Analysis of changes in water production using a rural water treatment plant as an example

Analiza zmian produkcji wody na przykładzie wiejskiej stacji uzdatniania wody

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The paper presents the characteristics of water production at a water treatment plant supplying rural areas. The main focus of the study was to determine the coefficients of daily (N_D) and hourly (N_h) irregularities in water production that occur in rural areas and to analyse the impact of the use of storage tanks in the process line of the water treatment station on the values of hourly irregularity coefficients. In order to achieve the objectives of the study, the readings of the values of water produced at the station were used and compared with the amount of treated water entering the water supply system from the SCADA system from the water meter installed at the raw water inflow to the water treatment station and at the outflow from the retention tanks. Water outflows were considered over the year 2021. A technological start-up of the water treatment plant took place during the study period, but this did not significantly affect the increase in water outflows on an annual basis. The coefficient of daily unevenness calculated for the study period was 1.50, while the coefficient of hourly unevenness assumed the value of 1.84.
Keywords: water production inequality coefficients, water treatment, rural areas

W pracy przedstawiono charakterystykę produkcji wody w stacji uzdatniania wody obsługującej obszary wiejskie. Główną problematyką poruszaną w pracy było określenie współczynników nierównomierności dobowej (N_D) i (N_h) godzinowej produkcji wody, które występują na obszarach wiejskich oraz analiza wpływu zastosowania zbiorników retencyjnych w ciągu technologicznym stacji uzdatniania wody na wartości współczynników nierównomierności godzinowej. Do osiągnięcia założonych celów pracy, wykorzystano odczyty wartości wody produkowanej w stacji i porównano je z ilością wody uzdatnionej trafiającej do wodociągu z systemu SCADA z wodomierza zainstalowanego na dopływie wody surowej do stacji uzdatniania wody i na odpływie ze zbiorników retencyjnych. Rozbiory wody rozpatrywano na przestrzeni roku 2021. W trakcie okresu objętego analizą miał miejsce rozruch technologiczny stacji uzdatniania wody, jednakże nie wpłynął on znacząco na wzrost rozbiorów wody w ujęciu rocznym. Obliczony dla okresu badawczego współczynnik nierównomierności dobowej wynosił 1,50, natomiast współczynnik nierównomierności godzinowej przyjmował wartość równą 1,84.
Słowa kluczowe: współczynniki nierównomierności produkcji wody, uzdatnianie wody, obszary wiejskie

Introduction

Despite the significant development of methods and techniques for the design of equipment and technical facilities directly related to the thematic scope of sanitary engineering, the issues related to their proper dimensioning in most cases rely on the experience and knowledge of the designer [Tuz and Gwóździej – Mazur, 2015, Ofman and Struk-Sokołowska, 2019]. In the case of water treatment systems, in addition to the technological aspects to be tazken into account in the design of the water treatment plant, the basic problem is to correctly determine the amount of water the water treatment plant must provide during its lifetime [Biedroń et al. 2013, Iwanek et al. 2018, Boryczko and Rak 2020]. In the case of facilities supplying water to cities and larger settlement units, the determination of the amount of water that will be required to meet the needs of residents is more predictable, as it is based on specific norms of unit water consumption, and generally accepted water distribution irregularity coefficients allow for the precise determination of the required maximum quantities of water produced [Oluwasanya and Carter 2017].

The opposite situation is observed in the case of small settlement units and rural areas, where the structure of water distribution depends not only on the number of inhabitants, but also on the very use structure of the area served by the water treatment plant [Rak and Tunia 2012, Kumar et al. 2013]. A key aspect identified here is the characteristics of the agriculture that is practised in the area. Although the standards and guidelines currently used for design indicate unit water use standards for specific types of crops and livestock, accurately determining the required water production is a relatively complex task. It should be emphasised that agricultural areas vary in terms of their water needs. Particularly noticeable differences are observed between areas oriented towards crops and areas where livestock rearing predominates [Li et al. 2015, Ghimire 2016].

In part, the issues of theoretical determination of water volume fluxes allow the determination of unit water consumption rates. However, it remains problematic to determine the maximum water consumption rates, which are indirectly a function of the

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daily and hourly unevenness coefficient values. Hence, especially in rural areas, a case-by-case approach and a determination of such quantities is necessary [Psomasa et al. 2017, Anh 2018].

Considering the problem of determining the magnitude of maximum volume fluxes of treated water in rural areas and small settlement units, the aim of the study was to determine the magnitude of the coefficients of daily and hourly irregularity of water production in a selected rural area.

Methodology and study area

The research work was conducted in 2021 at a water treatment station in a selected village located in Podlaskie Province. Vegetable agricultural production predominates in the areas covered by the water treatment station. In 2020-2021, a modernisation of the station took place, which included the replacement of equipment in the water treatment process line and the construction of two equalization tanks with a total capacity of 200 m^3. Prior to modernisation, the average daily volume of water produced was approximately 350 m^3/d. The water treatment technology at the station is based on aeration, single-stage filtration on pressure filters filled with a mixture of filter gravel and catalytic bed and disinfection. As a result of the aeration process, the raw water flowing into the station undergoes a process of oxidation of the impurities present in the water, which enables iron and manganese compounds to be removed from the water as part of the filtration process. On the other hand, disinfection of the water flowing out of the filters is carried out in expansion tanks, which makes it possible to secure the sanitary requirements for water intended for human consumption. The water treatment plant is equipped with a SCADA system, which allows for online collection of water production and consumption data. Data for analysis was taken from the water meter installed at the raw water inlet to the water treatment plant and at the outflow from the expansion tanks from the water meter installed downstream of the pumping set. A process diagram of the water treatment plant is shown in Figure 1.

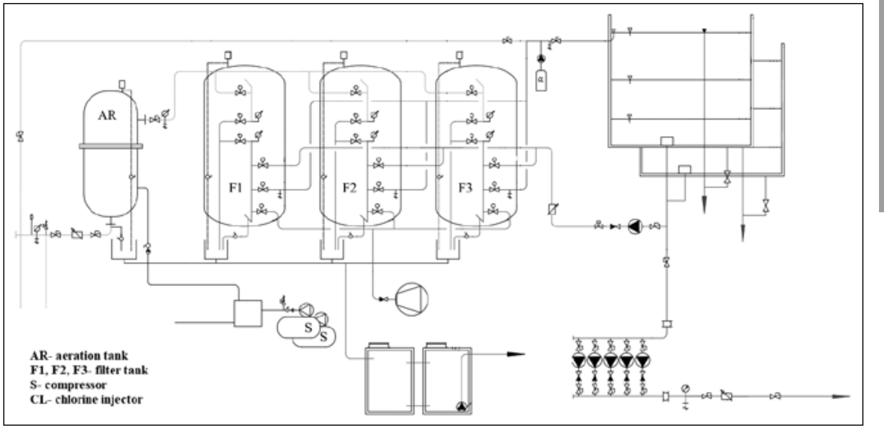


Figure. 1.
Technological scheme of the water treatment plant
Rysunek. 1. Schemat technologiczny stacji uzdatniania wody

The value of the daily unevenness coefficient is determined by observing the daily water production over a given period. By the value of this coefficient, the ratio of the maximum daily water production (Q_{dmax}) to the average daily water production (Q_{dav}) in the year 2021 is defined. This relationship can be described by the following equation [Ogiolda et al. 2019, Jasmin and Nedim 2020]:

$$N_D = \frac{Q_{d\,max}}{Q_{dav}}$$

The value of the hourly unevenness factor is determined on the basis of a day with maximum water production. The course of action in determining this value is to calculate the ratio of the maximum hourly water production (Q_{hmax}) to the average hourly water (Q_{hav}). The relationship discussed can be written with the following equation [Ogiolda et al. 2019, Jasmin and Nedim 2020]:

$$N_h = \frac{Q_{h\,max}}{Q_{hav}}$$

The analysis of the water production characteristics of the treatment plant was based on statistical analysis of the hourly water production measurement results. The arithmetic mean, median standard deviation, minimum, maximum and coefficient of variation were used to describe the data set. The coefficient of variation is defined as the ratio of the standard deviation and the arithmetic mean. However, the limits of the assessment interval for the value of this coefficient were assumed to be as follows:

- x ∈ (0; 25%) – low variability
- x ∈ (25; 45%) – average variability
- x ∈ (45; 100%) – high variability
- x > 100% – very high variability

Based on the values of these statistical measures, changes occurring in water production in the year 2021 were assessed. Statistical calculations were made using the STATISTICA 13.3 programme in the Polish language version.

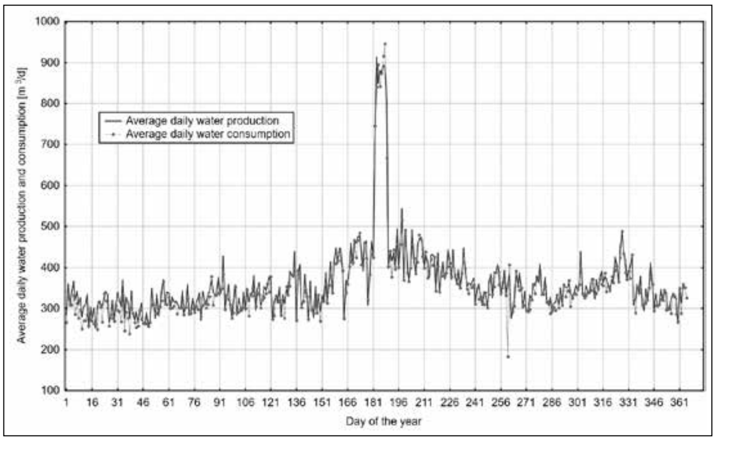
Results analysis and discussion

Table 1. Monthly average water production and distribution through 2021
Tabela 1. Średnia miesięczna produkcja i rozbiory wody na przestrzeni roku 2021

Month	Average water production in m^3/d	Average water withdrawals m^3/d
January	309.68	287.42
February	303.32	285.11
March	322.74	309.45
April	333.37	321.50
May	335.16	323.58
June	406.40	395.07
July	542.71	532.90
August	385.94	374.65
September	345.57	331.63
October	344.51	334.97
November	378.30	370.33
December	331.45	321.10

During the study period under consideration, daily water withdrawals varied

Figure 2:
Daily water production and consumption in 2021
Rysunek. 2. Dobowa produkcja i zużycie wody w roku 2021



from approximately 362.02 m^3/d to 914.00 m^3/d. The average water production per month is shown in Table 1.

During the study period, average water production gradually increased from January to July. The average values of monthly water production then fluctuated between 303.32 and 542.71 m^3/d. It should be noted that the highest water production was observed in June and July, which may be directly related to the characteristics of the area where crop production dominates. In addition, these months in Poland's climate are usually among the warmest periods, in which relatively low values of monthly precipitation are periodically observed. Additionally, it should be emphasised here that the value of water production was influenced by the first eight days of July, where water production varied between 697 and 914 m^3/d. On the remaining days of July, water production averaged 435.62 m^3/d. During the rest of the year, a decrease in water production was observed and between August and December, average water production varied between 344.51 and 385.91 m^3/d. The observed changes in water production indirectly indicate seasonal variations in water demand, which are characteristic of areas characterised by agricultural crop production. At this point, it should be emphasised that each time water production was close in value to water consumption. This observation is still particularly relevant from the point of view of the aforementioned increased water consumption taking place in July. Such a condition may indicate a failure of the water supply network, which resulted in unsealed water pipes and, consequently, uncontrolled water outflow from the water supply network pipes. The changes discussed are shown in detail in Figure 2.

A subsequent element of the analysis of water distribution in the area served by the water treatment plant was the analysis of hourly water production by hour during the day. Table 1 shows the descriptive statistics of water production that were determined for individual hours of the day. It should be noted that, irrespective of the time of day, the average value of water extraction was similar and varied between 12.63 and 14.18 m^3/h, while the middle value for individual hours varied between 13.59 and 15.18 m^3/h. This observation indicates the cyclic operation of the pumping set and the consequent gradual filling of the storage tanks. For all hours of the day, similar values of the arithmetic mean and median were observed, indicating that the hourly water production was similar over the considered period in all hours. The minimum value of water consumption observed in individual hours varied between 1.09 and 2.15 m^3/h, while the value of maximum hourly water distribution was 27.76 m^3/h.

It should be emphasised at this point that such an observation can be directly related to the automatic control system of the water treatment plant itself, as well as to the fact that the water treatment process line includes equalization tanks which were filled cyclically depending on the water table level in the said tank. Therefore, the maximum water consumption observed for individual hours of the day is related to the assumed operational capacity of the water treatment plant, which takes place under nominal operating conditions of the pumping set-pressure filters-retention tank system. In addition, it should be noted that the standard deviation values observed for individual hours were around 6 m^3/h, indicating relatively small changes in hourly water production at particular times of the day. In addition to the value of the standard deviation, this observation is reflected in the values of the coefficient of variation, which varied between 37.79 and 46.64% and indicated an average variation in the water distribution in individual hours during the day.

Figure. 3. Hourly water consumption during the maximum water consumption day
Rysunek. 3. Godzinowy rozbiór wody w dobie maksymalnego rozbioru wody

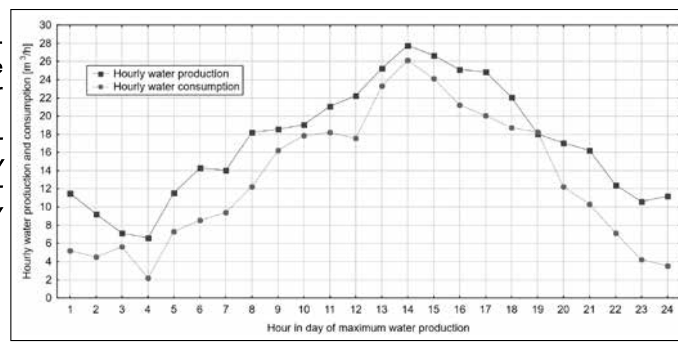


Table 2. Descriptive statistics of hourly water production in 2021
Tabela 2. Statystyki opisowe godzinowej produkcji wody w roku 2021

Hour	No of observation	Average mean	Median	Min	Max	Standard deviation	Variation coefficient
1	365	13,15	13,90	1,54	27,76	5,95	45,27
2	365	12,94	13,90	1,36	27,76	5,57	43,07
3	365	13,66	13,90	1,68	27,76	5,36	39,25
4	365	14,04	14,69	1,71	27,76	5,31	37,79
5	365	13,32	13,95	1,67	27,76	5,83	43,77
6	365	13,36	13,54	1,36	27,76	6,02	45,07
7	365	13,18	14,19	1,60	27,76	5,58	42,37
8	365	13,57	14,60	1,53	27,76	5,79	42,66
9	365	13,52	14,53	1,72	27,76	6,06	44,80
10	365	13,54	14,14	1,40	27,76	6,05	44,71
11	365	13,65	13,72	1,78	27,76	5,46	40,03
12	365	13,00	14,24	1,23	27,76	6,06	46,64
13	365	14,18	14,37	1,51	27,76	5,79	40,82
14	365	13,54	13,91	1,71	27,76	5,70	42,07
15	365	13,28	13,98	1,65	27,76	5,74	43,19
16	365	13,84	14,98	1,68	27,76	6,13	44,29
17	365	13,84	14,65	2,15	27,76	5,81	42,02
18	365	12,63	13,77	1,72	27,76	5,80	45,87
19	365	13,99	15,18	1,50	27,76	5,64	40,35
20	365	13,36	13,89	1,12	27,76	6,10	45,63
21	365	13,45	14,26	1,09	27,76	6,05	44,99
22	365	13,94	14,40	1,63	27,76	5,85	41,96
23	365	13,76	14,49	1,53	27,76	6,26	45,48
24	365	13,60	13,59	1,17	27,76	5,82	42,79

As defined, the coefficient of hourly water distribution irregularity is determined based on the maximum hourly water consumption on the day of maximum distribution. As previously mentioned, the day of maximum water distribution was observed in July. However, due to the large differences and the high probability of water mains failure, this period was discarded from the analysis. Excluding the aforementioned period, the maximum daily water production was 543.0 m^3/d, hence this day was taken for further analysis of the hourly water production irregularity factor.

On the day of maximum water production, the highest hourly production was around 28.0 m^3/h and occurred at 2 p.m. During the rest of the day, hourly water production varied from around 7.0 to just over 25 m^3/h. It should be noted that between 1 and 6 o'clock the average hourly water production averaged around 10 m^3/h. Then, from 6 am to 5 pm, an increase in hourly water production was observed, which was then around 24 m^3/h. Later in the day, a decrease in average water production was observed, which was around 15 m^3/h.

Table 3 shows the values of average and maximum water productions observed over the year 2021. According to the data presented, Q_{dmax} was 543.0 m^3/d, while Q_{dav} was at 362.03 m^3/d. The resultant of these two values is the value of the daily irregularity coefficient, which was 1.50. According to the methodology for determining the value of the hourly irregularity coefficient, the day of maximum water consumption indicated a value of Q_{hmax}, which was 27.76 m^3/h, and averaged the hourly water consumption (Q_{hav}), whose value was 15.08 m^3/h. According to the methodology for calculating the value of the hourly irregularity coefficient, its value for the study period was 1.84.

According to the adopted design guidelines, the values of the hourly irregularity coefficient are generally greater than the daily irregularity. This regularity is due to the need to adapt the water treatment technology and the operating capacity of the equipment to the occurrence of the most unfavourable operating conditions of the facility resulting from the treated water distribution in the area [Merkel et al. 2011, Kucera et al. 2018]. In this case, it is related to ensuring that an adequate volume flow of water meeting the chemical and sanitary conditions imposed by regulations can be introduced into the water supply network [Bartkowska and Wawrentowicz, 2018, Simukonda et al. 2018, Li and Han 2020]. Therefore, the value of the coefficient of irregularity of hourly water consumption is particularly important when dimensioning the individual elements of the technological line of the water treatment station. It should be emphasised at this point that the values of hourly water discharge depend on the size of the equipment intended for water aeration, the size of the filters and, indirectly, the characteristics of the water treatment technology [Cescon and Jiang 2020]. The study showed that the values of the coefficients of hourly and daily irregularity of water production were value-wise similar, however, the hourly unevenness was greater than the daily unevenness.

Table 3. Values of unevenness coefficients and characteristic distributions
Tabela 3. Wartości współczynników nierównomierności i rozbiory charakterystyczne

Parameter	Unit	Value
Q_{dmax}	m^3/d	543.00
Q_{dav}		362.03
Q_{hmax}	m^3/h	27.76
Q_{hav}		13.09
N_D	-	1.50
N_h		1.84

Such regularity may be due to the fact that in the process line of the water treatment station, retention reservoirs with a capacity of 200 m^3 are provided, which allow securing the water needs of the inhabitants of the area served by the station in the day of maximum discharge for almost 12 hours. Indirectly, this treatment translates into a lower value of the hourly irregularity coefficient [Nagashio et al. 2010, Klingel and Knobloch 2015]. It should be emphasised here that this approach is crucial in maintaining the operational reliability of the water treatment line equipment. With moderately varying hourly distributions, it is possible to operate the equipment within the optimum range of operating parameters, which is of particular importance in the case of water transfer pumps and compressors [Ermini et al. 2015, Tuhovcak et al. 2018]. In addition, equalised values of hourly water demand make it possible to maintain the assumed technological conditions of filter operation, and thus it is possible to reliably maintain the required quality parameters of treated water supplied to consumers [Tokajian and Hashwa 2003, Pundir et al. 2021].

Conclusions

The research carried out showed that in the process line of the water treatment plant, in which equalization tanks are installed, hourly water production is equalised at particular times of the day. The maximum water extraction is more related to the need to replenish the storage reservoir to the assumed water level, while the coefficient of irregularity of hourly and daily water production shows a relation that the N_h value is slightly higher than the N_D value. The probable reason for the observed dependence is the fact that water production is directly dependent on the water demand that occurs in the settlement unit area during the day. Not less, the value of daily water consumption is a kind of sum of instantaneous consumption, which is different at different times of the day. This observation may be due to the fact that the storage reservoir is a buffer for the amount of water that is used by residents in the area served by the water treatment plant. This type of buffer makes it possible to limit the occurrence of temporary phenomena associated with increased water production. This regularity translates into a similar continuity of operation of the submersible pumps and consequently results in a smaller variation in water production as observed in the hourly intake. Hence, the hourly irregularity is due to the need to cycle the storage reservoirs in the area of minimum and maximum set capacity. This, in turn, can translate into similar values for daily and hourly irregularity coefficients. If this value is appropriately chosen, it is possible to maintain uniform operation of the equipment without having to operate the equipment under maximum operating load conditions. In addition, the presence of storage reservoirs in the water treatment process line may make it possible to negate the impact of hourly water outages on the continuity and reliable operation of individual elements of the water treatment process line. In addition, based on the observations described above, it can be concluded that the operation of the submersible pumps is dependent on the water level in the buffer tank, which in turn makes it possible to adapt their performance to current needs, which in the case of smaller water consumption may contribute to prolonging the operation of the pumps in nominal conditions.

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