ELSEVIER

Agricultural Water Management 46 (2001) 201–213

Agricultural
water management

www.elsevier.com/locate/agwat

Salt distribution in the Senegal middle valley Analysis of a saline structure on planned irrigation schemes from N'Galenka creek

Laurent Barbiéro[a,*], Sébastien Cunnac[b], Landing Mané[c],
Caroline Laperrousaz[d], Claude Hammecker[a], Jean Luc Maeght[a]

[a]IRD exORSTOM, B.P. 1386, Dakar, Senegal
[b]ESA Purpan, 75 voie du T.O.E.C., 31076 Toulouse Cedex 3, France
[c]SAED, B.P. 74, St. Louis, Senegal
[d]ENSA, 65 Rue de St Brieuc, 35000 Rennes, France

Accepted 21 February 2000

Abstract

In the middle Senegal valley, the saline soil distribution is not related to the present faint topography. The absence of a relationship is one of the major constraints in establishing new irrigation schemes. The salt distribution was studied to understand its variability, and to describe its structure and spatial arrangement. Saline areas were delineated by measuring the electromagnetic soil conductivity (ECm), a rapid technique with a portable instrument (EM38). The results indicate that the saline soils are distributed as strips. A detailed examination revealed that the major strip is actually composed of two parallel minor strips, and a comparison with aerial photographs showed that one lies in a former creek bed, and the other fringes it on the southern bank. The strip is intersected by an actual creek bed, indicating that the salt distribution is ancient, related to previous geo-morphology, and does not result from a recent remobilisation of the marine salt deposits incorporated in the soil. The identification of this relationship between the present saline soil distribution and previous geo-morphology allowed us to survey the whole N'Galenka region (about 6000 ha) using ECm measurements on selected transects. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Salinity; Electromagnetic induction; Irrigation schemes; Senegal

---

[*] Corresponding author. Tel.: +221-8323480; fax: +221-8324307.
E-mail address: laurent.barbiero@ird.sn (L. Barbiéro).

PII: S0378-3774(00)00088-3

1. Introduction

The Senegal river valley has been recently developed by the surrounding countries taking advantage of the construction of two major dams, 'Diama' in the delta and 'Manantali' upriver in Mali (OMVS, 1975). On the Senegalese side, the development of irrigation projects involves about 240,000 ha. At present, about 60,000 ha are under full irrigation control. Most of the irrigation infrastructure was constructed by the aid agencies as a response to the droughts of the 1970s (Verheye, 1995). The ecological, economical and social changes induced by this new way of water management are reviewed in a common IRD/ISRA research program, whose main objective is to define the conditions for the establishment of a sustainable irrigated agriculture in the Senegal valley.

A review of the studies concerning the environmental side of the program is given by Boivin et al. (1995). The situation is mainly characterised by a lack of information prior to irrigation and the absence of environmental impact studies.

The soil salinity is one of the major constraints for the development of irrigated agriculture. For example, in the Nianga irrigation scheme, which has been operational since 1974–1975, a large area has been deserted by the farmers due to excess salinity. This is not due to secondary salinisation but to the expression of the salt already present in the soil prior to the establishment of the rice culture. An inventory of the most suitable sites and, particularly, of the salt distribution, which is dangerously lacking, is a prerequisite for successful implementation of sustainable irrigated agriculture. At present, many irrigation schemes are under construction along the N'Galenka creek, in the middle Senegal valley. This area has never been cultivated, therefore, the occurrence of saline soil can not be related to former land-use. Preliminary studies (Laval, 1996; Zanolin, 1997) have revealed that the salt distribution is not related to the present faint topography or geo-morphological formations. In this paper, a saline area was studied to better understand its variability, and to describe its structure and spatial arrangement. The results were used in a regional survey of the saline soil distribution along the N'Galenka.

2. Site

The N'Galenka creek is located in the region of Podor (Northern Senegal) from 16°26 to 16°30N and from 14°50 to 15°05W (Fig. 1). The climate is semiarid, characterised by a wet season (≈200 mm of rainfall) from July to September, a cold dry season from October to February and a hot dry season from March to June. Dry, warm winds increase evaporation and create a shift in the plant-water balance. Average Class A pan evaporation exceeds average rainfall in each month and by over 2000 mm annually.

The Senegal valley was subjected to a recent transgression, called Nouakchottian (or Duinkerke) transgression, which started about 4300 B.P. (Faure et al., 1980) up to Boghé, today located 380 km inland. According to Michel (1973), this transgression is responsible for salt incorporation (neutral chemical composition) in the sediments into which the soil sequences were formed (Maymard and Combeau, 1960). The soils have developed after the post-Nouakchottian (or Taffolian) regression, which was

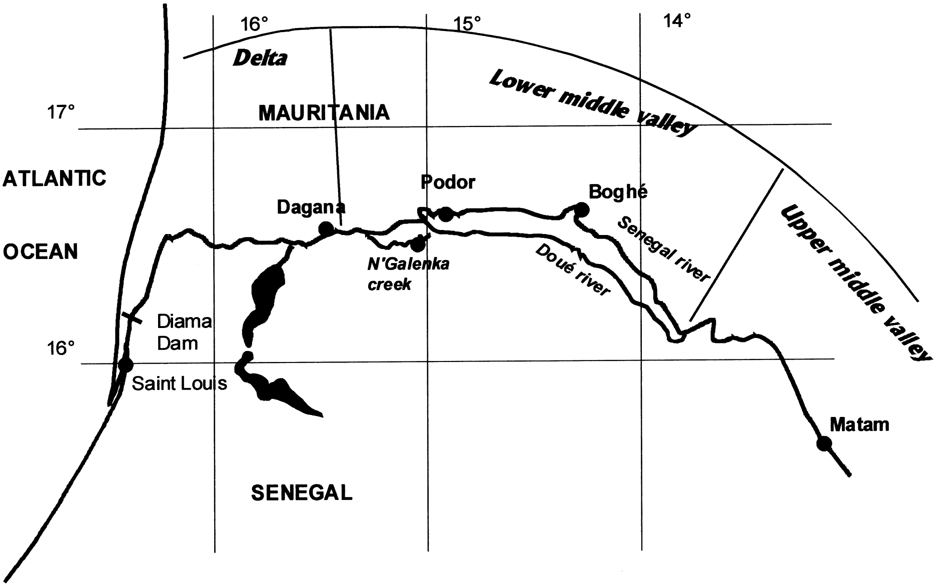

Fig. 1. Location of the study site in the middle Senegal valley.

accompanied by mangrove vegetation, in the roots of which considerable amounts of pyrite were formed by sulphur-fixing bacteria. The salts and acidity were subsequently leached in part by the river swelling, but traces of salinity are still observed up to 300 km inland. The saline soils are mainly characterised by high variability in the chemical composition of the salinity within small distances, which can be either sodium/chloride, sodium/sulphate, magnesium/sulphate or calcium/sulphate type (Barbiéro et al., 1998).

Two major geo-morphological formations are distinguished in this region: depression and former river banks (FAO-Sedagri, 1973), respectively, occupied by Vertic Xerofluvents and Typic Xeropsamments (USDA, 1975), locally known as Hollaldé and Fondé (Maymard and Combeau, 1960). Fondé soils exhibit a clay content around 30%, and a saturated hydraulic conductivity ranging from 10^{-6} to 10^{-5} m s^{-1} (Meyer, 1997). Hollaldé soils are characterised by clay contents around 65% (smectite and interstratified: 60%, kaolinite: 30%, illite: 5%, chlorite: 5%) and saturated hydraulic conductivity about 10^{-7} m s^{-1}. These clay soils constitute the best areas for irrigated rice cropping because of their suitable physical and chemical properties.

In the N'Galenka floodplain, where irrigation has never been performed, the water table occurs generally at about a depth of 7 m, but closer to the surface under the irrigation schemes. The salt concentration in the groundwater in the middle Senegal valley varies from place to place ranging from 0.2 to 85 g l^{-1} (Laval, 1996). In the N'Galenka region, the electrical conductivity (EC) in the water table ranges from 0.15 to 1 dS m^{-1}.

The irrigation water has a very low total dissolved content (EC ranges from 0.5 to 0.8 dS m^{-1}) and does not, therefore, reduce the quality of irrigation in terms of secondary salinisation hazard. However, it exhibits a positive calcite residual alkalinity, as it is often the case in continental waters (Vallés et al., 1991). Therefore, it could lead to secondary alkalisation if the carbonates supplied at each irrigation remained in the soil profiles. The calcite residual alkalinity is lower than in the river Niger, where secondary alkalisation has occurred. Therefore, the alkalisation hazard is lower in the Senegal valley than in the Niger valley. Specific research on soil degradation by alkalisation and the monitoring of this phenomenon has been carried out (Hammecker et al., 1998).

Our study was carried out prior to the establishment of 48 irrigation schemes along the N'Galenka creek. These will be constructed on the former floodplain locally known as 'walo' areas (Fig. 2) and are already allotted to the surrounding villages.

3. Materials and methods

3.1. Field salinity measurements

The soil salinity was measured using a portable electromagnetic conductivity meter (Geonics EM38). This portable device can be used to monitor spatial changes in soil salinity, and hence to delineate saline areas. This instrument measures apparent soil electrical conductivity in millisiemens per metre (mS m^{-1}). The calibration of the EM38 according to soil texture, moisture, and to the type of salinity was the subject of a specific study (Laperrousaz and Barbiéro, 1999).

This work has been carried out in three stages. In the first stage, an area of 73 ha, located at the eastern part of the N'Galenka region around a large winding of the creek (sector VI, Fig. 3), has been surveyed using vertical measurements according to a 25 m×25 m regular grid. In the vertical mode, 75% of the signal is estimated to come from the top 1.8 m of the soil (McNeill, 1980). The data was analysed geostatistically. In the second stage, a 2 ha area located in the original surveyed area (Fig. 3) was subjected to a more detailed salinity survey (10 m×10 m regular grid), coupled with topographical measurements. Finally, the saline area delineated on the computed map was compared to aerial photographs of the site (Geotronics, 1980) in order to identify the relationship between the salt distribution and the actual or previous geo-morphological formations. A regional survey of the whole N'Galenka was attempted from ECm measurement transects, located so as to maximise the intersection with the structures identified on the aerial photograph and suspected of being saline. ECm values over 100 mS m^{-1} were used to delineate the saline areas.

3.2. Geostatistical treatments

A chi-squared test showed that the data may not be assumed to have a normal distribution. Therefore, the calculation was performed on a theoretical distribution of the data by lognormal transformation as recommended by Dowd (1984),

$$z(x_i) = \ln(s(x_i) + 0.05) \tag{1}$$

where $s(x_i)$ is the ECm data at x_i, $z(x_i)$ the log-transformed data, and 0.05 a constant because some $s(x_i)$ were equal to zero. An estimate of the sample variogram is given by

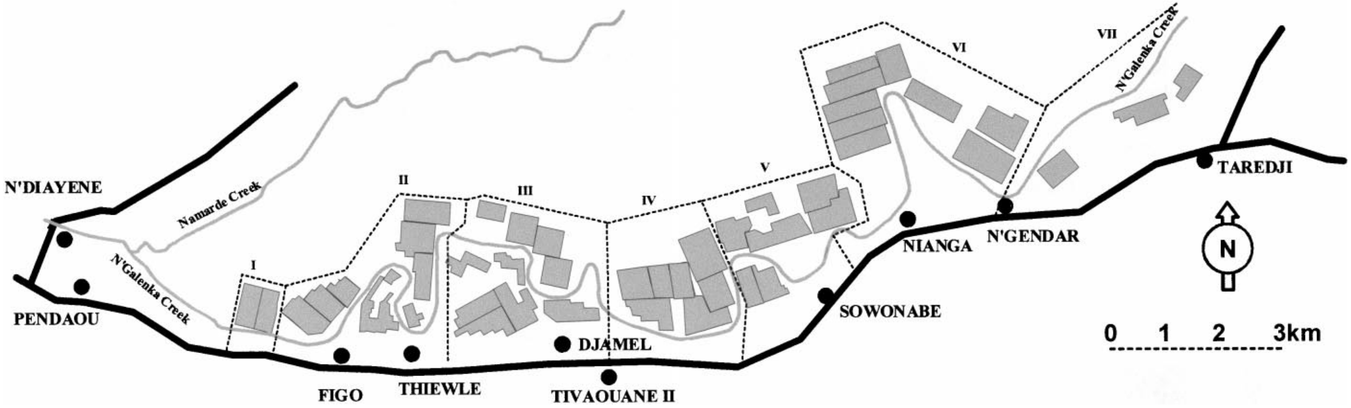

Fig. 2. Distribution of the planned irrigation schemes along the N'Galenka creek.

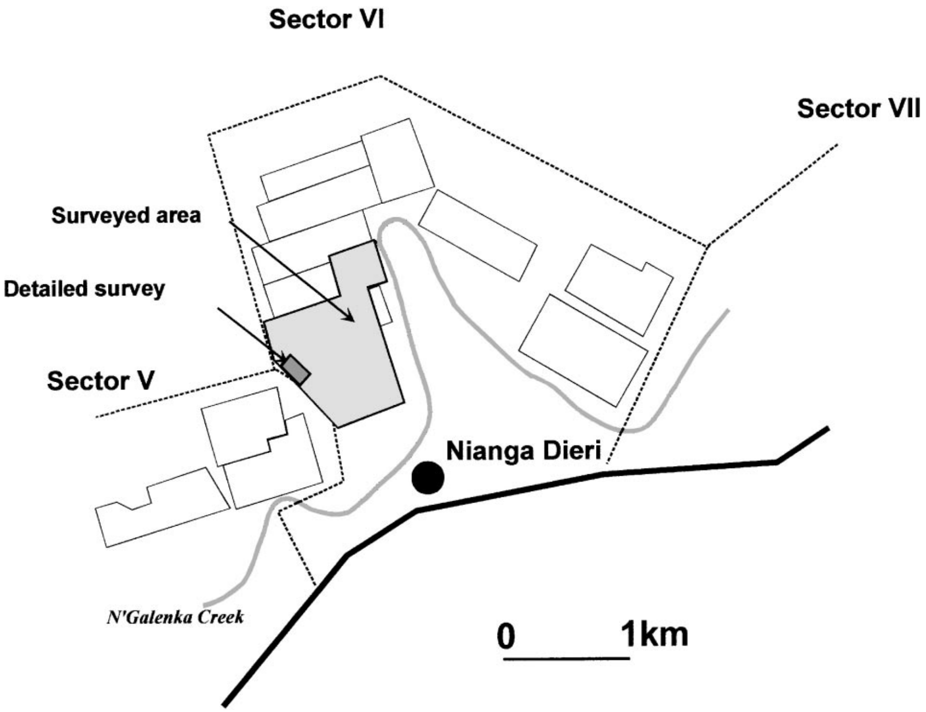

Fig. 3. Location of the surveyed area along the large winding of the N'Galenka.

the formula:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (z(x_i) - z(x_i + h))^2 \qquad (2)$$

where $N(h)$ is the number of pairs of points and $z(x_i)$ and $z(x_i{+}h)$ are the log-transformed ECm value at x_i and $x_i{+}h$. Raw and directional variograms were calculated to detect an eventual anisotropy in the field salinity. The kriged map is built from a spherical model fitted on the sample variogram. This automatic computation was performed using the GEOSTAT-PC software (Boivin, 1989).

4. Results and discussion

4.1. Structure of the saline area on the surveyed zone

High ECm values are observed, the maximum values being 390 mS m^{-1}, with an average value of 55.95 mS m^{-1}, and a standard deviation of 71.94 mS m^{-1}. The variation coefficient (128.6%) indicates a high dispersion of the data around this average value.

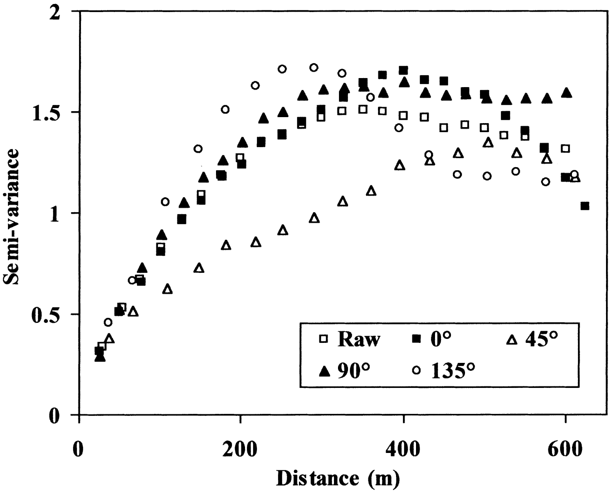

Fig. 4. Raw and directional sample variogram.

The experimental variogram built from the ECm data is presented in Fig. 4. The range is about 300 m and the nugget effect is low, indicating that the density of measurements is sufficient to describe the spatial structures at small distances. A slight anisotropy is detected by comparing the raw and directional variogram, but it has not been taken into account for the computation. It indicates a high dependence of the ECm values in the direction 45° (Northeast/Southwest) up to a distance of 300 m.

The computed ECm kriged map is presented in Fig. 5 and confirms the heterogeneity of the studied site in terms of salinity. A saline area clearly appeared as a strip about 200 m wide and 800 m long, running in a NE–SW direction. This ECm value distribution is consistent with the anisotropy detected by the directional variograms. Some small isolated saline areas were detected to the south of this main strip.

The characteristics of this strip are presented on Fig. 6. Detailed examination of the major saline strip reveals that it is actually composed of two parallel minor strips, which exhibit higher ECm values. An asymmetry can be detected in the boundary of the major saline strip, which is discrete in the north and more diffuse in the south. This asymmetry is reinforced by the topographic data. The minor strip located at north lies in a depression, whereas that located at the south is on higher ground (Figs. 6 and 7). Thus, the distribution of the saline area seems to depend on site morphology, which were further studied from aerial photographs.

4.2. Comparison with the aerial photograph

The salt distribution can be related to the remains of a former creek not easily perceptible in the field but detectable on the aerial photograph. The northern minor strip is located in the former creek bed, whereas the southern one fringes it on the southern bank (Fig. 8). This former creek can be followed on the aerial photograph, and therefore, used as support for a regional survey.

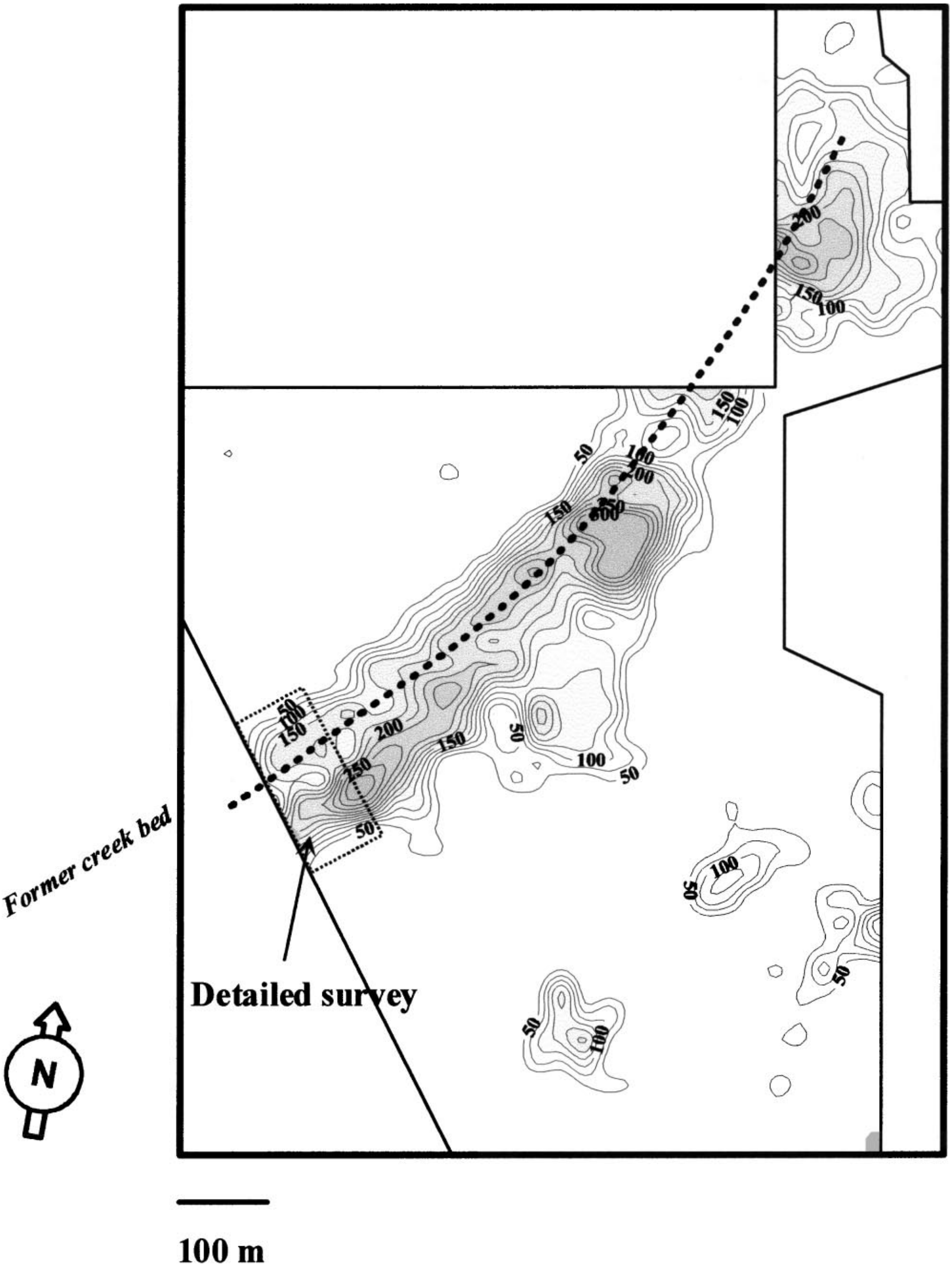

Fig. 5. ECm kriged map of the surveyed area.

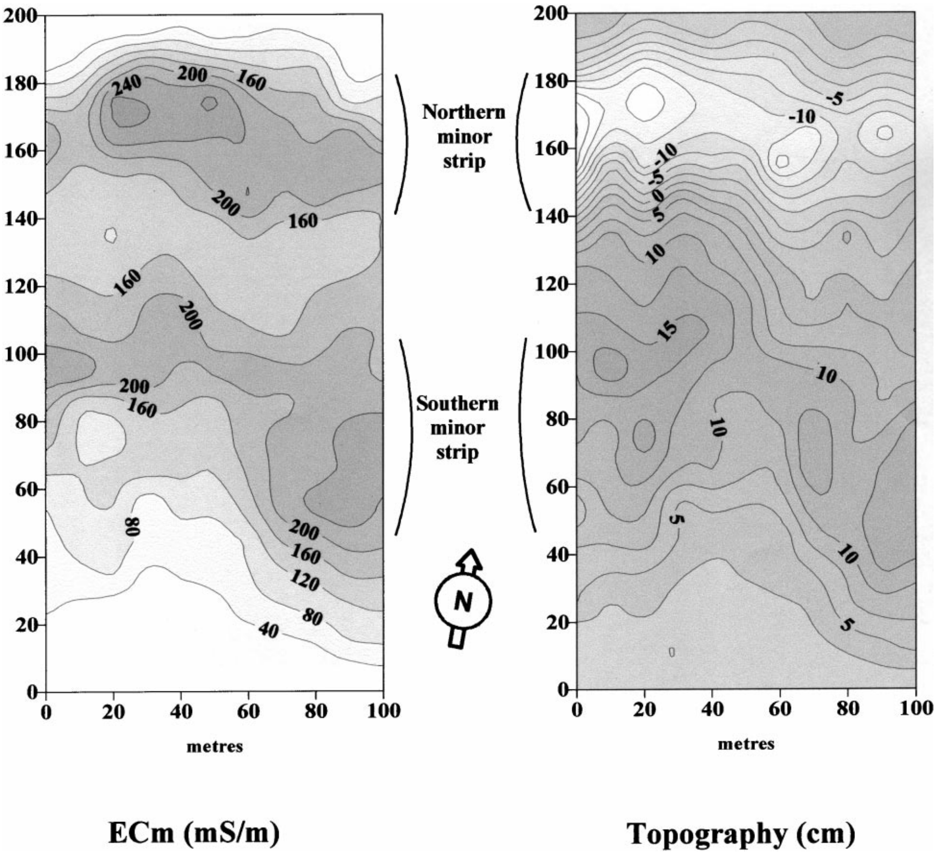

Fig. 6. Distribution of ECm and topography values in the major saline strip.

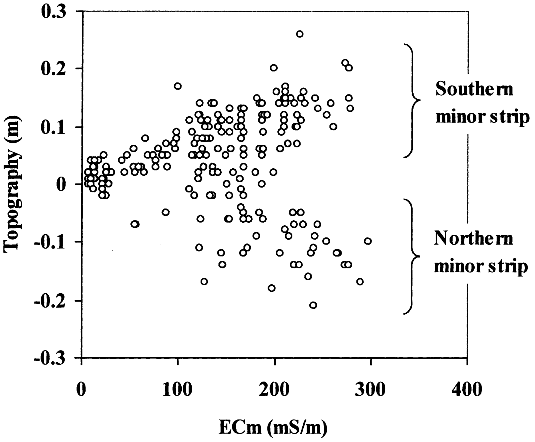

Fig. 7. Relationship between ECm and topography.

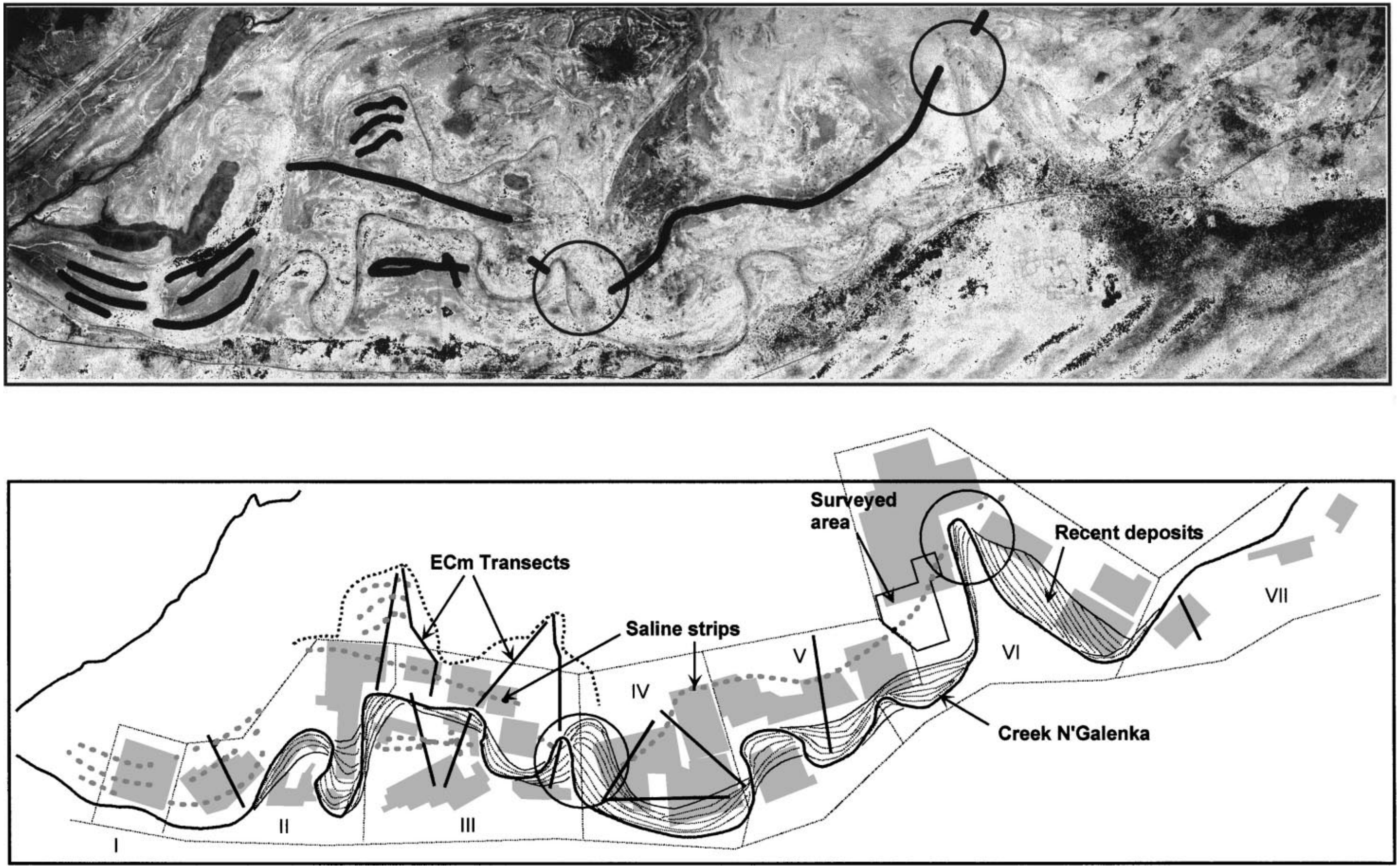

Fig. 8. Distribution of the saline soils in the whole N'Galenka region.

4.3. Survey of the whole N'Galenka area

The results of the regional survey, extrapolated from ECm measurements on 11 transects, are presented on the Fig. 8. The saline strip detected on the surveyed area in sector VI is continuous in the north of the present N'Galenka creek bed in sectors V and IV. This strip is intersected by the present bed and the most recent non-saline deposits of the N'Galenka at two points, the first along the large winding on sector VI, and the second one along another winding located between sectors III and IV. These two points are shown by circles on Fig. 8. This pattern of saline soil distribution indicates that it existed prior to the present N'Galenka and does not correspond to a recent remobilisation of the salt.

The saline strip appears again down to sector II, on the other side of the winding, where it is intersected by other deposits coming from the north in which three saline strips were detected. These strips coming from the north are continuous with the Pont Gary site where Gascuel-Odoux and Boivin (1994) also detected a saline strip. Another saline strip is detected in sector III on the other side of the N'Galenka. Fortunately, the Soil in sector VII, located upstream of the planned development area, is non-saline. From the investigation and mapping details (Fig. 8), verification in the field revealed that all the saline areas had been detected from these 11 transects, located so as to intersect the former geo-morphological formations. This confirms the efficiency of the method implemented on this site.

During this regional survey, it appeared that the morphological characteristics of the strip detected in sector VI were frequently observed and, therefore, they are representative of the whole N'Galenka region. In particular, the major strip is frequently composed of two minor strips exhibiting higher ECm values, the northern one located in a depression and the southern one on higher ground. This detail is not presented on Fig. 8 where only the global saline structure is drawn.

The survey revealed that a large proportion (almost 10%) of the planned irrigation schemes is composed of saline soils. Each irrigation scheme was allotted to the surrounding villages before its establishment, therefore, according to this allocation, it can be noted that some villages will be particularly affected by the saline soils pattern. In particular, the farmers of Nianga, Thiewle (sector V) and Pendaou (sector III) will be strongly affected whereas those of Djamel (sector III) will not suffer with this problem.

5. Conclusion

As a result of climatological problems in the past decades, the traditional agriculture in the Senegal valley has shifted to irrigated agriculture in the former floodplain areas. Many irrigation schemes are presently under construction along the N'Galenka creek. One of the prerequisites, generally lacking, is an inventory of the salt distribution in this area, which is a major constraint for a sustainable irrigated agriculture. The systematic survey of soil salinity using an electromagnetic conductivity meter (EM38), on a 73 ha survey area, reveals a unique pattern: the salt is distributed as a strip in a SW–NE direction. This saline strip, of ancient origin, is not correlated with the present but with the previous geo-morphology, and detectable on the aerial photographs. This relationship being established, it was possible to survey the whole N'Galenka region on selected transects for ECm measurements. The regional study confirms that the difference in salinity are quite pronounced and that the saline soil distribution followed a regular pattern as stripes that are more than 10 km long and about 100–200 m wide, and related to the previous geo-morphology. Similar saline strips were revealed by other survey studies in the lower middle valley, for example, in Ouromadiou, Nianga, Pont Gary, Guia, M'Boyo (Gascuel-Odoux and Boivin, 1994; Laval, 1996; Barbiéro et al., 1998). Therefore, this structure appears representative of the salt distribution in the lower middle valley. The specific characteristics of the saline strips, which are actually composed of two parallel strips, one in a depression and the other on higher ground, must be taken into account in proposing a model for the origin of this salt distribution.

The method developed here, far from being expensive in time and equipment, is recommended for fast mapping of saline soil distribution before establishment of new irrigation areas.

Acknowledgements

This work was partially supported by the Regional Centre for Research on Sudano-Sahelian Irrigation Systems (PSI-CORAF).

References

Barbiéro, L., Hammecker, C., Boivin, P., Aeolian origin of some saline soil stripes in the Senegal middle valley. In: Proceedings of the 16th ISSS World Congress on Morphological and Geo-Chemical Considerations. 20–26 August 1998, Montpellier, France.

Boivin, P., 1989. Geostat-PC. Logiciel interactif pour le calcul géostatistique. ORSTOM Ed.

Boivin, P., Dia, I., Lericollais, A., Poussin, J.C., Santoir, C., Seck, S.M., 1995. Nianga, laboratoire de l'agriculture irriguée en moyenne vallée du Sénégal. Colloques et séminaires, ORSTOM Ed., Paris.

Dowd, P., 1984. Lognormal geostatistical. Science de la Terre. Série Informatique Géologique 18, 49–68.

FAO-Sedagri, 1973. Etude hydro-agricole du bassin du fleuve Sénégal. Etude pédologique, map 1/50,000^{e}, 251 pp.

Faure, H., Fontes, J.C., Hebrard, L., Monteillet, J., Pirazzoli, P.A., 1980. Geoidal changes and shore-level tilt along holocene estuaries: Senegal river area, West Africa. Science 210, 421–423.

Gascuel-Odoux, C., Boivin, P., 1994. Variability of variograms and spatial estimates due to soil sampling: a case study. Geoderma 62, 165–182.

Geotronics, 1980. Couverture aérienne mission Teledyne Geotronics USA. Photographies Infra-rouge fausses couleurs 1/50 000éme.

Hammecker, C., Barbiéro, L., Boivin, P., Samba Diene, R., 1998. Contribution of modelling solute and water transfer to the irrigation of saline soils in the valley of river Senegal. In: Proceedings of the 16th ISSS World Congress. 20–26 August 1998, Montpellier, France.

Laperrousaz, C., Barbiéro, L., 1999. Influence de la variabilité du faciès chimique sur la conductivité électromagnétique. In: BRGM, INRA, IRD, UPMC (Eds.), *Geofcan*, Géophysique des sols et des Formations Superficielles. Orléans, pp. 63–66.

Laval, F., 1996. Rapport d'activités. Travaux d'expérimentation ORSTOM-FED dans la moyenne vallée du Fleuve Sénégal. Région de Podor. ORSTOM de Dakar Hann.

Maymard, J., Combeau, A., 1960. The residual effect of submersion on soil structure (Demonstrated by applying S. Henin's index of structural instability). Afr. Soils (Sols Africains) 5, 123–148.

McNeill, J.D., 1980. Survey Interpretation Techniques: EM38. Tech. Note TN-6, Geonics Pty, Ltd., Ont., Canada.

Meyer, L., 1997. Etude du transport des sels au cours des écoulements et de l'évolution des propriétés physiques du sol au contact de différentes solutions salines. Mém. EPF Lausane, 40 pp.

Michel, P., 1973. Les bassins des fleuves Sénégal et Gambie. Etude géomorphologique. Mém. ORSTOM 63, 752 pp.

OMVS, 1975. The objectives and the main outlines of the integrated development strategy of the Senegal river basin. OMVS, Dakar, Senegal, 30 pp.

USDA, 1975. Soil Taxonomy. A basic system for soil classification for making and interpreting soil survey. US Dept. Agric., Soil conserv. Serv., Agric. Handbook 436, Washington, DC, 754 pp.

Vallès, V., Y.A. Pachepsky, A.A. Ponizovsky, 1991. Invariant criteria for irrigation water quality assessment in arid and semi arid regions. In: Genesis and Control of Fertility of Salt Affected Soils. ISSS Sub-Commission on Salt Affected Soils Science, USSR, V.V. Dokuchaev Soil Institute, Moscow, pp. 330–333.

Verheye, W.H., 1995. Impact of climate and soil conditions on conception and implementation of irrigation schemes in the Senegal river basin. Agric. Water Manage. 28, 73–94.

Zanolin, A., 1997. Etude de site pour l'implantation d'un réseau piézométrique sur périmètres irrigués (Vallée du fleuve Sénégal). Rapport DESS, Univ. Grenoble/ORSTOM de Dakar Hann.