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Effects of the transfer of the São Francisco River waters on the performance of the water treatment plant of Gravatá, Paraíba, Brazil

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ABSTRACT

The objective of this study was to evaluate the effects of the transfer of the São Francisco River waters on the quality of the water produced by the water treatment plant of Gravatá (WTP-Gravatá) using multivariate statistics. Monthly means of the variables pH, apparent color and turbidity of raw, decanted and treated waters were used, in addition to the volume accumulated by the Epitácio Pessoa reservoir, during the period from January 2016 to December 2017. The arrival of the transposition waters abruptly changed the apparent color and turbidity of the raw water. In spite of that, the treated water presented low variability of the mentioned parameters, indicating that WTP-Gravatá was able to adapt its treatment. From the factor analysis/principal component analysis (FA/PCA) it was found that changes in reservoir volume alter the apparent color and turbidity of the raw water, requiring interventions in the coagulation/flocculation/decantation stages. The increasing of these parameters in the decanted water overloads the filtration step, raising the apparent color of the treated water. The cluster analysis distinguished the different phases experienced by the Epitácio Pessoa reservoir. The information obtained can help decision-making in WTPs, considering changes in reservoir volumes.

Key words: factor analysis, principal component analysis, water treatment

HIGHLIGHTS

- The water transference from the São Francisco River changed the characteristics of the raw water from Epitácio Pessoa reservoir.
- Changes in the volume of the reservoir influenced the water treatment performed by WTP-Gravatá.
- Raw water changes demand an adjustment in the coagulation/flocculation/decantation steps and the filtration step may be overloaded.
- Multivariate statistics can help decision making in water treatment plants in the face of changes in reservoir volumes.

INTRODUCTION

Due to the scarcity and deterioration of water quality, its use for human supply, in terms of quantity and quality, has become a global problem (Henning *et al.* 2014). This scenario is aggravated in regions with high temperatures and low rainfall, such as the Brazilian semi-arid region, where the integration of basins has been one of the alternatives to minimize the effects of drought and ensure the supply of drinking water to the population.

Epitácio Pessoa is one of the most important reservoirs in the Northeast region, responsible for supplying the city of Campina Grande and surrounding areas, which constitute one of the largest population clusters in Paraíba (Costa *et al.* 2017; Silva *et al.* 2017). Despite its importance, this reservoir has suffered management problems that, together with the drought cycle that started in 2012, evaporation losses and continuous abstraction for human supply and irrigation, contributed to it reaching 3.2% of its capacity in March 2017, according to data from the Executive Water Management Agency (Agência Executiva de Gestão das Águas – AESA).

The reduction in the reservoir volume compromised the multiple uses of its waters and became a concern for the entire population that depends on this water body to meet its demands, especially with regard to the supply of water for human consumption. This problem was mitigated through an emergency action of the competent authorities, which advanced the arrival of the waters of the transfer of the São Francisco River to April 2017.

The works of the Project for Integrating the São Francisco River with the River Basins of the Northern Northeast Region (Projeto de Integração do Rio São Francisco com as Bacias do Nordeste Setentrional – PISF) began in 2007, despite obstacles, criticisms and protests from various sectors of society (Oliveira 2017). The east axis of the transfer, which has an extension of 217 km, was designed to expand the water supply and ensure supply to about 4.5 million people in 168 municipalities of Paraíba and Pernambuco.

Studies indicate that climate changes related to dry and rainy seasons are capable of significantly altering raw water quality in rivers and reservoirs, and adjustments may be required to water treatment, ranging from changes in coagulant dosages to an increase in the frequency of filter washing (Almeida *et al.* 2017; Michelan *et al.* 2019).

The recharge of the Epitácio Pessoa reservoir from the transposition led to alterations in the physical, chemical and biological characteristics of its waters. In this context, it is important to monitor the quality of the water produced by the Gravatá water treatment plant (WTP-Gravatá), in order to evaluate the need to adapt the treatment process adopted at the WTP and to ensure the quality of the water produced, regardless of the changes in the characteristics of the water flowing into the station.

WTPs monitor the parameters of apparent color, turbidity and pH, known as operational parameters, in order to evaluate the water treatment efficiency and guide the system's operators in decision-making. For surface reservoirs, these variables should be monitored every two hours at the exit of the treatment. In addition, their values must meet the potability standards established in GM/MS Ordinance n° 888/2021 of the Ministry of Health.

Water quality assessment encompasses several variables, which are often difficult to analyze and interpret due to the large amount of data, especially when they are collected for many years. One of the alternatives available to overcome this problem is the use of multivariate approaches, such as factor analysis (FA) and principal component analysis (PCA), which are useful for better understanding the data and allow a reduction in the number of variables with minimal loss of information (Rocha & Pereira 2016).

Another equally useful procedure is cluster analysis, which aims to classify the values of a data matrix into discrete groups. Among the several existing methods, the most used is hierarchical clustering, in which the initial data matrix is used to obtain a symmetrical matrix of similarities and start the detection of pairs that show the highest degree of similarity to each other, or the lowest distance. This procedure generates a graph that is easily interpreted and representative of the multidimensional relationship between the variables (Bufon & Landim 2007).

Based on the problem addressed, factor analysis/principal component analysis (FA/PCA) and cluster analysis were applied to evaluate the influence of the recharge of the Epitácio Pessoa reservoir, due to the transfer of the São Francisco River waters, on the quality of the water produced by WTP-Gravatá.

METHODS

Characterization of the system

This study was developed at the Epitácio Pessoa reservoir and at WTP-Gravatá (Figure 1). They are part of the water supply system of Campina Grande (WSSCG).

The WSSCG consists of the surface reservoir (with maximum accumulation capacity of 466,525,964 m^3), a raw water piping system, raw and treated water lifting stations, WTP-Gravatá and a treated water piping system composed of four main lines, responsible for transporting water treated by WTP-Gravatá to the main water distribution reservoirs and supplying approximately one million users (Silva *et al.* 2019).

WTP-Gravatá is of the conventional type, with capacity to treat 1,500 L/s, and consists of: one Parshall flume, used as a rapid mixing unit, where aluminum sulfate is applied as a coagulating agent; eight mechanized flocculators; six conventional horizontal-flow decanters; 11 fast double-layer filters; and a contact tank with application of gaseous chlorine (Silva *et al.* 2019).

It is worth pointing out that in October 2016, when the Epitácio Pessoa reservoir had only 6% of its capacity, blooming of cyanobacteria and the presence of cyanotoxins were observed. This phenomenon caused the Water and Sewage Company of Paraíba (CAGEPA) to take preventive measures regarding the water produced by WTP-Gravatá, inserting in its treatment process a pre-oxidation step with hydrogen peroxide.

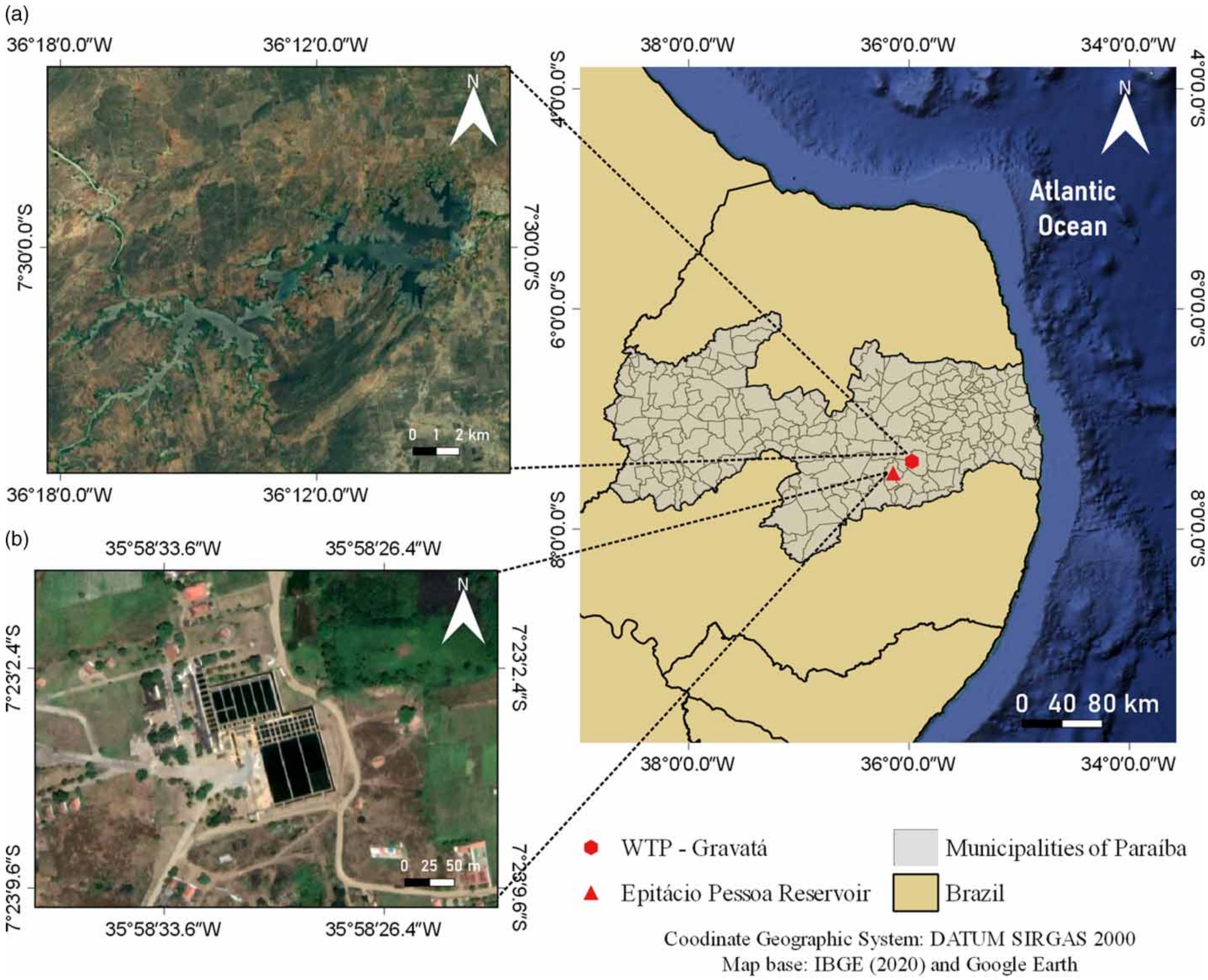

Figure 1 | Location of (a) the Epitácio Pessoa reservoir and (b) WTP-Gravatá.

In the state of Paraíba, the east axis channel conveys its waters to the bed of the upper course of the Paraíba River, in the municipality of Monteiro. From this point, the waters flow by gravity and are intercepted by the dams of Poções, Camalaú and Epitácio Pessoa, located in the municipalities of Monteiro, Camalaú and Boqueirão, respectively. The maximum expected flow rate for the east axis is 28 $m^3 s^{-1}$, although the average operating flow rate is 10 $m^3 s^{-1}$ (Brasil 2017; Oliveira 2017). The east axis was inaugurated in March 2017. On April 18 of the same year, the waters of the São Francisco River reached the Epitácio Pessoa reservoir, with an average flow rate of 3.92 $m^3 s^{-1}$ (corresponding to the period between April and December 2017) (AESA 2017).

Obtaining of raw and treated water quality data

The variables analyzed in this study were the ten physicochemical parameters: apparent color of raw water (*C-RW*), apparent color of decanted water (*C-DW*), apparent color of treated water (*C-TW*), turbidity of raw water (*T-RW*), turbidity of decanted water (*T-DW*), turbidity of treated water (T-TW), pH of raw water (*pH-RW*), pH of decanted water (*pH-DW*), pH of treated water (*pH-TW*) and percentage of the accumulated monthly volume of the Epitácio Pessoa reservoir (V%).

At WTP-Gravatá, these water quality parameters are monitored every four hours for raw and decanted water, and every hour for treated water. Analyses of the water samples were performed in the physicochemical control laboratory located in the treatment plant itself.

The data evaluated in this study correspond to the monthly averages of the daily monitoring performed in the period from January 2016 to December 2017 (15 months before and nine months after transfer), at three points of WTP-Gravatá: channel upstream of the rapid mixture (raw water), channel of decanted water (decanted water) and exit from the treatment plant (treated water). It is worth pointing out that the study period was limited to the data provided by CAGEPA. The monthly values of accumulated volume in the Epitácio Pessoa reservoir, for the same reference period, were obtained from the portal of the Executive Water Management Agency of Paraíba (AESA-PB). In total, there were 24 data for each variable.

Statistical analysis

The association between the variables that influence water quality at the different stages of treatment was identified using multivariate statistical analysis (FA/PCA).

The application of FA/PCA requires the execution of the following steps: (i) preparation of the correlation matrix, (ii) extraction of common factors and possible reduction of variables and (iii), when necessary, rotation of axes related to common factors, in order to make the solution simpler and easily interpretable (Toledo & Nicolella 2002). These analyses were carried out using R language.

At first, the data analyzed in the present study were organized in an $n \times p$ data matrix, where each row (n) represents one month of the time horizon, 24 months, and the columns (p) represent the variables (*ten* variables), totaling 240 data content (72 for apparent color, 72 for turbidity, 72 for pH and 24 for volume). From this, the data were standardized in order to prevent the scale factor from influencing the final decisions of the study, giving greater emphasis on a larger scale variable than on a smaller scale variable. The standardization of the variables was given by the ratio between the deviations in relation to the mean of each variable and its standard deviation, according to Equation (1):

$$Y_{np} = \frac{X_{np} - \bar{X}_p}{S(\bar{X}_p)} \tag{1}$$

where Y_{np}, X_{np}, $S(\bar{X}_p)$ and $\bar{X}_p$ are, respectively, the standardized variable, the original variable, the standard deviation and the mean of the p-th original variable.

The Kaiser–Meyer–Olkin and Bartlett sphericity tests ($p < 0.05$) were used to verify the adequacy of the data for factor analysis.

The number of factors to be extracted in the factor analysis was determined by the Kaiser criterion, where factors with eigenvalue lower than one are excluded. In addition to this criterion, Hair Jr. *et al.* (2006) suggest that the factors should have at least 60% of accumulated variance, which is an acceptable level to proceed with factor analysis.

In some cases, the results of PCA may be difficult to interpret. In this case, the orthogonal rotation procedure of the factor loading matrix is adopted, which aims to improve the interpretation of the factors by redistributing the variance explained by the components, without changing the accumulated variance of the set of components. The use of orthogonal rotation by the Varimax method enables a better fit to the possible factorial model of explanation.

Aiming to form clusters with similar characteristics, the variables selected by FA/PCA were subjected to cluster analysis. The method used was the hierarchical method of Ward Jr. (1963), with the Euclidean distance as a measure of similarity in the analysis of clusters.

RESULTS AND DISCUSSION

Figure 2 shows the accumulated water volumes, in cubic metres and percentage, in the Epitácio Pessoa reservoir in 2016 and 2017, and it is possible to observe the reduction of this variable throughout 2016, reaching 3.2% of its accumulation capacity in March 2017. From April of the same year, there was a continuous increase of its volume, which occurred due to the supply of water from the transfer of the São Francisco River waters.

In relation to physicochemical parameters of apparent color, turbidity and pH, Figure 3 presents the temporal distributions and their respective variabilities. It is observed that the apparent color of raw water increased as the reservoir volume decreased, from 9.87 uC in Jan/16 to 14.65 uC in Mar/17. During this same period, the turbidity of raw water also varied, reaching a value of 1.51 uT in Apr/17.

With the arrival of the transposition waters (Apr/17), the apparent color and turbidity of the raw water increased sharply (from 13.90 uC and 1.29 uT to 20.49 uC and 2.24 uT, respectively), which probably occurred due to the contact of the waters. However, with the gradual increase in the reservoir volume, a continuous reduction in these parameters was observed.

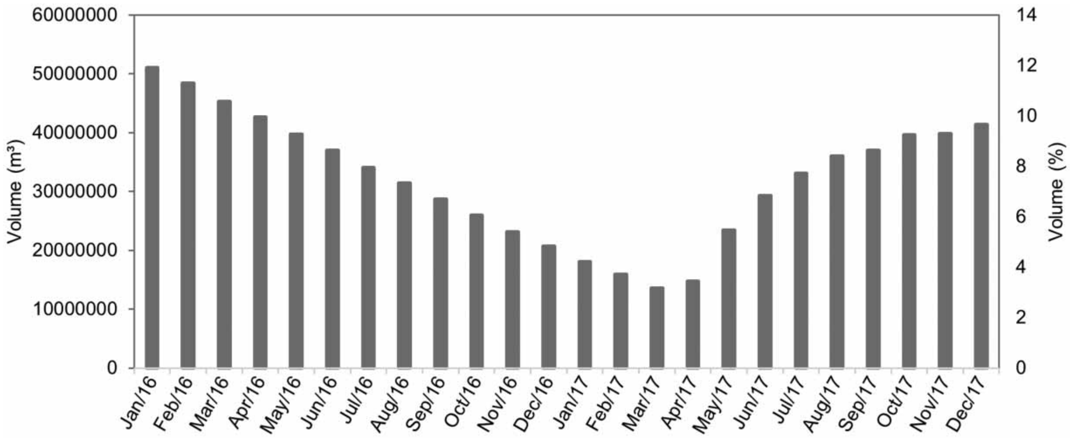

Figure 2 | Accumulated volume of the Epitácio Pessoa reservoir during the period between January 2016 and December 2017 (adapted from AESA 2016, 2017).

Considering the changes in values of apparent color and turbidity with the reduction and increase in the volume of the reservoir, the influence it exerts on raw water quality and, consequently, on the functioning of the water treatment plants is evident. This can be verified at WTP-Gravatá, where changes in the apparent color of raw water were directly reflected in the apparent color values of decanted water, which ranged between 8.02 and 11.72 uC. Despite this, the treated water showed low variability of the parameters, indicating that WTP-Gravatá was able to adapt its treatment to changes in raw water quality.

For the pH, no significant variation was observed in the raw, decanted and treated waters, along the studied series. The small reduction in this parameter during treatment can be inferred from the consumption of alkalinity by the metal coagulant used (aluminum sulfate) and also by the disinfection process, with chlorine.

Preliminary evaluation of the data made it possible to verify that the value of the Kaiser–Meyer–Olkin test, which quantifies the degree of correlation between variables, was 0.558, which enables the execution of the multivariate analysis (FA/PCA). Bartlett's sphericity test showed $p<0.0001$, which was used to verify the hypothesis that the correlation matrix is an identity matrix, in order to rule out the null hypothesis, confirming that at least one correlation between the variables is significantly different from zero.

The correlation matrix (Table 1) provides important information about the impact of the arrival of new waters in the reservoir in relation to water treatment. All variables were used to form principal components, except for turbidity of treated water (T-TW), whose elimination was justified by the factor-loading matrices (Tables 2 and 3).

Table 1 shows that all variables had correlation greater than 0.4 with at least two others. It is also observed that *C-RW* and *T-RW* showed the highest correlation (0.794), followed by *T-RW* and *T-DW* (0.643). The positive correlation between *C-RW* and *T-RW* was expected because the parameters of apparent color and turbidity are directly related (Libânio 2016).

In turn, the positive correlation between *T-RW* and *T-DW* attests that, during the studied period, the increase of suspended solids in the raw water resulted in the elevation of this parameter in the decanted water. This indicates that the clarification process required management measures to maintain the quality of decanted water regardless of raw water conditions, such as: adequacy of the type and dose of the coagulant employed and/or change in the speed gradients of the flocculation unit.

Regarding volume, there were negative correlations with *C-RW* and *pH-RW* and positive correlations with *pH-TW*. The negative correlation between V% and *C-RW* indicates that the smaller the volume, the higher the concentration of particles and, consequently, the higher the apparent color. However, it is worth pointing out that, exceptionally, in the initial period of arrival of the transferred waters, the increase in the volume of the reservoir (+59% from Apr/17 to May/17) led to sudden increase in the apparent color (Figure 3) due to the resuspension of the sediments present at the bottom.

The negative correlation between V% and *pH-RW* can be explained by the fact that a smaller volume of water results in a higher concentration of nutrients in the reservoir, which favor the development of algae, whose photosynthetic activity consumes carbon dioxide (CO_2) and promotes the conversion of bicarbonate ions (HCO_3^-) into hydroxyl ions (OH^-), raising the pH (Von Sperling 2002). This fact can be observed in Figure 3, where the reduction in the volume (−71% from Jan/16 to Apr/

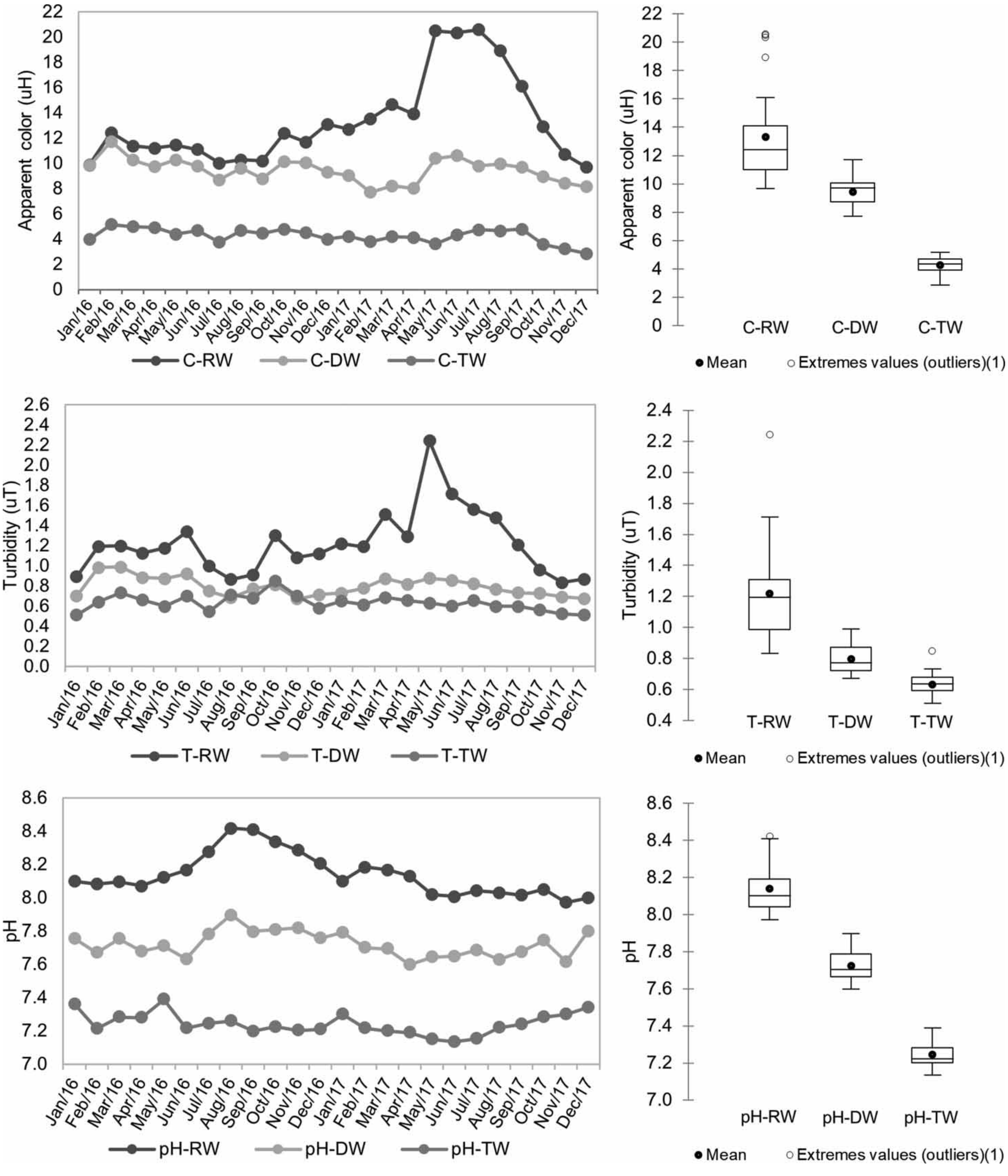

Figure 3 | Temporal distribution and variability of the monthly mean values of turbidity, apparent color and pH at the different points of WTP-Gravatá during the period between January 2016 and December 2017.

17) resulted in higher pH values. The opposite was observed after the arrival of the transferred waters and the consequent increase in volume (from Apr/17).

There was also a positive correlation between V% and *pH-TW*. Since the increase in reservoir volume reduces *C-RW* in the present study, lower coagulant doses become necessary for the treatment. Thus, the reduction in the pH of raw water during

Table 1 | Spearman correlation matrix for the evaluated variables

Variable	*C-RW*	*C-DW*	*C-TW*	*T-RW*	*T-DW*	*pH-RW*	*pH-DW*	*pH-TW*	V%
C-RW	**1**								
C-DW	0.217	**1**							
C-TW	0.120	**0.545**	**1**						
T-RW	**0.794**	0.392	0.319	**1**					
T-DW	0.313	**0.433**	**0.497**	**0.643**	**1**				
pH-RW	−0.294	−0.165	0.161	−0.190	−0.087	**1**			
pH-DW	**−0.495**	−0.093	−0.019	**−0.492**	**−0.490**	**0.586**	**1**		
pH-TW	**−0.620**	−0.123	−0.132	**−0.595**	−0.306	−0.121	0.310	**1**	
V%	**−0.486**	0.342	0.210	−0.380	0.110	**−0.456**	−0.098	**0.585**	**1**

Bold values are the significant values for each variable.

Table 2 | Matrix of factor loadings and commonalities of the evaluated variables

	Matrix of factor loadings			
Variable	**F1**	**F2**	**F3**	**Final commonality**
C-RW	**0.830**	0.295	−0.218	0.823
C-DW	0.473	**−0.550**	0.399	0.685
C-TW	0.407	−0.399	**0.683**	0.792
T-RW	**0.929**	0.115	0.031	0.877
T-DW	**0.717**	−0.333	0.232	0.679
pH-RW	−0.270	**0.508**	**0.747**	0.889
pH-DW	**−0.649**	0.225	**0.561**	0.787
pH-TW	**−0.690**	**−0.509**	−0.093	0.743
V%	−0.260	**−0.937**	−0.082	0.951
Eigenvalue	3.492	2.118	1.616	–
Explained variance (%)	38.805	23.528	17.951	–
Accumulated variance (%)	38.805	62.333	80.284	–

Bold values are the significant values for each variable.

the coagulation process is minimized, resulting in higher values of *pH-TW*. This correlation indicates the influence that transfer exerts on the quality of water treated by WTP-Gravatá.

From the correlation matrix, the factors (nine factors) were extracted, which correspond to the number of variables. However, only three factors met the Kaiser criterion (eigenvalues above 1). These explain 80.284% of the total data variance, 38.805% in the first factor, 23.528% in the second factor and 17.951% in the third factor.

Table 2 shows the unrotated matrix of factor loadings, which indicates the contribution of each variable in relation to the extracted components and their respective commonalities, which in turn express the proportion of variance of each variable that is explained by the selected factors (Toledo & Nicolella 2002). The values of the resulting commonalities were above 0.5, which according to Figueiredo Filho & Silva Júnior (2010) is the minimum acceptable value.

In the non-rotated matrix, factor loadings must have an absolute value above 0.5 and the same variable cannot contribute to the construction of more than one component (Rocha & Pereira 2016). In the present study, the T-TW parameter showed values higher than 0.5 in more than one component, even after rotation. For this reason, we chose to eliminate it and conduct the test again. A similar case occurred with the parameters *pH-RW*, *pH-DW* and *pH-TW*; however, after rotation of the matrix by the Varimax method, the problem was overcome (Table 3).

The first component (D1), after Varimax rotation (Table 3), explained approximately 32.052% of the total data variability and its significant variables were *C-RW*, *T-RW*, *pH-TW* and V%, whose relationship reflects the influence that the volume of water present

Table 3 | Factor-loading matrix of the three principal components after Varimax rotation

Variable	D1	D2	D3
C-RW	**0.818**	0.132	−0.370
C-DW	−0.016	**0.817**	−0.131
C-TW	0.033	**0.869**	0.191
T-RW	**0.770**	0.443	−0.297
T-DW	0.313	**0.717**	−0.260
pH-RW	0.129	0.017	**0.934**
pH-DW	−0.340	−0.131	**0.809**
pH-TW	−**0.853**	−0.124	−0.031
V%	−**0.816**	0.362	−0.394
Explained variance (%)	32.052	25.704	22.528
Accumulated variance (%)	32.052	57.756	80.284

Bold values are the significant values for each variable.

in the reservoir exerts on the characteristics of the raw water and on the final quality of the treated water. Thus, it can be affirmed that the transfer of the waters of the São Francisco River is closely related to the quality of the water treated by WTP-Gravatá.

Libânio (2016) reports that aluminum sulfate consumes water alkalinity, which results in decrease in pH. This statement is consistent with the correlations found in the present study, where *C-RW* and *T-RW* are inversely proportional to *pH-TW*, that is, as the apparent color and turbidity increase, the demand for coagulant can also increase and, consequently, reduce the pH of the treated water. In addition, it is worth mentioning that the aluminum sulfate doses applied at the treatment plant through the studied period were higher than 60 mgL^{-1}, which corroborates the reduction of alkalinity.

The second component (D2) explained about 25.704% of the data variance and was composed of the parameters *C-DW*, *T-DW* and *C-TW*. The relationship between these variables refers to the filtration operation in water treatment, responsible for retaining particles that remain in the water after the decanting stage. The positive correlations show that the increase in *C-DW* and *T-DW* result in the elevation of *C-TW*, which indicates the overload and/or inefficiency of the filters, as explained by Di Bernardo & Sabogal Paz (2008).

On the other hand, the third component (D3), which explained around 22.58% of the data variability, was represented by *pH-RW* and *pH-DW*, showing the importance of water alkalinity to minimize abrupt variations in pH and ensure the efficiency of the coagulation process, since the prevalence of hydrolyzed coagulant species depends on pH. This fact becomes more relevant when the coagulant employed is aluminum sulfate, whose efficacy is related to a more restricted spectrum of pH variation (Libânio 2016).

Figure 4 presents the dendrogram aimed at grouping the data from the dissimilarity between the points observed by the Euclidean distance method. Such a hierarchical clustering method identified the presence of four clusters or main groups.

Clusters C1 and C2 showed higher homogeneity of the data (smaller Euclidean distance between the points). Cluster C2, periods of Jul–Sep/16 and Nov–Dec/17, can be correlated with a moment of greater stability of the reservoir, where there was little variation in the raw and treated waters in terms of the parameters evaluated. This behavior can also be observed in the cluster C1, which includes Jan–Jun/16, in addition to Oct/17, and represents a period of non-recharge of the reservoir.

On the other hand, cluster C3 covers the period between Oct/16 and Apr/17, where the reservoir reached its lowest volumes (Figure 2), resulting from the prolonged drought. In this period, the blooming of cyanobacteria was intensified in the reservoir, so it was necessary to implement a pre-oxidation step at WTP-Gravatá using hydrogen peroxide, a promising oxidizing agent in the control of cyanobacteria and degradation of cyanotoxins, as described in the studies of Zhong *et al.* (2009), Qian *et al.* (2010), He *et al.* (2012), Fana *et al.* (2014) and Chen *et al.* (2016).

Finally, the months of May–Sep/17 are grouped into C4, where it is possible to observe the influence of the arrival of transferred waters on the characteristics of the reservoir. In this period, the water supply resulted in the increments in the accumulated volume (Figure 2) and in the values of color and turbidity of the raw water, which probably occurred due to the resuspension of solids present at the bottom of the dam (Figure 3).

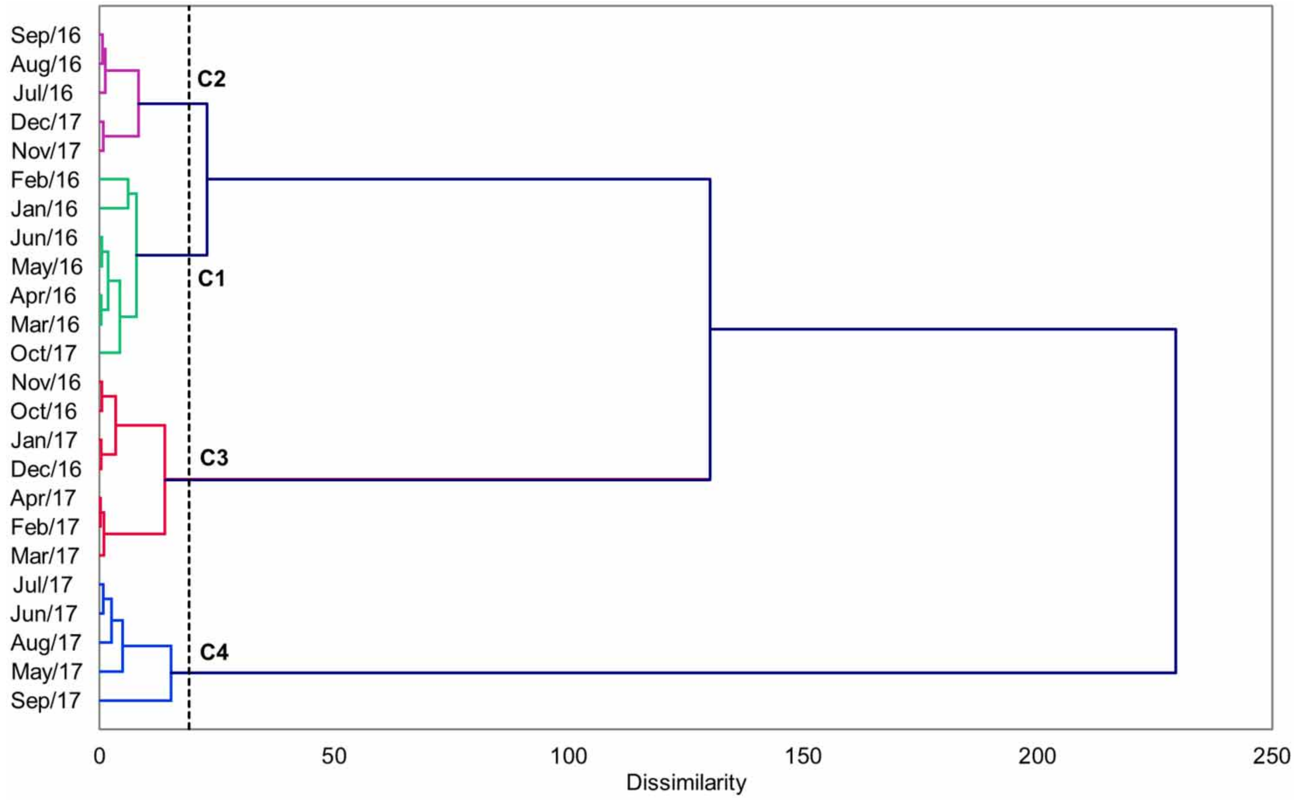

Figure 4 | Horizontal dendrogram for the studied period.

CONCLUSIONS

Based on the results obtained in this study, it was observed that factor analysis/principal component analysis facilitated the interpretation of the data and promoted a better understanding of the influence that the transfer of the São Francisco River waters exerts on the parameters of apparent color, turbidity and pH of the raw water of the Epitácio Pessoa reservoir and the water treated by WTP-Gravatá.

The analysis reduced the number of variables studied from ten to nine, and allowed the selection of three principal components that explained 80.28% of the total data variability. Based on these, it was identified that changes in the volume of the reservoir result in changes in the apparent color and turbidity of the raw water, demanding adjustments in the stages of coagulation/flocculation/decantation of the WTP. It was also found that the increase of these parameters in the decanted water improved the apparent color of the treated water, indicating that, if the adjustments in the WTP are not efficient, there will be overload in the filters and a consequent efficiency loss in the filtration step. It was also observed that changes in the reservoir volume can affect the pH of the treated water, due to possible changes in the dosage of chemical agents used in the treatment. Such information can help decision-making in WTPs in the face of changes in reservoir volumes.

Finally, the grouping by similarity made it possible to distinguish the different phases experienced by the Epitácio Pessoa reservoir, including the periods of drought and arrival of the transferred waters, which enables a better understanding of the impacts that the integration of basins can generate on the water quality of reservoirs of the Brazilian semiarid region and, consequently, on the water treated and distributed to the population.

DATA AVAILABILITY STATEMENT

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

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