Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga

ISSN 0100-316X (impresso)
ISSN 1983-2125 (online)
http://dx.doi.org/10.1590/1983-21252023v36n319rc

Water quality in underground dam areas in the semiarid region of rio grande do norte, Brazil

Qualidade da água em áreas de barragens subterrâneas do semiárido potiguar

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ABSTRACT - The federal public agencies have prioritized the financing of underground dams as a strategy to decrease water scarcity in rural semiarid regions in Brazil. The objective of this work was to evaluated water quality in underground dams, for agricultural irrigation purposes, in Rio Grande do Norte, Brazil, at the end of the dry season in 2018 and at the end of the rainy season in 2019. The variables with the greatest impact on water quality were identified through multivariate analysis, using the software Statistica 7.0. The results showed that concentrations of variables correlated with salinity and ion toxicity in water of the dams decreased after the rainy season, whereas those correlated with clogging of localized irrigation systems increased. Salinity, sodicity, and/or toxicity in areas of underground dams were correlated with natural mineralization of geological components of soils; however, they also were affected by rainfall with marine hygroscopic nuclei, presence of rural clusters and corrals, and decomposition of organic matter in the damming area. The variables correlated with salinity presented higher effect on the hydrochemical variability of water within these dams in both sampling periods; electrical conductivity and chloride ions were the most significant variables.

Keywords: Alluvial aquifer. Multivariate analysis. Salinity.

RESUMO - Os órgãos públicos federais têm priorizado o financiamento de barragens subterrâneas como forma de amenizar a escassez hídrica das regiões rurais semiáridas do Brasil. Este trabalho avaliou a qualidade da água, para fins de irrigação, de barragens subterrâneas do Estado do Rio Grande do Norte, no fim do período seco do ano de 2018 e fim do período chuvoso do ano de 2019. Além disso, elencou quais as variáveis apresentaram maior influência nessa qualidade, por meio de análise multivariada, utilizando o software Statistica 7.0. Os resultados indicaram que os problemas relacionados a salinidade e a toxicidade de íons das águas das barragens subterrâneas reduzem após o período chuvoso, enquanto que os problemas relacionados a obstrução dos sistemas de irrigação localizada aumentam. A salinidade, sodicidade e/ou toxicidade da água das barragens subterrâneas estão relacionadas a mineralização natural dos componentes geológicos do solo, porém também são influenciadas pelas precipitações com núcleos higroscópicos marinhos, presença de aglomerados rurais, existência de currais e decomposição de matéria orgânica na área do barramento. As variáveis relacionadas a salinidade apresentam maior influência na variação hidroquímica da água das barragens, nos dois períodos estudados, sendo a condutividade elétrica e o íon de cloreto os mais representativos.

Palavras-chave: Aquífero aluvial. Análise multivariada. Salinidade.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: May 31, 2021.
Accepted in: April 14, 2023.

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INTRODUCTION

Underground dams are hydro-environmental structures constructed in alluvial deposits, such as intermittent rivers and streams, and drainage lines to intercept the flow of underground or subsurface water by installing a waterproof septum transversely to the direction of water flow, which favors its accumulation inside the soil (MELO et al., 2011; LIMA, 2013).

This technology is widely used in the semiarid region of Brazil to combat water scarcity, as underground dams are simple to construct, have low implementation and maintenance costs, and are easy to operate and adapt to different environments (CIRILO et al., 2003; LIMA et al., 2013). They provide to farmers increased water availability for human and animal consumption and allow for income generation through agricultural crops in the dam areas.

Despite the investments made in the implementation of these dams, few studies have been conducted to assess the conditions of existing dams, their economic viability, benefits, and limitations, as well as to define standards of monitoring and technical follow-up (LIMA, 2013). Most studies conducted in the state of Rio Grande do Norte, Brazil, have focused on specific basins (CHIANCA, 2020), and thus do not present a comprehensive understanding of the water quality in the implemented dams in the region and the feasibility of using these waters.

The implementation of dams without proper location criteria, disregard for constructions techniques, failure to involve the community in the process, inadequate management, and absence of monitoring can make these dams ineffective and contribute to the degradation of water resources.

According to Santos, Paiva, and Silva (2016), water from underground dams can present high concentration of salts after prolonged drought periods, resulting in decreases in crop yields and making this water unfit for human and animal consumption, in addition to probably causing soil salinization and sodification, impairing the growth of crop species.

Furthermore, groundwater quality depends on aquifer lithology, groundwater flow velocity, quality of recharging water, interaction with other water types and aquifers, and human activities that can pollute aquifers or modify hydrological cycles (HELENA et al., 2000).

Considering the significant variability of water quality in alluvial aquifers, the use of multivariate analysis techniques can aid in the interpretation of large datasets by identifying correlations between variables and the sampled locations, facilitating the identification of the main factors that impact water quality.

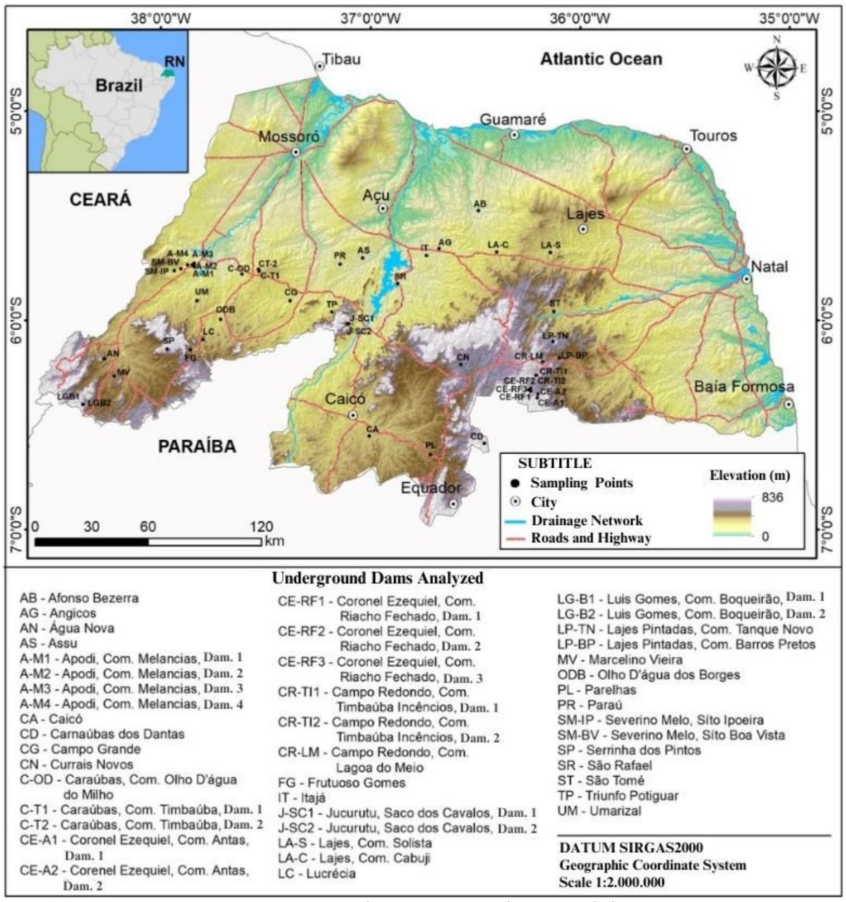
Helena et al. (2000) evaluated the groundwater quality of the Pisuerga River in Spain using multivariate analysis, which was essential for confirming and enhancing the initial hydrochemical findings derived from univariate statistics.

In this context, the objective of this study was to assess the water quality of in underground dams in the semiarid region of Rio Grande do Norte, Brazil, for irrigation purposes, and to identify the physicochemical variables that have the greatest impact on the hydrochemical variability of water within these dams.

MATERIAL AND METHODS

Selection of underground dams and characterization of the study area

The present evaluated the water quality in 45 underground dams (Figure 1) in the state of Rio Grande do Norte, Brazil. The selection of these dams was based on the following criteria: (a) the dam must have been installed by the Institute of Technical Assistance and Rural Extension of Rio Grande do Norte (EMATER/RN), which is responsible for installing the largest number of dams in the state (LIMA, 2013); (b) the dam must be considered completed by EMATER/RN, which means it must have wells, rows, and stone finishing, without grouting, over an waterproof septum; (c) the dam well must have water in it; and, (d) the dam must have been recommended by the local EMATER/RN technician.



Com. = community; Dam = underground dam

Figure 1. Location of underground dams analyzed in the study.

The underground dams in the state are in areas with a BSh climate, hot semi-arid, according to the Köppen classification. These areas present mean annual rainfall depths of 250 to 750 mm, in a rainy season from summer to autumn with high distribution irregularity and evaporation rates, and mean annual potential evapotranspiration of 1,500 mm (DINIZ; PEREIRA, 2015; DUBREUIL et al., 2018; LIMA et al., 2019a).

These dams are on crystalline basement rocks and soils. According to the EMBRAPA (2020), the soils were classified as: Argissolo Vermelho-Amarelo (AN, LC, LG-B1, LG-B2, MV, UM); Luvissolo Cromico (A-M1, A-M2, A-M3, A-M4, CA, CG, LP-BP, LP-TN, PL, SM-BV, SM-IP, ST); Neossolo Litolico (AG, CD, CE-A1, CE-A2, CE-RF1, CE-RF2,CE-RF3,CN, CR-LM,CR-TI1, CR-TI2, FG, IT, J-SC1, J-SC2, SP, SR, TP); Neossolo Regolítico (C-OD, C-T1, C-T2, ODB); Planossolo Haplico (LA-S); and Planossolo Natrico (AB, AS, LA-C, PR). The dams are in areas with flat (53%), gently undulating (29%), and undulating (18%) relief, according to the classification of Santos et al. (2018).

Most of the dams (73%) are in hydrographic basins that have the largest drained areas in the state, which flow into the north coast: 31% in the Piranhas-Assu River Basin and 42% in the Apodi-Mossoro River Basin. The remaining dams are part of the Trairi River Basin (20%), Potengi River Basin (5%), and Ceara Mirim River Basin (2%), which flow into the east coast of the state (ANA, 2012).

Collection of samples and analyzed variables

Water samples were collected from shallow excavated wells (Figure 2), known locally as cacimbas or amazons, within the underground dams, in two periods: the end of the dry season, between October and December 2018; and the end of the rainy season, in July 2019.

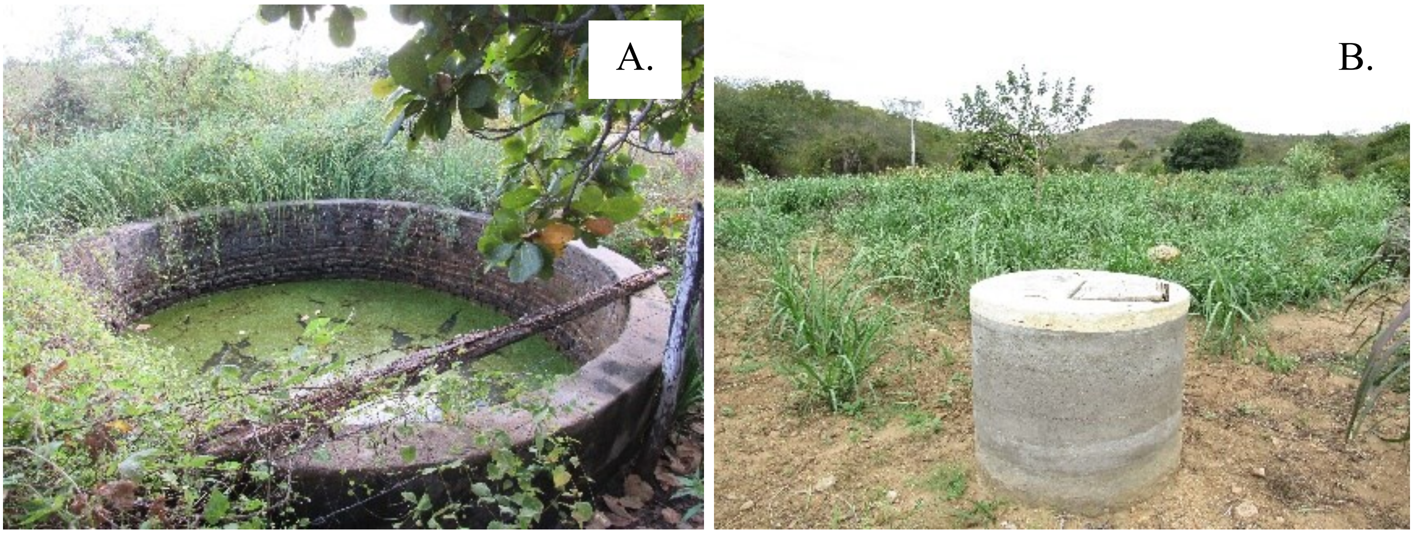


Figure 2. Examples of shallow wells within underground dams: C-T1 (A), CE-RF1 (B).

The water was collected using an aluminum bucket and rope, then stored in 1-liter polypropylene bottles, which were kept in thermal containers with ice during transport to the Laboratory of Soil, Water, and Plant Analysis (LASAP) of the Department of Engineering and Environmental Sciences (DECAM) at the Federal Rural University of the Semi-Arid Region (UFERSA), in Mossoro, RN. The aluminum bucket and the bottles used were previously washed with the water to be sampled, as recommended by Almeida (2010).

The physical-chemical variables evaluated and the analytical methods used are shown in Table 1. The analyses were conducted at LASAP, following the criteria established by Almeida (2010), with triplicates; the means were obtained from the replications. The results were then used to calculate the sodium adsorption ratio (SAR) and hardness.

In addition to laboratory analyses, the following characteristics of underground dams were considered to aid in the analysis of results: existence of protective devices in the shallow well, according to Funasa recommendations (2019), as these devices prevent runoff water from entering the wells; flooding of the dam area after the rainy season, as flooding of crop areas can increase the concentration of chlorides from plant decomposition; presence of surface dams upstream of the dam and at a maximum distance of 200 m, as these dams can transfer water to underground dams through underground flows; existence of rural agglomerations, corrals, sheep pens, pigsties, or chicken coops near the dam; and management of the dam regarding the use of its area and water within its well, as these last items can impact water quality

Table 1. Physical-chemical variables analyzed and test methodologies used.

Variable	Methods
Electrical conductivity (EC)	Laboratory method: conductivity meter (HACH-CDC401 probe)
Hydrogen potential (pH)	Electrometric method (Teckna T-1000 pHmeter)
Total solids (TS)	Gravimetric method
Total suspended solids (TSS)	Gravimetric method, using glass fiber filter with 1µm aperture.
Total dissolved solids (TDS)	Difference between TS and TSS
Sodium (Na^+) and potassium (K^+)	Flame photometer
Calcium (Ca^{2+}) and magnesium (Mg^{2+})	Complexometric method with EDTA
Chloride (Cl^-)	Mohr method
Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-)	Volumetric method
Nutrients: boron (B), copper (Cu), sulfur (S), iron (Fe), manganese (Mn), and zinc (Zn)	Atomic absorption spectrophotometry
Heavy metals: chromium (Cr), nickel (Ni), cadmium (Cd), and lead (Pb)	Atomic absorption spectrophotometry

Assessment of water quality in underground dams for irrigation purposes and statistical analysis used

Water quality was assessed according to the standards set by the Food and Agriculture Organization of the United Nations (FAO) through the Irrigation and Drainage Paper No. 29, which outlines the criteria for specific ion toxicity patterns and the risk of clogging localized irrigation systems (AYERS; WESTCOT, 1999). The risk of soil salinization and sodification was also assessed, according to the proposal of the United State Salinity Laboratory – USSL (RICHARDS, 1954) adapted by Santos (2008).

Physical-chemical variables in the water samples were evaluated through descriptive statistical to determine the maximum, mean, and minimum values and standard deviation to compare the water quality results of the two sampling periods, using the Excel 2016 software.

Multivariate analysis techniques were used to identify the variables that had the greatest impact on the hydrochemical variability of water within the underground dams, using the software Statistica 7.0 (demonstrative version, STATSOFT, 2004). Pearson's correlation (p £ 0.05) was performed between the analyzed variables before applying multivariate analysis techniques.

Principal component analysis (PCA) was carried out to identify the smallest number of components (factors) that could explain the variance in the data. Thus, principal components with eigenvalues greater than 1 and that together accounted for at least 70% of the accumulated variance were selected.

Factor analysis (FA) was then performed to identify the variables with the greatest impact on the water's hydrochemical characteristics. Thus, factors with eigenvalues greater than 1 from the PCA were used, and the factorial axes were rotated using the Normalized Varimax method. A significant factor loading value of 0.7 was considered.

Data from the variables SAR, hardness, and total dissolved solids were excluded from the multivariate analysis, as they presented multicollinearity. Cadmium data from the rainy season were also excluded due to concentrations below the limit of detection, and data on sulfur and boron were added.

RESULTS AND DISCUSSION

The minimum, mean, and maximum values of physical -chemical variables in the water from the underground dams evaluated, in the two sampling periods, and standard deviations are shown in Table 2.

A high dispersion of concentrations (high standard deviation) was found for most of the analyzed variables, which denotes a high variability in the chemical composition of water from these underground dams.

The concentrations of 16 variables decreased from the dry to the rainy season. This may have been caused by increased water volumes within the dams.

Cirilo et al. (2003) evaluated the physical-chemical quality of water from underground dams in the regions of Ouricuri, Sao Caetano, and Mutuca, in the state of Pernambuco, Brazil, and found decreases in salt concentrations from the dry to the rainy season and attributed this result to the recharge of water from rainfall. Additionally, they found the maximum salinity levels at the end of de dry season, which were attributed to a high evaporation.

Other studies reported the same climatological effect on water in alluvial valleys in the semiarid region and in underground dams in the agreste region of Pernambuco (ANDRADE et al., 2012; SANTOS; PAIVA; SILVA, 2016), and in underground dams in the Cobra River Basin, in Parelhas, Carnauba dos Dantas, and Jardim do Serido, in the state of Rio Grande do Norte (LIMA et al., 2019b).

Table 2. Minimum, mean, and maximum values and standard deviation (SD) of physical-chemical variables of water from underground dams in the state of Rio Grande do Norte, Brazil, collected at the end of the dry and rainy seasons.

Variables	End of the dry season (2018)				End of the rainy season (2019)			
	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD
pH	7.06	9.87	8.08	0.53	6.67	8.59	7.87	0.44
EC (µS cm^{-1})	134	13010	1708	2643	92	12365	1141	2025
K^+ (mmolc L^{-1})	0.02	1.08	0.24	0.23	0.01	0.81	0.19	0.17
Na^+ (mmolc L^{-1})	0.38	102.18	9.64	18.66	0.31	94.41	7.22	15.73
Ca^{2+} (mmolc L^{-1})	0.41	32.95	4.07	5.39	0.29	16.02	2.48	2.45
Mg^{2+} (mmolc L^{-1})	0.15	23.93	3.39	5.45	0.13	28.06	2.17	4.36
Cl^- (mmolc L^{-1})	0.70	134.40	12.12	25.38	0.60	102.93	7.15	17.09
CO_3^{2-} (mmolc L^{-1})	< Ld	2.00	0.51	0.54	< Ld	1.80	0.34	0.48
HCO_3^- (mmolc L^{-1})	0.58	18.00	5.01	3.59	0.50	12.45	4.00	2.70
SAR (mmolc $L^{-1})^{1/2}$	0.39	19.97	3.69	4.63	0.38	20.11	3.66	4.80
H (mg L^{-1})	40.5	2618.0	373.2	505.9	27.0	2203.8	232.8	332.3
TSS (mg L^{-1})	0.3	358.0	29.2	67.6	< Ld	487.0	37.6	81.4
TDS (mg L^{-1})	155.5	10695.5	1254.8	2016.1	11.4	9237.5	722.6	1449.1
S (mg L^{-1})	Nd	Nd	Nd	Nd	2.640	398.620	58.701	92.251
B (mg L^{-1})	Nd	Nd	Nd	Nd	< Ld	0.300	0.048	0.074
Cu (mg L^{-1})	< Ld	0.045	0.003	0.008	< Ld	0.070	0.010	0.017
Mn (mg L^{-1})	< Ld	2.621	0.495	0.720	< Ld	4.190	0.752	0.954
Fe (mg L^{-1})	< Ld	20.780	1.756	3.865	0.030	38.030	4.066	7.979
Zn (mg L^{-1})	< Ld	0.137	0.017	0.028	< Ld	0.370	0.058	0.091
Cr (mg L^{-1})	< Ld	0.022	0.002	0.004	< Ld	0.020	0.001	0.003
Ni (mg L^{-1})	< Ld	0.029	0.003	0.007	< Ld	0.010	0.002	0.004
Cd (mg L^{-1})	< Ld	0.040	0.004	0.009	< Ld	< Ld	< Ld	0.000
Pb (mg L^{-1})	< Ld	0.480	0.050	0.106	< Ld	0.010	0.002	0.004

Ld = limit of detection; Nd = not determined; pH = hydrogen potential; EC = electrical conductivity; K^+ = potassium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Cl^- = chlorides; CO_3^{2-} = carbonate; HCO_3^- = bicarbonate; SAR = sodium adsorption ratio; H = hardness; TSS = total suspended solids; TDS = total dissolved solids; S = sulfur; B = boron; Cu = copper; Mn = manganese; Fe = iron; Zn = zinc; Cr = chromium; Ni = nickel; Cd = cadmium; Pb = lead.

The water samples for the underground dams analyzed presented increases in concentrations of total suspended solids (TSS) and micronutrients (copper, manganese, iron, and zinc) after the rainy season (Table 2). The absence of protective devices in the dams' wells may have contributed to these increases, as it facilitates the entry of sediments from runoff water (Figures 2A, 4A, and 4B).

Lima et al. (2020) assessed copper, manganese, iron, and zinc concentrations in four underground dams in the Cobra River Basin, RN, and found decreased concentrations during the rainy season. Additionally, they found the highest concentrations of these micronutrients in the older dams.

Regarding the concentrations of heavy metals and micronutrients (Table 2), the analyzed water samples did not exceed the maximum recommended levels (AYERS; WESTCOT, 1999) for boron (< 0.7 mg L^{-1}), copper (< 0.1 mg L^{-1}), zinc (< 2.0 mg L^{-1}), chromium (< 0.1 mg L^{-1}), nickel (< 0.2 mg L^{-1}), and lead (< 5.0 mg L^{-1}). According to Almeida (2010), boron is usually more abundant in saline waters than in good-quality water.

Cadmium concentrations exceeding the recommended limit (0.01 mg L^{-1}) were found in water from seven underground dams: TP dam (in the municipality of Triunfo Potiguar), SR (Sao Rafael), LA-C and LA-S (Lajes), CG (Campo Largo), AG (Angicos), and AB (Afonso Bezerra). This metal has high potential for accumulation in soils and plants and can be toxic for plants and humans (AYERS; WESTCOT, 1999).

Eskinazi-Sant'Anna et al. (2006) conducted a water quality study in six reservoirs and in three stretches of rivers in the Piranhas-Açu Basin, Rio Grande do Norte, and found heavy metals at concentrations higher than those established by the Brazilian National Council for the Environment (CONAMA) Resolution 357/2005 for class-2 water bodies. Furthermore, they reported cadmium concentrations in the Armando Ribeiro Gonçalves Reservoir exceeding the allowed limit for human consumption.

Freire (2011) evaluated the concentrations of trace elements in the soil from four municipalities (Mossoró, Assu, Lajes, and Natal) with different land uses (native forest, agricultural crops, and waste disposal) in Rio Grande do Norte. The findings showed cadmium concentrations higher than the reference values in all the environments studied. According to the author, the source of this element may be attributed to the use phosphate fertilizers and deposition of materials such as batteries in the common waste.

Regarding the assessment of water suitability for agricultural use, the risk of soil salinization and sodification was evaluated following the USSL classification (RICHARDS, 1954) adapted by Santos (2008). According to the analysis, most of the underground dam water samples were classified as C2-S1 (Figure 3): 51% at the end of the dry season and 60% at the end of the rainy season. This classification indicates medium salinity level and low sodium risk for these waters, making them suitable for irrigation of crops with low tolerance to salinity, mainly those grown in sandy-silt, silty, or sandy-clay soils.

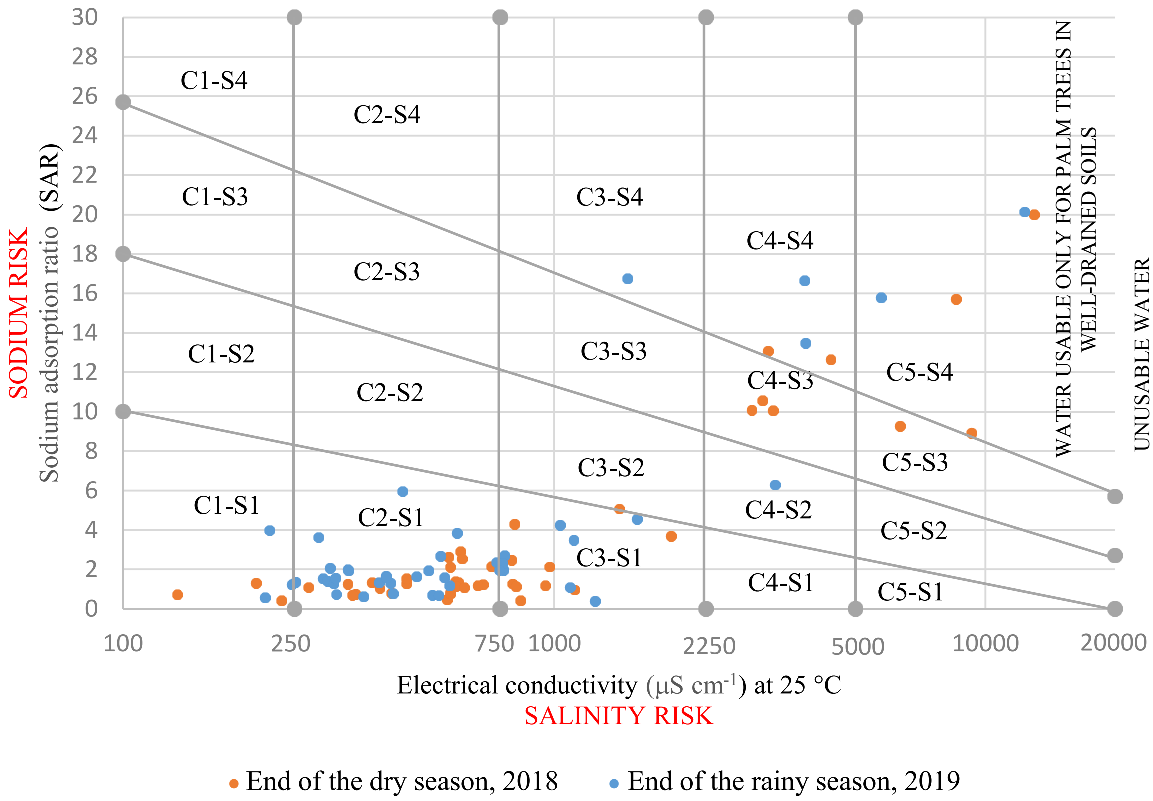


Figure 3. Classification of water from underground dams regarding risk of soil salinization and sodification, according to the United State Salinity Laboratory – USSL (RICHARDS, 1954).

Three underground dams were classified as having low salinity level and low sodium risk (C1-S1): dam 3 (A-M3) in the municipality of Apodi (Melancias community); dam 2 (J-SC2) in Jucurutu (Saco dos Cavalos community); and dam 2 (CE-RF2) in Coronel Ezequiel (Riacho Fechado community). The latter received this classification only during the rainy season.

These dams share a common purpose of providing water for irrigation and animal watering. The CE-RF2 dam also serves as a source of secondary human consumption. The areas surrounding the J-SC2 and CE-RF2 dams are used for growing grasses, and common bean and pumpkin crops.

The J-SC2 dam has a well wall at ground level and a small corral nearby. The CE-RF2 dam area is flooded for approximately six months after the rainy season due to a surface dam on its wall. However, the annual renewal of water and water quality characteristics of the streams that feed these dams were essential for maintaining acceptable salt concentrations in the water.

Silva et al. (2011) evaluated quality of water from two underground dams in the state of Paraiba (PB) and six dams in the state of Bahia (BA), Brazil, all them in semiarid regions. The dams in PB were classified as C2-S1, whereas most of those in BA were classified as C1-S1. These waters do not require special practices for salinity control. However, the authors recommended management strategies that promote the renewal of water in the underground dams and monitoring of water quality every two years. Additionally, they recommended growing crop species that are tolerant to salinity, such as cowpea, lemon, tangerine, sweet potato, pumpkin, melon, zucchini, cotton, coconut, beet, cucumber, and sugarcane, as well as grass species.

Overall, most underground dams had good quality water for agricultural irrigation purposes, with low risk of soil salinization and sodification. However, nine dams (20% of the analyzed dams) were found to have high salinity and sodicity:

four dams were classified as C5-S4 (CE-A2, LA-C, A-M1, and AG); three dams as C4-S4 (LA-S, SM-BV, and CR-TI1); one dam as C5-S3 (CR-TI2); and one dam as C4-S3 (CE-A1). Most of these dams are in the eastern region of the state.

Costa, Melo, and Silva (2006) reported that the high salinization found in the crystalline aquifer in the eastern region of Rio Grande do Norte is correlated with climate and topography factors. They explained that rainfall over this area is from marine hygroscopic nuclei, which are rich in sodium and chloride. In addition, the topography of the Sertaneja Depression is flat and not very dynamic, resulting in little water mobility and increases in salinity due to high evaporation demand.

The water from dam 2 (CE-A2) in Coronel Ezequiel (Antas community) presented the highest risk of soil salinization and sodification (C5-S4) in the two sampling periods. According to Santos (2008), this water should only be used for irrigating palm trees grown in well-drained soils. However, the water from this dam is used to irrigate commercial passion fruit crops around the hydrographic basin that contributes to the dam.

Helena et al. (1999) found higher salinity on the left bank of the alluvial aquifer of the Pisuerga River in Spain, possibly caused by groundwater recirculation. Therefore, in addition to the geological issues that affect the water quality of the stream that feeds the CE-A2 dam, high salinity in the dam's water may also be attributed to water recirculation, considering that the irrigated area was around the basin that contributes to the underground dam.

The water from dams in Angicos (AG dam), Lajes (LA -C dam, Cabugi community), and Campo Redondo (CR-TI1 dam, Timbauba community) presented similar classification (C5-S4 and C4-S4) for both sampling periods (end of the dry and rainy seasons, respectively) These dams are characterized by the flooding of their areas for approximately 3 months after the rainy season, presence of small corrals or pens in the dam's catchment area, and growing of grasses and sorghum plants and corn crops in the dams' areas. The AG and LA-C dams have surface dam upstream, which can contribute to maintain the water levels within underground dams, whereas CR-TI1 has an underground dam upstream. Only the AG and CR-TI1 dams are used for agricultural irrigation and watering of animals.

Cirilo et al. (2003) reported that the risk of salinization in damming areas can increase due to the combination of non-use of water from underground dams and high evaporation rates. Moreover, maintaining the water level above or at ground level (Figure 4A) can also contribute to this risk. Thus, in addition to geological factors, non-use of dam's water (CR-TI1 dam) and flooding of the dam after the rainy season (AG, LA-C, and CR-TI1 dams) can contribute to increases in salinity in the damming areas.

The dams in Apodi (A-M1 dam, Melancias community) and Severiano Melo (SM-BV dam, Boa Vista community) are the only ones in the western part of the crystalline aquifer that presented water with high potential of soil salinization and sodification if used for irrigation. These are in the same hydrographic basin and share common characteristics, such as rural clusters and growing of grass species surrounding them, presence of surface dams upstream, and usage of their waters for irrigation and animal watering purposes.

Helena et al. (2000) reported that high chlorine and sodium concentrations were found in the groundwater aquifer in Vila de Santovenia de Pisuerga, Spain, possibly due to leaks from public sewage systems and/or septic tanks. According to the authors, these elements were not of geological origin and their concentrations showed little variation between the dry and rainy seasons.

Rabemanana et al. (2005) evaluated the groundwater chemistry dynamics in southern Madagascar and found that water evaporation processes in the unsaturated soil zone can cause salts to crystallize and precipitate. These salts can be redissolved when the water table rises due to rainfall, thus leading to increased salinity in groundwater.

The SM-BV, A-M3, and A-M1 dams are in the same hydrographic basin, from upstream to downstream. Considering the risk of soil salinization and sodification, local factors such as soil type, dam management, and land use in the basin's area have significant effects on the water quality of an underground dam.

According to Table 2, 15 underground dams presented water with sodium and chloride concentrations greater than 3 $mmol_c\ L^{-1}$, in the two sampling periods, thus restricting the water usage for sprinkler irrigation. Most of these dams still have severe restrictions on the water usage for surface irrigation because they presented SAR greater than 10 (mmolc $L^{-1})^{1/2}$: 8 dams at the end of the dry season and 5 dams at the end of the rainy season. These dams are the same ones that have restrictions on the use of their waters for irrigation due to risk of soil salinization and sodification.

Lima et al. (2017b) attributed the adding of chloride concentrations in the surface waters of the Cobra River Basin to two mechanisms: weathering of biotite rocks and plant decomposition resulted from a great accumulation of organic matter from grasses for cattle grazing. They stated that atmospheric contributions were low due to the basin's distance from the coast. Accordingly, Costa, Melo, and Silva (2006) reported that the rainfall in the Serido region is mainly influenced by the intertropical convergence zone and the cyclone vortex of the upper troposphere, which are not necessarily connected to maritime winds.

Almeida (2010) pointed out that the chlorine ions from sprinkler irrigation are not retained by the soil exchange complex and are easily displaced by soil water and absorbed by plant roots and leaves. Excess chlorine ions can cause leaf chlorosis, in addition to contribute to reduction in the absorption of phosphorus and nitrogen by plants in calcareous soils. Additionally, the excess sodium ions can cause leaf burns and displacement of calcium and potassium from clay colloids in the soil, which can affect soil structure and potentially lead to desertification in the area.

Excessive amounts of bicarbonates in conventional sprinkler irrigation water can result in formation of scale and white deposits on leaves and fruits. Approximately 89% of the water from the evaluated underground dams has some restriction on its use due to high bicarbonate concentrations. Seven of these dams were classified with severe risk at the end of the dry season or in both sampling periods: AG dam (in Angicos), LA-C and LA-S (Lajes), SR (Sao Rafael), TP (Triunfo Potiguar), CE-RF2 (Coronel Ezequiel), and LC (Lucrecia).

According to Lima et al. (2017a), the presence of bicarbonates in water is correlated with dissolution of carbon dioxide from the atmosphere, decomposition of organic matter, and weathering of rocks containing silicates. High bicarbonate concentrations can favor the formation of carbonate and sodium bicarbonate, which may contribute to soil sodification problems (ALMEIDA, 2010; MAIA; RODRIGUES; LACERDA, 2012).

According to the restriction criteria for water use in localized irrigation systems proposed by Ayers and Westcot (1999), the most significant issues are correlated with water alkalinity (pH), followed by iron concentrations.

The standards established by Ayers and Westcot (1999) determine that water with pH above 7.0 can already cause some degree of restriction on its use for localized irrigation systems, as high temperatures combined with high pH levels can favor chemical precipitation due to excess carbonates or calcium and magnesium sulfates or due to iron oxidation, which can deteriorate irrigation devices. In this context, all evaluated underground dams showed some risk of clogging of localized irrigation systems, as they presented water with pH higher than 7.0 at the end of the dry season and/or end of the rainy season. Water with pH below 6.5 and above 8.4 can cause nutritional imbalances or contain toxic ions (AYERS; WESTCOT, 1999). These concentrations were found in water from 8 dams (18%) at the end of the dry season and only in one dam (2%) at the end of the rainy season.

The risk of clogging of localized irrigation systems increased from 11% to 20% due to higher concentrations of total suspended solids (TSS) at the end of the rainy season. This increase in TSS concentrations can be attributed to the entry of sediments carried by runoff into the wells, either through their walls or via side openings**.**

TSS-related problems in the underground dams at the end of the dry season were mainly caused by the presence of algae (Figure 2A). Regarding the end of the rainy season, some wells showed sediments and plant remnants (Figure 4B), in addition to algae. These results denote the need for water treatment measures, such as filtration, before using the water from these dams for localized irrigation systems.

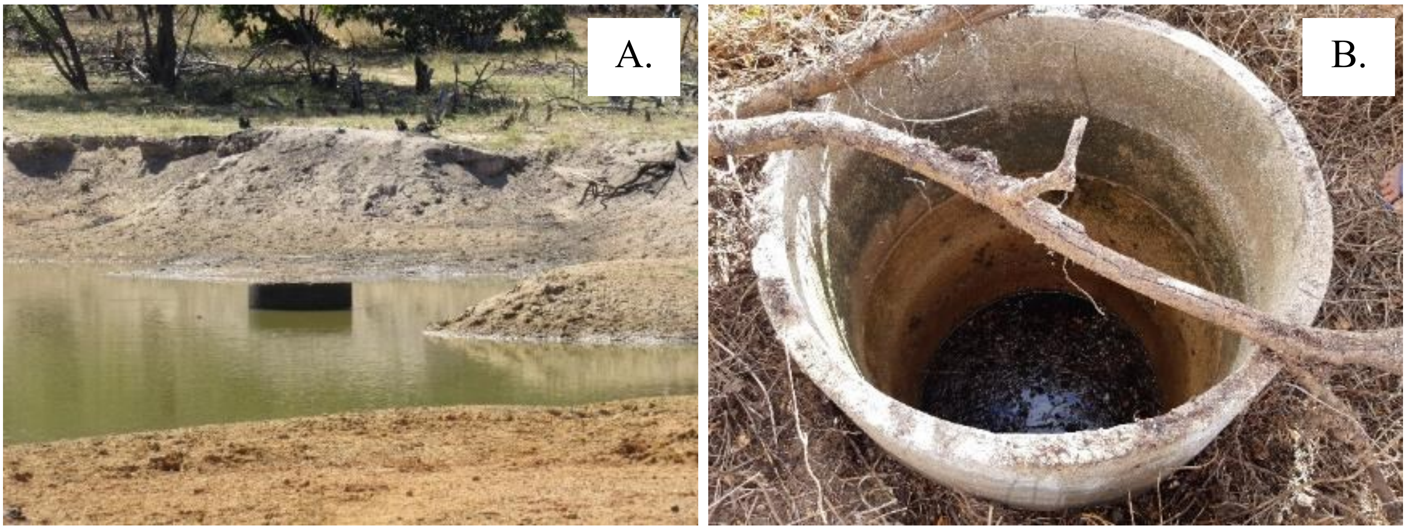


Figure 4. Problems related to increase in concentrations of total suspended solids in shallow wells of the analyzed underground dams: CD dam (A), TP dam (B).

The water analysis to assess the risk of clogging of localized irrigation systems due to high concentrations of total dissolved solids (TDS) showed that the dams with severe risk were predominantly those that presented severe toxicity risks due to sodium and chloride ions.

The number of dams with some restriction on water usage due to high TDS concentrations decreased from the end of the dry season (47% of the dams) to the end of the rainy season (22%). This decrease was expected when considering the increased water volume stored in the dams from rainfall, which led to decreases in concentrations of dissolved ions.

According to Ayers and Westcot (1999), iron and manganese contents above of 0.1 $mmol_c\ L^{-1}$ in water used for irrigation can physically obstruct piping and emitters within localized irrigation systems. The accumulation of these elements on the inner walls of pipes can cause an increase in head loss and compromise the entire irrigation system.

The restriction on the use of water from underground dams in localized irrigation systems increased due to higher iron and manganese concentrations at the end of the rainy season. This result may be attributed to the leaching of iron and manganese oxides present in the hydrographic basin that feeds the underground dam, as these elements are carried away by runoff and can enter the well or be deposited in the dam area.

The underground dams with the highest iron concentration, in descending order, were: CD (in the municipality of Carnauba dos Dantas; IT (Itaja); C-T1 (Caraubas); A-M3 (Apodi); and ODB (Olho D'Agua dos Borges). The dams that presented the highest manganese concentrations were: C-T1 and C-OD (Caraubas); CD (Carnauba dos Dantas), AG (Angicos); PL (Parelhas); CE-RF3 (Coronel Ezequiel); and CR-TI1 (Campo Redondo). Most of these dams are flooded for approximately 3 months after the rainy season.

Helena et al (2000) found increases in iron concentrations in water samples from the alluvial aquifer of the Pisuerga River after the rainy season. However, Lima et al. (2020) found higher concentrations of iron and manganese in underground dams in the Cobra River Basin at the end of the dry season; they correlated these high concentrations with the geology of the area.

The correlation matrix for the two sampling periods shows the correlations between the variables. Helena et al. (2000) stated that only correlations above 0.50 should be considered significant, however, in the present study, only correlations above 0.8 were considered for the dry season (Table 3).

A strong correlation was found between Cl^- and Na^+ ions (r = 0.98) for both periods. The presence of these ions is correlated with decomposition of rocks, rainfall with marine hygroscopic nuclei, presence of rural clusters (leaks from septic tanks), and decomposition of organic matter (grasses surrounding the dam area) (HELENA et al., 2000; RABEMANANA et al., 2005; COSTA; MELO; SILVA, 2006).

Similar results were found by Lima et al. (2017a) when evaluating the alluvial aquifer of the Cobra River Basin: correlation between Cl^- and Na^+ of 0.98. They stated that these ions are abundant in the study area and are primarily from decomposition of rocks.

Na^+ and Cl^- had high correlation (above 0.85) with Ca^{2+} and Mg^{2+} in the two periods. This result may be attributed to natural mineralization of geological components of soils.

Table 3. Correlation matrix for variables analyzed in water samples from underground dams in the state of Rio Grande do Norte, Brazil, collected at the end of the dry season, 2018.

	pH	EC	K^+	Na^+	Ca^+	Mg^{2+}	Cl^-	CO_3^{2-}	HCO_3^-	TSS	Cu	Mn	Fe	Zn	Cr	Ni	Cd	Pb
pH	1.00																	
EC	0.33	1.00																
K^+	0.61	0.61	1.00															
Na^+	0.40	0.97	0.64	1.00														
Ca^+	0.31	0.87	0.55	0.85	1.00													
Mg^{2+}	0.19	0.94	0.53	0.87	0.74	1.00												
Cl^-	0.33	0.99	0.62	0.98	0.91	0.90	1.00											
CO_3^{2-}	0.62	0.30	0.39	0.34	0.28	0.16	0.27	1.00										
HCO_3^-	-0.05	0.31	0.10	0.22	0.06	0.47	0.18	0.15	1.00									
TSS	-0.17	-0.03	-0.02	-0.01	-0.06	0.00	-0.03	-0.11	0.02	1.00								
Cu	0.32	0.63	0.55	0.70	0.72	0.48	0.70	0.16	-0.16	0.01	1.00							
Mn	-0.35	0.09	-0.11	-0.02	0.14	0.20	0.07	-0.22	0.27	0.44	-0.08	1.00						
Fe	-0.26	-0.16	-0.01	-0.15	-0.11	-0.13	-0.14	-0.25	-0.06	0.51	0.06	0.33	1.00					
Zn	0.37	0.23	0.35	0.28	0.28	0.19	0.26	0.17	-0.08	-0.01	0.42	0.03	-0.07	1.00				
Cr	0.19	0.39	0.36	0.47	0.56	0.22	0.46	0.14	-0.23	0.21	0.76	0.06	0.26	0.24	1.00			
Ni	0.18	0.86	0.51	0.81	0.81	0.85	0.87	0.20	0.13	-0.02	0.54	0.12	0.01	0.17	0.27	1.00		
Cd	0.04	0.38	0.29	0.27	0.21	0.45	0.30	-0.05	0.49	-0.05	0.01	0.14	-0.14	-0.13	-0.13	0.23	1.00	
Pb	0.00	0.72	0.32	0.59	0.47	0.79	0.66	-0.02	0.47	-0.03	0.22	0.18	-0.15	-0.08	0.05	0.57	0.60	1.00

pH = hydrogen potential; EC = electrical conductivity; K^+ = potassium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Cl^- = chlorides; CO_3^{2-} = carbonate; HCO_3^- = bicarbonate; TSS = total suspended solids; Cu = copper; Mn = manganese; Fe = iron; Zn = zinc; Cr = chromium; Ni = nickel; Cd = cadmium; Pb = lead.

Electrical conductivity (EC) was strongly correlated with Cl^-, Na^+, Ca^{2+}, and Mg^{2+} ions in the two sampling periods evaluated (r = 0.87 to 0.99). This result was expected, as these variables are directly correlated with water salinity.

Helena et al. (1999) found a strong correlation between chloride and sodium when evaluating the alluvial aquifer of the Psuerga River and attributed this result to anthropogenic origin; they also found significantly high correlation of EC with calcium, magnesium, sulfate, chloride, potassium, sodium, and nitrate.

A high correlation (above 0.81) was found between Ni and ions that cause EC increases (Na^+, Ca^{2+}, Mg^{2+}, and Cl^-). Higher correlations were found at the end of the rainy season for CO_3^{2-} and HCO_3^- (r = 0.86) and Zn and Cu (r = 0.86).

The principal component analysis (PCA) resulted in four factors for the dry season data and six factors for the rainy season data (Table 4), explaining 75.71% and 81.94% of the total hydrochemical variance, respectively.

Table 4. Rotated factor loading matrix using the Normalized Varimax method for physicochemical variables of water samples from underground dams in the state of Rio Grande do Norte, Brazil, collected in two periods (end of the dry and rainy seasons).

Variables	Factor axis for the end of the dry season (2018)				Factor axis for the end of the rainy season (2019)					
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
	Factorial loads									
pH	0.17	-0.04	-0.25	0.86	0.09	0.07	0.59	0.03	0.14	0.34
EC	0.93	0.26	-0.03	0.21	0.98	0.04	0.10	0.01	-0.03	0.09
K^+	0.54	0.08	0.02	0.61	0.13	0.25	0.39	-0.39	0.19	0.46
Na^+	0.91	0.12	-0.04	0.29	0.98	0.02	0.06	0.02	-0.07	0.04
Ca^{2+}	0.91	-0.04	0.00	0.19	0.91	0.09	0.13	0.08	0.17	0.13
Mg^{2+}	0.86	0.44	0.02	0.09	0.95	0.03	0.08	0.01	0.00	0.15
Cl^-	0.96	0.12	-0.04	0.19	0.98	0.05	-0.02	0.01	-0.04	0.10
CO_3^{2-}	0.08	0.10	-0.16	0.79	0.16	0.09	0.92	-0.11	0.04	-0.09
HCO_3^-	0.09	0.83	0.13	0.09	0.17	-0.06	0.87	0.09	0.09	-0.17
TSS	-0.04	0.01	0.84	0.03	-0.02	-0.89	-0.01	-0.08	0.26	0.17
Cu	0.77	-0.41	0.07	0.25	-0.06	-0.30	0.11	-0.09	0.89	-0.04
Mn	0.10	0.29	0.70	-0.23	0.00	-0.82	0.06	0.16	0.17	-0.05
Fe	-0.05	-0.20	0.78	-0.12	-0.10	-0.80	-0.19	-0.17	0.00	0.01
Zn	0.23	-0.25	0.10	0.49	-0.05	-0.09	0.12	-0.01	0.95	0.03
S	NU	NU	NU	NU	0.70	0.00	0.32	-0.05	-0.15	-0.26
B	NU	NU	NU	NU	0.60	-0.42	0.30	-0.03	-0.17	-0.21
Cr	0.55	-0.52	0.32	0.19	-0.07	0.09	-0.24	-0.85	-0.03	-0.06
Ni	0.87	0.13	0.01	0.06	0.01	-0.27	0.27	-0.80	0.11	-0.04
Cd	0.27	0.70	-0.04	-0.04	NU	NU	NU	NU	NU	NU
Pb	0.65	0.59	-0.05	-0.17	0.13	-0.14	-0.10	0.11	-0.07	0.84
Eigenvalues	7.51	2.63	2.24	1.24	5.99	3.09	2.35	1.57	1.51	1.07
Total variance (%)	41.72	14.63	12.47	6.89	31.50	16.24	12.36	8.26	7.93	5.64
Accumulated variance (%)	41.72	56.35	68.82	75.71	31.50	47.75	60.11	68.37	76.30	81.94

NU = parameter not used in the analysis of the period; pH = hydrogen potential; EC = electrical conductivity; K^+ = potassium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Cl^- = chlorides; CO_3^{2-} = carbonate; HCO_3^- = bicarbonate; TSS = total suspended solids; Cu = copper; Mn = manganese; Fe = iron; Zn = zinc; S = sulfur; B = boron; Cr = chromium; Ni = nickel; Cd = cadmium; Pb = lead.

The first factor for the dry season data grouped the variables EC, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, Cu, and Ni, which accounted for 41.72% of the total hydrochemical variance in this period. This factor was correlated with salinity, sodicity, and toxicity of water for irrigation purposes, and it is also directly correlated with natural mineralization of geological components of the soil, rainfall with marine hygroscopic nuclei, presence of rural clusters (leaks from septic tanks), and decomposition of organic matter (grasses in the dam area). These characteristics were also significant in the first factor for the rainy season data (Table 4), which grouped the variables EC, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and S and explained

31.50% of the hydrochemical variance in this period.

Similarly, Lima et al. (2017a) used factor analysis in a study on the alluvial aquifer of the Cobra River basin and found similar results for the first factor, which grouped variables correlated with natural mineralization of geological components of soils (EC, Na^+, Ca^{2+}, Mg^{2+}, and Cl^-) and explained 39.30% of the total hydrochemical variance.

The second factor for the dry season data grouped the variables HCO_3^- and Cd and accounted for 14.63% of the total hydrochemical variance in the period. These variables also were correlated with natural mineralization of geological components of soils.

The third factor for the dry season data grouped the variables TSS, Mn, and Fe, explaining 12.47% of the total hydrochemical variance. This factor was correlated with risk of clogging of localized irrigation systems. The main obstruction issues found were correlated with the presence of algae and iron in the water. Similarly, the second factor for the rainy season data grouped these same variables, explaining 16.24% of the total hydrochemical variance, and presented similar correlation characteristics.

The fourth factor for the dry season data grouped the variables pH and CO_3^-, explaining 6.89% of the total hydrochemical variance in the period. This factor was correlated with water alkalinity, since the CO_3^-concentration increases as the pH increases. These same variables plus HCO_3^- were grouped in the third factor for the rainy season, explaining 12.36% of the total hydrochemical variance in the period, with similar correlation characteristics.

The fourth, fifth, and sixth factors for rainy season were less expressive. The fourth factor grouped the variables Cr and Ni and the sixth factor was represented only by Pb, which explained 8.26 and 5.64% of the total hydrochemical variance, respectively. These factors were correlated with the presence of heavy metals in the water; however, these metals were found in small concentrations and, therefore, do not represent a risk to crops growing in the areas.

The fifth factor for the rainy season data grouped the variables Cu and Zn, explaining 7.93% of the total hydrochemical variance in the period. This factor was correlated with the presence of micronutrients in the water and do not represent a risk to crops growing in the areas.

CONCLUSIONS

The concentrations of variables correlated with soil salinization risks and plant toxicity had decreased after the rainy season, whereas those correlated with clogging of localized irrigation systems increased.

Most of the evaluated underground dams were classified as C2-S1 in terms of risk of soil salinization and soil sodification.

Alkalinity, presence of algae, and concentration of iron ions were the main variables correlated with clogging of localized irrigation systems when using water from these dams.

Variables correlated with salinity had a greater impact on the hydrochemical variability of water within the dams evaluated in the two sampling periods. Electrical conductivity and chloride ions showed the highest factorial loads for salinity.

The water quality of the underground dams evaluated were found to be affected by climate and topography factors, as well as by local factors such as geology, presence of rural clusters and animal husbandry in the vicinity of the dams, and the absence of protective devices in wells.

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