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Pore morphology related to water transfers in saturated and near-saturated conditions
Relations entre la morphologie des pores et les transferts hydriques en conditions saturées ou proches de la saturation

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Water transfers in saturated soils occur in a few part of the pore space, the preferential pathways; a morphological approach complementary to physical methods is required to characterize them. In this paper we present a method using image analysis to identify the pore space effective on water flows not only in saturated conditions, but also in near-saturated conditions during infiltration; pore space was quantified by the use of morphological parameters and related to hydrodynamic parameters.
The study was carried out on three silty horizons of a catena on schist in the Armorican massif (France), which represent three stages of the hydromorphy and degradation process. For each horizon we measured the hydraulic conductivity at saturation on undisturbed soil blocks, 20-cm wide, using methylene blue dye to colour the preferential pathways, and *in situ* hydraulic conductivity at low suctions with an infiltrometer. The pore space characterisation was performed by image analysis on thin sections, at 2 magnitudes, in order to measure the pore size, shape, connectivity and granulometry.
Our results allowed us to propose a pore typology related to the hydric behaviour of the horizons: the effective pores for saturated flows consisted mainly in packing voids and cracks, the connectivity of them being more efficient than their size; by contrast, channels were not much effective, even the largest ones. At last, this study revealed the importance of a thin eluvial albic horizon, under the ploughed horizon, responsible for subsurface lateral flows because of the low connectivity of its pore space.

Keywords : porosity, hydraulic conductivity, infiltrometry, image analysis
Mots clés : porosité, conductivité hydraulique, infiltrométrie, analyse d'images

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Evolution of irrigated soils in the Senegal river valley: alcaline or neutral salinisation process ?
Evolution des sols irrigués en moyenne vallée du fleuve Sénégal: voie saline, alcaline ou neutre ?

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Introduction

Some 200,000 ha in the West-African Sahel (which includes parts of Senegal, Mali, Mauritania, Niger, Burkina Faso, Chad, Cameroon and Nigeria) are now under full irrigation control. Part of the irrigation infrastructure in place was constructed by the international donor community as a response to the droughts of the 1970s. The main crop grown by Sahelian farmers under irrigation is rice. The potential production of irrigated systems in the Sahel is large (WARDA, 1995), but actual farmers' yields are low and variable in practice due to a range of agronomic and socio-economic constraints (a review is given by Jamin in Boivin et al., 1995).

A major constraint to farmers using irrigation in arid climates is land degradation due to salinization. Leaching of salts within the soil profile is often insufficient due to the high evaporative demand of the air and low soil infiltration rates. Farmers are increasingly abandoning rice fields in Sahelian irrigation schemes which is commonly attributed to salinity problems. Irrigation is often practiced without adequate drainage facilities, aggravating the situation. Salts may also be brought to the soil surface in the off-season through capillary rise if the water table is close to the soil surface. Soils in the Senegal river delta are mainly affected by neutral salinity (sodium chloride) as these soils are derived from marine sediments (Ceuppens et al., 1997). Except for this specific case of natural salinity, salinization in the Sahel is in general caused by concentration of irrigation water in the field and by capillary rise from rising water tables due to irrigation.

The Senegal river water is of good quality, according to Riverside classification, but has a positive calcite residual alkalinity (see Droubi, 1976, for definition of residual alkalinity). According to Vallès et al (1992), this may lead to soil degradation by sodication and alkalinisation, as soils are generally poorly drained and clayey. Most of the irrigated schemes are only a few years old. The alkalinisation process is slow and presents threshold effects. This paper gives a synthesis of studies that have been conducted in the field and in the laboratory, to predict changes in soil chemical and physical properties under rice cultivation. A particular focus was on assesment of soil alkalinization hazard. Reversing soil alkalinity and sodicity is extremely difficult as excessive amounts of calcium salts and acids are needed.

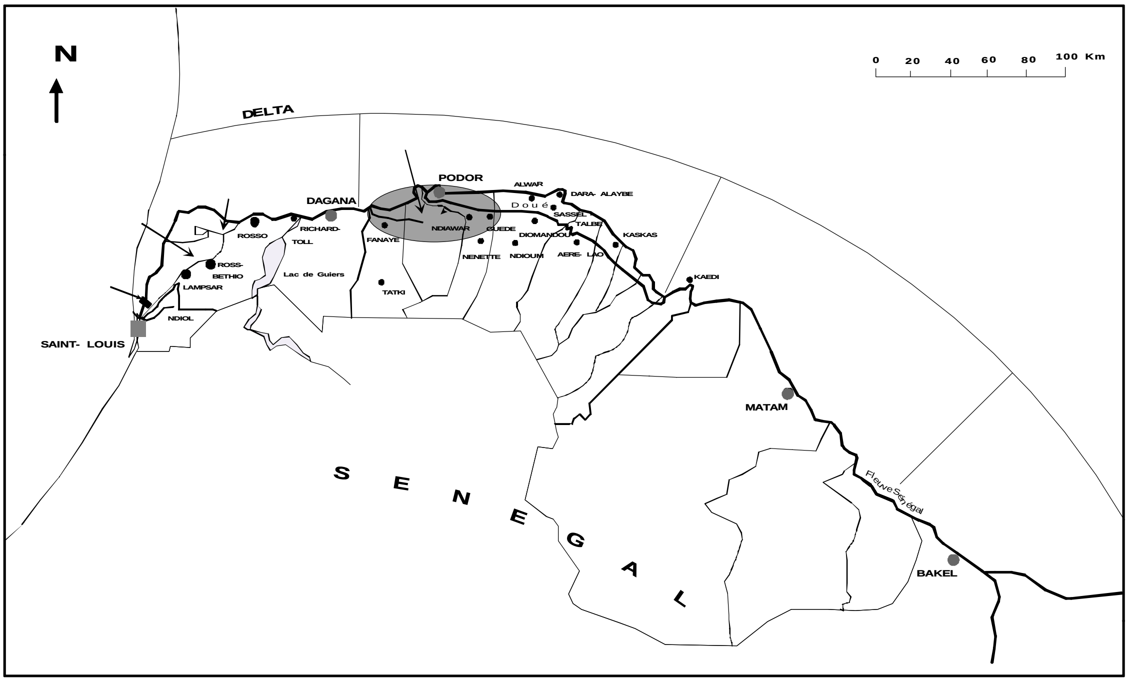

Figure 1 : Location map

Methods

Studies were conducted in the region of Podor (16^{o}40’N, 15^{o}W) in the Senegal river valley in Northern Senegal (Figure 1). The area has an arid climate with an average rainfall of about 200 mm, 95% of which falls between July and November. Average Class A pan evaporation exceeds average rainfall in each month and by over 2000 mm annually.

Two major geomorphological units can be distinguished in the Senegal river valley: (*i*) depressions and (*ii*) former river banks (FAO-Sedagri, 1973) with strong textural differences. Vertic Xerofluvents (Soil Survey staff, 1975), locally known as Hollaldé soils (55-90% clay, saturated hydraulic conductivity about 10^{-8} m s^{-1}) are found in the depressions. Typic Xeropsamments (Soil Survey Staff, 1975), locally known as Fondé soils (30-40% sand, saturated hydraulic conductivity about 10^{-5} m s^{-1}) are found on former river banks (Maymard and Combeau, 1960). Studies on soil spatial variability (Boivin et al, 1995) have shown that these geomorphological units are relatively homogenous. Irrigation schemes are generally small compared to the size of these units and are, therefore, often located within one unit.

Most of the irrigation schemes are less than 50 ha. They are often poorly leveled, with poor bund maintenance, and generally lack drainage facilities (Boivin et al, 1998). About 75% of them are located on Hollaldé soils.

Soil characteristics before irrigation development are generally unknown as no soil quality monitoring has been done in the past. It is, therefore, difficult to evaluate any soil evolution after installation of an irrigation scheme in a given area. As reported by Boivin (1997) and Boivin et al (1998), we assumed that soils around the schemes had kept the characteristics of the soil inside the schemes before irrigation. By systematic sampling of soils inside and outside the schemes, at the survey site (see figure 1), we tried to describe the soil evolution under irrigation. The data collected where soil pH (in situ and on soil extract), exchangeable cations, and cations and anions in soil extract, including carbonates.

Senegal river water, in the lab, was concentrated by evaporation, and its chemical evolution analyzed (Ilou, 1995). The experiment was also conducted with water in contact with soil samples from representative sites. The AQUA model (Vallès, et De Cockborne, 1992) was used to analyze the results.

Field water and salt balances where established, by monitoring all water and solute inputs and outputs, on four sites (2 Fondé and 2 Hollaldé sites), near Podor (see Figure 1).

We sampled 27 irrigation schemes (with and without drainage) in the Senegal river valley (cropped and non-cultivated sites) at the end of the 1993 and 1994 wet seasons. We tested three potential indicators of alkalinization hazard: pH, exchangeable sodium percentage (ESP), and the total amount of carbonates in 1:50 0.1N HCl soil extracts. We assumed differences in the total amount of carbonates extracted for rice fields and neighboring non-cultivated sites, just outside a scheme and on the same soil type, to be equivalent to the amount of carbonates accumulated as a result of irrigation.

Using porous cups, soil solution chemistry has been monitored during four cropping seasons, at several representative sites, including the sites where salt and water balances were monitored.

Using LEACHM (Hutson and Wagenet, 1992), Hammecker et al (1998) simulated the water and solute transfer monitored in the field at two sites in the Senegal river valley. They used experimental data to assess the validity of the simulations, and then simulated ten years of rice cultivation on those soils. They analyzed the impact of several water table depth scenarios on root zone soil quality.

The soil mineralogy has been determined (Favre et al, 1998), and the influence of redox evolution on clay properties evaluated.

Results

The evaporation experiment were driven up to concentration factors of 250 (Ilou, 1995). They showed an increase in pH and a decrease in calcium, as was predicted by simulation using the AQUA model. In the simulation, only calcite precipitation was ‘allowed’. These results suggest that magnesium does not precipitate, and thus that an

alkaline saline evolution threatens the soils.
When adding soil to the evaporation experimet , the residual alkalinity of the solution became negative, because of the amount of exchangeable calcium introduced. The saline evolution will be neutral, as soon as the soil can release calcium to the solution. Because of the importance of the exchangeable capacity of these soils (average CEC: 25 meq/100g of soil, average exchangeable Ca: 12 meq/100g), this 'buffer capacity' of the soil would allow theoretically hundreds of years of irrigation without alkaline evolution.

The surveys conducted in 27 irrigation schemes (Boivin et al, 1998) showed a neutral salinization process, without a significant evolution of ESP. Only carbonate accumulation rates were clearly related to both cropping history and presence or absence of drainage. Rates were high (0.65 meq HCO_3^- (kg soil)$^{-1}$ season^{-1}) in schemes without drainage, and low (0.16 meq HCO_3^- (kg soil)$^{-1}$ season^{-1}) in schemes with drainage. We concluded that carbonate accumulation rate is a robust, cheap and easy-to-measure parameter to determine soil alkalinization hazard in irrigation schemes in the Senegal River Valley.

Hammecker et al (1998), modeling the solute and water transfers, observed a neutral saline evolution in most cases, and a non-saline evolution if the water table is more than 2 meters deep. They also showed that simulation results were strongly dependent on the saturated hydraulic conductivity determined in the field. They used a disc permeameter (Perroux and White, 1981). Measured infiltration rates were relatively high as compared to the actual infiltration rates observed in the field during the growing season. .

Figure 2 shows infiltration rates determined when monitoring salt and water balances in the field (fig 2), using double-ring infiltrometers. It is shown (Boivin, 1997) that infiltration is generally less than one millimetre a day, due either to poor soil permeability and/or to the rising of the water table. This low infiltration rate may be dangerous for the soils, as it favors salt accumulation, and could eventually lead to soil alkalinization.

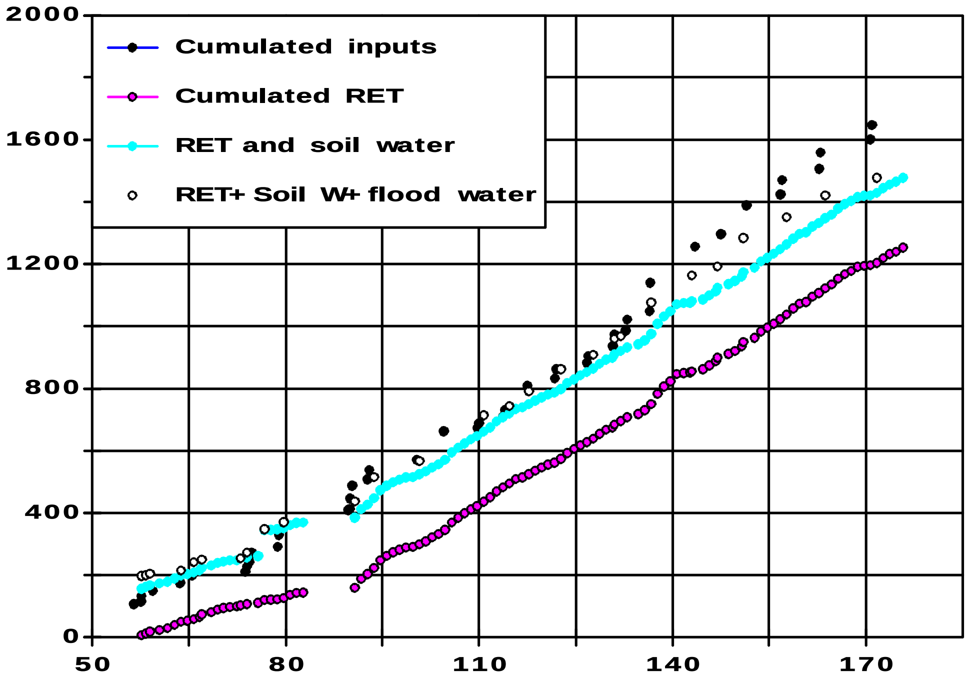

Figure 2 : Example of field water balance monitoring. First axis is days of the year, second axis is mm of water.

When monitoring the soil solution evolution under irrigation with porous cups, we found that the soil solution composition was modified from sodium chloride and calcium sulfate to sodium carbonate, during the croping cycle (fig 2 and 4). This evolution can be interpreted as a rapid alkalinization process. However, the soil solution seems to return to the initial situation between two crops.

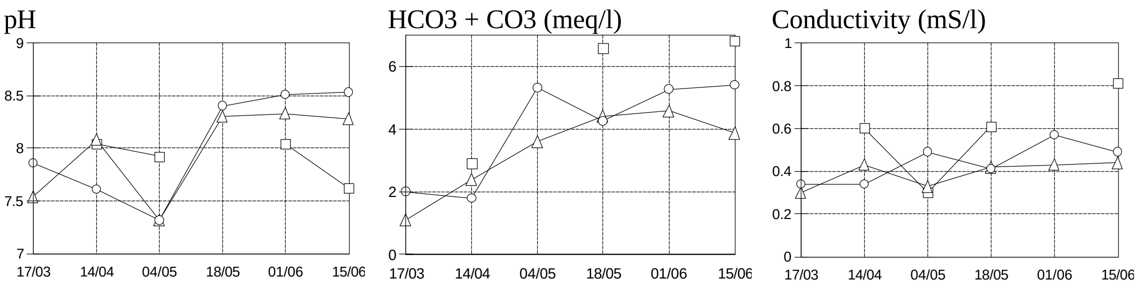

Figure 3 : Example of soil solution evolution during flooding in a vertisol rice field

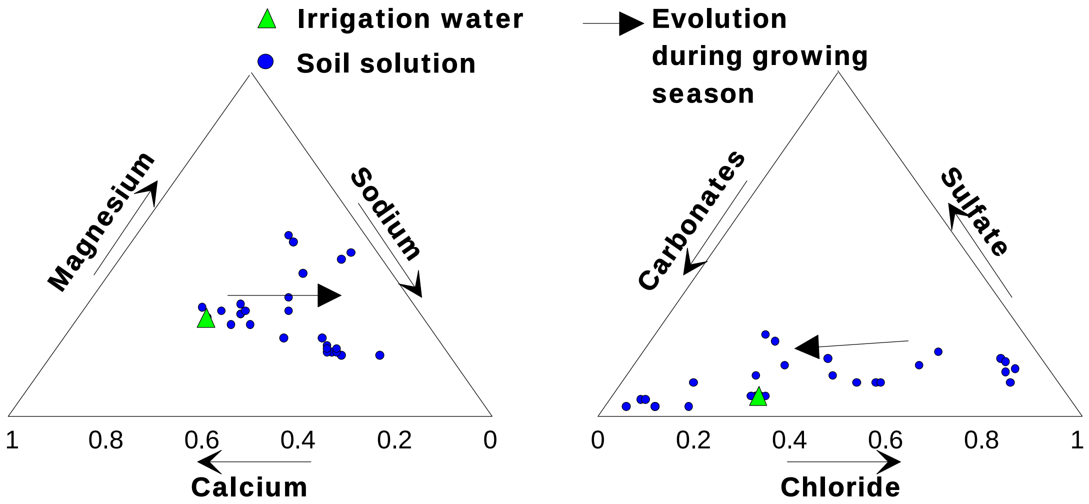

Figure 4 : Piper diagrams of soil solution composition during flooding in a vertisol rice field.

The soil clay mineralogy (Favre et al, 1998) is composed of Beidellites, with 3% of iron in the clay structure. This iron is partly reduced during flooding, and this leads to a doubling of the cation exchange capacity. It is important to note that it occurs when the soil solution becomes sodium-carbonated.

Discussion and conclusion

Soil alkalinisation hazard under irrigation in the Senegal river valley seems weak, judging from the results of the evaporation experiments, and considering the important 'buffer capacity' of the soils. LEACHM simulation results point towards a neutral rather than an alkaline pathway as far as soil salinization is concerned. However, soil solution analyses during the growing season showed rapid soil alkalinization.Phenomena such as iron reduction in clay particles augment the cation exchange capacity (CEC) and may govern to a large extent soil solution behavior. Thus, changes in soil solution composition cannot be predicted using classical models. Soil-pH at the onset of the growing season is usually slightly acid or neutral, indicating that the soil alkalinity build-up is neutralized during the off-season. More research on the impact of CEC changes as a result of Fe reduction in clay minerals during the growing season on soil alkalinization is needed to derive a better understanding and a more accurate prediction of changes in soil quality under irrigation in the Senegal river valley.

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Key words : irrigation, Senegal river, salinization, alkalinization, sustainability
Mots clés : vallée du fleuve Sénégal, irrigation, salinité, alcalinité, gestion durable