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Three dimensional simulation of seawater intrusion in coastal aquifers: A case study in the Goksu Deltaic Plain

Murat Cobaner [a,b,*], Recep Yurtal [c], Ahmet Dogan [d], Louis H. Motz [e]

[a] Erciyes University, Civil Engineering Department, Kayseri 38039, Turkey
[b] Erciyes University, Tomarza Vocational High School, Kayseri 38039, Turkey
[c] Cukurova University, Civil Engineering Department, Adana 01330, Turkey
[d] Yıldız Technical University, Civil Engineering Department, İstanbul 34240, Turkey
[e] University of Florida, Civil and Coastal Engineering Department, Gainesville, FL 32611, USA

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SUMMARY

Unplanned exploitation of groundwater from coastal aquifers may cause salt water intrusion in coastal aquifers. Coastal areas are generally overpopulated with fertile agricultural lands and diversified irrigated farming activities. The objective of this study was to develop a model to control/prevent seawater intrusion into the coastal aquifer with a case study of the Silifke–Goksu Deltaic Plain. A computer program for the simulation of three-dimensional variable density groundwater flow, SEAWAT, is used to model the seawater intrusion mechanism of the Goksu Deltaic Plain along the Mediterranean coast of Turkey. The calibration analysis of the developed seawater intrusion model is performed using field measured data in the water-year of 2008 including static groundwater head, electrical conductivity, total dissolved solid (TDS), and chloride concentration values collected from 23 observation wells and the existing data which were compiled and reviewed. The main objectives for applying the seawater intrusion model to the Goksu Deltaic Plain were (1) to determine the hydraulic and hydrogeologic parameters of the aquifer, (2) to estimate the spatial variation of the salt concentration in the aquifer and (3) to investigate the impact of the increase and decrease in groundwater extractions. The simulation results show that the Goksu Deltaic Plain aquifer is especially sensitive to the increase in groundwater extraction.

1. Introduction

During the last few decades, one-third of the world's freshwater demand has been provided from groundwater (Bear et al., 1999). However, excessive groundwater extraction may lead to freshwater scarcity, saltwater intrusion into coastal aquifers, and hence excessive salinity. Therefore, it is important that groundwater resources in coastal aquifers have their own management strategies. Groundwater simulation models for coastal aquifers are useful for understanding the behavior of the aquifer system.

The first quantitative approach to determine saltwater depth in coastal aquifers was developed independently by Badon Ghijben (1888) and Herzberg (1901). They introduced the sharp interface model known as the Ghyben–Herzberg relationship which is based on the hydrostatic balance between fresh and saline water in a U-shaped tube. They showed that the depth of the fresh water–seawater interface below mean sea level is expressed as

$$z = \left[\frac{\rho_f}{\rho_s - \rho_f}\right] h_f \tag{1}$$

where ρ_f and ρ_s are the density of fresh (1000 kg m^{-3}) and sea water (1025 kg m^{-3}), respectively, h_f is the elevation of fresh groundwater level above mean sea level. Thus, the depth of the fresh–seawater interface below mean sea level (z) is 40 times the elevation of the water table above sea level (h_f) (Reilly and Goodman, 1985). This formula was the only means available to quantitatively estimate the position of the interface. Generally, two different modeling approaches have been used in the literature to represent the freshwater–saltwater relationship, one of which is sharp interface approximation (Mercer et al., 1980; Polo and Ramis, 1983; Essaid, 1990) and the other approach is the transition zone between freshwater and seawater (Huyakorn et al., 1987; Das and Datta, 1995; Putti and Paniconi, 1995; Guo and Langevin, 2002). Reilly and Goodman (1985) provided a historical perspective of quantitative analysis of the freshwater and seawater relationship in coastal aquifers. Kohout (1960, 1964) studied coastal ground-water flow by installing numerous monitoring wells along a transect perpendicular to the coast in the Cutler Ridge area (near Miami) of southeastern Florida. He used chloride concentration as a proxy for salinity

* Corresponding author at: Erciyes University, Civil Engineering Department, Kayseri 38039, Turkey. Tel.: +90 352 2076666x32329.
E-mail address: mcobaner@erciyes.edu.tr (M. Cobaner).

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and fluid density. A cross section showing lines of equal chloride concentration for September 18, 1958, indicates that a tongue of relatively dense, saline ground water extended inland from the coast at the base of the Biscayne aquifer (Fig. 1). The cross section also indicates no apparent sharp interface between fresh and saline ground water; instead, the saltwater interface was a broad transition zone (Langevin, 2001).

During the last decades, these two approaches have been used for simulations of flow and seawater intrusion. Simulation models were developed with finite elements or finite difference techniques (Huyakorn et al., 1987; Guo and Langevin, 2002). Gorelick (1983), Hallaji and Yazicigil (1996), Essink (2001), Paniconi et al. (2001), Lu (2003), Rao et al. (2004), Qahman and Larabi (2006), Bhattacharjya et al. (2007), Giambastiani et al. (2007), Narayan et al. (2007), Shammas and Jacks (2007), and Rejani et al. (2009), among others, developed a number of such groundwater management models by using different simulation models like FEMWATER (Lin et al., 1997), SUTRA (Voss, 1984), SEAWAT (Guo and Langevin, 2002), MOCDENS-3D (Sanford and Konikow, 1985), MODFLOW (Mcdonald and Harbaugh, 1988), and MT3DMS (Zheng and Wang, 1998), etc. The SEAWAT code has been successfully used for simulating various types of variable-density fluid flow through complex geometries and geological settings, including seawater intrusion into coastal aquifers, submarine groundwater discharge, brine transport, and groundwater flow near salt domes. It has been tested in many common variable-density benchmark problems, such as the Henry (1964), Elder (1967), HYDROCOIN (OECD, 1988), and salt lake problems (Guo and Langevin, 2002; Langevin et al., 2003; Bakker et al., 2004). The applications of the SEAWAT code are described in Bakker et al. (2004), Bauer et al. (2006), Dausman and Langevin (2005), Langevin (2003), Langevin et al. (2005), Schneider and Kruse (2006), and Lin et al. (2009).

Cobaner et al. (2011) evaluate the spatial changes of EC (dS/m), TDS (mg/L) and Cl (mg/L) parameters observed in 23 irrigation and observation wells, located in Göksu plain, by applying Geostatistical methods. Based on the field observations in July, 2002, the EC, TDS, and Cl^- concentrations varied between 0.62 and 4.84 dS/cm, 436 and 3065 mg TDS/L, and 35.5 and 1241.1 mg Cl^-/L, respectively. They have reported that the use of groundwater at the 40% of the study area is inconvenient. The sustainability of agricultural production is under threat by the increase of EC, TDS and Cl parameters.

In this study, the groundwater quality subjected to saltwater intrusion in the region is evaluated based on irrigation water classifications indicated in the Water Pollution Control Regulations (WPCR) (1991). The results obtained from the model are plotted and Table 7 is prepared to interpret the irrigation water qualities. Those interpretations based EC and TDS parameters, 60% of agricultural areas can be irrigated with usable groundwater, 30% of the area can be irrigated with class 4 (less quality irrigation water) water with some precautions. When chloride concentrations are based on the interpretations, it is seen that 23% of the farmland has unusable class-5 (not usable–harmful) groundwater. At the same time 18.9% of the farmland is at the critical zone in terms of chloride based on quality assessment. Using these lower and/or bad quality water in irrigation may endanger the sustainability of agriculture in the study area (Cobaner et al., 2011).

The purpose of this study was to investigate the current condition of salinization by examining seawater intrusion in the Goksu Deltaic Plain, to determine the hydraulic and hydrogeologic parameters of the aquifer, and to investigate the effects fluctuations in pumping quantity have on seawater intrusion by applying the SEAWAT code which is based on density-dependent groundwater flow. The calibration analysis of the developed seawater intrusion model is performed using actual data measured in the field which included static groundwater head, electrical conductivity, total dissolved solid and the chloride concentration values of 23 observation wells taken in the water-year of 2008.

2. Site description

The study area is located near the coast of the Mediterranean Sea to the south of Silifke in south-central Turkey (Fig. 2). The delta covers an area of approximately 22,631 hectares (ha) and is surrounded by the Mediterranean Sea in the south and east and the outcrops of limestone bedrock that form the Taurus Mountains farther inland in the northwest and north. The delta is a highly fertile agricultural land that supports the growing of more than twenty types of crops (Association for Organic Agricultural Movements – ETO, 1997). The delta includes two major lakes, freshwater and brackish marshes, and sandy beaches. The lakes, Akgol and Paradeniz, attract more than 332 different species of migratory and breeding birds and are now internationally recognized as two of

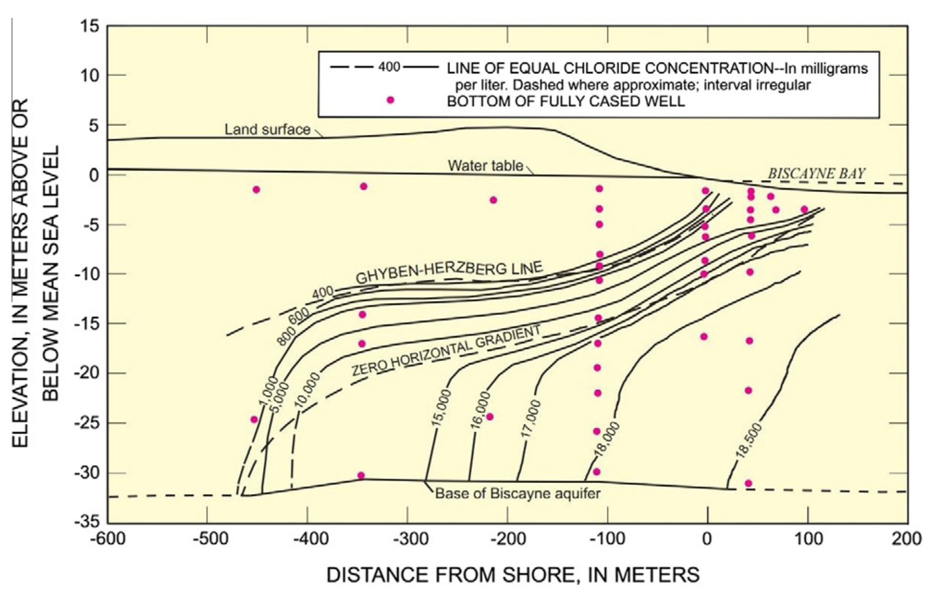

Fig. 1. Lines of equal chloride concentration for the Cutler Ridge area, September 18, 1958 (Fig. 8B in Langevin (2001); modified from Kohout (1964)).