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RESEARCH ARTICLE

Spatial estimation of soil salinity with ordinary kriging (Eastern Tunisia)

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Abstract

Irrigation using brackish water is generally practiced in arid regions, because of their limited conventional water resources. However, this use can lead to disastrous impacts, including soil salinization. Therefore, soil salinity monitoring by setting up valuable monitoring tools is essential. This study examines the spatial variation of soil salinity in the public irrigation zone Zelba 1 of the region of Mahdia (Easten Tunisia) using mapping techniques and ordinary kriging. Results showed that the soil of the irrigation zone is isohumic, presenting a sandy-silt to clay-silt texture. It is permeable with hydraulic conductivity values varying between 8 10^{-6} and 10^{-5} m/s. Electrical conductivity measurements revealed that the soil is moderately saline at the surface, with values varying between 0.7 and 1.3 dS/m. This salinity increased slightly with depth. The electrical conductivity varied between 1.3 and 1.8 dS/m for layer (120-150 cm), indicating a moderately saline and saline soil. The increasing gradient of the soil salinity is due to the salts leaching following the irrigation. Mapping of the soil salinity revealed a slight spatial variation of salinity in different soil layers. The southwestern part of the irrigation zone is the most affected by salinity, especially in the deepest layers. Electrical conductivity values varied between 1.6 and 1.8 dS/m. The low salinity observed in the north of the irrigation zone, could be explained by the fact that this part is closer to the water well. It receives more water, explained by the overflow of water from basins accelerating salts leaching to deeper layers.

INTRODUCTION

Major semi-arid and arid Mediterranean regions, are facing serious water scarcity (Rubio et al., 2009). These regions, with population expanding at a high rate, are characterized by water resources that fall below the level of shortage of 500 m^3 per person per year of renewable water (Masmoudi et al., 2011). The scarcity of renewable water resources has led to the use of non-conventional water resources to meet rising water demands, especially for the agricultural sector. According to (Qadir et al., 2007), seawater desalination technology has progressed significantly in many countries such as Gulf States in order to overcome water shortage. However, due to the high cost associated with this technology, its adoption is generally limited to domestic use in high-income countries. Other options, such as the use of drainage waters, marginal-quality waters with high salinity and treated wastewater were valorized in developing countries especially for land irrigation. Nevertheless, the overuse of these poor-quality waters may lead to serious environmental damages (Ziza et al., 2012). In fact, irrigation using poor-quality-water induces in the short term soil salinization and over time soil sodisation (Ben Ahmed et al., 2012). The effects of soil salinization are not destructive as those caused by earthquakes or floods but they can cause serious environmental risk and harm especially in irrigated lands of arid regions (Jianguo et al., 2014).

In Tunisia, soil salinization is a common phenomenon. Nearly 100 000 ha of the irrigation zones are affected by the problem of soil salinization, especially those located in the center and in the south of the country (Al Atiri, 2007). This process is mainly due to the lack of water resources used in irrigation and their often poor-quality. In the region of Mahdia (Eastern Tunisia), waters used in irrigation come from deep aquifers. These waters are quite rich in soluble salts (5<total dissolved solids<6 g/l) (Majdoub et al., 2012). Public irrigation zones of this region are therefore, characterized by a progressive soil salinization due to the use of these waters.

In this context, this paper examines the spatial distribution of soil salinization parameters in the Public Irrigation Zone (PIZ) Zelba 1 of the region of Mahdia using mapping methods based on ordinary kriging. Soil salinity was measured in 20 lots to a depth of 150 cm. Then, measurement results were introduced in the database of the GS+ software version 9 model and interpolated by ordinary kriging. The obtained maps were interpreted and discussed. These maps, identifying the most affected regions by soil salinization, may be considered as an interesting decision tool to fight against this phenomenon.

This paper is organized as follows: The material and methods section presents the study site and describes the water and soil samples collection, preparation and analysis. This section also presents the mapping methods used to describe soil salinity spatial variation. Section 2 and 3 present and discuss the principal results obtained from analysis and treatments, including soil salinity spatial distribution. Finally, some conclusions were drawn and several issues for future works were suggested.

2. Material and methods

2.1. Study site description

This study was conducted in the Public Irrigation Zone (PIZ) Zelba 1, located in the center of an alluvial plain in the region of Mahdia, Eastern Tunisia (Fig 1). The PIZ, created in 1986, falls under the arid conditions with an annual average precipitation of about 288 mm and an annual average temperature of about 19.3°C. The PIZ covers 60 ha consisting of 20 lots of 3 ha each. Adopted crops are mainly sorghum, barley and oat. Irrigation water comes from the water drilling Zelba 1, created in 1983, capturing a deep aquifer of the Sahel of Sfax (depth = 400 m) debiting 18 l/s.

2.2. Experimentation

2.2.1. Fieldwork

Water samples were collected from the water drilling Zelba 1 according to the norm ISO 5667-11 to measure pH, electrical conductivity (EC_w), total dissolved solid (TDS), Cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and anions (SO_4^{2-}, Cl^- and HCO_3^-). Soil samples were collected in 20 lots of the irrigation zone to a depth of 150 cm (Fig 2). Sampling was carried out in a systematic manner using an auger to have a soil sample for each layer of 15 cm.

The collected samples served for the reconstitution of soil profiles in the laboratory in order to characterize the different constitutive layers of the soil (color, presence or absence of calcareous nodules, presence or absence of plant debris, etc.). Then, a soil sample was taken from each identified layer of the reconstructed profile for analysis in the laboratory. Soil samples were air-dried, crushed and sieved at 2 mm. The fraction less than 2 mm was used to analyze the soil texture, the saturated hydraulic conductivity (K_{sat}) and the electrical conductivity (EC).

2.2.2. Irrigation water analysis

The pH was measured by a pH meter electrode immersed directly in the irrigation water. The water electrical conductivity (EC_w) was evaluated using a conductivity meter equipped with a temperature correction setup, which allowed direct reading at the reference temperature of 25°C. The Total Dissolved Solids (TDS) was measured by drying a total volume of 50 ml of the aqueous extract in an oven at 110°C for 24 hours. The ionic composition analysis was determined by volumetric proportioning based on the principle of Mohr for chlorides (Cl^-), carbonates (CO_3^{2-}), bicarbonates (HCO_3^-), calcium (Ca^{2+}) and magnesium (Mg^{2+}). The proportioning of sodium (Na^+), potassium (K^+) and sulfate (SO_4^{2-}) was based on the principle of flame spectrophotometer. Chlorides were measured using a standard solution of silver nitrate ($AgNO_3$, 0.02N) in the presence of potassium chromate ($KCrO_4$). These elements were precipitated in the form of silver chloride (AgCl). Bicarbonate proportioning was conducted by acidimetry using sulfuric acid (0.02N H_2SO_4). The colored indicator used is green bromocresol, which gives a blue color. Carbonate ions were absent. Calcium was proportioned by complexometry at pH = 10 in the presence of (NaOH). Titration was carried out using tetraacetic ethylene diamine. Magnesium concentration was calculated by the difference of the total hardness and the calcium concentration. Sodium and potassium proportioning was based on the atoms dissociation during their passage through the flame which emits energy when the electrons are excited in the atoms. Sulfates were analyzed using stabilized Barium Chloride ($BaCl_2$).

2.2.3. Soil analysis

Soil texture reflects the amounts of various sized particles in the soil. It was determined based on a representative sample for each layer of the PIZ using the Robinson pipet's method (Yoka et al., 2010). This method consists in separating the mineral portion of the soil in fractions classified according to the size of particles less than 2 mm. Soil permeability was characterized by measuring the saturated hydraulic conductivity (k_{sat}). The k_{sat} was determined by the double ring infiltrometer method based on the principle of vertical infiltration (Mathieu and Pieltain, 1998). Soil salinity was determined by measuring electrical conductivity of 1/5 ($EC_{1/5}$). In fact, soil/distilled water suspensions were prepared by weighing 10 g of soil into a pop-top tube, adding 50 ml of deionized water, and shaking for 5 mn on an end-over-end shaker. After being centrifuged, the $EC_{1/5}$ of the supernatant was directly measured with a Jenway type conductivity meter (USSL, 1954).

2.2.4. Data treatment

A high resolution satellite image was extracted from Google Earth. Then, the coordinates of each sampling point of the soil sample (X, Y and Z) were identified on this satellite image. These coordinates and the obtained results of $EC_{1/5}$ were introduced in the database of the GS+ software version 9 model. Variograms were obtained and maps of $EC_{1/5}$ were subsequently interpolated by ordinary kriging.

3. Results

3.1. Irrigation water

Results of the irrigation water chemical analysis showed that the water is slightly alkaline and rich in soluble salts. The pH value is equal to 7.9; EC_w is about 7.2 dS/m and TDS is almost 5.0 g/l. This water is characterized by the abundance of sulfates, chlorides and sodium (Table 1). Cation and anion concentrations are, ranked according to the following order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > SO_4^{2-} > HCO_3^-$. Thus, this water has a chlorinated and sodic sulfated geochemical facies. The SAR value is about 15.6. Therefore, the irrigation water falls in the C5S4 class according to the diagram of Riverside, indicating thereby water of a very high risk of salinization and alkalization (Durand, 1973).

As a result, this water may yield in the reduction of crop production and can even cause soil degradation by deterioration of its physical and chemical properties (Hu et al., 2013).

3.2. Soil

3.2.1. Soil physical characteristics

Soil profiles reconstitution showed a deep brown isohumic soil with calcareous nodules, which texture is dominated by silt. It is homogeneous soil, explained by the land geomorphology characterized by mild slopes of less than 3% (Louati et al., 2014).

Soil texture revealed a sandy-silt texture for the first 30 cm, a silty-sand texture at depths varying between 30 and 135 cm and a clay-silt texture at depths beyond 135 cm. In fact, clay content increased with depth ranging from 13 to 30%, while the content of coarse particles decreased from 45 to 26% for fine sand and from 8 to 6% for coarse sand (Louati et al., 2014) (Table 2).

Regarding soil permeability, mean values of saturated hydraulic conductivity (k_{sat}) measured at the soil surface are between 8 10^{-6} m/s and 10^{-5} m/s, indicating a permeable soil with k_{sat} values exceeding 5 10^{-6} m/s (Louati, 2015). This observed permeability could be explained, especially by the presence of a sandy-silt texture at the soil surface. Soil permeability could be also explained by the presence of cracks and organic matter at soil surface which improved the water infiltration rate (Coquet et al., 2005).

3.2.2. Electrical conductivity measurement

The soil electrical conductivity measurements are shown in Table 3. Indeed, the mean $EC_{1/5}$ values varied between 0.7 and 1.3 dS/m at the soil surface (0-30 cm) which correspond to moderately saline classes (USSL, 1954). The $EC_{1/5}$ increased slightly with depth. Mean $EC_{1/5}$ values varied between 1.3 and 1.8 dS/m, for layers of 90-120 cm and 120-150 cm respectively, indicating a moderately saline and saline soil based on USSL (1954) classification.

3.2.3. Electrical conductivity interpolation

A. Variographic analysis

The first step in kriging is the variogram modeling which can provide information on spatial variability of measurements susceptible to guide future sampling modes (Bovin et al., 1989). The mean variograms were calculated for electrical conductivity ($CE_{1/5}$) measured in five layers of the studied irrigation zone (Fig 3). Parameters of the variographic models are presented in table 4.

B. Kriging

Spatial distribution maps of the soil salinity of the PIZ and corresponding standard deviation are shown in Figs 4 and 5 respectively. These maps were carried out by ordinary kriging using GS+ software model (version 9).

Table 1. Irrigation water ionic composition

Ionic composition (meq/l)							SAR
Cations				Anions			
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}	HCO_3^{-}	
14	9.87	54	0.61	28	50	4	15.6

Table 2. Soil particle size

Depth (cm)	Particle size (%)		
	Clay	Silt	Sand
0-15	13	42	45
15-30	14	59	44
30-45	14	45	41
45-60	16	42	42
60-75	18	41	41
75-90	19	42	39
90-105	23	41	36
105-120	22	43	35
120-135	24	42	34
135-150	30	44	26

Table 3. Statistical data of the soil electrical conductivity

Depth (cm)	Minimum	Maximum	Mean	Standard deviation
0-30	0.70	1.30	0.97	0.18
30-60	0.80	1.50	1.16	0.23
60-90	0.90	1.6	1.32	0.20
90-120	1.30	1.70	1.46	0.12
120-150	1.30	1.80	1.53	0.09

Table 4. Variographic model parameters

Depth (cm)	Model	C_0 (m^2)	P (m^2)	A (m)	C_0/P (%)	C/(C_0+C)	r^2
0-30	Gaussien	$2.3\ 10^{-3}$	$4.2\ 10^{-2}$	914	0.054	0.945	0.853
30-60		$5.9\ 10^{-3}$	$8.2\ 10^{-2}$	1128	0.0719	0.929	0.924
60-90		10^{-4}	0.157	1517	$6.36\ 10^{-4}$	0.999	0.969
90-120		10^{-3}	0.022	947	0.045	0.952	0.784
120-150		10^{-3}	$8\ 10^{-3}$	605	0.125	0.87	0.721

Note: C_0: Nugget effect ; P = C_0+C: Sill ; A: range ; C_0/P: Nugget effect/Sill ; r^2: Correlation coefficient.

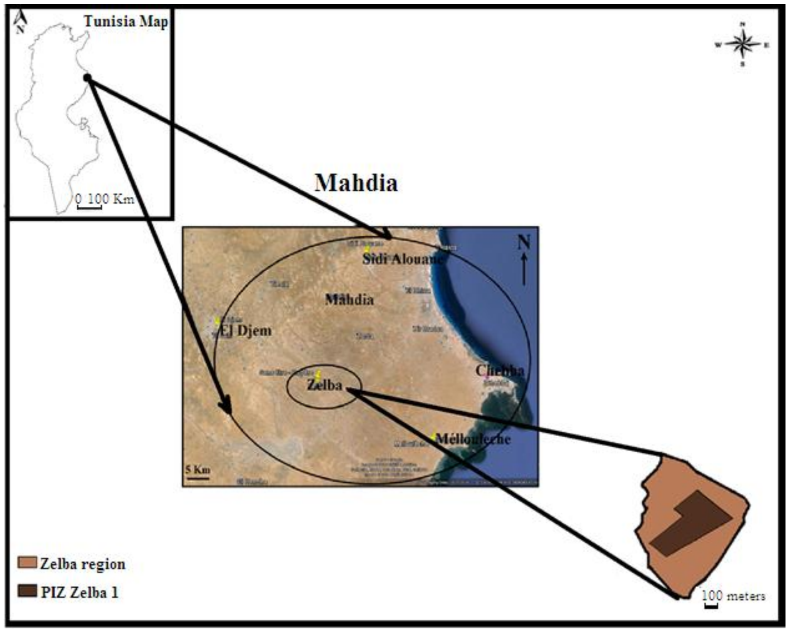

Fig 1. Study area presentation

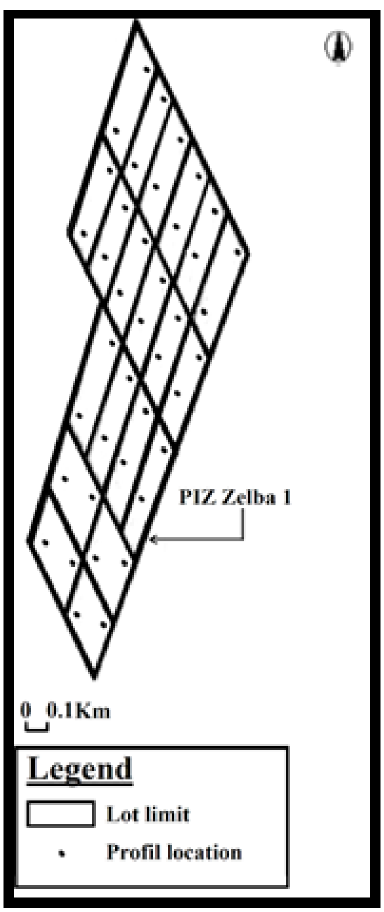

Fig 2. Sampling points locations

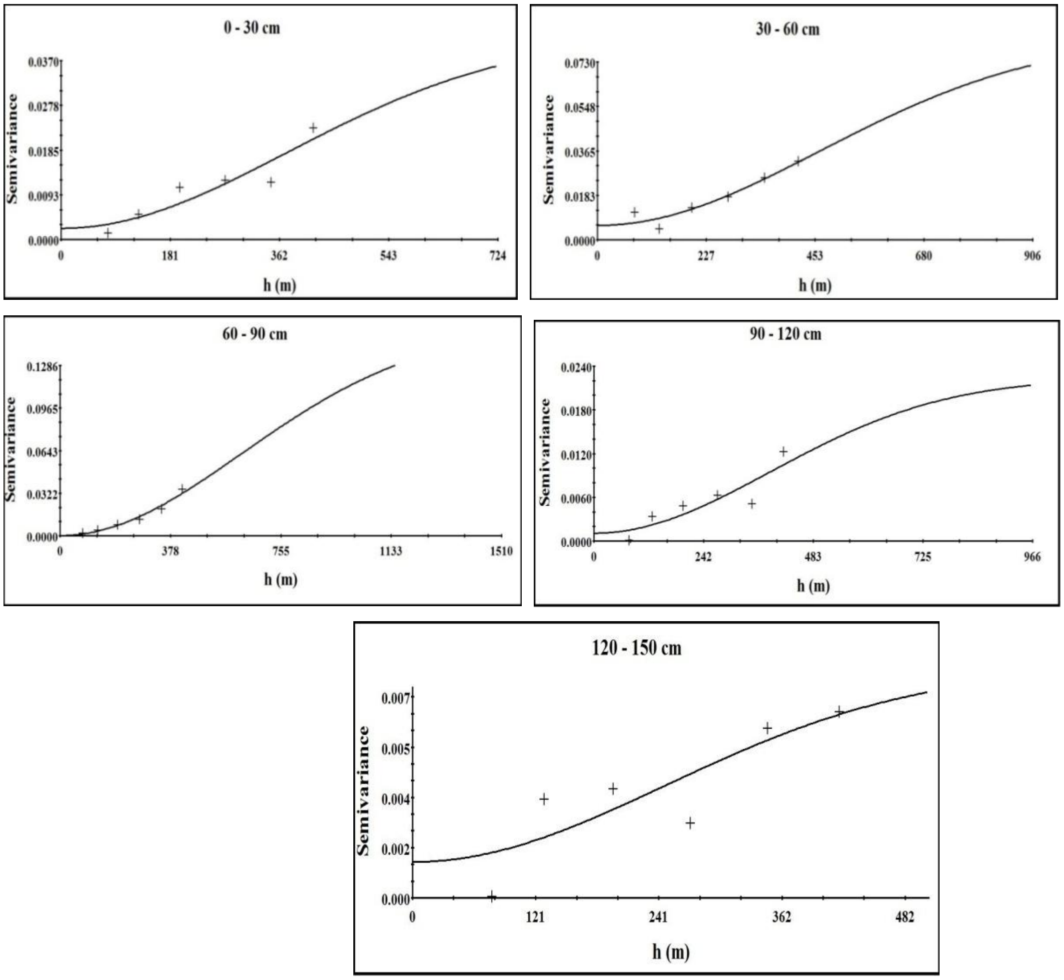

Fig 3. Mean variograms result for spatial prediction of soil $EC_{1/5}$

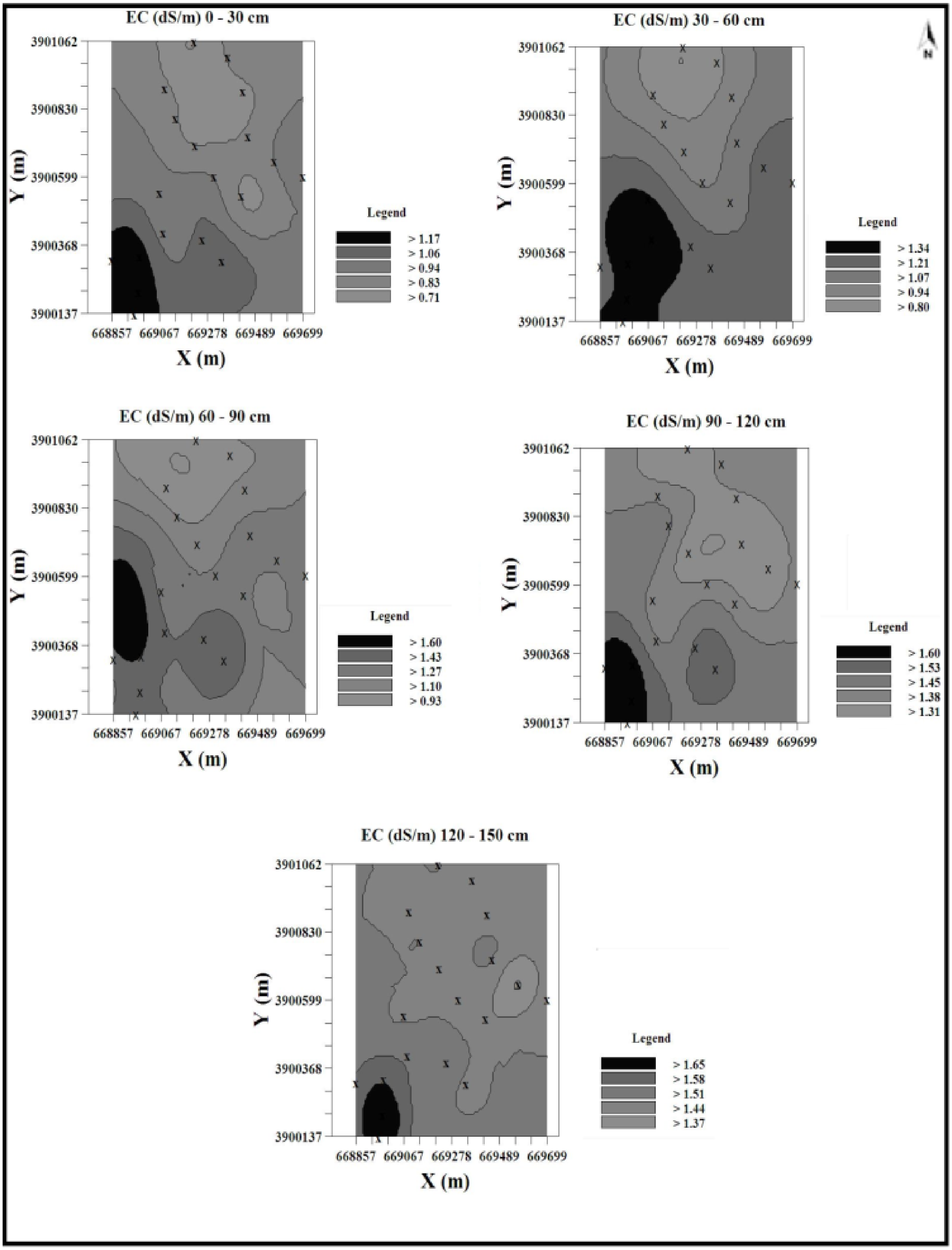

Fig 4. Kriged maps of soil salinity

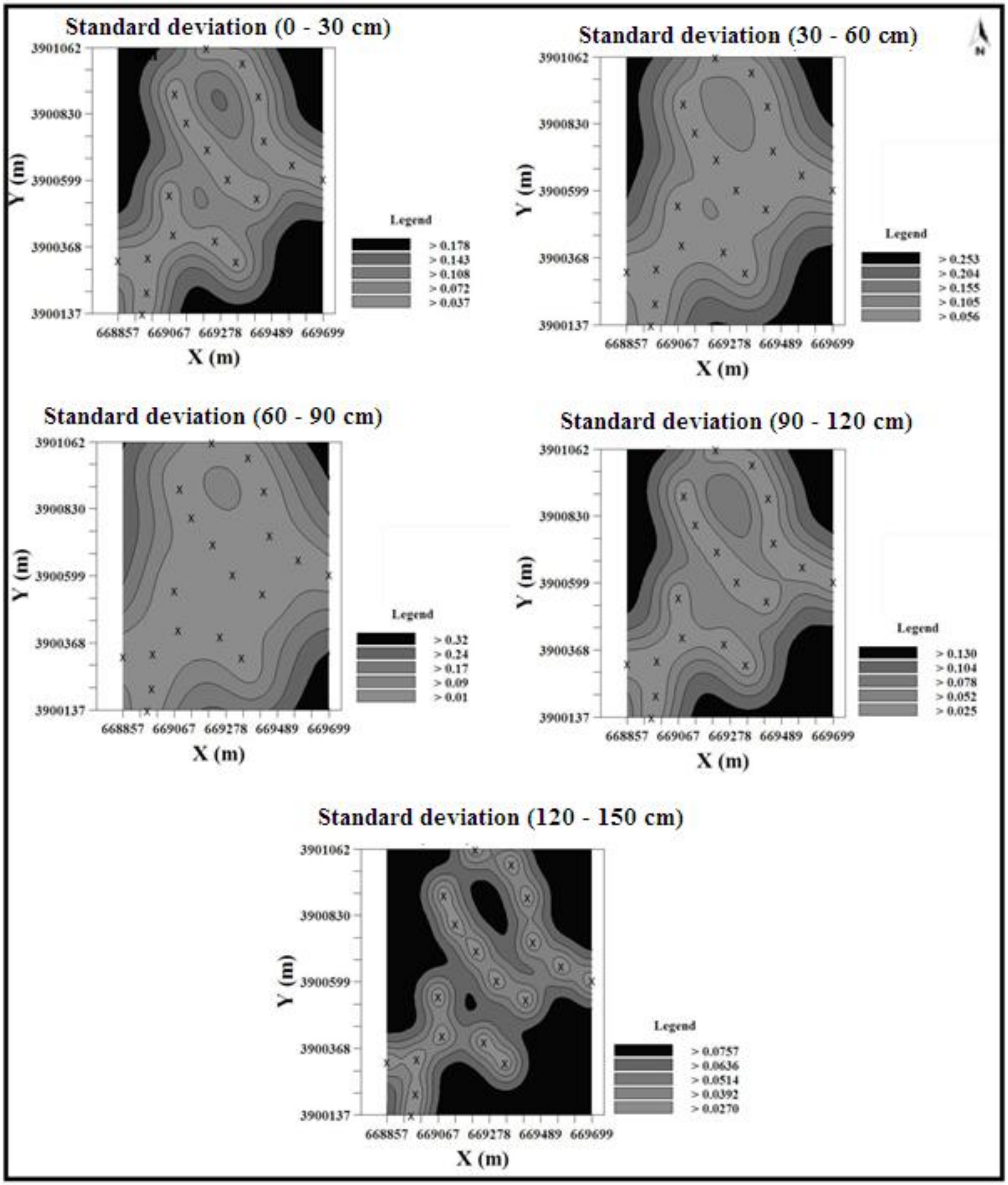

Fig 5. Corresponding standard deviation maps of soil salinity

4. Discussion

Calculated mean variograms confirm the existence of a good structure of the soil salinity within the public irrigation zone Zelba 1. In fact, these variograms were adjusted by a Gaussian variographic model. The nugget effects of $EC_{1/5}$ for different soil layers are low, indicating low errors in measurements. This may be explained by the relatively small distance between the sample points, the flat topography and the lithological homogeneity of soil. The ranges of experimental variograms varied between 605 and 1128 m. These ranges are high compared to those reported in the literature (Hachicha et al., 1997), where the estimated variance decreases. C_0/P ratio calculated for each depth is less than 25% and the coefficient (r) is close to 1, implying a strong positive spatial autocorrelation of salinity between sampled values and relatively good performance of the adopted model to predict the spatial distribution of the soil salinity.

The kriged maps of the soil salinity revealed a slight spatial variation of salinity in different soil layers. These maps also showed that the soil salinity for the layer (0–30 cm) is moderately saline, with $EC_{1/5}$ values varying between 0.7 and 1.3 dS/m. This salinity increased slightly with depth. The southwestern part of the irrigation zone is the most affected by the salinity process, especially in the deep layer (120-150 cm). $EC_{1/5}$ values varied between 1.6 and 1.8 dS/m, indicating a saline soil based on the USSL (1954) classification. Standard deviation maps of the soil salinity showed relatively low values. These values varied between 0.01 and 0.32, demonstrating reliable interpolation values and therefore a good mapping precision.

The upper layer of the soil, characterized by a sandy-silt texture and a good permeability, has undergone a slight desalinization and infiltration of soluble salts from irrigation water. In the deep layers, where the texture becomes finer, water diffused slowly which increased the risk of salts accumulation. This is confirmed by the slight increase of $EC_{1/5}$ values in depth. Furthermore, the low salinity observed in the north of the irrigation zone compared to the southern and the southwestern part could be explained by the fact that this part is closer to the water well. Thus, it receives more water, resulting in important overflows of water from basins located in the north of the irrigation zone, accelerating thereby salts leaching to deeper layers. This phenomenon can be attributed to another hypothesis. In fact, in the southwestern part of the irrigation zone, the presence of benches was noted favoring the salts accumulation in this part.

5. Conclusions

The observed soil salinization in the public irrigation zone Zelba 1, especially in the deepest layers depends largely on the quality of the irrigation water used for almost 30 years in this zone. This water is responsible for salt leaching and accumulation in the deepest layers. Salt accumulation can cause harmful effects in the long term, including soil degradation and even salinization of the aquifer. Regarding mapping, predicting soil salinity spatial distribution using ordinary kriging method is very easy to automate while providing accurate results. Finally, it would be necessary to push the work of soil salinity monitoring in this public irrigation zone. It would be also necessary to apply the mapping method by ordinary kriging in other larger zones irrigated by brackish waters before predicting possible soil structure degradation.

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