Article

Inflow Quantification in Urban Sewer Networks

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Abstract: The improper waterflow to wastewater treatment plants (WWTP) due to rainwater inflow, and infiltration is a growing concern due to the many problems it brings to the sector, ranging from infrastructure deterioration to environmental problems caused by untreated wastewater and to the eventual financial costs that these issues cause. The study was carried out at the Folhadela WWTP, Vila Real, Portugal, between May 2014 and May 2015, with the total effluent flows recorded every 2 min at the entrance of the WWTP. Rainfall data from the Vila Real Meteorological Station, corresponding to the same period, were used. The study allowed us to conclude that from the wastewater that flowed to the Folhadela WWTP, in the months of study, only 15% is domestic wastewater, and the remaining 85% were undesirable volumes. Of these, 47% were infiltration flows, and 38% were rainwater flows that are not taken into account when dimensioning networks and WWTPs. These flows also have the particularity of representing very high volumes in short periods of time, coinciding with heavy rains, representing a very high risk for drainage and treatment infrastructures. Regarding the infiltration flow rates, as a general rule, they are taken into account when dimensioning the networks as being a percentage of the total flow. However, it is necessary to take into account the magnitude and the evolution of these values according to the network age and state of conservation, as well as have straight regulations about the undue connections into the network.

Keywords: WWTP; flow monitoring; rainwater

1. Introduction

Wastewater is defined as the water and residues that flow from households, institutions, and commercial and industrial sources [1]. However, that definition per se does not include either groundwater or rainwater infiltrated in the sewage network. Groundwater infiltrations are simple to set aside. These are the infiltrations that constantly occur due to water in the soils and happen due to defects on the pipelines. Nevertheless, the infiltration/inflow due to rainfall events can be tricky to differentiate. That leads to the necessity of a solid distinction between inflow and infiltration of rainwater. Inflow (often referred to as direct infiltration) is from collected rainwater that flows directly through connections to the sewers. Infiltration of rainwater (also called indirect rainwater infiltration) is the consequence of its infiltration in the same manner as groundwater, which means that, unlike direct influx, it is not quite as quickly noticeable, taking possibly hours or even days after the rainfall to be noted [1]. That means rain-induced infiltration enters the sewers through defects in the network, whereas in-flowing stormwater comes through improper sanitation connections or openings in manhole covers.

Domestic wastewater drainage networks are designed for a flow that includes a percentage of the water used plus an infiltration flow related to the water in the soil and which enters the collectors through the joints. When it rains, it appears that the flow

effluent to the Wastewater Treatment Plants (WWTP) increases considerably due to the entry of rainwater (inflow) into the networks. This situation is highly undesirable because, in addition to causing a hydraulic malfunction in the networks, it brings many other problems, ranging from the deterioration of infrastructure, destruction of the biological balance of treatment systems, pollution caused by the discharge of untreated wastewater during times of rains, among others. It is therefore of utmost importance to know the undesirable flows from rainwater for the dimensioning and management of wastewater systems. Inflow and infiltration have long been recognized as primary hydraulic-related problems in urban wastewater collection systems, which can cause problems such as sewer overloading, sewer overflows, and the reduction of treatment facility efficiencies [2].

Excessive inflow and infiltration during wet weather periods into capacity-constrained sewer systems cause sanitary sewer overflows. The two major components of wet weather flow are inflow and infiltration and are the main factors found in sanitary sewer evaluation studies or inflow/infiltration studies [3]. Control and reduction of inflow and infiltration directly relate to effective controls for sanitary sewer overflows. The interaction and relative proportions of inflow and infiltration determine the extent, effectiveness, and cost of control measures. Usually, control of direct inflow is the first source pursued, with the infiltration component either lumped into part of the inflow as an immediate response or neglected because of the dominance of peak flow rates induced by inflow. The peak flow rate, as compared to sustained elevated flows from infiltration, is usually the sought-after result in sanitary sewer evaluation studies or inflow/infiltration studies. Successful and accurate estimates of both rainfall-derived inflow and sustained flows from rainfall-derived infiltration are, therefore, the prime determinants of the effectiveness of the controls [3].

Infiltration of groundwater and inflow of drainage and surface water, also referred to as infiltration/inflow, significantly influence costs and operation of both sewer systems and wastewater treatment plants (WWTP). Infiltration and inflow increase hydraulic loading and reduce wastewater treatment efficiency, thus resulting in additional costs and potential deterioration of the receiving water [4]. Furthermore, infiltration and inflow can cause heavier floods in urban areas and thus a deterioration of urban infrastructure through flood events. Groundwater infiltration may also accelerate pipe aging and increase the endangerment of adjacent infrastructure due to backfill material flushing around pipe leaks [5].

In fact, the negative impact of infiltration/inflow on the operation of sewer networks and wastewater treatment plants is well known and described [6]. Therefore, special attention was given to the development of methods for quantification of infiltration/inflow into sewer systems during past decades [7]. Conventional methods are usually based on water balance within the catchment [8] or on a simple assumption that the minimal diurnal discharge (or its given part) is equal to the infiltration rate [9].

Weiss et al. [6] conducted a study, including combined sewer overflow tanks and treatment plants to show up actual hidden reserves and bottlenecks in stormwater treatment. The study gave a general insight into the water pathways in urban hydrology. A special focus was given to undesired non-polluted water infiltrating into the sewer, labeled infiltration and inflow, or infiltration inflows, which is widely underestimated. It leads to a bad performance of the drainage system, although the parasite waters are themselves non-polluted. In existing combined systems, pollution control can be considerably improved by reducing infiltration and inflow. It is equivalent to the reduction of surface runoff, e.g., by separate drainage, as a frequently proposed alternative. Artificial infiltration of surface runoff may even increase infiltration inflows [6].

Kracht and Gujer introduced the concepts of a novel approach that allows for the quantification of infiltrating non-polluted waters by a combined analysis of time series of pollutant concentrations and discharged wastewater volume [10].

Bares presented a method for quantification of infiltrating groundwater based on the variation of diurnal pollutant load and continuous water quality and quantity monitoring [7].

In their study, Crawford et al. summarize and provide some critique of common flow projection methodologies, particularly methods that predict rainfall-derived inflow and rainfall-induced infiltration or rainfall-derived inflow/infiltration [3].

The Institute of Urban Water Management of the Technological University of Dresden submitted an article to the 12th International Conference on Urban Drainage in which the undue inflows to the WWTP of the City of Dresden in Germany between 2001 and 2002, which serves 1605 inhabitants and has an average total discharge of 156 m^3/day [5]. In their study, Karpf and Krebs presented a methodology to identify infiltration and inflow and estimate its quantity. For each flow fraction in sewer networks, an individual model approach was formulated whose parameters are optimized by the method of least squares [5].

Shelton investigated the flux stability of select chemical and biological sewage markers, including caffeine, total nitrogen (TN), total suspended solids (TSS), E. coli, and enterococci, and their suitability in assessing the severity of rainfall-derived infiltration and inflow in a residential sewer shed [11].

Wang proposed an uncertainty analysis for a pollutant-hydrograph model developed for assessing rainfall-derived inflow and infiltration based on wastewater conductivity. The model results indicate the confidence of inflow and infiltration rates in residential areas is much higher than that in the pump stations and WWTPs [12].

All these methods demonstrated successful capabilities to determine the inflow and infiltration. Nevertheless, all these rainfall-derived inflows and infiltration assessment methods require intensive measurements, which makes them uneconomic for long-term management, especially for large sewer systems [12]. It is also human resource-consuming, even for relatively small systems [13].

Correct estimation of rainfall-derived inflow and infiltration is required for the maintenance of sewer infrastructures, such as sewer rehabilitation and replacement. Zhang equipped ten monitoring sewer sites ranging from residential areas to a wastewater treatment plant (WWTP) for continuous measurements of waterflow and four wastewater indicators, including ammonia (NH_4^+-N), phosphate (PO_4^{3-}-P), chemical oxygen demand (COD), and conductivity. In order to identify the most representative indicator for modeling the rainfall-derived inflow and infiltration dynamics, simulations based on different wastewater indicators were compared. Sensitivities of different wastewater indicators to rainfall-derived inflow and infiltration estimations were evaluated using the Kolmogorov–Smirnov test. The results revealed that conductivity was the most sensitive indicator for rainfall-derived inflow and infiltration simulations [14].

In 2018, Zhang et al. [2] developed a study proposing a novel conductivity-based method for estimating rainfall-derived inflow and infiltration. The method separately decomposes rainfall-derived inflow and rainfall-induced infiltration based on conductivity data. Compared with traditional flow-based methods, the proposed approach exhibits distinct advantages in estimating rainfall-derived inflow and infiltration and overflow, particularly when the two processes happen simultaneously [2]. However, this methodology is only correct in cases where the runoff does not contribute dissolved matter to the water, which could increase its conductivity.

In Portugal, there are only a few studies about this subject and have applied different methodologies. In 1999, a 340-day study was started at the WWTP in Mirandela, Portugal. This WWTP serves approximately 12,500 inhabitants, the population of the city of Mirandela, and two villages in the county. The flow and precipitation records used for the study were total daily values recorded at the Mirandela WWTP and at the Mirandela pluviometric station, respectively [15].

This paper presents an application of the method developed by the Environmental Protection Agency (EPA) to determine and quantify the volume and the origin of the water that runs through the pipes to the WWTP [16,17]. This was possible with the continuous flow monitoring and recording at the entrance of the WWTP of Folhadela, Vila Real,

Portugal, and the rainfall records obtained from the Vila Real Weather Station. The goal is to quantify the improper flow of wastewater that is not from domestic usage.

2. Case Study

The study was carried out at the Folhadela WWTP, Vila Real, Portugal (Figure 1) between May 2014 and May 2015, with the record of the total effluent flows, continuously (every 2 min), using a PCM 4 ultrasonic meter, at the entrance of the WWTP. Rainfall data from the Vila Real Meteorological Station, located about 3 km from the WWTP, corresponding to the same period, were used. The flows corresponding to a period in which it did not rain, dry weather flow (DWF) representative of the wet season and the dry season were obtained, respectively, from the flow and rainfall records from the 5 to 22 of March 2015 and from 11 to the 18 of June 2014.
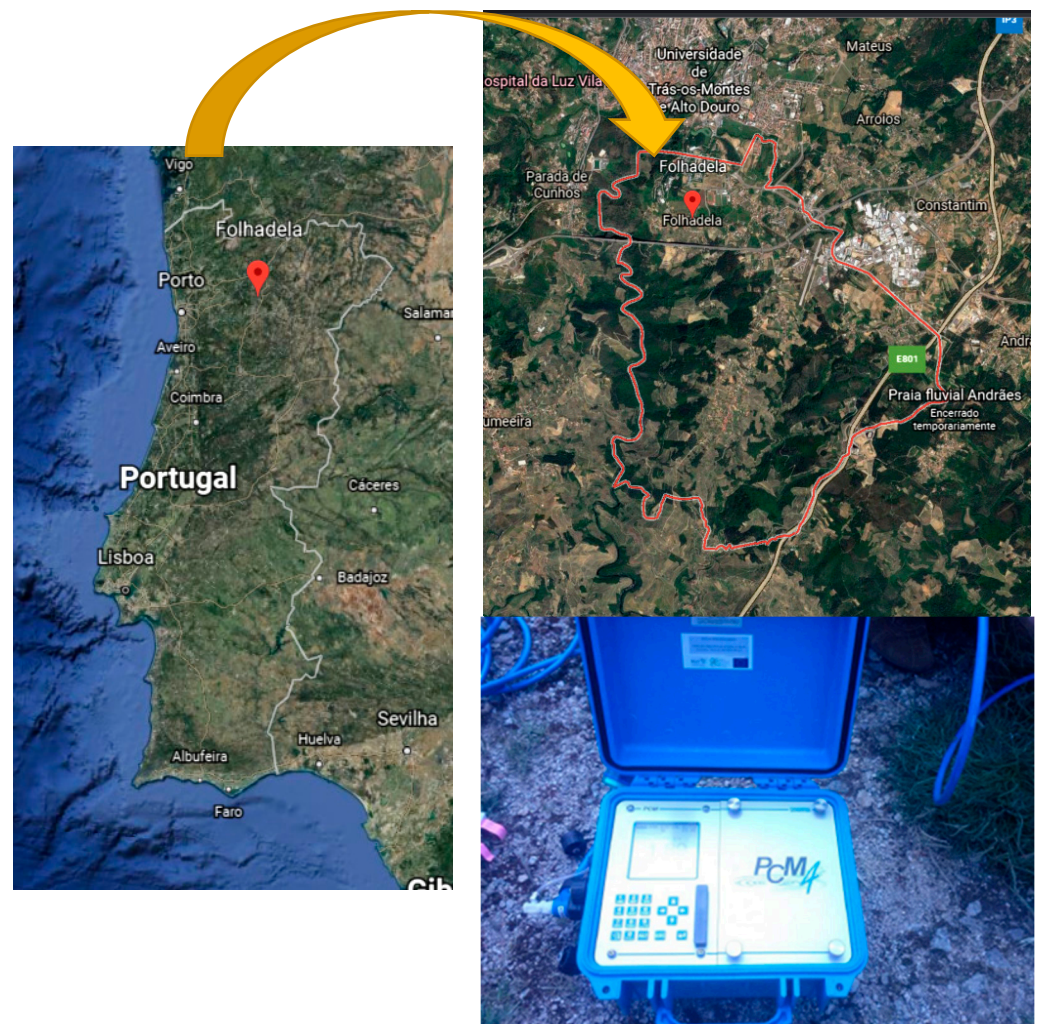
Figure 1. Folhadela location and flow meter used in the case study.

Materials and Methods

The methodology applied and recommended by the EPAand by the Massachusetts Department of Environmental Protection allows us to divide and quantify the total effluent flow in four distinct components [16,18]:

1. Sanitary flow is correspondent to wastewater flow from industry and commercial operations, institution flows, and domestic usage [17].
2. Groundwater infiltration (GWI), which corresponds to the water in the soil that enters the network through the joints.

3. Direct rainwater (SWI), which corresponds to rainwater that enters the networks directly through the lids of the manholes and by improper connections, among others.
4. Rain-induced infiltration water, which corresponds to water that infiltrates the soil after a rain and enters the network.

In order to do this, it is necessary to know the total effluent flow through a flow meter.

It is necessary to know the flow corresponding to a period in which it did not rain (DWF), which is representative of the wet season and the dry season, taking into account whether the soil is more or less saturated, respectively. Dry weather flow (DWF) is defined by the flow rate of the wastewater that is only due to sanitary flow and groundwater infiltration (GWI) [16], meaning it is only composed of water that flows through the pipes when there are no rainfall events. It is considered DWF periods between 7 and 14 days in which there were no rainfall events with precipitation superior to 0.3 mm [19].

In this period, when it did not rain, the water circulating in the network corresponds to the sum of the sanitary flow and the groundwater infiltrations (GWI) (Equation (1)).

$$\text{Dry Weather Flow} = \text{Sanitary Flow} + \text{Groundwater Infiltrations} \qquad (1)$$

Considering that in the night period between 0 and 6 am, consumption is practically negligible; that is, sanitary flow is practically zero, the total flow recorded between 0 and 6 am corresponding to periods without rain represents the flow of underground infiltration (GWI).

The difference between the total flow, corresponding to a period that did not rain (DWF), and the night flow for the same period (GWI), corresponds, roughly, to the average flow of sanitary flow.

In order to quantify the direct rainwater (SWI) and the rain-induced infiltration, it is necessary to know the precipitation records to know when the rainfall events begin and end as well as the hydrograph corresponding to that time interval. This work will not consider subsequent rainfall events that interfere with the previous hydrographs. Thus, direct rainwater (SWI) corresponds to the flows that enter the network quickly when a rainfall event begins and end quickly when the rain stops. The rain-induced infiltration can be quantified using the hydrograph considering the instant when the rainfall event ends until the flow corresponding to a period in which it did not rain (DWF) is reached again, Figure 2. Flow measurements were taken every two minutes.
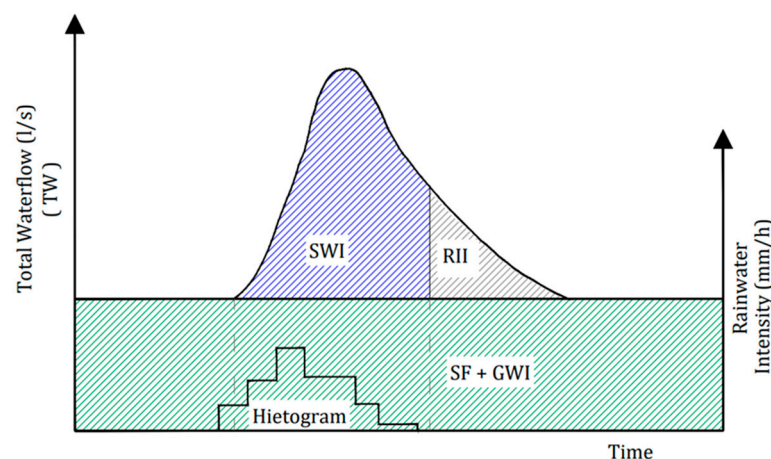
Figure 2. Process of decomposition and quantification of the effluent flow, adapted from [17]. SWI—direct rainwater; RII—rain-induced infiltration; SF + GWI—sanitary flow + underground infiltration.

In this way, it is possible to quantify volumes corresponding to each subdivision made of the total flow.

3. Results and Discussion

From the flow record obtained, the average flow was determined in each month, although due to the poor maintenance of the treatment plant in some months, there was clogging of the measurement sensors with waste from the wastewater, which caused some data failures and made it impossible to record data in some months, namely July and August of 2014 and December of 2015.

The total waterflow (TW), as well as the monthly effluent volumes to the WWTP, are shown in Table 1.

Table 1. Total waterflow (TW): mean monthly flow and corresponding total monthly volumes.

	TW	
	Mean Flow (L/s)	**Volume (m³)**
May 2014	3.16	8463.74
June 2014	1.40	3628.80
September 2014	1.34	3480.80
October 2014	4.33	11,597.47
November 2014	7.03	18,221.76
January 2015	3.83	10,258.27
February 2015	5.16	12,483.07
March 2015	2.64	7076.35
April 2015	1.32	3421.44
May 2015	1.77	4740.77
		83,372.47

It is possible to observe that in the months of October, November, January, and February, the flow and, consequently, the volume are significantly higher than in the other months due to the fact that these months are the rainiest ones. Figure 3 represents the precipitation records in November 2014, which was the month with the highest rainfall in the period from May 2014 to May 2015 and which corresponds to the highest flow recorded in the network at the entrance to the WWTP, was 18,221, 76 m³.
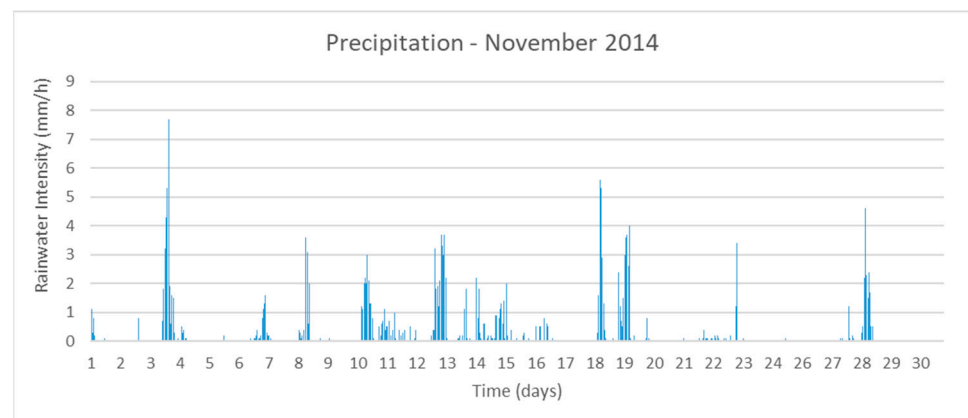

Figure 3. Precipitation records in November 2014.

This is an indicator of the importance of this study since it shows that rainfall events have a great influence on the flows that flow into the drainage network.

To be able to separate sanitary flow from groundwater infiltration (GWI), it is necessary to analyze the data when there is no interference from precipitation and, therefore, estimate the DWF for both the wet season and the dry season. For this purpose, the months of June 2014 (dry season) and March 2015 (wet season) were considered. To better represent the dry season, a month should be considered at the end of Summer, such as August or September;

however, in this study, given the rainy days and some data gaps, it was not possible to use these months. Both in June and in March, there were periods without rain that made it possible to calculate the DWF. In the case of the dry season, 8 days were selected (from 11 to 18 of June 2014), and for the wet season, 14 days were selected (from 9 to 22 of March 2015), Figure 4. In both cases, this period was preceded by at least 3 days without rain so as not to make the rain affect the flow entering the network.
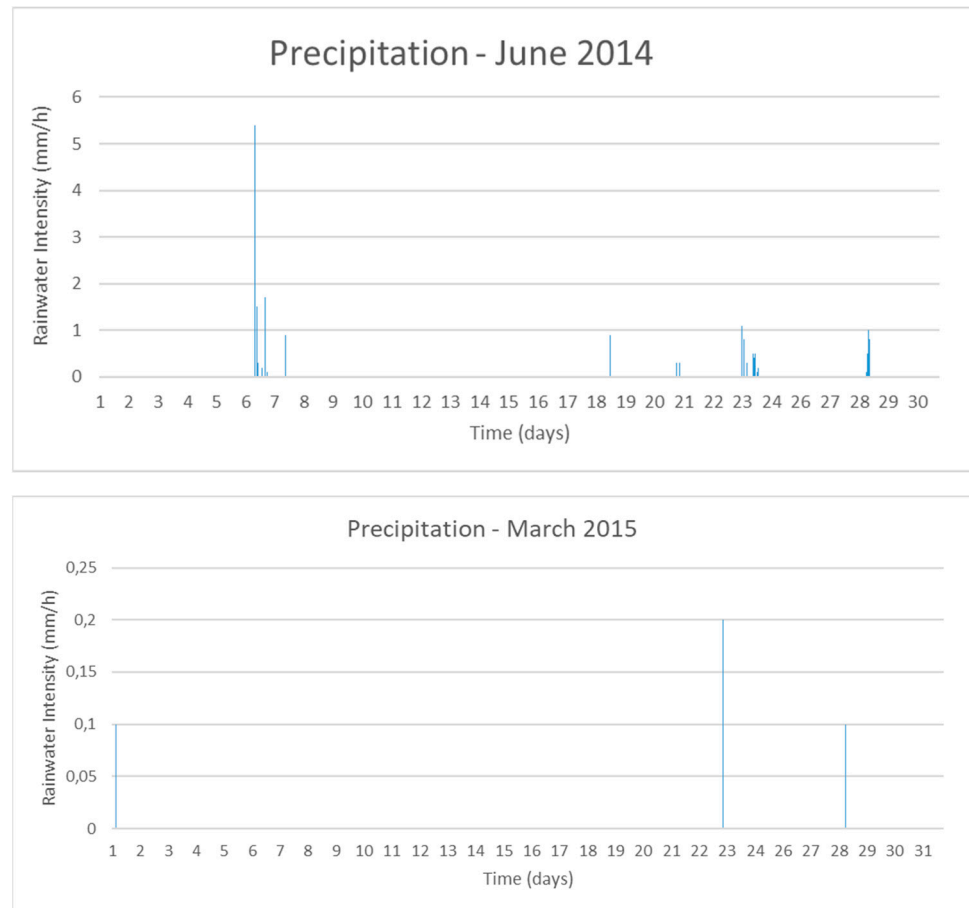
Figure 4. Rainfall records for June 2014 and March 2015.

Figure 5 shows the average hourly flows corresponding to the periods without rain, representative of the dry and wet seasons considered.
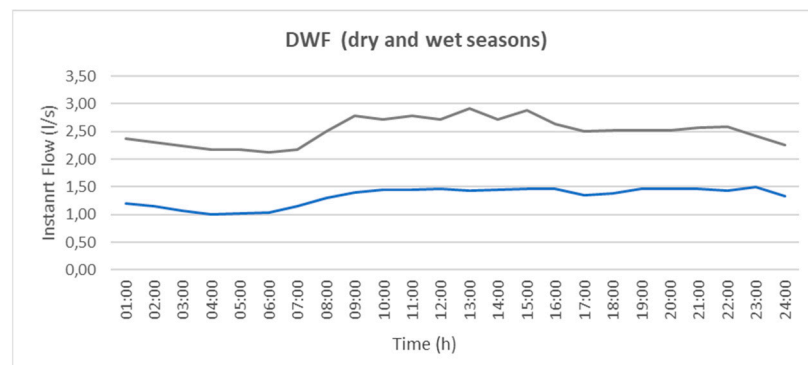
Figure 5. Average hourly flows corresponding to periods without rain (DWF) representative of the dry and wet seasons.

The analysis of these diagrams indicates, as expected, that in the wet season, the DWF diagram is larger than in the dry season due to the saturation of the soil causing more infiltration in the wet season.

Unexpectedly, the sewage entering the pipes by joint failures reached a high flow rate; this could indicate that the sewer is in poor condition and therefore should be checked. So high nocturnal base flow could also occur due to losses that can occur in the houses, but, in Portugal, the price of the water is very high, representing a high slice of the monthly expenses of the families, so people are very careful with this situation.

Table 2 presents the DWF for the dry and wet seasons (months of June and March, respectively). May, June, September, and April belong to the dry season and October, November, January, February, and March as the wet season.

Table 2. Representative flow of a rainless period (DWF) for dry and wet seasons: monthly mean flow and respective total monthly volumes.

	DWF	
	Mean Flow (L/s)	**Volume (m³)**
May 2014	1.30	3487.64
June 2014	1.30	3375.14
September 2014	1.30	3375.14
October 2014	2.62	7012.14
November 2014	2.62	6785.94
January 2015	2.62	7012.14
February 2015	2.62	6333.55
March 2015	2.62	7012.14
April 2015	1.30	3375.14
May 2015	1.30	3487.64
		51,256.61

3.1. Groundwater Infiltration (GWI)

Considering that during the night period between 0:00 and 6:00 am the wastewater flow is practically negligible, as the network under study does not transport industrial wastewater, the GWI was obtained through the flow records observed in that period. Table 3 shows the monthly average of the groundwater infiltration flow rates, registered GWI, as well as the respective volumes.

Table 3. Average monthly groundwater infiltration flow rates (GWI) and corresponding volumes.

	GWI	
	Mean Flow (L/s)	**Volume (m³)**
May 2014	0.86	2303.42
June 2014	0.80	2073.60
September 2014	0.96	2488.32
October 2014	2.29	6133.54
November 2014	2.17	5612.52
January 2015	2.29	6133.54
February 2015	2.23	5408.25
March 2015	1.75	4677.26
April 2015	0.65	1684.80
May 2015	0.86	2303.42
		38,818.67

3.2. Flow Rate Corresponding to the Rain Time (ST)

The flow corresponding to the rain time (ST) includes the direct rainwater flow (SWI) and the rain-induced infiltration waterflow. If the total waterflow (TW) is removed from the sum of GWI with the sanitary flow, the flow that enters the drainage network due to the occurrence of rainfall is obtained, Table 4.

Table 4. Average monthly flow corresponding to rainfall (ST) and corresponding volumes.

	ST	
	Mean Flow (L/s)	**Volume (m³)**
May 2014	1.86	4976.10
June 2014	0.10	253.66
September 2014	0.04	105.66
October 2014	1.71	4585.33
November 2014	4.41	11,435.82
January 2015	1.21	3246.13
February 2015	2.54	6149.52
March 2015	0.02	64.21
April 2015	0.02	46.30
May 2015	0.47	1253.13
		32,115.86

Table 5 presents the summary of the division of water effluent to the WWTP into the GWI, SW, and ST components in volume and in percentage.

Table 5. Division of wastewater effluent to the wastewater treatment (TW) plant in the components groundwater infiltration (GWI), domestic wastewater (SF) and rainwater (ST).

	TW	GWI	SF	ST(SWI + RII)
Volume (m³)	83,372.47	38,818.67	12,437.94	32,115.86
Percentage (%)	–	47	15	38

The analysis of Table 5 allows us to conclude that of the water that flowed to the Folhadela WWTP, in the months of study, only 15% is domestic wastewater, the remaining 85% being undesirable volumes. Of these, 47% are infiltration flows, and 38% are rainwater flows that are not taken into account when dimensioning networks and WWTPs. These flows also have the particularity of representing very high volumes in short periods of time, coinciding with heavy rains, representing a very high risk for drainage and treatment infrastructures. Regarding the infiltration flow rates, as a general rule, they are taken into account when dimensioning the networks, being an estimated percentage of the expected flow, but it is necessary to take into account the specific magnitude of these values and its evolution over time, as a consequence of the network aging.

There are some studies in other countries that also found high values of infiltration, such as the one conducted by Krapf and Krebs, that found important volumes of infiltration (52%) when they studied the undue inflows to the WWTP of the City of Dresden, in Germany, between 2001 and 2002, which serves 1605 inhabitants and has an average total discharge of 156 m³/day [5].

However, these studies bring highly variable results. For example, in a study conducted in Mirandela, Portugal, the values, when applied the triangle method, were 7.1% of the total volume was detected as infiltration, and 13.1% of the total volume was established to be undue inflows [15].

Paixão studied this subject by application of several methods in four WWTP in the north of Portugal. The values for direct and indirect infiltration varied between 22 and 53% of the total flow that arrived into the WWTP [20]. According to the author, this study

showed that the problem of undue inflows has a worrying dimension, mainly due to the inflow of direct and/or indirect infiltration flows, as indicated by the results obtained. The results obtained suggest the need to carry out inspections and possible repairs along the drainage network in order to mitigate this problem.

The analysis of the results obtained leads us to reflect on the importance of estimating DWF values. Indeed, the DWF estimate represents the most subjective part of this methodology and can influence the results obtained. The use of monthly values for DWF, when possible, instead of using only two values, one representative of the dry season and the other of the wet season, might be an improvement to be adopted in the application of the method. It is known, however, that, for months when it is not possible to calculate the DWF value because it is not possible to select a sufficiently long dry period (between 7 and 14 days plus three more before the period considered) as an example is the month of November 2014, Figure 2.

The consideration of the measurement of groundwater infiltration flow rates (GWI) of periods without rain corresponding to the same period used for the calculation of the DWF may also be a hypothesis to be explored for the improvement of the method.

When extrapolating these values to other case studies, it should be taken into account that the study, due to lack of data, did not take into account three very important months, namely the months of July and August, which are typically, for Portugal, the driest months of the year and the month of December, which in turn is one of the rainiest months of the year. In addition, it was considered that at night the flow of wastewater is zero, which is not completely true. The Folhadela wastewater plant is also a particular case in which it was already known, at the outset, that the undue flow was very large.

4. Conclusions

In this study, the methodology of the United States Environmental Protection Agency was used [17], which, in the last decades, has been dedicated to developing studies in this field, and has concluded that:

- By using the described methodology, it was possible to subdivide the effluent water into the following components: groundwater infiltration, sanitary flow, and direct rainwater flow together with Rain-induced infiltration.
- Only 15% of the water that flowed to the Folhadela WWTP corresponds to domestic wastewater, that is, the one that should flow to the station. The share of water due to precipitation represented 38%, in this case, which requires rethinking the materials and construction processes of the networks, as well as the inspection to detect improper connections.

This 38% is not taken into account when dimensioning networks and WWTPs. These flows also have the particularity of representing very high volumes in short periods of time, coinciding with heavy rains, representing a very high risk for drainage and treatment infrastructures. Regarding the infiltration flow rates, as a general rule, they are taken into account when dimensioning the networks, but it is necessary to take into account the magnitude of these values.

- The increase in effluent flows in periods of rain is noticeably greater than those calculated in dry periods.

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