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Spatial variability of water electrical conductivity in underground dam areas in the semi-arid region of Rio Grande do Norte, Brazil

Variabilidade espacial da condutividade elétrica da água em áreas de barragens subterrâneas do semiárido potiguar

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ABSTRACT - Underground dams have been widely deployed in the semi-arid region of Rio Grande do Norte, a state in the Brazilian Northeast, aiming to mitigate the effects caused by water scarcity. In this study, the geographic distribution of the electrical conductivity of water of underground dams was evaluated at the end of the dry season of 2018 and at the end of the rainy season of 2019. Maps were created in ArcGIS 10.4.1 software using the Inverse Distance Weighted interpolator. The results indicated high electrical conductivity variability in the evaluated underground dams. The highest values were obtained in the eastern portion of the Rio Grande do Norte state, except for two dams, located in the municipalities of Apodi and Severiano Melo. In most of the underground dams (64%), the water has an electrical conductivity with low soil salinization potential (EC < 0.7 dS m^{-1}). It was observed that the salinity of the underground dams is influenced by several factors, such as climate, relief, land use and occupation due to rural agglomerations and animal husbandry in the dam hydrographic basin, and intensive nutritional management with fertilizers in the dam area.

Keywords: Alluvial aquifer. Salinity. Geostatistics. Interpolation.

RESUMO - As barragens subterrâneas é uma tecnologia de convivência com a seca amplamente construída na zana semiárida do Rio Grande do Norte como garantia da segurança hídrica devido à escassez de água superficial. Neste trabalho avaliou-se a distribuição geográfica da condutividade elétrica da água (CEa) de barragens subterrâneas, no final do período seco de 2018 e no final do período chuvoso de 2019. Após a coleta e análise da CE da água das barragens foram elaborados os mapas utilizado o software ArcGIS 10.4.1, com auxílio do interpolador de ponderação do inverso da distância. Os resultados indicaram grande variabilidade da CEa nas barragens avaliadas, sendo os maiores valores de CEa registrados nas barragens situadas na porção leste do estado do Rio Grande do Norte – Classes C_2 e C_3, exceto nas duas barragens localizadas nos municípios de Apodi e Severiano Melo. A maioria das águas das barragens (64%), devido à baixa CEa, não tem restrição de uso quanto aos riscos de acúmulo de sais quando utilizadas para a irrigação (CE < 0,7 dS m^{-1}). Observou-se que a salinidade das barragens é influenciada por fatores edafoclimáticos, uso e ocupação do solo e, ainda pela presença de aglomerados rurais, criação de animais na bacia hidrográfica da barragem e, pelo uso intensivo do manejo nutricional com fertilizantes na área do barramento.

Palavras-chave: Aquífero aluvial. Salinidade. Geoestatística. Interpolação.

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INTRODUCTION

Underground dams are hydraulic structures that block and store the groundwater flow in the aquifer layers (AHMED et al., 2016). According to Stevanovic (2015), there are two types of underground dams: dams built in unconsolidated rocks, mainly alluviums, and dams built as a barrier within hard rocks, mainly in karst environments. The author also points out that the first model is more used in countries that have regions with arid and semi-arid climate.

Among the types of underground dams, which contain the alluvial aquifer, used in Brazil, the most used model in the semi-arid region is the Costa & Melo (LIMA et al., 2013). This type of dam has as characteristics the manual excavation of a rectilinear trench in the bed of a river or stream, perpendicular to the flow direction, in which a 200-micron polyethylene tarpaulin is inserted to waterproof the soil and prevent the passage of water. This waterproofed area is then covered with stones to protect the dam. One or more Amazon wells are installed in the underground dam area to enable the use of water for animal and domestic consumption and agricultural production. Piezometers should also be installed along the reservoir area of the dam, which will assist in the evaluation of water quality and quantity (FRANÇA; PINHEIRO; CARVALHO, 2016).

In addition, Lima et al. (2018) state that this type of dam is widely used because it is a simple construction structure, with low cost of implementation and easy operation, in addition to reducing water losses by evaporation, promoting greater protection of water from external pollution, and causing no losses of surface areas by flooding.

In recent years, the federal government has prioritized funding for the construction of underground dams as a social technology to meet the water needs of the rural population of the semi-arid region (LIMA et al., 2019). This fact can be observed in the state of Rio Grande do Norte, where 1591 underground dams were implemented only by the Technical Assistance and Rural Extension Company of the state (EMATER/RN) between 2008 and August 2018.

Despite the advantages and importance of underground dams for water and food security, there are many cases of failure, mainly due to location problems, of social nature – appropriation of technology, construction techniques and especially lack of management, which can compromise the sustainability and construction purposes of the dams (LIMA et al., 2020). In addition, seasonal monitoring of dam water and soil quality is essential for the success of the water abstraction and storage technology, which should involve beneficiary families through programs to monitor the use of dams in order to identify restrictions on the use of water for irrigation purposes.

With regard to water quality, Andrade et al. (2012) conducted a study to monitor the quality of water from underground dams in the state of Pernambuco, during three hydrological cycles, and identified that there are seasonal variations in the potential risks of water from underground dams, that is, water use restrictions vary spatially (dam location) and temporally (collection season).

Considering these aspects, a study was conducted to evaluate the quality and spatial variability of the physicochemical parameters of the water, as well as the degree of restrictions of use for irrigation purposes, of 45 underground dams located in the semi-arid region of the Rio Grande do Norte state, Brazil.

MATERIAL AND METHODS

The quality of water from the Amazon wells of the underground dams existing in the Rio Grande do Norte state, Brazil, was analyzed.

The 45 underground dams were selected for the study (Figure 1) according to the following criteria: a) the dam should have been built by the Technical Assistance and Rural Extension Company of Rio Grande do Norte (EMATER/RN), because this institution has the largest number of dams installed in the state (LIMA, 2013); b) the dam should be considered finished by EMATER/RN, that is, it should have wells, stone bunds and stone finish, on the impermeable barrier, installed; c) there must be water in the dam well; and, d) there must be an indication of the local technician of EMATER/RN.

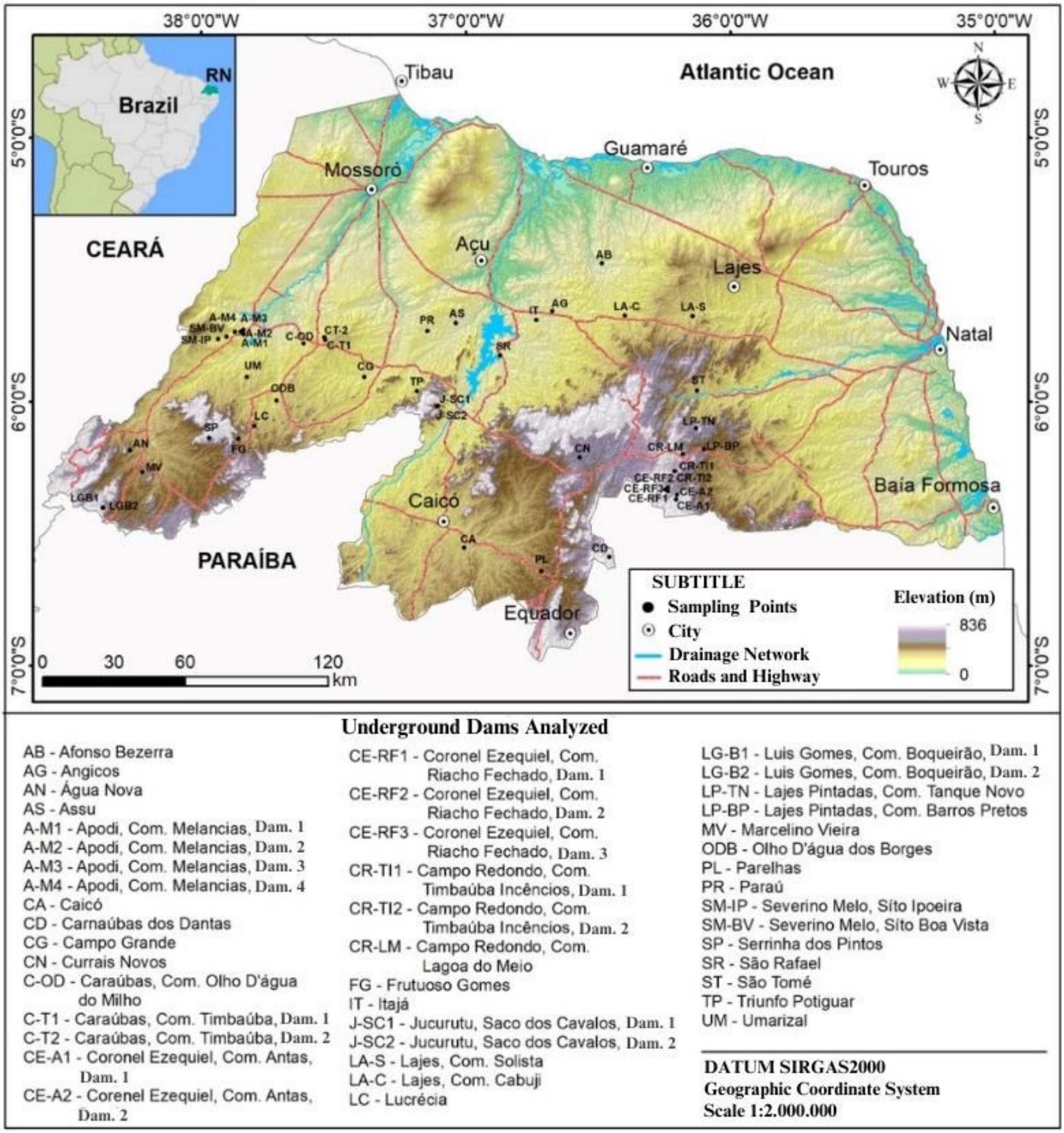
Most of the dams evaluated are located under a climate classified as BSh, characterized by scarcity of rainfall (250 – 750 mm), which occurs in the summer and extends until autumn, considerable irregularity in its distribution and high evaporation rates (DUBREUIL et al., 2018).

These dams are located on rocks of the crystalline basement and, according to Embrapa (2020), in the following types of soil: *Argissolo vermelho amarelo* (Ultisol) (NA, LC, LG-B1, LG-B2, MV, UM), *Luvissolo crômico* (Alfisol) (A-M1, A-M2, A-M3, A-M4, CA, CG, LP-BP, LP-TN, PL, SM-BV, SM-IP, ST), *Neossolo litólico* (Entisol) (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* (Entisol) (C-OD, C-T1, C-T2, ODB), *Planossolo háplico* (Alfisol) (LA-S) and *Planossolo nátrico* (Alfisol) (AB, AS, LA-C, PR). Regarding the type of relief, most of the dams are located on flat relief (53%), while the others are located on gently undulating relief (29%) and undulating relief (18%), according to the classification of Santos et al. (2018).

About 65% of the selected dams are located in the basins with the largest drained area in the state and that flow into the north coast, which are: a) Piranhas-Assu river basin (31% of the dams) and b) Apodi-Mossoró river basin (42%). The other dams are located in the Trairí river basin (20%), Potengi river basin (5%) and Ceará Mirim river basin (2%), which flow into the eastern coast of the state (ANA, 2012).

The water samples were collected in the excavated shallow wells, regionally called ‘cacimba’ or ‘amazonas’ (Figure 2), existing in the underground dams, in two periods: end of the dry season, between October and December of 2018, and end of the rainy season, in July of 2019. This site was chosen for collection because this water source is the one commonly used by farmers for consumption and especially for agriculture, except when cultivation is performed on the margins upstream of the dam under irrigation – in this case, the evaluation must be carried out in the soil.

Water collections were performed using an aluminum bucket and rope, and the samples were stored in 1 L polypropylene bottles and preserved in thermal containers with ice during transport to the Soil, Water and Plant Analysis Laboratory (LASAP) of the Department of Engineering and Environmental Sciences (DECAM) of the Federal Rural University of the Semi-Arid Region (UFERSA), Campus of Mossoró, RN. The aluminum bucket and the bottles used were previously washed with the water to be sampled, according to the sampling protocol described by Almeida (2010). The electrical conductivity of the water was determined at ambient temperature using a probe-type conductivity meter, HACH-CDC401 model (USA).



Com. – community; UD – Underground dam.

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

Figure 2. Shallow wells in the underground dams LG-B2 (A) and SM-IP (B).

The results obtained were analyzed by means of descriptive statistics, using Excel 2016 and Statistica 7.0 software, determining maximum and minimum values, mean, median, standard deviation, coefficient of variance, kurtosis and skewness, subjected to Shapiro-Wilk normality test at 5% significance level. Histograms and boxplots were also generated.

In addition to the determination of water electrical conductivity, characteristics of the underground dams were recorded through informal conversations with the owners: construction time; protection devices in the shallow well according to recommendations of Funasa (2019); flooding of the dam area after the rainy season; presence of surface dams upstream of the dam – distance of at most 200 m; existence of rural agglomeration, corral for cattle or pens for goat, pigs and poultry near the dam; and management of the dam with regard to the use of its area and water existing in its well.

Regarding the spatialization of electrical conductivity, the data produced were plotted with ArcGIS-10.4.1 software on maps created using the DATUM SIRGAS2000 and the geographic coordinate system.

To estimate the values of electrical conductivity at non -sampled sites from data obtained in the wells of the analyzed dams and to construct the maps of their geographical distribution, the Inverse Distance Weighted (IDW) interpolator was adopted in ArcGIS-10.4.1 software. According to Souza et al. (2010), IDW is a univariate deterministic interpolator of weighted means, so this method does not take into account the spatial correlation of the data but only relationships based on distance.

The IDW interpolation method predicts a value for an unmeasured site using values sampled around it, determining a higher weight for the nearest sampled values, according to Equation 1.

$$Z_e = \frac{\sum_{i=1}^{n}\left(\frac{1}{d_i^{\beta}} \times Z_{si}\right)}{\sum_{i=1}^{n}\frac{1}{d_i^{\beta}}} \qquad (1)$$

Where:
Z_e - estimated value;
Z_{si} - sampled value;
d_i - Euclidean distance between sampled value and estimated value;
b - exponent of weighting; and
i - Number of sampled points used to estimate the value of an unmeasured site.

Different values can be attributed to the exponent of the weighting, but the higher the value of this power, the greater the influence of the nearest neighbor on the estimation of the values. Exponent 2, which represents the inverse of the distance squared, and 7 sampled points closest to the site to be interpolated were used in this study.

The accuracy of the IDW interpolator was evaluated by means of mean absolute error (MAE), mean relative error (MRE) and mean squared error (MSE), estimated using Equations 2, 3 and 4, respectively.

$$MAE = \frac{1}{n}\sum_{1}^{n}|Z_{si} - Z_{ei}| \qquad (2)$$

$$MRE = \frac{1}{n}\sum_{1}^{n}\left(\frac{|Z_{si} - Z_{ei}|}{Z_{si}} \times 100\right) \qquad (3)$$

$$MSE = \frac{1}{n}\sum_{1}^{n}(Z_{si} - Z_{ei})^2 \qquad (4)$$

Where:
n - number of points sampled;
Z_{si} - sampled value, that is, value obtained in the analysis of electrical conductivity of the water from each well analyzed; and
Z_{ei} - value estimated by the IDW interpolator for the electrical conductivity of the water from each well analyzed.

RESULTS AND DISCUSSION

Figure 3 shows the distribution of the dams evaluated, in the two periods of collection, in relation to this classification regarding the degree of restriction of use, that is, risk of accumulation of salts in the soil. At the end of the rainy season, the salinity (EC) of the waters from the wells tend to decrease and, consequently, there is a reduction in the risks of salinization. In addition, most of the waters from the wells of the underground dams have no restrictions of use for irrigation regarding salinity, regardless of the period of collection.

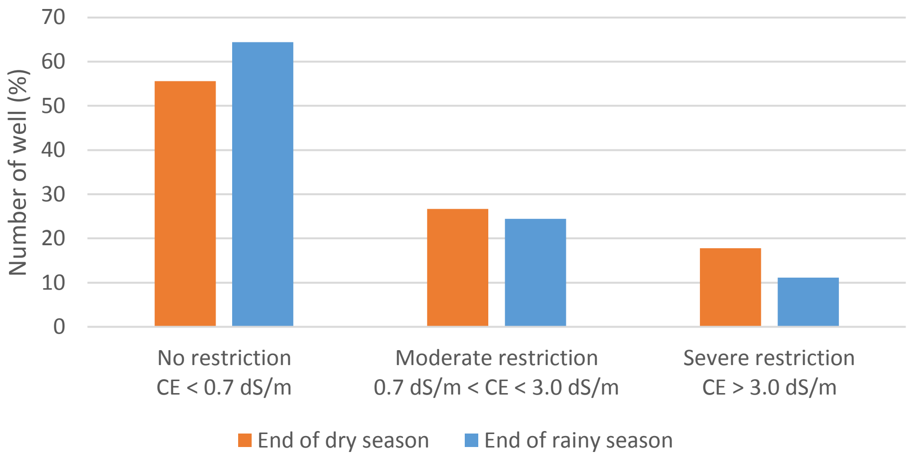


Figure 3. Classification of the water from the wells of the dams analyzed, regarding the degree of restriction for use in irrigation, considering the risks related to salinity.

On the other hand, in both periods of collection, less than 20% of the groundwater from the wells of the underground dams has severe restrictions regarding the risks of accumulation of salts. Severe risks of soil salinity are higher in the dry season, since there is a concentration of salts in the water due to the high evaporation of the semi-arid environment. These findings were also observed by several authors, such as Cirilo et al. (2003), who recorded reduction in the EC of water from underground dams in the Ouricuri, São Caetano and Mutuca sub-regions, in the state of Pernambuco, when they compared the dry and rainy seasons. The recharge of these areas, due to rainfall, reduces the concentration of salts, while the accentuated evaporation increases the concentration of salts, so maximum levels of salinity can be reached at the end of the dry season.

The same climatological influence was observed by Andrade et al. (2012), in the water from alluvial valleys of the semi-arid region of Pernambuco, and by Lima et al. (2019), in underground dams located in the Cobra river basin, which covers the municipalities of Parelhas, Carnaúba dos Dantas and Jardim do Seridó, located in the state of Rio Grande do Norte.

Andrade et al. (2012) warn that the continuous use of water with electrical conductivity above 0.7 dS m^{-1} in irrigation, without proper management, may contribute to increasing the concentration of salts in the soil. These salts can be transported to the saturated zone of the aquifer through rainfall and/or irrigation, causing an increase in groundwater salinity. When analyzing the electrical conductivity of the waters from the wells of the underground dams evaluated (Figure 3), considering the end of the dry season, it was observed that 44% had values higher than 0.7 dS m^{-1}.

Table 1 presents the results of the descriptive statistics for the electrical conductivity of the water, at the end of the dry season (year 2018) and at the end of the rainy season (year 2019), from shallow wells installed in the underground dams analyzed.

When evaluating the coefficient of variation of the electrical conductivity of groundwater used for irrigation in a rural settlement in the semi-arid region of Pernambuco, Andrade et al. (2012) obtained values above 160% in the various periods evaluated. Costa, Melo and Silva (2006) also found high coefficients of variation of electrical conductivity, above 100%, when analyzing waters from the crystalline aquifer of Rio Grande do Norte.

The difference observed between the mean and median values (Table 1), in the two periods studied, indicates that the electrical conductivity values obtained are not symmetrically distributed. This characteristic is confirmed by the positive and high value of the skewness coefficient. There was also a high value of kurtosis, in both periods, indicating a non-normal distribution, which is confirmed by the Shapiro-Wilk normality test at 5% significance level, as shown in Table 1 and Figure 4.

The results of electrical conductivity obtained in the collections from the wells of the underground dams, in both periods, presented in box plots, statistically show the existence of outliers (Figure 5).

Table 1. Descriptive statistics for the electrical conductivity of the water from the wells of the underground dams analyzed.

Description	EC – End of dry season (2018)	EC – End of rainy season (2019)
Minimum (dS m^{-1})	0.134	0.092
Maximum (dS m^{-1})	13.010	12.365
Amplitude (dS m^{-1})	12.876	12.273
Mean (dS m^{-1})	1.708	1.141
Median (dS m^{-1})	0.621	0.512
Standard Deviation (dS m^{-1})	2.672	2.048
Coefficient of Variation (%)	156.4	179.5
Fisher's Skewness Coefficient	2.843	4.284
Kurtosis	8.265	21.176
$p < 0.05$	0.000*	0.000*

*Does not follow normal distribution by the Shapiro-Wilk test at 5% significance level.

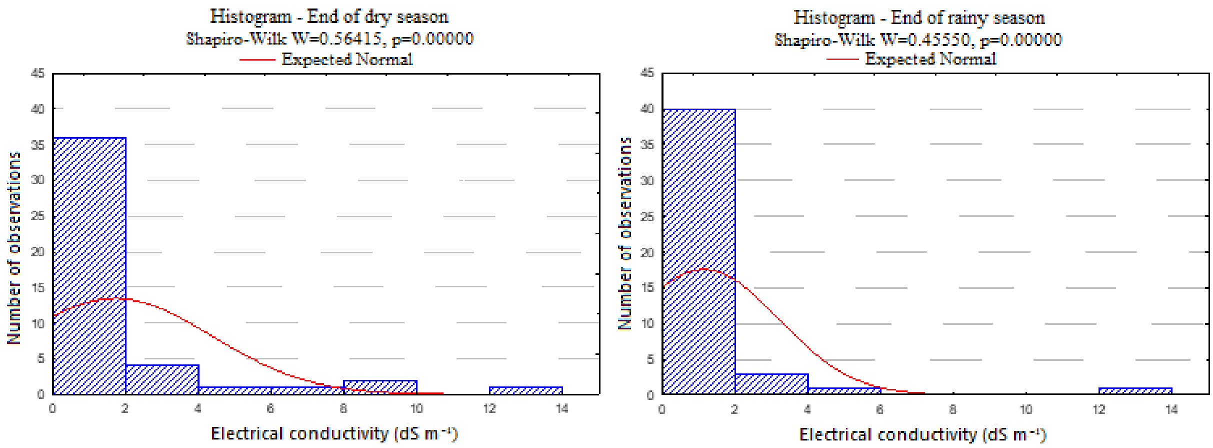


Figure 4. Histograms of the electrical conductivity of water from the wells of the underground dams at the end of the dry season of 2018 (A) and end of the rainy season of 2019 (B).

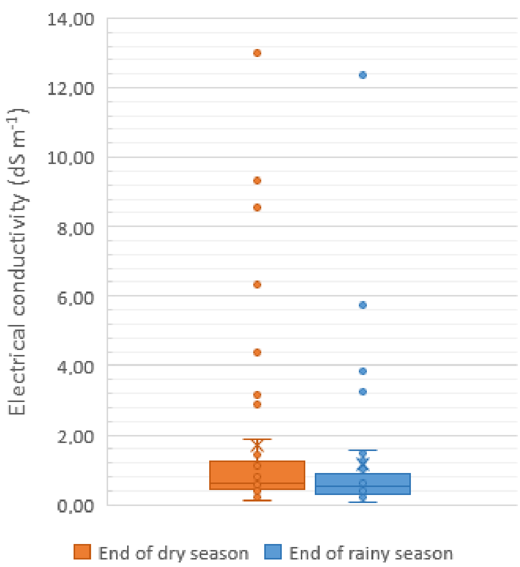


Figure 5. Box plot of the electrical conductivity of water from the wells of the underground dams, at the end of the dry season of 2018 and the end of the rainy season of 2019

Based on the values of electrical conductivity, in the two periods of collection, nine dams presented themselves as outliers, for having values higher than those of most dams. Despite that, these data were not discarded from the geostatistical analysis, because it was considered that the electrical conductivity measurements were carried out judiciously and that these discrepancies represent the physical -chemical characteristics of the soil, management, use and occupation of the basin of each underground dam.

Figures 6 and 7 show the IDW interpolation of electrical conductivity as maps of its spatial distribution.

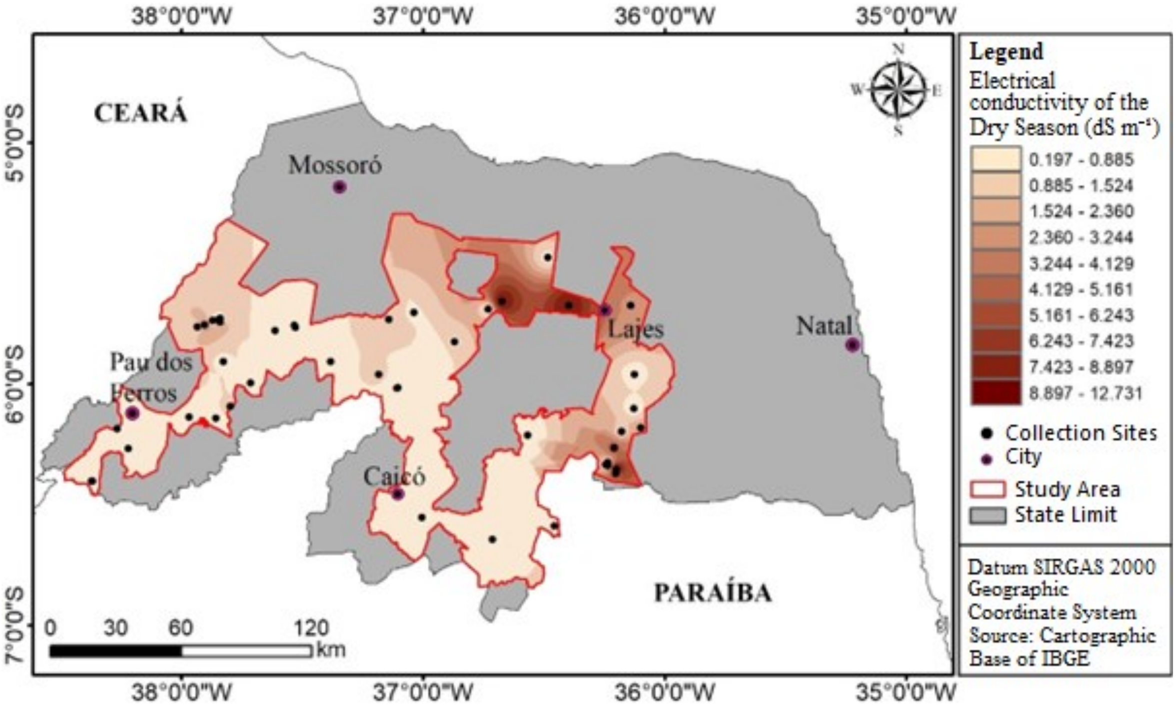


Figure 6. Spatial variation of the electrical conductivity of water from the underground dams at the end of the dry season of 2018.

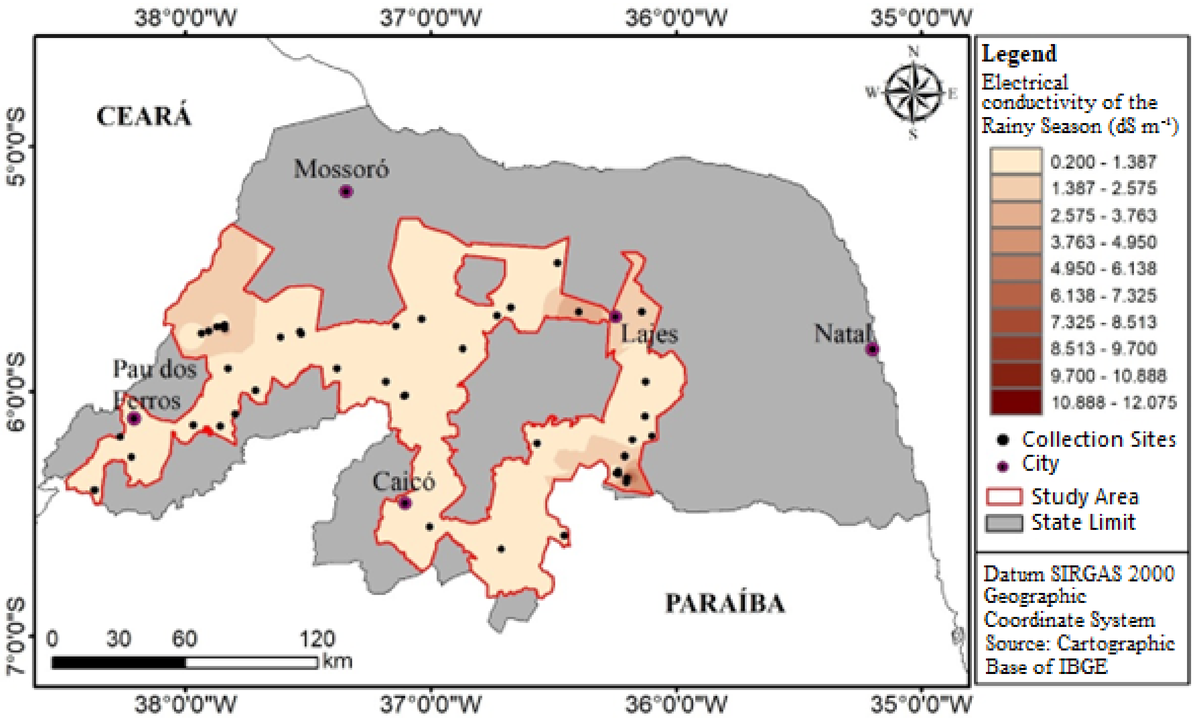


Figure 7. Spatial variation of the electrical conductivity of the water from the underground dams, at the end of the rainy season of 2019.

Most of the collection sites are well distributed, except for the municipalities of Apodi and Coronel Ezequiel, which have a higher concentration. As previously explained, the choice of the collection site was conditioned on the existence of water in the dam well and indication of the local technician of EMATER/RN.

It is observed that the areas that had highest electrical conductivity at the end of the dry season (Figure 6) are similar to the areas of highest electrical conductivity obtained at the end of the rainy season (Figure 7).

The underground dams that had waters with higher electrical conductivities – moderate and severe restrictions of use (C2 and C3 classes, respectively) – are mostly located in the eastern portion of Rio Grande do Norte, more specifically near the municipalities of Angicos and Coronel Ezequiel. In addition, there are records of high EC values also near the municipality of Apodi. For the other dams, the EC values of the waters are low – no restriction of use (C1 class), that is, there are virtually no risks of salinization.

Costa, Melo and Silva (2006) evaluated the EC of the water from the crystalline aquifer in the State of Rio Grande do Norte and recorded the highest salinities in the eastern region, and these values decreased toward the west direction of the crystalline aquifer. The authors concluded that the accumulation of salts in the aquifer water is influenced by the climatic conditions and the relief of the state and that the salinization processes can be intensified in periods of extreme weather situation.

The eastern region of the crystalline aquifer is located on the leeward side of the Borborema Plateau, characterized by low precipitation and high evaporation. In this area, rainfall is mainly caused by the action of Easterly Wave Disturbances, which are loaded with hygroscopic marine nuclei, rich in sodium and chloride. In addition, the flat and slightly rugged relief of the Sertaneja Depression leads to low mobility of the waters, which are subjected to evaporation, increasing salinity (COSTA; MELO; SILVA, 2006).

The outliers presented in Figure 5 corroborate the maps presented in Figures 6 and 7, since it can be observed that the highest salinities are located in the municipalities of Coronel Ezequiel, Campo Redondo, Angicos and Lajes, which are located in the easternmost portion of the crystalline aquifer, and in the municipalities of Apodi and Severiano Melo, located in the western portion.

The CE-A2 dam, located in the municipality of Coronel Ezequiel, Antas community, underground dam number 2, had the highest electrical conductivity in the two periods studied (13.010 dS m^{-1}, at the end of the dry season, and 12.365 dS m^{-1}, at the end of the rainy season). Despite that, water from the well is used in the cultivation of passion fruit for commercial purposes, located in the catchment area of the underground dam.

In this dam, cattle waste is used as fertilizer and acaricide is used to avoid pests in the crop. It is situated on an undulating terrain, according to the classification proposed by Santos et al. (2018), at an altitude of approximately 400 m and with no other surface dams nearby.

The higher EC values found in the present study may be related to agricultural activities and the use of water from the alluvial aquifer in irrigation, thus generating recirculation of groundwater and, consequently, greater mineralization due to evaporation and infiltration processes. This fact was also reported by Helena et al. (1999), who recorded higher values of salinity and nitrate concentration on the left bank of the alluvial aquifer of the Pisuerga River in Spain due to local agricultural activity.

In addition, the EC of the dam can be influenced by the type and characteristic of the soil. A study conducted by Cirilo et al. (2003), aiming to evaluate the physicochemical quality of the water in the dams of Mutuca, in the state of Permambuco, found that the waters of dams built in *Planossolos* (Alfisols) and Litholic soils have higher EC than those of dams built in alluvial soils. Rabemanana et al. (2005) also observed the influence of dam soils on water quality and found that wells located in the crystalline bedrock of Madagascar that had more saline water were associated with places where groundwater had low flow, weathered zones that are thin and formed by clay, and areas situated on hilltops (plateaus) or at valley bottoms.

The LA-C dams, located in the municipality of Lajes, Cabugi community, CR-TI1, in the municipality of Campo Redondo, Timbaúba dos Inocêncios community, underground dam number 1, and AG, in the municipality of Angicos, have in common the existence of a surface dam upstream, at a distance of approximately 200 m. In addition, the areas of the dams are used for the cultivation of grass, sorghum and/or maize, with application of animal waste as fertilizer.

Part of the area of these underground dams is flooded for approximately three months after the rainy season, which according to Cirilo et al. (2003) may increase the risk of salinization of the soil in the dam. The authors also stated that the non-use of water from the underground dam combined with the high rates of evaporation also increases the risk of salinization. However, in the present study it was not possible to obtain a correlation between the non-use of water from the dam and the existence of higher electrical conductivity levels. This fact suggests the need for continuous evaluation of water from the underground dams to reach a more accurate conclusion about the behavior of salinity.

The CRTI-2 dam, located in the municipality of Campo Redondo, Timbaúba dos Inocêncios community, underground dam number 2, is located upstream of the CRTI-1 underground dam and after a surface dam. The dam area is also used for the cultivation of grass, sorghum and/or maize, with application of animal waste as fertilizer.

The dams located in the municipality of Lajes, Solista community (LA-S), and in the municipality of Coronel Ezequiel, Antas community, underground dam number 1 (CE-A1), showed similar behavior of electrical conductivity in the two periods analyzed, on average 3.077 dS m^{-1} at the end of the dry season and 1.523 dS m^{-1} at the end of the rainy season. The dams have different characteristics regarding water use and area.

The well of the LA-S dam has protective devices and its water is used for animal consumption and irrigation. Its area is used for the cultivation of grass and vegetables fertilized with cattle waste. There is also a small pig farm located in the catchment area of the underground dam.

The well of the CE-A1 dam is unprotected and its wall is at ground level. Neither the area of the dam nor its water is used. A greater influence of geological and climatic factors on the salinity of these dams is presumed.

The dams located in the western portion of the crystalline aquifer, in the municipality of Apodi, Melancias community, underground dam number 1 (A-M1), and in the municipality of Severiano Melo, Boa Vista community (SM-BV), have in common the flat relief, with an average altitude of 125 m. In addition, there is the presence of rural agglomerations and surface dams upstream, approximately 200 m away from the underground dams; and their areas are used for cultivation, mainly of grass, with application of cattle waste as fertilizer only in the A-M1 dam.

The waters from the wells of the two dams had electrical conductivity above 3.0 dS m^{-1}, in the two periods studied, and are used for animal consumption. In the A-M1 dam, the water is also used for irrigation of crops near the dam area.

Rabemanana et al. (2005) warn that the residues of rural/urban agglomerations, the existence of septic tanks, and the presence of animal residues or manure/fertilizers can increase the concentrations of nitrate, chlorides and potassium in groundwater and consequently its electrical conductivity.

Helena et al. (2000) observed the influence of leakages in municipal sewage systems and/or septic tanks on the high concentrations of chlorine and sodium present in the water from the groundwater aquifer in the area of the village of Santovenia de Pisuerga, since they did not have geological origin and the concentrations showed little variation between the dry and rainy season.

In the same watershed of the Melancias creek, two more underground dams were evaluated (A-M4 and A-M3), located downstream of SM-BV and upstream of A-M1. Although the SM-BV and A-M1 dams had high electrical conductivity (above 3 dS m^{-1}), the A-M4 and A-M3 dams obtained electrical conductivity levels lower than 0.7 dS m^{-1} in both periods. It can be deduced that local factors, such as the type of soil, management of the underground dam, and land use and occupation in the basin have a great influence on the quality of the water of the dam.

Only 13% of the wells (CE-RF1, CE-RF2, LA-S, LG-B2, PR, ST) had protection devices, and it was not possible to correlate the existence of protection devices in the well with the occurrence of lower electrical conductivities or the collection period with salinity.

When analyzing the values of mean absolute error (MAE) and mean squared error (MSE) (Table 2), it is possible to infer that there was good efficiency in the estimation of electrical conductivity values, based on the data measured and estimated by geostatistics – determined by the IDW interpolator. Considering the values of mean relative error (MRE), the interpolator had good efficiency in the dry season (year 2018) and satisfactory efficiency in the rainy season (year 2019).

Table 3 shows the dams that had greater contribution to increasing the errors presented.

Table 2. Evaluation of the efficiency of the IDW interpolator for electrical conductivity of the water from the underground dams analyzed.

Description	MAE (dS m^{-1})	MRE (%)	MSE
IDW End of dry season	0.109	5.463	0.179
IDW End of rainy season	0.100	13.420	0.142

Table 3. Error presented by the IDW interpolator for electrical conductivity by type of error and underground dam.

Points	Electrical Conductivity (dS m^{-1})		Mean Absolute Error (dS m^{-1})		Mean Relative Error (%)		Mean Squared Error	
	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy
A-M1	3.225	5.745	0.081	0.153	2.5	2.7	0.01	0.02
A-M2	0.134	0.092	0.063	0.108	47.3	117.8	0.00	0.01
A-M3	0.234	0.214	0.070	0.123	29.9	57.5	0.01	0.02
CE-A1	3.050	1.562	0.368	0.419	12.1	26.8	0.14	0.18
CE-A2	13.010	12.365	0.278	0.289	2.13	2.33	0.08	0.08
CR-TI1	2.880	3.820	0.787	0.698	27.3	18.3	0.62	0.49
CR-TI2	6.350	0.761	2.683	2.361	42.2	310.2	7.20	5.57

The consecutive underground dams CR-TI1 and CR-TI2 are approximately 200 m apart, and CR-TI2 is located upstream of CR-TI1. These dams have the same type of management, climate actions, and it is believed that the same type of soil. The main difference between them is the proximity to a surface dam (CR-TI2 is closer) and the entry of flood water through the well opening in the CR-TI1 dam.

It can be observed that the electrical conductivity of the two dams shows divergent behavior in the two periods evaluated. In addition, the CR-TI2 dam has a great variation in electrical conductivity when comparing the two periods evaluated. There may be some contribution of the confined groundwater, through cracks in the underground dam, which cause this variation to become greater, or the surface dam can exert a strong influence on the underground dam, possibly being completely dry in the first period of collection. It would be necessary to evaluate these two dams for longer to understand the dynamics that occur between them. A negative influence of the data obtained at the CR-TI2 dam can be inferred in the generation of electrical conductivity maps with the IDW interpolator.

Also in the CR-TI2 dam, it can be observed that the mean absolute error and mean squared error obtained in the dry and rainy seasons are very close, but the mean relative error is quite different. This is due to the methodology used for error calculation, in which the mean absolute error is divided by the reference value, which in the case of the rainy season was lower than 1, considerably increasing the value of the error.

Despite the large difference in electrical conductivity between the CE-A1 and CE-A2 dams, the distance between them (2080 m) minimizes the errors presented in geostatistics.

When analyzing the data of the dams of the Melancias community, in the municipality of Apodi (A-M1, A-M2 and A-M3), it was observed that the A-M2 and A-M3 dams, which are located upstream of A-M1, have lower electrical conductivities than A-M1. The same influence of the A-M1 dam on the data obtained in the A-M2 and A-M3 dams using the IDW interpolator is noticed. This may have occurred because the distances between A-M1 and the A-M2 and A-M3 dams are virtually the same, 1,685 m and 1,490 m, respectively.

CONCLUSIONS

Most of the dams studied have no restriction of use regarding risks of salinization – accumulation of salts in the root zone, being indicated for most crops, including vegetables and fruit trees.

The areas of highest electrical conductivity at the end of the dry season are similar to the areas of highest electrical conductivity obtained at the end of the rainy season.

In most dams, salinity tends to decrease with the increase in water level, coming from rainfall.

Climatic factors, relief, and local factors (geology, presence of rural agglomerations, animal husbandry, use of fertilizers in the dam area) influence the accumulation of salts in the water of the dams.

REFERENCES

AHMED, M. F. et al. Groundwater dams, general characteristics and historical development. **Journal of Faculty of Engineering & Technology**, 23: 121-129, 2016.

ALMEIDA, O. A. **Qualidade da água de irrigação**. 1. ed. Cruz das Almas, BA: Embrapa Mandioca e Fruticultura, 2010. 234 p.

ANA – Agência Nacional de Águas. **Base Hidrográfica Ottocodificada Multiescalas**. 2012. Disponível em: <http://dadosabertos.ana.gov.br/datasets/b78ea64219b9498c8125cdef390715b7_0>. Acesso em: 20 nov. 2019.

ANDRADE, T. S. et. al. Variabilidade espaço-temporal da condutividade elétrica da água subterrânea na região semiárida de Pernambuco. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 16: 496–504, 2012.

CIRILO, J. A. et al. Soluções para o Suprimento de Água de Comunidades Rurais Difusas no Semi-Árido Brasileiro: Avaliação de Barragens Subterrâneas. **Revista Brasileira de Recursos Hídricos**, 8: 5-24, 2003.

COSTA, A. M. B.; MELO, J. G.; SILVA, F. M. Aspectos da salinização das águas do aqüífero cristalino no estado do Rio Grande do Norte, Nordeste do Brasil. **Águas Subterrâneas**, 20: 67-82, 2006.

DUBREUIL, V. et al. Os tipos de climas anuais no Brasil: uma aplicação da classificação de Köppen de 1961 a 2015. **Revista Franco-Brasilera de Geografia**, 37: 1-20. 2018.

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. **Mapa de Solos do Brasil**. 2020. Disponível em: <http://geoinfo.cnps.embrapa.br/layers/geonode%3Abrasil_solos_5m_20201104>. Acesso em: 14 jan. 2021.

FRANÇA, F. M. C.; PINHEIRO, J. C. V.; CARVALHO, R. M. Barragem subterrânea no Semiárido do Ceará: caracterização e análise da viabilidade econômica. **Parcerias Estratégicas / Centro de Gestão e Estudos Estratégicos**, 21: 17-44, 2016.

FUNASA - Fundação Nacional de Saúde. **Manual de saneamento**. 5. ed. Brasília, DF: Funasa, 2019. 545 p.

HELENA, B. A. et al. Temporal evolution of groundwater composition in an alluvial aquifer (Pisuerga river, Spain) by principal component analysis. **Water Research**, 34: 807-816, 2000.

HELENA, B. A. et al. A case of hydrochemical characterization of an alluvial aquifer influenced by human activities. **Water, Air, and Soil Pollution**, 112: 365–387, 1999.

LIMA, A. O. et al. Variation of the water table and salinity in alluvial aquifers of underground dams in the semi-arid region of Rio Grande do Norte, Brazil. **Bioscience Journal**, 35: 477-484, 2019.

LIMA, A. O. et al. Barragens subterrâneas no semiárido brasileiro: análise histórica e metodologias de construção. **Irriga**, 18: 200-211, 2013.

LIMA, A. O. et al. GPR 3D profile of the adequateness of underground dams in a sub-watershed of the brazilian semiarid. **Revista Caatinga**, 31: 523-531, 2018.

LIMA, A. O. et al. Concentration of Traces Metals in Underground Dams in the Semi-Arid of the Rio Grande do Norte State, Brazil: Case Study of the Sub-Basin of the Cobras River. **Water, Air and Soil Oollution**, 231: 1-9, 2020.

LIMA, A. O. **Nova abordagem metodológica para locação, modelagem 3D e monitoramento de barragens subterrâneas no semiárido brasileiro**. 2013. 243 f. Tese (Doutorado em Geodinâmica e Geofísica) – Universidade Federal do Rio Grande do Norte, Natal, 2013.

RABEMANANA, V. et al. Origin of the high variability of water mineral content in the bedrock aquifers of Southern Madagascar. **Journal of Hydrology**, 310: 143-156, 2005.

SANTOS, H. G. et al. **Sistema Brasileiro de Classificação de Solos.** 5. ed. rev. e ampl. Brasília, DF: Embrapa, 2018. 356 p.

SOUZA, G. S. et al. Krigagem ordinária e inverso do quadrado da distância aplicados na espacialização de atributos químicos de um argissolo. **Scientia Agraria**, 11: 73-81, 2010.

STEVANOVIC, Z. Subsurface Dams as a Solution for Supplementary Recharge and Groundwater Storage in Karst Aquifers in Arid Areas. In: LOLLINO, G. et al. (Eds.). **Engineering Geology for Society and Territory**. Springer, 2015. v. 5, cap. 90, p. 471-474.