Assessment of the infiltration in wastewater systems by applying the stable isotopes method. Case Study of the northern part of Alcântara's drainage basin, in Lisbon.

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Abstract: This paper aims to contribute to the research field in Portugal of groundwater infiltration in sewers. Therefore, it is presented and discussed the results of applying a non-traditional approach of assessing groundwater infiltration, in dry weather, on the northern part of Alcântara basin, in Lisbon, one of the largest and most complex drainage basins in Portugal. This approach, initially developed in France within the research project called APUSS (Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems), uses an intrinsic property of water, namely, the isotopic ration of oxygen and it is named as the Stable Isotopes Method. Moreover, it will be presented infiltration indicators as well as the results of the determination of a wastewater factor and the analysis of the proposed approach. By applying this methodology, in the northern part of Alcantâra’s drainage basin there was obtained an average annual infiltration flow of approximately 480 l/s, corresponding to about 40% of the total wastewater flow in the drainage system. In terms of infiltration indicators, there were obtained a unitary average annual infiltration flows of, approximately, 1.0 l/(s.km), where 4% corresponds to infiltration on manholes, a specific infiltration rate of 1.6 m$^3$/day.cm Φ.km) and a infiltration rate per impermeable drainage area of 0.3 l/s.ha.

Keywords: groundwater infiltration, sewers, stable isotopes, Alcântara drainage basin

Introduction

In urban areas, the drainage systems are valuable assets in the economy, health and well-being of the population. The structural integrity and functional efficiency of these systems are key parameters, regarding the guarantee of public and economic health, with respect to the necessary transport and treatment of wastewater flows. In the urban environment, these systems are the most valuable ones, involving, therefore, higher costs.

In major urban centres it appears that the state of infrastructure is quite aged and deteriorated. The main deficiencies detected result from impacts caused by infiltration/inflow (I/I), that is, by parasitic water that includes the groundwater infiltration and stormwater inflows. These inflows affect urban water sustainability, mainly in long term perspective. The economic impacts are quite significant in European cities, in addition to environmental and technical impacts (structural problems in the collecting and discharge surplus, among others) (Kracht et al., 2008). In major European capitals it is estimated that the costs associated with infiltration and inflow (I/I) reach, approximately, 1.3M€ per
m³/d of I/I, in case of the UK (Ellis B., 2001). In search of urban sustainability, there have been an effort to determine the magnitude of infiltration, with the goal of developing a more conscious planning.

In dry weather, that is, with no stormwater flow, infiltration is recognised as one of the components of the total wastewater flow, since it is almost impossible to avoid it, considering the fact that sewers are below the surface and, therefore, face the soil dynamics, like movements of water bodies and plant roots and the pressure exerted on the outside surface of pipelines. The magnitude of I/I depends, mainly, on hydrogeological characteristics of the surroundings, quality of sewer materials and its state of conservation. As shown in Figure 1, groundwater can enter into the sewer network through poorly sealed joints, as well as service line connections, cracks in sewers and in manholes, and due to porous concrete (Metcalf & Eddy, 2003).

![Figure 1: Main sources of groundwater infiltration.](image)

With the aim of assessing these parasitic waters, there are several methodologies, mainly, conventional ones. However, these methods are based on highly uncertain assumptions, which, frequently, result in underestimations and, consequently, causes unexpected negative impacts on the system.

Therefore, under the European research project named APUSS (Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems), it was developed and applied a non-conventional methodology that overcomes some gaps and uncertainties of conventional ones. This approach uses an intrinsic property of water, the isotopic ratios of oxygen, and it is called the Stable Isotopes Method (Ellis et al., 2010).

That said, the main purpose of this paper is to present and discuss the results of applying the Stable Isotopes Method to contribute to the assessment of groundwater infiltration, in dry weather, on the northern part of Alcântara basin, in Lisbon, one of the largest and most complex drainage basins in Portugal. This work was developed within a research project of SIMTEJO (Portuguese company responsible for Lisbon’s wastewater management), with the participation of IST-UL, that took place in 2013 and 2014. Moreover, this paper aims to contribute to the research field in Portugal of groundwater infiltration in sewers.

**Case study**

The Stable Isotopes Method was applied on the case study of the northern part of the Alcântara drainage basin. It is located in Lisbon, Portugal, where one part belongs to Amadora Municipality...
(34%) and the other one belongs to Lisbon Municipality (66%), and it is considered to be one of the largest urban basin in the country. The wastewater produced in this basin is treated in Alcântara WWTP, located downstream (Figure 2), which was built to serve more than 750 thousand inhabitants and treat a maximum flow of 6.6 m³/s (Chiron et al., 2008).

Figure 2: Location of the case study and the delimitation of the northern part of Alcântara basin

The basin of the case study serves, approximately, 254 000 equivalent inhabitants, with an area of 2746 ha. The sewer network, mainly a combined sewer system, has a total length of 460 km and is relatively aged, as half of the sewers are between 54 to 95 years old. Its main trunk sewer crosses the entire basin, with a total length of 13 km, and it is believed to be subject to significant interactions with the soil, and possibly, to groundwater infiltration, since, in the past, it was a natural riverside. Within the PGDL (Portuguese abbreviation for Lisbon General Drainage Plan) it was detected several structural and technical problems on the sewer network, mainly, related to the hydraulic performance, state of conservation and inadequate connections (Chiron; ENGIDRO; HIDRA, 2008). Therefore, it is expected to obtain a high fraction of groundwater infiltration.

In terms of the local hydrogeological characteristics, the permeability of the soil is low to medium, with high permeability near the main trunk sewer, so it is expected to be subject to a considerable infiltration rate (Oliveira, 2010; CM Lisboa, 2010).

Methodology

The Stable Isotopes Method, developed by Dr. Wili Gujer (EAWAG, Switzerland), refers to an intrinsic and conservative property, that is, the relative abundance of the stable isotope ¹⁸O. In wastewater, this property consists in a natural tracer, considering that each component of wastewater has a certain concentration of the tracer, distinct from other components. This characteristic takes the advantage of being constant and conservative, relatively independent from the conditions in which it is submitted to, namely, redox reactions, pH, temperature variations and, even, sewers infrastructures, among others (Rieckermann et al, 2010).

The relative abundance of the isotope ¹⁸O is determined in relation to the most abundant oxygen isotope, ¹⁶O, and is frequently named as isotopic ratio, represented by ¹⁸O/¹⁶O or by δ¹⁸O. The isotopic
ratio is expressed with respect to the international standard VSMOW (Vienna Standard Mean Oceanic Water) (De Bénédits & Bertrand-Krajewski, 2004a), according to equation 1:

$$\delta^{18}O = 1000 \frac{(^{18}O/^{16}O)_{\text{sample}} - (^{18}O/^{16}O)_{\text{VSMOW}}}{(^{18}O/^{16}O)_{\text{VSMOW}}}$$

(1)

The relative abundance depends, essentially, on the hydrological cycle, controlled by the effects of evaporation and weather precipitation, on a large scale. Therefore, the altitude effect, the proximity to the ocean, the latitude effect, as well as evaporation and condensation, determine the isotopic ratio $\delta^{18}O$ (Rieckermann et al., 2010).

Typically, the isotopic ratios are measured using the laboratory technique of mass spectrometry, named Isotope Ratio Mass Spectrometry (IRMS) (Sulzman, 2007) (Figure 3).

![Figure 3: IRMS of SIIAF’s laboratory, FC-UL, Lisbon, Portugal.](image)

This method takes into concern some assumptions that are worth being mentioned. Firstly, this method, as some conventional ones, is applied in dry weather, when there is no evidence of rainfall events, where it assumes that, in the sewers, there is only flowing wastewater and groundwater infiltration. The dry weather period could be determined by studying the rainfall regime in a given period. Based on that and on the literature consulted, it can be concluded that dry weather corresponds to a period when there is no evidence of precipitation on the two antecedents’ days.

The equations used in this method are relatively simple and require data on the total wastewater flow. The method admits the mass balance, expressed by equation 2, the infiltration ratio is determined by equation 3, whereas the relative uncertainty is estimated by equation 4:

$$Q_T \cdot \delta_T = Q_{WW} \cdot \delta_{WW} + Q_{inf} \cdot \delta_{inf}$$

(2)

$$b = 100 \frac{Q_{inf}}{Q_T} = 100 \frac{\delta_T - \delta_{WW}}{\delta_{inf} - \delta_{WW}}$$

(3)

$$\Delta b = 100 \frac{\sqrt{2} \cdot \Delta \delta}{\delta_{inf} - \delta_{AR}} \sqrt{b^2 - b + 1}$$

(4)

Where:
- $Q_T$, $Q_{WW}$ and $Q_{inf}$ – total, wastewater and infiltration flows, respectively
- $\delta_T$, $\delta_{WW}$ and $\delta_{inf}$ – isotopic ratios of, respectively, total, wastewater and infiltration
- $b$ – infiltration fraction
- $\Delta b$ and $\Delta \delta$ – uncertainties of, respectively, infiltration fraction and laboratory analysis
Thus, the $\delta^{18}O$ of groundwater samples corresponds to the reference value of the infiltration ratio, $\delta_{\text{INF}}$, while the $\delta^{18}O$ of potable water regards the reference value of strict wastewater, $\delta_{\text{WW}}$. In order to obtain conclusive results, this method should only be applied if $\delta_{\text{WW}}$ is significantly different from $\delta_{\text{INF}}$, which might not happen when the potable water has the same origin as the infiltration, that is, the groundwater. As such, it is essential to study the characteristics of drainage basin, as well as the water supply system. Moreover, it is defined a limit to the applicability of the method, which corresponds to $\Delta b/b$ being less than 1. A more complete description of the method is available in De Bénéditis & Bertrand-Krajewski (2004a). In order to obtain the isotopic ratios of the three mentioned sources (phreatic water, potable water and total flow), it is necessary to conduct sampling campaigns.

In what concerns the purpose of this paper, it is believed that the Stable Isotopes Method can be applied in the northern part of Alcântara drainage basin, since the main source of water supply in Lisbon is the Castelo de Bode dam (Zêzere hydrograph basin), which is responsible for about 70% of the water supply in Lisbon, in 2012 (EPAL, 2012). Moreover, this dam is at a distance of more than 100km from Lisbon, thus it is expected to observe a difference in the isotopic ration between the potable water (wastewater) and the phreatic water (groundwater infiltration). That said, it necessary to plan the sampling campaigns, in terms of choosing the suitable points (considering as well their accessibility) and to ensure the required human and material resources. In order to study the possible temporal variability, two sampling campaigns of three days took place, one in summer 2013 and the other one in winter 2014.

Results and Discussion

After the sampling campaigns and the laboratory analysis, there was obtained the isotopic ratios of each sample, which are presented in Figure 4, where AP1, AP2 and AP3 are potable collecting points, AF2, AF3 and AF4 refer to the phreatic collecting points and CANETAR refers to collecting point of wastewater in the Alcântara WWTP.

![Figure 4: Isotopic ratios $\delta^{18}O$ of each sample collected in summer (on the left) and winter (on the right) sampling campaigns. Adapted from Matos et al. (2014).](image-url)
It can be observed a clear decrease of most of the values in winter, in relation to the values collected in summer, in fact, in some cases, it is detected a 0.5% difference. Moreover, the samples of each source (potable, phreatic and total wastewater) are relatively in the same level, with the exception of a few ones. Just by studying this figure, it may be possible to confirm that, in dry weather, the total wastewater is a combination of strict wastewater (represented by potable water) and infiltration (represented by phreatic water). This is explained by the fact that the isotopic ratios of the total wastewater (CANETAR) is framed between the phreatic and potable ones. Furthermore, it is expected to obtain a higher value of infiltration in winter than in summer, since the isotopic ratio of CANETAR is closer to the isotopic samples of phreatic water in winter than in summer.

It is important to mention that, after a more close analysis of isotopic ratios presented previously, some values had to be disregarded, due to contaminated reasons (AF1), as well as not fulfilling the criteria of \( \Delta b/b < 1 \).

The infiltration and strict wastewater are obtained by applying the equations 2 and 3, mentioned previously, and the use of total wastewater flow information data, resulting in a value of infiltration flow per each sample collected in CANETAR. With those results, it was possible to obtain the hydrographs presented in Figure 5 for each studied period, with the hydrograph separation of infiltration and strict wastewater. It is clear the seasonal difference of infiltration flow between summer and winter, being greater in the last season, as expected.

![Figure 5: Hydrograph separation of strict wastewater and groundwater infiltration, for summer (on the left) and for winter (on the right). Adapted from (Matos et al., 2014).](image-url)

The average values of infiltration flow \( (Q_{\text{inf}}) \), strict wastewater flow \( (Q_{\text{WW}}) \) and total wastewater flow \( (Q_T) \), in each season (summer and winter), as well as annual values are presented in Table 1. It is also presented the infiltration fractions \( b \) and \( k \), which are in relation to, respectively, total wastewater flow \( (Q_{\text{inf}} / Q_T) \) and strict wastewater flow \( (Q_{\text{inf}} / Q_{\text{WW}}) \), as well as the average uncertainty \( \Delta b \) (determined by the equation 4) for each sampling campaign (summer and winter) and for the annual balance, considering the laboratory uncertainty of 0.07‰.

Furthermore, resorting to some of the characteristics of Alcântara’s sewer network, namely, the sewer length and diameters (excluding diameters < 200mm), it was determined the following infiltration indicators:
Ind 1. a unitary infiltration rate expressed in flow per kilometre of sewer (l/s.km);

Ind 2. a unitary infiltration rate expressed in flow per fictitious kilometre of sewer (l/s.km_{inf}) where it considers the infiltration in manholes;

Ind 3. a specific average infiltration rate expressed as the flow per kilometre of sewer and per centimetre of sewer diameter (m³/(day.cm Φ.km));

Ind 4. Infiltration rate expressed as flow per unit of impermeable drainage area (ia) (l/s.ha_{ia}).

The sewer network’s characteristics, namely, the sewer length and the diameters were determined by using the AutoCAD software for the part of the drainage basin that belongs to Lisbon Municipality, while using ArcGIS for the drainage area that belongs to Amadora Municipality. This information is available on PGDL (Portuguese abbreviation for the Lisbon General Drainage Plan).

In order to determine the above mentioned indicators, there was the need to assume some hypothesis. Firstly, since the sewer network of the case study has several sewers geometries, there was the need to determine the equivalent diameter for the non-circular sewers, to obtain Ind 1, Ind 2 and Ind3. Specifically, the Ind2 demand a few more assumptions, namely, applying the following equations (equation 5 to 6).

\[ L_{\text{fict}} = \frac{A_{\text{Cx}} + A_{\text{sewer}}}{\pi \times D_{\text{sewer}}} \]  

Where:
- \( L_{\text{fict}} \) – fictitious length;
- \( A_{\text{Cx}} \) – manhole’s wet area;
- \( A_{\text{sewer}} \) – sewer’s wet area;
- \( D_{\text{sewer}} \) – sewer’s diameter;
- \( D_{\text{Cx}} \) – manhole’s diameter (\( D_{\text{Cx}}=1m \) if \( D_{\text{sewer}}<600mm \); \( D_{\text{Cx}}=D_{\text{sewer}}+0.5\) m if \( D_{\text{sewer}}>600mm \));
- \( N \) – number of manholes (determined by admitting 40m distance between manholes);
- \( h \) – manholes’ depth in relation to the phreatic level (h=1m in summer and h=2 in winter);
- \( L_D \) – sewer length with respect to the diameter \( D_{\text{sewer}} \).

\[ A_{\text{Cx}} = N (\pi \times D_{\text{Cx}} \times h) \]  

\[ A_{\text{sewer}} = \pi \times D_{\text{sewer}} \times L_D \]  

In relation to Ind4, the impermeable area was determined by considering the coefficient C of the rational method (used in stormwater flow estimations) with the value of 0.67 for the drainage basin under study (CHIRON; ENGIDRO; HIDRA, 2006).

The results of the indicators estimations are presented in Table 1.

Table 1: Synthesis of the results from applying the Stable Isotopes Method on the northern part of Alcântara Basin.

<table>
<thead>
<tr>
<th>Period</th>
<th>Q_{inf}</th>
<th>Q_{ww}</th>
<th>Q_{r}</th>
<th>( b )</th>
<th>( k )</th>
<th>\Delta b</th>
<th>Ind 1 l/s.km</th>
<th>Ind 2 l/s.km_{inf}</th>
<th>Ind 3 m³/(day.cm Φ.km)</th>
<th>Ind 4 m³/(day.ha_{ia})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>304</td>
<td>852</td>
<td>1156</td>
<td>0.26</td>
<td>0.36</td>
<td>0.13</td>
<td>0.66</td>
<td>0.64</td>
<td>1.03</td>
<td>14</td>
</tr>
<tr>
<td>Winter</td>
<td>651</td>
<td>649</td>
<td>1300</td>
<td>0.50</td>
<td>1.00</td>
<td>0.12</td>
<td>1.41</td>
<td>1.34</td>
<td>2.20</td>
<td>30</td>
</tr>
<tr>
<td>Annual</td>
<td>478</td>
<td>751</td>
<td>1228</td>
<td>0.38</td>
<td>0.68</td>
<td>0.13</td>
<td>1.03</td>
<td>0.99</td>
<td>1.62</td>
<td>22</td>
</tr>
</tbody>
</table>
Therefore, by applying the approach described previously, there was obtained an average annual infiltration flow of approximately 480 l/s, corresponding to 40% of the total wastewater flow and approximately, 70% of the strict wastewater flow in the drainage system. In terms of infiltration indicators, there was obtained the values of 1.0 l/(s.km), where, according to the estimations, 4% corresponds to infiltration on manholes, 1.6 m³/(day.cm Φ.km) and 0.3 l/s.ha impermeable area.

The results described above can be compared with reference values, either found in the regulations and in the literature or values obtained in foreign case studies. According to the Portuguese regulation, infiltration flows could be between 0.5 and 4 m³/(dia.cm Φ.km), depending on the age and quality of the constructions of the sewers (Decreto Regulamentar 23/95, 1995). The values showed in Table 1 are within the mentioned range. In Metcalf&Eddy (2003) it is referred reference range values for two infiltration indicators, namely, 0.1-10.0 m³/(day.km.cm Φ) and 0.2-30 m³/(day.ha), which are respected by the values obtained for the respective infiltration indicators. On the other hand, in what concerns the results from the foreign case studies, where the stable isotopes method was applied, those are lower than the results obtained with respect to the Alcântara basin, as expected since their dimension are considerably lower than Alcântara basin (Prigiobbe & Giulianelli, 2010; Rutsch, et al., 2010).

Under the analysis of the results and the approach used itself, it was also made a comparison between them and other methodologies, namely, a frequently used conventional method, the night minimum flow method, and a method proposed by AdP (Portuguese Water Company). If it is applied the night minimum flow method to Figure 5, it can be obtained an approximate value of 1100 l/s, which is considerably higher than the infiltration flow obtained by applying the Stable Isotopes Method (average annual value of 478 l/s). Regarding the AdP methodology, it is based in the following equation, equation 5 (Águas de Lisboa e Vale do Tejo, SA):

\[ V_{dia} = 0.2 \times 0.048 \times K \times [L \times P + N \times A] \]  

(5)

Where:
- \( K \) – factor that depends on the annual season, the age and the position (submersed, influenced, and above) of the sewer in relation to the phreatic water
- \( L \) – sewer length (m)
- \( P \) – wet perimeter (m)
- \( N \) – number of manholes
- \( A \) – manhole’s wet area (m²)

To determine the infiltration flow based on the equation above it was used the same data as in the determination of the infiltration indicators. The factor \( K \) is tabulated, but there was the need to obtain a weighted value in order to consider different sewer positions. In spite of the simplicity of equation 5, it was necessary to make some assumptions, namely, the distance between manholes (40m) in order to estimate the number of them, the % of sewers with each position and the sewers’ depth in relation to the phreatic level, needed to estimate manhole’s wet area. Therefore, an average annual value of 278 l/s was obtained and, for summer and winter, there was obtained values of, approximately, 111 and 444 l/s, respectively, which are considerably different from the results of applying the Stable Isotopes
Method, presented in Table 1. This difference could be explained by the fact that the method requires
great detail of the basin’s characteristics, although in most cases there is little information regarding it,
which results in the need to make some assumptions, increasing the uncertainty of the method.
Moreover, the tabulated values of K could be questioned, mainly the nonzero ones with respect to the
sewer position – above the phreatic level.

By analysing the Stable Isotopes Method, it is recognized that it requires a considerable number of
human and material resources, which may not be available to all utilities in water sector. Hence, it was
resorted to the Stable Isotopes Method to calibrate the daily pattern of wastewater flow, in terms of the
fraction of strict wastewater in relation to the minimum night flow, represented by y. By following this
procedure, it was obtained an average annual value of 0.74, which implies that 74% of the night
minimum flow corresponds to the strict wastewater flow. With this procedure it can be admitted that,
depending on the size of the drainage basin (smaller to larger), y may vary between 0 and 1,
respectively. This procedure is simpler than the Stable Isotope Method (it is just needed the flow data)
and probably more accurate than some conventional ones, like the minimum night flow that, as it was
possible to verify, should not be applied in larger drainage basin, with a water consumption pattern of
24h/day.

Conclusions

Taking into account the results obtained, the average annual infiltration flow measured at CANETAR,
based on the infiltration flows in summer 2013 and winter 2014, corresponds to, approximately, 480 l/s
and to 40% of the total wastewater flow, with a clear seasonal difference between summer and winter.
Considering the infiltration rates, there was obtained a unitary average annual infiltration flows of,
approximately, 1.0 l/(s.km), a specific infiltration rate of 1.6 m³/(day.cm Φ.km) and a infiltration rate per
impermeable drainage area of 22 m³/day.ha. In spite of having some limitations and uncertainties,
when all the conditions are respected, the Stable Isotopes Method is considered to be a reliable
method, since it uses real data flow and an intrinsic and conservative water property (the oxygen
isotopic ratio, δ¹⁸O).

Comparing with other frequently used methodologies, like the night minimum flow method, it is
considered that the Stable Isotope Method has less uncertainty associated and, therefore, more
accurate to apply. However, it is important to have in mind that this method can only be applied if the
water supply source is distinct from the local groundwater. The values obtained are in agreement with
the regulatory requirements, that is, the “Regulatory Decree 23/95” (1995), where it states that, if no
information on infiltration is available, it can be admitted a value between 0.5 and 4.0 m³/(day.cm
Φ.km). As a conclusion of the analysis of the approach followed with other methodologies, it is noted
the importance of field work and recognition to overcome the uncertainties associated to the
assumptions in empiric approaches.

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