximum values of the measured volumetric flow were observed.

The graphs show significant differences in the variability of water demand for individual buildings. The most common situation can be observed in the case of building 9 (Figure 1d), with a markedly increased water consumption in the morning, at about 8 a.m., and the maximum water demand occurring on public holidays. In other cases, the water demand distribution is less typical. For building 1 (Figure 1a), higher water consumption was observed on working days, whereas on non-working days, the consumption was much lower. In the case of building 6 (Figure 1b), there was a sudden increase in water intake in the week analyzed (Friday), most likely due to damaged installation. For this reason, the second day in terms of the level of water demand was adopted for determination of the peak factors of water demand, while this anomaly was taken into account when choosing the water meter. Furthermore, Figure 1c shows the water demand distribution for a building equipped with an automatic watering system. An increase in water consumption in the morning can be observed in this case, but the maximum demand occurs at the start of watering, at about 8 p.m., when the hourly water consumption reaches values slightly below 0.5 m^3/h.

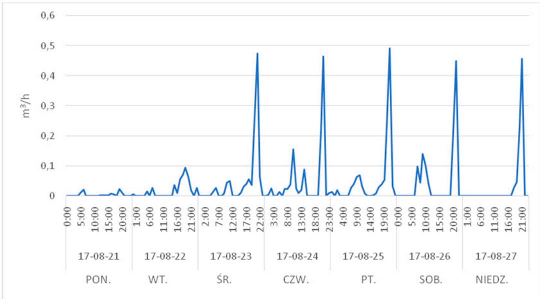
The following figure (Figure 2) shows the maximum volume flows observed in the following hours of the day for selected buildings. The data for these objects are presented as shown in Figure 1. The measured maximum flow rates were used to determine the suitability of the choice of water meters in the building and, if needed, the correction of their size.



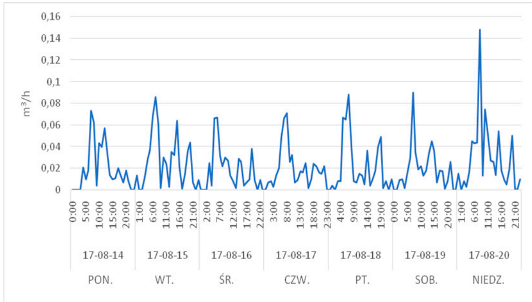
(**a**)



(**b**)

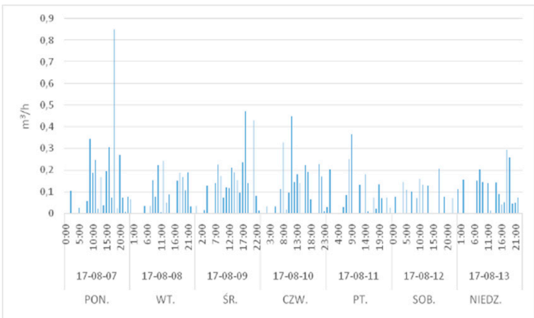


(**c**)

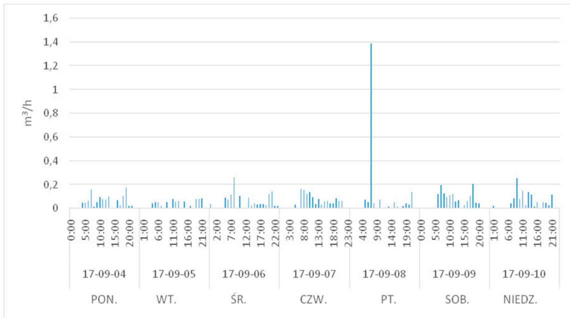


(**d**)

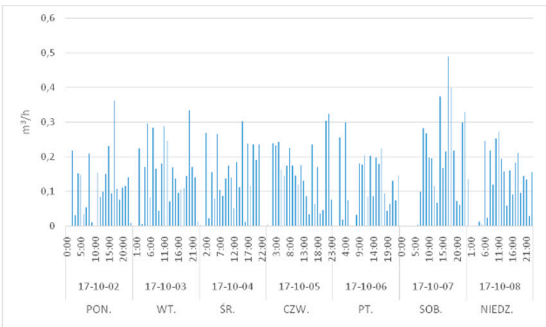
Figure 1. Examples of hourly water consumption in weekly periods in selected single-family houses: (**a**) Building No. 1, (**b**) building No. 6, (**c**) building No. 7 and (**d**) building No. 9.



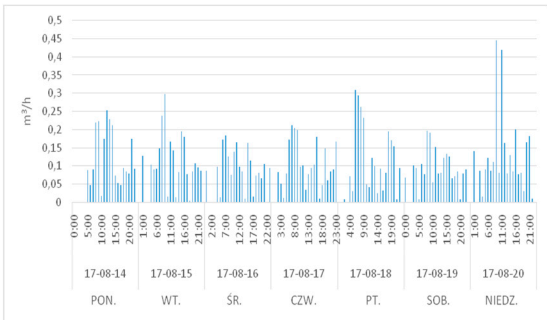
(**a**)



(**b**)



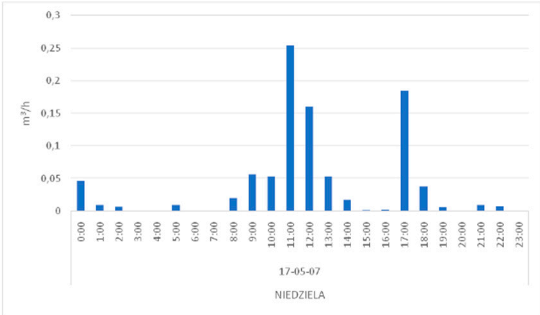
(**c**)



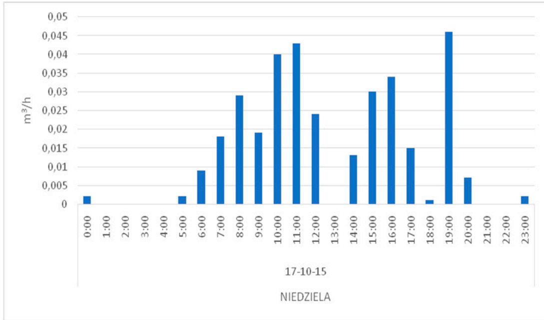
(**d**)

Figure 2. The maximum of momentary volumetric flows in selected single-family houses: (**a**) Building No. 1, (**b**) building No. 6, (**c**) building No. 7 and (**d**) building No. 9.

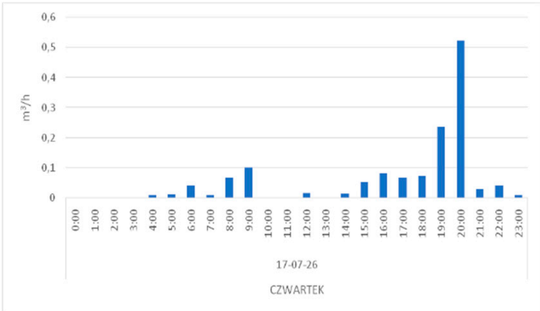
The following figure (Figure 3) shows the distribution of water consumption for a day with maximum demand for the same buildings, which is shown in Figures 1 and 2.



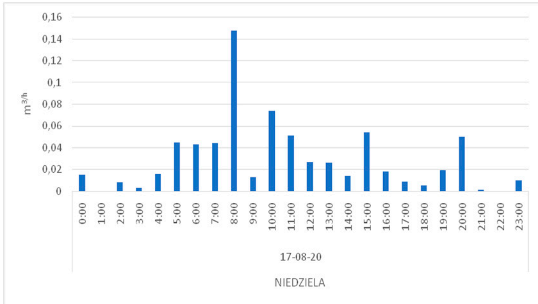
(**a**)



(**b**)



(**c**)



(**d**)

Figure 3. Examples of variability of hourly water consumption in a day with maximum demand in selected single-family houses: (**a**) Building No. 1, (**b**) building No. 6, (**c**) building No. 7 and (**d**) building No. 9.

The maximum of momentary volumetric flows were not always observed on the same day that the maximum demand for water appeared. This was the case for buildings 5, 6, 8, 9 and 10. For the remaining objects these were two different days. Using the obtained data the daily and hourly peak factors were calculated for each building. In the event of an installation failure (building 6 and 10), the calculations were based on the consecutive days in terms of the level of demand when the installation functioned properly.

5. Discussion of Results

For ten selected single-family houses, the average unit water demand was equal to q = 124 dm^3/(inhabitant * day) (Table 4). This value was higher than the consumption in the Regulation [25] for buildings equipped with water supply, toilet, bathroom and local hot water source (q = 80 ÷ 100 dm^3/(inhabitant * day)). Average consumption in the analyzed buildings was also higher than the average water consumption for Dabrowa Gornicza—q = 83 dm^3/(inhabitant * day).

Table 4. The results obtained for single-family buildings.

Building	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	Average
The number of inhabitants	3	4	4	4	5	4	2	3	3	5	3.7
q, l/M_k * d	109	108	167	104	96	60	231	181	80	107	124
$Q_{dśr}$, m^3/h	0.326	0.430	0.668	0.416	0.482	0.238	0.463	0.542	0.241	0.534	0.43
q_{max}, m^3/h	0.849	0.793	0.490	0.499	0.592	1.386	0.859	1.668	0.446	0.491	0.81
N_d	2.89	1.83	1.78	1.81	2.54	1.40	2.95	3.37	2.88	1.04	2.25
N_h	6.51	2.97	3.16	4.06	5.61	3.29	9.18	14.71	5.10	5.35	5.99

Q—average daily water consumption per customer, $Q_{dśr}$—average daily water demand per building, q_{max}—maximum momentary volumetric flow, N_d—daily peak factor, N_h—hourly peak factor and the maximum results haves been marked with a grey background.

The single-family houses were characterized by a large variation in water consumption per capita, in the range of 60 to 231 dm^3/(inhabitant * day). The highest consumption occurred in building No. 7 and 8. These buildings were relatively new and equipped with automatic watering systems. It should be noted that new single-family houses as well as urban green areas are increasingly equipped with automatic watering systems. They are becoming more and more popular in Poland. They may include part or all of the gardens: Lawns, flowerbets, vegetable plots or ground covered with trees and shrubs. They limit the time needed to care for the garden and usually work at night, when the use of water is optimal—it does not evaporate as in the daytime, but moisturizes the soil, reaching directly to the roots. Systems are equipped with rain sensors, which check the rainfall rate and turn off the system if necessary. Nevertheless, when used, water consumption is much higher than manual watering of the garden. In this case, it had a significant impact on increasing the average value of water demand. However, for most buildings, the average daily demand was close to or lower than the values in the regulation [25] and in the literature [4,27]. The lowest water demand was observed in buildings 6 and 9, built between the 1960s and 1970s.

Calculated values of daily (N_d) and hourly (N_h) peak factors for individual buildings ranged from 1.04 to 3.37 and from 2.97 to 14.71, respectively, and were usually higher than the values of the factors from the literature. This concerns both the values obtained for individual buildings and average values. The exceptions are buildings 6 and 10, where the calculated N_d coefficient was 1.4 and 1.04, respectively. The values provided in the literature are 1.3–1.5 (for single-family homes) for the coefficient of daily unevenness and 2.5–3.0 (for single-family homes) for the coefficient of hourly unevenness. Particularly high coefficients were obtained for buildings equipped with automatic watering systems, with N_h = 9.18 for building 7, and N_h = 14.71 for building 8. Comparison of the obtained values with those presented in the literature shows, however, that the literature data refer to larger clusters of buildings, and the analysis made referred to individual objects. In this case, the design flow rates are determined based on the number of pieces of water equipment in the buildings and the likelihood of them being used simultaneously. Calculation of the total coefficients of unevenness taking into account the water demand for all buildings at the same time was impossible due to the fact that the measurements were conducted at different times.

Based on the maximal volumetric flow rates, the accuracy in of choosing water meters and the possibility of operation of other devices were also analyzed. Electromagnetic water meters iPerl with DN 20 mm diameter were installed in buildings 1, 7 and 8, with the measurement class of R—800, whereas the volumetric water meters 640 (Sensus; DN 20 mm diameter) with measurement class R—400 were installed in buildings 2, 3, 4, 5, 6, 8 and 10. The maximum volumetric flow rates q_{max} recorded for the analyzed buildings ranged from 0.446 to 1.668 m^3/h and were lower than the lower values of flow rates recommended by the manufacturers ($q < 0.45$–$0.6\ Q_3$). For the water meter DN 20 mm, the recommended maximum value of q should range from 1.8 m^3/h to 2.4 m^3/h. The Sensus guidelines were also met in this case.

After analysis of the recorded volumetric flow rates in the above mentioned single-family buildings, water meters with a diameter of DN 15 mm can be used in the future after the expiry of the verification period to reduce the costs of the measurement. In the currently installed water meters DN20, the volumetric water flow rate Q_1 was 5 dm^3/h for the iPerl water meter and 10 dm^3/h for the 640 water meters. For water meters DN 15 mm, the minimum flow rates Q_1 will be 3.13 and 6.3 dm^3/h respectively. In turn, for all water meters with DN 15 mm diameter, the flow rate Q_3 will be 2.5 m^3/h and will be higher than the maximum real flow rates. The continuous flow rate will not be exceeded even for occasional flows, e.g., in case of an emergency. In the literature is also recommended to use the water meter DN20 for multi-family buildings [9].

6. Conclusions

The analyzed buildings were characterized by a diversified demand for water per capita. From one hand this indicator was closer or lower for most of the buildings compared to those contained in the regulation of the Ministry of Infrastructure on average water consumption standards. From the other hand for some buildings, equipped with automatic watering systems, water consumption was much higher. In Polish regulation, there is a lack of data for this type of devices. These standards are often used by designers to the dimensioning of new water supply networks and the introduction of changes in legal acts should be considered.

The calculated peak factor of daily N_d and hourly N_h unevenness ranged from 1.4 to 3.4 and from 3.0 to 14.7, respectively. These values are much higher than the peak factors available in the technical literature [13].

In technical conditions specified by some water supply companies, the use of DN 20 mm water meters for single-family houses is required. The analysis revealed that it is possible in these buildings to use water meters with a smaller diameter (DN 15 mm) instead of the currently used meters. This will allow for reduction in the cost of purchasing new water meters, whereas installation of devices with a different diameter will increase the costs insignificantly and the costs will be incurred only once. It should be also emphasized that current DN 20 water meters have very good metrological parameters and do not adversely affect the amount of water measured. For this reason, their replacement will be advisable only after the expiry of the verification period.

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