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The Impact of Atmospheric Precipitation on Wastewater Volume Flowing into the Wastewater Treatment Plant in Nowy Targ (Poland) in Terms of Treatment Costs

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Abstract: This study determined the influence of precipitation occurring in the sewerage catchment basin in Nowy Targ (Poland) on the amount of wastewater inflow to the wastewater treatment plant, and determined the costs resulting from the treatment of accidental (rain) water entering the analyzed sewerage system. The research was conducted from 2016 to 2019, for which daily precipitation and average daily wastewater inflows in the so-called dry, normal, and very wet periods were analyzed. The research period was divided into six characteristic intervals in terms of precipitation. It was found that, on days with different precipitation intensity, the amount of accidental water as a proportion of the total amount of wastewater flowing into the plant ranges from 9.6% to 34.1%. The annual costs incurred by the operator resulting from the environmental fee are 1625.8 EUR/year. Alternatively, the costs resulting from financial expenditures for wastewater treatment processes amount to 337,651 EUR/year. The results of the research provide important information for sewage network operators to take effective actions to eliminate illegal connections of roof gutters and/or yard inlets to the sanitary collectors, and to replace the combined sewage system in Nowy Targ with a distributed sewerage system. This would reduce the costs of wastewater treatment and the irregularity of wastewater inflow.

Keywords: accidental water; precipitation; sewer system; wastewater treatment costs

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1. Introduction

In recent years, numerous initiatives have been undertaken in Europe related to increasing rainfall water retention to mitigate the effects of the progressive phenomenon of drought [1,2]. According to the measures taken, rainwater should be managed at the site of precipitation (rain or snow) and not discharged to a watercourse in the short term [3–5]. Many combined sewerage systems discharge rainwater—known as accidental water—into rivers within a short period of time after a precipitation event; this action has only negative ecological and economic consequences [6]. The negative ecological effects of rainwater discharge into sewers are the problems of maintaining wastewater treatment processes at a sufficiently high level, which arise due to the high variability of the quantity and quality of wastewater. High variability in both the amount of inflowing wastewater and the concentrations of pollutants in the water, in addition to sudden changes in other parameters e.g., wastewater temperature and pH, make it difficult for operators to optimize treatment processes [7,8]. As indicated by reports described in the literature, rainwater illegally introduced into sewerage systems, which is referred to as accidental water, negatively affects the operation of wastewater treatment plants, in which the dimensions and capacities of individual technological facilities are not adapted to periodically increasing and decreasing wastewater flow rates [9–11]. Accidental water mixed with municipal wastewater also has a major impact on reducing pollutant concentrations in wastewater by diluting it with rainwater, thereby depleting it of the organic matter necessary for the growth of activated sludge microorganisms [12–14]. The negative impact of accidental water on the functioning of wastewater treatment plant processes consequently leads to a periodic decrease in the efficiency of their operation, and thus the occurrence of a threat of pollution of receiving waters with insufficiently treated wastewater [15,16]. Moreover, in terms of ecology, an important but negative effect of introducing rainwater into the sewerage system is the lack of capacity to recharge groundwater with rainwater in the territory of the sewerage basin where the rainfall occurred, thus lowering the groundwater level [17]. As already mentioned, apart from the ecological risks resulting from the introduction of rainwater into the sewerage system, there are also equally important economic effects of such an action. Each cubic meter of treated wastewater in a wastewater treatment plant translates into real costs related to electricity [18], chemical consumption, wear and depreciation of equipment, or environmental fees for discharging treated wastewater into the environment [19,20]. These costs are directly borne by the sewage system operator, but are indirectly borne by all users (residents, industrial plants) who use the sewage network.

The results of the research described in this publication contribute to the discussion regarding the need to reduce the inflow of rainwater to sewer systems as a negative phenomenon that limits rainwater retention and causes excessive operating costs.

The aim of the research was to determine the influence of precipitation height in the sewerage system of Nowy Targ (Poland) on the amount of wastewater flowing into the collective wastewater treatment plant, and to determine the costs associated with its treatment and discharge into the environment.

2. Materials and Methods

2.1. Characteristics of the Sewage System and Wastewater Treatment Plant

Nowy Targ is a town located in the southern part of the Małopolska Province, with a current population of 31,850. The analyzed sewage system is made of PVC and stoneware material, with diameters ranging from 200 to 400 mm. It is 86.9 km long and has approx. 4800 connected houses. The sewage network operates using a gravity system and is intended for the collection of domestic wastewater from residential buildings and for the collection of wastewater from tannery (furrier) shops. Sixty furrier shops are legally connected to the sewage network. Many furrier shops are also connected to the network illegally [21]. All sewage, i.e., domestic and industrial wastewater, flows to the collective wastewater treatment plant with the designed capacity of 21,000 m^3/d and PE = 116,000 inhabitants assumed in the project [21,22]. The wastewater treatment plant in Nowy Targ, which was modernized in 2016, is located at 49°29′ N, 20°3′ E, as presented in Figure 1. The wastewater treatment plant in Nowy Targ is a mechanical and biological type, where the mechanical part includes a dense screen, a horizontal sand trap, and a basic settling tank (two-chamber horizontal). In the biological part of the wastewater treatment plant there are 3 sequential SBR biological reactors, each 70 m long, 23 m wide, and 4.5 m deep. Biological reactors operate on an 8 h cycle and there are 5 phases in each cycle. In the technological process, the wastewater is raised in front of the grates to a height of 7.5 m so that the entire flow of wastewater in subsequent devices is gravitational. Wastewater from cesspools, which are installed next to buildings not connected to the sewage system, is also delivered to the wastewater treatment plant by means of slurry tanks. Sewage sludge, both from basic settling tanks and from biological reactors, is collected in a gravity thickener, and then biogas is produced from them in separate fermentation chambers, from which electricity and heat are generated. The treated wastewater inflows through a sewage collector with a diameter of DN = 1000 mm, a distance of 197 km to the Dunajec River.

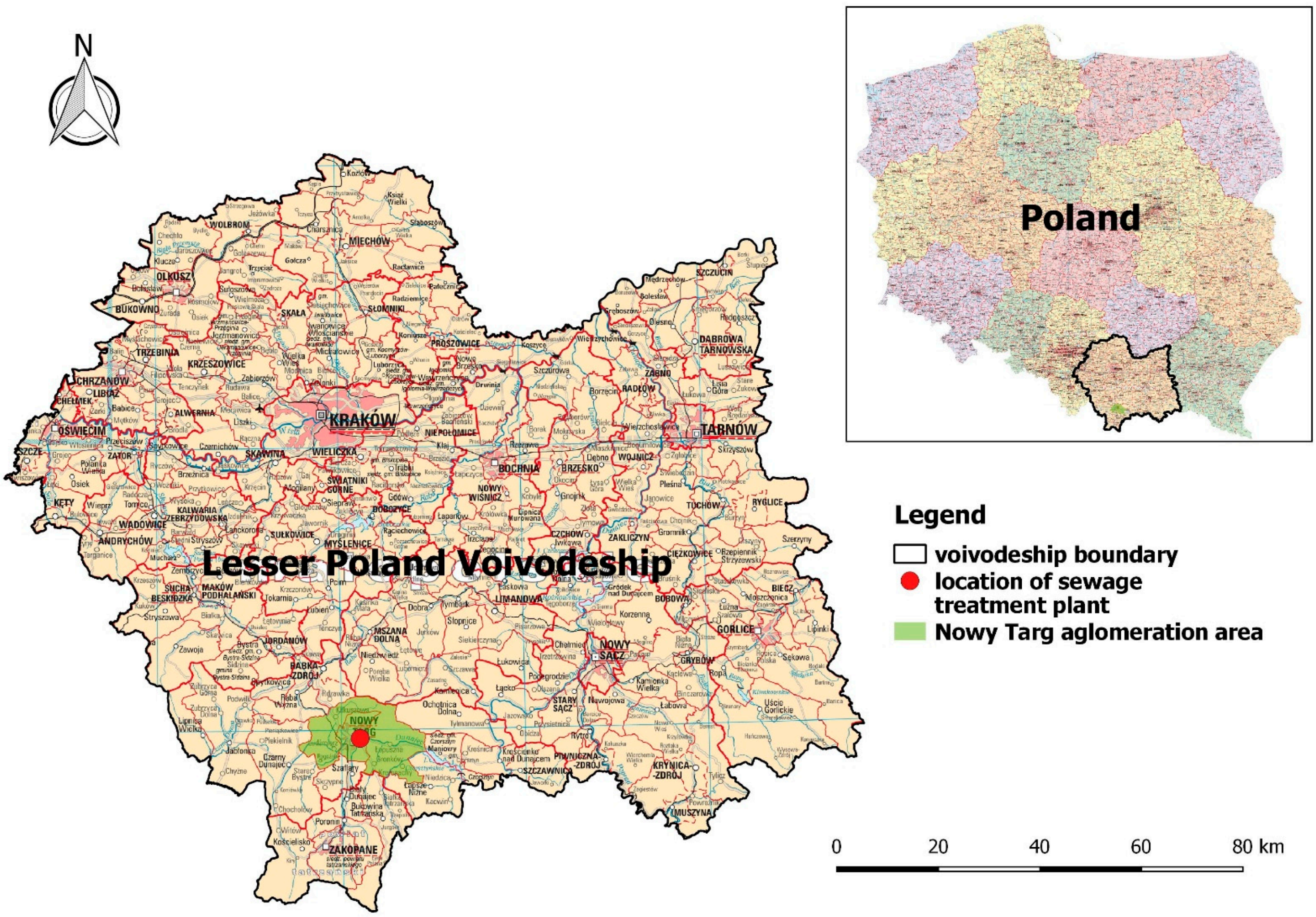

Figure 1. The location of the rural agglomeration of Nowy Targ against the background of the Lesser Voivodeship and Poland [source: own study].

2.2. Analytical and Statistical Methods

Surveys of daily wastewater outflow to the wastewater treatment plant and daily precipitation were conducted from 2016 to 2019, a period of 4 years. There was no increase in the number of sewer connections within the sewerage system during the analyzed time period, therefore the period of four years, i.e., 1461 days, was taken as homogeneous and authoritative. Wastewater outflow intensity was measured by means of an ultrasonic level probe (Waterpilot FMX 167) placed in an open channel over a triangular overflow behind the process line. The amount of precipitation on individual days was determined on the basis of indications from a Hellmann rain gauge installed in the analyzed sewage basin. According to the guidelines indicated by Kaczor [13], daily wastewater inflows were assigned to dry weather or wet weather. According to Kaczor [13], a given day of the year was classified as dry weather if, during its duration and in the five preceding days, no precipitation occurred, or it occurred but its daily amount did not exceed 1 mm. The average daily wastewater outflow during rainless (dry) weather was used to determine the average (averaged) amount of the so-called proper wastewater, i.e., not containing accidental water. As proposed by Chmielowski [23] in the case of wet weather, i.e., in days with precipitation, 6 characteristic groups were generated:

A—0.1 to 1.0 mm/d,
B—1.1 to 5.0 mm/d,
C—5.1 to 10.0 mm/d,
D—10.1 to 15.0 mm/d,
E—15.1 to 20.0 mm/d,

F—over 20.0 mm/d.

The calculation of the accidental water quantity Q_{dp} and its share Uwp in the wastewater mixture flowing into the wastewater treatment plant was based on the guidelines of Kaczor [13].

The first parameter Q_{dp} defines the volume of accidental (rainfall) water in the total volume of wastewater. Therefore, in the wet weather period the volume of accidental water in a given day was calculated according to Formula (1).

$$Q_{dp} = Q_{dm} - Q_{ds} \quad (1)$$

where:

Q_{dp}—daily inflow of accidental water to the sewer, [m^3/d];
Q_{dm}—daily inflow of the mixture of wastewater and accidental water during wet weather, (m^3/d);
Q_{ds}—average daily urban wastewater inflow (excluding accidental water) during dry weather, (m^3/d).

The second parameter, Uwp, represents the proportion of accidental water, which indicates, as a percentage, how much accidental water is contained in the total volume of the mixture of municipal wastewater together with accidental water [24]. The Uwp parameter was calculated according to Formula (2).

$$Uwp = \frac{Q_{dp}}{Q_{dm}} \cdot 100 \quad (2)$$

where:

Uwp—daily contribution of accidental water to sewerage flowing out of sewer, (%);
Qdp—daily inflow of accidental water to the sewer, (m^3/d);
Qdm—daily inflow into the sewerage system of the mixture of wastewater and accidental water during wet weather, (m^3/d).

Because the total retention time of wastewater in the sewer system is approximately 24 h, the daily precipitation amount was assigned to the amount of wastewater flowing on the following day.

3. Results and Discussion

3.1. Analysis of Atmospheric Precipitation in the Sewage Catchment Area

To verify the influence of precipitation on the amount of wastewater inflow to the sewerage system in Nowy Targ, years with different annual totals of precipitation were considered. Like Cebulska et al. [25], we assumed that the average annual precipitation in the area of Nowy Targ is 825 mm (825 dm^3/m^2) according to the classification proposed by Kaczorowska [26]; thus, the years 2016 and 2019 were average years. In 2016, total precipitation was 8.2% higher than normal, and in 2019, total precipitation was 4.7% higher. In contrast, 2018 was a very dry year, because the annual rainfall total was 64.5% of normal precipitation for this region. In contrast, 2017 was a wet year because the total precipitation was 23.2% higher than the multi-year average precipitation. Characteristic monthly totals and annual totals of precipitation in the sewerage system of Nowy Targ are presented in Table 1.

3.2. Characteristics of the Inflow of Wastewater

In the study period of 2016–2019, a high degree of irregularity in the amount of wastewater inflow to the wastewater treatment plant in Nowy Targ was found. In the four-year period, irregular average daily wastewater inflow to the wastewater treatment plant was found in individual years and in individual months. The main reason for the high variability (irregularity) of the amount of wastewater inflow to the wastewater treatment plant is the inflow of accidental water in the combined sewerage systems, in whole or in a significant proportion [24–28]. Moreover, in sewerage systems designed exclusively for the disposal of municipal sewage (distribution sewers), the reason for the appearance of an increased volume of wastewater during periods of intense precipitation is the illegal connection to sewers of outlets of roof gutters by residents [29]; outlets of drains used for land-property drainage [24]; or, as noted by Kaczor [30], manholes or ventilation holes of wastewater wells through which water flowing on the street surface enters the sewerage network.

Table 1. Monthly and annual precipitation amounts in the analyzed sewage system in Nowy Targ.

Month	2016	2017	2018	2019
	[mm]			
January	44.1	19.9	7.0	96.6
February	82.2	35.9	8.8	35.2
March	28.6	42.4	17.3	39.4
April	54.3	106.5	20.8	68.1
May	93.6	51.6	47.0	154.9
June	24.2	90.7	110.5	41.9
July	132.9	85.9	96.7	107.4
August	86.9	106.0	53.2	83.0
September	64.8	227.8	43.6	61.6
October	127.1	124.9	46.1	41.4
November	68.1	61.0	13.3	55.6
December	85.9	64.0	68.1	79.1
Total	892.7	1016.6	532.4	864.2

The average daily wastewater inflow at the WWTP in the 4 year research period was $Q_{a.d.}$ = 13,719 m^3/d with the variability expressed by the irregularity coefficient Cv = 23%, which indicates that the variability of the wastewater inflow was at an average level [31]. In average precipitation years, i.e., 2016 and 2019, the average daily wastewater inflow was 13,772.2 m^3/d and 14,050.8 m^3/d, respectively. In the wet year of 2017, the average daily wastewater inflow was 14,702.3 m^3/d, and in the very dry year of 1018, the average daily wastewater inflow was 12,351.5 m^3/d. Extreme wastewater inflows also occurred in each year. The lowest recorded mean daily wastewater inflow during the research period was 8.472 m^3/d, whereas the maximum was 41.754 m^3/d. Characteristic values of wastewater inflow to the wastewater treatment plant in Nowy Targ in particular years are presented in Figure 2.

The histograms shown in Figure 3A–D were developed to illustrate the variability of the mean daily inflows to the WWTP. The histograms include seven class intervals with a class span of 2000 m^3/d. In 2018, the year with the lowest annual precipitation, the average daily wastewater inflow appeared most frequently between 10,000 and 12,000 m^3/d (47.1% of cases) and between 12,000 and 14,000 m^3/d (34.8% of cases). The total wastewater inflow to the wastewater treatment plant in 2018 was 4,508,291 m^3/year. In 2017, a wet year, 10.1% of incidents were recorded in the wastewater inflow range of 10,000 to 12,000 m^3/d and 41.6% of incidents were recorded in the range of 12,000 to 14,000 m^3/d· In 2017, wastewater inflows in the range of 14,000 to 16,000 m^3/d were found to occur 34.8% of the time. Compared to the dry year (2018), the average daily wastewater inflow in the wet year (2017) occurred in the range of 14,000 to 16,000 m^3/d, representing an increase of 15.9%. In 2017, the total wastewater inflow to the WWTP was 5,453,719 m^3/year, which was more than 945,000 m^3 higher compared to the dry year (2018). In years with average rainfall, i.e., 2016 and 2019, the wastewater inflows to the wastewater treatment plant in the range of 12,000 to 14,000 m^3/d represented 40.4% and 36.4% of the cases, respectively. In these years, the inflows in the range of 10,000 to 12,000 m^3/d, i.e., 25.7% of cases in 2016 and 22.5% of cases in 2019, were recorded at similar levels. In addition, in the next range of 14,000 to 16,000 m^3/d, the number of cases of inflows was recorded at a similar level; in 2016, this represented 17.8% of cases, and in 2019 it was 15.1% of cases. The total inflow to the wastewater treatment plant in 2016 was 5,040,628 m^3/year and in 2019 it was 4,116,000 m^3/year.

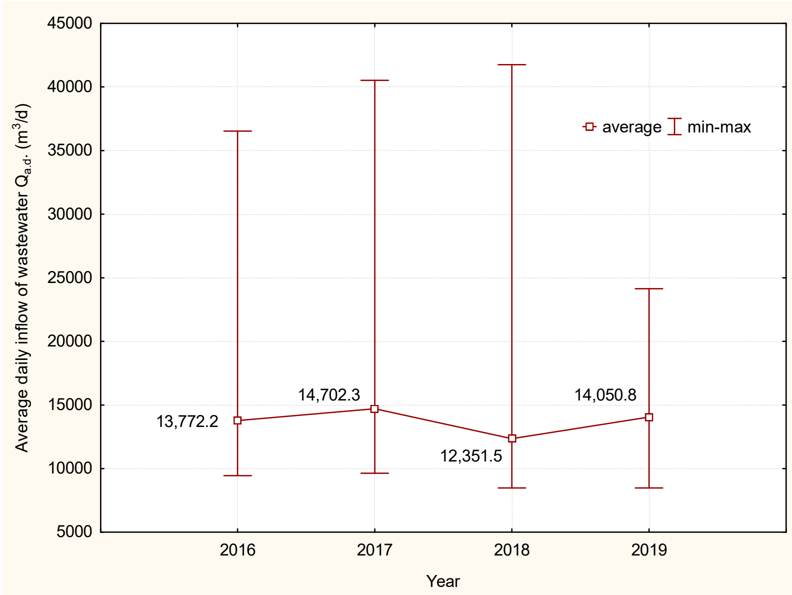

Figure 2. Daily average and extreme daily inflows of municipal wastewater and accidental water to the wastewater treatment plant in Nowy Targ.

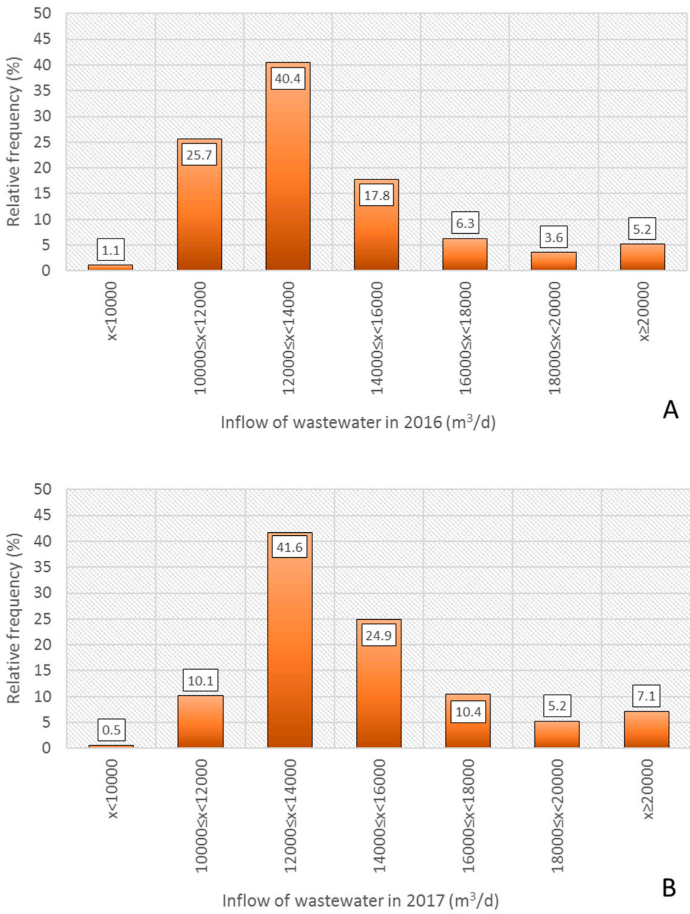

Figure 3. *Cont.*

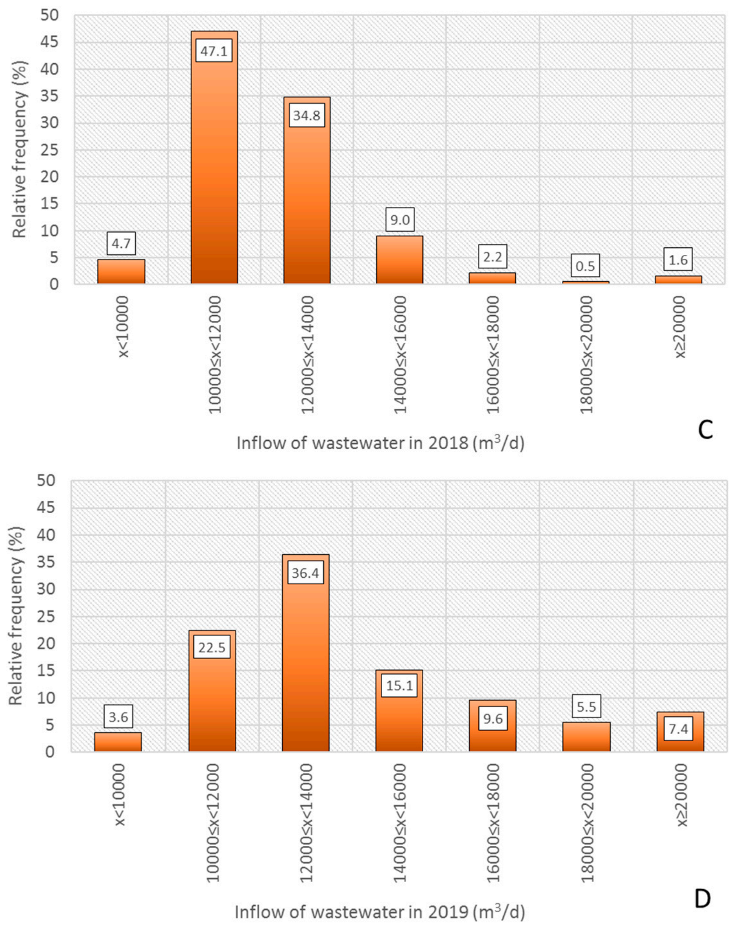

Figure 3. The histogram of the frequency of dependence of characteristic daily wastewater inflows in individual surveyed years. (**A**)-2016 year, (**B**)-2017 year, (**C**)-2018 year, (**D**)-2019 year.

As can be seen from the analysis, the volume of inflowing wastewater in particular years depends on the amount of precipitation in a given calendar year; this indicates the inflow of water from precipitation into the sewage network, which is defined as accidental water [32]. The next step in the analysis is to determine the volume of accidental water entering the wastewater treatment plant (Q_{dp}) and its contribution to the total volume of wastewater (Uwp). The calculation of the volume of accidental water and its contribution to the wastewater mixture was based on guidelines developed by Kaczor [13].

The analysis concerning the determination of the quantity of accidental water and the share of accidental water in the total quantity of wastewater inflow to the wastewater treatment plant was performed for the total of the four analyzed years, 2016–2019, assuming that, regardless of the type of year in terms of precipitation, the quantity of municipal sewage generated in dry weather is at the same level. Based on the described research methodology, during the four-year research period, 316 daily wastewater inflows were generated from 1461 daily wastewater inflows, which occurred during the rainless so-called dry weather. On the basis of recommendations proposed by Kaczor [13], it was assumed that the inflow of wastewater on a given day in dry weather was equivalent to a day during which there was no precipitation, and precipitation did not occur or was less than 1 mm in the 5 days preceding the measurement of wastewater inflow. In the research period the average wastewater inflow during dry weather (rainless) was Q_{ds} = 12,046 m^3/d (Table 1). Variability of wastewater inflow in dry weather, as described by the coefficient of variation, was Cv = 13%, which indicates a low variability of wastewater inflow in dry weather, according to the scale proposed by Wawrzynek [31]. The dry weather (rainless) wastewater inflow was 42.6% lower than the assumed design capacity of 21,000 m^3/d of the wastewater treatment plant in Nowy Targ [33]. Currently, there is no danger of exceeding the design capacity of the WWTP of 21,000 m^3/d, because the maximum daily dry weather inflow was 20,196 m^3/d, which is an inflow of 96% of the design inflow (Table 2).

Table 2. Statistical characteristics of wastewater inflow $Q_{a.d.}$ in dry weather.

Parameters	Statistics					
	Average m^3/d	Median m^3/d	Min. m^3/d	Max. m^3/d	Standard Deviation m^3/d	Coefficient of Variation %
$Q_{a.d.}$	12,046	11,824	8910	20,196	1609.8	13

3.3. Analysis of the Quantity of Accidental Water in the Sewerage System

Based on the average daily wastewater inflow at dry weather (rainless), which is 12,046 m^3/d, the average daily rainwater inflow was calculated using Formula (1) for the period of days on which precipitation occurred. The calculations of accidental water volumes were undertaken for particular groups—A, B, C, D, E and F—with appropriately assigned precipitation ranges. In group A, i.e., on days in which precipitation ranged from 0.1 to 1.0 mm/d, the average daily inflow of accidental water to the WWTP was 1276.2 m^3/d. On days with precipitation from 1.1 to 5.0 mm/d (group B), the average inflow of accidental water to the WWTP was 2202.7 m^3/d. On days with precipitation from 5.1 to 10.0 mm/d (group C), the amount of rainwater inflow was 3010.0 m^3/d. On days with precipitation between 10.1 and 15.0 mm/d (group D), the amount of rainwater entering the sewer system was 3451.4 m^3/d. In the next interval (group E), i.e., during the days with daily precipitation from 15.1 to 20.0 mm/d, the amount of inflow rainwater was 4838.3 m^3/d. In the last of the analyzed intervals (group E), in the days with precipitation above 20 mm/d, the inflow of accidental water to the WWTP increased to 6239.6 m^3/d. Average daily inflows of urban wastewater and inflow of rainwater on days with characteristic precipitation are presented in Figure 4.

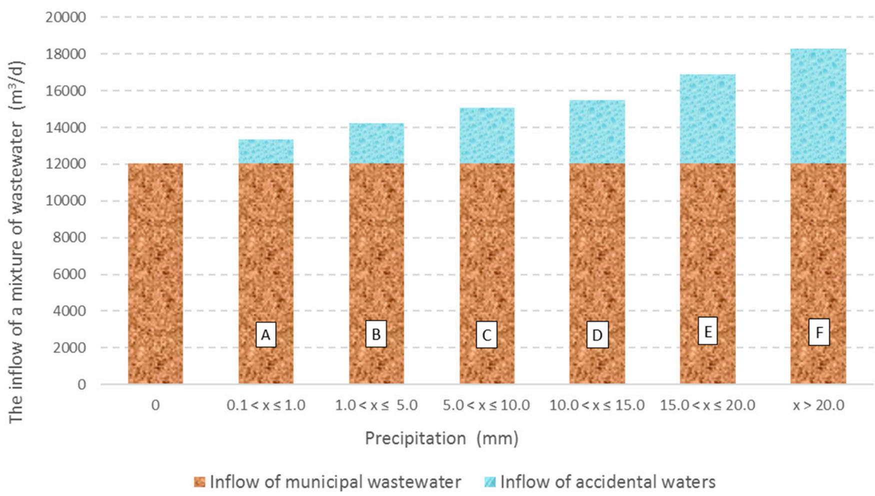

Figure 4. Volume of municipal wastewater and volume of accidental water (rainwater) flowing into the wastewater treatment plant against the background of precipitation in particular groups.

Based on Formula (2), the percentage share of accidental water (Uwp) in the total mixture of wastewater flowing into the wastewater treatment plant was calculated for days with precipitation. In the days with precipitation ranging from 0.1 to 1.0 mm/d, the percentage of accidental water in the total amount of wastewater was 9.6% on average. On the days with precipitation from 1.1 to 5.0 mm/d, the percentage of accidental water in the total amount of wastewater was 15.5%. On days with precipitation between 5.1 and 10.0 mm/d, accidental water contributed 20.0% to the total volume of wastewater. In the interval with precipitation from 10.1 to 15.0 mm/d, accidental water in the total mixture of inflowing wastewater accounted for 22.3%. In the days with precipitation from 15.1 to 20.0 mm/d in the sewerage catchment area, the proportion of accidental water in the total amount of wastewater was 28.7%. On days with precipitation above 20.1 mm/d, the percentage of accidental water in the total amount of wastewater flowing to the WWTP was 34.1%. The share of accidental water (rainfall) in the total amount of wastewater flowing to the wastewater treatment plant depending on the amount of precipitation in the basin area of Nowy Targ is presented in Figure 5.

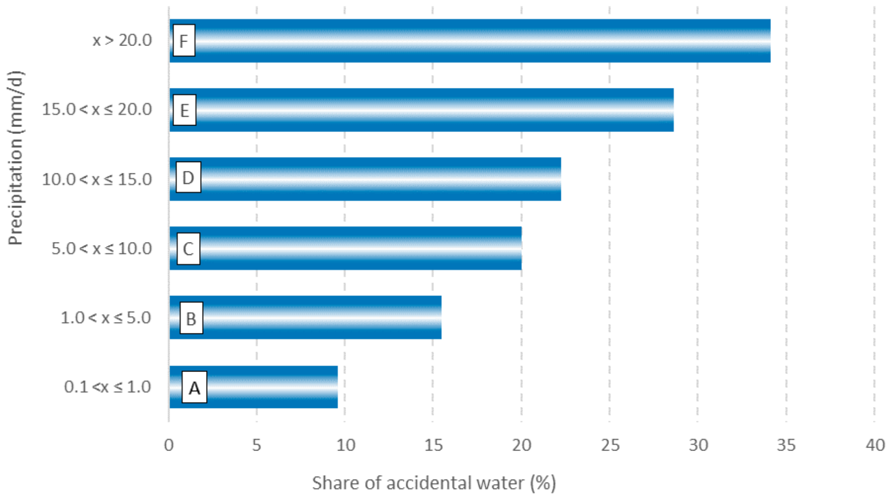

Figure 5. Percentage share of accidental water in the total amount of wastewater flowing into the wastewater treatment plant in Nowy Targ against the background of characteristic precipitation events.

3.4. Cost of Treatment and Discharge of Accidental Water

(*-current exchange rate of 1PLN = 4.5 €)

As indicated by Pajares et al. [34], Matej-Łukowicz and Wojciechowska [35], and Królikowska and Królikowski [36], the basic costs incurred by a wastewater treatment plant operator are the costs of the environmental fee for discharged wastewater and the costs of wastewater treatment processes. Thus, if accidental (rain) water flows into the treatment plant in addition to municipal wastewater, the costs increase relatively.

The analysis of treatment costs related to excessive inflow of accidental water was developed in terms of the environmental fee related to the discharge of treated wastewater into the receiving water body, and in terms of the costs resulting from the wastewater treatment processes at the treatment plant.

The cost of the environmental fee for the discharge of treated wastewater into the environment (watercourse) was based on the guidelines contained in the Ordinance [37]. Assuming that only municipal wastewater flowed into the WWTP during the research period (2016–2019) totaled 1461 m^3, the environmental fee resulting from the indicated tariff would be PLN 338,961 (€75,324.7) i.e., 84,740 PLN/year (18,831.1 €/year). However, due to the inflow of accidental (rain) water to the sewerage system and the related increase in the volume of wastewater discharged to the receiving body (River Dunajec), the total costs in the analyzed multi-year period amounted to PLN 368,225 (€ 81,827.8), i.e., 92,056 PLN/year (20,456.9 €/year). Therefore, during the period of 4 years, as a result of discharging an excessive amount of wastewater to the receiving body (the Dunajec river), the costs were higher by PLN 29,264 (€6503.1) i.e., in each year by PLN 7316 (€1625.8) on average.

The second financial aspect analyzed is the cost of wastewater treatment, in which accidental water has a significant share. According to Boruszko et al. [19], the unit cost of treating 1 m^3 of wastewater of a collective treatment plant is 4.01 PLN/m^3. A similar unit cost for wastewater treatment of 4.24 PLN/m^3 is given by Przybyła et al. [38] and

0.83 EUR/m^3 is given by Pajares et al. [34]. Thus, this analysis of the total cost of treating the mixture of municipal wastewater and accidental water at the wastewater treatment plant in Nowy Targ assumed a unit cost of treatment of 4 PLN/m^3. In the analyzed multi-year period, the total inflow of wastewater to the WWTP was $Q_{2016–2019}$ = 19,118,638 m^3. Based on the aforementioned analysis, of this total amount of mixed wastewater, accidental water represents $Q_{dp2016–2019}$ = 1,519,432 m^3. Based on the assumed unit cost of treating 1 m^3 of wastewater of 4 PLN/m^3, it was concluded that the cost of treating accidental water at the analyzed treatment plant was PLN 6,077,728 (€1,350,606), which, in terms of cost, is 1,519,432 PLN/year (337,651.5 €/year). These represent the real costs, because the environmental fee and costs of wastewater treatment processes are borne by the wastewater treatment plant operators, i.e., by the residents using the sewerage system in Nowy Targ.

4. Conclusions

As a result of the analysis, it is concluded that the inflow of accidental water from precipitation to the sewage system in Nowy Targ is a significant problem in terms of the variable hydraulic load of the wastewater treatment plant and the high financial costs associated with treatment. During the period of precipitation, rainwater constitutes 9% to 34% of the wastewater flowing into the wastewater treatment plant. In this sewage system, which should be regarded as a medium-sized system, the annual costs of treating the additional amount of wastewater (accidental water) averaged around 340,000 EUR/year. Therefore, it is recommended to take measures to limit the inflow of accidental water by modernizing (eliminating) sections of the sewage network, by upgrading from a combined system to a distribution system. Because the main source of accidental water inflow to the sewage system is rainwater discharged from roof gutters, it is recommended to inspect the sewage network to detect illegally connected roof gutters to the sewage system and eliminate this phenomenon. The developed research methodology and analysis of the costs of accidental water treatment in the sewage system in Nowy Targ (Poland) is universal and can be applied to any other sewage system. The basic ecological message of the conducted research is to raise awareness about how much rainwater, which can be a source of water for people and the economy, is wasted.

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