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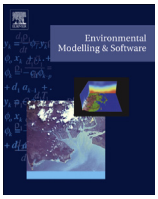

Development of a groundwater quality index for seawater intrusion in coastal aquifers

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ABSTRACT

Coastal aquifers are increasingly threatened by seawater intrusion due to increased urbanization, groundwater exploitation, and global sea-level rise. Pattern diagrams, which constitute the outcome of several hydro-geochemical processes, have traditionally been used to characterize vulnerability to seawater intrusion. However, the formats of such diagrams do not facilitate the geospatial analysis of groundwater quality, thus limiting the ability of spatio-temporal mapping and monitoring. This raises the need to transform the information from current pattern diagrams into a format that can be readily used under a GIS framework to define vulnerable areas prone to seawater intrusion. In this study, a groundwater quality index specific to seawater intrusion (GQI_{SWI}) was developed for the purpose of aggregating data into a comprehensible format that allows spatial analysis. The index was evaluated with data from various coastal regions worldwide and then applied at a pilot karstic aquifer along the eastern coast of the Mediterranean Sea.

1. Introduction

Seawater intrusion threatens coastal freshwater resources globally, rendering groundwater non-potable and invariably forcing well abandonment or requiring costly treatment systems. Nearly sixty percent of the world's population lives in coastal regions (Richter and Kreitler, 1993) vulnerable to seawater intrusion due to groundwater over-exploitation to meet increasing water demand associated with population growth. This vulnerability is also expected to exacerbate by future climate change and associated sea-level rise (Taylor et al. 2013). Blending these factors give rise to groundwater management challenges (Melloul and Collin, 1998; Appelo and Postma, 2005).

Seawater and freshwater have differing hydrochemistry, with the former being characterized by nearly uniform chemistry where chloride (Cl^-) and sodium (Na^+) make up ~84% of the total ionic composition. On the other hand, while freshwater composition varies widely, calcium (Ca^{2+}) and bicarbonate (HCO_3^-) commonly dominate (Richter and Kreitler, 1993). Mixing of these waters is traditionally depicted by increased Cl^- concentration within the aquifer, which is easily traceable due to the conservative nature of the anion (Appelo and Postma, 2005; Panteleit et al. 2011). In fact, the fraction of seawater (f_{sea}) in a water sample can be approximated from the concentrations of Cl^- (m_{Cl}) (in meq/l) as expressed in Equation (1) (Appelo and Postma, 2005):

$$f_{sea} = \frac{m_{Cl(sample)} - m_{Cl(freshwater)}}{m_{Cl(seawater)} - m_{Cl(freshwater)}} \tag{1}$$

Similarly, the increase in total dissolved solids (TDS) or electrical conductivity (EC) is a common simple indicator to identify an increase in salinity (Singhal and Gupta, 2010; Rhoades et al. 1992). Freshwater, brackish water, and seawater can be categorized by typical ranges of Cl^-, TDS, and EC (Table 1) although these values can vary widely in different aquifers. Groundwater exceeding chloride concentrations observed in seawater are considered brine (Hem, 1985), thus rendering seawater intrusion irrelevant.

While seawater intrusion is recognized as the mixing of seawater into freshwater aquifers, it is a complex process due to influences of hydrogeochemical reactions, shoreline geomorphology, biological processes, and aquifer flow, amongst others. Processes indicative of seawater intrusion include cation exchange reactions, calcite dissolution and carbonate diagenesis, dolomitization, and sulfate reduction, (Reactions 1–5).

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Table 1
Classification of water based on chloride, total dissolved solids, and electrical conductivity.

Class	Cl^- (meq/l)	TDS (ppm)	EC
Fresh groundwater	<2.8	0–500	<700
Slightly saline groundwater	2.8–7.1	500–1500	700–2000
Moderately saline groundwater	7.1–14.1	1500–7000	2000–10,000
Highly saline groundwater	14.1–28.2	7000–15,000	10,000–25,000
Very highly saline groundwater	28.2–282.2	15,000–35,000	25,000–45,000
Seawater	>282.2	>35,000	>45,000

Adapted from Konikow and Reilly, 1999; Rhoades et al., 1992.

$$2Na^+ + Ca - X_2 \rightarrow 2Na - X + Ca^{2+} \quad \text{(cation exchange)} \qquad \text{(Reaction 1)}$$

$$CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^- \quad \text{(calcite dissolution)} \qquad \text{(Reaction 2)}$$

$$CaCO_3 + CH_2O + O_2 \rightarrow Ca^{2+} + 2HCO_3^- \quad \text{(calcite dissolution)} \qquad \text{(Reaction 3)}$$

$$2CaCO_3 + Mg^{2+} \rightarrow CaMg(CO_3)_2 + Ca^{2+} \quad \text{(dolomitization)} \qquad \text{(Reaction 4)}$$

$$2CH_2O + SO_4^{2-} \rightarrow 2CO_2 + 2H_2O + S^{2-} \rightarrow H_2S + 2HCO_3^- \quad \text{(sulfate reduction)} \qquad \text{(Reaction 5)}$$

The cation exchange occurs when equilibrium in the groundwater is disturbed by seawater intrusion. Negatively charged surfaces, like sediments, come in contact with seawater and absorb the Na^+ ion and release the Ca^{2+} ion as expressed in Reaction 1 where X is the sediment exchanger (Appelo and Postma, 2005). The reverse reaction occurs in freshening aquifers whereby ion exchanger reactions also contribute toward the depletion of the Ca^{2+} cation and release of the Na^+ ion, resulting in $NaHCO_3$ rich water (Reactions 2 and 3) with water becoming undersaturated in calcite and resulting in dissolution (Appelo and Postma, 2005; Panteleit et al. 2011). In addition, dolomitization (Reaction 4) can be triggered by calcite dissolution, particularly in carbonate aquifers, resulting in an increase in the Ca^{2+} cation over Mg^{2+} (Jones et al. 1999; Hanshaw & Back, 1979). Finally, sulfate reduction (Reaction 5) is common in mixing zones due to conservative mixing as well as decay and organic matter mineralization (Panteleit et al. 2011; Richter and Kreitler, 1993).

Seawater intrusion can also be identified using one or more graphical methods such as pattern diagrams and GIS. Hydrochemical pattern diagrams include the Durov (1948), Stiff (1951)

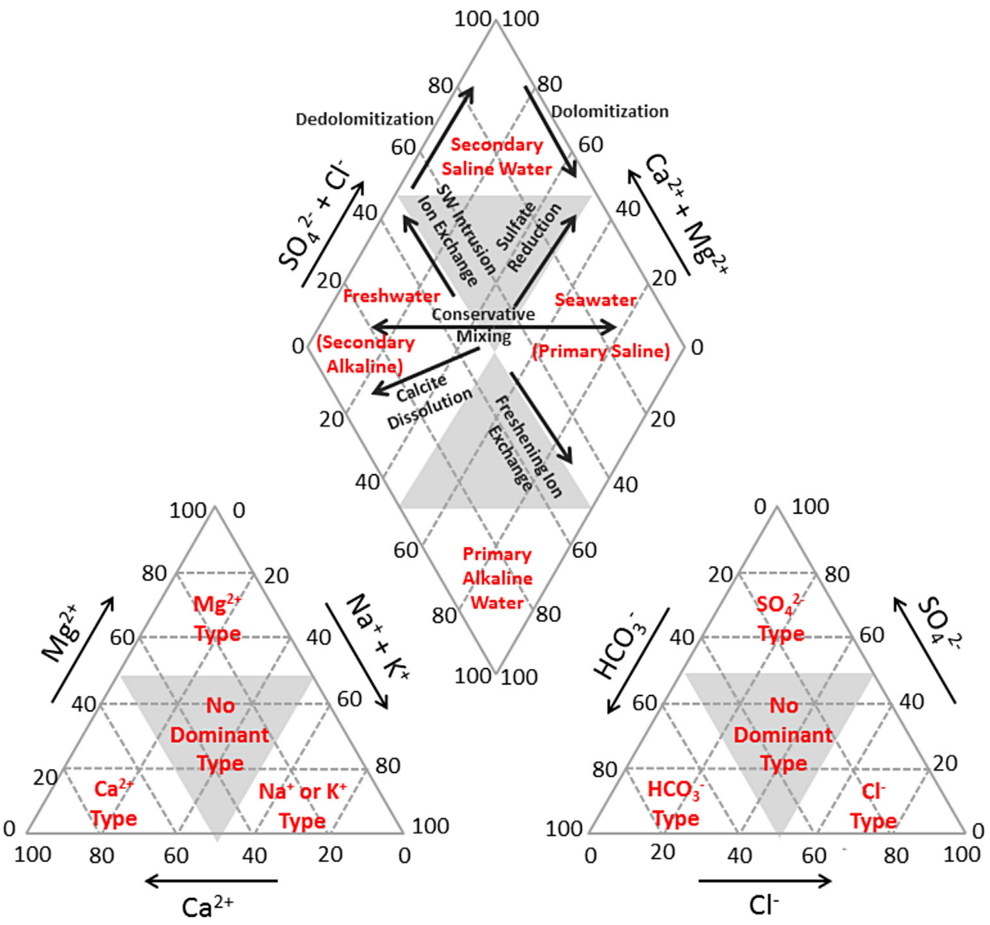

Fig. 1. Piper diagram illustrating general classifications of waters and seawater intrusion reaction pathways.
Adapted from Appelo and Postma, 2005; Hanshaw and Back, 1979; Singhal and Gupta, 2010; Panteleit et al., 2011