Relationships between water leaks and the materials and diameters of distribution pipes in the Prolagos concessionaire in the Lake Region, RJ, Brazil

Relações entre vazamentos de água e os materiais e diâmetros das tubulações de distribuição na concessionária Prolagos na Região dos Lagos, RJ, Brasil

Relaciones entre las fugas de agua y los materiales y diámetros de las tuberías de distribución en la concesionaria Prolagos en la Región de los Lagos, RJ, Brasil

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ABSTRACT
The aim of this study is to explore the correlations between actual water losses and the materials used, as well as the diameters of pipes, in the water distribution systems across five municipalities in the Lake Region of Rio de Janeiro State, Brazil. We analyzed 273 episodes of pipe bursting between June and July 2019, identifying the types of materials and pipe diameters where the leaks occurred and comparing them to the total length of each type of material and diameter. PVC pipes of 50 mm and DeFoFo pipes of 100 mm exhibited the highest percentages of ruptures exceeding anticipated levels (18.94% and
2.68%, respectively). The methodology employed in this study can be applied to analyze other water distribution networks.

**Keywords:** Real Water Loss, Water Distribution Network, Pipeline Breakage, Material and Diameter of Piping, Water Leakage.

**RESUMO**

O objetivo deste estudo é explorar as correlações entre as perdas reais de água e os materiais utilizados, bem como os diâmetros das tubulações, nos sistemas de distribuição de água em cinco municípios da Região dos Lagos do Estado do Rio de Janeiro, Brasil. Analisamos 273 episódios de rompimento de tubulações entre junho e julho de 2019, identificando os tipos de materiais e diâmetros das tubulações onde ocorreram os vazamentos e comparando-os com o comprimento total de cada tipo de material e diâmetro. Os tubos de PVC de 50 mm e os tubos DeFoFo de 100 mm apresentaram os maiores percentuais de rupturas acima dos níveis previstos (18,94% e 2,68%, respectivamente). A metodologia empregada neste estudo pode ser aplicada para analisar outras redes de distribuição de água.

**Palavras-chave:** Perda Real de Água, Rede de Distribuição de Água, Rompimento de Tubulações, Material e Diâmetro de Tubulações, Vazamento de Água.

**RESUMEN**

El objetivo de este estudio es explorar las correlaciones entre las pérdidas reales de agua y los materiales utilizados, así como los diámetros de las tuberías, en los sistemas de distribución de agua en cinco municipios de la Región de los Lagos del Estado de Río de Janeiro, Brasil. Analizamos 273 episodios de roturas de tuberías entre junio y julio de 2019, identificando los tipos de materiales y diámetros de tuberías donde se produjeron las fugas y comparándolos con la longitud total de cada tipo de material y diámetro. Las tuberías de PVC de 50 mm y las tuberías DeFoFo de 100 mm presentaron los mayores porcentajes de roturas superando los niveles previstos (18,94% y 2,68%, respectivamente). La metodología empleada en este estudio se puede aplicar para analizar otras redes de distribución de agua.

**Palabras clave:** Pérdida Real de Agua, Red de Distribución de Agua, Rotura de Tuberías, Material y Diámetro de Tuberías, Fugas de Agua.

**1 INTRODUCTION**

The current global picture of water resources is not very encouraging. In 2018, the World Bank and the United Nations stated that 36% of the global population lived in areas with water scarcity; in addition, the 2030 Water Resources Group projects a 40% water
deficit in the world scenario for 2030 (Biswas & Tortajada, 2019). This will be caused by accelerated population growth coupled with the maintenance of current consumption patterns and the lack of adequate water resources management.

The high level of water losses in distribution networks is one of the biggest challenges faced by sanitation companies around the world (Aschilean & Giurca, 2018). The main factor related to losses in water distribution systems are the leaks in the pipes (Fontana & Morais, 2016). In Brazil, 5146 municipalities guaranteed water supply to 173.2 million inhabitants in 2018, corresponding to 16 billion m³ of water volume. It should be noted, however, that the actual loss of this resource in the water distribution systems was approximately 38.5% (BRASIL, 2019). Tabesh et al. (2018) state that investigating the causes of leaks in water distribution networks is critical to reducing the problem. The authors raise flaws in the collection and analysis of rupture events and cite that the main causes of leaks are due to poor qualification of water distribution companies' employees and inadequate selection of pipes that make up the distribution network.

Within this scenario, the present work aims to analyse the occurrences of real water losses in the distribution network operated by Prolagos Sanitation Concessionaire. The main objective is to identify relationships between leaks and the materials and diameters of the pipes in the network. Prolagos company serves five municipalities in the Lakes Region, Rio de Janeiro State. This is a tourist region that demands a seasonal service, mainly from December to March, when the population increases five times more in relation to the local population, estimated at around 422 thousand inhabitants (IBGE, 2017). During the high season, which includes school holidays, festive dates, and long holidays, the mentioned municipalities have water supply problems.

### 2 MATERIALS AND METHODS

The study area corresponded to five municipalities (Armação dos Búzios, Arraial do Cabo, Cabo Frio, Iguaba Grande and São Pedro da Aldeia) located in the region of coastal lows, microrregion of Lakes, in the State of Rio de Janeiro. The basic sanitation concessionaire Prolagos has been supplying these municipalities with water and sewage
collection and treatment since 1998, with concession term extended until 2041. Its water supply network is 2,719.75 kilometers long (Prolagos, 2020).

To acquire the data regarding the distribution network and actual water losses, technical visits were made to the Operational Control Center of the Basic Sanitation Concessionaire Prolagos, with the monitoring of the sector coordinator. Three visits were made during the months of July and August 2019, during which data related to the distribution network and rupture events were requested.

Regarding the concessionaire's distribution network, Prolagos provided information on the type of material and the diameter of the pipes. This information, along with network location was made available in digital format in a vector file type KMZ which provided a spatial visualization of the networks and its features in Google Earth (Gorelick et al., 2017). The concessionaire also provided the coordinate records of leak positions in the network for June–July 2019 as a .xls digital spreadsheet.

2.1 DATA PROCESSING

First, we identified pipe material and diameter for each leakage event by importing both the information from the networks and the leakage events into the Geographic Information System QGIS 3.8.8 (QGIS Development Team, 2019). Then, we converted the KMZ file into a shapefile (.shp) vector file of the type rows, and the information of the networks became available in the attributes table of the file. The coordinates of the leak occurrences were also converted to a shapefile format file of the type points. In addition to this information, the " .shp" files referring to the limit of each municipality were inserted in the Geographic Information System (GIS). These data were obtained from the geographic database of the Brazilian Institute of Geography and Statistics (IBGE), year 2015 (IBGE, 2019).

In GIS environment, two tasks were performed: 1- the calculation of the total length of each type of material and pipe diameter of the network; 2- the identification of the types and diameters of the pipes where the leaks occurred. From these data, it was
possible to identify rupture tendencies in pipe material or diameter in relation to the total availability on these pipe features in the network.

The "Geometry" tool was used to calculate the total length of each type of material and pipe diameter of the net. The cartographic projection used to calculate the length of the nets was the Universal Transverse of Mercator Zone 32S, which has the meter as unit of measurement (QGIS Development Team, 2019). In the sequence, the total extension values were identified according to the type of net (material + pipe diameter) from the "Intersect" tool and converted to a Microsoft Excel table, containing columns identifying the materials, diameters and their lengths.

To relate the type of material and pipe diameter to each leakage event, it would only be necessary to intersect the location of the leakage events with the lines for each network. However, the geographical location of some of the leak sites and the networks did not match because the sites were not located exactly on top of the lines representing the networks. This pattern, identified in the majority of the points, made it impossible to use simple tools such as the intersection between lines and points in the GIS. From this type of tool it would be possible, for example, to quickly characterize in which type of material and diameter the leaks occurred. In an attempt to overcome this problem and to relate the characteristics of the network to the occurrences of leakage as well as to minimize the faults concerning the geographical location of the points and lines, a matrix of distance between this data set was calculated. The distance matrix was automatically calculated in the QGIS 3.8 software from the "Distance Matrix" tool (QGIS Development Team, 2019). In this step, the data set referring to the lines and the data set referring to the points had a unique identification. For each point, all possible distances between the lines were calculated, so if a point was located between two or more lines, all distances would be calculated.

When a line and a point intersected, the calculated distance consisted of the value zero. However, when the point did not intersect with any line, the value of the shortest distance between the point and all nearby lines was identified. Thus, it was assumed that the occurrence of leakage in relation to the type and diameter of the network corresponded
to the nearest network. This procedure had to be performed for 84 percent of the data points.

2.2 DATA ANALYSIS

The analysis of the rupture patterns was produced from the elaboration of quantitative charts, based on the information described in the previous section. The analyses considered the lengths of each type of pipe in the distribution network, since the predominant materials tend, by simple probability, to present a higher incidence of ruptures than little used materials. The percentage of breaks above or below the expected was calculated - Eq. (1).

\[ PB = \frac{MB}{TB} - \frac{ML}{TL} \times 100 \]  

(1)

Where:

- \( PB \) is the percentage of breaks above (if positive) or below (if negative) the expected;
- \( MB \) is the amount of breaks in a given material;
- \( TB \) is the total amount of breaks;
- \( ML \) is the total length of the material in the distribution network; and
- \( TL \) is the total length of the distribution network.

We also tested/considered the effect of pipeline extension on the number of breakages by applying Spearman Rank Correlation analyses, nonparametric partial correlations, and Chi-square tests. The Spearman Rank Correlation is a nonparametric statistical analysis to investigate the strength (0 to 1, or 100%) and direction (negative or positive) of an association between two variables measured on at least an ordinal scale. The partial nonparametric correlation is an extension of a simple correlation in which we perform a correlation between two variables while controlling for a third one (in this case, pipe extension) that might interfere with the analysis simply by being correlated itself with both other variables. The Chi-square test, in turn, allows us to test for deviations of observed frequencies from expected frequencies. For all analyses, we used \( \alpha \)
(“significance level”) = 0.05 (that is, 5%) as the probability of rejecting the null hypothesis when the null hypothesis is true. For (partial) correlations, the null hypothesis is that there is not a relationship between the (main) variables analysed. The null hypothesis for the Chi-square test is that the observed number frequency of pipe ruptures does not differ from the expected frequency of ruptures, herein assumed to be a consequence of pipe extension. In this case, the expected number of breakages was estimated by multiplying the total number of pipe breakages by the percentage of each pipeline type (material)/diameter in the network. For Chi-square tests, we clumped data into categories to have expected values greater than 5, which is an assumption of this statistic test. Therefore, for pipeline diameter, we clumped data into 6 diameter categories (up to 50 mm; 60−100mm; 110−150mm; 160−200mm; 225−250 and ≥300 mm), trying to keep equal intervals of 50mm diameter between pipeline classes. For pipe type, we considered only those that had expected number of breakages higher or equal than 5 (that is, DeFoFo, cast iron, HDPE, and PVC). For additional information on basic statistics, see Zar (2010). We used SPSS 21 Program (IBM CORP, 2012) for correlation and partial correlation analyses and Graph Pad (https://www.graphpad.com/quickcalcs/chisquared1/) for Chi-square tests.

Graphs were generated containing comparative information grouped by different parameters, considering the percentage of ruptures per material/diameter of the pipes and their respective lengths in relation to the total length of the network and in relation to the network of the respective pipe material. The graph generation was produced through the dynamic graph generation resource available in Microsoft Excel.

3 RESULTS AND DISCUSSION

In June, 134 pipeline ruptures were reported while in July there were 139 ruptures. Of the 273 rupture episodes, 15 had no record of pipeline material because there was no information of the pipeline in the network record provided by the concessionaire. These 15 records were disregarded, leaving a total of 258 records for analysis.
The types of piping materials in the analysed water supply network were: PVC, HDPE, FRP, DeFoFo, asbestos, cast iron, forged steel, and smaller diameter hook. Details about the characteristics of these materials are discussed by Gama et al. (2019). There was no break in the FRP and forged steel materials in this period.

3.1 TYPES OF PIPES AND RUPTURE PATTERNS

PVC and HDPE showed the highest number of ruptures; breakage of PVC 50mm and HDPE 63mm were particularly high, but were also the two most common types/diameters of pipes composing the network. Indeed, the number of ruptures in each pipe type correlated with its total availability in the network (rs = 0.82; n = 7; p = 0.023), with PVC and HDPE materials comprising more than 70% of the total extension (Fig. 1) and also the highest number of ruptures.

![Figure 1 - Prolagos piping amounts (%).](image)

Despite the fact that the PVC and HDPE pipes stand out in number of breaks but also in total extension, when making the comparison with the total extent of each material
in the network, we found a significant deviation from expected frequencies of ruptures ($\chi^2 = 66.38; \text{d.f.} = 3; p < 0.0001$); the materials that stood out the most in occurrences of breaks were PVC and DeFoFo. The percentage of PVC pipe breaks over the total breaks was 21.19\% higher than the percentage of its length in relation to the total length of the distribution network. In the case of DeFoFo material, the percentage of breaks over the total presented a value 4.70\% higher (Fig. 2 and 3). In turn, HDPE – particularly 63mm – and forged steel had fewer breakages than expected by chance, considering their total extension. It is important to emphasize that the concessionaire did not provide data on the time of installation of the materials, which may imply in a higher number of ruptures, when their useful life is exceeded due to loss of resistance of the material.

Figure 2 - Comparison between the percentage of breaks in relation to the predominance of each type of pipe in the distribution network.

Source: The Authors.
The number of ruptures in each pipe diameter was also proportional to their respective availability in the network ($r_s = 0.69; n = 53; p < 0.0001$), but the comparison between observed and expected leakages in distinct pipe diameters was significant ($\chi^2 = 44.07; d.f = 5; p < 0.0001$), showing that there were significant deviations on the number of ruptures expected by chance. Indeed, the partial correlation between pipe diameter and number of breaks showed a significant negative relationship ($r = -0.423; d.f = 50; p = 0.002$), meaning that pipeline with lower diameters showed higher number of breakages, after controlling for their availability in the total network. These results confirm the research carried out by Adedeji et al. (2017) that smaller diameter tubes are more susceptible to the risk of rupture as the service pressure increases.

By analysing the pipe breaks and examining both their diameters and the type of material, 12 different types of pipes showed number of leakages above expected. Equation (1) was also used to verify this trend, considering the types of materials and their different diameters for each algebraic term. Important prominence is given to PVC pipes 50 mm and DeFoFo 100 mm with this latter one showing a tendency to break more than 7 times lower when compared to the former (Fig. 4). Moreover, the tendency of
rupture of DeFoFo 100 mm is greater than the sum of all the tendencies of other DeFoFo diameters (Fig. 4).

Figure 4 - Pipes that present above expected ruptures.

Focusing only on nets of a specific material, such as PVC and DeFoFo, which had a greater tendency to break, it is important to consider which diameters had more breakages than others. In the case of the PVC-type piping network, this deserves due attention because the quantity of breaks is expressive for its extension (Fig. 2 and 3). Within PVC, there is a marginally significant difference between pipes with 50, 75 and 100 mm ($\chi^2 = 4.667$; d.f.=2; $p < 0.097$; diameter categories with expected ruptures equal or greater than 5), showing a tendency of more ruptures in 50mm pipes and relatively less on 75mm pipes (Fig. 5 and 6). It is important to notice that considering the total extension of the network, indeed PVC 50mm pipes showed a discrepant number of ruptures above expected (Fig. 4). Moreover, it should be noted that the PVC pipes with diameters 32 mm, 85 mm, 150 mm and 400 mm did not present ruptures and that for the PVC data only, there was no significant relationship between diameter and number of breakages after controlling for extension (partial correlation $r = -0.57$; d.f. = 6; $p = 0.451$).
For the pipe network of DeFoFo material, there was a negative correlation between pipe diameter and number of ruptures (partial correlation $r = -0.96$; $d.f = 3$; $p = 0.009$). The large difference related to the diameter of 100 mm, the smallest of all, contributes to this negative correlation (Fig. 7 and 8).
Analysis of the characteristics of the different pipe materials can help to identify possible causes of rupture as well as to define the most suitable material options for replacement. Considering that the PVC pipes in Prolagos distribution network are PVC-O type and that DeFoFo and PVC-O present more breaks, we can observe some weaknesses in both, such as risk of displacement, average water tightness, and greater...
ground movement, floor decomposition, and loss of material (for more details see ABPE (2017) and Lemos (2020)). An important factor that interferes in the resistance of materials are the pressure oscillations associated with demand variations, which confers reduced resistance limit for PVC and DeFoFo (Almeida et al., 2011). These two characteristics are widely observed in the Lake Region, which has fluctuating demand on weekends, holidays, and school holidays.

4 CONCLUSIONS

Losses in water supply systems are a problem to be faced by sanitation utilities to ensure sustainability for the population and the environment. Within this perspective, the contribution of the work was made by the analysis of the events of ruptures in the distribution network, focusing on the relationships with the materials and diameters of the pipes.

Considering the amount of ruptures according to the types of pipes and their respective extensions in relation to the total length of the network, only PVC and DeFoFo materials presented rupture trends above the expected. By including the analysis of the diameters, along with the different pipe materials, 12 different types of pipes showed higher than expected leakage trends. The largest number of ruptures above the expected by chance were on PVC 50 mm, with rupture percentages of 18.94% above expected. Focusing on the PVC type piping network, the diameter 50 mm presented a difference of 3.47%. For the DeFoFo pipe network, the highlights of breaks were in diameters 100 mm, with differences of 23.51%. We believe that these information can help the company to make decisions and to prioritize actions to replace pipes in the network in order to avoid future disruptions.

This survey was limited to data provided by the concessionaire Prolagos, corresponding to only two months of operation. Access to a broader set of data would enable a more meaningful analysis. The methodology proposed and used, another contribution of this work, could be replicated for any volume of data. In addition, other variables should be evaluated in future works, such as the operating pressure at the
moment before the rupture, the piping quota, the installation time of each material, the
type of paving and the types of vehicles and traffic intensity at the rupture site. Therefore,
it is suggested to the concessionaire to collect these data in the future, which may
comprise more in-depth studies of the causes of water losses and, consequently, improve
the performance in combating and controlling these losses.

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