'IAIA15 Conference Proceedings'
Impact Assessment in the Digital Era
35th Annual Conference of the International Association for Impact Assessment
20 - 23 April 2015 | Firenze Fiera Congress & Exhibition Center | Florence | Italy | www.iaia.org

Vulnerability indices for SWI assessment

Grace Rachid, Mutasem El-Fadel*, Ibrahim Alameddine and MajdiAbouNajm
Department of Civil & Environmental Engineering
American University of Beirut, Lebanon
*Corresponding author: mfadel@aub.edu.lb

Abstract

Saltwater intrusion (SWI), an impact of the synergy between population growth, urbanization and groundwater overexploitation, is invariably an increasing threat to coastal freshwater aquifers. This threat is expected to exacerbate under climate change impacts due to projected sea level rise. This study assesses SWI impact along the Eastern Mediterranean at a coastal densely populated pilot area that is greatly dependent on groundwater resources for domestic purposes. It evaluates the spatial variability and intensity of the SWI impact through vulnerability indices and spatial analysis based on hydrochemical data and geostatistical techniques. A spatial and temporal groundwater monitoring program was developed representing wet and dry seasons. Parameters analyzed included TDS, major ions as well as microbiological indicators. Signs of salinization were ascertained through chloride concentrations and hydrogeochemical ratios. Hydrochemical facies and domains, as water type indices, were analyzed using the piper diagram. Generalized indices to groundwater quality (GQIs) and specific to saltwater intrusion GQI_{SWI} were estimated to characterize SWI occurence. Spatio-temporal vulnerability maps were generated using geostatistical interpolation. The scale and magnitude of SWI impact in the study area was quantified and hot spots identified, being primarily influenced by the wide proliferation of building wells and groundwater overexploitation. Vulnerability indices and mapping proved to be key in synthesizing parametric results under a single framework that can be relied upon for informed impact assessment and decision-making.

Introduction

The vulnerability of coastal groundwater aquifers to saltwater intrusion (SWI) is increasing globally due to the synergy between population growth, urbanization and groundwater over-exploitation. The threat of SWI in such systems is expected to further intensify under projected climatic changes, due to sea level rise and reduced aquifer recharge (Barazzuoli *et al.* 2008; Kumar *et al.* 2007). The process of SWI degrades natural ecosystems and renders groundwater resources unsuitable for domestic, agricultural, industrial or recreational uses. Accordingly, assessment and management of SWI has become integral to impact assessments towards sustainable coastal development and management. This study targets the development of indices that can be used in assessing SWI in coastal areas. For this purpose, a pilot area was selected with the aim to evaluate the spatial variability and intensity of SWI through vulnerability indices and spatial analysis based on hydrochemical data and geostatistical techniques. The pilot area (Beirut Lebanon), used as a test field, is located midway along the Eastern Mediterranean (Figure 1) on a triangular shaped-peninsula of a total area of 20km^2 with a diverse shoreline. The area is heavily populated and subdivided into districts of varying densities and socioeconomic conditions (SOER 2011; CAS 2008) and greatly dependent on groundwater resources for domestic purposes. The sub-surface is characterized by fractured and karst systems (Shaaban *et al.* 2006) and is heavily jointed and faulted (Ukayli 1971). Groundwater occurs in two principal aquifers, sand and carbonate. The area is underlaid with cenomanian limestone overlaid with quaternary sediments and miocene beds. The aquifer, a single saturated zone with an estimated thickness of 700m of limestone and dolomite as well as some intercalations of marl (Khair 1992), is heavily exploited, with a large number of small scale building wells that operate without an official permit (SOER 2011; Saadeh 2008).

Methodology

A spatial and temporal groundwater sampling program was developed and implemented to characterize the groundwater quality. For this purpose, two rounds of sampling were undertaken in June and October representing late wet and dry seasons and targeting a total of 170 residential building scale wells. Parameters analyzed included EC, TDS, hardness and major ions (HCO_3^-, CO_3^{2-}, NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Cl^-, Br^-, Na^+ and K^+) as well as microbiological indicators (e.g. fecal and total coliforms). Signs of salinization were detected through elevated chloride and total dissolved solids concentrations, which were used to classify water into fresh, brackish and saline, and through different hydrochemical ratios symptomatic of SWI (i.e. Na^+/Cl^-, Ca^{2+}/Mg^{2+}, Br^-/Cl^-, SO_4^{2-}/Cl^-, Cl^-/HCO_3^- and $Ca^{2+}/(SO_4^{2-}+HCO_3^-)$). Hydrochemical facies and domains were analyzed using the piper diagram, which graphically represent the chemistry of the water samples. Groundwater quality indices were calculated to characterize its quality and SWI occurrence, particularly: a) the fraction of seawater (f_{sea}), which represents the percentage of seawater in the freshwater sample, is estimated based on the Cl^- ion as a conservative tracer taking into account the Cl^- concentrations of the sample, freshwater and seawater (Appelo and Postma, 2005), b) the generalized groundwater quality index (GQI), normalized for the different water quality concentrations using the World Health Organization threshold-standards and aggregated into a single water quality value with quality indicators of potential health impacts weighted heavier than other indicators (Babiker *et al.* 2007), and c) the SWI specific GQI (GQI_{SWI}), a representative index that translates information from the Piper diagram and the fraction of seawater into a numerical seawater intrusion index of 0% (seawater) to 100% (freshwater) range (Tomaszkiewicz *et al.* 2014). Based on the analysis of this ensemble of indices and indicators, spatial-temporal vulnerability maps were generated using the GIS geospatial analyst through geostatistical interpolation, particularly Ordinary Kriging, which allows predicting concentration values at unmeasured points in the study area by computing a weighted average of the measured values in the neighborhood of each point.

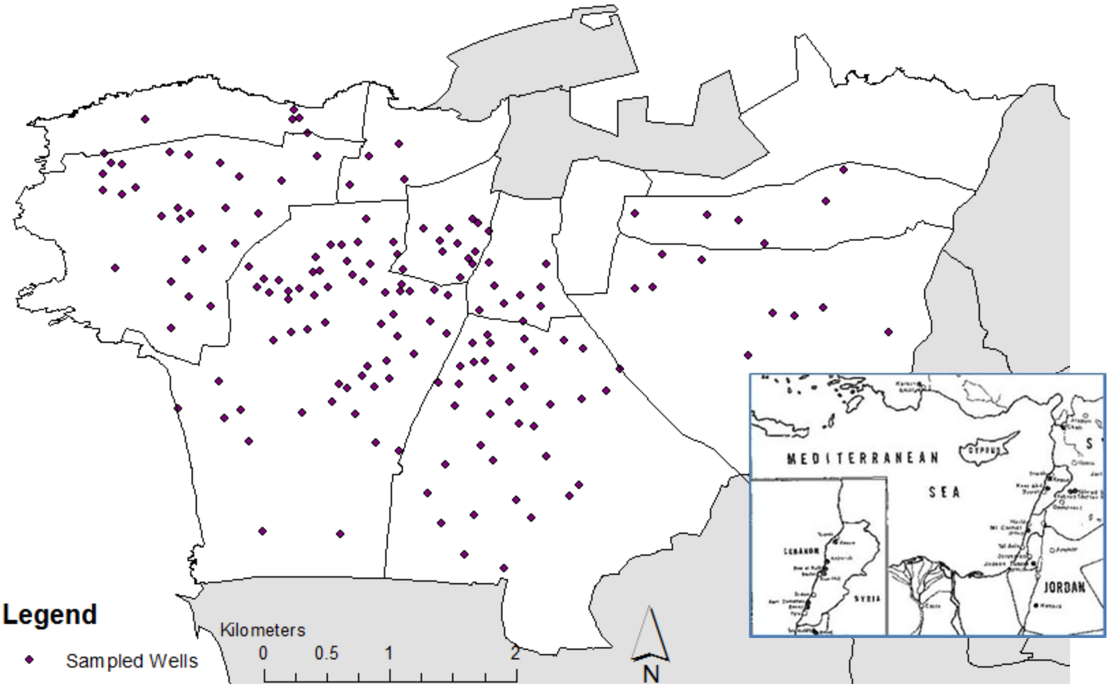


Figure 1 Pilot area with sampling locations

Results

Table 1 presents a summary statistics of the physio-chemical characteristics of groundwater and SWI indicators of the tested aquifer. Concentrations exhibited large spatial variability across and within seasons primarily attributed to the karstic nature of the geology in the area. The electrical conductivity, TDS and chloride concentrations indicated a slightly-to-moderately saline groundwater in the late wet season that further evolved to highly saline in the dry season. Cl^- and SO_4^{2-} anions coupled with Na^+ and Mg^{2+} cations dominated the composition of groundwater in October ascertaining the heavy intrusion of saline water in the study area in the late dry season. Analysis of the ionic ratios also substantiated the occurrence of well advanced saltwater intrusion in October, while also confirming signs of salinization earlier in June. The Na^+/Cl^- ratio remains the symptomatic indicator of seawater intrusion revealing a mean ratio at or below 0.86 for both seasons suggesting well developed saltwater intrusion in the study area. The piper diagram (Figure 2) reveals that in June, groundwater was of the Cl^--SO_4^{2-}-Na^++K^+-Mg^{2+}-Ca^{2+} type with Cl^- and Na^++K^+ as dominant ions where sulfate reduction and SWI ion exchange were occurring, leading to the presence of secondary saline water (hydro-geochemical domain V i.e. CaCl) as well as primary saline water (hydrogeochemical domain II i.e. NaCl). Dedolomitization was also observed but to a lesser extent. In October, the water was of the Cl^--Na^++K^+-Mg^{2+} type with Cl^- as the dominant anion but no dominant cation. SWI ion exchange and migration of samples from secondary saline water (domain V) to primary saline water (domain II) were observed as the mixed CaMgCl water type (domain IV) emerged which pinpoints towards freshwater-seawater mixing with an increase in the salt water intrusion process in the dry season i.e. October.

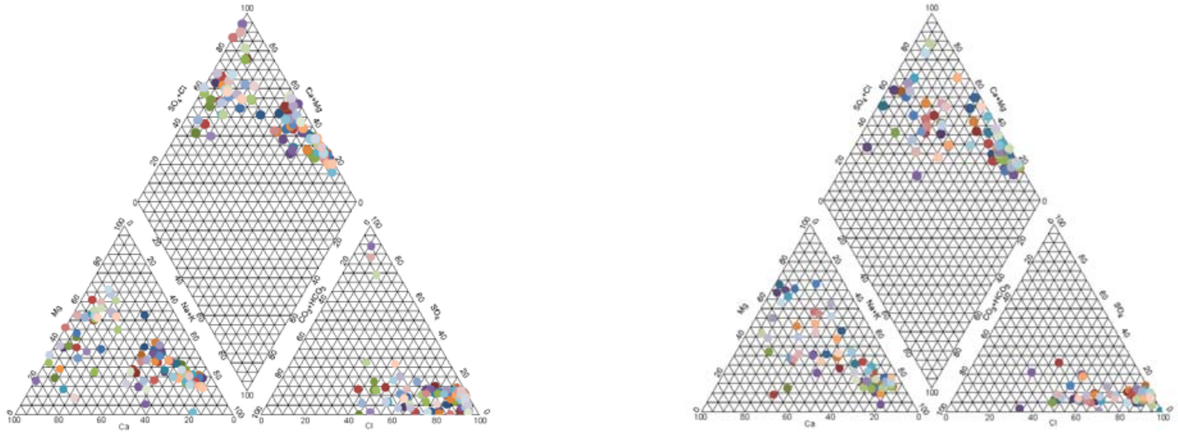
Table 1 Summary statistics of physiochemical characteristics, indicators and indices

Season *Parameter/	June (late wet)			October (late dry)			*Threshold*
	Min	Max	Mean	Min	Max	Mean	
pH	6.4	8.2	7	6.5	7.73	7.045	6.5-8.5
EC	908	47106	9504	740.6	65047	12008	
TDS	560	23320	4610	425.7	31460	5943.8	600
Ca^{2+}	56	1362	282.7	32	1190	249.3	300
Mg^{2+}	19.4	1297.6	229.9	14.82	1129.95	246.8	300
Na^+	2.27	7000	1132.5	4.24	10561	1629.3	200
K^+	0.534	212.3	19.7	0.877	328.2	45.3	300
Cl^-	100	13080	2358	105	17670	3203	300
HCO_3^-	141.8	493	258.6	34.4	460.4	274.8	
NO_3^-	2	219	39.8	1.7	66.5	27	50
SO_4^{2-}	7	2200	391	7	2900	418.6	250
Na^+/Cl^-	0.02	1.09	0.529	0.044	0.99	0.617	≤ 0.86
Cl^-/HCO_3^-	0.778	122.17	18	0.508	162.8	24.38	20-50
Mg^{2+}/Ca^{2+}	0.078	4.65	1.47	0.147	5.3	1.74	4.5-5.2
Br^-/Cl^-	0	0.017	0.0027	0	0.00445	0.00117	0.0015
$Ca^{2+}/(HCO_3^-+SO_4^{2-})$	0.315	15.3153	1.6168	0.298	10.187	1.3	>1
SO_4^{2-}/Cl^-	0	0.803	0.14	0.0345	0.7	0.13	0.103
$GQI_{generalized}$	25.2	83.67	53.63	21.276	83.364	52.26	
GQI (w/o NO_3^{--}, FC)	20.24	89.63	61.27	17.794	91.747	60.1	
f_{sea}	0.005	0.652	0.118	0.0052	0.879	0.159	
$GQI_{Saltwater\ Intrusion}$	24.13	86.084	62.74	11.252	89.526	59.01	<75

While the mean fraction of seawater was 11.8% and 15.9% for wet and dry seasons respectively, wide inter-seasonal ranges were reported in both June (0.05-65%) and October (0.05-88%) strongly suggesting considerable seawater-freshwater mixing with coexistence of fresh and highly saline waters as well as an increasing mixing trend from the wet to dry conditions. The generalized GQI exhibited comparable medium water quality in the pilot area for both seasons albeit spatial heterogeneity revealing zones of minimum (20-30) to maximum (>80) water quality. Figure 3a illustrates better water quality in the eastern zones of the pilot area as compared to its western zones. The same trend was observed for the GQI without accounting for water quality indicators that have health impacts (e.g. nitrates, total and fecal coliforms). A clear improvement is observed in the water quality in June (Figure 3b), particularly in the eastern and middle zones as well as along the north-west coast, suggesting that nitrates and fecal coliform have contributed to the lower generalized GQI. The less-apparent improvement observed in the GQI in the dry season, which was only limited to the eastern zones, suggests that the reported minimum to medium water quality is not due to direct anthropogenic pollution. This is confirmed with the SWI specific GQI vulnerability (Figure 3c) which showed SWI to be more developed in the dry season particularly in the western zones, and hence responsible for the reported poor water quality. A minimum freshwater contribution of 11.25% (GQI_{SWI}) was reported in October (with a mean of 59%) strongly suggesting that the aquifer suffers from advanced seawater intrusion. In parallel, the minimum GQI_{SWI} of 24% observed in June (with a mean of 63%) also suggests ongoing seawater-freshwater mixing in the late wet season. Hence, given the spatial heterogeneity and temporal trends observed for SWI for the wet and dry seasons, the occurrence and intensity of SWI in the pilot area proves to be more influenced by groundwater abstraction and less responsive to the aquifer recharge.

Conclusion

The scale and magnitude of saltwater intrusion at the pilot area along the Eastern Mediterranean was quantified and hot spots identified, being primarily influenced by the wide proliferation of building wells and subsequent groundwater over-extraction. Vulnerability indices and mapping, based on interpolations of GQI and GQI_{SWI} which synthesize multiple parametric results into a single proxy of water quality and salinization, proved to act as an effective one-stop framework that can be relied upon by decision makers for informed impact assessment and management planning for sustainable coastal aquifers.



June

October

Figure 2 Hydrochemical piper diagram

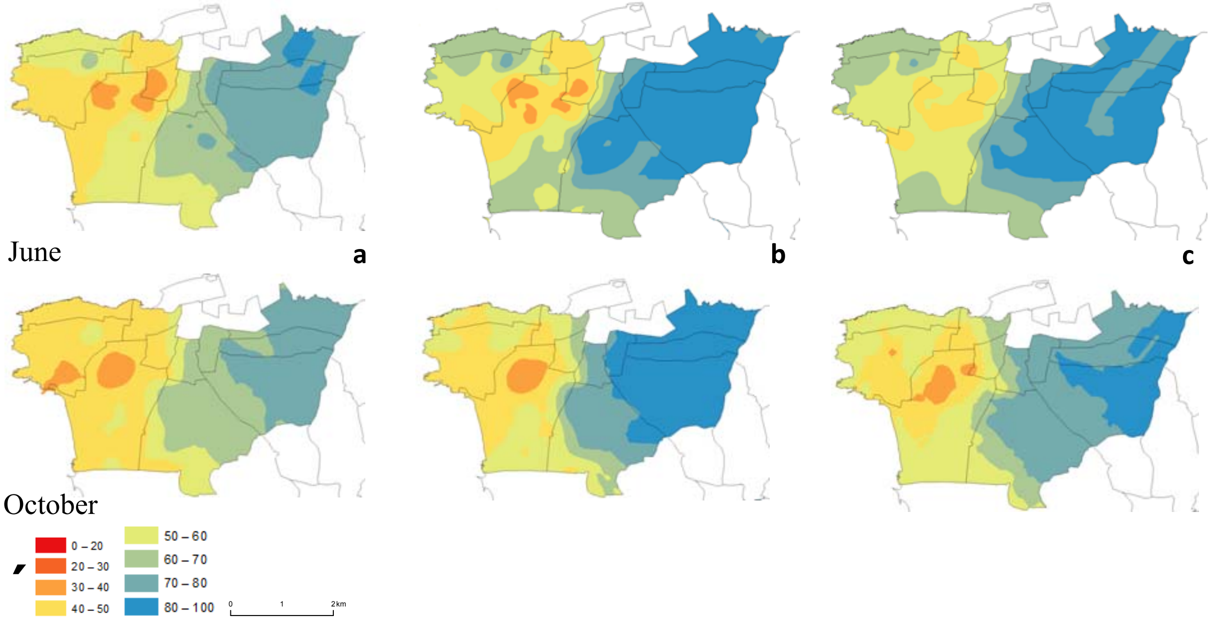


Figure 3 Spatial and temporal vulnerability maps
a) GQI generalized; b) GQI without nitrates and microbiological parameters; c) SWI specific GQI

References

APHA/AWWA/WEF. 2005. Standard Methods for the Examination of Water and Wastewater, 21st ed. American Public Health Association/American Water Works Association/ Water Environment Federation, Washington, DC.

Appelo, C.A.J., Postma, D., 2005. Geochemistry, Groundwater and Pollution. CRC Press.

Babiker, I. S., Mohamed, M. A. and Hiyama, T. 2007. Assessing groundwater quality using GIS. Water Resources Management, 21, 699–715

Barazzuoli, P., M. Nocchi, R. Rigati, and M. Salleolini. 2008. A conceptual and numerical model for groundwater management: a case study on a coastal aquifer in southern Tuscany, Italy. Hydrogeology Journal,16 (8), 1557-1576.

CAS 2008. Statistical Yearbook 2007. Central Administration for Statistics.

Kumar C. P., Chacahadi A. G., Purandara B. K., Kumar S., and Juyal R. 2007. Modelling of Seawater Intrusion in Coastal Area of North Goa. Water Digest, 2 (3), 80-83.

Khair, K. 1992. The Effects of Overexploitation on Coastal Aquifers in Lebanon, International Association of Hydrogeologists, 3, 349-362.

Saadeh, M. 2008.Influence of overexploitation and seawater intrusion on the quality of groundwater in Greater Beirut. Masters of Science Thesis. RWTH Aachen, Germany

Shaban, A., Khawlie, M., Abdallah, C., 2006. 2006. Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. Hydrogeology Journal, 14, 433-443. http://dx.doi.org/10.1007/s10040-005-0437-6.

SOER 2011. State of the Environment Report 2010. MOE/UNDP/ ECODIT

Tomaskiewicz, M., Abu Najm, M. and El Fadel, M. 2014. Development of a groundwater quality index for seawater intrusion in coastal aquifers. Environmental Modelling and Software, 57, 13 -26

Ukayli, M. 1971. Hydrogeology of Beirut and Vicinity, Master of Science Thesis, American University of Beirut, Lebanon

Acknowledgments

This study is part of a program on the assessment of the impact of climate change on saltwater intrusion along the Eastern Mediterranean, funded through a grant from the International Development Research Center (IDRC), Canada.