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Hydrogeochemical Analysis, Geophysical Assessment and Geological mapping of the Recharge Zone of the Guarani Aquifer System in Santa Cruz do Sul, Brazil

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Abstract. A large part of the Guarani Aquifer is in the state of Rio Grande do Sul (southern Brazil). Aquifer's recharge area is in the central and western regions of the state. So, this work was focused on the municipality of Santa Cruz do Sul. Because there is no water resources plan in the state by 2022, the hydrogeochemical, geophysical properties, and geological characteristics of the aquifer recharge region were evaluated. Field data were gathered, including chemical analysis of water in different wells and geophysical surveys in refraction seismic and geoelectrical methods. In addition, geological information was obtained from the Groundwater Information System (SIAGAS) public database. The different chemical parameters were mapped to perceive some elements' concentrations in Santa Cruz do Sul according to the SIAGAS data. In addition, the seismic refraction data and geoelectric method were processed and interpreted, concatenating all these results with the geology obtained from SIAGAS wells. The existing formations and the static level of the Guarani Aquifer were mapped using geological data. A high concentration of lead in the region which is a possible aquifer was found using geophysical methods. If located in this area aquifer could be used for human, agropastoral, or industrial after treatments.

Key words:
Hydrogeochemistry; Geoelectric methods; Refraction Seismic; Geophysical inversion; Geological modelling; Santa Cruz do Sul.

Абстракт. Држави Rio Grande do Sul (јужни Бразил) припада велики део водоносног слоја Guarani, који се прихрањује водама централног и западног региона, те су истраживања обухваћена овим радом била фокусирана на подручје општине Santa Cruz do Sul. До 2022. године у држави није постојао план водних ресурса, те је циљ овог рада процена хидрогеохемијских и геофизичких својстава, као и приказ геолошких карактеристика региона прихрањивања водоносног слоја. Због тога су прикупљени неки теренски подаци, извршене хемијске анализе вода у различитим бунарима и извршена геофизичка истраживања рефракционим сеизмичким и геоелектричним методама. Уз све ове податке, приступило се изради различитих мапирања хемијских параметара да би се сагледале концентрације неких елемената у области Santa Cruz do Sul. С друге стране, подаци добијени помоћу рефракционе сеизмике и геоелектричних метода су обрађени и интерпретирани, спајајући све ове резултате са геологијом добијеном из SIAGAS бушотина. На основу добијених података утврђена је висока концентрација олова у региону, што указује на потребу пречишћавања вода које би се могле користити за људске, пољопривредне или индустријске потребе.

Кључне речи:
Хидрогеохемија; Геоелектричне методе; Рефракциона сеизмика; Геофизичка инверзија; Геолошко моделирање; Santa Cruz do Sul.

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Introduction

In the world, water might be translated into life, being more than a chemical formula. Due to its importance, which is irrefutable, it is essential in daily life. Because of this water has a direct consequence on the economy, energy, and manufacturing industry, as well as to agriculture, ecological and environmental activities. Hence, water is the essence of sustainable development.

The water demand is strongly linked to the increase in world population, and the panorama of its availability in the future could be better. The industrial market and domestic consumption will need more water than the agricultural area, especially in developing countries (or regions) with emerging economies. This is where Brazil is in focus (Unesco, 2018). According to the Secretary of Planning, Budget and Management in the Socioeconomic Atlas of Rio Grande do Sul (2019), agriculture contributed 12.1% of the gross value in Rio Grande do Sul when compared to the whole country (the first place). Besides, in 2015, the state presented the most extensive irrigation area (Conejo et al., 2017) and over 50% of Brazilian municipalities have been using groundwater (Soares et al., 2010) exclusively.

Knowing the hydrological potential of the groundwater in Rio Grande do Sul due to the presence of the Guarani Aquifer, the main objective of this work was to investigate the recharge zones and outcrop regions of the Guarani Aquifer System. Therefore, the municipality of Santa Cruz do Sul was studied because it is one of the essential municipalities in Rio Grande do Sul. This municipality's economic growth is based on agricultural activities. For that reason, this area was studied using hydrogeochemical, geophysical, and geological characterization to perform a hydrographic inventory.

Geological setting

The municipality of Santa Cruz do Sul is located approximately 155 km from Porto Alegre (Capital of Rio Grande do Sul; 29°43'59'' S and 52°24'52'' W) (Fig. 1). This municipality is part of the Jacuí River Basin, in the southeast part of the Paraná Basin (Noronha et al., 2012). More specifically, it is in the Central Gaúcha Depression, which consists of sedimentary rocks and volcanic spillovers from the Serra Geral Formation.

In this region, some outcrops belong to the Guarani Aquifer System (Fig. 1), which is locally presented by five main Formations (Fig. 2): Serra Geral, Botucatu, Caturrita, Santa Maria, and Sanga do Cabral, of Mesozoic age (Martínez & Silva, 2004). It is necessary to remark that it might not be possible to observe information across all ages because Caturrita and Sanga do Cabral suffered erosion and a posterior non-depositional environment.

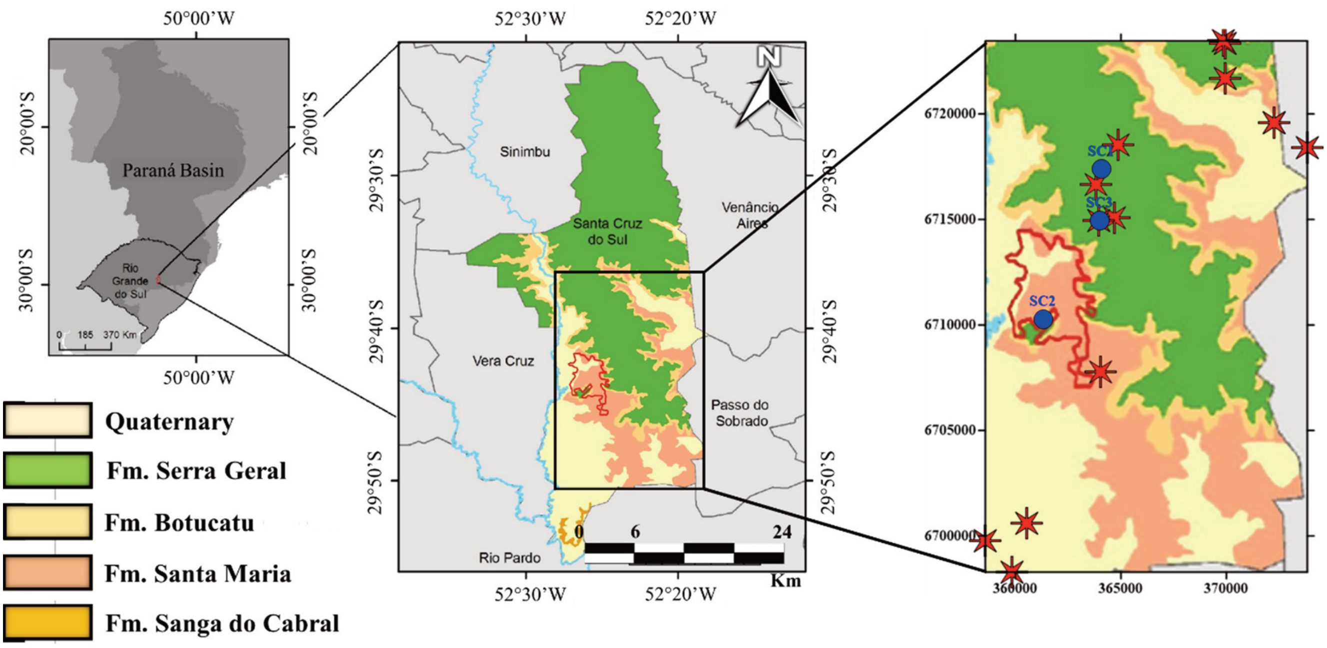

Fig. 1. *Outcrop formations in Santa Cruz do Sul and the surveys. Modified from Pinheiro et al. (2012).*

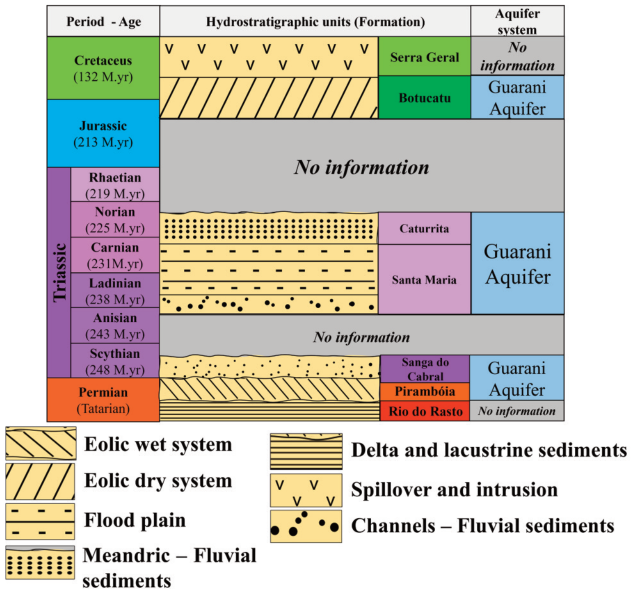

Fig. 2. *Guarani Aquifer System by hydrostratigraphic units.*

- **Rosario do Sul Formation:** In the state of Rio Grande do Sul, it is commonly called Sanga do Cabral Formation, consisting of fine sandstones, which appear as a free or confined aquifer and indicate a fluvio-deltaic paleo-environment (Martínez & Silva, 2004).
- **Santa Maria Formation:** This formation only appears in Rio Grande do Sul along a strip of 250 km (east-west direction). Two members of sandy characteristics lithostratigraphically constitute it. These two members of the formation are named Passo das Tropas (lower member), which is predominantly siliciclastic (Martínez & Silva, 2004; Noronha et al., 2012), and Alemoa (upper member), which is formed by reddish clayey siltstones, clay minerals which belong to the montmorillonite group and have low permeability (Pinheiro et al., 2012). The unit's base is composed of coarse- to medium-sized Upper–Middle Triassic sands, characteristic of a fluvial paleoenvironment.
- **Caturrite Formation:** Rubert & Schultz (2004) dated this formation of the Norian age (Upper Triassic) based on the fossil record. This formation consists of layers of fine sandstone to well-selected conglomerates, as an association of alluvial facies (Noronha, 2010), forming the aquifer with the highest capacity to accumulate water in the region, with an average porosity ranging between 14% to 30% (Martínez & Silva, 2004).
- **Botucatu Formation:** Noronha (2010) mentions this formation as Jurassic–Cretaceous. Faccini et al. (2003) reported that the lithotypes correspond to an association of facies of medium aeolian systems formed by fine to medium quartz sandstones with the presence of feldspars.
- **Serra Geral Formation:** Stands out because it is presented with three heterogeneous and poorly developed basaltic strokes (Pinheiro et al., 2012). This magmatic body is a product of the separation of Gondwana during the Lower Cretaceous (Noronha, 2010). All this causes the formation of a fissural aquifer (formed by fractures) which may be connected (Martínez & Silva, 2004).

Methodology

Hydrogeochemical analysis

The samples were obtained conclusively with ABNT NBR 15847 (ABNT, 2010) from 14 different wells. Most of them are in rural areas where agricultural activities are present. The water was sampled from wells using a purging time of 10 minutes, and subsequently, the samples were acquired, without applying any treatment. After the acquisition, the water samples were stored at 4°C. The geographical information is in Table 1.

Table 1. *Sampled wells.*

Well name	UTM X (22J)	UTM Y (22J)	Area
SEI	373838	6718421	Rural
MMA01	372245	6719590	Rural
MA02	372245	6719595	Rural
LNA01	369930	6723346	Rural
LNA02	369859	6723462	Rural
LNA03	369932	6721699	Rural
SEM	363960	6714928	Rural
SJR01	359836	6698293	Rural
SJR01	358569	6699783	Rural
SJR02	360547	6700609	Rural
SJR03	363820	6716636	Rural
LSC06	364865	6718511	Urban
LBV02	364709	67145091	Urban
LSC04	364020	6707760	Urban
LSC17			

The measurement of anions and cations was performed via ionic chromatography. The equipment used for these measurements was different. The *ICS 5000* was used for anions, and the *Dionex DX 500* was used for cations. Metals were measured via optical emission spectrometry with plasma (*Perkin Elmer Optim*a equipment).

To obtain physicochemical parameters such as dissolved oxygen, electrical conductivity, and pH, the samples were measured in situ using multiparameter equipment, which had a flow cell. Water hardness and alkalinity were measured using Standard Methods (Clesceri et al., 1998). Ionic chromatography was used to estimate water hardness after using the Eq. 1.

$$CaCO_3 = \left[\,2.497Ca\left(\frac{mg}{l}\right)\right]+\left[4.118Mg\left(\frac{mg}{l}\right)\right]$$

Eq. 1 Calculation of water hardness.

Ca = calcium concentration	*Mg = magnesium concentration*
2.479 = *conversion from Ca to* $CaCO_3$	4.118 = *conversion from Mg to* $CaCO_3$

Geoelectrical Survey

A resistivity–meter named *X5xtal Control* (the dipole-dipole as acquisition matrix) was used for the geoelectrical survey, due to its acquisition and processing geometry. This instrument was also used because of its average horizontal and vertical reso-lution if it is compared to Wenner e Schlumberger methods (Cogon, 1973). The separation between the current electrodes (A–B) was 5 m, and the same was for potential electrodes (M–N). Arraying lines were 100 m long, using the highest n=11 (as shown in Fig. 3).

Refraction seismic survey

The refraction seismic survey was aligned with the geoelectrical surveys. The three lines were 60 m long (the maximum extension of the cables); 12 geophones spaced every 5 m (due to the extension of the cable divided by the number of geophones) and 5 shot points spaced every 30 m (30 m next to the geophone in each side, also 2 more shots in each side next to geophones and one in the middle of them). In each shot point, 3 measurements were made (3 gathers) to select the best of them. A final arrangement is shown in Fig. 4.

Results and discussions

This work was based on data from water geochemistry (or hydrogeochemistry), geophysics, and geological data from SIAGAS wells. The studied area

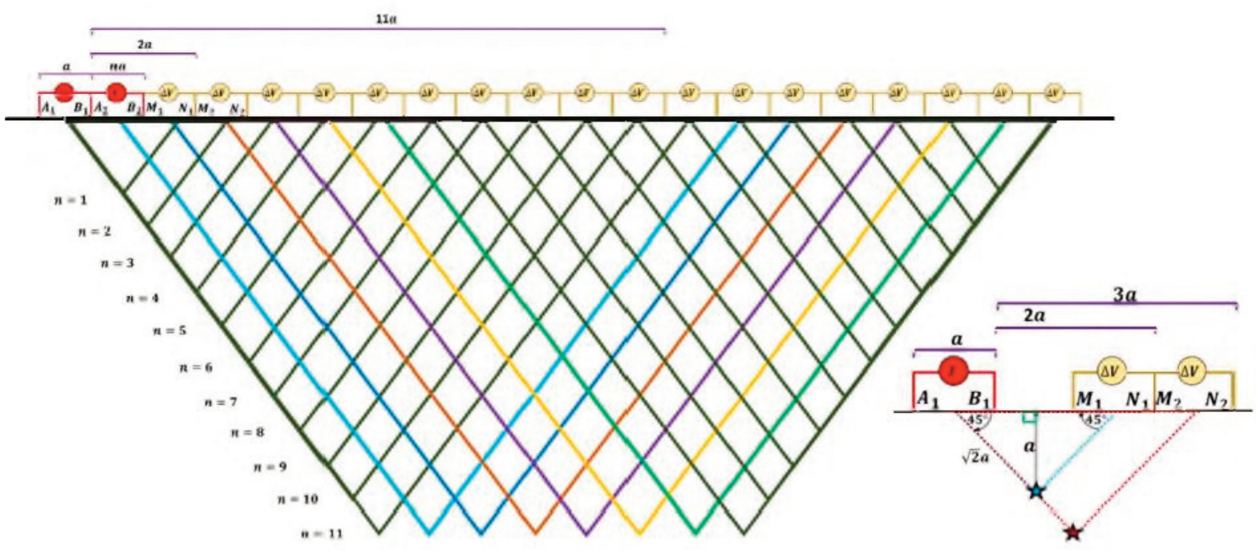

Fig. 3. *Representation of the acquisition.*

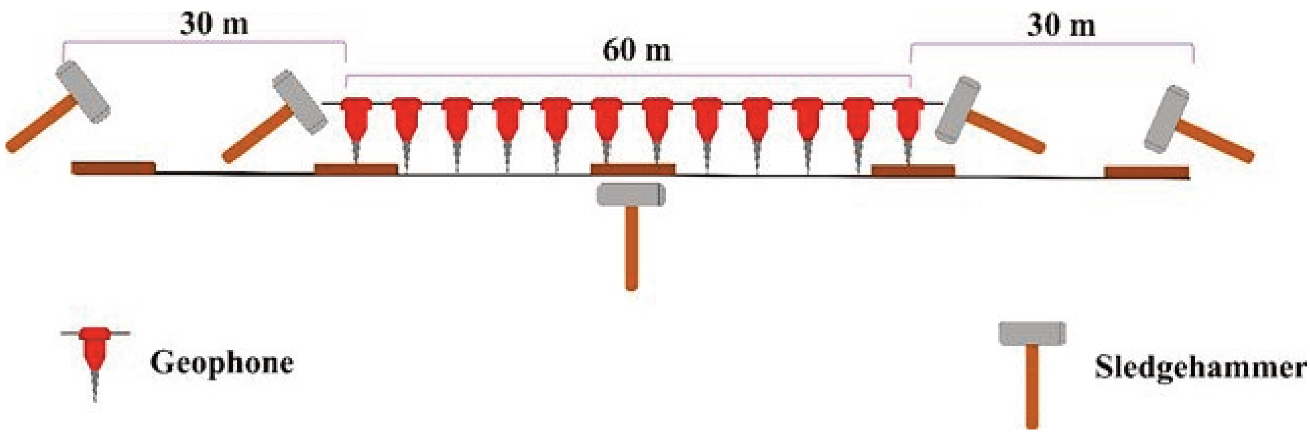

Fig. 4. Acquisition of refraction seismic.

is presented in Fig. 5. Firstly, the hydrogeochemical parameters were mapped to mark their concentrations at the analyzed region. This method gives insight into how polluted the water is, or how polluted it would be if a possible reservoir was found in this area. Then, the geophysical data were processed and analyzed to define geological settings in the first few meters. The priority was to determine probable reservoirs. This geophysical survey was independent of the hydrogeochemical tests because the chemical analysis was made where there were existing wells. Also, to complement all of this, the geological data was modeled to present different contour maps, showing the regional behavior of geological formations and the aquifer system.

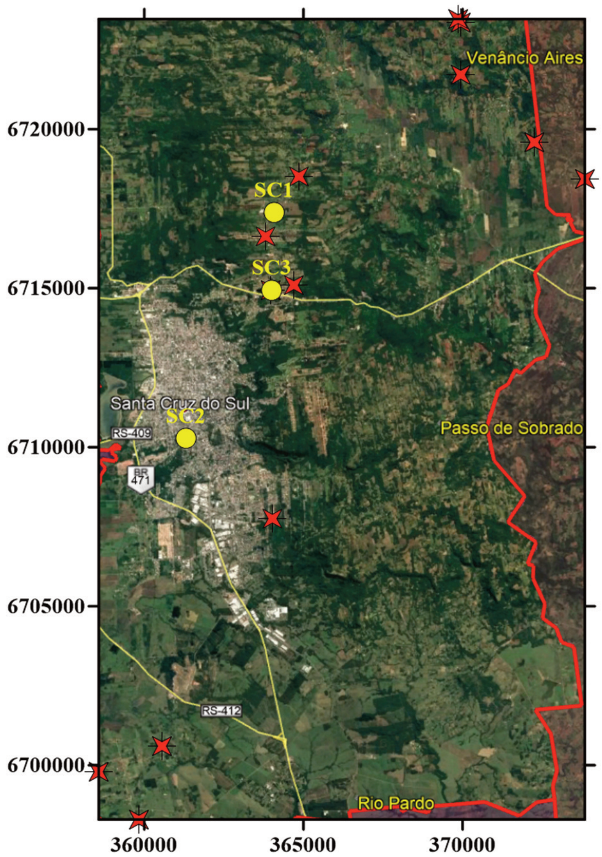

Fig. 5. Location of the studied area, where yellow dots indicate the geophysical surveys and red stars where the chemical parameters were obtained.

Hydrogeochemistry

The information on hydrogeochemistry came from the water analysis of 14 (black stars in the chemical maps) wells in Santa Cruz do Sul. This resulted in 21 contour maps (considering the most important parameter for use in concordance with the Geological services of Brazil) that are showing the spatial behavior of the different chemical parameters (Table 2). The maximum accepted value (Table 3) is in the title of the images. These maps are divided in:

– Physicochemical parameters: electrical conductivity, water hardness, dissolved oxygen, pH, redox potential, and salinity.

– Anions: chloride concentration, fluoride concentration, phosphate concentration, nitrate concentration, and sulfate concentration.

–Cations: calcium concentration, magnesium concentration, potassium concentration, and sodium concentration.

Metals: aluminum concentration, barium concentration, lead concentration, copper concentration, chromium concentration, and iron concentration

Table 2. *Chemical Values.*

NOME	UTM X	UTM Y	Dissolved Oxygen	Electrical Conductivity (S/m)	pH	Redox (mV)	Salinity	F^-	Cl-	NO3-	SO4-2	PO4-3	Na+
SEI	373838	6718421	4	0.0101	6.37	192.00	0.06	0.36	13.81	4.49	16.99	0.00	8.63
MA_01	372245	6719590	3	0.0101	6.24	190.00	0.05	0.38	4.54	6.40	1.97	0.40	9.11
MA_02	372245	6719590	7	0.0424	9.00	42.00	0.20	4.99	5.80	0.55	57.93	0.00	109.45
LNA_01	369930	6723346	7	0.0147	7.09	152.00	0.07	0.37	2.57	1.12	1.58	0.00	2.89
LNA_02	369859	6723462	6	0.011	6.94	152.00	0.06	0.21	2.40	1.15	1.38	0.00	3.53
LNA_03	369932	6721699	10	0.005	6.50	196.00	0.03	0.20	5.76	6.91	0.73	0.00	6.08
SEM 01	363960	6714928	7	0.007	6.78	170.00	0.04	0.20	3.41	1.13	0.39	0.21	4.26
SJR_01	359836	6698293	7	0.0062	6.22	240.00	0.03	0.13	5.52	2.79	1.31	0.00	3.70
SJR_02	358569	6699783	9	0.0066	6.85	173.00	0.03	1.21	1.22	0.61	1.29	0.43	10.63
SJR_03	360547	6700609	8	0.0103	6.84	167.00	0.05	0.27	6.33	7.05	0.53	0.00	10.97
LSC_06	363820	6716636	4	0.0237	7.42	118.00	0.11	0.27	6.43	3.67	3.74	0.20	11.62
LBV_02	364865	6718511	5	0.0281	7.25	141.00	0.14	0.93	4.48	0.90	2.20	0.00	18.79
LSC_04	364709	6715091	8	0.0146	7.03	152.00	0.07	1.14	5.55	2.11	1.15	0.16	7.99
LSC_17	364020	6707760	6	0.0353	9.43	27.00	0.17	0.44	8.94	0.25	7.45	0.02	104.30

NOME	UTM X	UTM Y	K+	Mg+2	Ca+2	Al	Ba	Pb	Cu	Cr	Fe	$CaCO_3$
SEI	373838	6718421	4.37	4.20	11.24	75.91	0.10	19.00	2.20	0.00	57.39	43.35
MA_01	372245	6719590	0.34	1.19	5.56	150.00	0.08	8.00	0.70	0.00	60.00	18.76
MA_02	372245	6719590	0.09	0.03	3.01	9.00	0.00	0.00	0.00	2.52	1.65	7.65
LNA_01	369930	6723346	0.09	4.55	10.95	13.50	0.02	10.00	0.00	5.00	3.00	46.05
LNA_02	369859	6723462	0.16	6.06	13.74	1.00	0.02	36.00	0.00	6.50	12.50	59.26
LNA_03	369932	6721699	1.15	2.71	3.29	60.00	0.12	14.00	1.50	0.00	0.00	19.36
SEM 01	363960	6714928	1.36	2.31	7.00	0.00	0.02	13.00	0.00	4.85	2.50	26.98
SJR 01	359836	6698293	0.90	1.27	4.79	12.50	0.13	8.00	0.50	0.00	2.50	17.18
SJR_02	358569	6699783	0.50	0.13	2.94	102.00	0.02	4.00	0.00	0.00	0.50	7.92
SJR_03	360547	6700609	0.82	0.94	7.26	20.00	0.05	6.00	5.00	0.00	3.50	21.98
LSC_06	363820	6716636	0.19	10.17	30.28	0.00	0.00		0.00	0.00	0.00	117.49
LBV_02	364865	6718511	0.19	10.53	3.64	30.00	0.01		0.00	0.00	0.00	127.37
LSC_04	364709	6715091	0.85	5.48	17.35	60.00	0.03		0.00	0.00	0.00	65.91
LSC_17	364020	6707760	0.14	0.18	2.24	9.00	0.01		0.00	3.00	6.70	6.32

Table 3. *Maximum Hydrogeochemical values.*

Parameter	Maximum value $\frac{mg}{l} = 1ppm = 1000\frac{\mu g}{l}$	Reference
Alkalinity	200	(ENRESS, 2018)
Aluminium (Al)	0,2	(CONAMA, 2008)
Arsenic (As)	0,01	(CONAMA, 2008)
Barium (Ba)	0,7	(CONAMA, 2008)
Cadmium (Cd)	0,001	(Health Canada, 2019)
Calcium (Ca^+)	100	(ENRESS,2018)
Lead (Pb)	0,1	(CONAMA, 2008)
Chloride ($^-$)	250	(CONAMA, 2008)
opper (Cu)	2	(CONAMA, 2008)
Chromium (Cr)	0,5	(CONAMA, 2008)
Water Hardness	500	(CONAMA, 2008)
Iron (Fe)	0,3	(CONAMA, 2008)
Fluoride (F^-)	1,5	(CONAMA, 2008)
Phosphate (Po_4^{-3})	0,45	(Pinheiro *et al.*, 2012)
Magnesium (Mg^{2+})	30	ENRESS, 2018)
Manganese (Mn)	0,1	(CONAMA, 2008)
Nitrate (NO_3^-)	10	(CONAMA, 2008)
Dissolved oxygen	6	(CONAMA, 2008)
Potassium (K^+)	10	(FAO, 2005)
Selenium (Se)	0,01	(CONAMA, 2008)
Sodium (Na^+)	200	(CONAMA, 2008)
Sulfate (SO_4^-)	250	(CONAMA, 2008)
Zinc (Zn)	5	(CONAMA, 2008)

Physicochemical parameters

A total of 6 physicochemical parameters were studied. The values are shown in Fig. 6 to Fig. 11. It was observed that the pH and dissolved oxygen have higher values than allowed (6 mg/l for dissolved oxygen and pH larger than 9). The dissolved oxygen concentration might be attributed to the absence of organic matter which is the principal cause of oxygen consumption (Jobbágy et al., 2017). Also, according to Wiesel et al. (2018) the region of Santa Cruz do Sul suffers from eutrophication. If this is the case, the concentration of dissolved oxygen could reach up to 10 mg/l. The electrical conductivity, pH, and redox concentration could be the result of the location of the well in the urban area. Moreover, Wiesel et al. (2018) mentioned that the most critical point of pollution of the environment at this point is a little urban polluted stream.

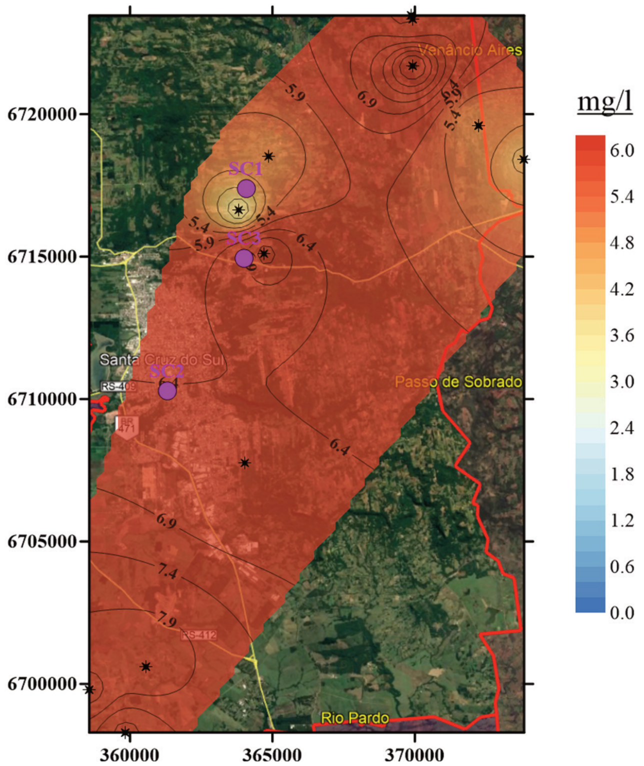

Fig. 6. Dissolved oxygen in the water.

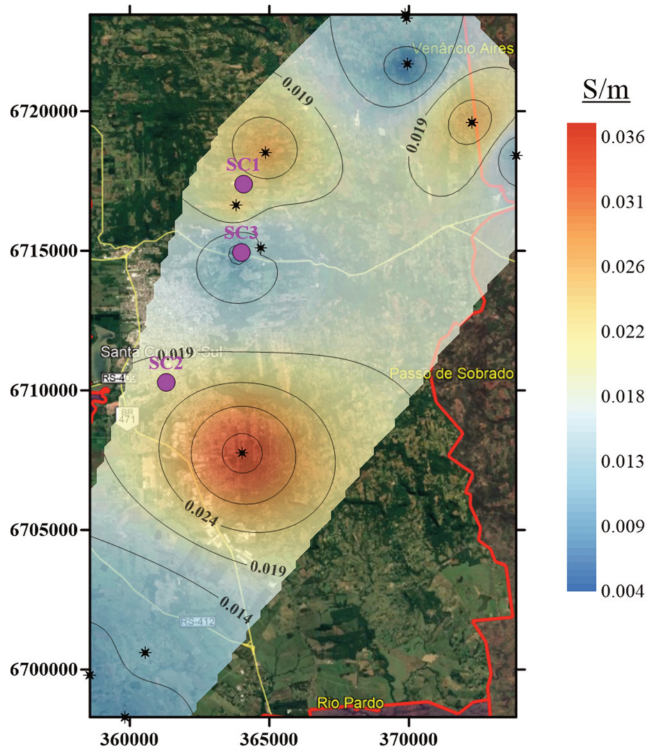

Fig. 7. Electrical conductivity of water.

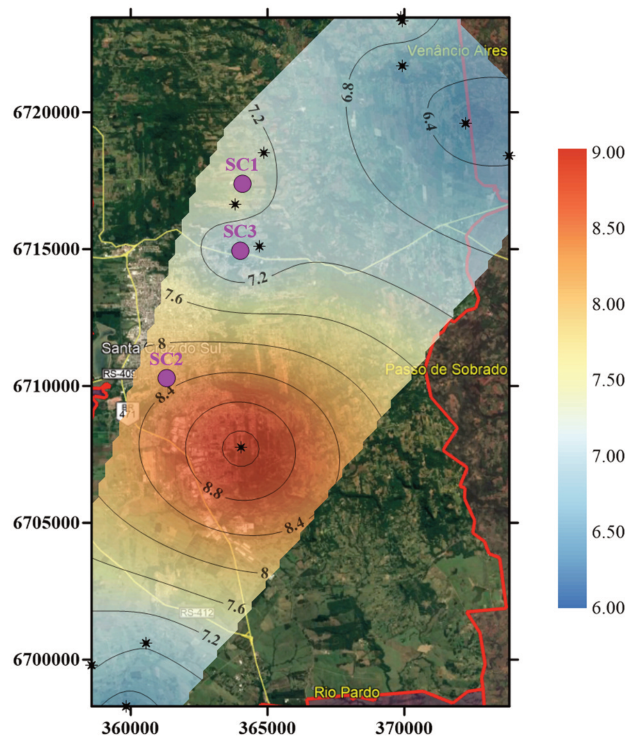

Fig. 8. pH of the water.

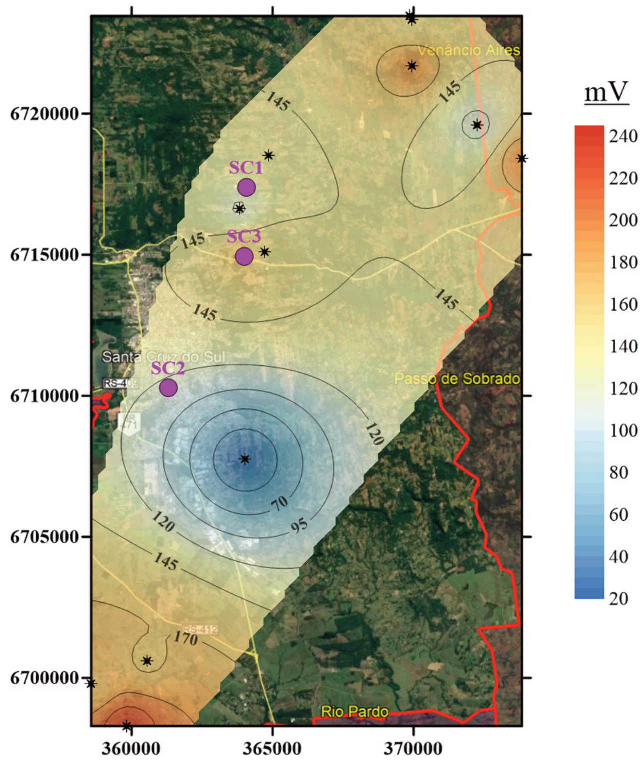

Fig. 9. Redox potential of water.

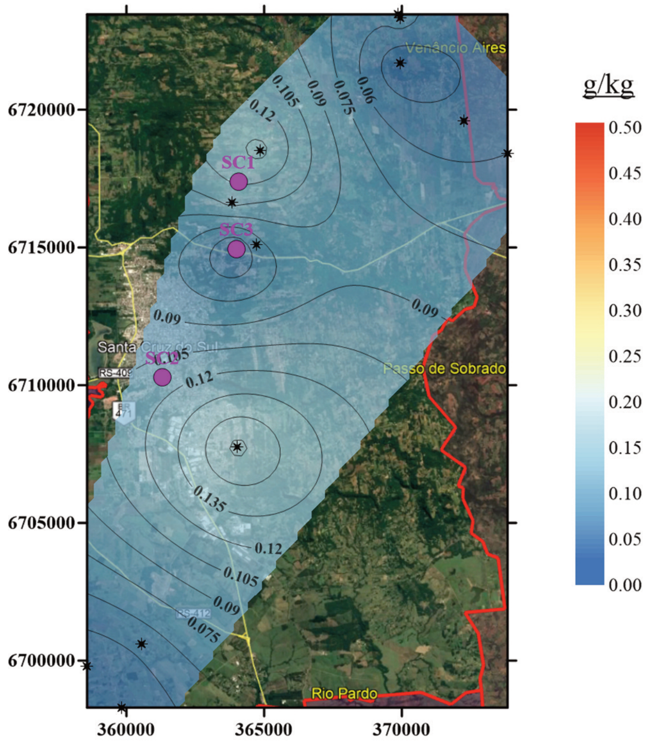

Fig. 10. *Salinity of water.*

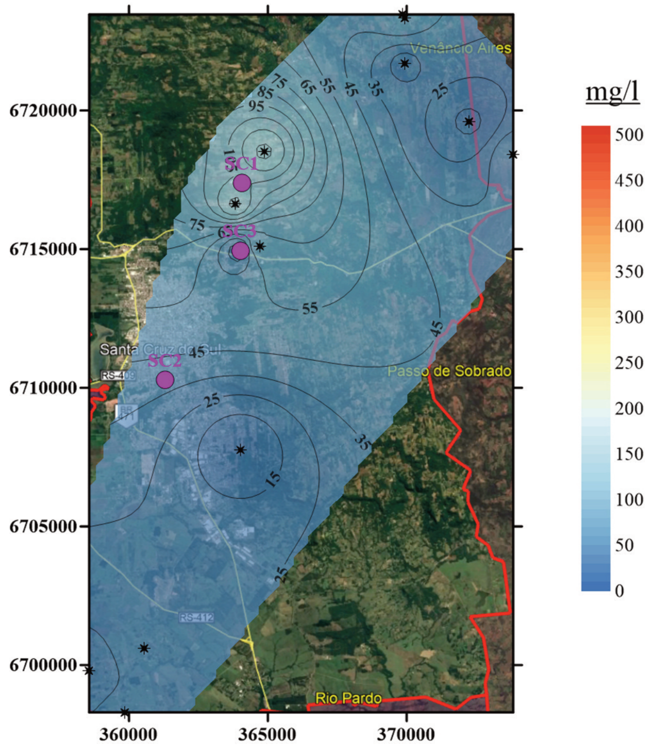

Fig. 11. *Water hardness.*

Anions

Five parameters were modeled in the case of anions, as shown in the maps from Fig. 12 to Fig. 16. The fluoride concentration is exceeding the allowable limit. Ribeiro et al. (2009) mentioned that the occurrence of fluorides is related to igneous or magmatic processes. Observing the profile of the well located in the SC1 line (the line closest to the place with a high concentration of fluoride), it is noted that basalts are the predominant lithology (the Serra Geral Formation). On the other hand, Marimon et al. (2007) mentioned that fertilizers can play a role as an important external source of fluoride in the area, with a considerable potential for groundwater contamination. The geological map suggests that the SC1 line is around the quaternary sediments' deposits, so perhaps the concentration of fluoride comes from both basalts (which are around) and farms that are in this region.

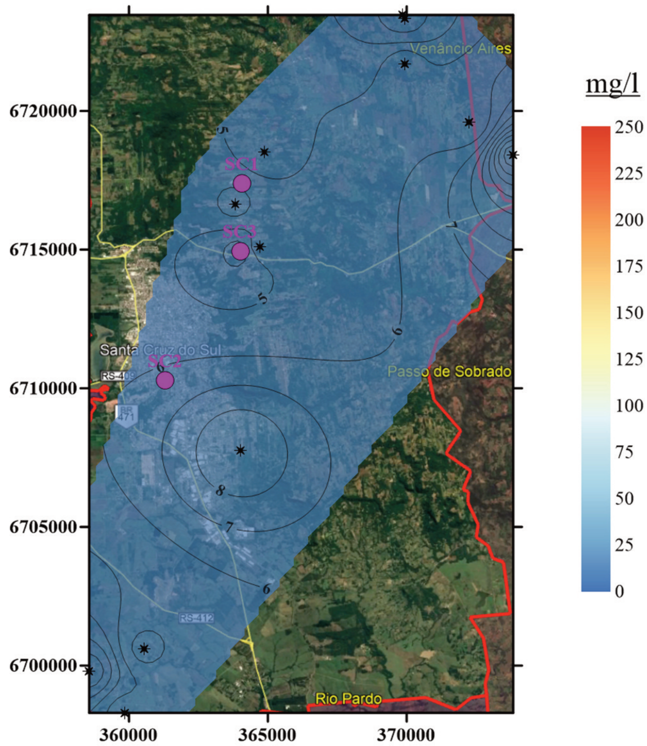

Fig. 12. *Chloride concentration.*

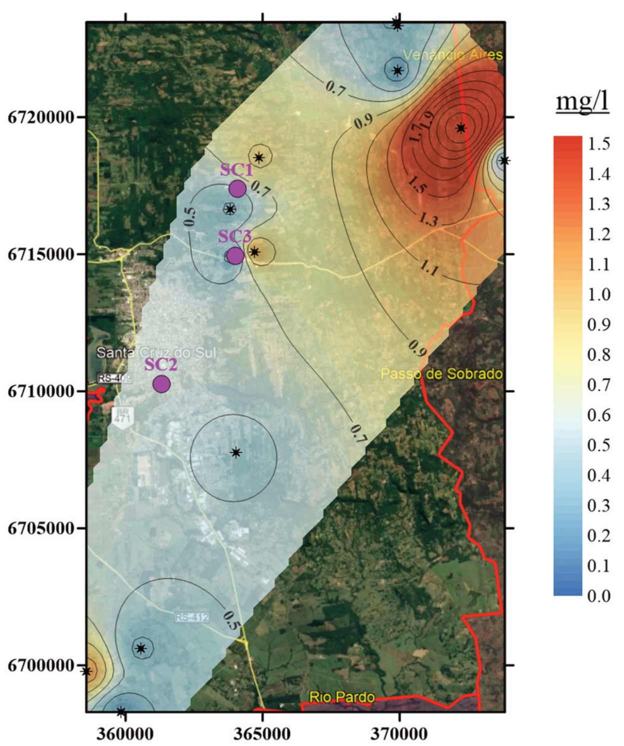

Fig. 13. Fluoride concentration.

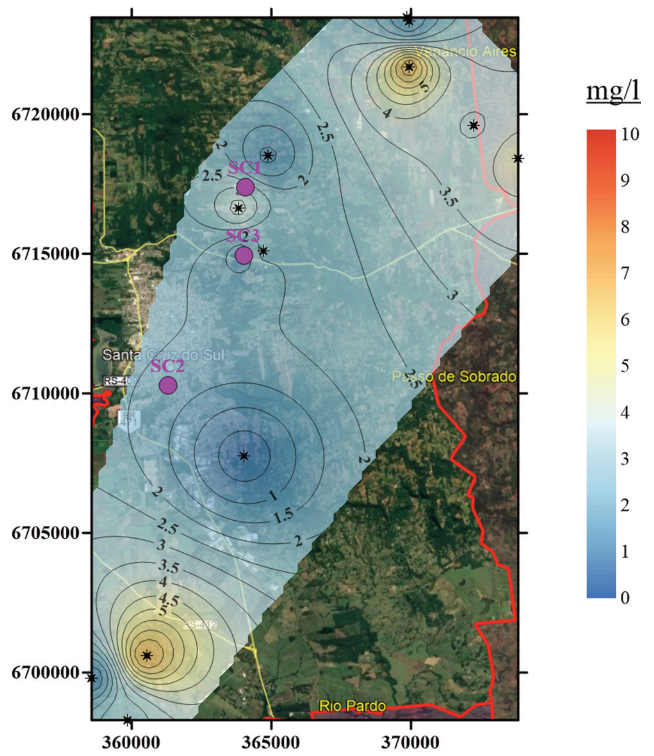

Fig. 14. Nitrate concentration.

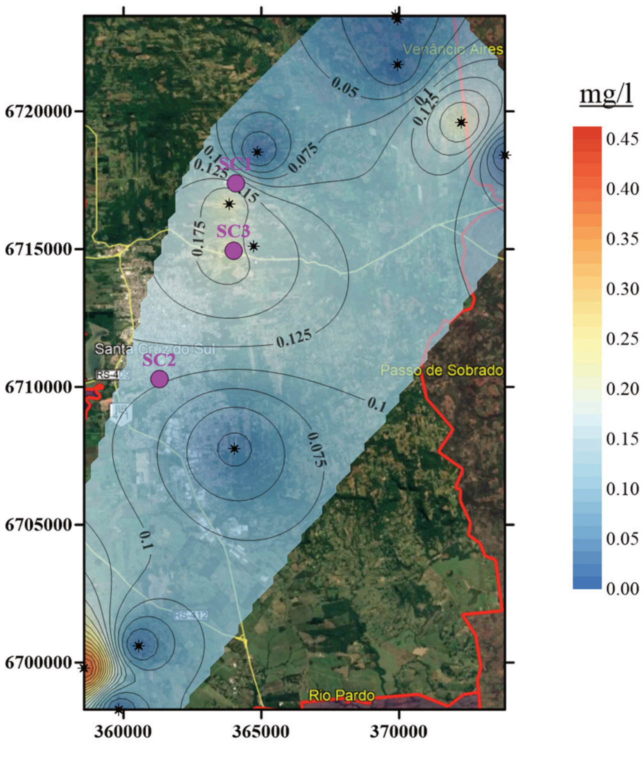

Fig. 15. Phosphate concentration.

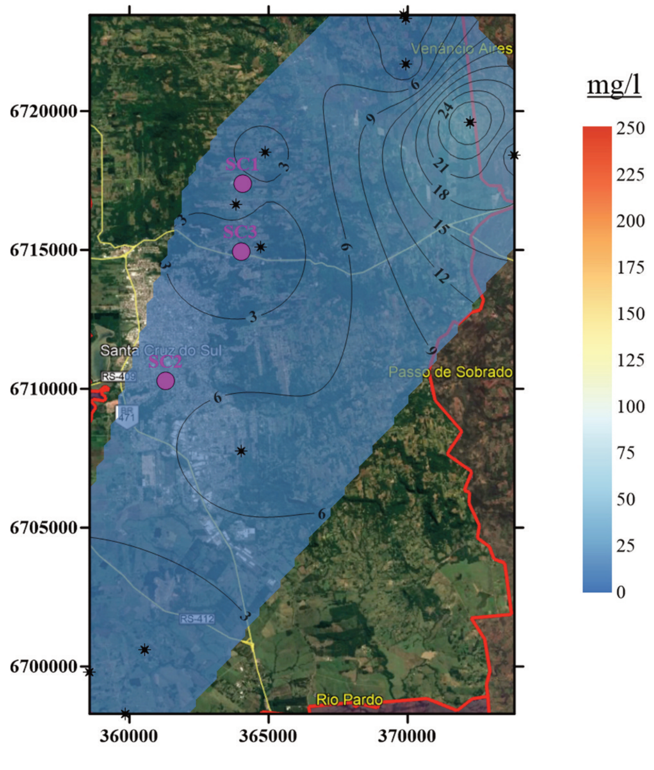

Fig. 16. Sulphate concentration.

Cations

The studied cations have values within the allowed limits as shown in the contour maps from Fig. 17 to Fig. 20. The well with the highest sodium concentration is the same one that had out-of-bound pH values. It also includes the highest salinity and electrical conductivity values. According to Magalhães (2006), electrical conductivity is linked to the number of ions dissolved in the water. Also, because

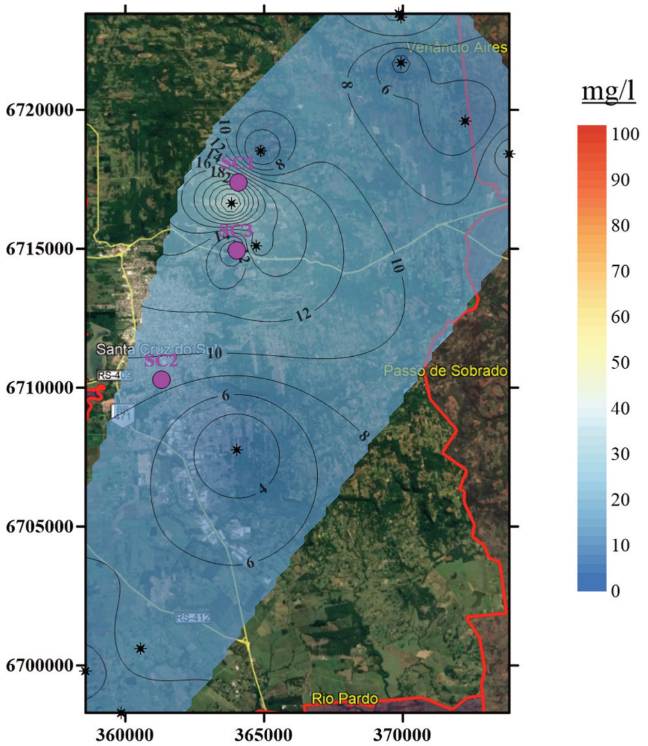

Fig. 17. Calcium concentration.

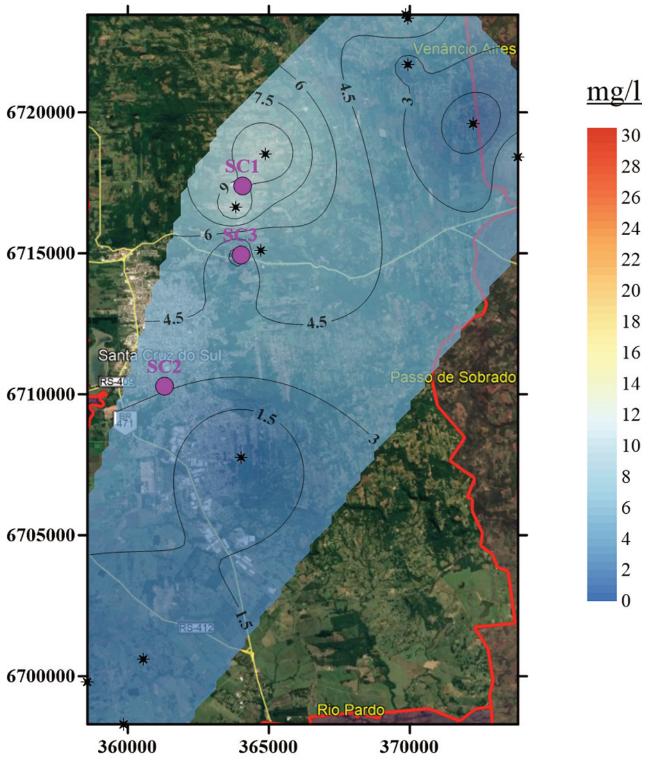

Fig. 18. Magnesium concentration.

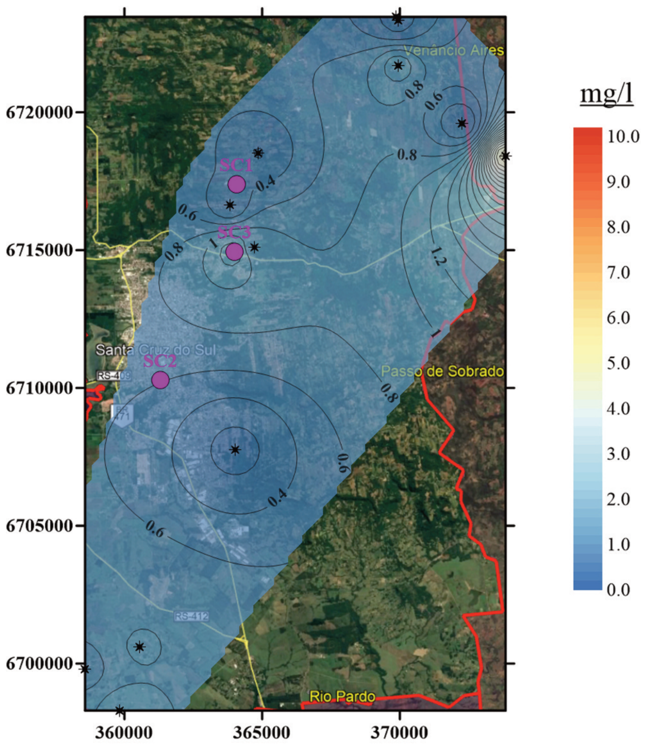

Fig. 19. Potassium concentration.

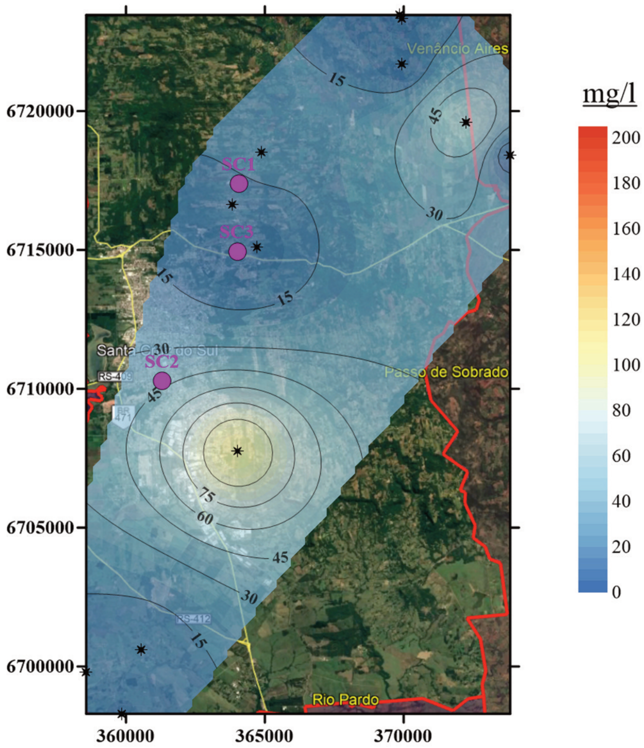

Fig. 20. Sodium concentration.

sodium has low chemical stability inside the minerals, it can get diluted in water, increasing its concentration. One of the minerals which could contribute to sodium concentration is plagioclase, which is common in basalts (Fm. Serra Geral) (Silva & Migliorini, 2014). Also, another mineral that could be presented in this region is feldspar, which could be seen in clays, as it is noticed in the line SC2 and in Fig. 2. So, these are possibly the main reasons for higher sodium concentration.

Metals

Six different metal concentrations were analyzed. Their concentration maps are shown in Fig. 21 to Fig. 26. It was observed that the concentration of lead was high in almost all studied wells. Savazzi (2009) mentions that the concentration of this metal in aquifers is not very common. Normally high concentrations correspond to discharges of effluents from mechanical and metallurgical industries. Also, according to Tiecher et al. (2017), Rio Grande do Sul was the state which presented the highest percentage of contaminated groundwater in Brazil, around 50%, and one of the principal reasons was the fecal slurry by swine used as fertilizer. This is increasing elements like As, CD, Cr, Hg, and Pb, however, high concentrations of those elements were not found. Pazand et al. (2018) mentioned that having lead concentration in groundwater is mostly of anthropogenic origin, however, observing the whole area, the lead is not clustered, it is dispersed, suggesting that it could be geogenic, restricted to volcanic rocks and sediments. This analogy to the local geology suggests that the principal supposition for lead concentration in Santa Cruz do Sul is geology.

Geophysics

In this work data from 6 surveys were used. They were divided into 3 seismic refractions and 3 geoelectrical methods (dipole-dipole array). These two techniques had their data acquired concomitantly and in the same places, hence being perfectly comparable with each other (Table 4.). The two of the three lines had geological information from near wells. The line SC1 was separated 3 m from the well, and the second line (SC2) was 2 m apart.

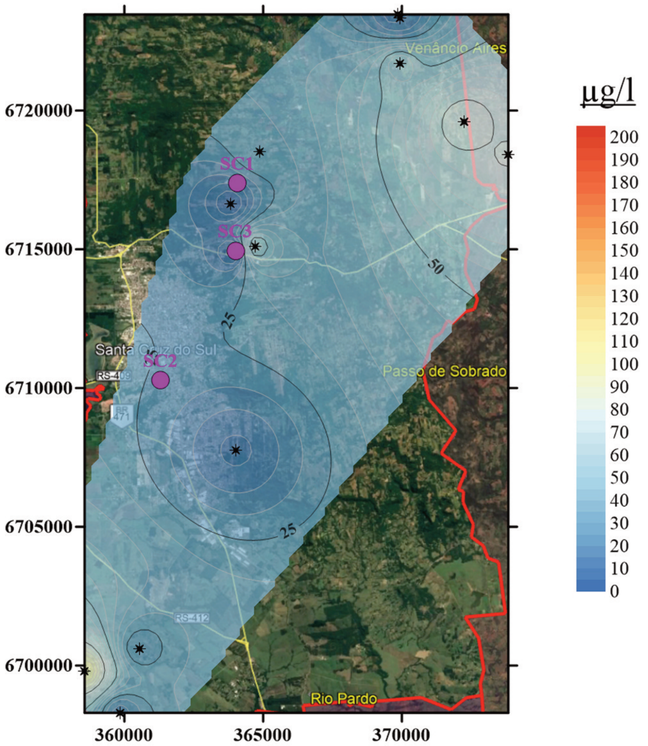

Fig. 21. *Aluminium concentration.*

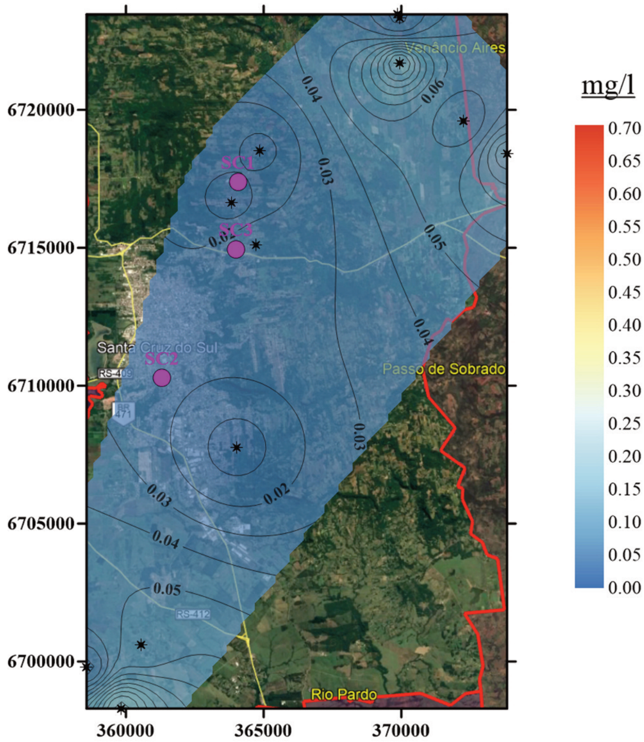

Fig. 22. *Barium concentration.*

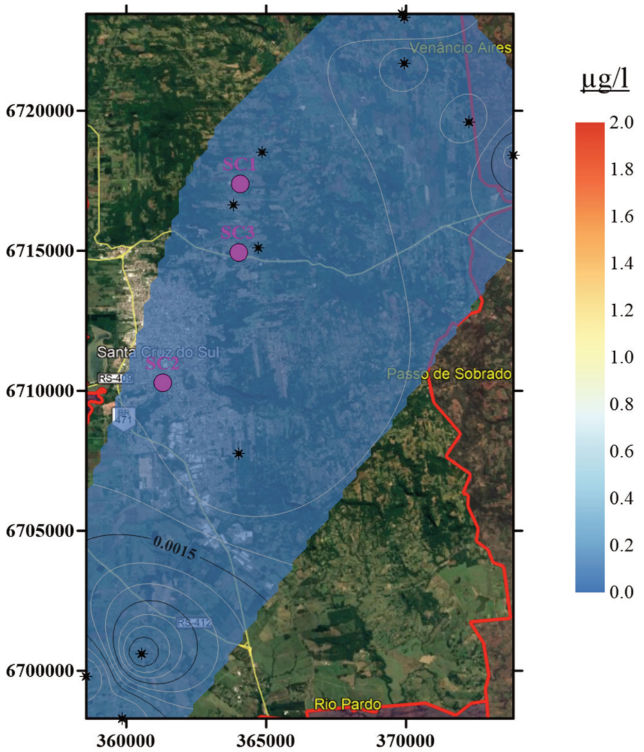

Fig. 23. *Copper concentration.*

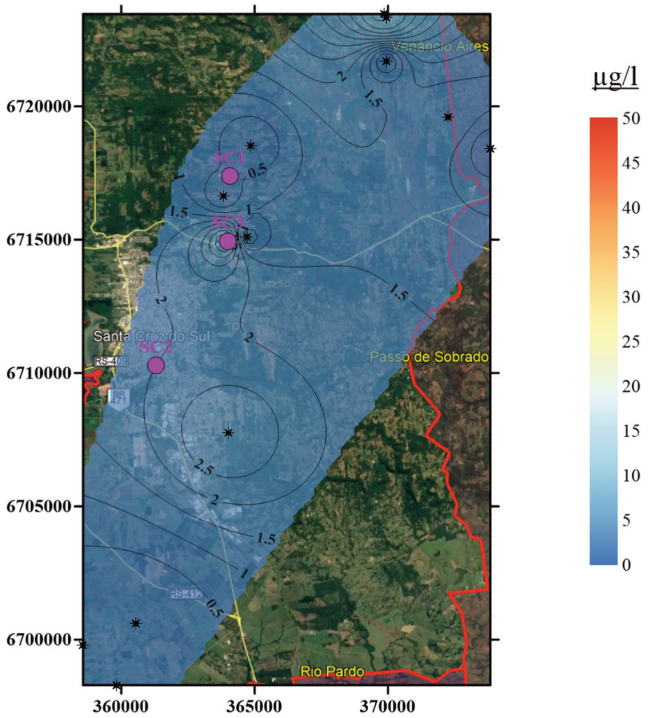

Fig. 24. *Chromium concentration.*

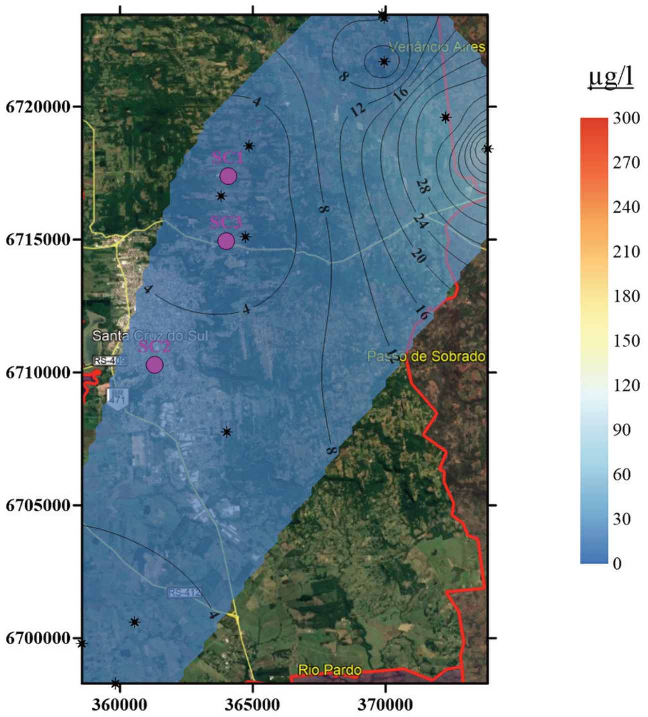

Fig. 25. *Iron concentration.*

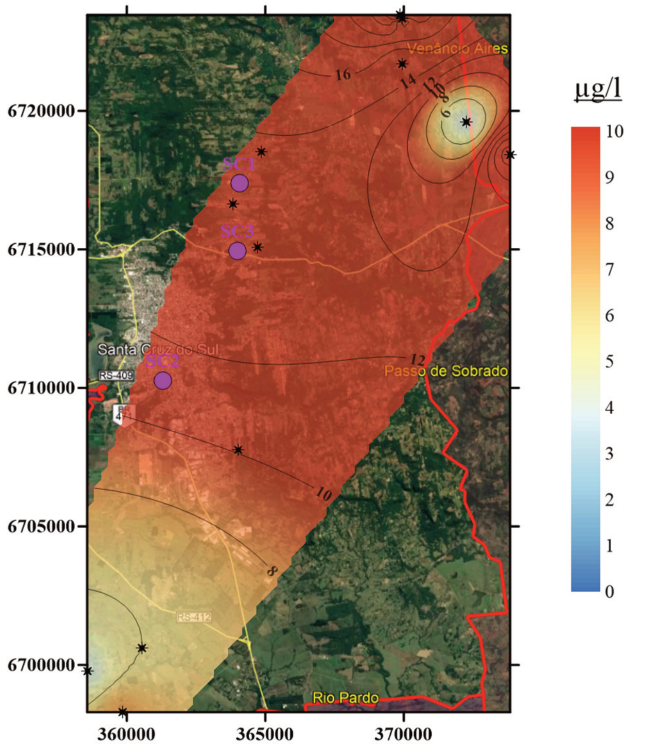

Fig. 26. *Lead concentration.*

Table 4. *Reference values of Vp and Resistivity (Glover, 2015; Dondurur, 2018).*

Material	Vp (m/s)	Resistivity (Ωm)
Water	1450–1530	10–100
Alluvial sediments	1800–2200	10–800
Saturated sand	1500–2000	30150
Dry sand	4001–200	80–1050
Sandstone	1400–4500	$1 - 7.4 \times 10^{8}$
Clay	1000–2500	1–2000
Clayey sand	–	30–215
Clayey soil	–	8–33
Basalt	5500–6500	$10–1.3 \times 10^{7}$
Limestone	3000–6000	50–107
Dolomite	2500–6500	$350–5 \times 10^{3}$
Granite	4500–6000	$5000–1.3 \times 10^{6}$
Unconsolidated sediments	100–500	81–700
Schist	2000–4100	1010^{4}

Line SC1

In line SC1, shown in Fig. 27, the geological data shows the existence of two lithologies. The first layer of clayey soil, and the second layer of basalt. In the seismic model, the first layer was observed with a low velocity of 500–750 m/s, which was interpreted as unconsolidated clayey soil. The second layer in the seismic model had a velocity of 2000–2500 m/s and could be considered as consolidated clays (not weathered as in the first seismic layer). Finally, in the third layer, there is an increase in velocity, which may represent the transition of clay to basalt, having a velocity in the range of 4500–6000 m/s.

In the geoelectrical survey of line SC1, two well-differentiated layers were detected as shown in the

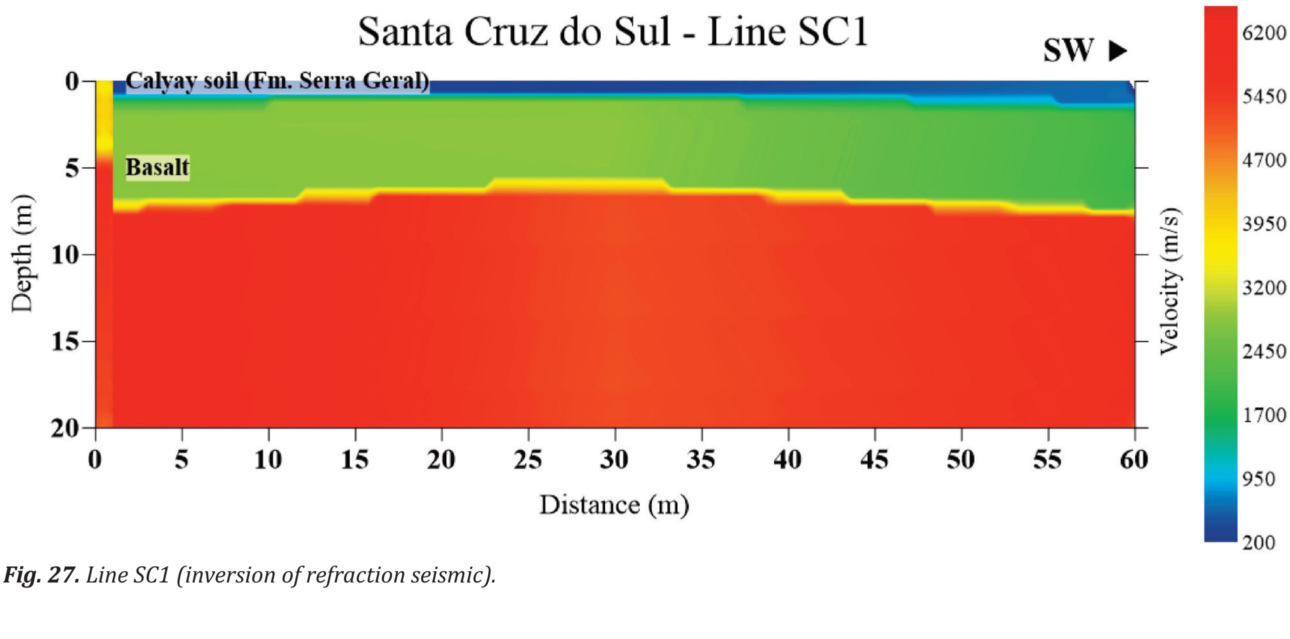

Fig. 27. *Line SC1 (inversion of refraction seismic).*

inversion of Fig. 28. The upper layer corresponds to clayey soil with an average resistivity of 60 Ωm up to approximately 5 m depth. In this first layer, the variation in resistivity (blue/green and yellow) was interpreted as a mixture of unconsolidated (superficial soil) and more consolidated clay sediment. Below, the presence of a basalt layer was constrained, as reflected in its resistivity value, above 300 Ωm, being eight times more resistive. Also, in both profiles, it can be observed that geophysics matched the geology.

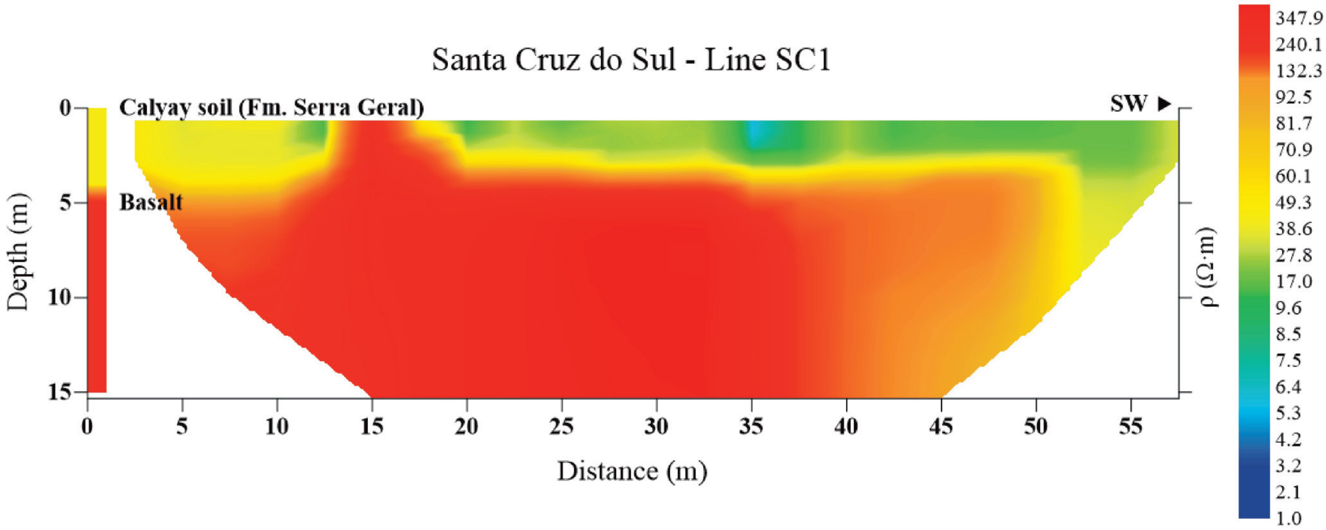

Fig. 28. *Line SC1 (inversion of the geoelectrical survey).*

Line SC2

Geological data from wells suggests that the subsurface of the SC2 line is composed of clays – the layer of clayey soil overlying claystone. The inversion of the seismic data from this line is shown in Fig. 29. The inversion indicates that the first layer of 350–500 m/s corresponds to unconsolidated clayey soil. The second layer starts with the consolidation of soil which is increasing the speed up to 800–1300 m/s. In the third layer, the velocity exceeds 2500 m/s, indicating the possible presence of claystone. It is important to remark that variation in values in the layers could be due to the extreme sides of seismic, coming from the processing step and the gathers. Due to this, it is important to take the central values of the seismic section, even more, if the lines are not so long.

In line SC2, the geological profile indicates that the first layer is clayey soil, as in the case of SC1. The inversion of geoelectric survey data, shown in Fig. 30 showed resistivity values of approximately 50 Ωm. In the second layer, the values decreased to 5 Ωm, suggesting that there could be groundwater in this layer. However, if there were an aquifer, it would be difficult to extract it, because the clays are poorly permeable. In addition, these values are as expected, since this line was carried out in the Rosário do Sul Formation, which is characterized by sediments. Additionally, if the lead concentration is around SC2 line, it could be noticed how much this region is polluted by this element, which would surely affect the probable reservoir.

Line SC3

The lower seismic velocities were observed in Line SC3, as shown in Fig. 31. The geological model constructed from seismic data contains three layers. From the velocities shown in the model, it might be assumed that the first layer is composed of unconsolidated sediments, getting more consolidated in the second layer, which appears to be a sandy medium. The third layer has a sandy-clayey characteristic.

The geoelectric survey of the SC3 line in Fig. 32, shows a water-saturated surface soil due to the low resistivity around 0.1 to 3.5 Ωm. In the second layer, there is a sharp increase in resistivity, which varies from the southernmost to the northernmost of the line. This is likely to be an edge effect from the in-

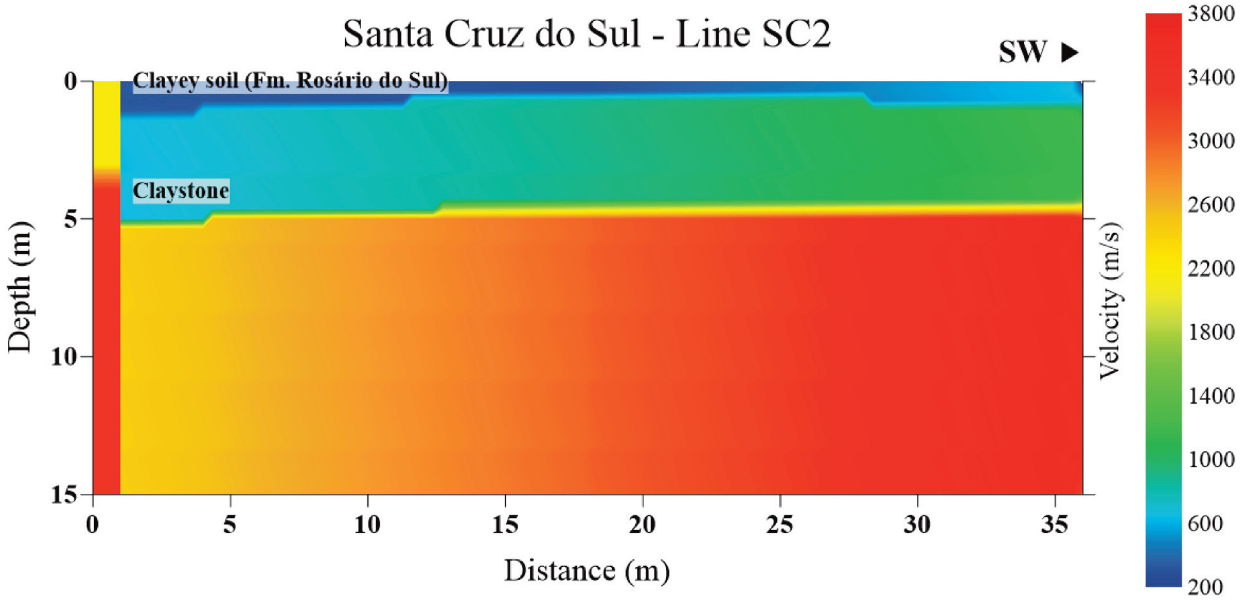

Fig. 29. Line SC2 (inversion of refraction seismic).

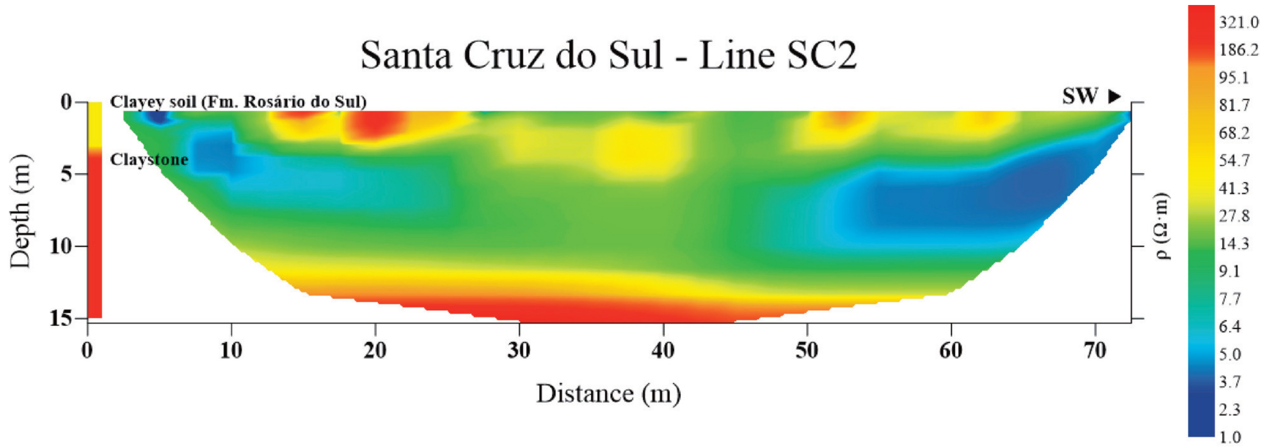

Fig. 30. Line SC2 (inversion of the geoelectrical survey).

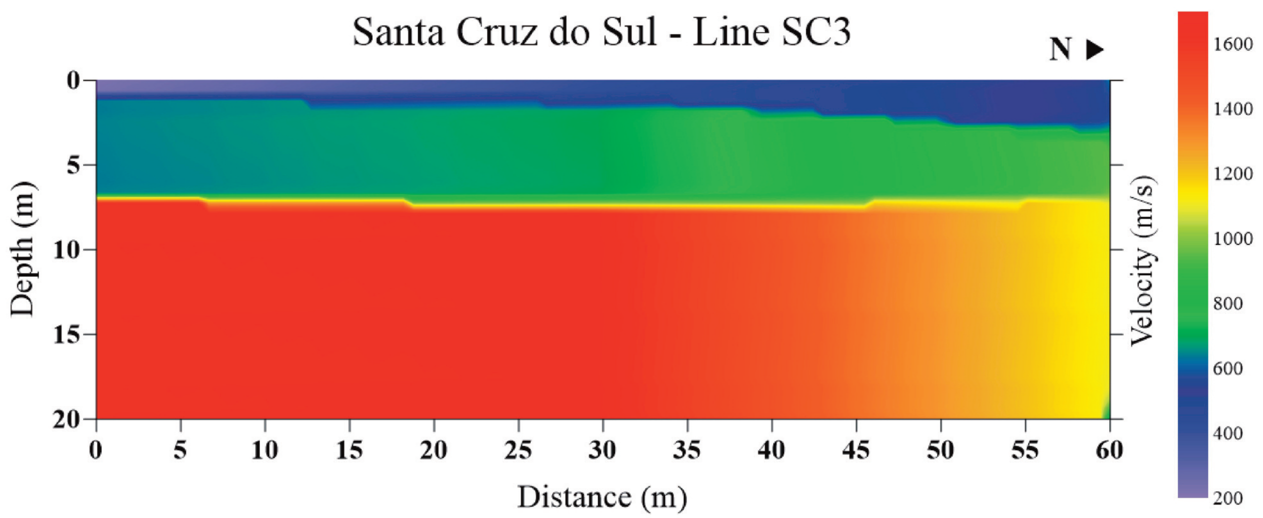

Fig. 31. Line SC3 (inversion of refraction seismic).

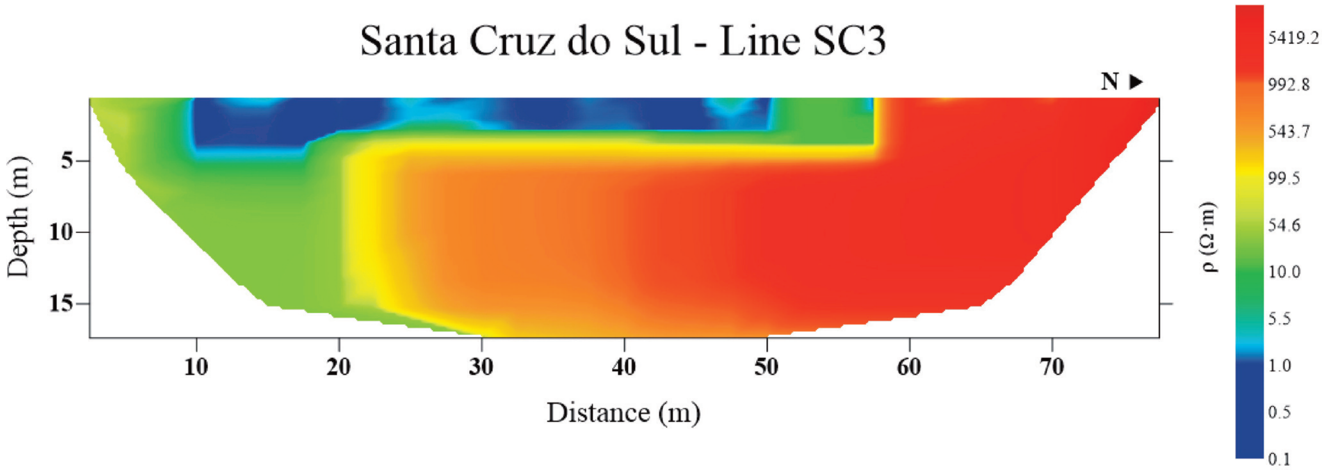

Fig. 32. *Line SC3 (inversion of the geoelectrical survey).*

version process. Therefore, to avoid the influence of these edge feats, a resistivity value found in the region between 30 and 40 m along the length of the line was taken as a reference. In this range, the resistivity was between 500–800 Ωm which could be the result (as in refraction seismic) of a sandy-clayey environment.

Geological modeling

The modeled area followed the exact coordinates used to map the hydrogeochemical parameters. The geological information was gathered from 43 SIAGAS wells, using the absolute altimetry value (referenced to sea level) of Serra Geral, Santa Maria and Rosario do Sul Formations and the static level of the aquifer, to generate their respective contour maps and a 3D model.

The contour map of the Serra Geral Formation is shown in Fig. 33. The Santa Maria and Rosario do Sul Formations are shown in Fig. 34 and Fig. 35, respectively. This last formation occupies the smallest area in the investigated region, appearing to have a esser extension in the well data. The Serra Geral Formation possesses the largest variation in altitude.

In Fig. 37 a three-dimensional representation of Fig. 33 to Fig. 36 is shown to observe the static level of the reservoirs, indicating a migration towards SSW. Moreover, in the three-dimensional representation of Fig. 37 is noted that the highest static level is located below the Serra Geral Formation. At Santa Maria Formation, the static level is at a lower level. Finally, from these modeling, it is possible to see how the aquifer is not only found in one formation but that it could be able to concentrate in both the Serra Geral and Rosário do Sul formations, as shown in line SC2.

Conclusions

It is concluded that integration of all the existing data is possible, which results in the successful characterization of the Santa Cruz do Sul via different methods (hydrogeochemical, geophysical, and geological). An overview of the water quality, possible lithologies, as well as probable prospects for aquifers and how they are distributed among the different formations was obtained. This is the first step towards a water geo-inventory in Santa Cruz do Sul and the base for a state water plan of geohydrological resources.

The hydrogechemical parameters imply that Santa Cruz do Sul has a high concentration of lead in its aquifers, as well as high dissolved oxygen. This is the reason why it is recommendable to have a treatment of water before consummation. This study suggests that most of the contaminants could come from the local geology (e.g., lead or dissolved oxygen).

Refraction seismic and geoelectrical methods were performed in a total of 3 geoelectric soundings and 3 lines by refractive seismic. These methods' results are consistent with each other and with the

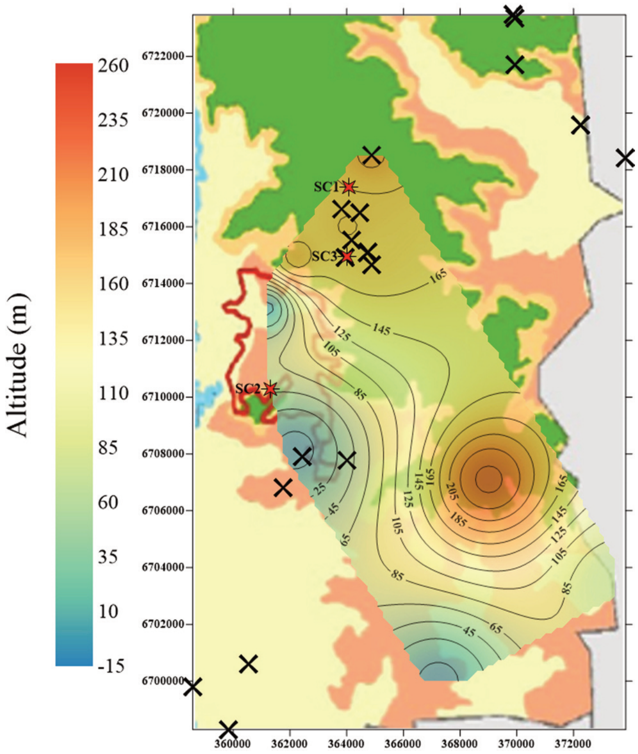

Fig. 33. *Contour map of Serra Geral Formation in Santa Cruz do Sul.*

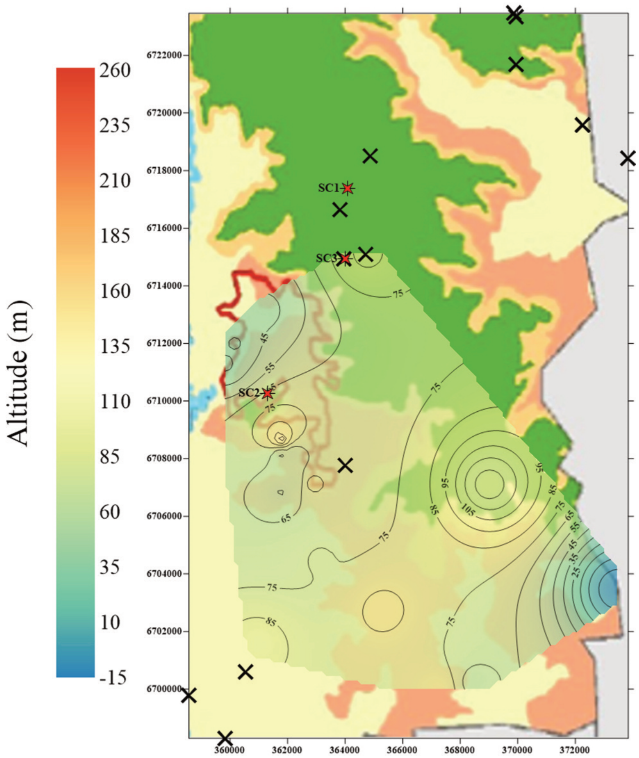

Fig. 34. *Contour map of Santa Maria Formation in Santa Cruz do Sul.*

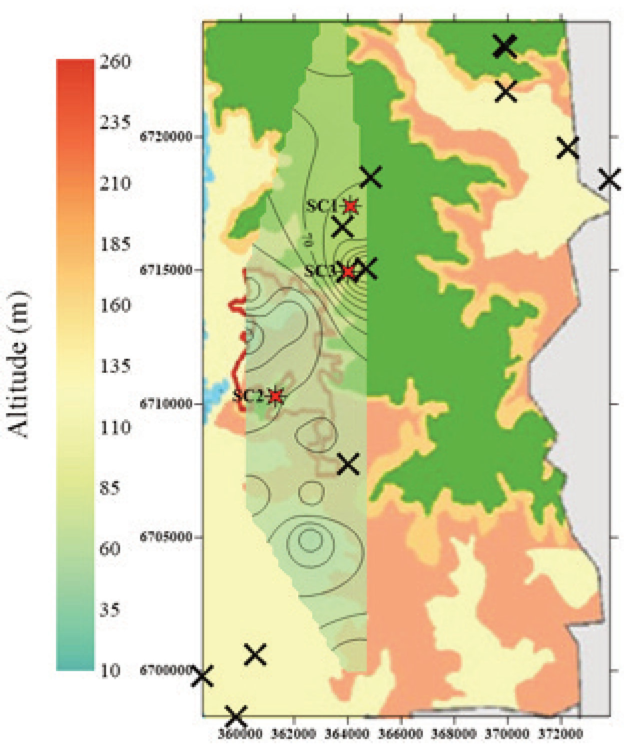

Fig. 35. *Contour map of Rosario do Sul Formation in Santa Cruz do Sul.*

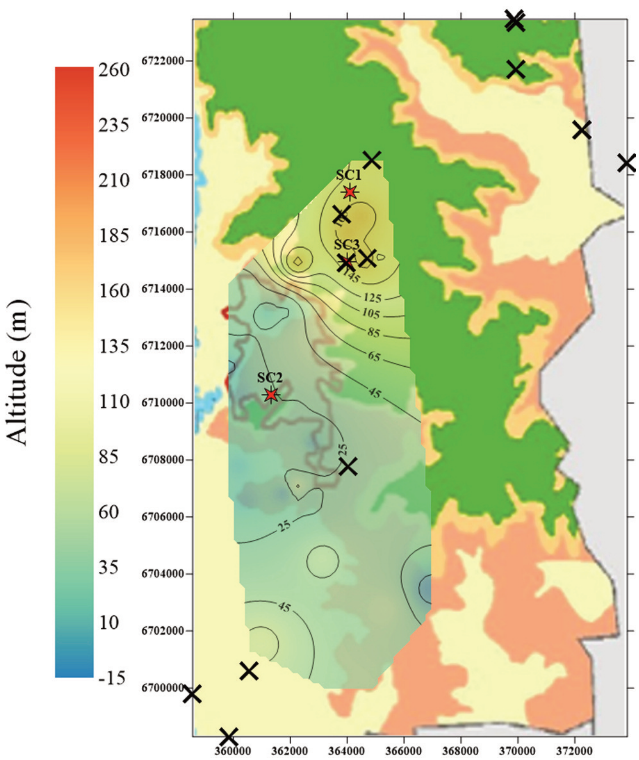

Fig. 36. *Contour map of static level of water in Santa Cruz do Sul.*

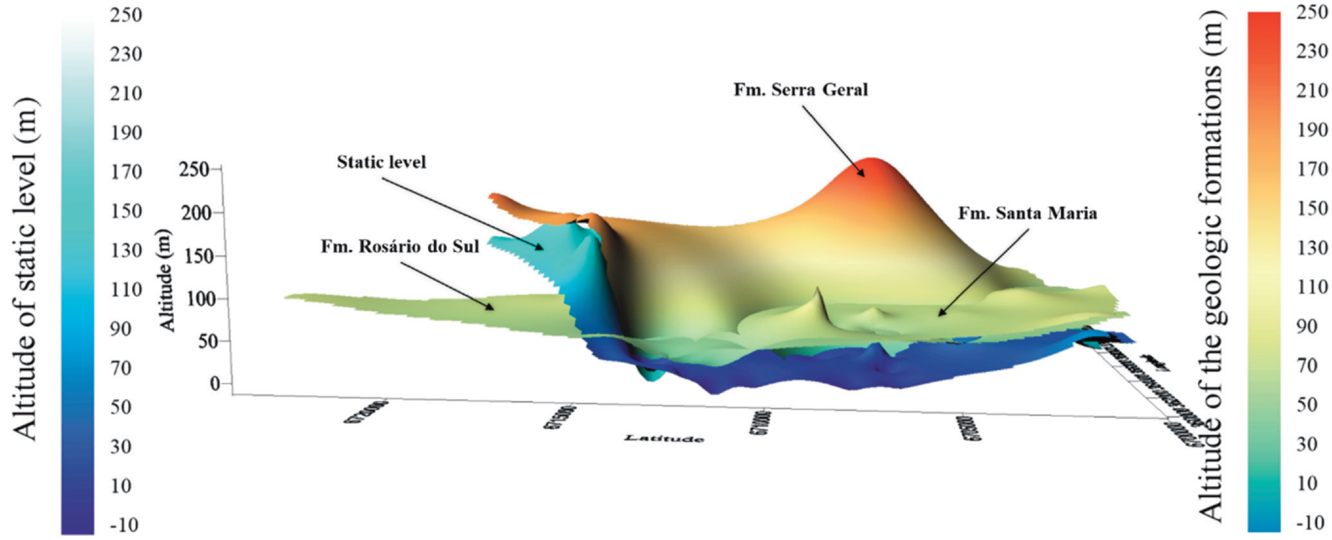

Fig. 37. *3D geological modelling in Santa Cruz do Sul.*

local geology. This implies that these geophysical methods are useful for discriminating lithologies and in the search for water.

It was possible to distinguish a three-layer model in refraction seismic. The first layer was weathered soil in all cases. The following two were either rock or consolidated sediment layers. The geoelectric sounding also obtained coincidence to the lithology and agreement with the results of the refraction seismic. In addition, a probable location of an aquifer in the case of SC2 line was indicated.

Furthermore, different formations have been modeled on 2D and 3D maps to the static level of existing aquifers, varying along the three modelled formations, finding the Guarani Aquifer in two formations, Serra Geral and Rosario do Sul.

Finally, geochemistry, geophysics, and geology can be correlated. Through geophysics, it is possible to identify the layers in the subsoil and the location of reservoir prospects, which, through chemical analysis, perceives the portability of this water, in addition to the probable geological origin it has, and the static level of the aquifer can be modeled.

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Резиме

Хидрогеохемијска анализа, геофизичка процена и геолошко картирање зоне пуњења водоносног система Guarani у Santa Cruz do Sul, Бразил

Држави Rio Grande do Sul (јужни Бразил) припада велики део водоносног слоја Guarani, који се прихрањује водама централног и западног региона, те су истраживања обухваћена овим радом била фокусирана на подручје општине Santa Cruz do Sul. До 2022. године у држави није постојао план водних ресурса, те је циљ овог рада процена хидрогеохемијских и геофизичких својстава, као и приказ геолошких карактеристика региона прихрањивања водоносног слоја. Због тога су прикупљени неки теренски подаци, извршене хемијске анализе вода у различитим бунарима и извршена геофизичка истраживања рефракционим сеизмичким и геоелектричним методама. Уз све ове податке, приступило се изради различитих мапирања хемијских параметара да би се сагледале концентрације неких елемената у области Santa Cruz do Sul. С друге стране, подаци добијени помоћу рефракционе сеизмике и геоелектричних метода су обрађени и интерпретирани, спајајући све ове резултате са геологијом добијеном из SIAGAS бушотина. На основу добијених података утврђена је висока концентрација олова у региону, што указује на потребу пречишћавања вода које би се могле користити за људске, пољопривредне или индустријске потребе.

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