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Serge Marlet et Pierre Ruelle (éditeurs scientifiques), 2002. Vers une maîtrise des impacts environnementaux de l'irrigation. Actes de l'atelier du PCSI, 28-29 mai 2002, Montpellier, France. CEMAGREF, CIRAD, IRD, Cédérom du CIRAD.

Evaluation of the salinization pattern of irrigated fields in the Maniçoba irrigation scheme (Brazil)

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Résumé
Evaluation de la salinisation dans le périmètre irrigué de Maniçoba. Depuis la mise en opération du périmètre irrigué de Maniçoba, situé dans le *nordeste* semi-aride du Brésil, environ 10 % des terres ont été abandonnées. Des échantillons de sol ont été prélevés sur dix-huit parcelles où la salinisation des sols est invoquée par les producteurs comme raison principale de leur abandon. Les objectifs étaient de vérifier cette hypothèse par la collecte de données quantitatives, et de déterminer l'origine et la distribution spatiale de la salinisation. Des prélèvements de sol ont été réalisés en zone abandonnée, en zone cultivée et irriguée, ainsi que sur des sols encore non exploités. Les résultats confirment le problème de salinisation dans la plupart des parcelles abandonnées. En l'absence de sels géologiques, et l'eau d'irrigation étant d'excellente qualité, il est assumé que la salinisation résulte de la concentration de fertilisants lessivés dans certaines parties du périmètre. L'hétérogénéité du sous-sol, l'existence de bassins souterrains et de couches imperméables peu profondes, représentent des risques de nappe phréatique superficielle et de salinisation dans ces parties. Néanmoins, ces contraintes ne semblent être prises en compte ni dans l'élaboration de politiques de préservation des sols ni dans les programmes d'assistance technique.

Abstract
Evaluation of the salinization pattern of irrigated fields in the Maniçoba irrigation scheme. Since the start in 1980 of the Maniçoba irrigation scheme, located in the semi-arid northeast of Brazil, about 10 % of the irrigated fields have been abandoned. Soil samples have been collected at four sites in each of the 18 selected fields, ranging from abandoned plots where crops can no longer grow, to irrigated plots with no detectable problems. Since the irrigation water of the São Francisco River is of excellent quality and salts of geological origin are absent, it is assumed that soil salinization is the result of the concentration of flushed fertilizers in specific areas of the irrigation scheme and of the capillary rise from a shallow water table. The over-irrigation by small farmers, observed in a previous stage of the research, and the actual fertilizer application indicate that important parts of fertilizers are likely to be flushed out of the root zone. Dissolved fertilizers will drain out of the root zone together with the irrigation water that is applied in excess of the crop water requirements. The flow of the groundwater might subsequently concentrate the fertilizers below or in the root

zone in certain fields. After some years, the concentration might reach such high levels that the root zone becomes very saline and crop growth is no longer possible.

Introduction

The study area is situated in Northeast Brazil, in the heart of the semi-arid *sertão*, around the irrigation growth pole formed by the cities Petrolina and Juazeiro. This area is part of the Lower-Middle Sub-basin of the São Francisco River. It is the case with the largest area of irrigated agriculture in Northeast Brazil and the most significant in terms of production and exports.

The semi-arid climate is characterized by a relatively constant solar radiation, a low relative humidity and a mean monthly air temperature ranging from 24,5°C in July to 28,6°C in November. The yearlong difference between minimum and maximum daily temperature is about 12°C. These climatic conditions make the region very favourable for irrigated agriculture.

The rainy season (November-April) in Petrolina-Juazeiro is highly unreliable and variable in space and time. This variability is related to the location of the area in the border region of different air circulations (Nimer, 1979) and influenced by the effects of El Niño Southern Oscillation and sea surface temperature (Kane, 1999; Rao, 1997).

The mean yearly reference evapotranspiration amounts to 1 890 mm, exceeding by far the mean annual precipitation (435 mm). The daily evapotranspiration, calculated by means of the FAO Penman-Monteith equation (Allen et al., 1998), is minimal in early June (4,1 mm/day), and maximal in early October (6,5 mm/day). Even during the rainy season, irrigation is required to supplement the deficit in the water balance.

The soils that are interesting from agricultural point of view result from a complex geological history (FAO, 1966; Projeto Radam, 1985). Soil formation mainly occurred in Quaternary eolic deposits that cover an impermeable basement rock. The wind deposits of variable depth covered an immature drainage network with endorheic characteristics. This led to formation of irregular underground basins. The shallow soils that are located in depressions or in closed basins cope with a problematic drainage and a high probability of water table rise (Sondotécnica, 1975).

Irrigation in the area is relatively recent (20-30 years). The CODEVASF (Company for the Development of the São Francisco Valley) is the federal government agency in charge of implementing large-scale public irrigation projects in the São Francisco River Basin. This agency established in the irrigation projects in Petrolina-Juazeiro a joint installation of small farmers (*colonos*) and medium-size agricultural firms (*empresas*). Most *colonos* were former landless poor who used to work and live in or nearby the expropriated lands. The mean irrigable area of their fields is about 8 ha.

The irrigation projects have been originally designed for annual crops such as rice, maize and beans. In the 1980s, the crop choice changed rapidly to watermelon, melon, onion and tomato. In the 1990s, fruit trees (mango, guava and coconut, among others) were increasingly introduced (Marinozzi, 2000).

CODEVASF started with the transfer of the irrigation schemes to water user associations or *distritos* in the late 1980s. However, many uncertainties exist about the nature and evolution of responsibilities of both the *distrito* and CODEVASF in the management of the irrigation schemes (De Nys, 1999). The absence of a clear soil protection policy addressing prevention and precaution, and the uncertain public financing of technical assistance to farmers, may severely compromise the sustainability of the irrigation schemes in the future.

Problem statement

Despite a relatively short operation time, most public irrigation schemes in the Northeast seem to face salinization problems (Batista, 1992; Sampaio and Salcedo, 1997). This problem affects agricultural crop production and often pushes farmers to abandon (partly) their field. However, very little quantitative data of salinization on these schemes is reported in scientific literature or local official reports (Codevasf, 1995; FAO, 2000).

This research was conducted on the Maniçoba irrigation scheme (4 500 ha). This is a gravitary irrigation scheme that was constructed by CODEVASF. Several farmers have abandoned parts of their fields because of alleged soil salinization. However, no quantitative evidence of soil salinization exists for these abandoned parcels. Moreover, the soil water in still irrigated parcels has shown electrical conductivities (EC_e) well below the threshold level for salinity. This made suggest some authors (Cordeiro et al., 1996; Vandersypen, 2001) that the term *salinization* used by farmers might be a rather general term for different types of soil degradation and restrictions, i.e. not specifically related to accumulation of salts in the root zone.

The aim of this study was to verify this assumption and diagnose the salinity problem by focusing on the abandoned parcels. The major objectives were (1) to obtain quantitative evidence for soil salinization; (2) to determine its origin and (2) to explain its spatial distribution.

Materials and methods

Sample composition

Several fields were visited where farmers claimed salinization as the main reason to discard several parcels from irrigated cultivation. Three different types could initially be distinguished: (1) totally abandoned fields; (2) partly abandoned fields with one or more discarded parcels; and (3) fields with alleged salt problems but nonetheless entirely cultivated. Eighteen fields were selected for further analysis. These are spatially well distributed and cover the identified three types.

Four locations were selected on each field together with the farmers:

- P1: *Worst* part of the officially abandoned area, as indicated by the farmer or through visual signs of salinization;
- P2: *Better* part of the officially abandoned area, as indicated by the farmer or through visual signs of salinization
- P3: Rainfed area or area recently under irrigation;
- P4: Irrigated area without apparent salt problems.

Chemical diagnosis

A chemical diagnosis was elaborated to collect quantitative evidence for soil salinization and determine its origin. At each location (P1, P2, P3 and P4), mixed soil samples were taken at three different depths: 0-30 cm, 30-60 cm and 60-90 cm. Water samples were taken from three different water sources: the irrigation canals, the water table and the field or collector drains. The chemical analyses consisted of:

- the composition of the sorption complex (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and soluble P, extractable Al^{3+} and pH;
- the electrical conductivity (EC_e) and composition of the soil saturated paste extract (Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, Cl^{-}, CO_3^{2-}, HCO_3^{-});

- the electrical conductivity (EC_w) and composition of the water samples (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, CO_3^{2-}, HCO_3^-, SO_4^{2-}).

Quality of the irrigation water

The quality of the irrigation water is assessed in terms of salinity hazard; sodicity hazard and infiltration problems; and specific ion toxicity. The salinity hazard of the water is expressed by the electrical conductivity (EC_w). The sodicity hazard of the water is determined by calculating the sodium adsorption ratio (SAR) or adjusted SAR° (Suarez, 1981). Besides these two parameters, the quality of the irrigation water is evaluated on specific Cl^- toxicity. The chemical quality of irrigation waters is assessed by the classification scheme of Richards (1954) and by the scheme of Ayers and Westcot (1999). The last one is believed to provide a better classification of water quality since it incorporates the influence of water salinity on infiltration problems.

Soil salinity and sodicity

The soil salinity is assessed by the electrical conductivity of the soil saturated paste extract (EC_e). Five soil salinity classes are distinguished, ranging from non-saline to very strongly saline, based on the EC_e and their effect on crop growth (Abrol et al., 1988). Yields of many crops are restricted above a threshold level of 4 dS/m.

Soil sodicity is in general expressed by the exchangeable sodium ratio (ESR). This expression relates the concentration of sodium on the exchange complex to that of calcium and magnesium (Shalevet, 1976; Mc Neal, 1983). The exchangeable sodium percentage (ESP) gives the absolute proportion of sodium on the exchange complex. Richards (1954) set the critical value for ESP on 15 %. However, recent research provides evidence of soil degradation at lower levels of ESP i.e. in the range of 5-6 % (Sumner, 1993; Kuper, 1997)

Several classes of salt affected soils are distinguished based on the previous parameters (EC_e and ESP). The two major classes are saline soils (EC > 4 dS/m and ESP < 15 %) and sodic soils (EC < 4 dS/m and ESP > 15 %) (FAO, 1988). There also exist saline-sodic soils that have an EC > 4 dS/m and ESP > 15 %. Soils with EC values below 4 dS/m and ESP below 15 % are non saline – non sodic.

Source of salinity

The comparison between the chemical compositions of the water samples and the saturated extracts must enable to conclude on the source of salinity. The aim is to search relations between chemical compositions of: (1) the saturated soil extract; (2) irrigation water; and (3) groundwater of saline and non-saline fields.

Two methods of comparing the different water compositions are used: Piper diagrams and Stiff diagrams. In the Piper diagram, ions are plotted as percentages in two base triangles. The total cations and the total anions are set equal to 100%. Data points in the two triangles are projected onto an adjacent grid. Samples with similar composition will be clustered in the obtained diagrams. In the Stiff diagram, the concentration of selected anions and cations is plotted for several samples and the form of the diagrams allows identifying samples with similar composition (Rockware, 1997).

Spatial distribution of salinity

In order to theorize the spatial distribution of salinity in the irrigation scheme, additional physical parameters were collected at each sampling location (P1, P2, P3 and P4). The soil physical analyses mainly consisted of:

- soil texture and colour pattern of the different soil layers;
- depth of the water table and the impervious layer;

- bulk density and saturated hydraulic conductivity. These two last parameters were mainly measured on a selected number of profile pits on abandoned parcels (P1 and P2).

Farmers' perception on salinity

The quantitative results formed a starting point of an open interview with the individual farmers. The discussion was principally focused on the contrast between EC_e values for the different sampling locations (P1, P2, P3 and P4). The farmers were asked to comment the salinization problem (origin, evolution, solutions), and to discuss the representativeness of the data. As such, their knowledge and perception of the salinization problem could be appraised. Moreover, a particular attention was given to the analysis of farmers' fertilization strategies.

Results

Quantitative evidence for salinization

Quality of the irrigation water

The EC of the irrigation water from the São Francisco River ranges from 0.05 to 0.11 dS/m. This indicates an extremely low salinity risk according to the Ayers and Westcot classification (1999). However, following this classification, there exists a substantial risk for infiltration problems. Indeed, the sodium adsorption ration (SAR) of the irrigation water is situated between 0.18 and 0.28, which in combination with an extremely low salt content represents severe restrictions to its use. Finally, the irrigation water represents no risk on chloride toxicity, since all values are situated below the reference value (4 mmol/l) for no restriction.

Soil salinity

Based on the measured EC_e values in the worst part of the abandoned parcel (P1), the sample of 18 fields was subdivided into two categories: *salt affected* (13 fields) and *non-affected* (5 fields). The first category presents EC_e values in P1 that exceed the threshold soil salinity level of 4 dS/m. The second category presents values that are much lower (Fig.1 and 2). Similarly, the EC_e values for P2 and P3 are higher in the first category.
Several visual symptoms distinguish P1 and P2 of salt-affected and non-affected fields. On salt affected fields, P1 typically presents a spotty cover of halophyte vegetation and superficial salt crusts; P2 contains other plant species (salt resistant grasses, shrubs and trees) and less or no salt crusts. On non-affected fields, these visual signs of salinization are absent. P1 and P2 on these fields, although officially abandoned for alleged soil salinization, are often normally cultivated and irrigated.
Different variations of salinity with depth are observed. On salt affected fields, salinity in P1 clearly decreases with depth. No clear tendency is observed in P2, although the total salt content in the profile is substantially lower than in P1. At other points, both on salt-affected and non-affected fields, salinity remains relatively constant or slightly increases with depth. These observations indicate differences in salt accumulation and evapotranspiration between the distinct locations.

Soil sodicity

A similar subdivision as above can be made from the values of exchangeable sodium percentage (ESP). On salt affected fields, the mean ESP of the P1 location is close to the threshold sodicity level of 15%. At the other locations, the mean ESP decreases following a clear pattern (P1>P2>P3>P4) and remains rather constant with depth. On the non-affected fields, ESP values are much lower and vary more with depth (Fig. 3 and 4). If the selected threshold level for ESP is lower than 15%, however, sodicity problems may be diagnosed at a much wider scale.

Soil classification

The observed levels of salinity (EC_e) and sodicity (ESP) give evidence for the soil salinization problem in the Maniçoba scheme. Indeed, the vast majority of abandoned parcels (P1 and P2) can be classified as either saline (40%) or saline-sodic (25%). Soil salinization is thereby recognized as a valid motive for their abandonment. However, nearly a third of abandoned parcels are non-saline non-sodic (35%). These parcels show no clear evidence of soil salinization as a reason for their abandonment. On the other hand, the totality of the sample of currently irrigated parcels (P4) are non-saline non-sodic.

Source of salinization

The Piper diagrams contribute in theorizing about the origins of salts. It is shown (Fig. 5) that the composition of the saturated soil extract of salt-affected parcels is substantially different from that of the irrigation water. In fact, the composition of the saturated extract approximates that of the underlying groundwater. The different shapes of the Stiff diagrams visually reinforce the dissimilar composition of irrigation water in comparison with the saturated soil extract and the groundwater. They also illustrate the similar compositions of the saturated soil extract and the groundwater of salt-affected parcels (Fig. 6).
Hence, it may be concluded that other salt input sources than merely irrigation water determine the composition of the saturated soil extract. The higher relative amounts of several ions (K^+, Cl^-, SO_4^{2-}) in the groundwater and the saturated extracts may be explained by fertilization practices. Simplified calculations reveal that salt input by fertilization is of the same order of magnitude as the salt input by irrigation water (ca. 800 $kg.ha^{-1}.year^{-1}$). Fertilization is thus believed to be a substantial salt input factor.
The influence of fertilization on the P-status of the soil might be indicative for other substantial changes in the chemical composition of the soil. This is obtained by comparing the soluble phosphorus on formerly (P1 and P2) and presently (P4) cultivated and fertilized locations, in comparison with the virgin soils (P3) or the reference situation before the start of the project. This analysis reveals a three- to fourfold increase of the P-status at P1 and P2, and a nine-fold increase at P4, in comparison with the reference situation. This indication of over-fertilization might subsequently result in high concentrations of salts in the soil. Further research is required to analyse the role of fertilization in the salinization process. Anions that are present in large quantities in fertilizers, such as NO_3^- and PO_4^{3-}, could thereby be analysed on comparative water samples.

Spatial distribution of salinization

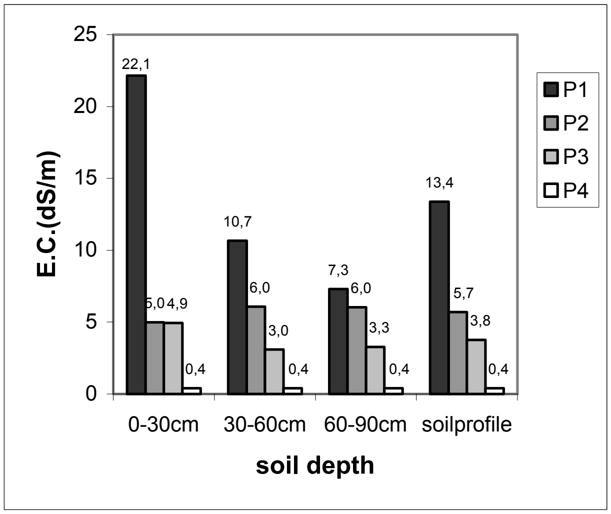
There exist only subtle textural differences between the four different locations (P1, P2, P3 and P4). In general, texture varies from sand to sandy loam in the upper layer, and from sandy clay loam to sandy clay in the deeper layers. In all locations, the clay content increases with depth and forms a textural B-horizon. As such, texture is believed to be of minor importance for explaining the spatial distribution of salinity in Maniçoba.
On the other hand, the depth of the impervious layer is much more superficial in the abandoned (P1 and P2) than in the cultivated and irrigated (P4) parcels. The presence of a superficial impediment hinders the internal drainage. As such, this may increase the risk on a shallow water table and salinization through capillary rise. This concurs with the observation that abandoned parcels with a shallow impediment show high salinity levels.

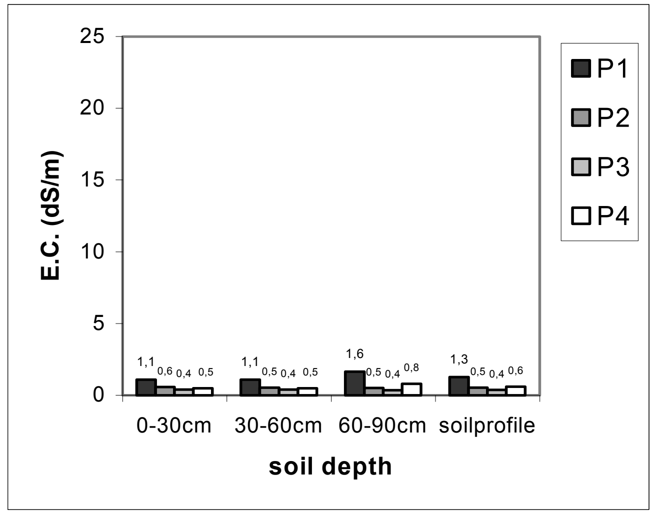
From the soil colour pattern, it is deduced that continuing waterlogging occurred at P1 and P2 in the past. This assumption is based on the presence of reduction colours, relatively close to the soil surface, in the majority of the abandoned parcels. In the better-drained irrigated parcels (P4), these reduction colours are entirely absent At present, the generalized absence of a shallow water table in the abandoned parcels can be related to the fact that irrigation has been suspended on those locations for several years.
As such, the spatial distribution of salinity in Maniçoba seems largely related to the heterogeneity of the underground. A simplified representation for the subsoil configuration in Maniçoba is provided in Fig. 7. This proposal is an attempt to visualize the differences in salinity and water table depth between abandoned (P1 and P2) and irrigated (P4) locations.
It is believed that when P1 and P2 locations were cultivated in the past, significant inputs of irrigation water and fertilizers (and subsequent salts) came into this area. Since the water could not easily drain out of the closed basins, a water table built up progressively. This explains the reduction colours in the soils. As a result of the shape of the basin, more water and salts accumulated in P1 than in P2. This explains the higher observed salinity level in P1 than P2.
On the actually irrigated parcels (P4), a water table may arise because of over-irrigation. However, the salts will not exceedingly accumulate since this area is naturally drained and the excess water subsequently leaches the salts.
This configuration of the underground can also explain the variability of the water table depth in space and time. This is a highly simplified representation that cannot be used to explain every individual case. Topography, soil physical properties and other factors may interfere with this scenario. For example, several saline profiles were observed at locations where the impediment is deeper than 1.5 m.

Discussion

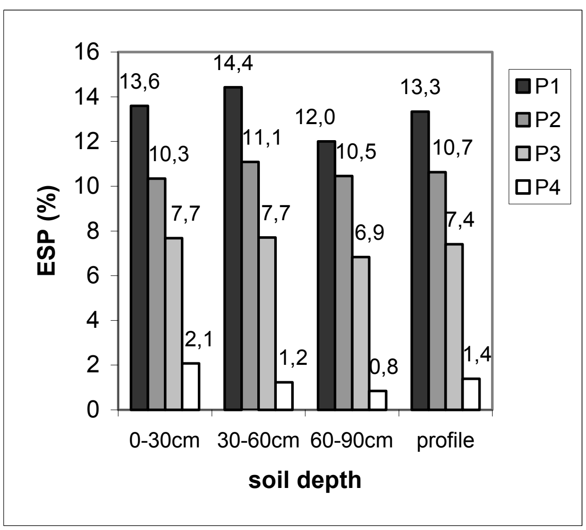
The interest in soil management seems unequally distributed over the different evolution stages of the irrigation scheme. At the design stage, relatively detailed feasibility studies were made to evaluate the irrigation potential of the different soil complexes. The combination of the heterogeneity in the subsoil, the occurrence of underground basins, and the impermeable parent material situated at shallow depth were thereby reported as serious limitations for irrigation development that make the soils susceptible to shallow water tables and soil salinization. At the operational stage, insufficient measures (drainage, technical assistance) have been taken to address these limitations and to anticipate soil salinization processes. Moreover, farmers have hardly been informed about the heterogeneity of soil characteristics.
It is mainly the less suitable soils that have rapidly become saline after irrigation. In general, farmers abandon the salinized parcels and ask the CODEVASF to modify their official land status from irrigable to non-irrigable. In search for compensation, farmers often start clearing unexplored areas for irrigation activities. However, these areas are mostly located on soil units that are classified as marginally suited for irrigation. These are theoretically destined for cattle-breeding or rainfed cultivation. It is expected that similar salinization processes may occur on these soils if no preventive measures are taken.
The question remains how to define adequate measures to prevent salinization or to recover saline soils. This not only requires a deep comprehension of the processes of soil salinization and the local specificities such as the configuration of the underground. It also involves coordination between different stakeholders (government, irrigation district, technical assistance, farmers) in a general context of management transfer from the State to the water users. It is believed that researchers can play an intermediate role through actual diagnoses and scenario simulations. However, this role is not always manifest in the different life stages of the irrigation scheme.

Figures 1 and 2. Mean electrical conductivities (EC) of the *salt-affected* (left) and *non-affected* fields (right) for abandoned parcels (P1 and P2), virgin soil (P3) and irrigated parcels (P4)





Figures 3 and 4. Mean exchangeable sodium percentage (ESP) of the *salt-affected (left) and non-affected* (right) fields for abandoned parcels (P1 and P2), virgin soil (P3) and irrigated parcels (P4)



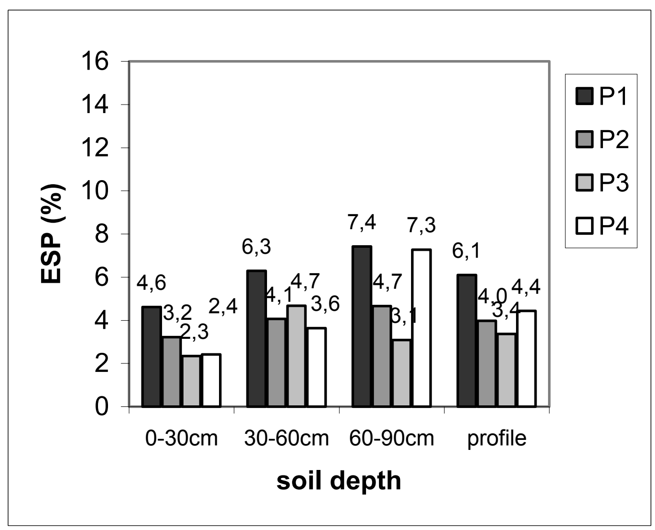


Figure 5. Composition of water samples visualized in Piper diagram

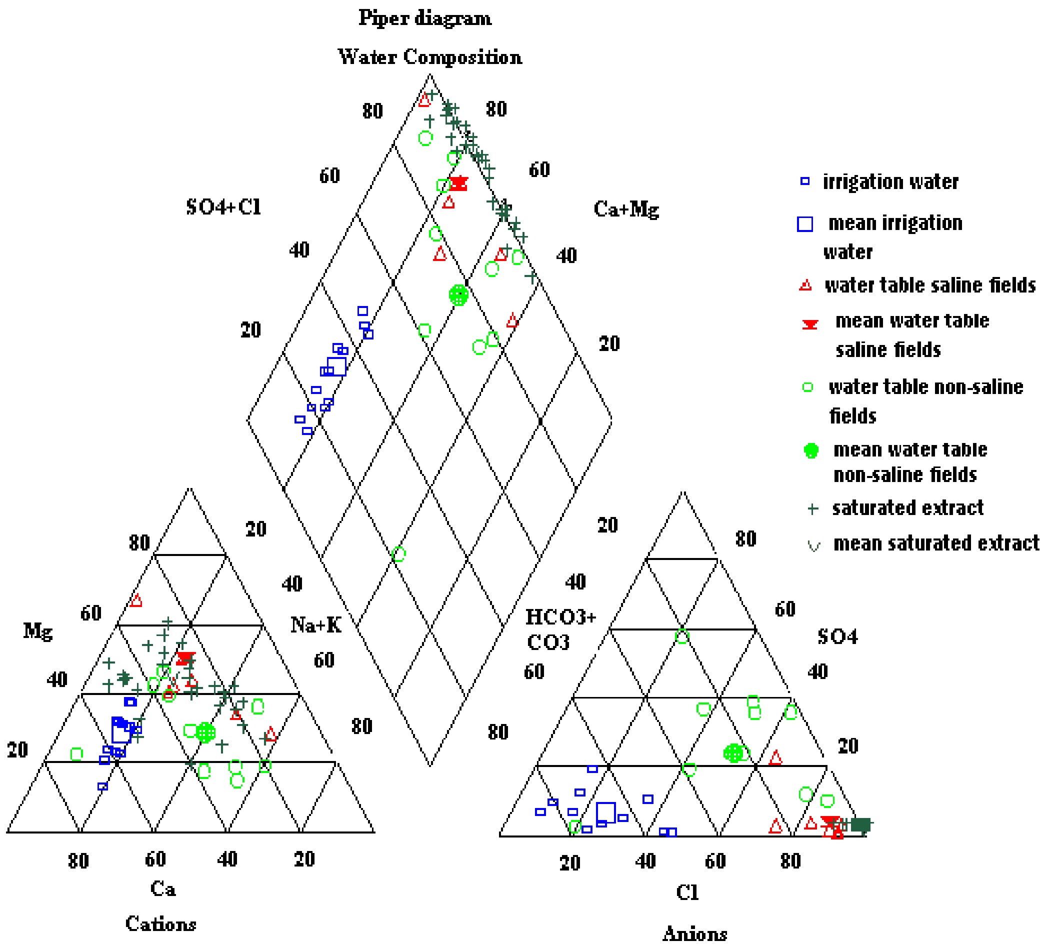


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Figure 6. Composition of water samples in Stiff diagrams (remark the different scales)

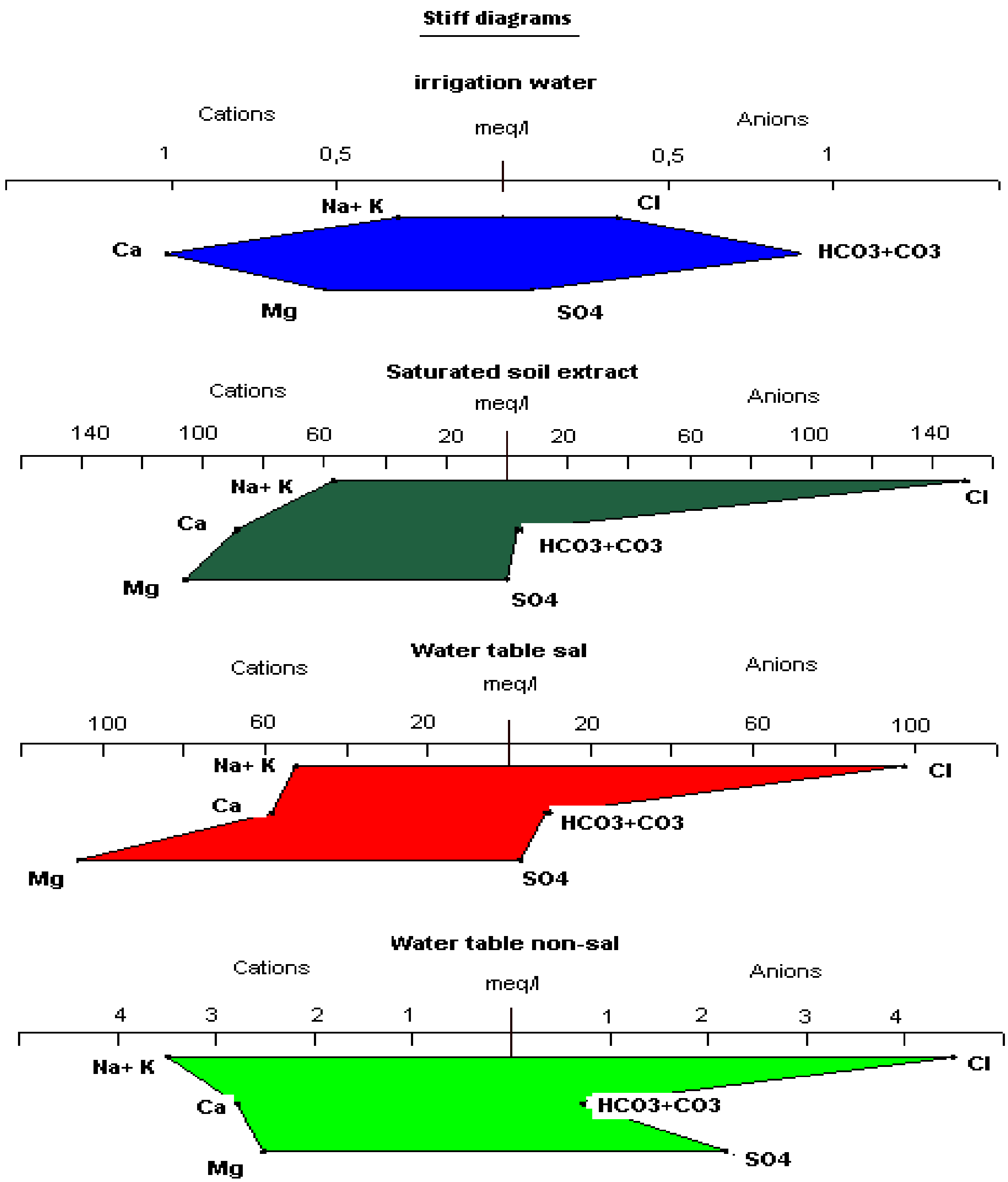
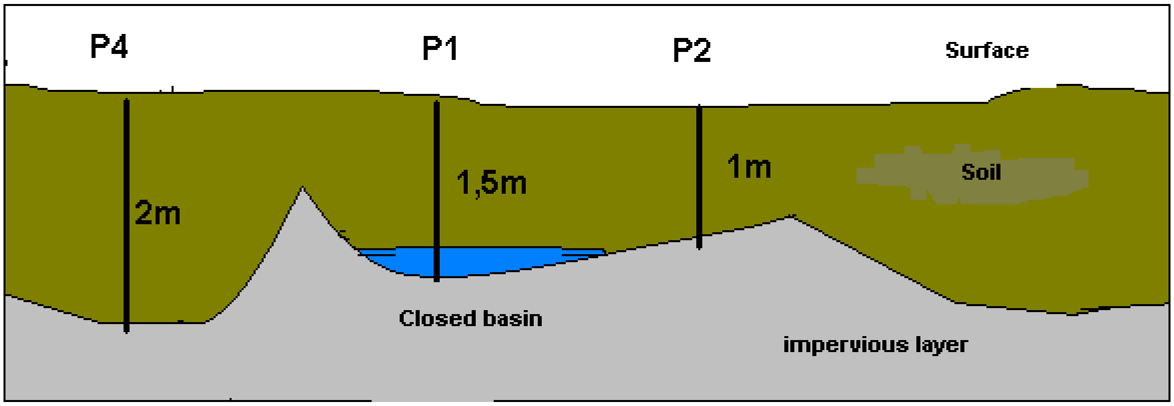


Figure 7. Representation of the configuration of the subsoil in Maniçoba



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