



ELSEVIER

Agricultural Water Management 60 (2003) 13–32

Agricultural  
water management

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## Actual and potential salt-related soil degradation in an irrigated rice scheme in the Sahelian zone of Mauritania

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Accepted 14 October 2002

### Abstract

Salt-related soil degradation due to irrigation activities is considered a major threat to the sustainability of rice cropping under semi-arid conditions in West Africa. Rice productivity problems related to soil salinity, alkalinity and topographic position were observed in an irrigated rice scheme in southern central Mauritania. Detailed study of soils in a toposequence revealed that highest topsoil salinity and alkalinity were found at the shallow soils (<1.2 m) of the middle and upper slopes. Here, soils have formed in situ from the schist parent rock, which releases carbonate rich salts upon weathering. Within these soils large differences in salinity and alkalinity level occur at short distances, indicating minimal groundwater flow and a strong variation in the geochemical composition of the vertically positioned bedrock. Further downslope, soils have a (partly) colluvio-alluvial origin. Here, sedimentation during annual floods increased soil depth (>2.5 m) and salinity levels remained low due to leaching. Fom Gleita's irrigation water used is amongst the most alkaline in the Sahel. However, no clear indications of secondary salinization or alkalization due to irrigation activities were observed. A comparison of historical data revealed no significant changes of topsoil salinity and pH over the last 30 years. The PHREEQC 2.0 model was used to study actual and potential development of soil salinity and alkalinity problems, by simulating excessive concentration of the irrigation water through evaporation. The evolution into a strongly sodic-alkaline solution due to precipitation of Mg-calcite and -silicate minerals did not fit with current composition of ground and surface water, which showed geochemical control of alkalinity at high concentrations. Incorporation of cation exchange processes, using a small (1.0 mmol<sub>c</sub> per 100 g dry soil) but calcium saturated CEC, resulted in a better fit with field data. Results indicate that the soil's buffer capacity to

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counteract alkalization processes is large. However, the soil water and salt balance needs to be quantified in order to determine development rate and equilibrium levels of soil salinity and alkalinity for different soil type  $\times$  water management combinations. This study does neither reject the hypothesis that salt-related soil degradation jeopardizes the sustainability of rice cropping in the Sahel, nor does it provide evidence for its verification. However, our results are in line with other studies in west Africa, in that current salt-related production problems are inherited, rather than being induced by irrigated rice cropping.

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*Keywords:* Alkalinization; Irrigated rice; Sahel; Mauritania; Geochemical modeling

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## 1. Introduction

In response to the droughts, which devastated crops and livestock in the Sahel in the 1970s and 1980s, massive investments were made by international donors and Sahelian countries to establish large irrigation schemes that would improve food security. Irrigated rice (*Oryza sativa* L.) was introduced as the main crop in these schemes. Rice cropping in the Sahel requires large amounts of water due to the high evaporative demand of the hot and dry climate. Although most irrigation waters in the Sahel are of good quality (i.e. low mineralized water), excessive concentration through evaporation can become hazardous as these waters often possess a positive calcite residual alkalinity ( $RA_{\text{calcite}} = \text{Alkalinity} - \text{Ca}$ , in mol/l) (Valles et al., 1992; Bertrand et al., 1993). Soil degradation through salinization and alkalization is considered one of the most important threats jeopardizing sustainable irrigated rice cropping in the Sahel (Bertrand et al., 1993; Boivin, 1995; Ceuppens et al., 1997; Boivin et al., 2002). Given the high investment costs of irrigated agriculture and the high costs of reversing alkalization processes, precaution has to be taken when salt-related production problems are found in these environments. Crop production problems related to soil salinity and alkalinity have been reported throughout the Sahelian zone, i.e. the Senegal river delta (Wopereis et al., 1998), Office du Niger—Mali (Bertrand et al., 1993), Sourou valley—Burkina Faso (Barro et al., 2000), Lossa—Niger (Marlet et al., 1998) and Fom Gleita—Mauritania (van Asten et al., 2002). However, the results of soil studies at these sites were not always in line with the hypothesis that irrigated rice cropping increases salinization or alkalization in the Sahel. On the contrary, Ceuppens and Wopereis (1999) showed that soil salinity in the Senegal river delta, originating from marine deposits, progressively decreased as a function of rice cropping intensity. In the Office du Niger, rice yields increased significantly over the last 10 years as a function of improved management practices, while soil alkalinity decreased slightly on the clayey soils used for rice cropping, but increased on the more sandy soils where vegetable cropping prevailed (Marlet, 1999). In the Sourou valley zinc deficiency in rice was found, which seemed more related to the calcareous origin of the parent material than to active alkalization induced by irrigation (Barro et al., 2000). In the Lossa irrigation scheme, Barbiéro and van Vliet-Lanoe (1998) found that soil alkalization was no longer occurring and Barbiéro et al. (2001) observed that alkaline soils in Lossa de-alkalinized more rapid when cultivating the local fodder crop 'Bourgi' (*Echinochloa stagnina*) under submerged

conditions, similar to irrigated rice cropping. From the above studies it follows that salt-related soil degradation in irrigated rice schemes in the Sahel needs careful study before drawing conclusions about its importance, its source and its (potential) evolution.

In this study, we focus on the irrigation scheme of Foug Gleita (16°08'N, 12°46'W), southern central Mauritania (Fig. 1). Constructed between 1985 and 1989, with a surface area of 1950 ha, it is one of the many recent and typically large irrigation schemes in the Sahel. Plans to extend the irrigation scheme to 3600 ha have so far not been materialized, partly due to productivity problems. Both yield levels and cropped area started to decline a few years after installation of the scheme (SONADER, 1998). In addition, farmers increasingly complained about salinity problems and by 1993 about 12% (237 ha) of the area had been abandoned. Farmers and extension workers in the area fear that salt-related soil degradation threatens the existence of the irrigation scheme. van Asten et al. (2002) showed that productivity problems in Foug Gleita were the result of both soil quality problems and sub-optimal crop management. Rice yields increased and the percentage of abandoned land declined going from shallow (<1.2 m to schist parent rock) soils upslope to deeper soils further downslope. The topsoil pH and EC values of shallow soils were significantly higher than for deeper soils, but they could not be classified as saline nor sodic following USDA classification. Furthermore, van Asten et al. (2002) reported that the  $RA_{\text{calcite}}$  of the irrigation water varied between 0.5 and 1.2 mmol/l, which is up to three times higher than concentrations reported by Bertrand et al. (1993), Marlet et al. (1998) and Boivin et al. (2002) for the Niger and Senegal river. This makes Foug Gleita irrigation water potentially more dangerous, with respect to alkalization hazard, than the waters of the two major Sahelian rivers. We hypothesize that soil alkalization will develop more rapidly in Foug Gleita than elsewhere in the Sahel. Hence, the site could act as an early warning system.

The objectives of this study were: (i) to characterize the distribution of alkaline salts in Foug Gleita, thereby focusing on both the (potential) role of the schist parent rock and the irrigation water as sources of alkaline salts, and (ii) to create insight into the dynamics of the soil degradation, by looking both backward (i.e. comparing actual to historical soil data) and forward (i.e. using geochemical simulation tools) in time, in order to obtain a semi-quantitative idea on the evolution of these soils under the current irrigation practices.

## 2. Materials and methods

### 2.1. The research site

The climate in Foug Gleita is typically Sahelian with erratic rainfall (250 mm per year) between July and October, followed by a short cool period (November–February) with minimum air temperatures as low as 10 °C and a hot dry season (March–June) with maximum air temperatures up to 46 °C. Reference evapotranspiration is 2700 mm per year.

The Gorgol Noire river watershed upstream of Foug Gleita is located on the 'Mauritanides' geological region, consisting mostly of Precambrian and Primary metamorphosed rock, which was folded and lifted in the Appalachian era (Carité, 1989). The soils have formed from a parent rock observed at a depth ranging from 0 m upslope to 4 m downslope,

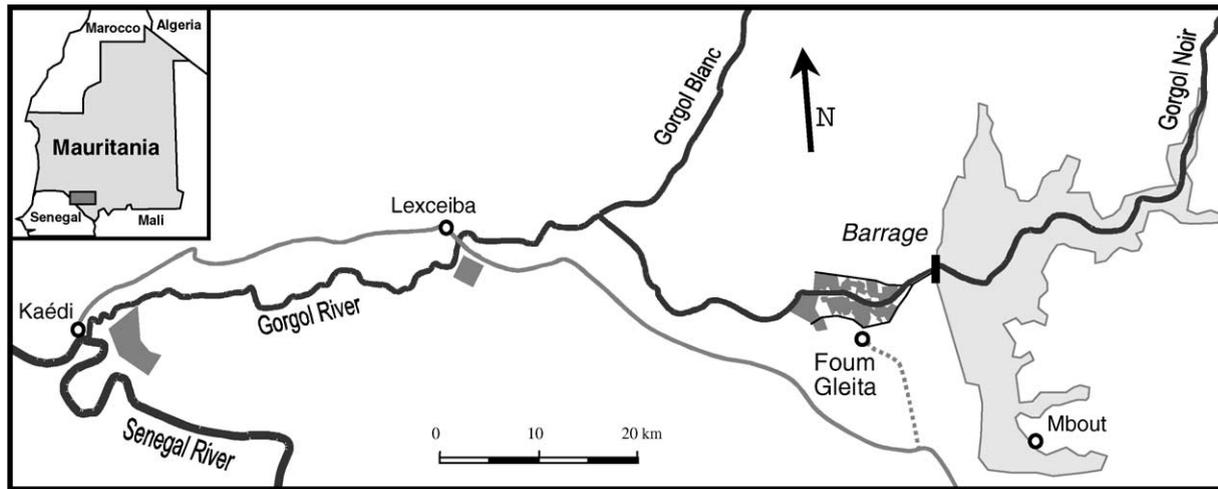


Fig. 1. Overview of the location of the Foug Gleita barrage and irrigation scheme within the Gorgol river catchment.

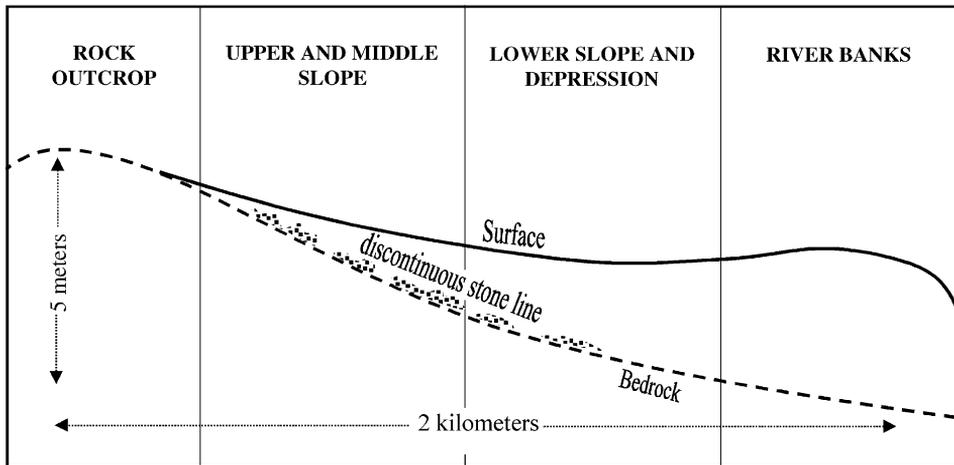


Fig. 2. Schematic cross-section of the Foug Gleita landscape.

and consisting mostly of chloritoschists (green schist), calc-chloritoschists, micaschists, and quartz. In the schist, pyrite and iron oxide minerals are also frequently observed (Chiron, 1973). The vertically positioned schist has a north–south orientation. Sporadically some secondary dolerite intrusions can be observed in the form of small rock outcrops (BCEOM, 1986). The landscape is characterized by large slightly sloping (1–2%) barren plains, interrupted by rock outcrops and valley bottoms that are generally marked by the presence of some shrubs and small trees. Four major geomorphological units can be distinguished in the Foug Gleita irrigation scheme: (i) rock outcrops, (ii) upper and middle slopes, (iii) lower slopes and depressions, and (iv) river banks (Fig. 2). Soils at the upper part of the landscape are shallow (<1.2 m) and have formed in situ from the weathered parent rock. Further downslope, these soils are covered with local colluvial and alluvial deposits, which increases soil depth up to 3.5 m. Soils at the riverbanks consist of alternating sandy and clayey deposits parallel to the (former) river course and soils are up to 4 m deep. (BCEOM, 1986).

The Gorgol river is a tributary to the Senegal river. Originally the river regime was intermittent with peak floods during rain events. The construction of the dam, blocking the river's narrow passage through the Oua–Oua mountain chain, reduced peak floods and assured a minimum discharge flow even in the dry season. Water from a 8950 km<sup>2</sup> large watershed now accumulates in a shallow (3–4 m) but large artificial lake (25–170 km<sup>2</sup>). The normal retention capacity of the dam is large (500 Mm<sup>3</sup>) compared to simulated needs, but irrigation water is excessively used which sometimes leads to depletion of stocks down to the minimum storage capacity (100 Mm<sup>3</sup>) required to ensure complete irrigation of the command area (SONADER, 1992). The general situation in Foug Gleita is one of excessive water use, poor canal maintenance, excessive weed growth, non-application of drainage practices and non-functional drains; conditions that are increasing the risk of alkalinization. Evaporative demand is very high and accounts for 60–70% of total water losses from the dam (SONADER, 1992). As a result, irrigation water quality varies

throughout the year, i.e. pH  $\sim$  7.5 and EC  $\sim$  0.10 dS/m just after the wet season and increasing to pH  $\sim$  8.3 and EC  $\sim$  0.25 dS/m at the end of the dry season (van Asten et al., 2002).

## 2.2. Detailed study of a soils in a toposequence

The distribution pattern of (alkaline) salts was studied in a toposequence, in order to create further insight into the origin and evolution of alkalinity in Foum Gleita. All soil samplings occurred between January 1999 and October 2000. Based on the BCEOM (1986) soil map and statements of farmers and extension workers, a 532 m long toposequence was selected for detailed study in the northern part of the irrigation scheme (irrigation block S4/1). The toposequence covered both the geomorphological units ‘upper and middle slope’, as well as the ‘lower slope and depression’ (Fig. 3) and can be considered representative for the majority of the Foum Gleita rice soils. The toposequence included four irrigation blocks (blocks I–IV) with an average width of 130 m. Each irrigation block was delimited by an irrigation canal upslope and a drainage canal downslope. Due to poor maintenance, drainage canals were shallow (<60 cm), heavily weed infested and several contained water throughout the year, even during fallow periods. Farmers abandoned rice cultivation in the upper-slope irrigation block (block I), only a few years after construction of the scheme. According to farmers, soil quality was poor and the topsoil too stony.

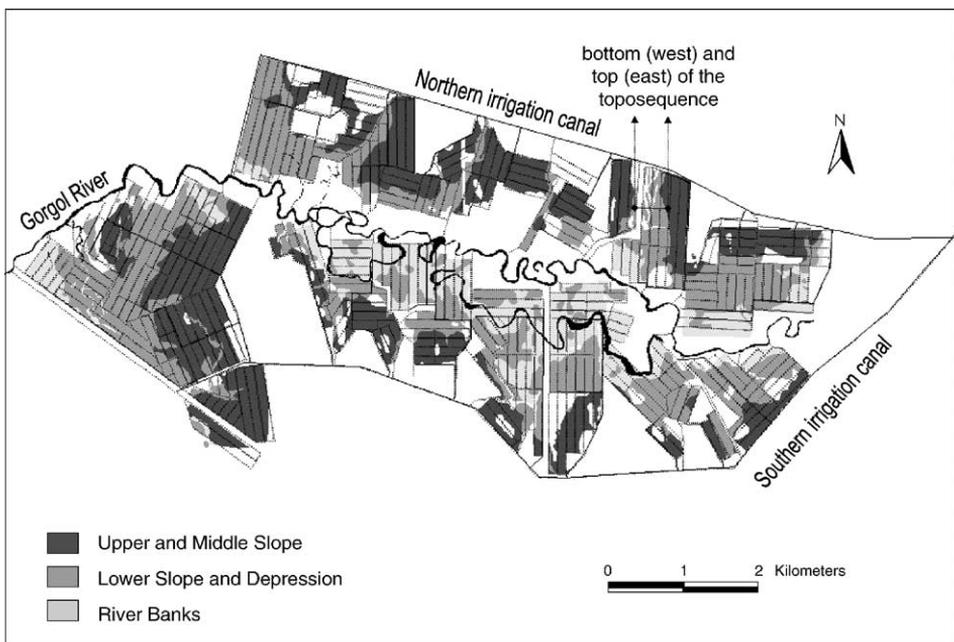


Fig. 3. Map of the Foug Gleita irrigation scheme with the location of the sampled toposequence.

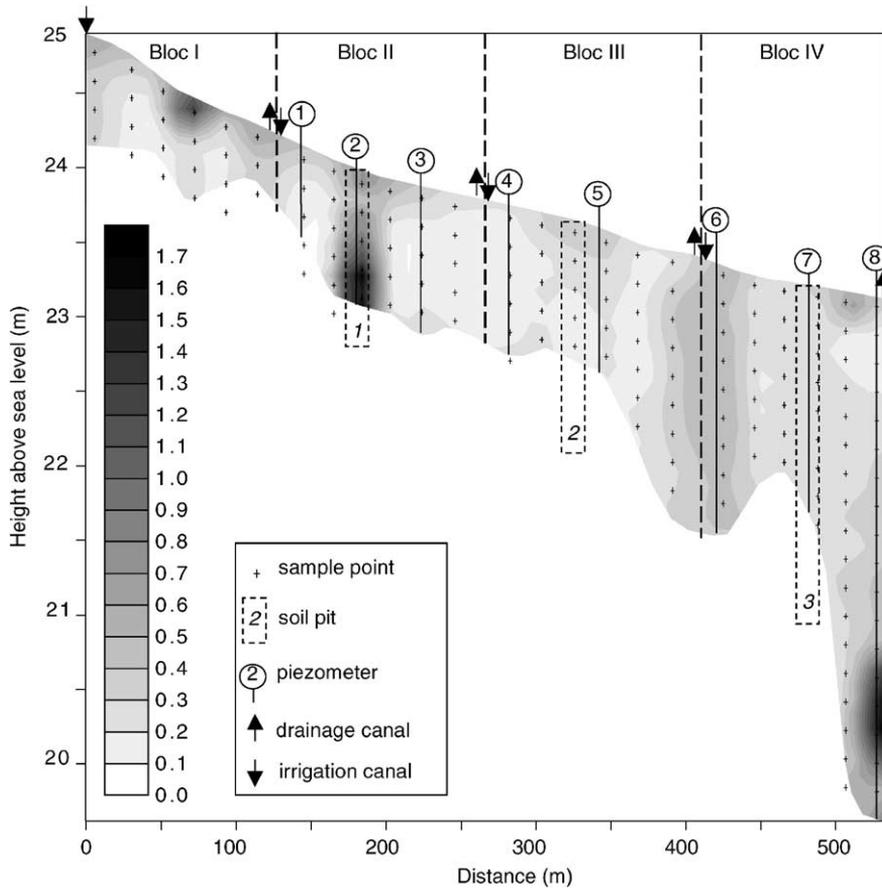


Fig. 4. Cross-section map of the toposequence showing  $EC_{1:5}$  (in  $dS/m$ ), soil depth, the location of piezometers, irrigation and drainage canals, sample points, soil pits, and irrigation and drainage canals.

In each irrigation block, six sample sites were chosen at evenly spaced intervals (20–25 m), resulting in a total of 24 sample points, covering the complete toposequence. A total of 158 samples was taken at 0.2 m depth interval up to the parent rock, using a hand auger. Samples were oven-dried (80 °C) and ground before analyzing pH in a 1:2.5 paste ( $pH_{1:2.5}$ ) and EC in a 1:5 paste ( $EC_{1:5}$ ). Results of these analyses were interpolated in order to obtain cross-section maps.

Soil pits were dug down to the parent rock at three different sites in the toposequence (Figs. 4 and 5). The soil profiles were described following the FAO guidelines for soil profile description (FAO, 1990) and soil samples were taken of each horizon for analysis. Samples were analyzed for  $pH_{1:2.5}$ ,  $pH\text{-}KCl_{1:2.5}$  and  $EC_{1:5}$ . Exchangeable bases ( $Ca^{2+}$ ,  $Mg^{2+}$ ,  $K^+$ ,  $Na^+$ ) were determined using an AAS after extraction with ammonium chloride. Cation exchange capacity (CEC) of the samples was determined as described by Chapman (1965). Soil texture was analyzed using the pipette method and classified following the FAO guidelines (FAO, 1990).

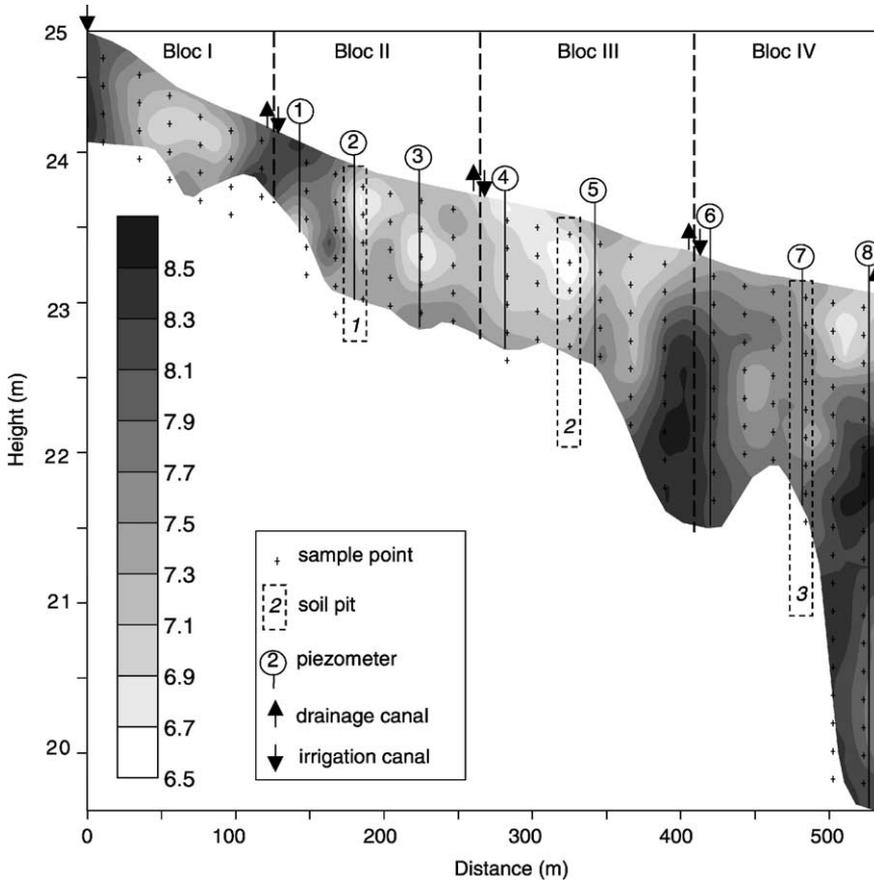


Fig. 5. Cross-section map of the toposequence showing  $\text{pH}_{1:2.5}$ , soil depth, the location of piezometers, irrigation and drainage canals, sample points, soil pits, and irrigation and drainage canals.

In 1997, eight piezometers were installed along the toposequence, covering irrigation blocks II–IV of the toposequence (Figs. 4 and 5). Piezometers reached down to the parent rock or to hard quartz layers. In August 2000 all piezometers contained water, which allowed for simultaneous comparison of groundwater quality along the toposequence. Water samples were taken at each piezometer and filtered ( $0.45 \mu\text{m}$ ) after on site (i.e. field) determination of pH, EC and alkalinity (Gran, 1952). Filtered sub-samples were acidified ( $\text{pH} < 2.0$ ), using concentrated  $\text{HNO}_3$ , and stored in polypropylene bottles for laboratory analysis. Cations were determined using an AAS, chloride was analyzed colorimetrically using mercury(II) thiocyanate (Fixen et al., 1988),  $\text{SO}_4^{2-}$  was determined colorimetrically using  $\text{BaCl}$  and methyl blue, and Si concentrations were determined following the silicomolybdic acid procedure (Jones and Dreher, 1996). Saturation indices (SI) for minerals defined in the WATEQ4 database were calculated using the PHREEQC 2.0 geochemical simulation model (Parkhurst and Appelo, 1999). This allowed for the assessment of minerals that could potentially precipitate in this environment, thereby altering the soil solution composition.

### 2.3. *Historical analysis of soil data*

Historical soil data were compared to the results of recent soil studies in order to verify whether soil quality decreased since irrigation activities started. The area bordering the Gorgol Noir River downstream of the Oua–Oua mountain chain has been the subject of several soil studies over the last 30 years. The first study, investigating the soil's potential to sustain irrigated agriculture, was carried out by the [UNDP \(1970\)](#). It was a reconnaissance study (1:50,000), identifying the major soil types between the future dam location and Lexceiba, 40 km further downstream. About 45 samples of topsoil horizons, varying in depth from 0.15 to 0.45 m, were taken and EC and pH were measured in the saturated paste extract ( $EC_{SP}$ ,  $pH_{SP}$ ). A second more detailed study was carried out by [Il Nuovo Castoro \(1977\)](#), focusing on 6850 ha potential irrigable land just downstream of the current dam, including the actual 1950 ha Foug Gleita irrigation scheme. Electrical conductivity and pH were determined in a 1:2 water extract ( $EC_{1:2}$ ,  $pH_{1:2}$ ) for all topsoil horizons of 266 soil pits covering the total area. In 1986, a third soil study was conducted by BCEOM, focusing only on the 1950 ha of the current scheme. Some 114 soil pits throughout the scheme were studied and sampled. Soil samples from the top horizon (average 0–0.23 m depth) were analyzed for pH and EC in a 1:5 extract ( $pH_{1:5}$  and  $EC_{1:5}$ ). A fourth soil study was carried out in 1993, by the Mauritanian 'Laboratoire Nationale des Sols' (LANASOLS) to investigate soil degradation problems in Foug Gleita. By that time, 12% of the irrigation scheme's land had already been abandoned. Topsoil horizons (0–0.2 m) of all abandoned fields were sampled and analyzed for  $pH_{1:5}$  and  $EC_{1:5}$ . The most recent soil samples were taken for this study by WARDA at the onset of the 1998 and the 1999 wet season. Topsoil samples (0–0.2 m) were taken in 100 farmer fields throughout the irrigation scheme, and included both cultivated and uncultivated fields. The samples were analyzed for  $pH_{1:2.5}$  and  $EC_{1:5}$ .

Means for topsoil  $EC_{1:5}$  from the [BCEOM \(1986\)](#) and WARDA (1998–1999) soil studies were compared with the Newman–Keuls test using the STATISTICA 5.5 software. Results from other soil studies were compared qualitatively as methodological differences did not allow for statistical comparisons (i.e. different sample area and extraction methods).

### 2.4. *The composition and evolution of surface and groundwaters*

Throughout the year 2000, irrigation, drainage and groundwater samples were taken (if present) at various sites within the irrigation scheme at 2–3-month intervals. Samples were treated and analyzed as described in [Section 2.3](#).

The evolution of irrigation water upon concentration (evaporation of water) was modeled using the PHREEQC 2.0 hydro-geochemical simulation model and the WATEQ4 database ([Parkhurst and Appelo, 1999](#)). The initial irrigation water composition used for modeling was the average of values measured in 2000. Aluminum concentration was calculated, assuming equilibrium with kaolinite. For the model exercise, we selected those minerals that were likely to precipitate in natural soil environments within the observed salinity range, i.e. Mg-calcite, sepiolite, illite, gypsum. Precipitation of pure calcite was not allowed. Chemical analysis of carbonate nodules sampled during the detailed toposequence study revealed that these contain on an average 2% of  $MgCO_3$ , which is similar to findings of [Suarez and Rhoades \(1982\)](#). The precipitation of a Mg-calcite

( $\text{Ca}_{0.98}\text{Mg}_{0.02}\text{CO}_3$ ) solid solution was allowed, using the equilibrium constant of calcite [ $\log(k) = -8.48$ ]. Several authors—Gac (1980) for Lake Cad, Gueddari (1984) for Chott el Djerid, Barbiéro (1995) for Niger irrigation water, and Condom et al. (1999) for Punjab irrigation waters suggested control of silica and magnesium through formation of sepiolite, although they were unable to give evidence for the presence of these minerals in the soils. However, precipitation of sepiolite mimics well the precipitation of more complex Mg-montmorillonite minerals that can only be modeled if Al complexing is taken into account (Valles et al., 1989). Gac et al. (1977) and Barbiéro (1995) observed that the evolution of Mg concentrations in the soil solution could not be explained by simply concentrating irrigation water. Mg in the soil solution was much more controlled (i.e. decreased more rapidly) than what could be expected from the model simulations. They hypothesized that existing Si rich minerals in the soil act as a Si buffer, providing the necessary source material for the formation of Mg-rich montmorillonite clays. We introduced this soil's Si buffer function by allowing dissolution of quartz ( $\text{SI} = 0.6$ ) from an infinite stock, the moment Si concentrations in the soil solution reach those of the groundwater samples. PHREEQC allows the user to specify the SI value at which precipitation of a specific mineral occurs, in order to account for the occurrence of supersaturation (Appelo and Postma, 1996). SI values for all minerals that could potentially precipitate were set zero, except for Mg-calcite, which precipitated at  $\text{SI} = 0.9$ . The  $\text{SI}_{\text{Mg-calcite}}$  was based on the (near) maximum value of the August 2000 groundwater samples at  $p\text{CO}_2 = 10^{-1.8}$  atm. All simulations were done at a constant  $p\text{CO}_2$  of  $10^{-1.8}$  atm, which corresponds to the average  $p\text{CO}_2$  of tropical soil environments (Brook et al., 1983). Temperature was maintained at a constant 30 °C. Concentration of irrigation water by evaporation was simulated by extracting pure water from the initial solution. At each simulation step, the water content of the solution was decreased by half (0.50 kg). The mass of concentrated solution was then doubled, i.e. after each simulation cycle the initial amount of water was restored (1.00 kg). Each concentration step was followed by precipitation of minerals for which the given saturation index had been exceeded. This simulation cycle was repeated 10 times, resulting in a final concentration factor of 1024. The above simulation procedure was performed a second time, but now cation exchange processes were included. Equilibrium with the exchange complex was calculated after each concentration–precipitation cycle. The initial composition of the exchange complex was calculated assuming equilibrium with the irrigation water. In PHREEQC 2.0 the exchange complex was defined as the number of exchange sites per kg water. Simulations were conducted with CEC values varying between 0.015 and 1.200 M/kg water (i.e. 0.25 and 20.00  $\text{mmol}_c$  per 100 g dry soil, respectively, when soil bulk density equals 1.8 kg/l and water content equals 0.3 kg water/l).

### 3. Results

#### 3.1. Analysis of soil properties in a toposequence

Results of the toposequence sampling in relation to the location of irrigation blocks, soil pits and piezometers are shown in Figs. 4 and 5. Soils were shallow (<0.8 m) in irrigation block I and relatively deep (1.4–3.6 m) in block IV. Highest topsoil  $\text{pH}_{1:2.5}$  and  $\text{EC}_{1:5}$  values were observed in the upper part of the toposequence. However, variability was large both

Table 1

Texture class and basic soil chemical parameters for soil pits of the detailed toposequence study at irrigation block S4/1

Pit number	Depth (m)	pH <sub>1:2.5</sub> water	Texture class <sup>a</sup>	Ca	Mg	K	Na	CEC	ESP (%)	EC <sub>1:5</sub> (dS/m)
				(mmol <sub>c</sub> per 100 g dry soil)						
1	0.00–0.20	8.3	SiL	12.63	3.50	0.35	2.34	10.74	21.79	0.52
1	0.20–0.35	8.0	SiCL	14.50	3.88	0.34	4.89	13.25	36.91	0.69
1	0.35–0.80	8.3	SiCL	18.50	3.13	0.29	5.45	14.39	37.87	0.79
1	0.80–1.00	8.5	CL	23.88	2.63	0.19	4.76	13.31	35.73	1.32
1	1.00–1.15	8.5	SiL	23.25	2.00	0.21	5.38	8.23	65.31	1.03
2	0.00–0.20	7.1	SiCL	12.50	4.38	0.35	0.68	13.93	4.85	0.12
2	0.20–0.60	6.6	SiCL	11.85	4.38	0.23	0.53	17.15	3.06	0.13
2	0.60–1.15	7.1	SiCL	15.50	4.50	0.19	0.49	16.73	2.90	0.09
2	1.15–1.40	7.3	SiCL	20.88	4.50	0.28	0.54	18.47	2.92	0.16
2	1.40–1.55	7.6	SiL	35.63	2.88	0.17	0.43	13.17	3.23	0.12
3	0.00–0.20	7.3	SiCL	11.63	5.00	0.31	0.86	13.93	6.17	0.22
3	0.20–0.60	6.9	SiCL	11.25	3.88	0.19	0.87	13.81	6.26	0.15
3	0.60–1.30	7.3	SiCL	12.13	3.63	0.17	1.05	14.01	7.46	0.25
3	1.30–2.10	8.4	CL	29.25	4.38	0.15	1.80	13.71	13.13	0.37
3	2.10–2.15	8.4	SiCL	29.13	5.88	0.18	2.66	16.06	16.56	0.47
3	2.15–2.25	8.5	SiL	30.00	3.88	0.07	2.08	8.37	24.85	0.47

<sup>a</sup> Texture classes according to FAO guidelines for soil description (1990).

horizontally as vertically and the cross section maps did not show a clear pH<sub>1:2.5</sub> and EC<sub>1:5</sub> gradient as a function of topography. A slight increase in pH<sub>1:2.5</sub>, and to a lesser extent EC<sub>1:5</sub>, was observed near most irrigation and drainage canals.

The first two soil pits (PIT-1 and PIT-2) are part of the ‘upper and middle slope’. The third soil pit (PIT-3) is part of the ‘lower slope and depressions’ mapping unit. Results of chemical and soil texture analysis are shown in Table 1.

Soil texture varied little between soil pits (average 29% clay, 53% silt, 18% sand) and was classified as silt loam, silty clay loam and clay loam. A horizon with abundant angular medium to coarse quartz fragments was found overlying the schist parent rock in PIT-1 and PIT-2. Its thickness varied strongly at short distances (0.05–0.35 m). In PIT-3, many fine angular quartz fragments were found in a thin layer at 2.15 m depth just above the weathered schist, and some rounded medium-sized quartz fragments were observed between 0.60 and 2.00 m depth.

Very few fine hard calcareous nodules were observed in PIT-1 at 0.35–0.80 m depth and none in PIT-2. In both pits, precipitation of carbonate minerals was observed in the partly weathered parent rock, i.e. in between the schist platelets. Furthermore, soil and salt deposits in the weathered parent rock had a very talc-like structure. In PIT-3, the presence and size of calcareous nodules increased rapidly from 1.3 m depth onwards. From 1.6 m onwards calcareous nodules were hard in the center with a more soft powdery exterior cementing the nodules up to 10 cm diameter at 2.0 m depth.

The soils had a moderate to strong structure, being sub-angular blocky in PIT-1 and PIT-2, and more prismatic in PIT-3. The latter pit showed vertic properties in the upper

horizons. The porosity throughout the toposequence was generally medium to high, but was distinctly lower near the soil surface. No evidence of degradation of the soil structure by sodication could be found. Biological activity observed in all pits was important, with termite nests and channels being the main features.

The topsoil (0–0.2 m) of all pits showed actual hydro-morphological features with grayish-brown matrix colors and iron oxidation colors around (former) root channels. PIT-1 and PIT-2 seemed well drained with no actual hydromorphic features below 0.2 m and only few iron–manganese mottling and nodules in the deeper horizons of the profile. In PIT-3, some soft iron–manganese concretions could be found at shallow depth (0.2–0.6 m) and iron mottling was abundantly present from 0.6 m onwards, with the appearance of grayish-blue reduction colors at 2.15 m depth. In the 1999 and 2000 wet season, this soil was temporarily inundated during floods of the Gorgol Noire river.

Results of the August 2000 groundwater sampling are given in Table 2. Groundwater from all piezometers, were classified as sodic-alkaline waters according to Valles et al. (1991), except for piezometer 2, which was classified ‘sulfatic saline’. Saturation indices indicated supersaturation (SI 0.07–1.04) in the groundwater with respect to calcite at  $p\text{CO}_2 = 10^{-1.8}$ .

### 3.2. Analysis of historical soil data

Analytical methods, sampling depth, and the number and location of sampling points varied strongly amongst the studies. A summary of basic statistics on pH and EC and the sampling and extraction method are given in Table 3. Soil pH and EC values of the 1985 study did not differ significantly from the soil samples taken in 1998/1999.

Table 2

Chemical characteristics of Foug Gleita irrigation water (average of the year 2000) and of groundwater (August 2000) at irrigation block S4/I

August 2000	Average irrigation water	Piezometers							
		1	2	3	4	5	6	7	8
pH	7.54	8.3	8.0	8.0	7.7	7.3	7.9	7.6	7.3
EC (dS/m)	0.16	0.66	9.03	0.72	1.16	1.11	2.65	1.24	0.76
Ca <sup>2+</sup> (mmol <sub>c</sub> /l)	0.78	1.42	7.78	3.64	6.29	6.19	1.92	6.29	2.42
Mg <sup>2+</sup> (mmol <sub>c</sub> /l)	0.38	0.77	3.99	1.09	1.81	1.89	3.87	2.88	1.00
K <sup>+</sup> (mmol <sub>c</sub> /l)	0.12	0.06	0.06	0.03	0.02	0.12	0.27	0.07	0.39
Na <sup>+</sup> (mmol <sub>c</sub> /l)	0.32	5.05	83.74	2.61	5.05	4.87	22.8	5.74	2.96
Alk (mmol <sub>c</sub> /l)	1.40	6.67	6.94	5.84	9.16	9.92	23.5	9.89	8.07
Cl <sup>-</sup> (mmol <sub>c</sub> /l)	0.11	0.18	35.89	0.74	2.55	1.57	6.14	1.00	0.33
SO <sub>4</sub> <sup>2-</sup> (mmol <sub>c</sub> /l)	0.09	0.32	52.39	0.71	0.57	0.35	0.29	1.65	0.08
Si (mmol/l)	0.12	0.48	0.42	0.52	0.60	0.52	0.45	0.42	0.42
RA <sub>calcite</sub> (mmol <sub>c</sub> /l)	0.62	5.3	-0.8	2.2	2.9	3.7	21.5	3.6	5.7
SAR <sup>a</sup>	0.42	4.8	34.5	1.7	2.5	2.4	13.4	2.7	2.3
SI <sub>calcite</sub> at $p\text{CO}_2 = 10^{-1.8}$	-1.39	0.07	0.11	0.35	0.89	0.95	1.04	0.93	0.46
SI <sub>quartz</sub> at $p\text{CO}_2 = 10^{-1.8}$	-0.01	0.58	0.55	0.63	0.69	0.63	0.56	0.53	0.53

<sup>a</sup> Sodium adsorption ratio =  $(\text{Na}^+)/((\text{Ca}^{++} + \text{Mg}^{++})/2)^{0.5}$ , concentrations in mmol/l.

Table 3  
EC (dS/m) and pH measurements of topsoil samples from different soil studies in the Fom Gleita area

Source	UNDP (1970)		Il N. Castoro (1977)		BCEOM (1985)		LANASOLS (1993)		WARDA (1998–1999)	
Number of observations	46		266		114		331		100	
EC method	Saturated paste		1:2 extract		1:5 extract		1:5 extract		1:5 extract	
pH method	Saturated paste		1:2 extract		1:5 extract		1:5 extract		1:2.5 extract	
	EC	pH	EC	pH	EC	pH	EC	pH	EC	pH
Average	0.49	7.2	0.24	6.9	0.12	7.1	0.16	7.4	0.13	7.4
Median	0.27	7.2	0.13	7.0	0.08	7.0	0.14	7.4	0.12	7.1
Minimum	0.15	6.0	0.02	5.5	0.03	5.7	0.04	6.9	0.03	5.3
Maximum	3.21	8.4	2.20	8.5	1.20	8.7	1.11	8.3	0.55	8.2
Sample area and strategy	Includes samples outside the irrigation scheme		Regular grid, covering the initially planned 3600 ha		Random sampling within the current irrigation scheme		Only fields that had been abandoned by 1993		Random sampling within the current irrigation scheme	

### 3.3. The composition and evolution of surface and groundwaters

Irrigation, drainage and groundwater samples taken in Fom Gleita were classified as sodic-alkaline waters according to Valles et al. (1991). The results of the chemical analysis of all irrigation, drainage, and groundwaters sampled in the year 2000, are presented in the concentration diagrams of Fig. 6. Electrical conductivity was taken as a tracer for concentration processes, because chloride concentrations were relatively low and showed large scatter. The average irrigation water composition is given in Table 2. The evolution of the solution composition upon concentration can be observed in Fig. 6. Small amounts of illite precipitate at concentration factor (CF) = 4 (EC ~ 0.6 dS/m), but sepiolite is quantitatively the dominant Mg silicate mineral and precipitates from CF = 32 onwards (EC ~ 2.2 dS/m). A large part of the Si that precipitates with Mg is released by dissolution of quartz. This Si buffer maintains Si concentrations in the soil solution at ~ 0.5 mmol/l. Mg-calcite precipitates from CF = 16 (EC ~ 1.1) onwards. When only taking into account concentration processes, the precipitation of Mg-calcite, sepiolite and illite results in a decrease of Mg and Ca concentrations in the soil solution at EC > 1–2 dS/m. Alkalinity concentration continues to increase, which is in line with the  $RA_{\text{calcite}}$  concept. Likewise, the pH increases up to 8.9 (data not shown) upon concentration. Including exchange processes into the simulation of concentration processes drastically altered the evolution of the solution composition. In equilibrium with the irrigation water, the percentages of Ca, Mg and Na adsorbed at the CEC are 75, 23, and 1, respectively. Using a CEC equivalent to 20.00 mmol<sub>c</sub> per 100 g dry soil, the quantity of calcium released from the exchange complex upon concentration was so important, that the  $RA_{\text{calcite}}$  became negative, resulting in a sulfatic saline solution. Only when the CEC was reduced to the equivalent of 1.0 mmol<sub>c</sub> per 100 g dry soil, the alkalinity of the solution remained stable at high EC values (>2.0 dS/m) and was balanced by Ca, as observed in the field data. With increasing

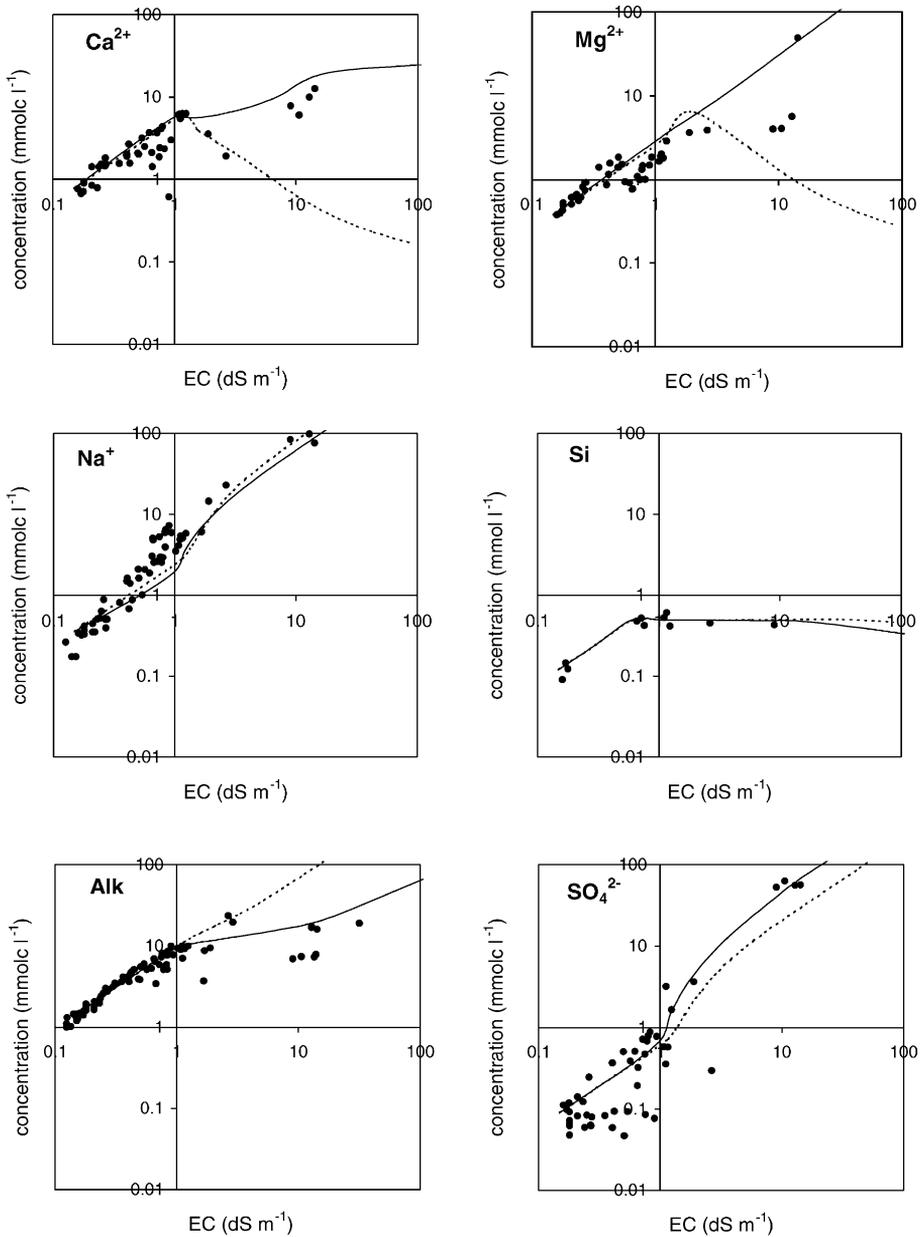


Fig. 6. Concentration diagrams showing field data (dots), simulated evolution of the irrigation water upon concentration (dotted line), and simulated evolution of the irrigation water upon concentration when exchange processes (CEC = 1.0 mmolc per 100 g dry soil) are included (solid line).

concentrations, the pH of the soil solution initially increases but then stabilizes around 7.5 (data not shown). Simulation exercises with slightly smaller (0.5 mmol<sub>c</sub> per 100 g dry soil) or higher (1.5 mmol<sub>c</sub> per 100 g dry soil) CEC values lead to completely opposite evolution of the solution composition, i.e. into a strong alkaline sodic solution and into a sulfatic saline solution, respectively.

## 4. Discussion

### 4.1. *The distribution and origin of soil salinity and alkalinity*

Highest topsoil pH and EC values were found on the highest positioned soils in the toposequence, which is in line with observations by van Asten et al. (2002) who found that topsoil pH and EC increased when moving from the river banks and lower slopes to the middle and upper slopes. However, pH and EC showed strong horizontal variation, which seems to suggest that salt distribution through horizontal groundwater movement is minimal. The groundwater samples showed a heterogeneous pattern similar to that of the soil EC and pH shown on the cross-section maps. Although all groundwater samples, except for piezometer 2, were classified as sodic-alkaline, the composition of the groundwater varied distinctly, suggesting differences in geochemical origin.

The soil texture analysis of the soil pit samples did not reveal any differences in the origin of the parent material. Indications on the origin of the parent material could be obtained from the quartz fragments observations. In PIT-1 and PIT-2, angular quartz fragments had accumulated in a horizon (stone line) that varied strongly in thickness, overlying the schist weathering front. BCEOM (1986) hypothesized that this stone line separated in situ soil material from colluvio-alluvial deposits. However, the angular shape of the fragments and the irregular thickness of the horizon leave us to believe that that the stone line is the result of accumulation of coarse fragments at the base of the bioturbated horizon; a classical phenomenon under more humid climate (Boulet et al., 1995). This implies that soils at the upper part of the toposequence have formed from in situ weathering of the schist parent rock. In combination with our assumption that salt distribution through horizontal groundwater flow is minimal, this suggests that (alkaline) salts in PIT-1 and PIT-2 originate from the parent rock. The presence of precipitated carbonate minerals in between the schist platelets and increasing salinity and alkalinity levels near the parent rock are in line with this hypothesis. The presence of carbonate minerals in the lower horizons is also reflected in the high exchangeable Ca values compared to the CEC. Overestimation of exchangeable cations is largely due to the dissolution of (Ca–Mg carbonate) salts when extracting with ammonium chloride. The similarities between PIT-1 and PIT-2 do not hold with respect to salinity and alkalinity levels. Both the soil analysis and the groundwater sample of piezometer 2 show high salinity levels near PIT-1, with sulfate as the major anion. The striking differences between PIT-1 and PIT-2 can only be explained by differences in the geochemical composition of the underlying parent rock. The presence of pyrite could be a possible explanation for the high sulfate concentrations and lower pH of the groundwater at piezometer 2. The north–south orientation (perpendicular to the slope) and the vertical

position of the schist parent rock provide the ideal conditions needed to obtain large geochemical heterogeneity at short distances.

The presence of rounded quartz fragments in PIT-3 at 0.6–1.95 m depth suggests that this soil partly has a colluvio–alluvial origin. Only at a depth of 2.15 m, some angular quartz fragments were observed. The alluvial origin of the upper horizons of PIT-3 is also reflected in its vertic properties. Although the Foum Gleita dam reduced peak floods, these soils are regularly flooded even after installation of the irrigation scheme. These floods allow for deposition and neo-formation of swelling clays, and the leaching of easily soluble salts from the upper horizons (0–1.3 m). The grayish-blue reduction colors at 2.15 m depth and the presence of abundant iron mottling below 0.6 m suggest that the groundwater level shows large annual fluctuations. We conclude that the accumulation of calcareous nodules (salts) at 1.3–2.0 m depth is related to the alluvial character of this soil and the alternating wetting–drying conditions (accumulation–precipitation) that result from occasional flooding and a fluctuating groundwater table.

#### 4.2. *The recent and potential evolution of alkalinity problems in Foum Gleita*

Although methods to measure EC and pH in 1970, 1977, 1985, 1993 and 1998 sometimes differed, soil salinity and pH levels have not significantly evolved over the last 30 years. This is in line with results of the detailed toposequence study, in that soil salinity/alkalinity problems originate from the parent rock and not from the irrigation water. No clear symptoms of secondary alkalization/salinization were observed, although pH values tend to slightly increase near irrigation and drainage canals. In combination with observations made by van Asten et al. (2002), the increasing productivity problems observed in Foum Gleita seem more the result of soil nutrient mining practices (i.e. non-application of phosphorus fertilizer) on soils that already had a low nutrient status, than the result of recent soil salinization/alkalinization.

Both soil and groundwater analyses showed that pH increased with salinity (EC) level. However, at high salinity levels, pH values tended to stabilize or even decrease, which is in contrast to normal alkalization processes, where pH values continue to increase. In the concentration diagrams (Fig. 6) alkalinity levels of water samples initially increased with EC, but eventually stabilized or decreased above EC values of 1–2 dS/m. Results of PHREEQC simulations using Foum Gleita irrigation water (dotted line in Fig. 6) showed that the Foum Gleita irrigation water evolves towards a strongly alkaline sodic solution when excessively concentrated. This type of concentrated solution eventually leads to physical and chemical soil degradation.

The geochemical composition of most groundwater samples that have an EC higher than 1–2 dS/m cannot be derived simply by concentrating of irrigation water, i.e.  $RA_{\text{calcite}}$  is not conservative, but decreases upon concentration. The detailed toposequence study revealed that the contrasting geochemical composition of groundwaters could well be due to differences in geochemical background. Release of  $\text{Ca}^{2+}$  from the cation exchange complex upon concentration can also (partly) explain the seemingly contrasting geochemical composition of groundwaters. PHREEQC simulation exercises including cation exchange processes yielded concentration diagrams that fitted well with field observations and that explain a decrease in  $RA_{\text{calcite}}$  with concentration. Calcium release from the

exchange complex upon increasing concentrations of the soil solution was so important that alkalinity could not further increase due to the precipitation of carbonate minerals. Including exchange processes did not improve simulation of  $\text{Mg}^{2+}$  concentrations due to the increased solubility of sepiolite that resulted from the lower pH (7.5). The simulation of Mg-silicate precipitation needs further study but is of limited relevance to the understanding of alkalization processes in Foum Gleita, as control of alkalinity by Mg is limited. The number of water samples with an EC > 1–2 dS/m is too limited to conclude with certainty that decreasing alkalinity at high salinity levels is due to exchange processes. However, the CEC value that yielded the best fit with  $\text{Ca}^{2+}$  and alkalinity concentrations observed in the field was very small (1.0 mmol<sub>c</sub> per 100 g dry soil). This suggests that the soil's cation exchange capacity contributes substantially to the buffering of alkalization processes. Nonetheless, the soil's buffering capacity might eventually run out and the evolution and rate of alkalization processes in Foum Gleita can only be determined with detailed studies on the soil's salt and water balance.

## 5. Conclusions

Topsoil salinity and alkalinity levels are highest on the shallow soils of the upper slope. Here, soils have formed in situ from the schist parent rock, which releases alkaline salts upon weathering. Soils in the lower part of the landscape have a (partly) colluvio–alluvial origin. The topsoil contains less salt due to regular flooding, which led, in combination with an alternating groundwater table, to the accumulation of carbonate minerals below the root zone (>1.3 m). The differences in the origin of the parent material, and the vertical position and north–south orientation of the schist parent rock, perpendicular to the sampled toposequence, led to large differences in the geochemical composition of the soil and groundwater at short distances. The salt distribution pattern did not show clear signs of horizontal groundwater flow, nor of secondary salinization due to irrigation activities. Soil salinity and alkalinity are inherited from the parent rock. A comparison of soil studies over the last 30 years showed no clear evolution of Foum Gleita's salinity and alkalinity levels.

Alkalinity and pH of groundwater samples decreased at higher salinity levels (EC >2 dS/m) on Foum Gleita's most saline soils, suggesting that their geochemical origin differs from the majority of the soils. Their composition could not be derived from concentration of the irrigation water only. Simulation exercises using the PHREEQC 2.0 geochemical model showed that most groundwaters in Foum Gleita are supersaturated with respect to Mg-calcite at  $p\text{CO}_2 = 10^{-1.8}$  atm. Concentration of Foum Gleita's irrigation water will lead to the precipitation of this mineral, resulting in a highly alkaline and sodic solution that eventually may lead to the formation of sodic-alkaline soils. Model simulations that incorporated soil exchange processes showed a drastically altered evolution of Foum Gleita's irrigation water upon concentration. The release of exchangeable Ca from a small (CEC = 1.0 mmol<sub>c</sub> per 100 g dry soil) but calcium dominated soil complex led to the control of alkalinity in the soil solution. Inclusion of exchange processes in the simulations resulted in a good fit with field data. Evolution of Mg concentrations could not be well modeled due to insufficient knowledge on the type of Mg-silicates that play a key role in Foum Gleita. We concluded that exchange processes have (partly) resulted in the

seemingly contrasting composition of Foug Gleita's most saline groundwaters. Moreover, the model simulations show that the soil's exchange complex forms an important buffer against alkalization processes. The comparison of model simulations with concentration diagrams of field measurements created a good insight into the potential for soil alkalization in Foug Gleita. However, quantitative studies on the water and salt balance at field level will be needed to determine development rate and equilibrium levels of soil salinity and alkalinity given soil types and current water management practices.

Our results are in line with other studies focusing on salt-related soil degradation in Sahelian irrigation schemes, in that no signs were found of secondary salinization or alkalization in irrigated rice fields.

## Acknowledgements

We would like to acknowledge Dr. S. Diatta (WARDA), Prof. S. Furian (USP), and N. Mall (WARDA) for assisting in the fieldwork and the development of hypotheses on the distribution and evolution of soil alkalinity in Foug Gleita. Furthermore, we would like to thank Dr. C. Hammecker (IRD) for assisting in the mineralogical aspects of this study.

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