Saltwater Intrusion in karst aquifers along the Eastern Mediterranean

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ABSTRACT

The scale and magnitude of saltwater intrusion in the karst aquifer of the coastal city of Beirut-Lebanon, a densely populated area that is heavily dependent on groundwater for domestic purposes, was quantified. The city suffers from saltwater intrusion primarily from the wide proliferation of building wells and over-extraction. A monitoring program was developed and implemented to characterize groundwater quality and investigate the severity of saltwater intrusion. Multiple physical, chemical and microbiological parameters were analyzed. Additionally, socioeconomic indicators were collected in an attempt to correlate salinity levels with these factors. Groundwater chemistry, ionic relationships, hydro-chemical diagrams and groundwater quality indices (GQI) were also used to delineate saltwater intrusion hotspots. Concentration data exhibited large spatial variability in salinity levels across districts with Total Dissolved Solids (TDS) levels ranging from a low of 400 to as high as 29,000 ppm. The results can help assess the extent and intensity of saltwater intrusion and improve existing policy planning and management tools for coastal aquifers.

INTRODUCTION

The vulnerability of coastal groundwater aquifers to saltwater intrusion (SWI) is increasing globally due to high water demands in densely populated coastal regions that are increasing their reliance on groundwater resources. SWI in such systems is expected to further increase with projected population growth and urbanization. Moreover, the potential sea level rise, associated with climate change, is also expected to exacerbate the problem (Barazzuoli *et al.* 2008; Kumar et al. 2007). Despite widespread studies of SWI, its investigation in karst aquifers remains limited, particularly in view of the multiple challenges in understanding, characterization, as well as modeling of karst aquifers. This study quantifies SWI along the Eastern Mediterranean coastline, known for its fractured and karst nature, through examining a case study that looks at groundwater salinity in the city of Beirut, Lebanon.

Municipal Beirut lays on a 20km^2 triangular shaped-peninsula that extends westward into the Mediterranean Sea. The city has a 9km shoreline (Figure 1). It is highly urbanized and hosts a population of 400,000 (CAS 2008), inhabiting various districts with varying densities, land uses, and socioeconomic conditions. Cenomanian limestone (C4) underlies the study area, with quaternary sediments mainly overlying it (alluvium, soils or moving dunes) (50% of the area) with some Miocene beds forming a single saturated zone with an estimated thickness of 700m (Khair 1992). The resulting aquifer is heavily exploited, with an estimated 4000 small building scale wells tapping into it (SOER 2011).

Being heavily jointed and faulted (Ukayli 1971) coupled with its proximity to the sea, makes Beirut's underlying aquifer susceptible to SWI. The telltale signs of SWI were observed as early as 1969, through geo-electrical processing that confirmed SWI through tectonic fractures (FAO 1997). Chloride concentrations in the aquifer have continued to increase with time to reach more than 4,200 mg/l in 2005 (Khair 1992; Saadeh 2008).

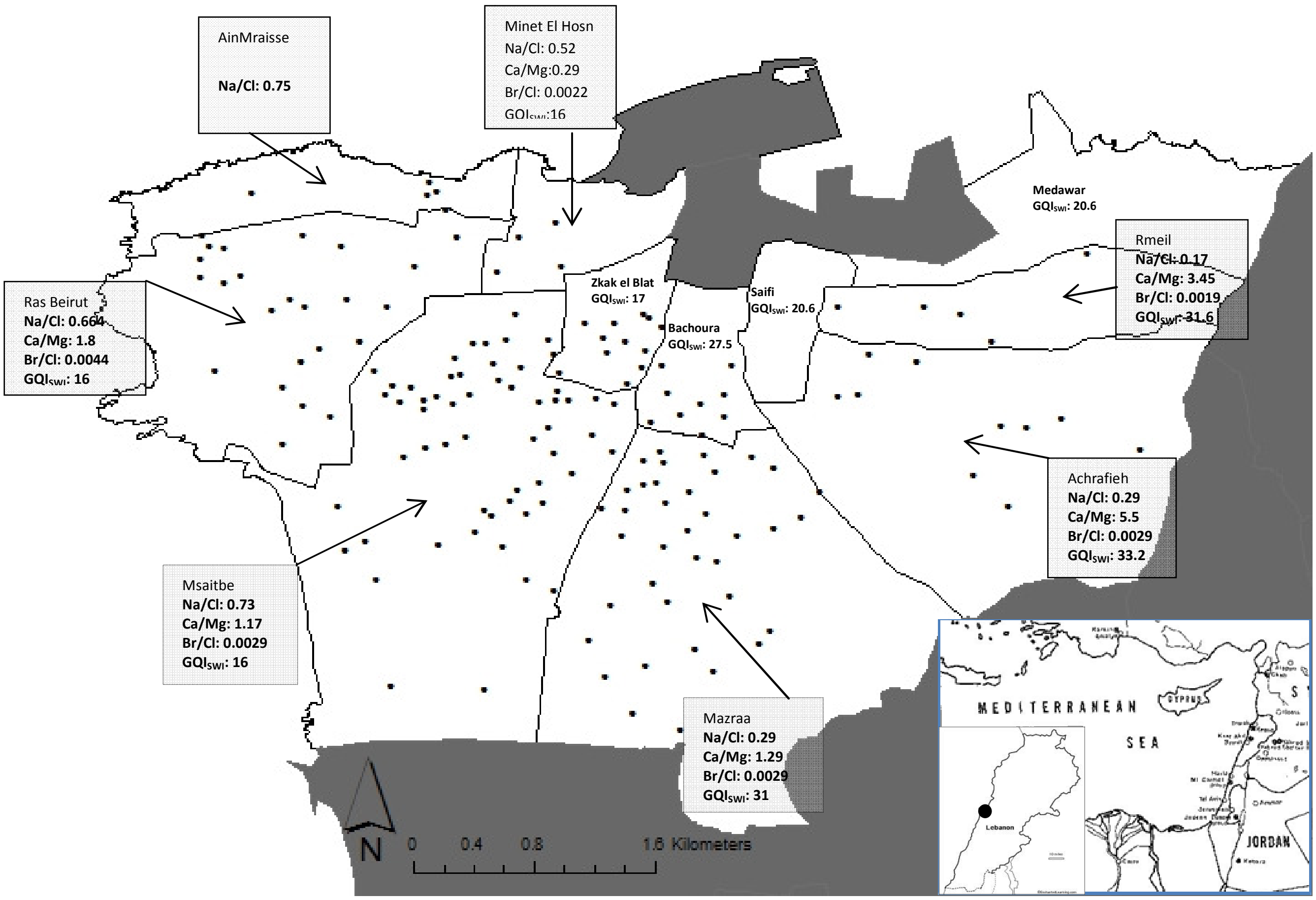


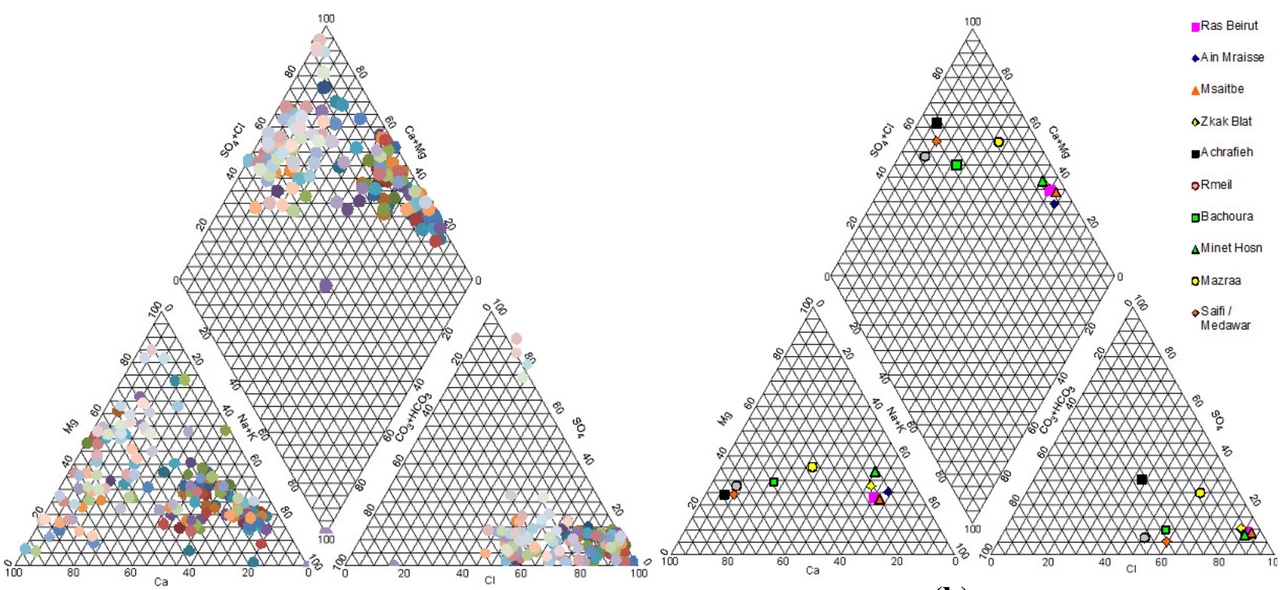
Figure 1. Study area with distribution of groundwater wells and ionic ratios per district

Methods

A monitoring program was developed to characterize the groundwater quality and examine the extent of saltwater intrusion. Sampling was initiated in the early summer of 2013 (June), whereby samples were collected from 165 groundwater wells in residential districts. A stratified sampling approach was used, whereby the density of sampled wells in each district was based on the corresponding population density. Parameters analyzed included TDS, hardness, HCO_3^-, CO_3^{2-}, NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Cl^-, Br^-, Na^+ and K^+ ions, along with microbiology. Analyses were undertaken in accordance with Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF, 2005). Ionic ratios, specifically Na^+/Cl^-, Ca^{2+}/Mg^{2+}, Br^-/Cl^-, SO_4^{2-}/Cl^- and $Ca^{2+}/(SO_4^{2-}+ HCO_3^-)$, were used to assess the geochemical state of groundwater. The hydro-chemical Piper diagram was also generated in order to analyze and characterize water type and quality. Groundwater quality indices (GQI) were calculated based on Babiker et al. (2007), who developed a generalized GQI, and on El-Fadel et al. (2013), who developed SWI specific GQI (GQI_{SWI}). Based on hydrogeochemical processes associated with saltwater intrusion, GQI_{SWI} indicates the contribution of freshwater and ranges from 0 (seawater) to 100 (freshwater). Information about socioeconomic indicators, including household size, education level, employment and income were collected to correlate with measured salinity levels.

Results and Discussion

Concentration data exhibited large spatial variability across and within districts particularly manifested in TDS and Cl^- values. Elevated TDS concentrations with an average of 4,061 mg/l were recorded, and exceeding 20,000 mg/l at several locations. As expected, Cl^- values correlated well with TDS ($R^2 = 0.913$). The Cl^- mean concentration over Beirut was 1,898 mg/l; yet some areas had concentrations >10,000 mg/l suggesting strong SWI. This spatial heterogeneity could be attributed, primarily, to the karstic nature of the geology in the area. Overall, the study area exhibited a low Na^+/Cl^- (0.5 – 0.82 meq/l) and a high Ca^{2+}/Mg^{2+}(1.1 – 5.5 meq/l), both typical signs of saltwater intrusion. The Br^-/Cl^- ratio averaged 0.0033 (Figure 1). Average SO_4^{2-}/Cl^- ratio of 0.1 meq/l was observed for all districts except for Mazraa (1.4 meq/l). Similarly, the average $Ca^{2+}/ (SO_4^{2-} + HCO_3^-)$ ratio was high (> 1) for all districts. Accordingly, ionic ratios in the early summer (i.e. before the water table drops with the dry summer) indicate that SWI is well developed in most districts: Zkak el Blat, Msaitbe, Ain Mraisse and Minet el Hosn (Figure 1). Other districts are showing evident signs of SWI.



(a) (b)

Figure 2 Piper diagram representing Beirut's groundwater quality in early summer (June 2013) (a) at the well level; (b) at the individual districts level (averaged across wells)

The generated piper diagrams (Figure 2) reveal the major hydro-geochemical facies of (Ca^{2+}-Mg^{2+}- Cl^-, SO_4^{2-}) and (Na - Cl^-) in the study area. The diagrams point towards SWI together with dolomitization. The generalized GQI for Beirut, which includes various parameters (Ca^{2+}, Mg^{2+}, Na^+, Cl^-, NO_3^-, SO_4^{2-}, TDS, FC, TC), was 59.67 reflecting a very poor water quality. Recalculating GQI without the nitrates and coliforms so as to directly capture the effects of salinization, the GQI increased to 69.3, a value that still reflects poor water quality. For the specific GQI_{SWI}, the study area had a mean value of 21 reconfirming the severity of SWI. In an effort to characterize individual districts, mean concentrations were calculated for each. Groundwater in the Zkak el Blat, Msaitbe, Ain Mraisse, Minet el Hosn, and Ras Beirut districts was found to be primary saline ($Na^+ – K^+ – Cl^-$), whereas other districts had secondary saline ($Ca^{2+} – Cl^-$) waters. The GQI for Zkak el Blat (56.5), Msaitbe (58.35), Ain Mraisse (62) and Ras Beirut (60) confirmed high salinization; whereas the districts of Achrafieh, Rmeil, Saifi and Medawar had GQI > 86, indicating relatively good water quality. For the specific GQI_{SWI}, all individual districts reported an average $GQI_{SWI} < 33$, with the lowest value reported in Ain Mraisse ($GQI_{SWI} = 14$).

Conclusions

Hydro-chemical analyses and groundwater quality ratios and indices confirmed the scale and quantified the magnitude of groundwater salinization in much of municipal Beirut. While proximity to shoreline, population and water demand induces variability, the spatial heterogeneity in Beirut could be greatly attributed to the karstic nature of the area's geology. Further groundwater mixing and salinization is expected to occur later in the dry season as the water table level drops. The monitoring program and socio-economic indicators' analysis is ongoing to further understand the drivers, extent, intensity and impact of saltwater intrusion in the area to better inform policy planning and management of coastal aquifers.

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