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Seawater intrusion mapping using electrical resistivity tomography and hydrochemical data. An application in the coastal area of eastern Thermaikos Gulf, Greece

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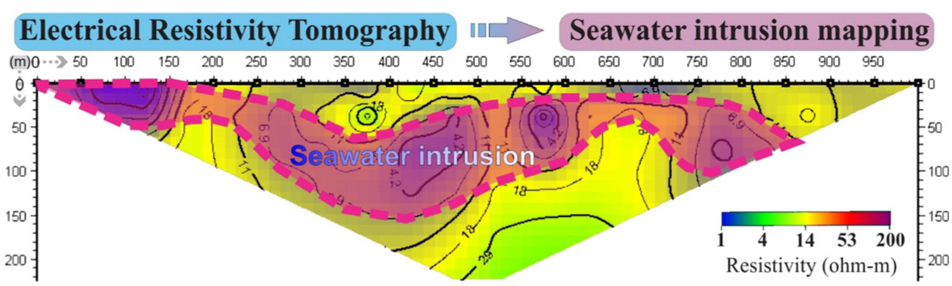
HIGHLIGHTS

- ERTs determined the geometrical characteristics of the saline aquifer.
- An abnormal distribution of seawater intrusion was recorded.
- Four ionic ratios overlapped and a seawater intrusion map was produced.
- Cl^- concentrations increased significantly from 2005 to 2010 by up to 1800 mg/L.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study was to determine the extent and geometrical characteristics of seawater intrusion in the coastal aquifer of the eastern Thermaikos Gulf, Greece. Hydrochemical data and geoelectrical measurements were combined and supplemented to determine the hydrochemical regime of the study site in regard to seawater phenomena. Chemical analysis of groundwater was performed in 126 boreholes and fifteen electrical resistivity tomographies (ERT) were measured, whereas in two sites the ERT measurements were repeated following the wet season. The Cl^- concentrations recorded reached 2240 mg/L indicating seawater intrusion which was also verified by ionic ratios. The ionic ratios were overlapped and a seawater intrusion map (SWIM) was produced. A significant part of the coastal aquifer (up to 150 km^2) is influenced by seawater intrusion. The areas with the most intensive salinization are located between Nea Kallikratia–Epanomi and Aggelochori–Peraia. According to the ERTs, in the influenced areas the salinization of the aquifer exceeds 1 km toward the mainland and its depth reaches 200 m. In the area surrounding Thessaloniki airport, the ERTs revealed salinization of the upper aquifer to depths of up to 40 m, whereas the lower aquifer is uninfluenced. This abnormal distribution of seawater intrusion demonstrates the value of geoelectrical methods in the study of seawater intrusion especially in areas with limited available hydrochemical data.

1. Introduction

Coastal aquifers are the primary source of drinking water for up to one billion people worldwide (Small and Nicholls, 2003) while the needs of freshwater in coastal regions are constantly growing due to

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the increasing global population (Singh, 2014). Seawater intrusion constitutes the main environmental problem facing coastal aquifers worldwide (Don et al., 2006; Trabelsi et al., 2007; Sherif et al., 2012). The mixing of saltwater with freshwater, even in small quantities, renders groundwater unsuitable for domestic, agricultural and industrial use (Abd-Elhamid and Javadi, 2011). The extension of seawater intrusion into coastal aquifers is a dynamic and interconnected phenomenon that depends on various factors such as recharge, coastal topography and groundwater abstraction from coastal aquifers (Oude Essink et al., 2010; Ferguson and Gleeson, 2012). The indiscriminate and unplanned exploitation of groundwater from coastal aquifers is the primary cause of coastal aquifer salinization (Sreekanth and Datta, 2010). In addition, global sea level rise, as a result of climate warming, also contributes to seawater intrusion and therefore, the salinization of coastal aquifers (White et al., 2005; Sanford and Pope, 2010). The prevention and/or restriction of coastal aquifer salinization demands appropriate management plans that designate maximum feasible pumping rates and optimum well allocation (Katsifarakis and Petala, 2006; Singh, 2014). Management models have been widely used for pumping optimization so as to minimize pumped water, pumping cost and movement of seawater volume into aquifers (Finney et al., 1992; Emch and Yeh, 1998; Das and Datta, 1999). However, applying a management plan to coastal aquifers prerequisites understanding of the origin and distribution of saline waters (Post, 2005). Salinity measurements in wells and hydrological modeling are efficient methods for the study of seawater intrusion (Melloul and Zeitoun, 1999). Additionally, seawater intrusion has been evaluated in coastal areas using ionic ratios of groundwater (Sánchez-Martos et al., 2002; El Moujabber et al., 2006).

Vertical electrical sounding (VES) and electrical resistivity tomography (ERT) have been used to map saline zones of aquifers and delineate fresh-saline interfaces (Batayneh, 2006; Mario et al., 2011). However, according to recent studies the combination of hydrochemical data and geoelectrical methods is more efficient at mapping an aquifer's saline zones (Anil Kumar et al., 2015; Galazoulas et al., 2015). ERT can provide a vertical two-dimensional (2-D) image of an aquifer's saline zones due to its inherent ability to detect formation resistivity variations based on pore water salinity (Abdul Nassir et al., 2000; Wilson et al., 2005; Bighash and Murgulet, 2015). Consequently, this method illustrates the seawater–groundwater interface (Francés et al., 2015). The method has been used worldwide in many coastal aquifers, coastal deltaic deposits and inland saline environments. ERT was applied by Morrow et al. (2010) and Ebraheem et al. (2012) to study seawater intrusion in coastal aquifers of Kapiti Coast, New Zealand, and Wadi Al Bih, UAE, respectively. Coastal deltaic deposits were studied by Martínez et al. (2009) and Gurunadha Rao et al. (2011) in Vélez-Málaga (southern Spain) and Godavari Delta Basin (India), respectively. Additionally, inland saline environments such as the Jordan aquifer in the Dead Sea (Batayneh, 2006) and the Okavango Delta in Botswana (southwestern Africa) (Bauer et al., 2006) have been studied using ERT.

In this study, the ERT method was used in conjunction with hydrochemical data to determine the extent and geometrical characteristics of seawater intrusion in the coastal aquifer of the eastern

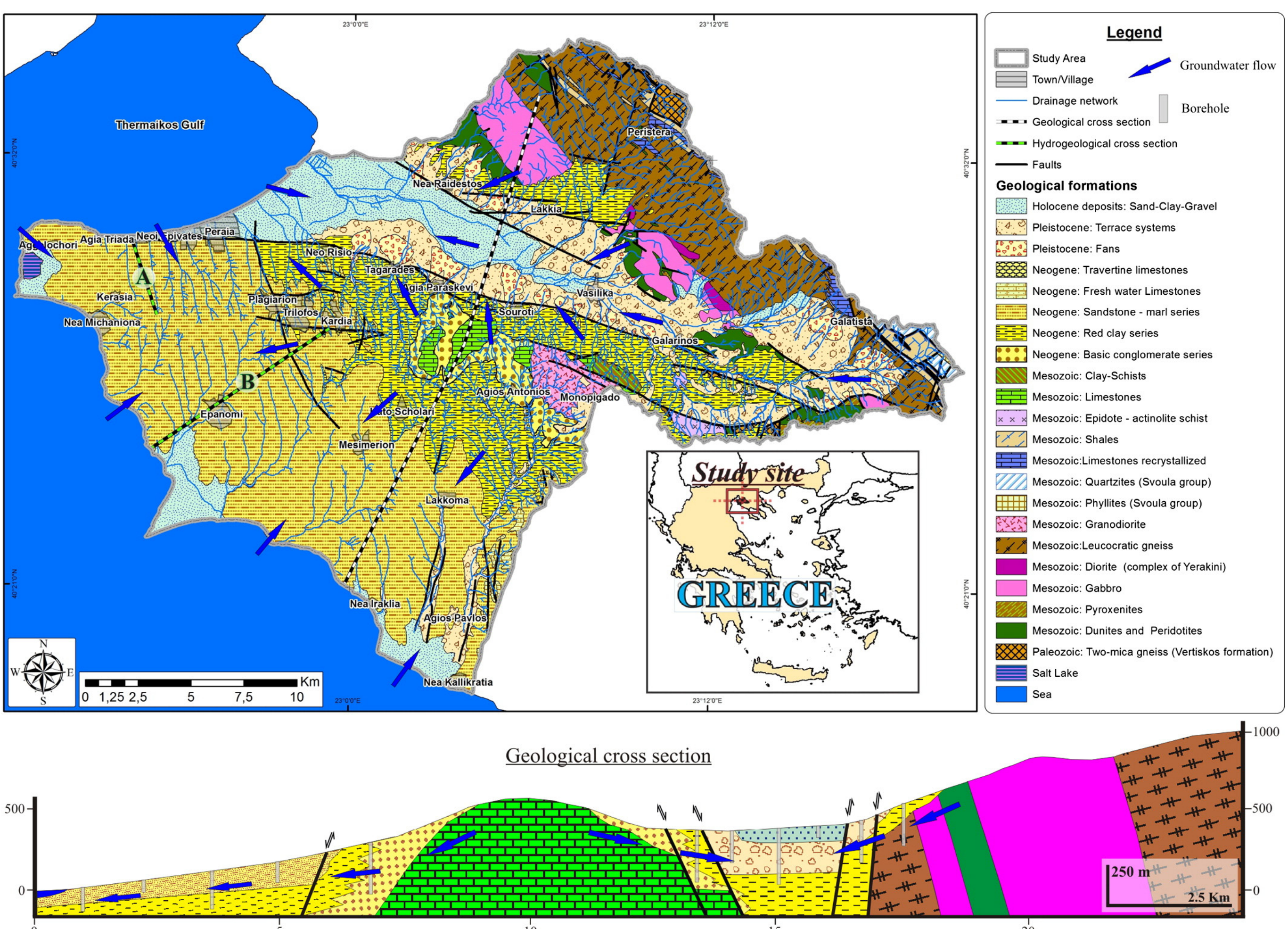

Fig. 1. Geological map and cross-section of the study site (modified from IGME maps, Sheets: Thessaloniki, Epanomi, Vasilika, Thermi, Polygiros, Zagliveri).