

The effect of vinasse application in lowland areas cultivated with sugarcane on spatiotemporal variability of groundwater salinity in the northeast of Brazil

ABSTRACT

Aims: The aim of this study was to evaluate the spatiotemporal variability of electrical conductivity in groundwater under vinasse application on a lowland area cultivated with sugarcane in the northeast of Brazil.

Place and Duration of Study: This area is located in a sugarcane/ethanol plant in Pernambuco state (Brazil) and receives an average annual rainfall of 2100 mm, between January 2011 and August 2011.

Methodology: The experiment was composed of 54 georeferenced wells spread over an area of five hectares of sugarcane crop. This sampling was carried out six times from the 54 wells during eight months to evaluate the temporal variability of electrical conductivity (EC) in the groundwater. Descriptive statistics and geostatistical methods were used for spatial modeling and to create maps. A correlation matrix using Spearman's method was calculated by SAS to evaluate if there was a temporal correlation among the electrical conductivity values of groundwater over a long period of time.

Results: The mean EC does not present any risk of soil salinization, and do not produce a limit for irrigation. All data had normal frequency distributions. A Gaussian model was adjusted for all samplings. The range of spatial dependence was from 20.43 m (4th sampling) to 34.64 m (before vinasse application), with an average of 25.17 m. EC values in the groundwater during the monitoring period were not high enough to indicate a severe degree of restriction on use, i.e. $< 3\text{dS}\cdot\text{m}^{-1}$.

Conclusion: Groundwater electrical conductivity was reduced by rainfall events and did not present a risk of salinization. The range of spatial dependence values demonstrated that it was necessary to use 32 m spacing between observing wells for the sustainable management of vinasse in lowland areas.

Keywords: *Saccharum spp.*; hydric monitoring; geostatistical method; electrical conductivity.

1. INTRODUCTION

Sugarcane (*Saccharum spp.*) has been driving the economic development of Brazil for hundreds of years, especially in the southeast and northeast regions. Brazil is currently the world's largest producer of sugarcane—9.11 million hectares of this crop are cultivated [1]. Sugarcane can grow in tropical and subtropical climates, and produces significant amounts of biomass [2], especially when adequately supplied with water and nutrients. It can be used for fermentation products, such as ethanol and acetic acid. Ethanol is a fuel produced from renewable sources with low carbon levels, and these two characteristics confer upon it strategic importance in the fight against the intensification of greenhouse effects and their influence on global climate change, which falls in line with sustainable development principles [3].

The expansion of sugarcane plantations requires the use of areas with high potential productivity, such as lowland. These areas have flat topography and a favorable natural fertility and hydric regime, but in dry seasons irrigation is needed to supply the water demand, particularly in regions such as the northeast of Brazil, where precipitation is less than potential evaporation, the rivers are intermittent, and there is scarcity of hydric resources. The use of vinasse is promising, as it

provides water and nutrients such as organic compounds (acids, alcohols, aldehydes, ketones, esters, and sugars) and soluble ions (K^+ , Ca^{2+} , Mg^{2+} , and SO_4^{2-}) [3] and [4]. Vinasse is wastewater generated during the production of ethanol from sugarcane, in a ratio of 10 to 15 liters per liter of distilled ethanol [5] and [6].

In general, each year the area subject to fertigation with vinasse has increased as a result of the search for higher productivity and reduced use of chemical fertilizers, as well as the fact that the required vinasse dose doesn't cause damage to the environment [7]. Therefore, this process provides sustainable development with the wastewater application as a source of nutrients delivered by the irrigation system, as well as an economic alternative due to the low cost of production [3]. On the other hand, the application of vinasse in lowland areas can have a deep impact on groundwater quality due to the high amounts of organic components and soluble salts. In relation to this, few studies have been conducted to evaluate the soil-vinasse-groundwater relationship, or to analyze the impact of vinasse on natural resources over time.

According to [8], vinasse applied in high doses could cause negative effects such as reduced quality of sugar, soil salinization, and pollution of groundwater besides that high potential of soil acidification [4]. The electrical conductivity (EC) is the variable most commonly used to assess the salinity level or the soluble salt concentration in water and soil [9], and it has been used as a parameter to analyze the quality of natural resources in many studies, such as [3], [8] and [10].

Traditionally, farming practices such as irrigation are used uniformly without considering soil spatial differences. According to [11] and [12], one way to compensate for this would be by using geostatistical techniques, since they are applied to discover the spatial variability of soil properties. The spatial dependence study by regionalized variables theory of geostatistical analysis allows the interpretation and projection of results based on the structure of their natural variability. Once quantified, the spatial dependence on the analyzed variable can be used in interpolation methods between observations, allowing the estimation of values in locations not observed, with minimal variance [13].

The aim of this study was to evaluate the spatiotemporal variability of electrical conductivity in groundwater under vinasse application in a lowland area using geostatistical techniques.

2. MATERIAL AND METHODS

2.1 Characterization of the study area and experimental device

The study was conducted in an experimental area located in 08°38'91" S and 35°16'08" W city of Rio Formoso, Pernambuco State, Brazil (Fig. 1). The elevation of the study area is around 60 m and the topography is flat, located in a lowland area. The climate is classified as Ams', according to Köppen [14], and characterized as rainy tropical with dry summers, and a rainy season between May and August. The region has an average annual rainfall of 2100 mm, and annual temperatures between 24 and 29°C. The sugarcane variety (*Saccharum* spp.) grown in the experimental area was RB92579 [15] and it was planted in Typic Fluvaquent according to Soil Taxonomy [16].

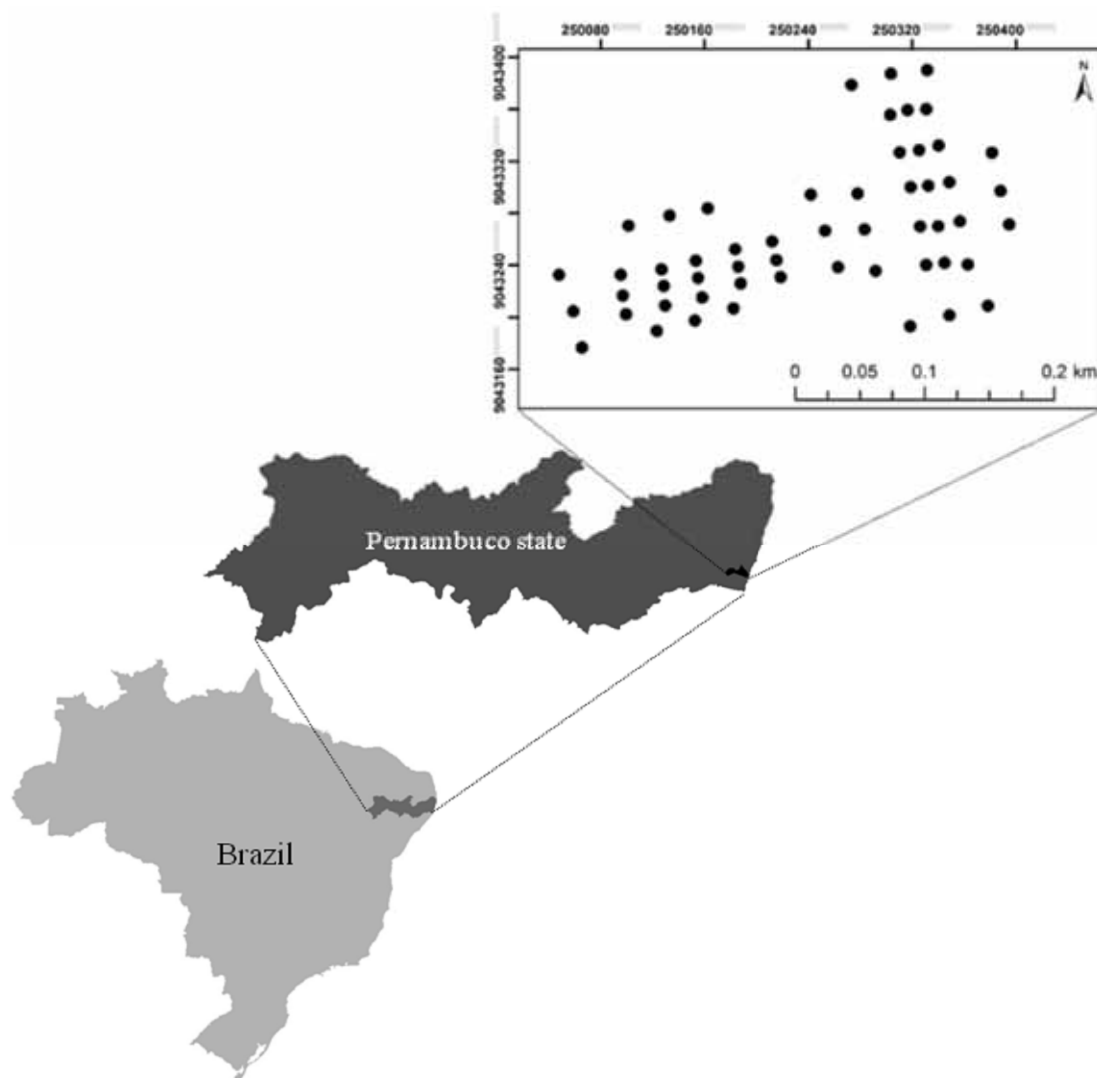


Fig. 1. Location of the study area and spatial distribution of wells in the experimental area

The experiment was composed of 54 georeferenced wells spread across five hectares, under sugarcane crop. These wells were distributed in two ways: 30 wells under vinasse application (spacing at 15 x 30 m) and 24 wells in outside the vinasse application area (spacing at 30 x 30 m) (Fig. 1) which were installed at 1.30 to 3 m depth, according to the presence of groundwater.

The wells were made with PVC tubes of 75 mm diameter and 3 m length, drilled with a filter screen in the lower middle third, according to [17]. Wells were closed with a PVC cap to avoid any contamination by the external environment of the groundwater, and were identified with a number (Fig. 2). This tube numbering was very important to identify and locate them when the area was completely covered by sugarcane.

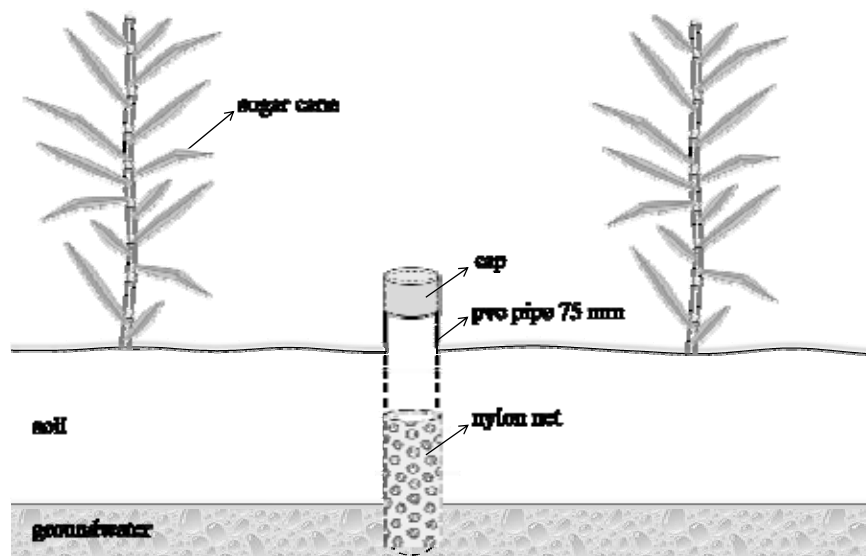


Fig. 2. Experimental device used in the study

One lateral line along the center of the area with three sprinklers spaced at 60 m was installed for vinasse application, with 6.5 mm irrigation depth. This vinasse was produced by the Cucaú Plant, whose chemical composition is shown in Table 1.

Table 1. Chemical composition of vinasse used in the study

Parameter	Value
pH	3.98
Electrical conductivity (dS.m ⁻¹)	9.32
K ⁺ (mg.L ⁻¹)	18,894.00
Na ⁺ (mg.L ⁻¹)	759.00
Ca ²⁺ (mg.L ⁻¹)	57.90
Mg ²⁺ (mg.L ⁻¹)	423.45

2.2 Sampling from groundwater

Sampling from groundwater was achieved using a manual vacuum pump. The samples were stored in containers of 100 mL, properly preserved for transport to an accredited laboratory where the analyzes were performed. This sampling was carried out six times during eight months to evaluate the temporal variability of electrical conductivity (EC) in the groundwater. The EC was determined at 25°C by the electrometric method according to Standard Methods for Examination of Water and Wastewater [18].

The first sampling was carried out before vinasse application (07/01/2011). After the fertigation, three samples were taken at intervals of 15 days (12/01, 28/01, and 12/02/2011) in order to identify any changes in groundwater chemical composition. The fourth sampling was performed after 30 days from the third sampling (11/03/2011), since some uniformity of EC was observed in preliminary results. The final sampling was carried out after 150 days after the fourth sampling (31/08/2011), aiming to evaluate the groundwater salinity during the rainy season, the capillary rise influence, and the elevation of the water level (Fig. 3).

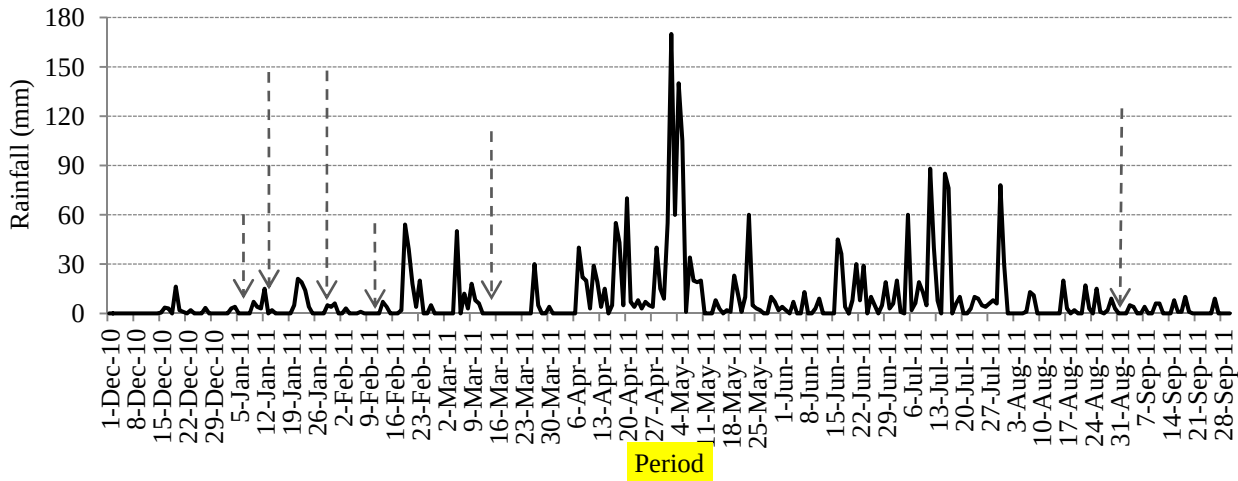


Fig. 3. Daily rainfall from December 2010 to September 2011 and sampling dates (dashed arrow) of water from the groundwater.

2.3 Statistical and geostatistical analysis

Classical statistical analysis was done to check the data distribution according to statistical parameters of position and variability (mean, median, mode, minimum and maximum values, standard deviation, coefficient of variation, skewness, and kurtosis) using R 3.3.2 [19]. The coefficient of variation (CV) was classified according to [20] as low ($CV < 12\%$), medium ($12 < CV \leq 60\%$), or high variability ($CV > 60\%$). Maximum deviation from a normal distribution was evaluated by the error probability of the Kolmogorov-Smirnov test (KS) with a 0.05 probability level.

A correlation matrix using Spearman's method was calculated by SAS to evaluate if there was a temporal correlation among the electrical conductivity values of groundwater over a long period of time.

The spatial dependence structure was evaluated using geostatistical techniques based on semivariograms created with semivariance according to intrinsic hypothesis theory [12], using Equation 1.

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (1)$$

where $\hat{\gamma}$ is the semivariance estimated from experimental data at distance h ; $N(h)$ is a set of pairs of observations; $Z(x_i)$ and $Z(x_i + h)$ are observed values of regionalized variables separated by distance h .

When stationarity is not present, the trend must be removed before performing the variographic analysis, working with the residuals of a trend surface [21]. Therefore, it was verified whether the mean and covariance of the values showed a trend, i.e. if there was stationarity. When this condition was not satisfied, a filtering of the data trend was performed using the polynomial regression method of the Surfer software (version 7, Golden software Inc., Cold Spring Harbor, NY, USA). With the experimental semivariogram, the data was fitted to various theoretical models to choose the best model by trial and error using GS+ software [22]. Semivariograms were validated using a jack-knifing test [23]. Mathematical adjustment enabled the following parameters to be defined: nugget effect (C_0), structural variance (C_1), sill ($C_0 + C_1$), and the range of spatial dependence (a).

The Spatial Dependence Index ($SDI = C_0 / (C_0 + C_1) \times 100$) was calculated and classified according to [24], which defines the spatial dependence as strong ($< 25\%$), moderate ($25 - 75\%$), low ($> 75\%$), or independent among samples (100%).

Ordinary kriging was used as the interpolation method to estimate values for non-sampled points, which gives unbiased intermediate values with minimum variance. This analysis was used in order to evaluate the spatial variability of EC in six samplings. Contour maps were drawn using Surfer software for visualizing the spatial distribution of EC in the groundwater.

3. RESULTS AND DISCUSSION

3.1 Descriptive statistics and Spearman's correlation

137 The mean EC decreased after the first sampling, and more strongly after the fourth sampling, whereas the lowest value
138 was in the fifth sampling (0.11 dS.m^{-1}) (Table 2). This result is lower than that found before the application of vinasse. In
139 this case, there are two assumptions: nutrient removal by sugarcane uptake, and vinasse percolated after each heavy
140 rainfall event (Fig. 3). Besides that, soil water movement, floating table water, and aquifer recharge provided dilution of
141 vinasse chemical elements in the groundwater. On the other hand, according to [25], water with EC less than 0.7 dS.m^{-1}
142 does not present any risk of soil salinization, and do not produce a limit for irrigation. Besides that, according to [4]
143 vinasse's dose, days after irrigation and land use had a relevant effect on most nutrients effluent concentration. [26]
144 studied the quantity of inorganic and organic ions in the profile of the soil under sugarcane and their results showed that
145 after 63 days, no traces of those anions were found in the soil.

146
147 **Table 2. Descriptive statistics of groundwater electrical conductivity (dS.m^{-1}) in different samplings**

Parameters	Sampling					
	Before vinasse application	1 st	2 nd	3 rd	4 th	5 th
Minimum	0.01	0.01	0.01	0.01	0.01	0.01
Maximum	1.45	1.85	1.76	1.89	1.07	0.62
Mean	0.31	0.34	0.32	0.30	0.18	0.11
Median	0.20	0.22	0.19	0.19	0.13	0.12
Variance	0.08	0.14	0.14	0.13	0.04	0.01
Standard deviation	0.28	0.37	0.37	0.36	0.20	0.11
Coefficient of variation (%)	91.78	111.00	115.65	120.30	107.56	97.36
Skewness	2.28	2.18	2.70	2.30	3.38	1.93
Kurtosis	8.53	7.92	9.70	11.28	14.19	9.50
D	0.19 n	0.21 n	0.26 n	0.29 n	0.30 n	0.18 n

148 *D: Maximum deviation from a normal distribution with 0.05 probability level; n: Normal distribution.*

149
150 There was high amplitude of the minimum and maximum values in all samplings, which influences the high coefficient of
151 variation (CV). The CV increased until the third sampling, and after that decreased, probably because of the temporal
152 distribution of rainfall events (Fig. 3). According to [20] and [27], high values of this coefficient can be considered to be
153 early indicators of the existence of heterogeneous data. The soil properties determine the chemical composition of the
154 groundwater, once the water is constantly in contact with it and can circulate until it reaches equilibrium with the soil.
155 Besides that, groundwater can have extreme variations in its composition, due to pollutants and various contaminants.
156 All data had normal frequency distributions, as shown by the skewness, kurtosis, and D (Table 2). The presence of a
157 normal frequency distribution favors the application of geostatistical tools.
158 There is a high correlation among the data of groundwater electrical conductivity over time, which shows that there is a
159 temporal correlation (Table 3) and that it was significant at the 0.1 probability level.

160
161 **Table 3. Spearman's correlation matrix of groundwater electrical conductivity (dS.m^{-1}) in different samplings**

Sampling	Sampling					
	Before vinasse application	1 st	2 nd	3 rd	4 th	5 th

Before vinasse application	1	1.00*	1.00*	1.00*	1.00*	0.98*
1 st	1	1.00*	1.00*	1.00*	1.00*	0.98*
2 nd		1	1.00*	1.00*	1.00*	0.98*
3 rd			1	1.00*	1.00*	0.98*
4 th				1	1.00*	0.98*
5 th						1

*Significant at .1 probability level

3.2 Geostatistical analysis

Table 4 presents the adjustment parameters of the experimental semivariogram to EC values that describe the behavior of spatial variability in different samplings.

Table 4. Estimated parameters of adjusted semivariograms for electrical conductivity (dS.m⁻¹) of groundwater at different samplings

Sampling	Nugget effect (C0)	Structural variance (C1)	Sill (C0+ C1)	Range (m)	SDI (%)
Before vinasse application	0.00001	0.0248	0.0248	34.64	0.04
1 st	0.00010	0.0901	0.0902	25.28	0.11
2 nd	0.00010	0.0961	0.0962	22.34	0.10
3 rd	0.00001	0.0152	0.0152	26.67	0.07
4 th	0.00001	0.0122	0.0122	20.43	0.08
5 th	0.00001	0.0069	0.0069	21.65	0.15

A Gaussian model was adjusted for all samplings. The range of spatial dependence was from 20.43 m (4th sampling) to 34.64 m (before vinasse application), with an average of 25.17 m. This information is vital for the management and conservation of soil and groundwater, which indicates the maximum distance to new observing wells, especially when there is trend of reducing concentrations over time.

The groundwater EC showed strong spatial dependence according to [24] (Table 4), indicating that there is a spatial grouping of the data. Strong spatial dependence is also influenced by external factors resulting from the soil-plant-groundwater interaction, causing a heterogeneous distribution of data.

The spatial pattern of pairs of semivariance persists throughout the study period (Fig. 4), emphasizing again the importance of using a range of spatial dependence values in the planning and management process in water and soil conservation.

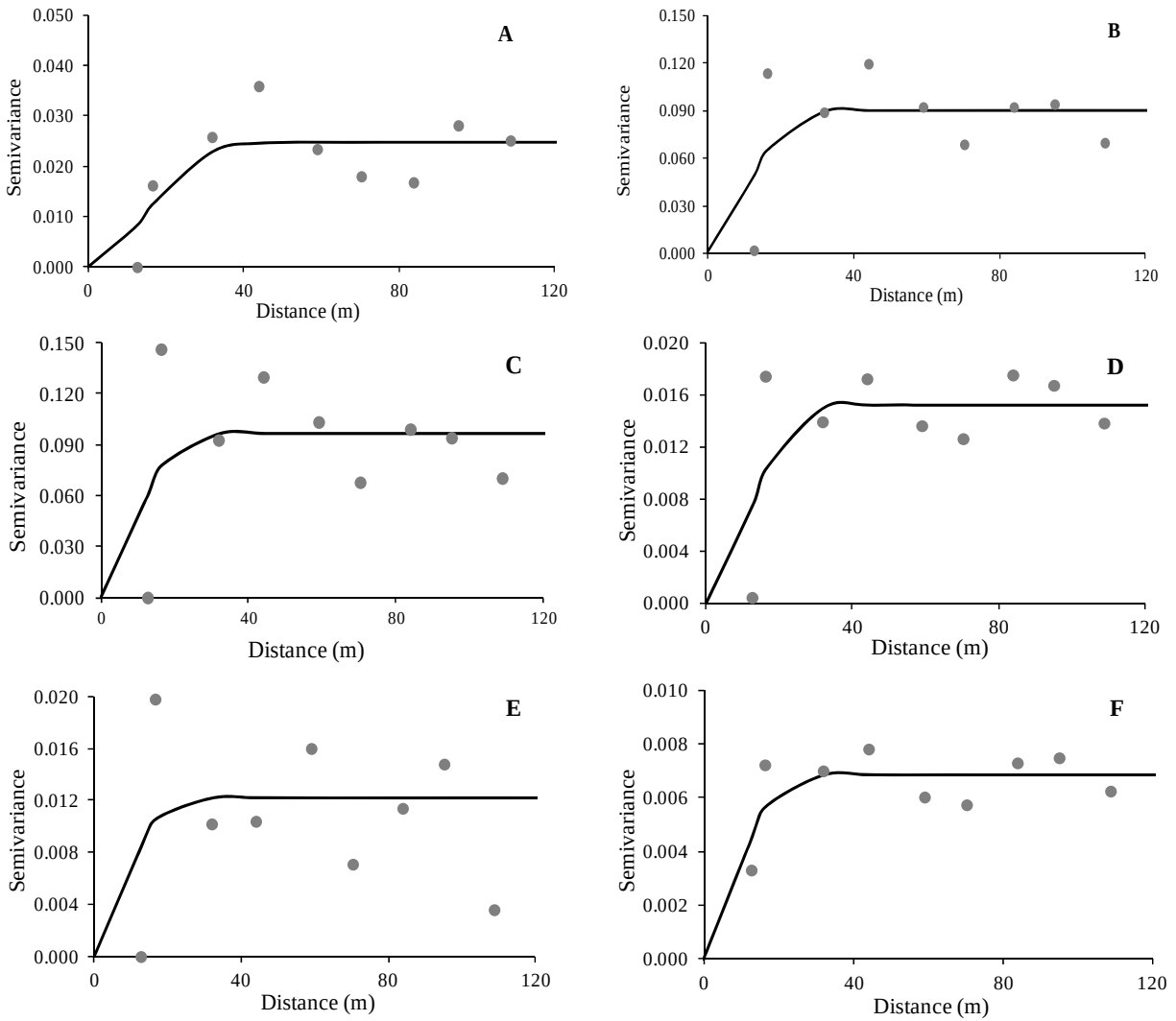


Fig.4.Semivariogram adjusted for groundwater electrical conductivity at different samplings: A – before vinasse application; B – 1st; C – 2nd; D – 3rd; E – 4th; and F – 5th sampling

The maps clearly indicate that after the application of the vinasse (Fig. 5B) there was a considerable increase in EC values compared to before vinasse application (Fig. 5A). During the period of monitoring, the occurrence of the rainy events contributed to the homogenization of these values in the area. This fact is characterized in Figure 5F, when the observed values are totally homogeneous in the area and lower than those found at the beginning of the experiment (Fig. 5A). Besides that, EC values in the groundwater during the monitoring period were not high enough to indicate a severe degree of restriction on use, i.e. $< 3\text{dS.m}^{-1}$ [25].

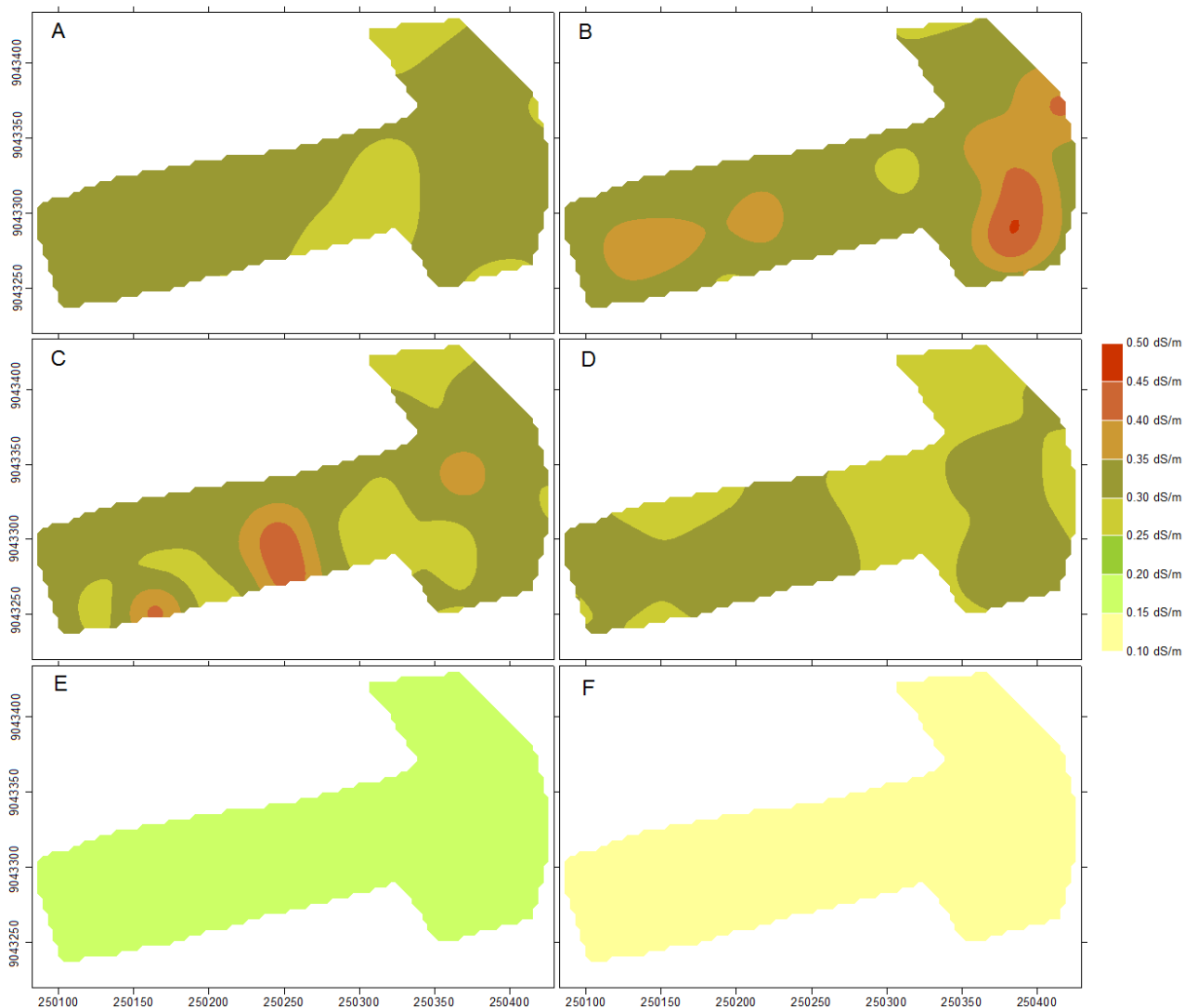


Fig. 5. Spatial variability maps of groundwater electrical conductivity in different samplings: A – before vinasse application; B – 1st; C – 2nd; D – 3rd; E – 4th; and F – 5th sampling

The EC map had the scales standardized with values ranging between 0.100 and 0.500 dS.m⁻¹. This was done to provide the observation of EC temporal variability. The EC values ranged from 0.170 to 0.190 dS.m⁻¹ in the fourth sampling and in the fifth collection, there was a reduction to values between 0.110 to 0.130 dS.m⁻¹. Because of these low values found in these samplings, the spatial variability was imperceptible in these maps (Fig. 5E and 5F) due to map scale adopted. As a result, these values don't present risk of salinization.

4. CONCLUSION

Geostatistical analysis was shown to be an auxiliary tool for the monitoring of groundwater; The range of spatial dependence values demonstrated that it was necessary to use 32 m spacing between observing wells for the sustainable management of vinasse in lowland areas; Groundwater electrical conductivity was reduced by rainfall events and did not present a risk of salinization; The Spatial Dependence Index indicated a strong dependence of groundwater electric conductivity for all samplings, indicating the existence of spatial grouping of the data.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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