Influence of land use change and water management on soil properties and water quality from combined geomodelling and geochemical modelling

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Abstract

Multisecular land use change and difficulties in water management lead to changes in soil properties, but the slow kinetics, the spatio-temporal variability of soils, land use and water quality makes these changes difficult to decipher. The method used here combines geomodelling (gOcad geomodel) and geochemical modelling (PHREEQC) to integrate multiple sources of information. The gOcad geomodel has long been recognized as an appropriate tool to reconstruction of 3D architectures in fundamental geology and geology engineering for minerals and oil prospection. It is used here to interpolate soil data, land use data and outputs of the geochemical model. The groundwater quality is the input of PHREEQC geochemical model. The output of the geochemical model is the saturation index (SI) of water with respect to calcite. By using classical data such as soil, hydrogeological and land use maps (Figures 1, 2), soil profiles, piezometric water analyses in time and combining the tools gOcad and PHREEQC (Figure 3) on a demonstration area in the Crau's plain, it is shown that: i) multisecular irrigation modifies soil properties by a recarbonatation process which counterbalances the general geochemical tendency towards decarbonatation; this results in the presence of active limestone in the topsoil; ii) water shortage for irrigation during dry years results in smaller SI (smaller oversaturation or slight undersaturation) in grasslands, and larger SI in land used for orchards, where groundwater was used for irrigation; iii) the presence in the subsoil of a "poudingue" of pedogenetic origin (pebbles cemented by a calcrete), thick, but fractured and discontinuous, does not prevent the land use to impact directly the water quality of the underground water.

Key Words

Soil, water, geomodelling, geochemistry, land use

Introduction

Land use change driven by demographic pressure and urbanization lead to change in soil properties. Climate change may result in larger interannual variations of temperature and rainfall, and shortage in water supply for irrigation. Soil and water resources are needed for food production, water supply and their degradation can impair the possibilities of cities to generate wealth and the economic resources for financing local development and managing public resources. Degradation of soils and waters thus impair the capacity of cities to develop and satisfy the needs of populations who live in. Data on soils, land use and water quality are generally available but dispersed, heterogeneous and incomplete. The aim of this paper is to show the interest to combine the geomodeller gOcad (Mallet 2002; Bile *et al.*2009) and the geochemical model PHREEQC (Parkhurst and Appelo 1999) to integrate multiple sources of information on the soil, land use and groundwater quality. More specifically, in many regions such as Mediterranean, soils have been irrigated since several centuries, and land use and soil properties are well known. This is the case of Crau's plain: this region is pedologically homogeneous, and one of the few remaining steppes of Europe, and soil and water resources are threatened by urban spreading, land use change and climate change. Parts of it have been irrigated since the XVIth century, with water from an alpine river that brings carbonate to the soil system, while other parts remained in the original land use (nomadism, sheep breeding). All region has been subjected to recent climate change and drought, so this study tries to assess both the influence of land use changes and water management on soil and groundwater quality, through the consideration of calcium carbonate geochemistry, which affects soil pH, soil buffer capacity, soil biota and hence all biogeochemical cycles.

Methods

Demonstration area, pedological and hydrogeological context

The Crau's plain results from the continental deposits of the Durance river before its stream way changed during the Alpille's mountains orogenesis and its capture by the Rhone river about 12,000 yrs BP. Crau in provençal language defines a field covered by stones. Today only 10,000 ha of this original steppe remain in the centre of the plain, named “dry Crau” (Figure 1, 2). In the North, the “wet Crau” or “green Crau” is characterized by grassland irrigated since the XVIth century. The pebbles of Durance come from the Alps and are either of limestone or of siliceous nature, accumulated on large thickness, and are cemented by pedogenic precipitation of calcite (calcrete locally named “taparas”) between 40 and 60 cm depth, forming the “poudingue” horizon. The upper horizons of soil were decarbonated during the warmer and more humid period that succeeded to the Last Glaciation Maximum (18,000 yrs BP). The deposits moved progressively from the NW to the SE before the capture of Durance, hence the age of the parent material changes but not its nature (Figure 1). Soils are red fersiallitic soils in all the Crau’s plain. The thickness of the “poudingue” ranges from some meters on the upland zones to 50 m in the old stream ways of Durance river with a small slope oriented NE-SW. The Crau’s plain has a large underground water table, which flows from the NE to E and from NE to SW. There is no more direct connection between the groundwater and the Durance river, but water pumped upstream in the Durance river constitute 70% of the input of this water table via the agricultural irrigation. In the North, from E to W, grasslands predominate. In the SW of the area, the groundwater itself is used for irrigation of orchards. Just out of the limits of the groundwater (Figure 1, blue), in the South, there are natural wetlands and rice crops irrigated with water from the Rhône river. This Crau’s plain of 20,000 ha supplies drinking water to 250,000 inhabitants and water to the large industries located in the south of the territory. This area is submitted to diverse pressures, all in relationship with the spreading of the cities: (i) urban and industrial pressures concentrated in the South in relationship with the Fos industrial zone; (ii) spreading of urbanization from the districts of Saint-Martin de Crau, Miramas, Salon-de-Provence and Arles; (iii) increase of pressures on the underground water table: uptake, urban sludge spreading, diffuse pollution; (iv) increase of greenhouse fruit production.

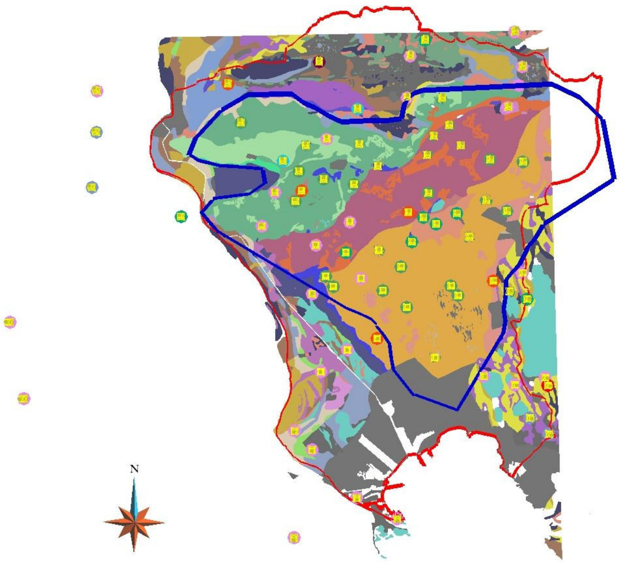

Figure 1. Soil map, soil profiles (points), underground water table limits (in blue) and limits of the study area (in red).

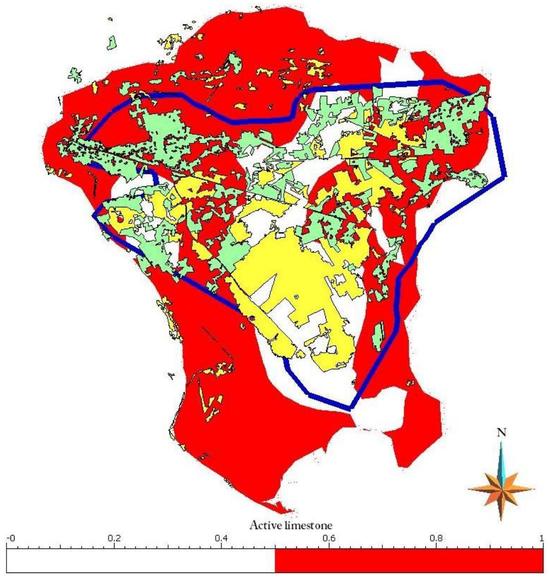

Figure 2. Land use: irrigated grassland, (in green), steppe (in yellow), soil containing active limestone (in red), or without active limestone (white).

Methods

Soil and parent material heterogeneities in these conditions have been mainly taken into account via Geographical Information Systems (GIS). But the main problem is that GIS split information in different strata, and natural objects, either soils or geological formations disappear. A priori knowledge on the objects, and different constraints, either as geometrical or physical, cannot be introduced in GIS. Geological Object Computed Aided Design (gOcad) instead is a geomodeller, designed for petroleum and mining applications in Nancy, on the basis of Discrete Smooth Interpolation by Mallet (2002). Constraints due to the nature of geological objects, such as a sedimentary basin, strata, faults, folds, ores etc. can be incorporated in the model. Soil data were obtained from the soil map (Bouteyre and Duclos 1994) considering not only limits of soil units but the exact location of soil profiles, succession of horizons and soil analyses (Figure 1). Among these latter, active limestone analysed in the upper two horizons was selected. It was transformed into a Boolean variable, as the presence or absence of active limestone is more important from a geochemical point of view than the content of active limestone: its presence indicates that irrigation water or rain water will rapidly react with calcium carbonate, irrespective of its content, before reaching the subsoil and groundwater.

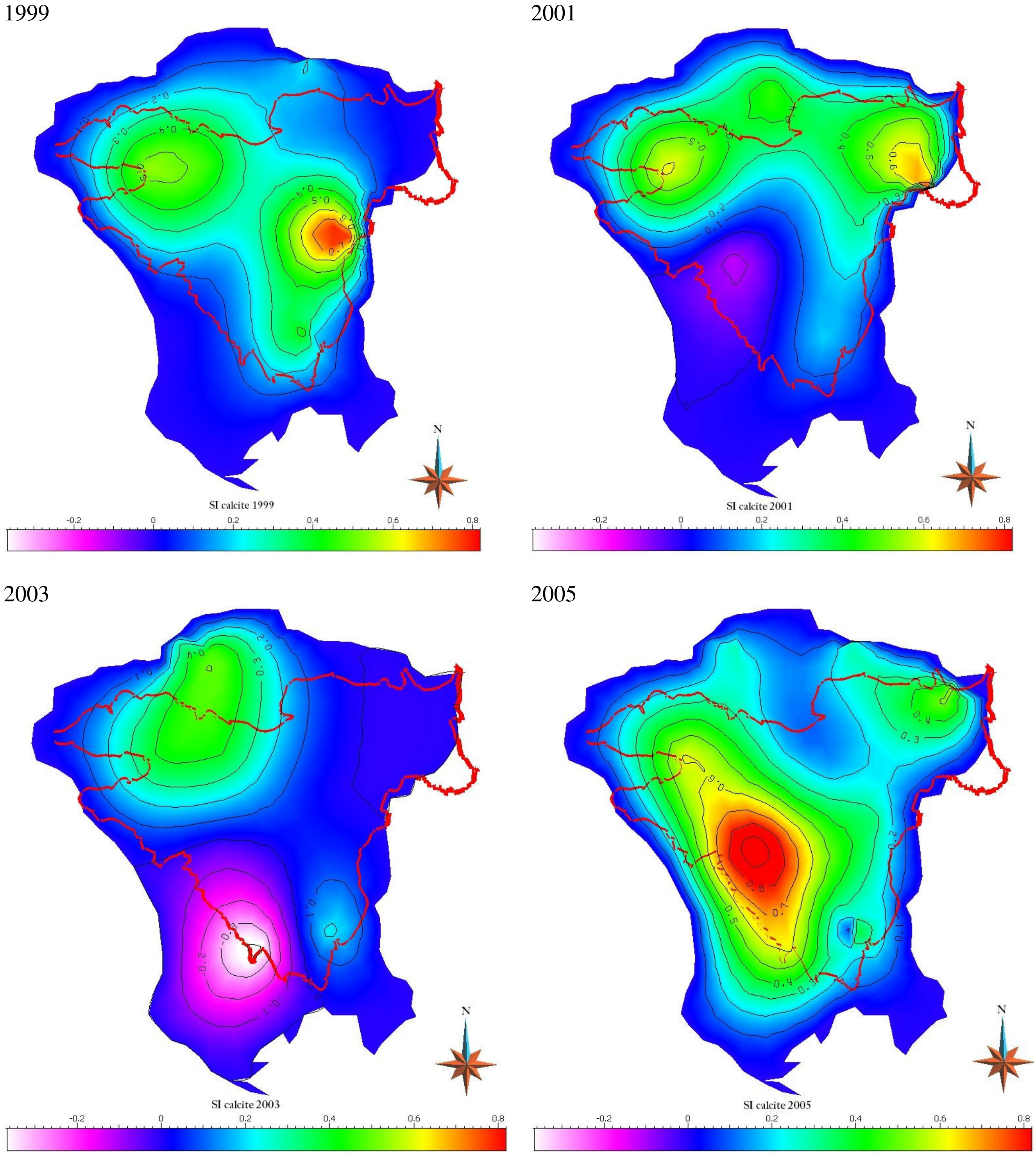

Figure 3. Computation by PHREEQC of the Saturation Index of calcite in underground water and spatial representation with gOcad at different dates.

Active limestone presence was spatialised using gOcad (Figure 2). Land use was obtained from the regional database of the Centre Régional de l'information géographique (CRIGE) and superimposed on active limestone in gOcad.. Water quality of the groundwater table was derived from the database Ades ("Analyse des eaux souterraines") of BRGM. This database gathers analyses of groundwater from 50 – 70 piezometers. The data were selected at the autumnal season, which is at the end of summer, the period when both concentration of water by evaporation is the largest and when irrigation stops. The contrast is then maximum between irrigated areas and "natural" steppic areas at this time. Rainfall and irrigation resources were normal in 1999 and 2001, while in 2003 and 2005 there were severe shortages of water supply due to unfavourable climatic conditions (warm temperature, low rainfall both locally and in the Alps), that generated social conflicts for water. Concentrations of inorganic elements, pH, alkalinity, temperature of aqueous solutions obtained from this database were used as inputs for geochemical modelling using PHREEQC (Parkhurst and

Appelo 1999). PHREEQC model was chosen because the calcium carbonate system was particularly refined in this model, both for thermodynamic modelling and kinetics. Saturation indexes (SI) with respect to calcite were thus locally obtained, providing for activity coefficients, ion pair formation and temperature dependence of equilibrium constants and of the solubility product of calcite. Due to the low ionic strength of solutions, Debye-Hückel extended law was used and not Pitzer equations. These data cannot be directly compared at different times and locations, as the database is not complete, but SI computed by PHREEQC were used as inputs to gOcad to obtain a spatial interpolation of SI that can then be used to evaluate the variations of SI with time and space (Figure 3).

Results and Discussion

Comparison of land use (Figure 2) and SI for calcite (Figure 3) shows that in “normal years” (1999 and 2001), irrigated areas are spatially correlated with large oversaturations of groundwater with respect to calcite, while the original non irrigated area corresponds to slight oversaturation or undersaturation with respect to calcite. This is consistent with the prevailing present geochemical conditions in the North Mediterranean: calcite tends to dissolve. The input of irrigation water from the Durance, whose basin is rich in limestones, and its concentration by evapotranspiration counterbalances this natural tendency and tends to favour calcium carbonate precipitation in the topsoil. This is confirmed independently by the spatial correlation between irrigated areas in the North of the study area and the presence of active limestone (Figure 2) and is in agreement with field observations by Duclos (Bouteyre and Duclos 1994) concluding to the “recarbonatation” of topsoil in irrigated soils. In years when water shortage was such that irrigation was stopped during the summer (2003 and at a lesser degree 2005), SI for calcite are smaller in the North. In 2003, just outside the study area, very small SI correspond to input of irrigation water from the Rhône river for rice crop. In 2005, the large SI in the SW of the study area corresponds to irrigation of orchards by pumping in the groundwater: when shortage of irrigation water from the Durance river occurs, farmers can afford to let grassland suffer, but not orchards.

Conclusion

Combining geomodelling and geochemical model is a powerful tool to integrate soil, land use and geochemical data, and to discuss spatio-temporal correlations. In temperate oceanic climate, there exists a general geochemical tendency towards calcium carbonate dissolution, calcium desaturation of the exchange complex and acidification. In Mediterranean climate, this tendency is smaller, but still exists if evaporation of waters with a positive alkalinity does not compensate it. This is the case in the North of Mediterranean. In the study area, multisecular irrigation with water from the Durance river has counterbalanced this tendency, which explains the presence of active limestone in the topsoil. This of course affects soil pH, buffer capacity, soil biota and all biogeochemical cycles. Another result of this study is that land use, via irrigation, and climatic variations (water shortage) directly affect the geochemistry of subjacent groundwater, despite the presence of a calcrete, which does not constitute a continuous geochemical barrier. This can be ascribed to the fracturation of this calcrete, which is a result of active tectonics in the region.

Acknowledgments

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