



Assessment of extraneous water inflow in separate sewerage system by different quantitative methods

Bartosz Bogusławski¹ · Piotr Sobczak¹ · Anna Głowacka¹

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Abstract

Extraneous water that inflow to the sewage system is basically divided into two streams—accidental water (mainly rainwater) and infiltration water. The aim of the research was to assess the amount of extraneous water inflow to the considered system. Five different quantitative approaches were applied. Three well-known methods were used: the triangle method, the minimum night flow method, and the moving minimum method. The annual balance of water consumption and sewage supply to the wastewater treatment plant were calculated. Also, some analysis of sewage discharge during wet and dry weather was carried out. The study covered data from 6 years from 2014 to 2019. It was established that the main source of extraneous water was infiltration, because three methods which concern both streams (triangle method, minimum night flow, variability in wet and dry weather) confirm the conclusion. Merely the moving minimum method results differ from the others. In this investigation, accidental water (basically rainwater inflow) poses a significantly less share in the total volume of sewage compared to infiltration water. The total amount of extraneous water was estimated as in the range from 38 to 53% of annual sewage supply to wastewater treatment plant, depending on the year. Share of infiltration and accidental water is changing in different methods. Share of infiltration was in a range between 18 and 68%, depending on the year and the method used. Share of accidental water was in a range between 7 and 22%.

Keywords Infiltration inflow · Extraneous water · Stormwater · Accidental water · Separate sewerage system

Introduction

Besides water used by inhabitants, sewage inflow to the wastewater treatment plant (WWTP) consists of some extraneous water (or external). This water input does not come directly from water users. External water in separated sewerage systems included two main fractions. Basically, these are infiltration inflow, through leaky pipes and rainwater inflow (Karpf and Krebs 2005). Rainwater-induced flows could penetrate the sewage system by the illicit connection of drains from private properties, misconnection of drains from gullies, misconnection of storm sewers, and entry of surface water through manhole covers (Machado et al. 2007). That is why in literature, rainwater input in the sanitary sewage system is calling accidental water. This term

is also used in this paper. Regardless of its origin, extraneous water causes increasing hydraulic loads and consequently costs for pumping and treatment (Dimova et al. 2015).

Permeated groundwater in the sewerage system is non-polluted or a little polluted (Schultz et al. 2005). Its input is essentially related to the periodicity of the groundwater level (Wittenberg and Brombach 2002). In German sewers, wastewater flow contains up to 40% of groundwater (Wittenberg and Brombach 2002). A case study of the system in Brussels shows a considerable seasonal variation in infiltration inflow (de Ville et al. 2017). It ranged from 15% (in summer) to 45% (in winter) of dry weather flow. In Berkhamsted (UK), chemical oxygen demand (COD) analysis results in 37.4% infiltration inflow (Brian and Bertrand-Krajewski 2010). The same method was used in Mueva and Lockwitz (Germany) and results in 46% and 57% of infiltration inflow. Hydraulic overloading due to infiltrated volumes can reach up to and even exceed 100% of wastewater volume (Brian and Bertrand-Krajewski 2010). According to Peters et al. (2002), approximately 50% of stormwater is discharged into the sanitary sewers and transported to WWTP. In another

✉ Bartosz Bogusławski
bboguslawski@zut.edu.pl

¹ Department of Sanitary Engineering, West Pomeranian University of Technology in Szczecin, Al. Piastów 50, 70-311 Szczecin, Poland

study (Weiss et al. 2002) during 4 years of investigation in 34 WWTP, 70% of inflow was not domestic sewage. An investigation carried out in Trondheim indicated that during dry weather 46% of sewage discharge to WWTP was extraneous water (Beheshti and Saegrov 2018). A review of infiltration and inflow (I/I) in Norway, Sweden, Denmark and Finland showed also large amounts of extraneous water volumes (Jenssen Sola et al. 2018). In big Norwegian systems, the average value of I/I in 2017 was 66% and a small decrease in comparison to the 2009 year was noticed. For Danish districts, the amount of I/I was 30%, in Finland—about 40% and in Sweden—46% (in 2016). Calculations made for the Suzhou district in China (for years 2014–2017) showed about 30% of external water share annually (Wang et al. 2019). All mentioned studies show a considerable fraction of external water addition in WWTP supply.

There are several methods to assess the infiltration and inflow into sewer systems. These methods can be divided into two groups: quantitative methods (for assessing the volume) and qualitative methods (for detecting the sources) (Beheshti et al. 2015). In the work (De Benedittis and Bertrand-Krajewski 2005), 15 traditional quantitative approaches were mentioned. They base on general data like water consumption and wastewater supply to WWTP. These data are analysed in different periods from daily to annual depending on a using method. An undoubted advantage of these approaches is that they are relatively easy to access data and well-known measuring methods. They are also easy to implement (de Ville et al. 2017). The disadvantages are mostly uncertainties due to assumptions (Kracht and Gujer 2005) specific to each method and also measurement uncertainties. Kracht et al. (2007) indicate that the minimum night flow method is oversimplified in the context of growing agglomerations and it might lead to erroneous results.

Materials and methods

The aim of the research was to attempt an assessment of extraneous water that inflowing to the sanitary sewer system. The investigation is based on data obtained from a wastewater treatment plant (WWTP) in a considered town. The daily precipitation data were received from the Polish Institute of Meteorology and Water Management (Historical Meteorological Data from Poland Area n.d.).

Five different methods and approaches were considered:

- Annual water consumption and sewage discharge balance
- Triangle method
- Minimum night flow method
- Moving minimum method
- Analysis of sewage supply to WWTP in dry and wet weather

The annual balance was the started point which indicated that there exists a problem of extraneous water. Other procedures were chosen mostly because they were well described and explained in available literature sources. Thus, it was possible to use them properly. Some approaches were rejected due to sufficient data collected.

Characteristics of the catchment and annual balance

The catchment is located in north-western Poland. The analysed system is a separate sewerage system. It serves one city and six smaller rural areas around. The total length of the main system is approximately 83 km. Additionally, there is about 139 km of sewer house connections. The total community served by the system is about 25,000 inhabitants. It was built in the 70 s of the twentieth century. Sewer pipes are made of PCV, stoneware, and concrete. Their diameters range from 0.2 to 0.8 m. Sewage from whole the system reaches a collective WWTP located in the largest city. This WWTP was modernized in 2012 r. Its actual capacity is 900 m³/h.

A considerable difference between sewage supply and water consumption was observed in the catchment. It led to the supposition that there is an inflow of extraneous water. The share of extraneous water was calculated by the formula (1):

$$S_e = \frac{Q_{in} - Q_c}{Q_{in}} \cdot 100\% \quad (1)$$

where

S_e —a share of extraneous water, %

Q_{in} —annual sewage inflow to WWTP, m³

Q_c —annual water consumption, m³

The addition of extraneous water was calculated by the formula (2):

$$A_e = \frac{Q_{in} - Q_c}{Q_c} \cdot 100\% \quad (2)$$

where

A_e —the addition of extraneous water, %

The results of the calculations are presented in Table 1.

Research concerns years 2014–2019. The estimated share of extraneous water was in a range between 38 and 53%. The estimated addition of extraneous water was between 62 and 115%. The maximum value of external water was occurred in the year (2017) with the highest precipitation (856 mm). On the other hand, in the year (2018) with the lowest precipitation (403 mm), there was the second-largest volume of extraneous water. The relation between the yearly sum of rainfall and sewage supply to WWTP is not clear in this catchment. Probably due to insufficient data. The collection

Table 1 Share and addition of extraneous water in years 2014–2019 (Water Company 2019)

Years	Annual water consumption (m ³)	Annual amount of sewage supply to WWTP (m ³)	Difference (m ³)	Share of extraneous water (%)	Addition of extraneous water (%)	Yearly sum of precipitation (mm)
2014	1,135,791	2,031,030	895,239	44	79	648
2015	1,177,015	2,053,681	876,666	43	74	505
2016	1,215,584	2,017,350	801,766	40	66	567
2017	1,242,735	2,667,605	1,424,870	53	115	856
2018	1,301,726	2,353,796	1,052,070	45	81	403
2019	1,333,082	2,157,580	824,498	38	62	575

of data consist of only 6 years, so it is not enough to provide precise conclusions.

Minimum night flow method

This method was described by Hager et al. (1985). It was also mentioned by De Benedittis and Bertrand-Krajewski (2005). This approach is based on the assumption that infiltration inflow is constant. During a dry period in hours 02:00 and 06:00, there occurs the minimum discharge. It is only composed of sanitary sewage and infiltration water. Night sanitary sewage can be calculated using indicators of flow per capita. Then infiltration inflow can be simply calculated by measured sewage supply to WWTP minus sanitary sewage inflow. Measurements should be made free of workdays to reduce inflow from service establishments or processing plants (Kaczor and Bugajski 2012).

There are several various definitions of dry weather. Stier and Fisher (1995) provide guidelines that 1 day with precipitation less than 1 mm can be considered as dry weather. According to Kaczor and Bugajski (2012) observations, larger flows in sewerage occur 2 to 5 days after rainfall. Based on the daily inflow to WWTP and daily precipitation described in point 2.5, the above remark in this catchment was not confirmed. It was decided to consider three successive days with rainfall lower than 1 mm as a dry period according to the definition by Brian and Bertrand-Krajewski (2010).

To determine the night flow of strictly sanitary sewage, Fisher's (1990) indicators were applied. For the number of inhabitants between 5000 and 100,000, the indicator equals 0.5 dm³/s for each of 1000 inhabitants.

Triangle method

The triangle method is one of the quantitative methods. It is used to estimate both infiltration and accidental inflow. The application of this method was described by some authors (De Benedittis and Bertrand-Krajewski 2005; Wang et al. 2019; Weiss et al. 2002). In this method, daily sewage inflow

to WWTP is ranked in ascending order. It is based on the assumption that sanitary sewage inflow is on average constant. Sanitary sewage inflow is calculated simply by the number of inhabitants times average potable water consumption. The next assumption is that sewage inflows larger than water consumption are firstly caused by infiltration inflow and secondly are caused by accidental inflow.

In this study, 6 years of daily measurements were elaborated.

Moving minimum method

The moving minimum method was described by Weiss et al. (2002). It is based on the assumption that the "sum of sanitary sewage plus infiltration flow at any day is equal to the minimum daily inflow during the past 21 days". This method can be applied to estimate the share of rainwater in the total amount of sewage. It has an advantage compared to the triangle method that rainy days and dry weather days are equally included. The moving minimum method was applied to whole the data from 6 years. The results are shown in point 3.4.

Short time variable of sewage supply to WWTP in dry and wet weather

Analysis of variable sewage supply during wet and dry weather was referred to Bugajski et al. (2017). They investigated changes in sewage inflow during dry and rainy periods. It was noticed that on specific daily periods with high precipitation, the share of accidental water in a total volume of sewage was up to 75%.

The data from the considered 6 years were divided into dry and wet periods. The criteria for beginning dry weather were 3 days after the last precipitation without rain until the next precipitation occurs. Days with rain and 3 days after were considered a wet period. Sometimes there were long periods up to 20 or 30 days without or with a single day with relatively small rain which does

not cause larger flows to WWTP. These were also treated as dry weather if no influence on inflow to WWTP was observed.

Results and discussion

Minimum night flow method

Attempting to choose appropriate periods to the minimum night flow method with relatively low variation was difficult. Finally, 29 night flows were considered in 2018 and 2019. The measurements were read from WWTP flow graphs, so the results might be subject to an error estimated as 10 m³/h. The outcomes are presented in Fig. 1.

The average flow equalled 110.3 m³/h, and the standard deviation of the mean is 5.7 m³/h. The total measurement uncertainty is 11.5 m³/h. The maximum value of minimum night flow occurs on 5.03.2018, and it was 175 m³/h. It is about 59% more than the mean value. The minimum value was 60 m³/h (in 17.06.2018), and it is 46% less than the mean value. The maximum night flow was about 3 times higher than the minimum recorded value.

The estimated number of inhabitants is 25,000; thus, according to Fisher’s approach (Fisher 1990), the minimum night flow of sanitary sewage equals about 45 m³/h. The infiltration inflow was calculated by the following formula:

$$q_{inf} = Q_{in} - q_s, \frac{m^3}{h} \tag{3}$$

where

q_{inf} —infiltration inflow, m³/h.

Q_{in} —total measured inflow to WWTP, m³/h.

q_s —sanitary sewage inflow, m³/h.

The infiltration inflow equals 65.3 ± 11.5 m³/h. Thus, the share of infiltration water in the total volume of sewage is in a range between 54 to 63% and 59% on average. The addition of infiltration water is in the range of 119% to 171% and 145% on average.

Triangle method

In each of the 6 years, the triangle method was applied. Wastewater inflow was calculated by total annual water use divided by 365 days. It represents the average daily flow (Q_{dav}). The green vertical line indicates the maximum infiltration inflow (Q_{maxi}). It is also an edge between days with and without precipitation. The yellow line means the border between infiltration and accidental water inflow. Results of plotting are illustrated in Figs. 2, 3, 4, 5, 6, 7.

The volumes of each stream were calculated by the sum of the area below the plotted lines. The sanitary sewage inflow is an area under the orange line; infiltration water volume—a surface between blue curve and orange line but from 0 to yellow line; accidental water—a surface between yellow and blue curve. Share and addition of infiltration water and accidental water for each year have been calculated using the formulas (1) and (2) with the numerator changed for infiltration or accidental water volume. The results are presented in Table 2.

The year with the largest amount of extraneous water was 2017. It reflects in triangle methods calculations. There is the largest share and addition for both infiltration water (37% and 80%) and accidental water (16% and 35%). According to this method, accidental water share is much lower than the infiltration water share every year. The volume of groundwater is from 2.3 (2017) to 3.86 (2018) times higher than

Fig. 1 Values and date of observed night flows

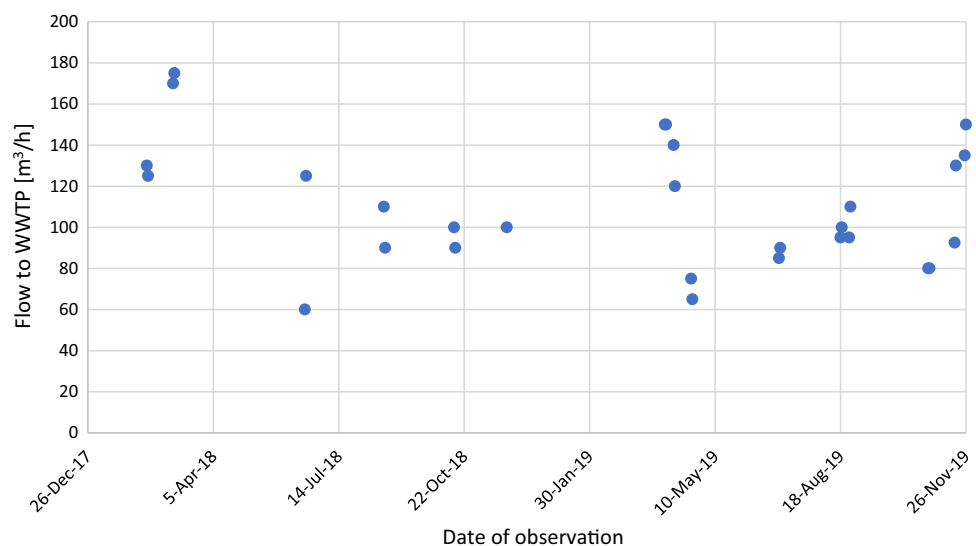


Fig. 2 Volumes of infiltration and accidental water inflow to WWTP in 2014 determined using the triangle method

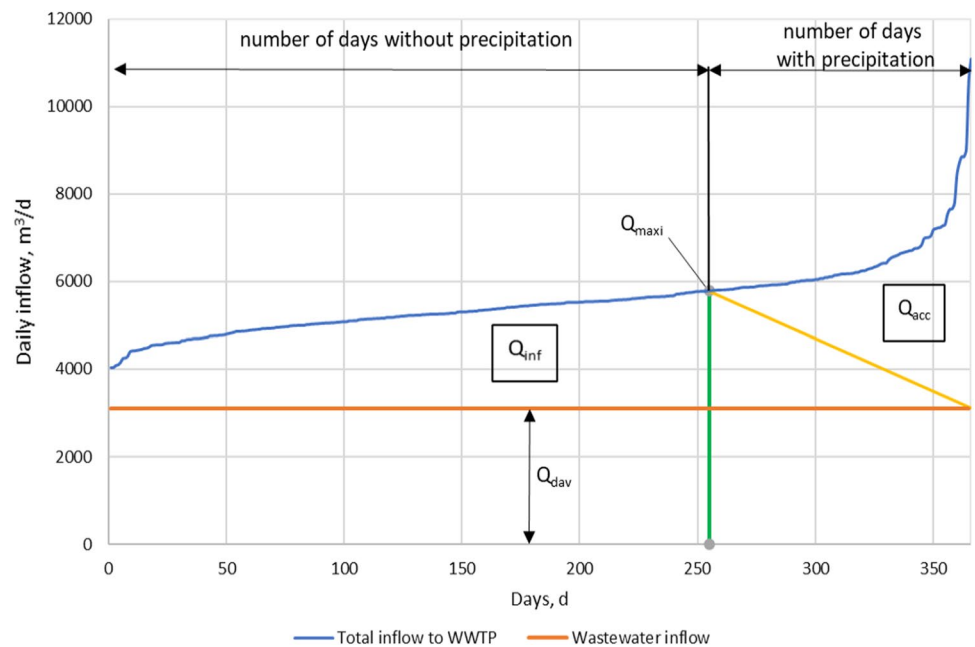
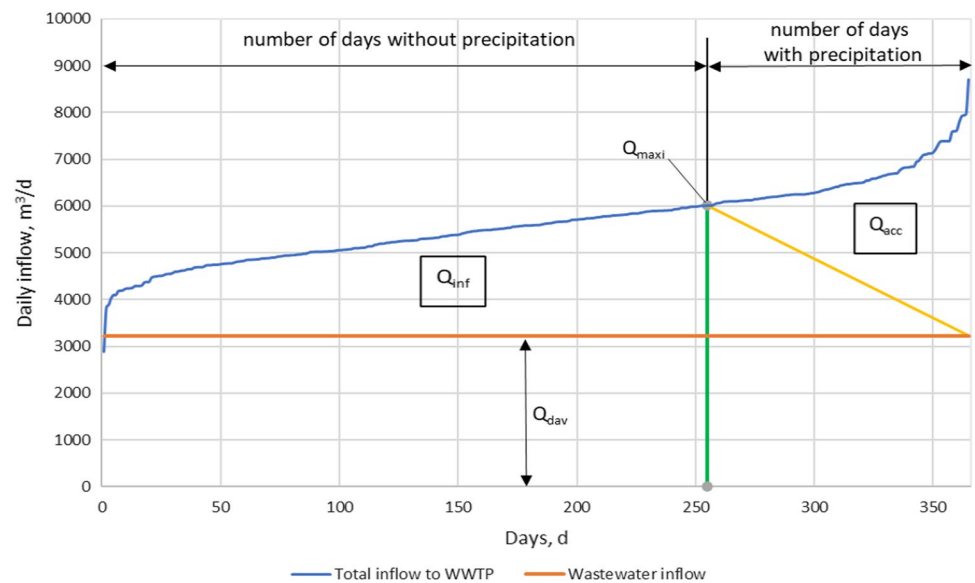


Fig. 3 Volumes of infiltration and accidental water inflow to WWTP in 2015 determined using the triangle method



accidental. Base on this method, it seems that infiltration is the main source of extraneous water in this catchment.

Moving minimum method

It was assumed, similarly to the triangle method, that sanitary flow is equal to mean water used by inhabitants. Results of plotting the moving minimum on a daily flow graph for each of 6 years are illustrated in Figs. 8, 9, 10, 11, 12, and 13.

Infiltration water inflow for each day was calculated by the difference between moving minimum inflow minus

sanitary sewage. Accidental water stream was calculated by the difference between daily inflow to WWTP minus moving minimum. Table 3 shows the calculation results.

The largest amount of infiltration water was in the year 2017 (33%), but the largest amount of accidental water was in the year 2015 (22%). The differences between infiltration water shares (18%-33%) in each year are larger than in accidental water (17%-22%). According to this method, infiltration inflow is generally more significant than accidental water, but differences between both streams are not very high (from 1 to 13 percentage points).

Fig. 4 Volumes of infiltration and accidental water inflow to WWTP in 2016 determined using the triangle method

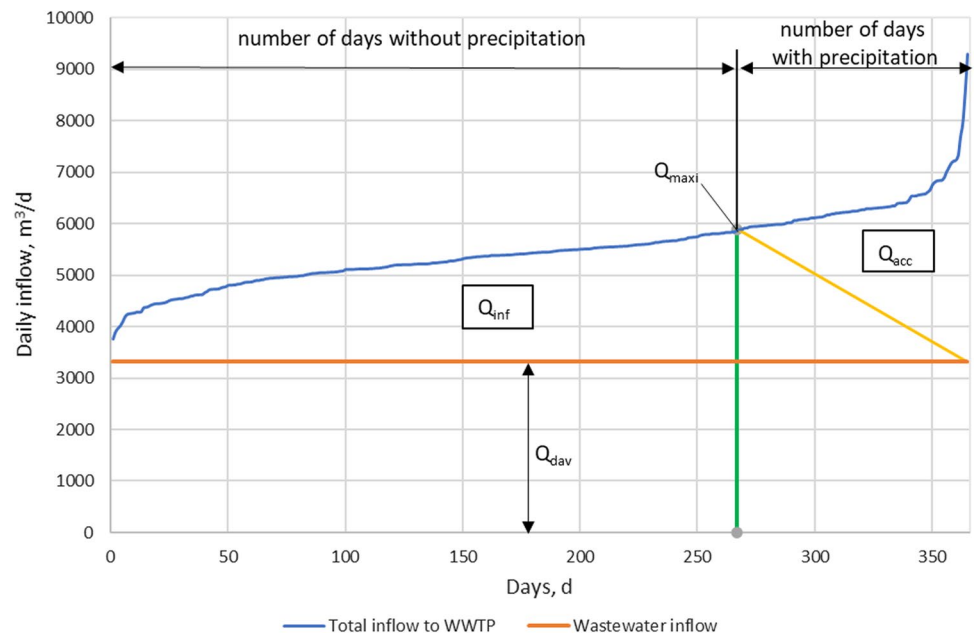
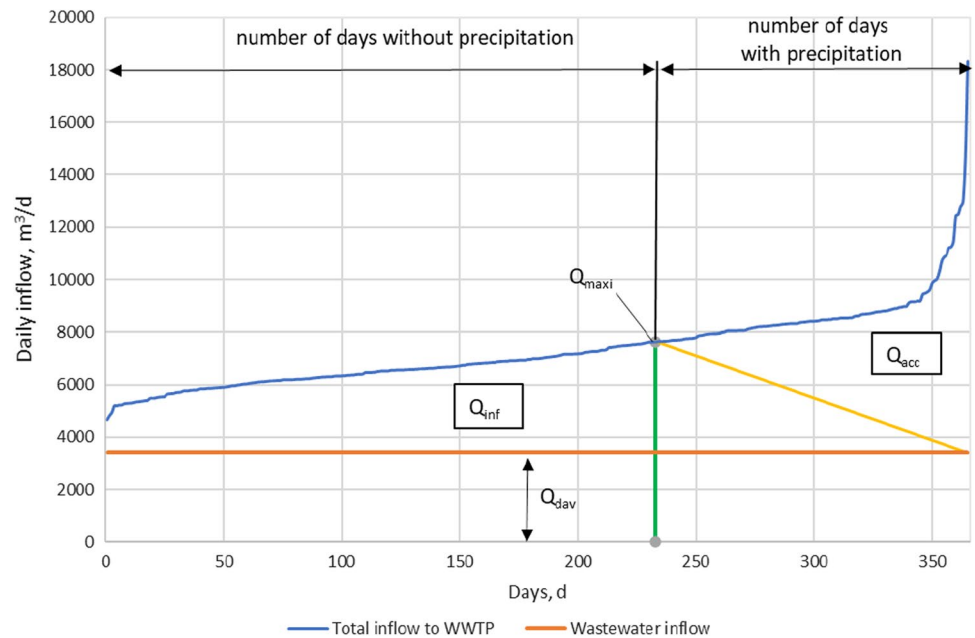


Fig. 5 Volumes of infiltration and accidental water inflow to WWTP in 2017 determined using the triangle method



Variability of sewage supply to WWTP in dry and wet weather

All 6 years were considered, and the average daily supply to WWTP was calculated during dry and rainy periods every year. Table 4 shows the summary of calculations.

Years 2017 and 2018 which had maximum and minimum yearly precipitation have simultaneously the largest variability measured by standard deviation—1560 and 1547 m³/d. In other years the variability was significantly lower—from 758 to 909 m³/d. Also, a standard deviation

of inflow in rainy weather is larger than in dry weather each year. The difference between dry and wet periods equals merely 7–14%.

Figures 14 and 15 show the daily supply of WWTP and daily precipitation during, respectively, dry and rainy weather.

The year 2018 was the dries one in the considered period. The daily sewage supply shown in Fig. 14 in May 2018 was in a range of about 5500 to 7200 m³/d. Looking at days with precipitation, it does not seems to influence the sewage inflow.

Fig. 6 Volumes of infiltration and accidental water inflow to WWTP in 2018 determined using the triangle method

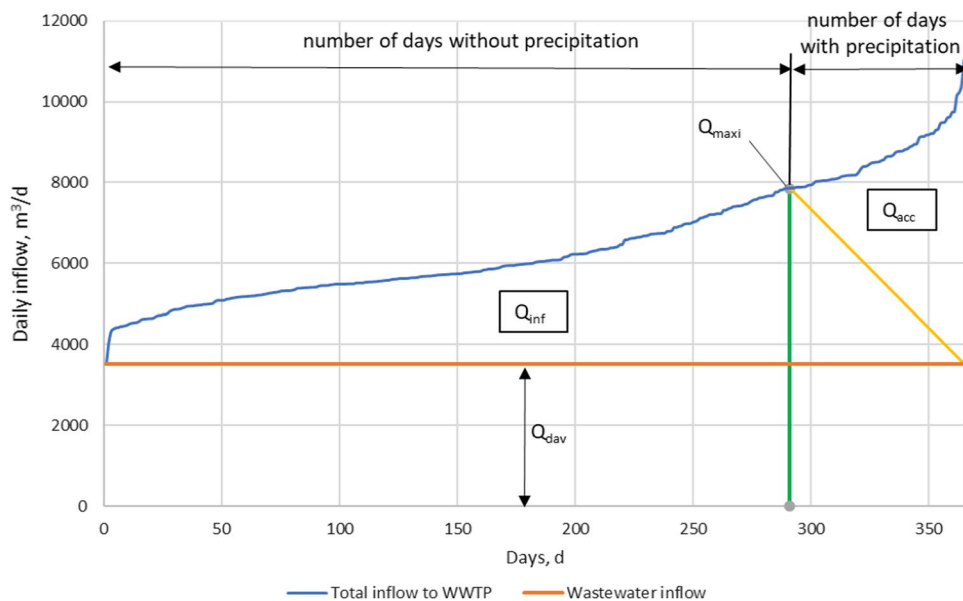


Fig. 7 Volumes of infiltration and accidental water inflow to WWTP in 2019 determined using the triangle method

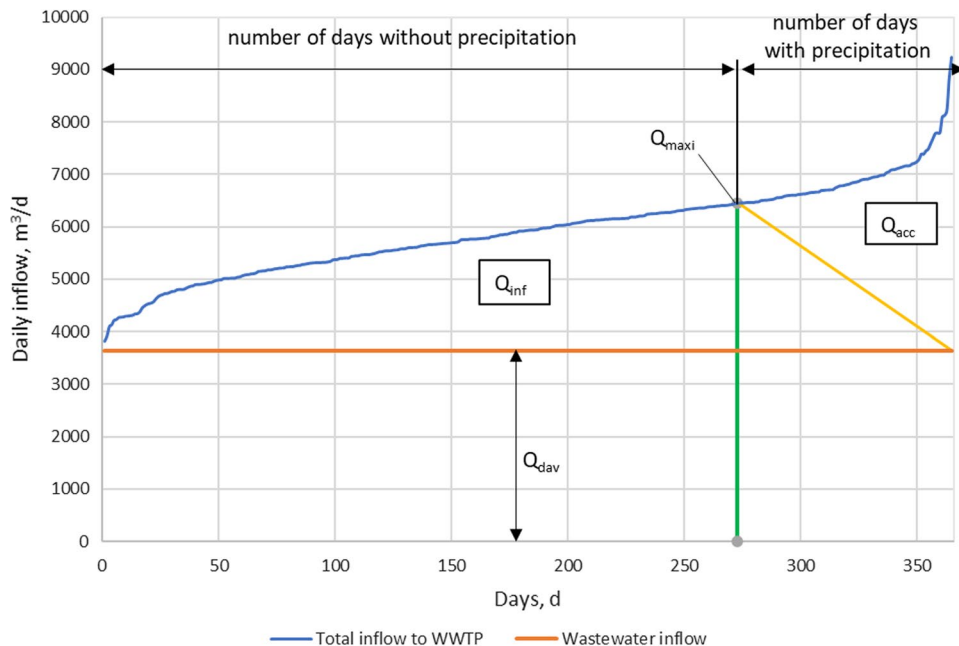


Table 2 Share, additions, and annual volumes of extraneous water in the considered catchment in 2014–2019, calculated by the triangle method

Years	Annual amount of sewage supply to WWTP (m ³)	Inf. water volume (m ³)	Acc. water volume (m ³)	Share of inf. water (%)	Addition of inf. water (%)	Share of acc. water (%)	Addition of acc. water (%)
2014	2,031,030	672,439	228,946	33	59	11	20
2015	2,053,681	660,805	215,861	32	56	11	18
2016	2,017,350	622,160	179,606	31	51	9	15
2017	2,667,605	992,902	431,968	37	80	16	35
2018	2,353,796	847,190	219,296	36	66	9	17
2019	2,157,580	653,214	174,927	30	49	8	13

Fig. 8 Moving minimum flow plotted on a daily inflow diagram in the year 2014

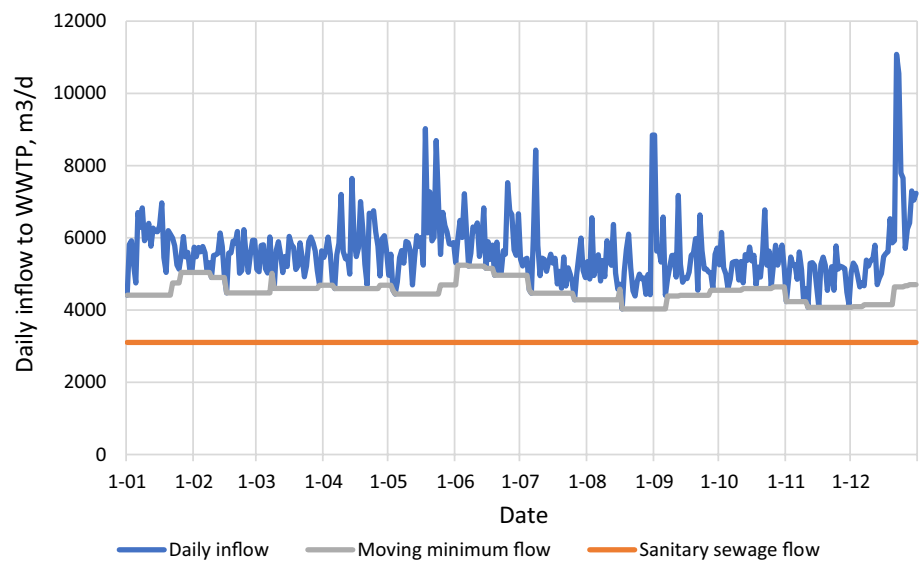
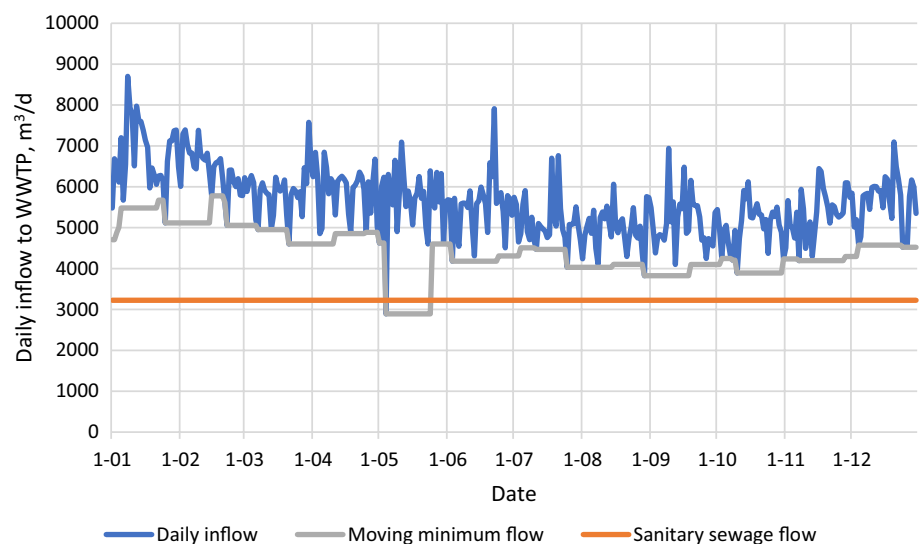


Fig. 9 Moving minimum flow plotted on a daily inflow diagram in the year 2015



In the year 2017, there was the largest precipitation. The daily sewage supply shown in Fig. 15 was in a range between 5300 and 18,300 m³/d. In the first 2 weeks from 15.06 to 28.06, precipitation does not have a clear influence on sewage inflow. In the year 2017 mean daily sewage flow in dry weather was 6451 ± 677 and during the largest rain in 29.06 daily flow was about 18,322; thus, the share of accidental water equals 65%. It corresponds to the 75% that was obtained by Bugajski et al. (2017).

Based on Figs. 14, 15 and Table 4, it was found that only the largest rains have an explicit impact on the inflow to WWTP.

Summary of results

The most significant results are summarized in Table 5.

The annual balance reveals that there is a significant extraneous water inflow in the system. Applied methods confirm that observation, but there are some qualitative differences.

Results from the minimum night flow methods indicate that there is a significant addition of infiltration water. On the other hand, the data have a large variability which implies considerable uncertainties. There is also an issue

Fig. 10 Moving minimum flow plotted on a daily inflow diagram in the year 2016

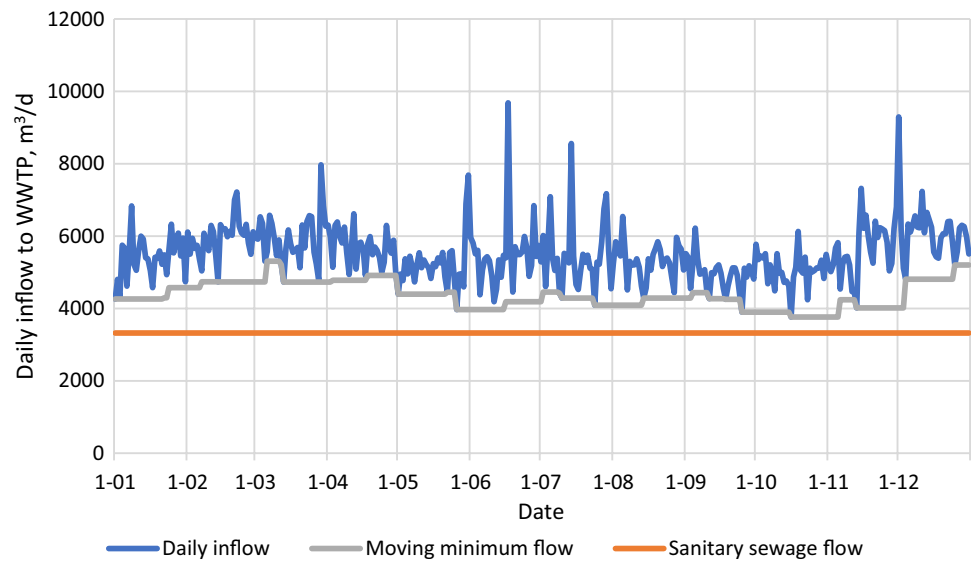
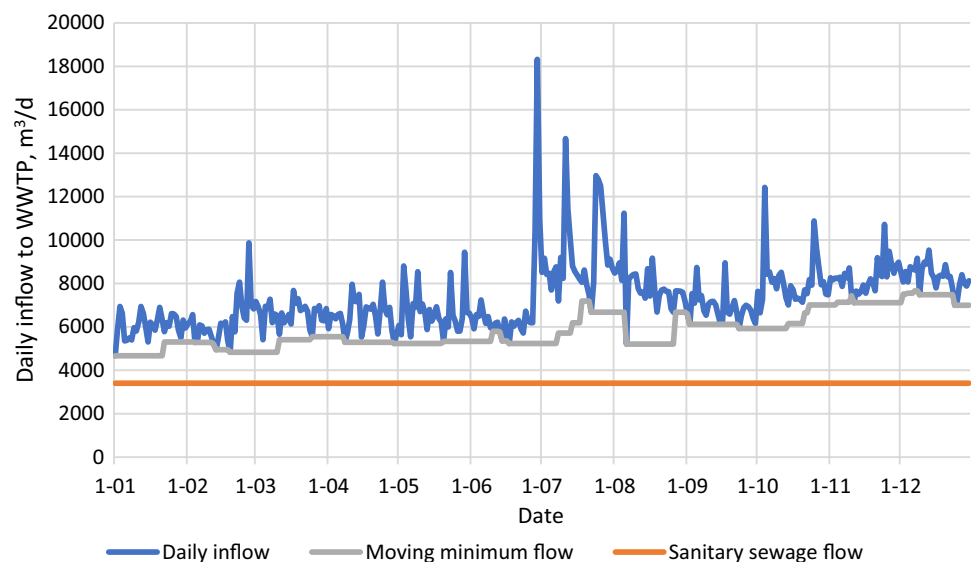


Fig. 11 Moving minimum flow plotted on a daily inflow diagram in the year 2017



that there are a few methods to calculate the sanitary sewage night flow. In this study, Fisher's approach was chosen in reference to another study (Kaczor and Bugajski 2012).

However, results obtained by this method are compared with the analysed variability during wet and dry weather. It seems that most of the extraneous water poses the infiltration water because the difference was only between 7 and 14%. Merely the largest precipitation causes an explicit impact on the sewage supply. It is also visible in the triangle method. In every year the infiltration inflow was considerably larger. The infiltration volume was about 3 times higher (except for the year 2017 with the highest precipitation) than the accidental water volume. There is a visible discrepancy between the moving minimum method and the others. In this method amount of infiltration water and accidental water is rather

similar. Only in the years 2017 and 2018, there is a difference in favour of groundwater water.

Conclusions

In the system, there is a large amount of extraneous water in a range between 38 and 53% of total sewage volume. All of the methods except variability in wet and dry weather confirm that there was significant input of extraneous water. It was established in three methods (triangle method, minimum night flow method, and variability in wet and dry weather) that the most significant source of extraneous water is infiltration inflow. The share of infiltration water in these methods was in the range of 30% to 68%. There was a visible

Fig. 12 Moving minimum flow plotted on a daily inflow diagram in the year 2018

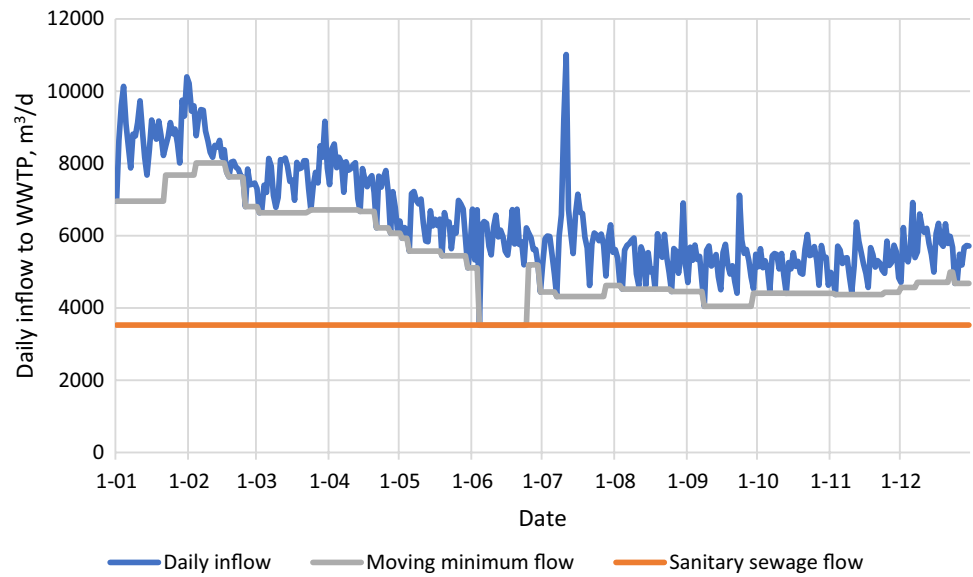


Fig. 13 Moving minimum flow plotted on a daily inflow diagram in the year 2019



Table 3 Share, additions, and annual volumes of extraneous water in the considered catchment in 2014–2019, calculated by the moving minimum method

Years	Annual amount of sewage supply to WWTP (m ³)	Inf. water volume (m ³)	Acc. water volume (m ³)	Share of inf. water (%)	Addition of inf. water (%)	Share of acc. water (%)	Addition of acc. water (%)
2014	2,031,030	516,420	384,966	25	46	19	34
2015	2,053,681	433,017	443,649	21	37	22	38
2016	2,017,350	385,816	415,950	19	32	21	34
2017	2,667,605	882,594	542,276	33	71	20	44
2018	2,353,796	661,342	405,144	28	51	17	31
2019	2,157,580	383,698	444,443	18	29	21	33

Table 4 Variability of sewage supply to WWTP in dry and rainy periods in each year

Years	Mean inflow—dry weather Q_{dry} (m ³ /d)	Standard deviation	Mean flow—rainy weather Q_{rain} (m ³ /d)	Standard deviation	$\frac{Q_{rain}-Q_{dry}}{Q_{dry}}$, %
2014	5218	448	5743	909	10
2015	5480	699	5870	850	7
2016	5291	593	5681	758	7
2017	6451	677	7339	1560	14
2018	6162	1016	6581	1547	7
2019	5682	766	6107	844	7

discrepancy between these three methods and the moving minimum method. In this approach, the streams were similar. Share of infiltration inflow equalled 17% to 33%. In the author’s opinion, the volume of external water is large enough to be considered in designing or modifying sewage systems and WWTPs. Even if the catchment is specific and not all conclusions should be transferred to other systems, the literature review shows that the problem concerns many systems in all the world. The streams of extraneous water are variable in time and amount. This is an important issue in WWTP, where most objects and processes need constant operation conditions. To provide that properly selected retention tank is needed, especially in small WWTPs where fluctuations of inflow are generally more significant than in larger WWTPs.

Fig. 14 Daily sewage supply associated with daily precipitation in a selected dry period in May 2018

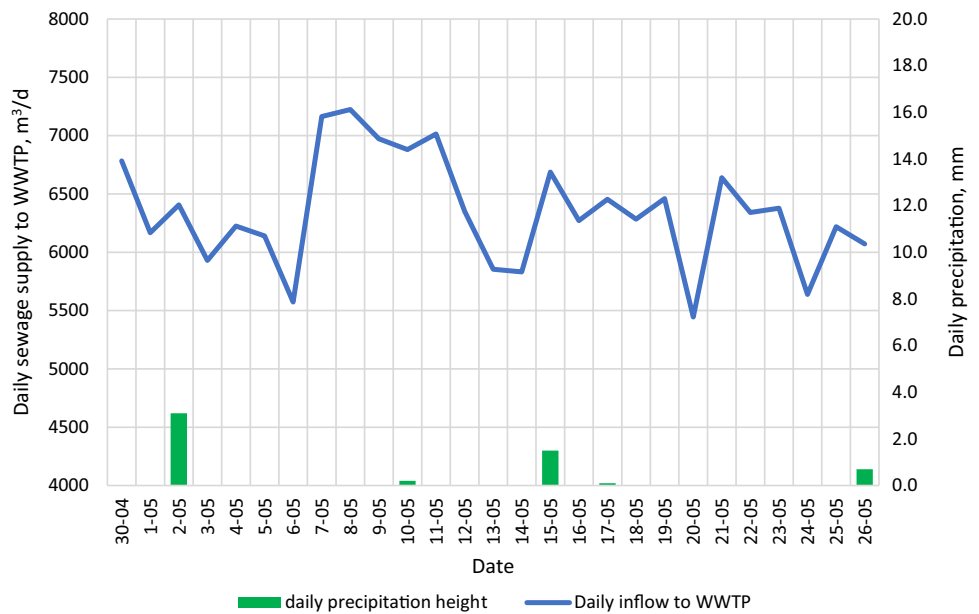


Fig. 15 Daily sewage supply associated with daily precipitation in a selected wet period in June and July 2017

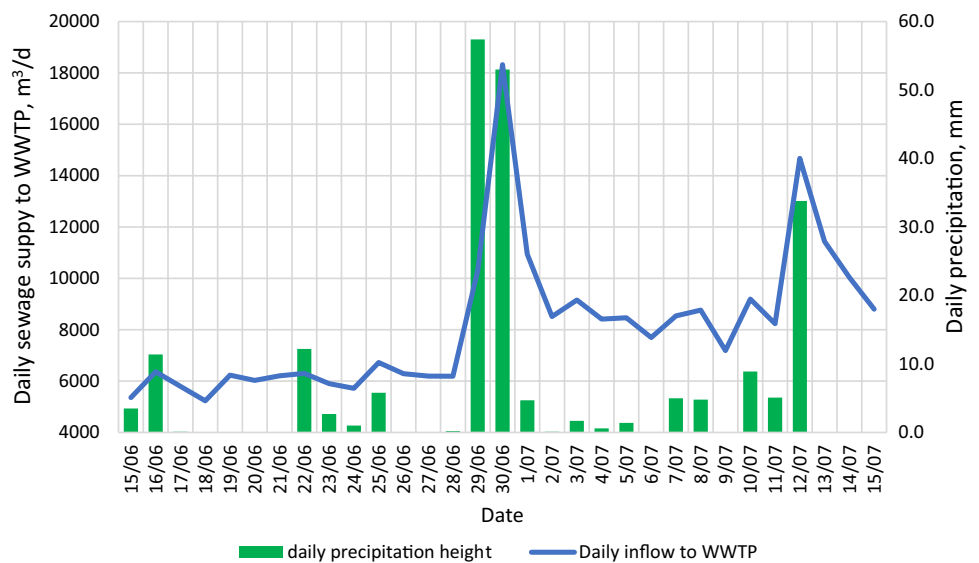


Table 5 Results obtained from every considered method

Years	Annual balance	Triangle method		Moving minimum method		Minimum night flow method	Variability in wet and dry weather
		Share of extraneous water (%)	Share of infiltration water (%)	Share of accidental water (%)	Share of infiltration water (%)		
2014	44	33	11	25	19	44–68	10
2015	43	32	11	21	22		7
2016	40	31	9	19	21		7
2017	53	37	16	33	10		14
2018	45	36	9	26	17		7
2019	38	30	8	18	21		7

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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