Agricultural Water Management 97 (2010) 1423–1433

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Quality of groundwater for irrigation in tropical karst environment: The case of Yucatán, Mexico

C. Delgado[a], J. Pacheco[b], A. Cabrera[b], E. Batllori[c], R. Orellana[a], F. Bautista[d,*]

[a] Unidad de Recursos Naturales, Centro de Investigación Científica de Yucatán (CICY), Calle 43, No. 130 Colonia Chuburná de Hidalgo, C.P. 97200 Mérida, Yucatán, Mexico
[b] Departamento de Ingeniería Ambiental, Facultad de Ingeniería, Universidad Autónoma de Yucatán (UADY), Av. Industrias no contaminantes por Anillo Periférico Norte S/N, Apdo. Postal 150 Cordemex, Mérida, Yucatán, Mexico
[c] Departamento de Ecología Humana, Centro de Investigación y Estudios Avanzados (CINVESTAV), Unidad Mérida, Carretera antigua a Progreso km. 6, Apdo Postal 73 Cordemex, C.P. 97310 Mérida, Yucatán Mexico
[d] Centro de Investigación en Geografía Ambiental, Universidad Nacional Autónoma de Mexico, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex-Hacienda de San José de La Huerta, C.P. 58190 Morelia, Michoacán, Mexico

ARTICLE INFO

Article history:
Received 12 June 2009
Accepted 13 April 2010
Available online 18 May 2010

Keywords:
Karstic aquifer
Salinity
Sodium content
Geostatistics
Kriging
Semivariogram

ABSTRACT

The Yucatán Peninsula has the largest reserve of water in Mexico. It is generally believed that groundwater is of good quality although its agricultural quality has been scarcely studied. The aims of this study were to identify and characterize zones with distinctive groundwater qualities for agricultural use in Yucatán. Water samples were collected at 113 supply wells. The concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, NO_3^{-}, Cl^{-} and the electric conductivity (EC) were determined. Sodium adsorption ratio (SAR), potential salinity (PS) and effective salinity (ES) were also calculated. A geostatistical analysis by kriging interpolation was performed. ES, PS and SAR as well as Na^{+}, EC, Cl^{-}, SO_4^{2-}, and Ca^{2+} were selected to make maps, in accordance with the values of semivariogram and values of cross-validation. The map of the ES was taken as the base to make the map of zones of agricultural quality groundwater. The quality of karstic groundwater in the state of Yucatán cannot be recommended for agriculture in Zones I (EC and ES), II (EC, Chlorides, PS and ES) and III (EC, sulfates and ES); in Zones IV and V the water is of medium quality and in the Zone VI, water is considered good for agricultural use. This information will be relevant in decision-making for government's agricultural and environmental planning.

1. Introduction

In regions with karstic landscapes, such as the Yucatán Peninsula (Mexico), bodies of surface water and streams are scarce or absent. For this reason, groundwater is the main source for human consumption as well as for industrial and agricultural activities (Doehring and Butler, 1974; Escolero et al., 2000, 2002; Perry et al., 2002). In Yucatán, slash-and-burn agriculture is the predominant farming technique but modern agriculture (using chemical fertilizers and pesticides) is beginning to be developed in the south, weast and the east of Yucatán and will require water for irrigation, specially in areas where rain is falling for less than 4 months or where very long drought periods occur (FAO, 1996).

Yucatán exhibits considerable spatial heterogeneity in soil groups of which Leptosol and Cambisol dominate the landscape. These are very shallow soils with low regeneration capabilities in response to human activities (Bautista et al., 2003, 2005). An important synergy has been observed between water quality, soil heterogeneity and human intervention in agricultural areas. Karstic areas in Yucatán are very permeable and are thus highly susceptible to aquifer contamination (Doehring and Butler, 1974; Marín and Perry, 1994; Pacheco and Cabrera, 1996; Pacheco et al., 2000; Escolero et al., 2002). Since deforestation and overgrazing are the main factors causing land degradation (Bot et al., 2000), agricultural management of soils and water becomes essential to achieve a more effective conservation of natural resources and thus of the entire managed system.

In the state of Yucatán, several studies have been conducted to evaluate groundwater quality, examples of which are: research from a hydrogeological standpoint (Perry et al., 2002; Marín et al., 2004); human health hazards related to nitrate concentration, fecal and total bacterial content (Pacheco et al., 2000; Escolero et al., 2002); flux direction, water permeability, hazards of saline intrusion from the sea (Marín and Perry, 1994; Marín, 1995; Steinich and Marín, 1997; Escolero et al., 2000, 2002); and contamination due to municipal, industrial and agricultural residues (Pacheco and Cabrera, 1996; Marín et al., 2000). However, studies focused on the distribution of groundwater quality from an agricultural perspective are scarce. Furthermore, spatial analyses of these resources have not yet been conducted although this could

* Corresponding author. Tel.: +52 443 3223869; fax: +52 443 3223880.
E-mail address: leptosol@ciga.unam.mx (F. Bautista).

0378-3774/$ – see front matter. © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2010.04.006

lead to a better use of water and to a decrease of soil degradation hazard.

The characteristics of the rocks in contact with groundwater are of great interest for the spatial analysis of groundwater quality because they greatly influence the quality of the aquifer. However, the available maps of geology and lithology of Yucatán do not have sufficient resolution for some types of analysis (Isphording, 1975). It is necessary to develop maps with higher resolution for planning agricultural projects. On the other hand, geostatistics is a methodological tool that allows for the analysis and prediction of continuous variables that are distributed in space and time (Isaaks and Srivastava, 1989; Webster and Oliver, 1990). Such an approach could substitute or compensate for the lack of resolution in the current maps (Burrough, 2001) thus making possible the spatial analysis of groundwater quality.

In order to foresee and achieve the modernization process of agricultural activities in the state of Yucatán, which would necessarily involve an irrigation alternative, it is essential to evaluate the current state of water quality (Richards, 1954; Palacios and Aceves, 1970; Ayers and Wescott, 1994). Seasonal agriculture is characterized by a very low productivity and in several regions it barely provides enough produce for subsistence. The evaluation of water quality is a fundamental requirement for implementation of rural developments projects at state level (some of which are already being developed). The present study considers chemical parameters related to variations in water salinity and hardness because both conditions are important limiting factors for commonly grown crops in the region, such as maize, beans, grasslands, fruit trees (mainly citruses) and other produce for human consumption.

The main purpose is to identify and characterize zones in the state of Yucatán by distinctive groundwater qualities as regards agricultural use, based on the geostatistical validation of agricultural parameters.

2. Materials and methods

2.1. Area of study

The state of Yucatán is located in the north of the Yucatán Peninsula, southeast Mexico. Yucatán is bordered by the state of Campeche and the Gulf of Mexico to the southwest, by the Yucatán channel to the north, and by the state of Quintana Roo to the east. The geological formations in the state of Yucatán are made up of Tertiary limestones, which are sequentially distributed from earlier in the north (Pliocene-Miocene) to older in the south (Eocene) (Fig. 1). The main soil groups in the southern part of the state of Yucatán are Cambisol, Luvisol, Vertisol and Leptosol, overlaid by sediments of the Pliocene epoch that constitute karstic plains and hills, made mainly of Cambisols and Leptosols. The coastal zone is made up of plains of sediments from the Quaternary period, mainly consisting of Arenosols, Solonchaks, Gleysols and Histosols (from the Pleistocene and Holocene epochs) (Lugo and García, 1999; Bautista et al., 2007).

Yucatán is characterized by a “warm” to “very warm” climate, and there is a gradient of average annual precipitation ranging from 200–400 mm in the northwest to 1000–1200 mm in the southeast (Bautista et al., 2009; SEDUMA, 2010) (Fig. 2). The climate in Yucatán, based on Köppen’s classification, as modified by García (2004), has the following subtypes: BS$_0$wh, the driest of the semi-arid climates with summer rains; BS$_1$x′(w)h, the least dry of the warm semi-arid climates, without a definite rainy season (irregular); Aw$_0$, the driest of the subhumid, warm and very warm climates with summer rains; and Aw$_1$, with an intermediate humidity among the warm subhumid climates with summer

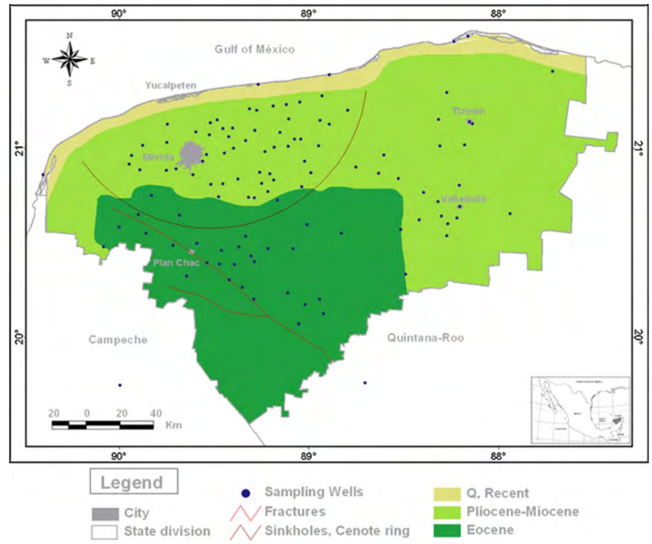

Fig. 1. Geology of Yucatán and geographical location of the sampling wells.

rains (Orellana et al., 2009). The climate of the region is important because the water supply of the aquifer comes from rainfall, however, the main aquifer recharges enter from the wettest zones in the southern part of the Yucatán Peninsula, with over 1200 mm of annual precipitation (South of Yucatán, Campeche and Quintana Roo). The distribution of the vegetation is a consequence of the climatic zones and of the rainfall regime. The types of vegetation present in Yucatán are: coastal dune scrub, mangrove swamp, thorn forest, deciduous seasonal forest (most common type), savannah, semi-evergreen seasonal forest and, in a small extension, evergreen seasonal forest.

2.2. Chemical analyses

One hundred and thirteen water samples were collected at supply wells with the sampling depth at 20 m below the water table. Each sample point corresponds to a municipality in the state of Yucatán (Fig. 1). Samplings took place between July and November of 2003. Before each groundwater sample collection, one 1 L and two 250 mL new polyethylene sampling bottles were rinsed with distilled water. A global positioning system receiver (GPS) was used

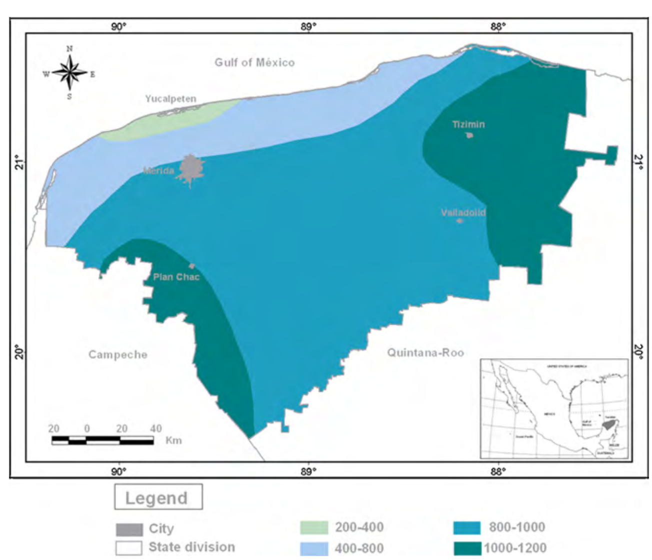

Fig. 2. Rainfall (mm) distribution over Yucatán.