Advances in Science and Technology
Research Journal

Advances in Science and Technology Research Journal, 18(6), 392–405
https://doi.org/10.12913/22998624/192021
ISSN 2299-8624, License CC-BY 4.0

Received: 2024.07.13
Accepted: 2024.08.15
Published: 2024.09.08

Influence of Incidental Water on Changes in the Amount of Wastewater Flowing into the Treatment Plant

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ABSTRACT

The paper determines the effect of daily precipitation, occurring in the sewerage catchment area located in the Jastków Commune, on the volume of wastewater, flowing into the treatment plant in Snopków. Daily and annual volumes of incidental water, caused by precipitation, flowing into the selected sewerage system were determined, and then the annual costs incurred for their treatment were calculated. The sewerage system selected for the study is located in the eastern part of Poland, in the Lublin Voivodeship, within the Jastków Commune. The design average daily inflow of wastewater to the classical treatment plant with activated sludge is 1200 $m^3 \cdot d^{-1}$. To the sewage network made of PVC with a length of 67.22 km domestic wastewater from 1119 single-family buildings from 3350 residents are discharged. The study was carried out in 2019–2022, and the daily precipitation totals and daily sewage inflows to the treatment plant were analyzed. The results of the calculations were related to the humidity classification of the year (dry, average and wet) under temperate climate conditions. The study showed that during precipitation events, the share of incidental water in the average daily volume of wastewater flowing into the treatment plant ranged from 3 to 26%. Annually, 7,471 to 10,325 m^3 of rainwater flowed into the studied treatment plant, which accounted for 5.0 to 6.3% of the annual volume of wastewater. The incidental waters flowing into the sewage system resulted in the need to spend additional sums – from PLN 47,814 (€10,897) to PLN 70,233 (€16,007) per year. Thus, the annual cost of wastewater treatment in the studied system increased by about 5–6%. The results of the study are important and valuable information for the operators of the analyzed sewerage network and the wastewater treatment plant, as well as for other units that use similar systems. They will allow to initiate actions to detect and eliminate illegal connections of roof gutters and/or yard drains to sanitary sewers in the analyzed area, which would then allow to reduce the cost of wastewater treatment in the studied case.

Keywords: incidental water, precipitation, sewerage network, hydraulic conditions, wastewater treatment plant, wastewater treatment costs.

INTRODUCTION

In recent years, various changes have been observed, occurring in the surrounding environment, both environmental, as well as economic and social. In most countries around the world, urbanization processes are accelerating, requiring better integration of planning and development in terms of providing various services [1]. An issue that is troubling the public and scientists still more and more is the progressive and increasingly noticeable climate change [2]. It is observed, among other things, that stormy precipitation is becoming more frequent, with the most severe effects in urbanized areas prone to flooding [3, 4]. In between these rainfall events, periods of drought are increasingly common [5]. These problems have a significant impact on the operation of the technical infrastructure that is associated with them. This mainly concerns storm and combined sewerage. However, as pointed out by many authors [6–9] this unfortunately also applies to separate sanitary sewage systems. According to Polish law, "it is prohibited to introduce rainwater, groundwater and drainage water into the sanitary sewerage system" [10]. However, as the experience from many countries show, it is not possible to effectively protect sanitary sewerage networks from the inflow of incidental water, which most often comes from rainwater that enters sewers through manholes or vents inside sewer wells [11–16]. Despite legal prohibitions, there are still detected many illegal discharges of drainage water from building drainage systems into domestic or industrial sewers [17], as well as rainwater from roof gutter downspouts and yard drains [18], and snowmelt water, which is produced during snow melt and flowing into the sewage system through openings in manhole covers of inspection chambers [16, 17]. Inflow of foreign water into sewerage is a serious problem in urban water management due to its environmental, social and economic consequences [19]. The inflow of large volumes of rainwater into the sewage system has many negative consequences, such as lowering the temperature of wastewater and changing the concentrations of individual pollutants in it [12, 13, 20]. In addition, especially in situations of heavy rainfall, rainwater runoff from residential, urban and agricultural areas can be contaminated with various chemicals and pathogenic microorganisms [21–24]. The inflow of incidental water into the sewerage system increases the amount of wastewater entering the wastewater treatment plant, which can result in exceeding the allowable design capacity [15]. In sewers, incidental water leads to hydraulic overloading of sewer interceptors, manholes on the sewerage network, and pumping stations, resulting in increased energy consumption, faster deterioration of pipelines, failures, and consequent flooding of surrounding areas [25–27]. Occurring after heavy rainfall, increased volumes of domestic wastewater mixed with rainwater cause significant damage to human health and surrounding infrastructure [28, 29].

In addition to the effects of climate change, in recent years, European societies have also been affected by dynamic economic changes, triggered by the effects of the COVID-19 pandemic and the war in Ukraine [30]. Many countries are witnessing an economic crisis caused by these problems, linked to rising inflation. All these factors are prompting it to pay more attention to the need to look for potential opportunities to reduce the rising costs of economic activity. One of the directions to which local government units are devoting significant financial resources is transportation and wastewater treatment. It is obvious, that the greater the volume of wastewater that enters the sewerage system, the greater the cost of transporting it to the wastewater treatment plant and their subsequent disposal [18, 31, 32]. Thus, if the sewerage system receives, in addition to municipal wastewater, incidental water (rainwater), the costs in question are increased in relative terms. Precipitation water entering the sewerage system causes an increase in the flow rate, and consequently increase the value of pollutant loads in wastewater discharged to the receiver. Therefore, higher costs paid for discharging wastewater into the environment are generated. There is then also a risk of pollution of the receiving water [33–35].

All the enumerated aspects point to the urgent need to set goals, and then to develop a strategy for proceeding and implementing multidirectional measures to improve the financial health of water and wastewater services, while taking care of the environment, in view of the observed climate and economic changes [14].

These aforementioned needs prompted the authors to carry out a study aimed at assessing the impact of incidental water flowing into the sewage network on the increase in wastewater treatment costs in a selected commune in southeastern Poland. The scope of the study included the analysis of daily precipitation totals and daily sewage inflows to the sewage treatment plant in a dry, average and wet year, under conditions of a temperate climate. On the basis of the research, the daily and annual volumes of incidental water caused by precipitation flowing into the analyzed sewage system were determined, and then the annual costs incurred for their treatment were calculated.

MATERIALS AND METHODS

Experimental facility and research area

The sewerage network, by which wastewater is fed to the analyzed treatment plant in Snopków, is located in the Jastków Commune, in the Lublin Voivodeship, in southeastern Poland. It has a length of 67.22 km and is made of PVC. The number of sewer connections is 1119. The sewage system is used by 3350 residents of the commune. The location of the wastewater treatment plant is described by geographical coordinates: 51°18’35” N, 22°29’32” E and are shown in Figure 1.

The wastewater treatment plant, which receives wastewater flowing from the sanitary sewage system under study, as well as delivered by sewage trucks, is used to dispose of domestic and industrial wastewater. The facility was put into operation in December 2006, and was reconstructed and upgraded during years 2020–2022. A detailed description of the facility was presented in the studies of Jóźwiakowska and Marzec [36] and Dubiel [37]. According to the “Construction and working design of the reconstruction of the wastewater treatment plant in Snopków, Jastków Commune” [37], the analyzed facility was designed for the following parameters: $Q_{a.d.}$ = 1200 $m^3 \cdot d^{-1}$, $Q_{a.h.}$= 50 $m^3 \cdot h^{-1}$, 3675 PE. Wastewater treatment is carried out in 3 stages. In the first stage (mechanical), wastewater is treated on the grid, in a screen-sand trap, and then in a radial horizontal-flow initial settling tank. The second stage of pollutants removal is biological treatment, carried out by the activated sludge method in a three-chamber flow reactor, in which the processes of defosfatation, nitrification and denitrification take place. Separation of activated sludge from biologically treated wastewater takes place in a secondary radial settling tank. The third stage of wastewater treatment at the studied facility is a flow-through hydroponic lagoon, equipped with a panelized bed system that provides a habitat for macrophytes (*Zantedeschia* Spreng.). This element is the equivalent of a biological pond with multiplied capacity. The facility operates year-round, which allows increasing the efficiency of removing pollutants from wastewater, before discharging it to the receiving water body. An additional buffer element, before treated wastewater is discharged to the receiver, i.e. to the Ciemięga River, is a pond.

Characteristics of precipitation in the study area

The average annual precipitation, in the analyzed area, is 560 mm. An uneven distribution of precipitation is observed throughout the year, an increased frequency of precipitation is in July (77.0 mm) and a reduced frequency in January (29.6 mm). In individual seasons, precipitation shows considerable variation both in terms of intensity as well as duration. In winter and autumn, precipitation tends to be long-lasting, while in summer it is shorter but more intense [38].

Statistical and analytical methods

The analysis included daily precipitation heights, obtained from a meteorological station located in Lublin, 20 km from the treatment plant [39]. The study was conducted in the years: 2019, 2020 and 2022. At the same time, with the help of electromagnetic flow meters, daily wastewater inflows to the treatment plant in Snopków were measured. Flowmeter No. 1 is located at the catchment station and it is used to measure the volume of wastewater delivered by sewage trucks. Flowmeter No. 2 is installed in the measuring chamber, behind the hydroponic lagoon, and it is used to measure the volume of treated wastewater discharged to the receiver. The volume of wastewater flowing into the treatment plant through the sewerage system was calculated according to formula (1):

$$Q_{d.ss.} = Q_{d.tw.} - Q_{d.st.} \quad (1)$$

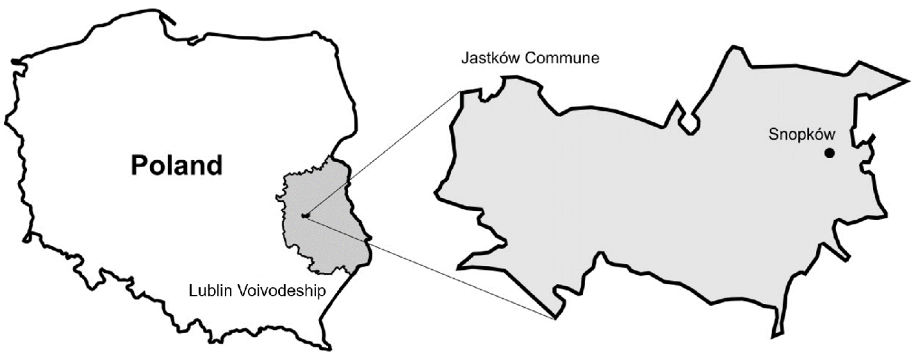

Fig. 1. Location of the research facility – Poland, Lublin Voivodeship, Lublin County, Jastków Commune, Snopków Village

where: $Q_{d.ss.}$ – daily volume of wastewater inflowing to the treatment plant through the sewerage system [$m^3 \cdot d^{-1}$], $Q_{d.tw.}$ – daily volume of treated wastewater discharged to the receiver [$m^3 \cdot d^{-1}$], $Q_{d.st.}$ – daily volume of wastewater delivered by sewage trucks to the treatment plant [$m^3 \cdot d^{-1}$].

In order to analyze the volume of wastewater flowing into the treatment plant, a statistical analysis of the obtained data was performed. There were determined such basic parameters of descriptive statistics as:

1) Positional measures, i.e.:
   - mean value ($\bar{x}$),
   - median (*Me*),
   - minimum value (*min*),
   - maximum value (*max*),
   - range (*R*),
2) Dispersion measures, i.e.:
   - standard deviation (*s*),
   - coefficient of variation (V_s).

For the study years 2019, 2020 and 2022, individual wastewater inflows to the treatment plant were associated with daily precipitation that occurred on the same day. In addition, wastewater flow – precipitation pairs were assigned to 5 groups (from A to E), differing in the range of daily precipitation (*x*), i.e.:

a) $0.0 \leq x \leq 1.0$ $mm \cdot d^{-1}$,
b) $1.0 < x \leq 5.0$ $mm \cdot d^{-1}$,
c) $5.0 < x \leq 10.0$ $mm \cdot d^{-1}$,
d) $10.0 < x \leq 15.0$ $mm \cdot d^{-1}$,
e) $x > 15.0$ $mm \cdot d^{-1}$.

According to the guidelines developed by Kaczor [18] a given daily inflow of wastewater to a wastewater treatment plant can be attributed to so-called dry weather if during that day, and in the five days preceding, there was no precipitation, or there was, but its daily amount did not exceed 1 mm. Thus, wastewater flows assigned to group A, characterize the hydraulic load on the wastewater treatment plant during dry weather. The average daily wastewater inflow during rainless (dry) weather was used to determine the average inflow rate to the treatment plant of proper wastewater, i.e. not containing incidental water.

The remaining ranges from B to E characterize the daily inflow of wastewater to the wastewater treatment plant during wet weather at different ranges of daily precipitation.

Based on the guidelines of Kaczor [18], the daily inflow rate of incidental water caused by rainwater to the sewerage system was calculated according to formula (2):

$$Q_{d.i.} = Q_{d.w.} - Q_{d.d.} \qquad (2)$$

where: $Q_{d.i.}$ – daily inflow of incidental water to the sewerage system [$m^3 \cdot d^{-1}$], $Q_{d.w.}$ – daily inflow of a mixture of domestic wastewater and incidental water to the sewerage system during wet weather [$m^3 \cdot d^{-1}$], $Q_{d.d.}$ – average daily inflow of domestic wastewater (excluding incidental water) to the sewerage system during dry weather [$m^3 \cdot d^{-1}$].

The percentage share of incidental water in relation to the total volume of the mixture of domestic wastewater together with incidental water was calculated from the formula (3) [40]:

$$\%i.w. = \frac{Q_{d.i.}}{Q_{d.w.}} \cdot 100\% \qquad (3)$$

where: $\%_{i.w.}$ – daily percentage share of incidental water in the wastewater flowing into the sewerage system [%], $Q_{d.i.}$ – daily inflow of incidental water to the sewerage system [$m^3 \cdot d^{-1}$], $Q_{d.w.}$ – daily inflow of a mixture of domestic wastewater and incidental water to the sewerage system during wet weather [$m^3 \cdot d^{-1}$].

Analytical calculations were performed using Microsoft Excel 2019, and statistical calculations were performed using Statistica 13.3.

RESULTS AND DISCUSSION

Characteristics of daily wastewater inflows to the treatment plant

The data, verified in terms of accuracy of recording, which included the values of daily wastewater inflows to the treatment plant, were used to determine the values of the basic parameters of descriptive statistics. These parameters made it possible to characterize the diurnal variation in the intensity of wastewater inflow to the sanitary sewerage system and treatment plant in Snopków in individual years (Table 1). In the analyzed three-year observation period, there was a significant variability in the volume of wastewater, flowing daily to the treatment plant. This was evidenced by the range of daily inflows in the multi-year period, which was from 119 to 1017 $m^3 \cdot d^{-1}$. Such a large

Table 1. Basic descriptive statistics of the volume of wastewater flowing daily to sewerage system and to the wastewater treatment plant

Year	$\bar{x}$	Me	min	max	R	s	Vs
	[$m^3 \cdot d^{-1}$]						[%]
2019 (average)	405.6	401.0	119.0	804.8	685.8	72.7	17.9
2020 (wet)	448.1	436.9	281.2	862.5	581.3	62.6	14.0
2022 (dry)	555.5	555.0	242.0	1017.0	775.0	83.7	15.1

range over three years indicated that an independent factor appeared periodically, significantly affecting the increase in daily wastewater flow. The fact that this factor appeared incidentally was evidenced by the low dispersion of the data around the mean value, as indicated by the low values of the standard deviation (from 62.6 to 83.7 $m^3 \cdot d^{-1}$) and the values of the coefficient of variation (from 14.0 in 2020 to 17.9% in 2019). There was a noticeable increase in the average value in subsequent years, which was related to the progressive expansion of the sewerage network over the years and the connection of more households to it.

Figure 2 graphically shows the development of the daily hydraulic load of the studied wastewater treatment plant in each year. The illustrated data shows that the average daily hydraulic load of the treatment plant, in relation to the facility's design capacity of 1,200 $m^3 \cdot d^{-1}$, remained at a level from 36% in 2019 to 46.3% in 2022. This shows that there is still a large reserve of capacity, allowing the expansion of the sewerage network in the commune. Provided that the quality of wastewater is controlled, there can be considerated increasing the volume of sewage carried to the treatment plant by sewage trucks from septic tanks located in the commune. Similar conclusions, based on the low hydraulic load of the studied facility, were made by Chmielowski [41] and Bugajski et al. [42].

The results of the hydraulic load of the treatment plant, shown in Figure 2, indicated a group of daily inflows, statistically treated as outliers and extreme data. Outlier data, located below the value of the standard deviation, are most often the result of emergency conditions at the treatment plant or possibly at the measuring equipment. On the other hand, outlier data and extreme values, located above the upper value of the standard deviation, indicate the influence of an external independent factor on wastewater flows, which may be rainwater. This provided the basis for further analysis to investigate the potential influence of precipitation on the increase of daily wastewater inflow to the Snopków wastewater treatment plant. The link between the two factors has been indicated by the results of other authors'

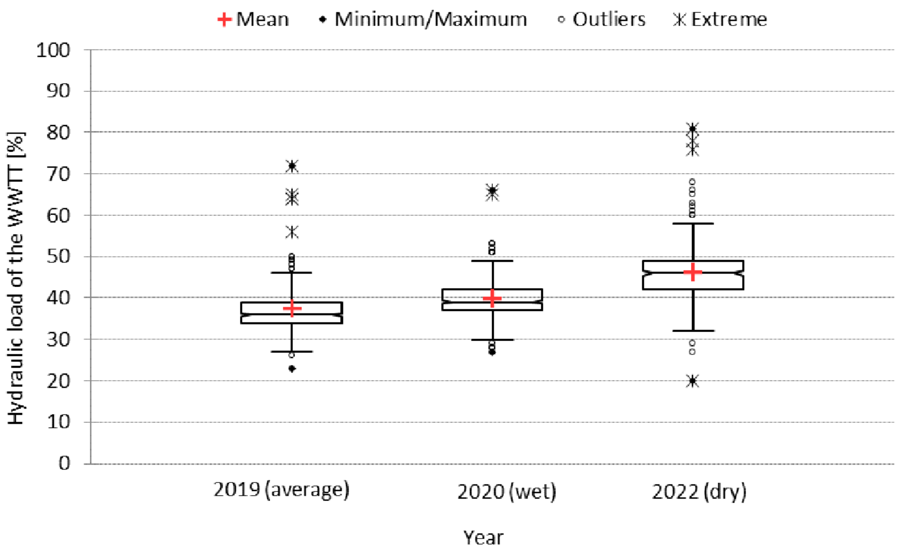

Fig. 2. Mean, outliers and extreme values of daily hydraulic loads of the analyzed wastewater treatment plant in Snopków

research and analysis. The results of Kaczor [18] and Chmielowski [41] showed a strong statistical correlation between annual precipitation and the share of incidental water in annual wastewater inflows to the treatment plant. The causes of this relationship were most often, made illegally by residents, connections to sewers of roof gutter outlets [43], drainage outlets used to drain properties [40] or manholes or vents through which rainwater flowing down the street surface entered the sewerage network [18]. Rainwater inflowing to the sewage system, defined by Pecher [40] as accidental, causes an increase in the irregularity of daily wastewater flows [18]. This is a significant operational problem, since most of the technological facilities for wastewater treatment require fairly constant operating conditions for pollutants disposal processes. In wastewater treatment plants, which are heavily hydraulically overloaded during wet weather, the constancy of the facility's loading conditions can only be ensured by an appropriately designed retention tank [44, 45]. A lower incidence of connection to sewerage systems of streams other than sewage is observed in settlements where continuous raising of environmental awareness of residents is implemented, for example, by conducting training on proper operation of sanitation facilities and providing information on the harmfulness of discharging rainwater into sewerage systems [46].

Analysis of the distribution of daily precipitation in the studied sewerage catchment area

In the first stage of verifying the effect of precipitation on the volume of wastewater flowing into the sewerage system in the Jastków Commune, a humidity assessment was made for each year of the study. For this purpose, the classification proposed by Kaczorowska [47] was used. For the analyzed area, i.e. Lublin Voivodeship, the annual normal precipitation is determined at 560 mm [38]. The assessment of precipitation conditions of the years under study showed that 2019 should be considered normal (average), as its annual total precipitation of 530.7 mm was between 90 and 110% of normal precipitation (560 mm). The year 2020 was assessed as a wet year, as its annual total precipitation was 698 mm, which was between 111 and 125% of normal precipitation. The year 2021 was also a wet year. Since the analysis was carried out for only one year with a given humidity condition, 2021 was excluded from further study. 2022 turned out to be a dry year, as its annual total precipitation of 469 mm represented between 75 and 89% of normal precipitation.

In the next stage of the study, all daily precipitation heights that occurred in the final years selected for analysis (i.e. 2019, 2020 and 2022), were grouped together. Figure 3 shows histograms

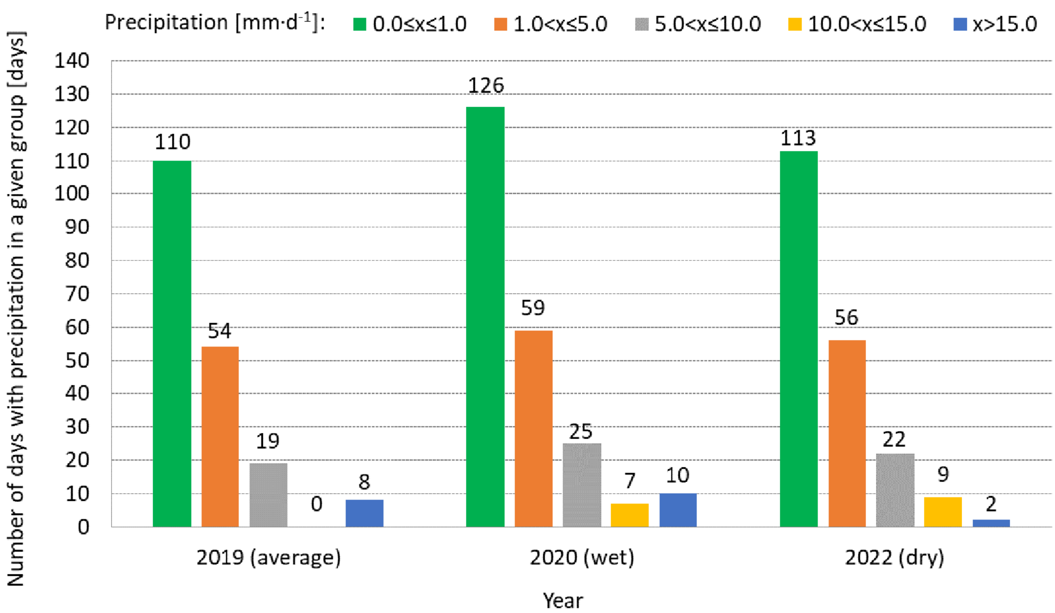

Figure 3. Histograms of the frequency of precipitation in given groups with a certain range of daily rainfall in each year of the study

of the frequency of precipitation in given groups differing in the range of daily rainfall in each year. In each year, precipitation of less than 1 mm·d^{-1} was observed most often. The highest number of days with such precipitation was recorded in 2020 (126 days), and the lowest in 2019 (110 days). The number of days with precipitation from group B, i.e., above 1.0 and up to 5.0 mm·d^{-1}, was similar in the years under study and ranged from 54 in 2019 to 59 in 2020. Precipitation from group C ($5.0 < x \leq 10.0$ mm·d^{-1}) was recorded most frequently in 2020 (25 days) and least frequently in 2019 (19 days). In 2019 there was not a single day with precipitation belonging to group D ($10.0 < x \leq 15.0$ mm·d^{-1}), while in 2022 there were 9 such days. The highest number of days with precipitation, from group E, characterized by the highest daily height of more than 15 mm·d^{-1} was observed in 2020 (10 days).

In general, in 2020 a total number of 227 days with precipitation were recorded, while 101 days were classified as wet weather ($x > 1.0$ mm·d^{-1}). This year was considered wet based on Kaczorowska's classification [47]. In 2019 (an average year), 81 days of wet weather were recorded, while in 2022 (a dry year) 89 days of wet weather were recorded.

Determining the volume of incidental water flowing into the analyzed sewerage system

The volume of incidental water, originating from precipitation, flowing into the sewerage system in the Jastków Commune was calculated for the three analyzed years 2019, 2020 and 2022. Figure 4 graphically illustrates the percentage of incidental water in the average daily volume of wastewater inflowing to sewerage systems and wastewater treatment plant in each studied year. The graphs additionally indicate which group of precipitation caused the largest inflow of incidental water to the analyzed sewerage system. The analysis showed that precipitation of up to 1 mm did not cause an increased inflow of wastewater to the Snopków treatment plant. Precipitation in the range of $1.0 < x \leq 5.0$ mm·d^{-1}, generated a share of incidental water accounting for a maximum of 7.1% of the average daily inflow of wastewater to the treatment plant. Elevated inflows of incidental water to the sewage system were generated by rainfall with a daily height above 5 mm. On the other hand, rains with a daily height of more than 15 mm generated incidental water inflows reaching a maximum of nearly 26% of the value of the average daily wastewater inflow to the sewage system and treatment plant. It should be noted, however, that rains from the last group ($x > 15.0$ mm·d^{-1}), occurred very rarely in a given year 2020 (Figure 2). Hence, the question arises as to which group of rains generated the highest volumes of incidental water on an annual basis. The results of such calculations are shown in Figure 5.

The analyses showed that there was no routine relationship between daily precipitation height, it's frequency and annual inflow of incidental water to the sewerage system in individual years with different annual humidity condition. To establish average relationships, average annual inflows of incidental water caused by precipitation were calculated in fixed daily height ranges for the entire study period. The calculations showed

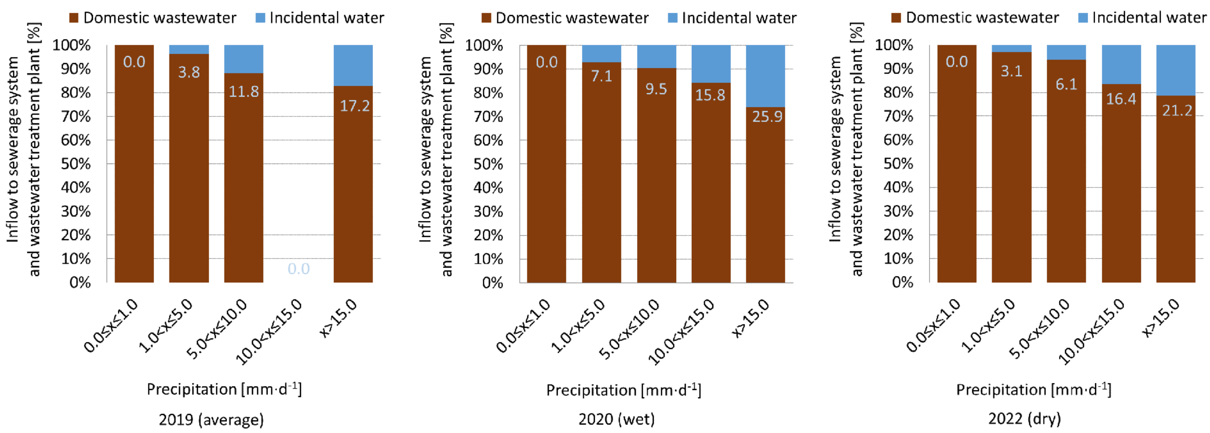

Fig. 4. Share of incidental water in average daily sewage inflow to the sewerage system and wastewater treatment plant in the Jastków Commune

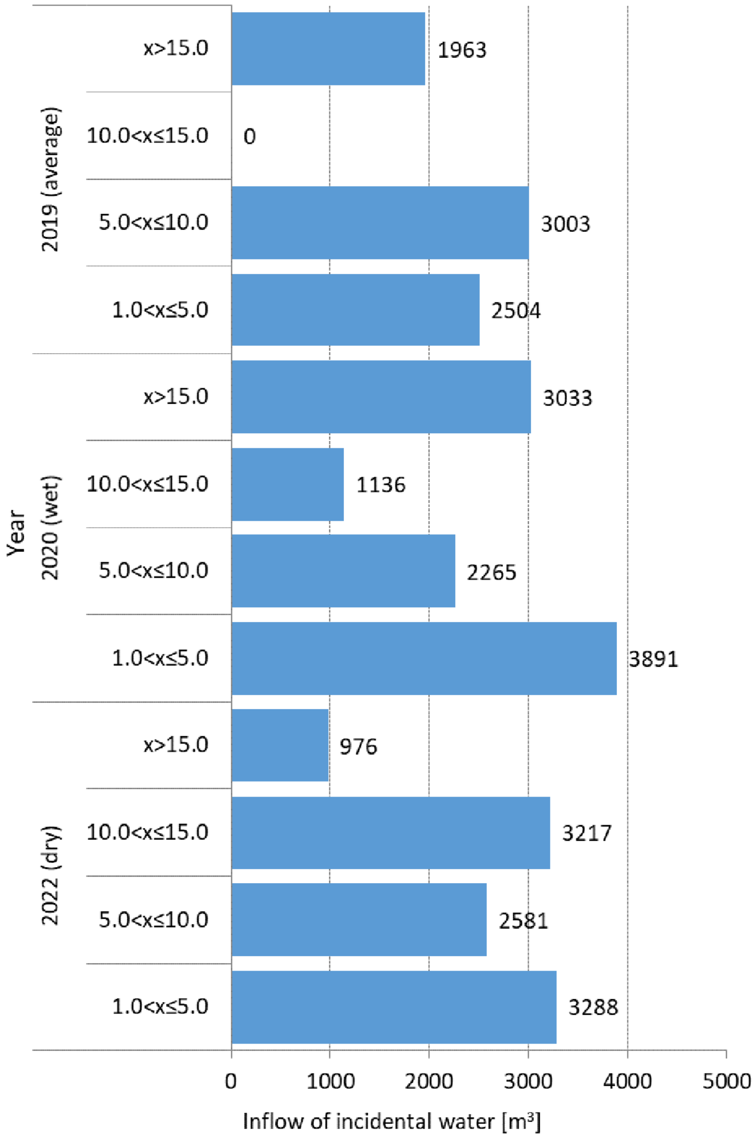

Fig. 5. Annual volumes of incidental water caused by precipitation of different daily heights in a dry, average and wet year

that precipitation with daily heights above 1.0 and up to 5.0 mm·d^{-1} generated annual average incidental water inflows of 1257 m^3, precipitation with daily height of $5.0<x\leq10.0$ mm·d^{-1} – 974 m^3, precipitation with a daily height of $10.0< x \leq15.0$ mm·d^{-1} – 507 m^3, while precipitation with a daily height above 15.0 mm – 824 m^3.

The obtained results indicated that in the analyzed commune, on average, most incidental water in the sewerage system was caused by precipitation with a daily height in the range of $1.0 < x \leq 5.0$ mm·d^{-1}. This was due to the fact that these precipitation events had the highest frequency of occurrence in particular years, and in the entire multi-year period. The results of the detailed analysis carried out in this stage of the study can to be used to calculate the costs incurred by the treatment plant operator for pumping and aerating the increased, by incidental water, wastewater flows.

The research proved relatively low percentage shares of incidental water in daily wastewater inflows to the sewage system and treatment plant in the Jastków Commune. They ranged from 3 to 26% (Fig. 4). Other authors obtained much higher values of this parameter. Kaczor et al. [48] showed in their study that the share of incidental water in the inflow to the studied facility ranged from 23 to 41%. Wang et al. [49] reported that in the studied treatment plant incidental water accounted for about 27–33% of the total volume of wastewater entering the facility during the year, while in the research of Bogusławski et al. [45] the share was between 38 and 53%. Alarming results, regarding the calculated volume of incidental water entering the treatment plant, were shown by Bugajski et al. [50], where the share of incidental water, in the total volume of wastewater flowing into the treatment plant, ranged from 27 to as much as 75%. However, there are also known research results that indicate that in some sewerage networks the inflow of incidental water may be low and similar to the results obtained in this study. Młyńska et al. [13] reported that in the sewerage they studied, the share of incidental water ranged from 2.7 to 5%. However, it should be borne in mind that incidental water, even in small amounts, can adversely affect the biological processes of wastewater treatment. Wałęga and Kaczor [51] showed that inflows of incidental water to a wastewater treatment plant operating on the basis of activated sludge technology resulted in a weakening of its activity. The activated sludge is more negatively affected by wastewater cooled by incidental waters from melting snow [33]. In addition, wastewater diluted with rainwater is characterized by reduced concentrations of organic compounds and nutrients and are characterized by lower susceptibility to biochemical decomposition [12].

Costs of incidental water treatment

The main costs to be borne by the operator of the treatment plant are the environmental fee for the wastewater discharged to the receiver, the energy costs necessary for wastewater transporting and pumping, and the costs necessary for wastewater treatment processes [41]. Thus, if, in addition to domestic wastewater, incidental (rainwater) flowed into the studied facility, it should be assumed that the cost of wastewater treatment increased relatively [32]. In the studied case the unit gross cost of treating 1 m^3 of wastewater was PLN 6.40 (€1.46) in 2019, PLN 6.46 (€1.47) in 2020, and PLN 7.08 (€1.61) in 2022 (calculated based on [52, 53]). Table 2 summarizes the annual inflows to the analyzed wastewater treatment plant and incidental water, as well as the separated volumes of these streams. The tabulated values again confirmed that the volume of incidental water flowing into the sewerage system and then into the wastewater treatment plant did not depend on the humidity classification of the year. In a dry year (2022), only 264 m^3 or 2.56% less incidental water flowed into the sewage system than in a wet year (2020). In contrast, in 2019 which was classified as an average year, the least volume of incidental water reached the studied sewerage, and its annual share was the same as in the dry year (2022) and amounted to only 5%. The results presented indicated that annual precipitation does not always determine unequivocally the volume of incidental water flowing into the sewerage system. Of a great importance is also the intensity of the individual rainfall events during year, their duration and, above all, the length of the time periods between successive rainfall events. In the latter case, the sewerage system will not yet have time to discharge to the treatment plant the mixture of incidental water and wastewater retained in the pipes and manholes, when another wave of

Table 2. Annual inflows of domestic wastewater and incidental water to the sewerage system and to the wastewater treatment plant in the Jastków Commune

Years and humidity classification	Tested parameter	Unit	Value of the parameter
2019 (average)	Wastewater and incidental water combined	m^3	148,060
	Wastewater excluding incidental water		140,589
	Incidental water		7,471
	Share of incidental water	%	5.0
2020 (wet)	Wastewater and incidental water combined	m^3	164,001
	Wastewater excluding incidental water		153,677
	Incidental water		10,325
	Share of incidental water	%	6.3
2022 (dry)	Wastewater and incidental water combined	m^3	202,842
	Wastewater excluding incidental water		192,782
	Incidental water		10,061
	Share of incidental water	%	5.0

precipitation and incident water appears. Analysis of such specifics of rainfall incidents will be the subject of further research.

In the penultimate stage of the study, the annual costs incurred by the treatment plant operator for treating incidental water were calculated. In the dry year (2022) 10,061 m^3 of incidental water flowed into the treatment plant, so the costs of their treatment amounted to PLN 71,233 (€16,007), in the average year (2019) 7,471 m^3 of incidental water flowed into the treatment plant and their treatment costs amounted to PLN 47,814 (€10,897), whereas in the wet year (2020) the volume of incidental water that flowed into the studied facility was 10,325 m^3 so their treatment costs amounted to PLN 66,706 (€15,202). Thus, as a result of incidental water flowing into the sewage system, the annual costs of wastewater treatment in the studied system increased by about 5–6%. The calculated values indicate that despite the relatively low share of incidental water in the annual sewage inflows to the treatment plant in the Jastków Commune, the costs that can be saved, after eliminating the sources of incidental water inflow to the sewage system are significant – more than PLN 70,000 (€16,000) can be saved annually.

Figure 6 illustrates the annual costs incurred for the disposal of incidental water entering the Snopków wastewater treatment plant, considering the division into individual groups of precipitation. The costs, shown graphically in Figure 6, indicate that there is no clear relationship between the classified humidity of the year and the distribution of costs in conjunction with the grouping of precipitation on the basis of its daily height. More clear information is provided by averaging the amounts, in individual precipitation groups, over the entire three-year study period. Such calculations indicate that the highest amount, on average PLN 21,372 (€4,871), related to rainwater treatment, is generated by precipitation with daily heights above 1.0 and up to 5.0 mm, a slightly lower amount, PLN 17,290 (€3,940) by rainfall between 5.0 and 10.0 mm, and the lowest amount, PLN 9,930 (€2,263) by rainfall between 10.0 to 15.0 mm.

The obtained results of the study are worth relating to the results of other authors' analyses. Kaczor [18] studied the costs incurred for wastewater treatment in 5 sewerage systems, located in the Małopolska Voivodeship in Poland. The share of incidental water in annual inflows to the treatment plants in these systems ranged from 9.4 to 57%. The cost of treating 1 m^3 of wastewater was then PLN 3.0 (€0.69). Therefore, in dry years, the costs of treating incidental water reached PLN 238,000 (€54,240), in average years PLN 311,000 (€70,877), while in wet years as much as PLN 395,000 (€90,020). Based on these values, it is evident that in the Jastków Commune the sums spared for the treatment of incidental water are much lower. However, this does not mean that measures should not be taken to detect and neutralize the inflow of incidental water in the analyzed case.

There is a range of methods for detecting irregularities in the inflow of incidental water into sewage network [28, 54]. According to the experience of Kaczor and Cupak [9] video inspections of the interior of sewers are helpful in diagnosing the causes and sources of incidental water inflows. Closed-circuit television (CCTV) inspections and Fibre-optic Distributed Temperature Sensing (DTS) surveys of pipes make it possible to detect and eliminate improperly and illegally made connections to sewage collectors [55–57]. Significant inflows of incidental water into sewerage networks can also be eliminated by sealing or improving the leveling of sewer manhole finials,

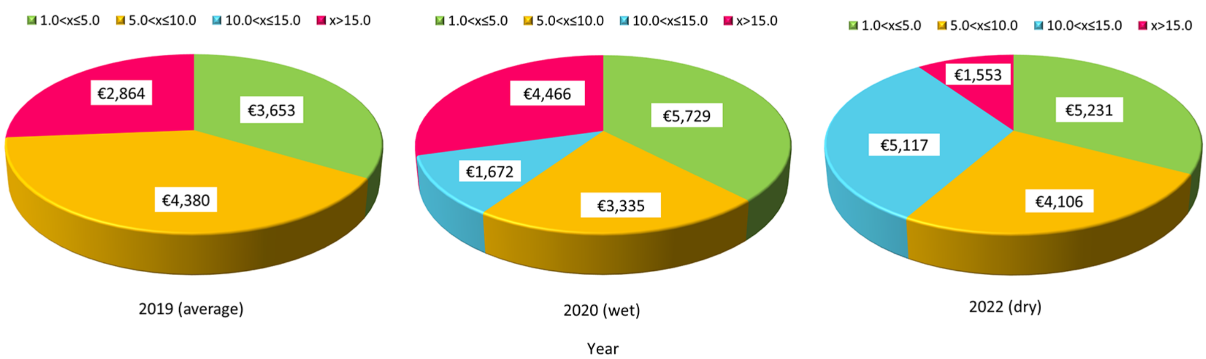

Fig. 6. Annual costs of treating incidental water considering individual precipitation groups

through the use of appropriate spacer rings, as pointed out by Bogusławski et al. [16]. Proper education of sewage system users is also of utmost importance [46].

In analyzing the dynamic fluctuations of wastewater and incidental water in the sewage system and in assessing the efficiency of wastewater treatment plant operation under different conditions, computerized forecasting and modeling software effectively helps [5, 28, 58–65].

CONCLUSIONS

Rainwater-induced incidental water inflows to the sewerage system located in the Jastków Commune pose a problem in terms of the variable and increased hydraulic load in the Snopków wastewater treatment plant. The irregularity of daily sewage inflows, characterized by the value of the statistical coefficient of variation, ranged from 14.0% in 2020 to 17.9% in 2019.

The share of incidental water in daily wastewater inflows to the treatment plant ranged from 3.1 to 25.9%, depending on daily precipitation. The share of incidental water in annual wastewater inflows to the treatment plant ranged from 5.0 to 6.3%. The study showed slight differences in the share of incidental water flowing to the analyzed sewage system in a dry year and an average year. Due to inclusion of a relatively short multi-year period of the analysis, the differences in annual precipitation totals in individual years are insignificant. On the other hand, obtaining a longer study period is difficult, due to the lack of archiving of long data sequences for small wastewater treatment plants. An additional problem is that annual rainfall totals do not always determine the volume of incidental water that flows into the sewerage system. As already indicated in this work, the intensity of individual precipitation events in a year, their duration and, above all, the length of the time intervals between successive precipitation events are also of great importance. Despite the aforementioned difficulties, quite significant differences were shown regarding the share of incidental water in the total amount of wastewater flowing into the treatment plant when analyzing the wet year and the other years.

In the dry year (2022), 10,061 m^3 of incidental water flowed into the sewerage system, so their treatment costs amounted to PLN 70,233 (€16,007), in the average year (2019), 7,471 m^3 of incidental water flowed into the sewerage system, so their treatment costs amounted to PLN 47,814 (€10,897), whereas in the wet year (2020), 10,325 m^3 of incidental water flowed into the sewerage system, so their treatment costs amounted to PLN 66,706 (€15,202). As a result of the inflow of incidental water into the sewage system, the annual cost of wastewater treatment in the studied system increased by about 5–6%.

The calculated values indicated that despite the relatively low share of incidental water in the annual sewage inflow to the wastewater treatment plant in the Jastków Commune, the costs that could be saved, after eliminating the sources of incidental water inflows to the sewerage system, are significant. More than PLN 70,000 (€16,000) could be saved annually.

In order to detect the sources of rainwater inflow into the sewage system in the Jastków Commune, it is recommended to use portable flow meters mounted directly in sewer manholes. They will allow to select sewers hydraulically loaded with incidental water inflow. Subsequently, these sewers should be inspected using video technology. This will make it possible to identify illegal connections of rainwater to sanitary sewage system, as well as to detect various irregularities in the construction of sewers and manholes. The sealing of manholes and the leveling of sewer manhole finials should also be improved during these activities, with the use of appropriate spacing rings.

Acknowledgements

This paper was written on the basis of the data obtained from the Jastków Commune. Special thanks go to Mr. Sławomir Zdyb – Head of the Water and Wastewater Management Department of the Jastków Commune for his help in collecting the data from the wastewater treatment plant in Snopków.

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