Multivariate analysis of the pressure variation in intermittent water supply systems and the impact on demand satisfaction

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ABSTRACT

In intermittent drinking water distribution systems, large volumes of the water are wasted due to leaks in the distribution networks. Similarly, user service is not always satisfied in the time required to fill the storage, nor with sufficient pressure. Hence the importance of this study. Measuring the variability of pressure in the distribution network and determining the factors that influence the definition of a sufficient minimum hours of service, is a first step to change to a continuous service 24/7, in order to minimize the volumes of lost water and meet demand. In total, 347 pressure sensors were placed in a network to detect changes in pressure and obtain data for 3 years. This study presents a new approach to determine the operating policy of the operating agency that provides the service intermittently. Two objectives are pursued: pressure variability – to minimize leaks – and define the minimum hours of service. The analysis was performed using multivariate statistical techniques, including principal component analysis, correlation matrix and ANOVAs, to explore the association between objectives. The results obtained show that the pressure distribution has a Gaussian behavior and that the hours of service have a Poisson distribution.

Key words | duty cycle, intermittent water supply, multivariate statistical techniques, pressure sensors

HIGHLIGHTS

- A pressure range between 7 and 30 mwc is essential for user satisfaction.
- A minimum of 6 hours of service is recommended in IWS systems.
- The behavior of service hours is not linear but exponential in its effect on the satisfaction of demand.
- Multivariate analysis is an adequate technique to facilitate the decision making in a water supply system.
- Pressure variation has normal behavior regardless of the number of hours supplied.
INTRODUCTION

In reality, there are large gaps in the ‘conception’ of an efficient drinking water distribution service. The components and type of installation that make up the distribution system are described as: extractions through wells that use pumps, storage or regulation tanks, pipes, primary and secondary pipe network (CONAGUA 2015) and evaluation of the hydraulic performance of a pipe network.

The analysis of the design and operation of the network is based on the pressure and flow rate circulating in its pipes; it depends on their behavior over time. If there is no change, it is defined as permanent flow and if there is, it is known as variable, non-permanent or dynamic flow rate (Arias & Zabala 2013; Anmatecnologia 2018).

However, the premise is given that water distribution networks are designed and operated to continuously supply water to meet demands while maintaining adequate pressure throughout the network. Therefore, from its incorporation into the system, it was not contemplated that the section of network or pipeline could be emptied. Rather, it would maintain the loading conditions defined in its design.

One of the Sustainable Development Goals requires universal and equitable access to safe drinking water at an affordable price. This objective is regulated by the indicator of ‘drinking water supply services, managed in a safe and sustainable way’ (WHO 2019).

However, in many countries pipelines do not always meet projected planning and operating standards. That is, maintaining the water load 24 hours a day, which is known as continuous supply (24/7). Failure to comply with the standard requires additional recharges that could affect the quality of the water, spoiling its potability (Christodoulou & Agathokleous 2012).

In continuous supply systems, water is provided 24 hours a day and the needs of the user are met in a timely manner, at the appropriate speed and pressure, in accordance with the demand scheme, allowing the system to operate under pressure and supply in peaks of demand per hour and per day.

When a system does not deliver water 24 hours a day to the end user, it is defined as an intermittent water supply (IWS) system, known in Mexico as ‘tandeo’ (Figure 1).

In an intermittent system, the service is provided by cycles (duty cycle), (Taylor et al. 2019), which vary in areas and schedules, so the user must store water in tanks and cisterns (Cabrera-Béjar & Tzatchkov 2012), to cover their needs during water shortages (Totsuka et al. 2004; Milanés 2011).

The World Bank’s Benchmarking International report on water and sanitation networks shows that only 16% of drinking water operating agencies in developing countries comply with a continuous 24-hour supply. The average supply estimate in these countries is only 16 hours a day (Van den Berg & Danilenko 2011).

The most frequent increase in physical water scarcity may be due to the following factors: climate change, increased demand, population growth and lack of investment in hydraulic infrastructure (maintenance and new works).

These factors cause the frequent appearance of intermittent supply systems (Tsegaye & Eckart 2011). The financial resources of the operating agencies are limited because the funds are often used in new infrastructure and not to modernize the existing one.

So, it is necessary to improve drinking water systems to make them profitable and sustainable (Piratla & Goverdhanam 2015).

During filling and emptying processes, depression or overpressure occur in the network, causing recurrent...
failures and leaks in the system, due to air pockets inside the pipes (PIGOO 2018).

The annual study of Mexico 2018 indicators shows that 22% of users of drinking water service systems have an intermittent supply, on average 13 hours per round. Therefore, IWS agencies present seven times more leaks in household intakes than those with a 24/7 service (PIGOO 2018).

Leaks damage the infrastructure and cause economic losses, excessive energy consumption and costs that are transferred to the end users (Casillas 2013). In addition, they do not meet end user demand (Taylor et al. 2019).

Although the immediate effect of a new leak or vacuum in the network causes the propagation of a transient wave in the pipe network, the effect disappears during the ‘hours of vacuum.’ When the assigned supply process begins, the wasted volume is considerable and requires a greater load for the fluid to displace the air contained in the network (Taylor et al. 2018).

Strategies are currently being applied in public services to control pressures in affected areas, including managing pressure through tight control over isolated sub-sectors or district measured areas (DMA) (Navarro & Yamanaka 2010; Perelman et al. 2015; Samir et al. 2017). The pressure sensor is the most effective device to measure the water pressure in a pipe network (Martínez-Solano et al. 2019).

The research carried out develops a framework to identify the duration of the supply required in the sector, with the following objectives: a minimum pressure between 7 meters of water column (mwc) and 30 mwc, enough load to supply a two-storey house with storage on top; and avoid pressures less than 7 mwc, which generate vacuum or suction or greater than 30 mwc to reduce failures and losses of water volumes through leaks.

The definition of applicability of the technique of multivariate analysis (MA), is essentially the approach and study of variables in simultaneous resolution.

For example, we take a variable (pressure or leakage) and not only measure one aspect (quantitative or time span), but we consider several aspects and try to determine the relationship between the other variables in the statistical model.

Before defining the multivariate statistical techniques, the applicability of the techniques was first checked by analyzing the statistical power (Devore 2008).

The MA technique was chosen based on two possible criteria: the first one is known as independent methods, which are applied when it is of interest to investigate the associations between variables that are difficult to distinguish and the second one is identified as dependent methods which are used when the association between variables with component similarity is appreciated and they depend or are measured depending on the others.

To measure the association of variables and determine which factor has the greatest weight and make a ‘quantitative’ proposal to improve drinking water service in the city, the following should be considered: sufficient pressure variation in the service program to allow response to the user demand, as well as minimizing leaks to avoid losses in water volume (Fienberg 2007). Tools used: EXCEL, ORIGIN, MINITAB and SPSS.

The main analysis variable was found in the pressure variation in different sections of the network, whose distribution is influenced by two factors, mainly time and space.

Problem statement

This methodology was applied in the city of Chihuahua, with a population of approximately one million inhabitants. Due to the growth of the urban area in the 1970s and 1990s, the intermittent supply operation policy was chosen.

There are large areas of influence or distribution of supply, identified by source and hours of service. These are classified according to the size, topographic characteristics and socioeconomic level of these areas.

Consistent with the characteristics of the zones, the number of points for the placement of pressure recording sensors was weighted and determined.

Pressure recording, control and measurement systems were installed at the entrance of each sector or zone (Figure 2).

The system is described as follows:

1. Isolation valve
2. Pressure regulating valve
3. Battery pack
4. Data logger
5. Pressure controller and antenna.
Additionally, pressure measurement equipment was installed within the sector. The equipment was configured for the measurement and data storage every 15 minutes, in order to monitor the ‘normal’ daily behavior of the pressure variation according to its assigned service schedule (Figure 3).

The MA exposes the different factors that are associated or affect the response variable (Pressure). In addition, it determines the variables that most influence the behavior of pressure, these factors are important to each polygon or sector defined by the hours of service and its source of supply and thus determine the quality of the service. The results of the MA are expressed in equation or vector representation and are used in research (Johnson & Wichern 2007).

The following factors were considered: ‘number of hours scheduled for water supply’; topographic features such as ‘terrain elevation’; ‘diameter of pipes’ (classified in secondary network of 3’ or less and primary network with diameters greater than 4’) and area or ‘surface’ in which they distribute according to the type of source that feeds them (wells, tanks and pumping).

The operating policy has not had a significant variation in the last 5 years (no change in the physical delimitation of sectors). Therefore, it is considered that, in addition to measuring the association and determining the influence between the variables previously determined, it was relevant to see the effect of leaks in the system. For this reason, the leaks of the last 5 years were registered in the database of the Information and Service Center (ISC), classified as ‘network leaks’ and ‘meter leaks’.

**METHODS**

Due to the permanence of the policy of operation and review of the daily behavior of the pressure in the 347

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**Figure 2** | Pressure recording control and measurement system at the entrance to the sector.

**Figure 3** | Pressure recorders (data loggers multilog) used in the sector.
points distributed in the city that did not present significant variation, it was decided to represent the measures of the 3 years on a typical day of behavior. o pressure profile of each of the 347 points and facilitate the management of data matrices.

Pressure was considered as a dependent variable to classify or group, as follows:

- P_{MIN}, minimum pressure recorded at each of the observation points
- P_{MAX}, maximum pressure recorded at each of the observation points
- P_{PROM}, mean pressure recorded at each of the observation points
- P_0, range of recorded pressures, from negative to 0 meters of water column, in each of the observation points.
- P_7, range of recorded pressures, from 0.1 to 7 meters of water column, in each of the observation points.
- P_{15}, range of registered pressures, from 7.1 to 15 meters of water column, in each of the observation points.
- P_{30}, range of registered pressures, from 15.1 to 30 meters of water column, in each of the observation points.
- P_{m30}, registered pressure range, greater than 30.1 meters of water column, in each of the observation points.

The independent variables were classified between those that are constant and those that are variable, in the 3-year period.

1. Those that remain unchanged over time are:

   - Hours of service (HS), Supply hours in ranges, to observe the effect on spatial distribution and pressure magnitude.

   As for the flow rates, the HS were classified according to the openings of the supply source for the analyzed sector. The agency considers as its most common operating policy to assign the following supply schedules (Duty cycle):

   - 4H, up to 4 hours (generally in a single block)
   - 8H, up to 8 hours (divided into two blocks, morning and evening)
   - 12H, up to 12 hours (divided into two blocks, morning and evening)
   - 16H, up to 16 hours (divided into two blocks, morning and evening)
   - 24H, continuous service 24 hours.

2. The variables or factors that vary over time are:

   - Meter leaks (ML), leaks in the user meter, identified every year, ML_{15}, ML_{16} and ML_{17}
   - Network leaks (NL), leaks in the pipe network, identified each year, NL_{15}, NL_{16} and NL_{17}

   It is assumed that these have an effect on the operation that remains the same plus physical deterioration, among other causes.

   The statistical process determines the variables or factors that have association, relationship or impact on the expected response or ‘pressure considered sufficient for the service (from 7 to 30 mwc)’.

   The statistical methods used: correlation matrix (CM), principal component analysis (PCA) and factor analysis (FA) with factor rotation and analysis of variance (ANOVA).

   FA is a data dimensionality reduction technique whose purpose is to find the minimum of factors or variables that explain the information contained in the sampled data. In the FA all the variables have the same role, since they are independent and, a priori, there is no conceptual dependence between them.

   The grouping or classification of pressure was made based on the research of previous studies (Al-Ghamdi 2011), where the physical relationship between the leak rate and pressure was determined. This relationship can be expressed in general form of the equation:

   \[ Q = aP^n \]  \hspace{1cm} (1)

   where Q is the leakage rate (litres/second), and P is the pressure (bar). The coefficient ‘a’ and exponent ‘n’ are constants determined from the field investigations.

   Figure 4 illustrates the representative daily pressure behavior in the supply distribution area or sector called IZALCO in which eight sensors or measurement points were installed; two in the pressure regulating valve, upstream and downstream (identified with vrp p-c

D_3 length of pipes with diameters up to 3 inches
D_4 length of pipes with diameters greater than 4 inches
The pressure responses were associated with the independent variables according to the following:

\[ \text{Matrix} = NxV \]  

(2)

where \( N \) = number of samples (347 observations) and \( V \) = variables (PMIN, PMAX, P0, P7, P15, P30, Pm30, HS, ML, NL, D3 and D4).

The CM between the variables was calculated to quantify the Pearson correlation coefficients of all possible pairs. The criterion was to consider a strong correlation for values greater than 0.5 and the probability of dispersion between 0 and 0.05 (Jolliffe 1986).

PCA is a linear transformation that chooses a new coordinate system for the original data set, in which the largest variance of the set is captured on the first axis (called the first principal component); the second largest variance is the second axis. Therefore, it can be interpreted in a vector way, where each principal component has a magnitude and direction of the coefficients of the original variables. The higher the absolute value of the coefficient, the more important the corresponding variable will be in the calculation of the component.

The matrix of components reports the relationship between the variables, grouping them and reducing the amount of original data.

The ANOVA technique is one of the most widely used methods for analyzing data from experimental designs. It is used when looking to contrast more than two means of the sampled groups (Pressure results groups against Hours of Service groups) (Table 1).

First, the table that would form the Factor Response (Pressure) and Hours of Service (Treatment) model was constructed. The responses were the replies or observations by pressure ranges at the different HS, considering as the treatments defined by the established service hours and the rows show areas or sectors that have that service hours (4 for each service hours defined as replicas).

Columns represent pressure (response) ranges. The values in the table represent the percentages of the pressure ranges in the measurement districts (rows) (Table 2).

![Distribution of pressures in the Izalco sector](image)

**Figure 4** | Example of distribution of pressure in DMA.

**Table 1** | Summary for the implementation of the ANOVAs

| Factor or variable | Levels | Values |
|--------------------|--------|--------|
| Pressure           | 5      | P0, P7, P15, P30, Pm30 |
| Hours of Service   | 5      | 4H, 8H, 12H, 16H, 24H |
ANOVA between groups is performed, called one-way ANOVA, considering pressures and independent flow rates/hours of service.

RESULTS AND DISCUSSION

As the behavior of the demand for drinking water service by the user is documented, the supply has a pattern of a Gaussian curve, daily and hourly; its pattern depends on the time, regardless of the location characteristics of the user. For this reason, the maximum hourly and daily demand curves in the 24/7 service are considered to define the operation of the drinking water distribution systems to the communities.

To determine the validity of the statistical analysis, in the intermittent supply that followed the Gaussian behavior, a normality tests were first performed by observations, (measurements at each of the 347 points) the results of this analysis indicated that only 10 sampling points reveal a behavior pattern that deviates from the ‘normal’ line during hours of service of less than 4 hours, and whose supply sources are Tanks B and Cerro Grande, as shown in the following figure. These 10 points show a lognormal or poissonic model (Figure 5).

For each group of data or observations of the variables described, it is corroborated that they comply with the assumptions of the classical statistical tests (normality, homogeneity, independence).

However, more than 80% meet the test of normality in observations, so the tests were carried out by factors or variables, since it is considered to have sufficient statistical capacity to do so.

A Pareto table was constructed on the standardized effects of the variables in order to determine the magnitude and importance of each one of them in the pressure, hours of service and diameter of the pipe and that cause leaks in the network, in the meters and user dissatisfaction.

The terms or variables are graphed in the decreasing order of their absolute values. The reference line in the graph indicates which variables are significant. (the method of Lenth-1993)

By default, a significance level $\alpha$ of 0.05 is used to draw the reference line (Figure 6).

In these results, the effects for six terms are statistically significant ($\alpha = 0.05$). The significant effects are: hours of service (HS), minimum pressure ($P_{MIN}$), 3' pipe diameter

\begin{table}[h]
\centering
\begin{tabular}{|l|ccccc|}
\hline
Flow rate (supply hours) & P0 & P7 & P15 & P30 & Pm30 \\
\hline
4H & 0.26 & 26.59 & 22.03 & 27.84 & 19.48 \\
& 0.69 & 33.96 & 14.58 & 20.00 & 28.33 \\
& 3.13 & 39.03 & 16.67 & 22.22 & 1.39 \\
& 4.11 & 39.06 & 28.13 & 9.64 & 0.00 \\
\hline
8H & 2.08 & 4.86 & 61.80 & 31.25 & 0.00 \\
& 1.36 & 21.68 & 13.98 & 35.90 & 27.08 \\
& 1.16 & 39.35 & 15.97 & 25.31 & 18.21 \\
& 1.06 & 30.90 & 28.47 & 39.24 & 1.39 \\
\hline
12H & 4.34 & 23.96 & 12.97 & 48.44 & 10.58 \\
& 0.00 & 20.83 & 35.07 & 39.93 & 4.17 \\
& 3.33 & 41.46 & 33.75 & 15.85 & 5.63 \\
& 16.93 & 31.77 & 8.85 & 24.48 & 17.97 \\
\hline
16H & 0.00 & 3.13 & 13.80 & 63.54 & 19.53 \\
& 0.50 & 3.00 & 14.00 & 63.00 & 19.00 \\
& 1.00 & 2.80 & 13.50 & 64.00 & 20.00 \\
& 1.20 & 3.50 & 13.20 & 63.20 & 19.50 \\
\hline
24H & 1.39 & 16.74 & 17.27 & 42.22 & 22.38 \\
& 1.40 & 16.00 & 17.50 & 43.00 & 23.00 \\
& 1.50 & 17.10 & 17.30 & 41.20 & 22.00 \\
& 1.30 & 16.80 & 17.80 & 42.00 & 22.50 \\
\hline
\end{tabular}
\caption{Presence percentage of the pressure range at the DMA}
\end{table}

Figure 5 | Examples of normality test by observations that do not meet.
(D₃), meter leaks (ML), network leaks (NL) and maximum pressure (P_MAX). The effects of 4’ pipe diameter (D₄) and average pressure (P_PROM) are not statistically significant.

The greatest effect is the time or hours of service provided to the network. In other words, for services that satisfy demand, it depends on the frequency or the duration of the supply cycle.

In the following concentrated table of the CM, the elements marked with light gray are those that have a strong relationship or association between the variables, determined by the Pearson correlation coefficient, with magnitudes greater than 0.5 and a p-value less than 0.05. The ones highlighted in dark gray blue are not important in the analysis since their close association with themselves is ‘logical’ (Table 3).

Through this analysis, it is corroborated that the number of hours supplied is the most important variable or factor to maintain the pressures that arise in the assumption of ‘pressure considered sufficient for the service (from 7 to 30 mwc)’.

Minimum pressures and pressures up to 30 mwc are also important, although to a lesser extent and in the opposite direction. Associations related to network and meter leaks are presented in the 3 years. This is basically due to the association with the 3’ diameter pipes. There is only a strong relationship in 4’ diameter pipes with the presence of NLs.

As we can see, in PCA, that the factors are grouped into three sets: The NL-ML-D₃-D₄ grouping stands out, where the most important vector is the NL and the highest correlation with D₃; with less influence D₄ in ML.

The group of pressures P15-P30-Pm30-PMAX is inverse to the group P0-P7-PMIN, noting that the vectors P15, P7 and P30 have an angle almost similar to the HS, which has a strong and similar relationship with all the clusters.

The numerical equations of the two main components are as follows:

\[
P C_1 = 0.437HS + 0.383D_4 + 0.417D_3 + 0.472P_{\text{MAX}} + 0.038P_{\text{MIN}} - 0.038P_0 - 0.351P_{15} + 0.265P_7 + 0.171P_{30} + 0.210P_{m30}
\]

\[
P C_2 = -0.358HS + 0.301D_4 + 0.262D_3 + 0.153P_{\text{MAX}} - 0.453P_{\text{MIN}} + 0.186P_0 - 0.112P_{15} - 0.479P_7 - 0.452P_{30} + 0.037
\]

The first main component has variance (eigenvalue) of 8.26 and explains 51.7% of the total variance.

The second main component has a variance of 2.60 and explains 16.3% of the variability of the data.
|     | HS   | D3    | D4    | PMAX  | PMIN  | P0    | P7    | P15   | P30   | Pm30  | NL15  | ML15  | NL16  | ML16  | NL17  | ML17  |
|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| HS  | 0.195| 0.739 | 0.561 | 0.129 | 0.121 | 0.007 | -0.754| 0.624 | 0.671 | 0.010 | 0.084 | 0.038 | 0.032 | 0.082 | 0.051 | 0.842 |
| D3  | 0.439| 0.982 | 0.995 | 0.591 | 0.352 | 0.152 | 0.081 | -0.224| 0.131 | 0.171 | 0.979 | 0.943 | 0.951 | 0.977 | 0.962 | 0.842 |
| D4  | 0.001| 0.001 | 0.001 | 0.341 | 0.431 | 0.001 | 0.018 | 0.018 | 0.018 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| PMAX| 0.001| 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| PMIN| 0.001| 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| P0  | 0.007| 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 |
| P7  | 0.978| 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 | 0.978 |
| P15 | 0.046| 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 | 0.046 |
| P30 | 0.001| 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Pm30| 0.010| 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| NL15| 0.968| 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 | 0.968 |
| ML15| 0.741| 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 | 0.741 |
| NL16| 0.038| 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 |
| ML16| 0.881| 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 | 0.881 |
| NL17| 0.039| 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 |
| ML17| 0.878| 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 | 0.878 |

Table 3 | Concentrated correlation matrix
Between the two components the variability variance in more than 68% is explained. In this way, most of the data structure can be captured in two underlying dimensions (Figure 7).

One-way ANOVA, this procedure is done by analysis by Factor (Pressure) and by Treatment (Hours of Service/Duty Cycle) (Table 4).

Considering the pressures as an answer (Figure 8) the behavior of the pressures is completely Gaussian; only a few points move away from the Gaussian line.

There are also significant differences between the pressures worked by Tukey and Fisher (Figure 9) that is to say, it is concluded that the groups associated by pressure, if they present a significant difference that is influenced by hours of service.

It is clear that the main and the most influential factor is the pressure of 30 mwc and the one with the least influence is the pressure equal to and less than 0.

The significant differences between the group means were obtained with a 95% reliability.

This exercise confirms that the importance of the hours of service (treatment) is still significant and that the main effects are due to the factor (Figure 10).

The summary of the results in this exercise shows that the behavior of the hours of service are not Gaussian, rather a Poisson distribution. They move away from the Gaussian line (semilog) by a large number of points to the ends.

Adjustment of the exponential treatment equation (hours of service):

$$y = y_0 + A_1 e^{-(x-x_0)/t_1}$$

(5)

where:

| Adjustment | Residue |
|------------|---------|
| $Y_0 = 0$  | $Y_1 = 0$  |
| $X_0 = -20$ | $X_i = \infty$ | $A_1 (Y_0) = 16.23328$ | $A_1 (Y_i) = 2.98119$ |
| $t_1 (Y_0) = 32.90057$ | $t_1 (y_i) = 10.36542$ |

The results of the exercise produced by MINITAB are as follows: ANOVA considering both factors: (Pressure) and...
Treatment (Hours of Service) as well as the interaction between them (Table 5):

\[ S = 8.91368, \quad R-Sq = 78.56\%, \quad R-Sq (adj) = 71.70\% \]

where:

- \( S \) = Standard error of the regression;
- \( R-Sq \) = R-Squared or Coefficient of Determination; and
- \( R-Sq (adj) \) = Adjusted R-Squared.

In the results of the variance analysis model it can be seen that there is an acceptable adjustment of 71.7\% and that the dispersion of the values is very low, \( S = 8.91368 \).

The equation obtained from this exercise is shown: Adjusted marginal equation:

\[
RF = 19.80 + 0.22\text{Treatm}\cdot H12 + 0.27\text{Treatm}\cdot H16 + 0.22 \\
\text{Treatm}\cdot H24 - 0.95\text{Treatm}\cdot H4 + 0.85\text{Treatm}\cdot H8
\]  

(6)
CONCLUSIONS

As a conclusion of the application of the ANOVAs, the effects of the Hours of Service can be contrasted, by analyzing the means of various groups (sectors/replicas) of a single dependent variable (Pressure). It also gives us information about the interactions. The study presents a balanced model.

It was found that both models (observed and adjusted) have a normal distribution behavior in terms of pressures, which gives us the certainty that the adjusted and experimental regression value is reliable on the significance of the factors.

However, regarding the hours of service, it was found that their behavior is a Poisson distribution or exponential order.

It is important to highlight that the treatment (4H) and the factors (P0, P7, Pm30) have a negative impact, in other words, this pressure range should be avoided.

In conclusion, despite the fact that the hours of service are granted in blocks of 4 hours and in this way the Operating Agency increases or decreases the supply to the sectors in a linear manner, in reality the quality of the service does not behave in a linear manner, as the operating policy orders, but the quality of the service decreases exponentially.

It is also observed that 4 hours of service are insufficient since, in many cases, it takes 2 hours to reach the end user, so a minimum of 6 hours of service is recommended if supplied in a single block, since in blocks of 8 hours, 2 hours of the evening shift are used to fill the domestic storages, which is displayed with the obtained coefficient similar to that of 4 hours (Equation (5)).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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