



## Towards a framework for the assessment of saltwater intrusion in coastal aquifers



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### ABSTRACT

Saltwater intrusion (SWI) represents a threat to coastal aquifers worldwide by rendering groundwater quality not viable for its intended purposes. Therefore, understanding SWI impacts is indispensable for informed decision-making on aquifer management. Despite advances in methods to assess the impact of SWI, it remains challenging to select appropriate methods that are effective, timely, and affordable under the influence of a range of factors including aquifer characteristics, hydro-geochemical dynamics, shoreline geomorphology, biochemical reactions, and data availability among others. This study examines commonly used methods that assess the impact of SWI towards the development of an assessment framework in coastal aquifers underlying densely populated urban areas. The methods were selected using complexity-functionality criteria and then tested at a pilot aquifer by coupling Strengths, Weaknesses, Opportunities and Threats (SWOT) and Multi-Attribute Decision Making (MADM) analyses to evaluate the effectiveness of the methods and identify elements of the framework. The framework proved functional in synthesizing parametric results, assessing the dynamics of SWI and quantifying its potential impact, as well as providing an effective platform for informed impact assessment and planning for sustainable exploitation of coastal aquifers.

### 1. Introduction

Saltwater intrusion (SWI) is a global coastal threat caused primarily by groundwater over-exploitation due to population growth, development, and urbanization. The extent of SWI is expected to exacerbate under potential impacts associated with future climate change such as sea level rise coupled with increased water demand due to temperature increase and precipitation decrease. When combined (Fig. 1), these factors would reduce aquifer recharge with SWI manifesting itself in the mixing of freshwater with seawater, often rendering groundwater resources non-suitable for domestic, agricultural, industrial or recreational uses (Zhang et al., 2011; Sales, 2009; Conrads and Roehl, 2007; Sanford and Pope, 2010; Bobba, 2002; de Montety et al., 2008; Fatoric and Chelleri, 2012; Duque et al., 2008). The importance of understanding the dynamics and impacts of SWI lies in the need to plan, manage and adapt towards protecting the biophysical elements (i.e. subsurface aquifers and groundwater quality) from contamination and curtailing associated socioeconomic burdens on coastal communities (i.e. the impairment of an important water source, damages to water fixtures and infrastructure, soil salinization, treatment cost or alternative water sources, and potential health issues).

Efforts towards understanding the vulnerability to and the impact of

SWI are widespread and rely on geochemical and geophysical characterization as well as on laboratory experiments, hydrodynamic techniques, and modeling often coupled with multivariate statistical analysis, geo-spatial analysis, and environmental tracers (Kumar et al., 2015; Werner et al., 2013; de Montety et al., 2008; Duque et al., 2008). Each SWI assessment method has its requirements, limitations, as well as advantages and disadvantages which frames its applicability, use, and implications of associated findings. Most methods are highly data-driven and prohibitively expensive to apply, affected by environmental noises, and vulnerable to interactions and interventions from processes that may mask their results (Werner et al., 2013).

Despite advances in SWI research, it remains challenging to assess and manage its impact due to influences of complex factors, including hydro-geochemical dynamics, shoreline geomorphology, biochemical reactions, and aquifer flow and transport processes among others (Werner et al., 2012, 2013; Melloul and Goldenberg, 1997). This is particularly the case in fractured, karstic and semi-karstic media, which despite multiple attempts to characterize, remains poorly studied worldwide (Sebben et al., 2015; Werner et al., 2013; Cherubini and Pastore, 2011; Papadopoulou et al., 2005; Langevin, 2003). The understanding of the heterogeneity, discontinuities, fractures, conduits and faults' networks as well as the individual and synergistic effect of

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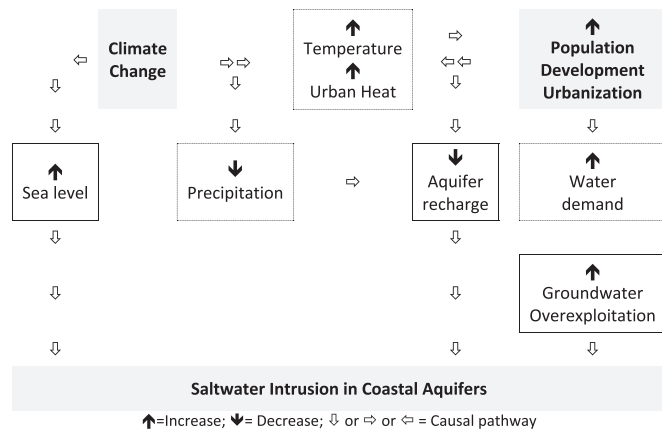


Fig. 1. General dynamics of saltwater intrusion driving processes. ↑ = Increase; ↓ = Decrease; ⇓ or ⇔ or ⇐ = Causal pathway.

these complex features greatly shape how the aquifer allows and reacts to saltwater intrusion (Papadopoulou et al., 2005; Allen et al., 2002). These features affect the pollutant flow, transport and concentration, here salinity, in the aquifer, hence defines how saltwater intrusion occurs and advances. This complexity is further aggravated in data-scarce regions where coastal managers need to plan and act under incomplete knowledge and uncertainty to delineate impacts and protect coastal communities (Cardenas and Halman, 2016; Werner et al., 2013; Tribbia and Moser, 2008).

In this study, we identify common techniques, methods and metrics used to assess the impact of SWI and analyze and appraise their characteristics and differences as well as their applicability in fractured media. These techniques were tested at a highly exploited but data-scarce, heterogeneous aquifer to understand the status and progression of saltwater intrusion in the aquifer. The study presents a first attempt at coupling a quantitative assessment of the outcomes of various methods with a qualitative comparison of their inherent characteristics resulting in the development of an assessment framework that provides a novel platform for informed impact assessment and sustainable exploitation of coastal aquifers reducing the gap between SWI knowledge on one side and management needs for practice and implementation on the other. The resulting framework is the first to apply SWOT and MADM analysis to SWI where ‘fit for purpose’ assessment techniques were identified based on functionality and simplicity. Such a framework, based on hydro-geochemical techniques coupling indicators and indices with geo-statistical analysis, is able to scrutinize the distribution and intensity of SWI and assess its impact on groundwater quality, applicable to heterogeneous systems.

Table 1  
Criteria for assessing complexity and functionality.

Factor	Criteria	Explanation
Complexity/Simplicity	Level of input data	Relative level of input data required and specialization in the analysis and interpretation (i.e. <i>relatively specialized, specialized, highly specialized</i> )
	Accessibility and availability	Relative level of accessibility/availability and feasibility in terms of requirements for sampling and analysis; challenges (i.e. <i>feasible/expensive; readily accessible/challenging</i> )
	Decision makers friendly	Ease of use by decision makers (i.e. <i>easy, medium, complex</i> )
Functionality	Output of the method	Level of contribution to understand the different aspects of SWI (spatial distribution, geochemical reactions, hydrochemical facies etc.) (i.e. <i>limited, varies, wide</i> )
	Use for monitoring	Potential to use the method in monitoring i.e. flexibility and feasibility for spatio-temporal analysis; (Yes, No, not applicable)
	Integration in framework	Potential to integrate method in a framework (Yes, No)

## 2. Theory

Saltwater intrusion is governed by coastal hydrostatic pressures at the hydraulic interface between saline and freshwater. Under undisturbed conditions, a state of dynamic equilibrium between freshwater and seawater is maintained where the hydraulic gradient pushes freshwater towards the sea. As a result of prolonged changes in coastal groundwater levels due to pumping, land-use change, climate variations or sea-level fluctuations, this hydraulic gradient is reversed, resulting in seawater infringement into the aquifer (Bear, 1979). Studies on saltwater intrusion have focused on the process itself, the measurement of propagation and concentration, the prediction of intrusion as well as on the management of vulnerable aquifers (Werner et al., 2013). As the intrusion of saltwater is primarily a function of the hydrogeological characteristics of the aquifer and its hydrodynamics, and as uncertainty is always associated with aquifer characterization, there exists an ‘inherent uniqueness of each case of intrusion’ (Werner et al., 2013) which accentuates the need for case-studies of aquifers to build the knowledge. Field data are often inadequate but indispensable for a proper characterization and assessment of saltwater intrusion. Currently, coastal aquifers worldwide are suffering from variable degrees of salinization, with a need for a better understanding of the process especially in complex aquifers. Capitalizing on accessible data in an integrated systematic framework can act as a preliminary assessment tool to inform decision makers and facilitate aquifer management.

## 3. Materials and methods

The methodology consisted of a comprehensive analytical approach including: 1) review and selection of methods commonly used to assess SWI; 2) fieldwork for aquifer characterization and testing of methods; 3) evaluation of the effectiveness of tested methods based on predefined criteria; and 4) development of a SWI assessment framework towards informed planning and decision-making for improved groundwater management.

### 3.1. Review and selection of methods for SWI assessment

The selection of methods for SWI assessment represents the first step towards decision-making whereby alternative methods are analyzed and assessed against clear criteria. For the purpose of this research, two levels of assessments were undertaken: a qualitative comparative assessment of families of methods (i.e. geochemical, geophysical, laboratory, modeling...etc.) followed by a semi-quantitative assessment of individual alternatives. The assessment of families of methods was based on a complexity-functionality assessment (CFA), adapted from Faludi et al. (2016) into a high-level qualitative evaluation because

**Table 2**  
Evaluation of methods' families against the CFA selection criteria.

Criteria method	Level of data & analysis	Accessibility/availability of data	Decision makers friendly	Output (coverage of SWI aspects)	Use for monitoring	Integration in framework
Geo-chemical (fieldwork, lab analysis, geo-chemical analysis)	Relatively specialized	Sampling-based/usually accessible/relatively feasible	Relatively easy	Relatively wide	Yes/continuous	Yes
Geophysical (fieldwork, results interpretation)	Highly specialized	Noise interference in built-up areas/technology-based/not readily accessible/expensive	Complex	Limited (only SWI level and extent)	Not applicable	No
Laboratory experimental set-ups	Relatively specialized	Challenging in coastal heterogeneous aquifers/not readily accessible/relatively expensive	Relatively easy	Varies	No	No
Statistical analysis	Specialized	Accessible/feasible	Level varies	Limited (Correlations; distribution)	Yes	Yes
Environmental tracers (field work, sampling, lab analysis)	Specialized	Challenging in coastal heterogeneous aquifers/tracers and analysis not readily accessible/relatively expensive	Medium complexity	Limited (specialized use)	Not feasible	No
Modeling (model set-up, simulations)	Highly specialized	Challenging in coastal heterogeneous aquifers/software-based/expensive	Medium complexity	Limited (targeted use)	No	Yes

**Table 3**  
Classification of water based on chloride, TDS, and EC concentrations (Konikow and Reilly, 1999; Rhoades et al., 1992).

Class	Cl (ppm)	TDS (ppm)	EC
Fresh groundwater	< 100	0–500	< 700
Slightly saline groundwater	100–250	500–1500	700–2000
Moderately saline groundwater	250–500	1500–7000	2000–10,000
Highly saline groundwater	500–1000	7000–15,000	10,000–25,000
Very highly saline groundwater	1000–10,000	15,000–35,000	25,000–45,000
Seawater	> 10,000	> 35,000	> 45,000

criteria to select methods for SWI assessment have not been reported (Table 1).

A wide variability in the complexity, feasibility and accessibility to the required input data as well as in the utility was observed (Table 2) among various methods used to assess the SWI impact. Geochemical techniques were selected for further analysis and field testing because of their inherent characteristics of being moderate in complexity, feasible in terms of data collection and analysis, able to cover a spectrum of SWI-related outputs, easy to replicate for monitoring, and popular with decision makers.

Commonly used hydro-geochemical techniques rely on the concentrations of chloride, total dissolved solids, and electrical conductivity which are the first and most common signs for detecting salinization (Table 3) as well as on indicative ratios such as  $Na^+/Cl^-$ ,  $Ca^{2+}/Mg^{2+}$ ,  $Br^-/Cl^-$ ,  $SO_4^{2-}/Cl^-$ ,  $Cl^-/HCO_3^-$  and  $Ca^{2+}/(SO_4^{2-} + HCO_3^-)$ , the seawater fraction, ionic deltas, the Base Exchange indices (BEX), the Chloro-Alkaline indicators ( $CAI = [Cl^- - (Na^+ + K^+)]/Cl^-$ ), and composite techniques that integrate multiple parameters into single metrics. Composite techniques in particular (Table 4) encompass the:

- Stuyfzand classification method, (Stuyfzand, 1989; 2008), which is used to characterize the water type and quality the intensity of the SWI impact;
- Generalized groundwater quality index (GQI), that synthesizes water quality data by indexing them numerically relative to WHO standards, and then used to summarize water quality with and without indicators of pollution (nitrates and coliforms), and cross-check or complement aquifer vulnerability assessments (Babiker et al., 2007); and
- GQI specific to seawater intrusion ( $GQI_{SWI}$ ), developed as a spatial mapping tool that couples the fresh-saline water mixing (sea fraction) with the piper diagram (Piper, 1953) analysis into a numerical indicator of the SWI polluting effect (Tomaskiewicz et al., 2014).

Multivariate statistical analysis, geo-spatial analysis and geostatistical interpolation (i.e. Ordinary Kriging, indicator kriging, co-kriging...) are commonly coupled with the hydro-geochemical techniques (Zghibi et al., 2014; Tomaskiewicz et al., 2014; Villegas et al., 2013; Mondal et al., 2010; Abu Zakhem and Hafez, 2007). Geo-statistical analysis and interpolation can prove to be highly functional and informative in hydrogeological studies (Triki et al., 2014; Agoubi et al., 2013; Castrignano et al., 2007) as it allows for the interpretation of spatial and temporal distributions of studied factors, as well as the extrapolation to areas where data is not available or cannot be collected, based on correlations among the available data. The inherent feature in geostatistical analysis to recognize and manage uncertainty in the prediction domain and data through space and time is key in the assessment of SWI (Tomaskiewicz et al., 2014; Triki et al., 2014).

Given that aquifer analysis is usually constrained by the lack of data, which is more intricate in heterogeneous aquifers (De Filippis et al., 2016; Khadra and Stuyfzand, 2014; Werner et al., 2013; Mascopianti,

**Table 4**

Stuyfzund's method and the generalized water quality indices (Stuyfzund, 1989, 2008; Babiker et al., 2007; Tomaskiewicz et al., 2014).

Stuyfzund water type method		
Code	Parameter salinity	Description (chloride in mg/l)
g	Oligohaline	5–30
F	Fresh	30–150
f	Fresh-brackish	150–300
B	Brackish	300–1000
b	Brackish-salt	1000–10,000
S	Salt	10,000–20,000
H	Hypersaline	> 20,000
	Alkalinity	Alkalinity as HCO <sub>3</sub> (mg/l)
*	Very low	< 31
0	Low	31–61
1	Moderately low	61–122
2	Moderate	122–244
3	Moderately high	244–488
4	High	488–976
	Dominant cation and anion	
Ca	Calcium	The most important cations and anions are placed in the appropriate fields inside two triangles constructed for this purpose
Mg	Magnesium	
Na	Sodium	
HCO <sub>3</sub>	Bicarbonate	
Cl	Chloride	
Mix	No anion > 50% sum of anions	
	Base exchange index (BEX) in meq/l	BEX = Na + K + Mg - 1.0716Cl BEX = Na + K - 0.8768Cl
e	Equilibrium	0 (zero) or no BEX (e)
f	Freshened	> +(0.5 + 0.02Cl) or positive BEX (+)
s	Salinized	< -(0.5 + 0.02Cl) or negative BEX (-)
	Stuyfzund hydrochemical facies	
Code	Descriptor	Value
N	Neutral pH	> 6.2
a	Slightly acidic	5.0–6.2
A	Acidic	< 5.0
M	Mixed redox	-
o	(Sub)oxic	1–3
r	Reduced (anoxic)	4–5
D	Deeply(anoxic)	6–7
	Groundwater quality indices	
GQI <sub>generalized</sub>	$GQI = (100 - ((r_1w_1 + r_2w_2 + \dots + r_nw_n)/N)); C = (X' - X)/(X' + X); X'$ : sample concentration; X: WHO threshold; r = is the rank value calculated as $0.5 \cdot C^2 + 4.5 \cdot C + 5$ ; N = is the total number of parameters; w = relative weight of the parameter	
GQI <sub>SWI</sub>	$GQI_{SWI} = (GQI_{piper} + GQI_{fsea}) / 2$ $GQI_{piper}(\%) = [((Ca^{2+} + Mg^{2+}) / Total\ cations) + (HCO_3^- / Total\ anions)] \cdot 50$ (in molar mass) $GQI_{fsea} = (1 - f_{sea}) \cdot 100$ $f_{sea} = \text{seawater fraction} = (Cl^- \text{ sample} - Cl^- \text{ freshwater}) / (Cl^- \text{ seawater} - Cl^- \text{ fresh})$	

2013), all identified geochemical methods for field application were tested for consideration in the assessment framework coupled with geostatistical analysis and interpolation.

### 3.2. Pilot aquifer characterization and testing of methods

The pilot aquifer is located along the Eastern Mediterranean (Beirut, Lebanon) underlying a 20 km<sup>2</sup> peninsula (Fig. 2) with around 9 km of rocky coastline with patches of sandy shores and cliffs. The aquifer is overexploited by a large number<sup>1</sup> of unregulated residential wells (SOER, 2011; Saadeh, 2008). The subsurface geology belongs to the Cretaceous (Cenomanian c4 (Sanine), and Senonian c6 (Chekka)

formations) and Quaternary (deposits of moving dunes and soils) periods with pockets of Tertiary (Miocene). The main exposed geological units are the Sannine Formation (C4) and the unconsolidated Quaternary deposits. The aquifer is heterogeneous and characterized by fractured and semi-karst systems (Masciopanti, 2013; Shaaban et al., 2006) and heavily jointed and faulted with at least two faults known to run in parallel along the NE to SW direction from the Eastern coast towards the center (Ukayli, 1971; Peltekian, 1980). The groundwater is stored in two principal aquifers of carbonate<sup>2</sup> and sandy<sup>3</sup> origins, making up one thick (~700 m) and extensive formation consisting mainly of limestone and dolomite, as well as some intercalations of marl (Khair, 1992). The Cenomanian formation (c4) is characterized by a dual porosity matrix and by solution enlarged channels and cavities from joints and fractures. This high porosity enables groundwater to move laterally and vertically to great depths (Ukayli, 1971) however the Cenomanian- Quaternary formation is underlain by an aquiclude that separate it from deeper aquifers (Abdel Basit, 1971).

The aquifer is poorly studied, generally in terms of its characteristics and specifically in terms of groundwater quality. Little is reported on the nature of faults and dislocation conditions and implications on the compartmentalization of the aquifer with no lithostratigraphic cross-sections within the boundaries of the study area (El-Fadel et al., 2014). As such, information on the degree and spatial distribution of structural and physical heterogeneity of the aquifer, the underlying water table, the depth of wells, as well as extracted groundwater volumes are generally limited to non-existent. Additionally, wells are invariably cased and seldom accessible for water level measurements.

#### 3.2.1. Groundwater sampling and quality analysis

A spatial and temporal sampling and analysis program was implemented to characterize the groundwater quality and track seasonal changes. In total, 170 wells were targeted with three sampling rounds undertaken to capture both the dry (early dry - June 2013 and late dry - October 2013) and the wet (late wet - April 2014) seasons. Parameters analyzed included TDS, hardness and major ions (HCO<sub>3</sub><sup>-</sup>, CO<sub>3</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Cl<sup>-</sup>, Br<sup>-</sup>, Na<sup>+</sup> and K<sup>+</sup>) as well as microbiological indicators (fecal and total coliforms). The analyses were conducted in accordance with Standard Methods for the Examination of Water and Wastewater (APHA-AWWA-WEF, 2012) at the American University of Beirut.

The hydro-geochemical data were analyzed for descriptive statistics and correlations using the Statistical Package for Social Sciences (SPSS 16.0) software. Inferential statistical analysis, particularly 'Repeated Measures ANOVA', was used to assess the significance of the mean differences of sampled parameters between seasons, and to evaluate possible correlations among parameters. When needed, the parameters were transformed to comply with the normality condition and a Greenhouse-Geisser correction (i.e. when tests of sphericity failed) was adopted when needed. Post hoc tests using the Bonferroni correction were applied to identify the pairwise difference.

#### 3.3. Evaluation of techniques and development of SWI assessment framework

The assessment of geochemical alternatives can be based on a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, Multi-Criteria Decision Support (MCDS) or Multi-Attribute Decision Making (MADM) analyses, Analytical Network Process (ANP) or fuzzy analyses, a Life Cycle Assessment (LCA) approach, or a combination of methods to compare, weigh and select among alternatives (Faludi et al., 2016; Baycheva-Merger and Wolfslehner, 2016; Ruiz Padillo et al.,

<sup>2</sup> Cenomanian limestone.

<sup>3</sup> Quaternary with deposits directly overlaying the Cenomanian carbonates in many places.

<sup>1</sup> Four to ten thousands.

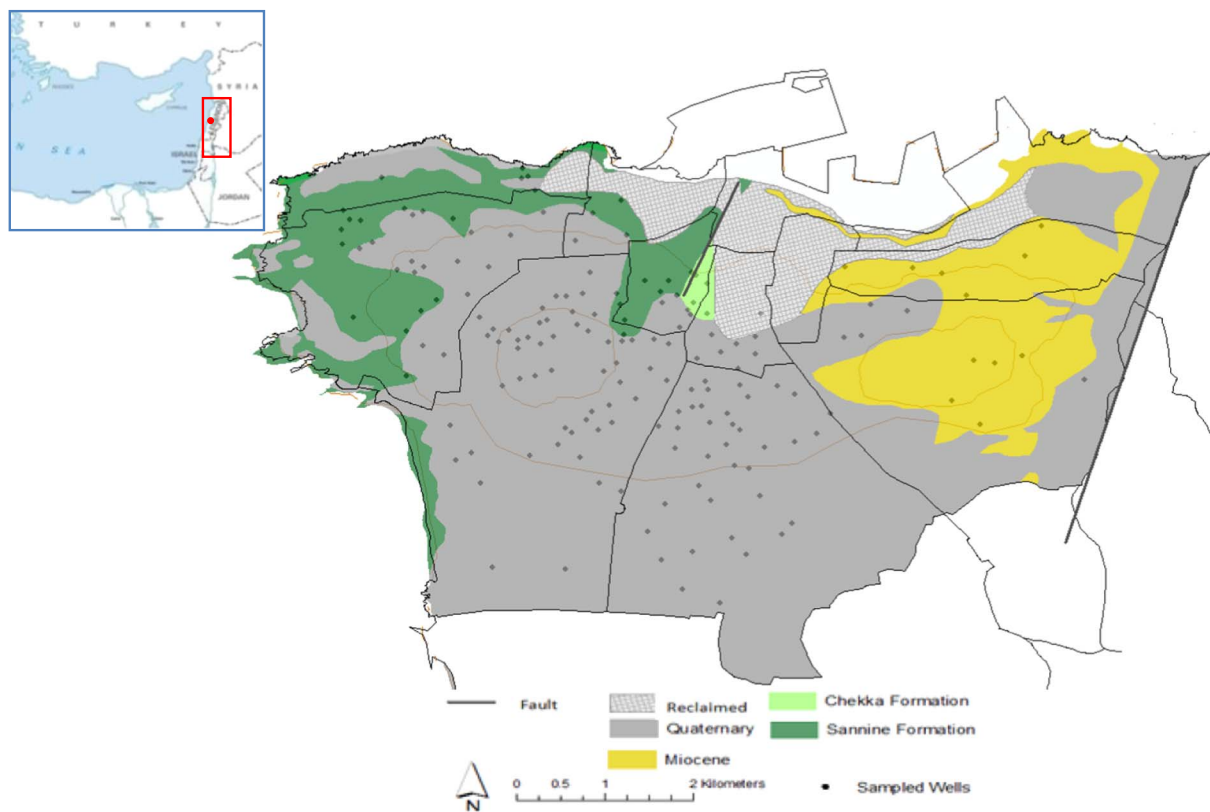


Fig. 2. General location and layout of pilot aquifer with sampled wells.

2016; Garing et al., 2013; Rachid and El-Fadel, 2013; Svekli et al., 2012; Yuksel and Dagdeviren, 2007). In this study, a semi-quantitative approach was adopted whereby a SWOT analysis was coupled with a CFA and MADM analysis.

A. Determination of evaluation criteria for SWOT coupled with CFA

As the objective is to develop a SWI assessment framework, the main measure of effectiveness is the contribution of a method to the comprehensiveness, reliability and feasibility of this framework and its responsiveness to interpretation by decision makers. However, since this effectiveness could come at a prohibitive cost, the complexity of the method is also considered. As such, criteria for the comparative assessment of the effectiveness of alternative methods focused on two levels: functionality and complexity. These are evaluated under the same performance areas defined above and categorized into internal (I) and external (E) factors (Table 5). Internal factors are intrinsic to the method and present a property or an integral element of the method. These were proposed to include input data (the scope of data needed to

perform the method), interpretation (easiness of interpretation by decision makers), representativeness (the extent of coverage of SWI traits by the output), and distinctiveness (the extent of uniqueness of a method). On the other hand, external factors are those that influence the method or affect how it is interpreted and used. These were proposed to include independence (whether the method stands alone or requires supporting elements for proper interpretation), framework integration (the applicability of the method in a monitoring framework), and interference (the degree of misanalyses of the results due to interference).

B. Definition of scores and scoring system

A weighing and scoring system is imperative for a semi-quantitative complexity-functionality assessment. While SWOT, MADM or any other assessment method that includes scoring of methods to evaluate SWI impacts has not been reported for benchmarking, a scoring system was proposed to reflect the functionality and complexity of alternatives (Table 5). The scoring ranged from 0 to 3 with 0 representing poor

Table 5  
Scoring system for assessment of alternatives on pre-set criteria and factors.

Scoring range	3	2	1	0
Internal factors				
Input data (C)	Limited	Low	Moderate	High
Interpretation (C)	Guidance	Need help	Need knowledge	Specialized
Representativeness (F)	Comprehensive	Rich	Fair	Limited
Distinctiveness (F)	Integrative	Unique	Share aspects	Redundant
External factors				
Independence (C)	Standalone	Need supplementary data	Complementary	Dependent
Framework (F)	Basic block	Direct	Possible	Limited
Interference/reliability (F)	None	Minimum	Possible	High

C: Complexity; F: Functionality.

**Table 6**  
Summary of descriptive statistics of physio-chemical parameters, ionic ratios and indices for the pilot aquifer across the three sampling periods.

Season parameter <sup>a</sup>	June 2013 (early dry)				October 2013 (late dry)				April 2014 (late wet)				WHO Threshold (2011)
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	
pH	6.4	8.2	7	0.3	6.5	7.73	7.04	0.31	6.71	8.0	7.1	0.22	6.5–8.5
EC	908	47,106	9504	10,468	740.6	65,047	12,008	15,905	1550	65,565	16,391	15,666	
TDS	560	23,320	4610	5088	425.7	31,460	5943	7709	390	32,220	8389	7838	600
Ca <sup>2+</sup>	56	1362	282.7	212.7	32	1190	249	222	14.4	1126	270.7	196	300
Mg <sup>2+</sup>	19.4	1297	229.9	213	14.8	1129.9	246.8	261	11.9	1883	431.7	430	300
TH	450	8740	1651.5	1267	336	7620	1637.6	1548.2	131	10,200	2451.8	2136	
Na <sup>+</sup>	2.27	7000	1132.5	1519	4.24	10,561	1629	2472.5	8.83	9315	2103	2092	200
K <sup>+</sup>	0.53	212	19.7	35	0.87	328.2	45.3	76	1.9	638	83.69	104.9	300
Cl <sup>-</sup>	100	13,080	2358	2818	105	17,670	3203	4312	47.6	19,030	4453.5	4422	300
CO <sub>3</sub> <sup>2-</sup>	0	1	0.019	0.13	0.13	25.6	0.98	4.44	0	0	0	0	
HCO <sub>3</sub> <sup>-</sup>	141.8	493	258.6	65	34.4	460	274.8	73.7	76.4	490	276.2	69.3	
NO <sub>3</sub> <sup>-</sup>	2	219	39.8	30.6	1.7	66.5	27	16.8	0.8	84.8	30.8	17.12	50
SO <sub>4</sub> <sup>2-</sup>	7	2200	391	477	7	2900	418.6	606	7	2750	583.8	592	250
Ionic ratios <sup>b</sup> (based on meq/l)													Criteria <sup>c</sup>
Na <sup>+</sup> /Cl <sup>-</sup>	0.02	1.09	0.529	0.0227	0.044	0.99	0.617	0.273	0.068	1.65	0.78	0.30	≤ 0.86
Cl <sup>-</sup> /HCO <sub>3</sub> <sup>-</sup>	0.778	122.17	18	1.92	0.508	163	24.38	38.25	0.281	178.5	31.76	36.8	20–50
Mg <sup>2+</sup> /Ca <sup>2+</sup>	0.078	4.65	1.47	0.88	0.147	5.3	1.74	1.08	0.1758	13	2.5	1.91	4.5–5.2
Cl <sup>-</sup> /Br <sup>-</sup>	0.017	0.00014	0.0027	0.0003	0.00445	0.00007	0.00117	0.0007	0.005	0.000018	0.0008	0.0009	0.0015
Ca <sup>2+</sup> /(HCO <sub>3</sub> <sup>-</sup> +SO <sub>4</sub> <sup>2-</sup> )	0.315	15.315	1.617	0.146	0.298	10.187	1.3	1.597	0.1778	4.369	0.908	0.638	> 1
SO <sub>4</sub> <sup>2-</sup> /Cl <sup>-</sup>	0	0.803	0.14	0.0009	0.0345	0.7	0.13	0.111	0.018	10.5	0.265	0.995	0.103
GQI <sup>generalized</sup>	25.2	83.7	53.6	1.195	21.27	83.36	52.3	15.46	19.74	83.69	46.55	15.46	
GQI (w/o NO <sub>3</sub> <sup>-</sup> ,TC,FC)	20.2	89.6	61.3	1.61	17.79	91.74	60.1	21.53	18.2	91.2	51.36	22.02	
f <sub>sea</sub>	0.005	0.652	0.118	0.011	0.0052	0.879	0.159	0.214	0.0024	0.947	0.222	0.22	
GQI <sub>SWI</sub>	24.1	86	62.7	1.21	11.25	89.53	59	18.65	8.18	86.9	54	17.8	< 75

<sup>a</sup> All values in mg/l except pH and EC (µs/cm).

<sup>b</sup> Parameters in ratios expressed in meq/l.

<sup>c</sup> Indicators of salinity.

functionality and high complexity while 3 reflects high functionality and low complexity. The score of each criterion (complexity and functionality) was derived by summing the normalized performance score for each contributing factor (internal and external). Normalization was undertaken based on a benefit-criterion system (Chang and Huang, 2006) then the average normalized score of each criterion was used as a benchmark value to calculate the overall weighted score for direct comparison among assessment alternatives over a complexity and functionality numerical scale.

#### C. Framework development

Based on method effectiveness, a framework for the assessment of the impact of SWI was developed. It consists of several assessment methods to be undertaken in series and/or in parallel to provide an adequate understanding of the SWI extent towards informed aquifer management. The initial selection allows the identification of methods applicable to the aquifer of interest. Then, the testing of these methods allows the evaluation of the role and contribution of each method in assessing the impact of SWI. The semi-quantitative approach sheds light on advantages, disadvantages, limitations and effectiveness of each method and identify those that should define a framework with minimal complexity, highest functionality in terms of water quality characterization, spatially able to capture the aquifer heterogeneity, and easy to understand by decision makers.

## 4. Results and discussion

### 4.1. Application and testing of metrics

#### 4.1.1. Physiochemical parameters: groundwater quality and spatiotemporal effects

Summary statistics of the physio-chemical characteristics of the groundwater (GW) in the pilot aquifer are presented in Table 6. Groundwater of neutral pH and (sub)oxic redox potential (having

oxidation-reduction reactions at low oxygen levels) dominated during all seasons. High variability was observed for TDS in and between seasons ranging from 390 ppm (fresh GW) (June) to as high as 32,220 ppm (highly saline GW) (April), with only 21% of samples showing fresh to slightly saline water quality (< 1500 ppm). A statistically significant increase in TDS values ( $p < 0.001$ ) reaching ~35% was observed in the late dry sampling (October) round in comparison with the early dry (June) sampling. Similarly, based on the Cl<sup>-</sup> classification, only 14% of groundwater samples reported fresh to slightly saline quality (< 250 ppm), whereas the majority of samples exhibited saline to highly saline water quality.

Reduced recharge<sup>4</sup> coupled with continuous groundwater abstraction explains the increase in EC, TDS and Cl<sup>-</sup> in April 2014, as compared to June 2013. A significant intra-variability was observed in samples collected in April 2014 where fresh and highly saline groundwater was reported to exist concurrently but spatially apart. This variability hints towards the possibility of having two major groundwater hydrosomes, where one has undergone freshening, probably due to a decrease in abstraction rates that balanced the reduced recharge driven by the drought, while the other suffered from increased SWI caused by continuous abstraction driven by the lack of water exacerbated by the drought (Fig. 3).

Fig. 3 was generated using the geostatistical analysis and interpolation tool within the GIS. Ordinary kriging was applied to present and analyze TDS and Chloride measurements at sampled locations and extrapolate concentrations based on spatial autocorrelations between neighboring observation points to non-sampled locations. The geostatistical analysis allowed the generation of predictive maps over the entire domain to visually emphasize hotspots spatially and temporally. An exponential semi-variogram model (nugget of 0.22, range of 190 m and RMSSE of 1.2) was used for lognormal transformed TDS data while

<sup>4</sup> Due to an unusually dry 2013/2014 wet season (with total precipitation ~50% lower than the annual average).

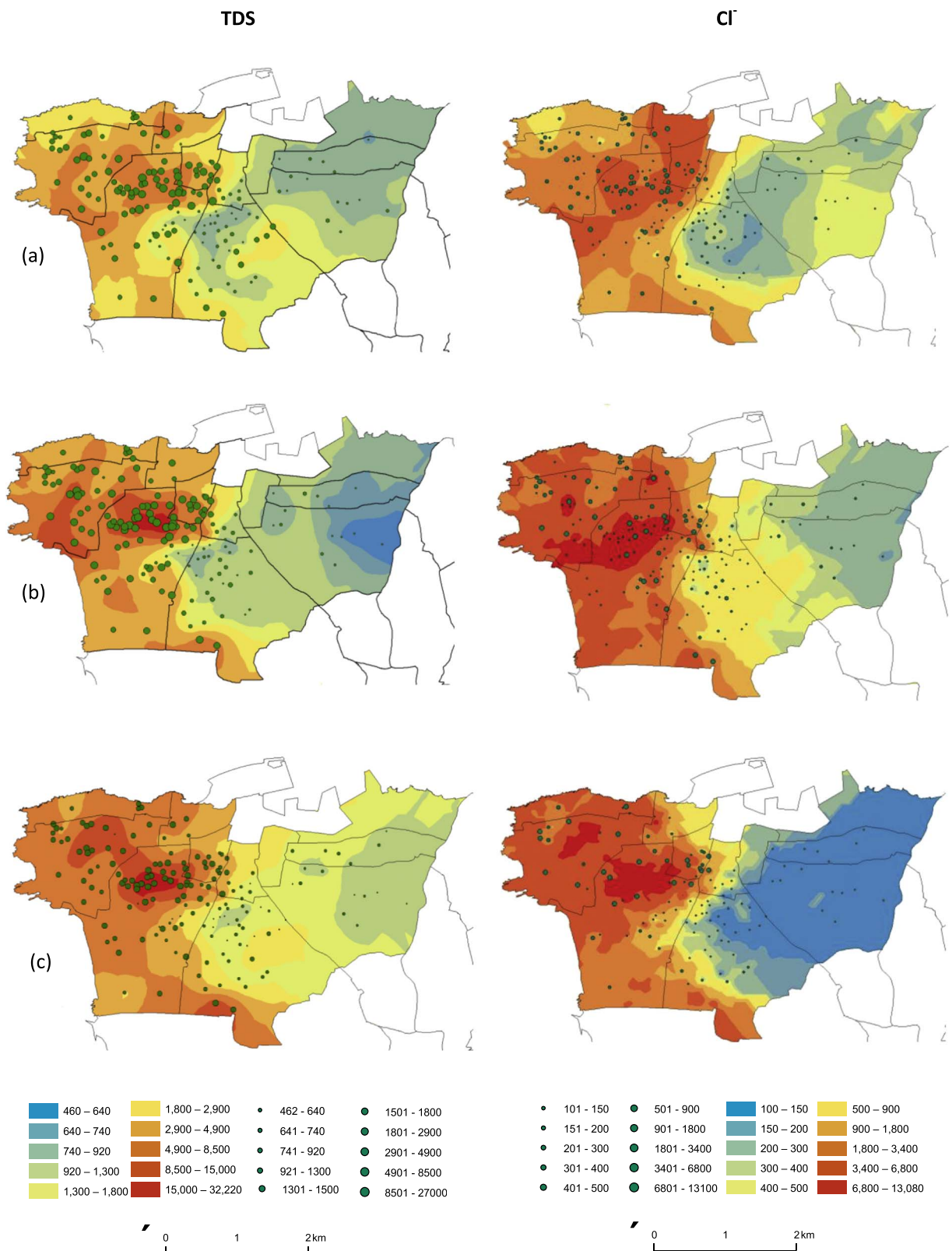


Fig. 3. Spatial and temporal distribution of TDS (ppm) and Cl<sup>-</sup> (mg/l) in the pilot aquifer a) early dry season - June 2013, b) late dry season - October 2013 and c) late wet season - April 2014.

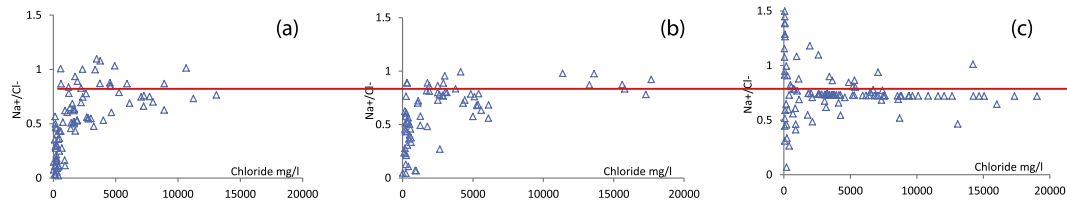


Fig. 4.  $\text{Na}^+/\text{Cl}^-$  ratio (based on meq/l) versus  $\text{Cl}^-$  (mg/l) for a) June, b) October and c) April. The redline represents the salinity indicator value of 0.86.

a spherical model (nugget of 0.28, range of 210 m and RMSSE of 1.5) was used for lognormal transformed chloride data.

#### 4.1.2. Correlation analysis, indicator ratios and geochemical processes

The various ionic ratios indicated a wide variability within seasons, particularly in April, generally indicating an increasing trend of salinity from June to April (Table 6). The mean  $\text{Na}^+/\text{Cl}^-$  ratio, the symptomatic indicator of seawater intrusion, was at or below 0.86 for all seasons, suggesting well-developed SWI. Fig. 4 shows that in June, samples with  $\text{Cl}^- < 1000$  mg/l generally had a  $\text{Na}^+/\text{Cl}^-$  ratio of  $< 0.6$  whereas samples with  $\text{Cl}^- > 1000$  mg/l were scattered around the 0.86 value. The October samples with  $\text{Cl}^- < 1000$  mg/l migrated upwards on the plot. In April, the samples were divided in two envelopes: one saline and another fresh suggesting their concomitant existence.

The positive values of the seawater fraction or mixing rate ( $f_{\text{sea}}$ ) and its wide range suggest considerable seawater–freshwater mixing within the aquifer (Table 6). It also indicates the coexistence of fresh and highly saline waters. Overall, the mixing rate increased ( $p = 0.001$  – Repeated Measures Anova) from June (11.8%) to October (15.9%), suggesting greater mixing along this timeline. Inter-elemental correlations showed that in June, TDS was highly correlated to  $\text{Cl}^-$ ,  $\text{Na}^+$ ,  $\text{SO}_4^{2-}$  and  $\text{Mg}^{2+}$ , suggesting signs of early salinization. In October and April, the TDS exhibited a stronger correlation with the same ions suggesting further salinization. The scatter of  $\log\text{TDS}$  as a function of  $\log\text{Cl}^-$  and of  $\log\text{Cl}^-$  versus  $\log\text{Na}^+$  (See Supplementary material Fig. S1) reveals a strong correlation in all sampling rounds, suggesting that  $\text{Na}^+$  and  $\text{Cl}^-$  have the same seawater origin.

The ionic changes/deltas for major ions also exhibited spatial and temporal variability indicating patterns of deficiency and surplus of the same ion over the entire study area and across seasons (See Supplementary material Table S1). While this reflects a groundwater experiencing mixing with seawater however the complexity of the hydrochemical changes such as the dissolution of gypsum and carbonate, de-dolomitization, direct and indirect cation exchange, as well as other potential sources limits clear conclusions from the observed changes in ionic deltas.

The piper diagram (Fig. 5) reveals the presence of secondary saline water (hydrogeochemical domain V i.e.  $\text{CaCl}$ ) as well as primary saline water (hydrogeochemical domain II i.e.  $\text{NaCl}$ ) in June with the predominance of groundwater quality of the  $\text{Cl}^- - \text{SO}_4^{2-} - \text{Na}^+ + \text{K}^+ - \text{Mg}^{2+} - \text{Ca}^{2+}$  type. In October, the water was of the  $\text{Cl}^- - \text{Na}^+ + \text{K}^+ - \text{Mg}^{2+}$  type. Ion exchange and migration of samples from secondary saline water (domain V) to primary saline water (domain II) are observed when the mixed  $\text{CaMgCl}$  water type (domain IV) is detected. In April, three major water types were identified: freshwater (domain I, i.e.  $\text{CaHCO}_3$ ), seawater (domain II, i.e.  $\text{NaCl}$ ) in addition to domain IV (i.e. mixed  $\text{CaMgCl}$ ). This highlights the occurrence of freshening processes in April and also confirms the occurrence of fresh and saline water concomitantly, albeit with spatial variability (Figs. 3 and 6).

Water types as classified by the Stuyfzand method were mapped against the area's geology to explain potential relationships between spatial and temporal processes at play and the geological characteristics of the aquifer. Fig. 6 shows that in October, fresh, fresh-brackish and brackish waters were observed in the Eastern districts within both the quaternary and tertiary geological formations, while brackish saline water was observed in the western districts with selected pockets of saline water. It also illustrates the spatial heterogeneity of the groundwater quality in April where two main phenomena are observed: a) freshening processes occurring in the northeastern part (dilution of brackish and fresh-brackish water to fresh water) within the Miocene formations, and b) persisting salinization in the western districts with potential upconing of saline water particularly in the southwestern part within the Quaternary and Cenomanian formations. The disruption in the salinization in the eastern flanks of the aquifer coupled with the persistence of pumping in the 2014 late dry to early wet season, support either that 1) the pumping rates during this period dropped due to increased water supply from the public network, or 2) that groundwater recharge happens earlier and/or faster in that sector, potentially as a result of lateral flow from the north-northeastern highlands and/or the Beirut River, or 3) the impact of the degree of heterogeneity and complexity of fractured networks, or 4) the role of the geology particularly that the eastern flanks are characterized by an upper Miocene layer, or 5) that the study area consists of two aquifers responding

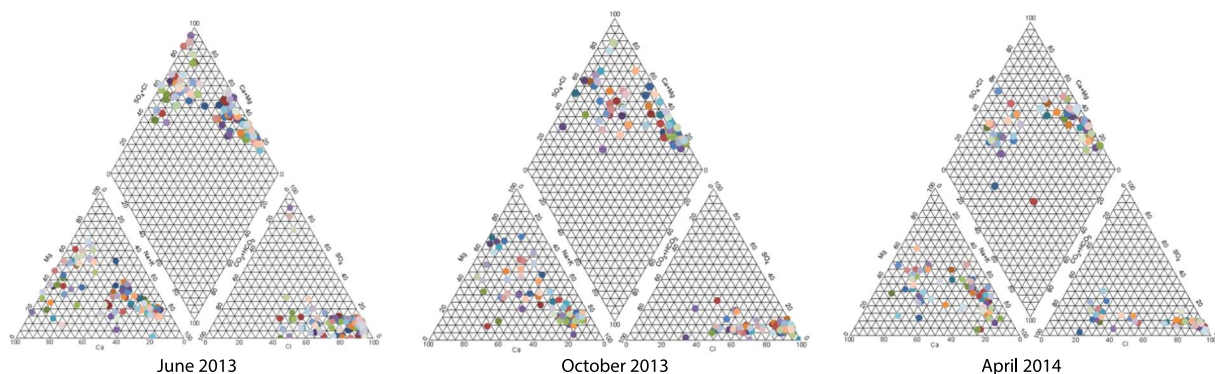


Fig. 5. Piper diagram for the pilot aquifer. Each circle represents a well.

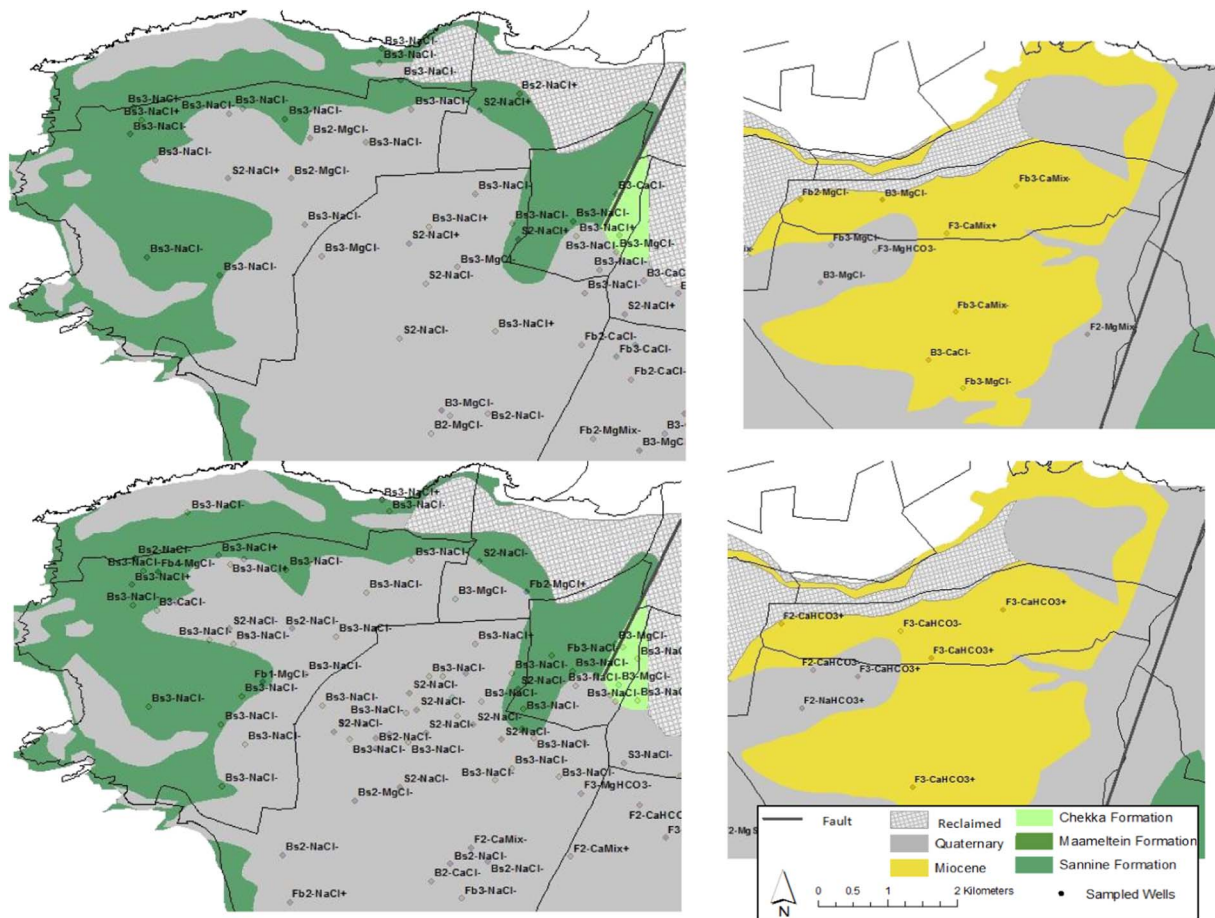


Fig. 6. Water types based on Stuyfzund classification for the western (left) and northeastern (right) parts of the pilot aquifer for late dry - October (upper) and late wet - April (lower). F: fresh; Fb: fresh-brackish; B: brackish; Bs: brackish-saline; S: saline – See Table 4.

differently and independently to similar stimulus. Further aquifer characterization and additional data on recharge, water level and water supply are needed to ascertain the interpretation of the results.

#### 4.1.3. Groundwater quality indices

The generalized GQI (Table 6) exhibited average water quality for the three sampled seasons albeit with spatial heterogeneity. Fig. 7 shows that the eastern zones tend to have better water quality under the three indices as compared to the western zones, with a general trend of degrading quality from June to October to April. This figure was generated using the geostatistical analysis and interpolation tool within GIS where ordinary kriging was first applied to the relevant water quality parameters and the GQI indices were then calculated from the predicted median concentrations in a two-step process (Tomaskiewicz et al., 2014; Babiker et al., 2007) to generate predictive maps of pollution and salinity hotspots spatially and temporally. When removing the health-based water quality indicators (e.g. nitrates, total and fecal coliform) (Fig. 7b), an improvement in water quality is observed in June suggesting that nitrates and fecal coliforms may be responsible for the low generalized GQI unlike October that showed no improvement (except in the eastern zones).

The  $GQI_{SWI}$  impact mapping (Fig. 7c) demonstrates that the SWI is more developed in October and April, particularly in the western zones. Repeated measures ANOVA showed that the  $GQI_{SWI}$  values differed significantly between seasons whereby post hoc tests using the Bonferroni correction revealed a statistically highly significant decrease between June and October ( $p < 0.001$ ) and June and April ( $p < 0.001$ ). The  $GQI_{SWI}$  recaps and confirms the spatio-temporal impacts of SWI, particularly in terms of saline freshwater mixing

dynamics and the hydro-geochemical domains.

#### 4.2. Evaluation of methods towards an assessment framework

Table 7 summarizes the qualitative SWOT analysis of the methods used to assess SWI. Table 8 summarizes the quantitative scoring of these methods based on their performance against set internal and external factors for SWOT and visually illustrates the evaluation on a numeric scale. While most parameters are good indicators of salinity, the type, scope and reliability of the results vary significantly. The variability was inherent among parametric versus composite methods in terms of complexity, feasibility, and ability to represent SWI impacts. However, the specificity of how each method is able to uniquely represent different aspects of SWI and the supplementary nature of outputs of the various parametric methods are also perceptible.

Simple indicators such as TDS,  $Cl^-$  and the seawater fraction act as a quick first screening of salinity while only hinting to its source. Nevertheless, being relatively easy to undertake, they form good candidates for monitoring and constitute a main building block in a SWI assessment framework. Hydrochemical ratios and the piper diagram add another layer of information to ascertain sources of salinity highlighting the impact of SWI, as well as interpret geochemical reactions to define water types and evolution. Ionic deltas, saturation and BEX/CAI indices provide input on geochemical reactions and their direction; however, they are data demanding requiring the knowledge of rock formations and on-going reactions to avoid misunderstandings due to interferences; hence, can only be useful if the aquifer is well characterized and understood particularly in terms of rock-water interactions.

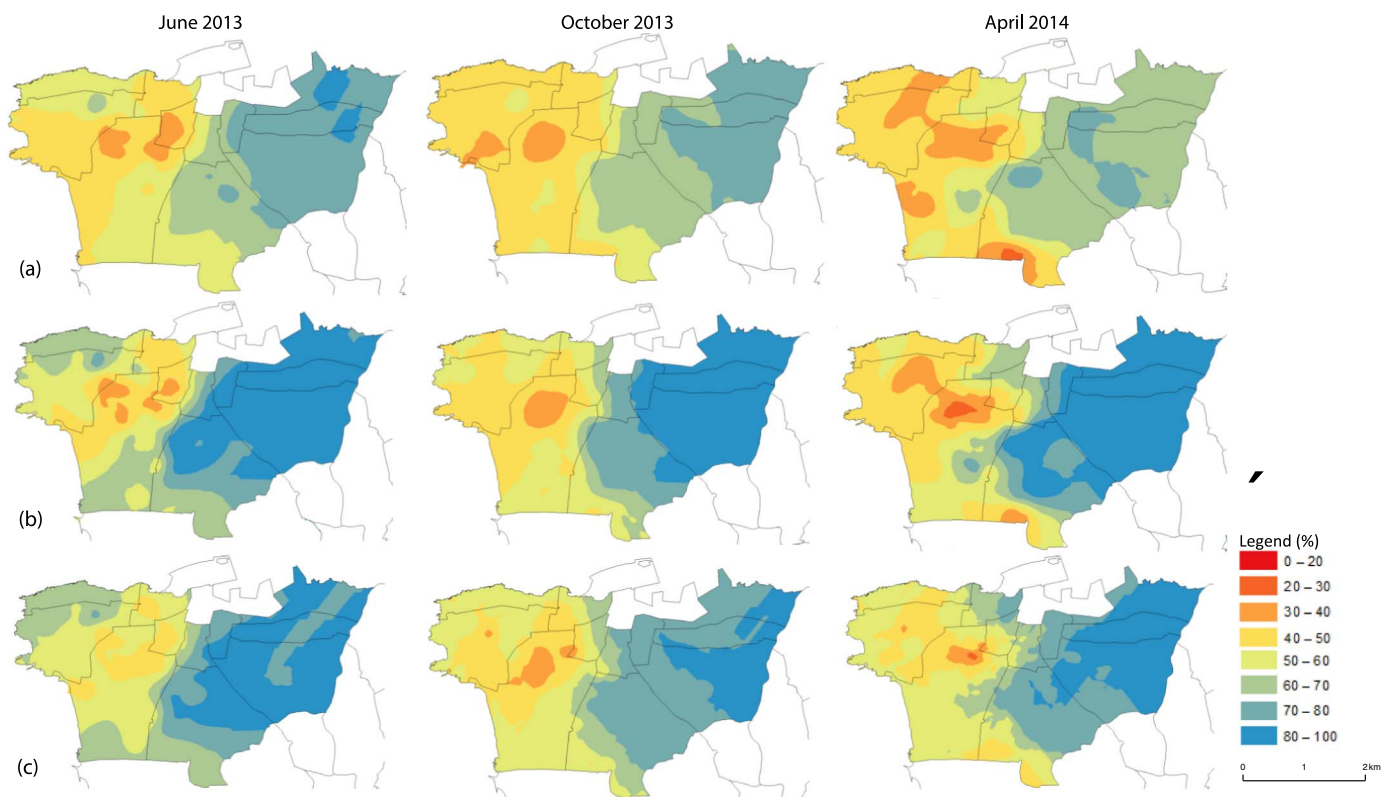


Fig. 7. Groundwater quality indices (GQI).

a) Generalized GQI; b) Generalized GQI without  $\text{NO}_3^-$ , Fecal and Total Coliform; c) Specific  $\text{GQI}_{\text{SWI}}$ .

The Piper diagram, acting here as a surrogate of hydrochemical diagrams, is also based on individual parameters and delivers multiple layers of information with a visual aspect that resonates with decision makers. The Stuyfzand hydrochemical classification, while comparable to the Piper diagram, is more data dependent yet also provide more layers of information. Being integrative, this composite index can also act as a standalone tool that encompasses most aspects of SWI. However, it is complex to undertake and also difficult to interpret. Nevertheless, its relative complexity is compensated for with high functionality.

The generalized water quality indicators act as a final layer of confirmation of water quality serving as a one-stop shop that can be easily plotted to show spatio-temporal evolution of the quality in general (GQI) and of the impact of SWI in particular ( $\text{GQI}_{\text{SWI}}$ ) for informed decision making. While both the GQI and the  $\text{GQI}_{\text{SWI}}$  are similar in their complexity, the  $\text{GQI}_{\text{SWI}}$  is a standalone robust and integrative tool for SWI assessment and monitoring. The embedded geo-statistical analysis offers the advantage of visual interpretation coupled with temporal and spatial representation of parameters and processes.

Based on input from the field application and results, the qualitative SWOT analysis coupled with the semi-quantitative overall assessment, a framework is suggested for the assessment of SWI impacts in less characterized heterogeneous aquifers. As adopting a suite of methods to assess the impact of SWI reduces the uncertainty that may obscure the interpretation of results (Garing et al., 2013; Vengosh, 2003), this framework is based on the concentrations of chloride, total dissolved solids (TDS) and electrical conductivity (EC), the seawater fraction ( $f_{\text{sea}}$ ), the piper hydro-chemical diagram, the Stuyfzand's hydrochemical classification, and the SWI specific  $\text{GQI}_{\text{SWI}}$ . It requires groundwater sampling and lab analysis of major ions ( $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{Na}^+$  and  $\text{K}^+$ ) and TDS/EC. Measurements of  $\text{Br}^-$  and  $\text{NO}_3^-$  ions are optional, though recommended, particularly for eliminating other potential sources of pollution. TDS and EC are correlated

and can be used interchangeably. They are also correlated with  $\text{Cl}^-$ . While a high  $\text{Cl}^-$  concentration can alone hint to salinity, this is not true for TDS and EC which represent a suite of all ions and charges. Nevertheless,  $\text{Cl}^-$  coupled with TDS or EC should be a starting point for a SWI assessment. The seawater fraction is also correlated to  $\text{Cl}^-$ ; however, its unique representation of the freshwater-saline water mixing differentiates it from the mere measurement of  $\text{Cl}^-$  concentration in groundwater, which might also point to other pollution sources. Here, the hydrochemical ratios become handy. Ratios will also consist part of this framework, capitalizing on their high score on simplicity despite their low score on functionality, as they can give insights on pollution sources and help understand interactions that confirm or invalidate conclusions of the TDS/EC and  $\text{Cl}^-$  concentrations.

Plotting concentrations of major ions on the piper diagram allows direct inference on the water type and the hydrochemical reactions at each sampling point which is a very effective visual summary of concentrations, reactions, and water type. Coupling the piper diagram and the seawater fraction, the  $\text{GQI}_{\text{SWI}}$  further validates the salinization progress into the aquifer as well as allows a spatio-temporal representation of this progress. The framework's elements provide a good understanding of the freshwater-saline water mixing dynamics in the aquifer and can stand alone as a comprehensive assessment tool of the SWI impact (Fig. 8). The metrics complement one another as each contributes different input layers to the analysis of processes, dynamics and impact of SWI within the aquifer. This ensures that results are double-checked against one another, while optimizing resources, input data and time. Further, interpretation through the Stuyfzand method, despite its relative complexity, can lead to additional detailed valuable knowledge about the aquifer of study. While this method does not necessarily have to be part of the assessment framework to be effective, it ensures a complete analysis cycle. Since it is a composite method, its main advantage is in summarizing levels of data and providing a profile of groundwater quality, and can be easily represented spatially and

**Table 7**  
Contribution, advantages and disadvantages of indicators, indices and assessment methods.

Method factors	Strengths	Weaknesses	Opportunities	Threats
TDS, Cl <sup>-</sup> , EC concentrations	<ul style="list-style-type: none"> <li>- Limited input data</li> <li>- Quick first assessment</li> <li>- Common simple indicator of salinity</li> </ul>	<ul style="list-style-type: none"> <li>- No input on process, source or geochemical reactions</li> </ul>	<ul style="list-style-type: none"> <li>- Integral building block of framework</li> <li>- Useful for monitoring</li> <li>- Easy test</li> </ul>	<ul style="list-style-type: none"> <li>- Can be misinterpreted if not complemented by other detailed/advanced analysis</li> </ul>
Hydrochemical ratios	<ul style="list-style-type: none"> <li>- Low to moderate input data</li> <li>- Good indicators of reactions, direction of reactions and pollution source</li> <li>- Good indicators of salinity &amp; SWI</li> <li>- Limited input data</li> <li>- Quick first assessment</li> <li>- Common simple indicator of salinity</li> <li>- Useful for monitoring</li> <li>- Presents geochemical reactions and changes</li> </ul>	<ul style="list-style-type: none"> <li>- Weak but could be used in interpreting geochemical reactions</li> <li>- A suite of ratios is needed for complete representation</li> <li>- Presents concentration only</li> <li>- Doesn't represent geochemical reactions</li> </ul>	<ul style="list-style-type: none"> <li>- Relies on conservative nature of Cl<sup>-</sup>, Na<sup>+</sup>, Br<sup>-</sup></li> <li>- Relatively easy to test</li> <li>- Useful for monitoring</li> <li>- Relies on conservative nature of Cl<sup>-</sup></li> <li>- Easy test</li> </ul>	<ul style="list-style-type: none"> <li>- Due to overlapping ranges, values may mask or over-represent SWI</li> <li>- Can be misinterpreted if rock-water reactions are not understood</li> <li>- Could be misinterpreted for SWI as it does not consider the effects of geochemical reactions</li> <li>- High sensitivity to Cl<sup>-</sup> may overestimate SWI</li> </ul>
Seawater fraction	<ul style="list-style-type: none"> <li>- Limited input data</li> <li>- Quick first assessment</li> <li>- Common simple indicator of salinity</li> <li>- Useful for monitoring</li> <li>- Presents geochemical reactions and changes</li> </ul>	<ul style="list-style-type: none"> <li>- Require input data and prior knowledge</li> </ul>	<ul style="list-style-type: none"> <li>- Useful for understanding rock-water interactions</li> <li>- Indicates paths of evolution of reactions</li> <li>- Visual aid for decision makers</li> <li>- Relatively easy to undertake</li> </ul>	<ul style="list-style-type: none"> <li>- High potential for interference due to multiple pathways for rock water interactions</li> <li>- Require aquifer understanding</li> <li>- Focus only on major parameters</li> <li>- Not readily spatially mapped</li> <li>- Could be misinterpreted</li> </ul>
Ionic deltas Saturation indices	<ul style="list-style-type: none"> <li>- Limited input data</li> <li>- Quick first assessment</li> <li>- Common simple indicator of salinity</li> <li>- Useful for monitoring</li> <li>- Presents geochemical reactions and changes</li> </ul>	<ul style="list-style-type: none"> <li>- Require input data and prior knowledge</li> </ul>	<ul style="list-style-type: none"> <li>- Useful for understanding rock-water interactions</li> <li>- Indicates paths of evolution of reactions</li> <li>- Visual aid for decision makers</li> <li>- Relatively easy to undertake</li> </ul>	<ul style="list-style-type: none"> <li>- High potential for interference due to multiple pathways for rock water interactions</li> <li>- Require aquifer understanding</li> <li>- Focus only on major parameters</li> <li>- Not readily spatially mapped</li> <li>- Could be misinterpreted</li> </ul>
Piper hydrochemical diagrams	<ul style="list-style-type: none"> <li>- Graphical representation</li> <li>- Represent water types reflecting intensity of salinity contamination</li> <li>- Indicates paths of evolution of water types</li> <li>- Good indicators of reactions, direction of reactions, pollution source and water type</li> <li>- Comprehensive integrative standalone indicator</li> </ul>	<ul style="list-style-type: none"> <li>- Only generally indicates geochemical changes</li> </ul>	<ul style="list-style-type: none"> <li>- Comprehensive representation of water type</li> <li>- Can be easily plotted</li> <li>- Translate major parameters into one indicator</li> </ul>	<ul style="list-style-type: none"> <li>- Focus only on major parameters</li> <li>- Not readily spatially mapped</li> <li>- Could be misinterpreted</li> </ul>
Stuyfzund hydrochemical classification	<ul style="list-style-type: none"> <li>- Good indicators of reactions, direction; pollution source</li> <li>- Test pollution by NO<sub>3</sub>, TC and FC</li> <li>- Good indicators of reactions, direction; pollution source</li> <li>- Comprehensive integrative standalone indicator</li> <li>- Specific to SWI</li> </ul>	<ul style="list-style-type: none"> <li>- Heavily relies on data</li> <li>- Not easy to interpret</li> </ul>	<ul style="list-style-type: none"> <li>- Easy to calculate and interpret</li> <li>- Translate major parameters into one indicator</li> <li>- Easy to calculate and interpret</li> <li>- Translate major parameters into one indicator</li> </ul>	<ul style="list-style-type: none"> <li>- Could be misinterpreted with no specialized help</li> </ul>
GQI generalized	<ul style="list-style-type: none"> <li>- Good indicators of reactions, direction; pollution source</li> <li>- Test pollution by NO<sub>3</sub>, TC and FC</li> <li>- Good indicators of reactions, direction; pollution source</li> <li>- Comprehensive integrative standalone indicator</li> <li>- Specific to SWI</li> </ul>	<ul style="list-style-type: none"> <li>- Relies on concentrations of all major ions</li> </ul>	<ul style="list-style-type: none"> <li>- Easy to calculate and interpret</li> <li>- Translate major parameters into one indicator</li> <li>- Easy to calculate and interpret</li> <li>- Translate major parameters into one indicator</li> </ul>	<ul style="list-style-type: none"> <li>- Presents general groundwater quality but not SWI</li> <li>- Needs to be complemented</li> </ul>
GQI <sub>SWI</sub>	<ul style="list-style-type: none"> <li>- Good indicators of reactions, direction; pollution source</li> <li>- Test pollution by NO<sub>3</sub>, TC and FC</li> <li>- Good indicators of reactions, direction; pollution source</li> <li>- Comprehensive integrative standalone indicator</li> <li>- Specific to SWI</li> </ul>	<ul style="list-style-type: none"> <li>- Relies on concentrations of all major ions</li> </ul>	<ul style="list-style-type: none"> <li>- Easy to calculate and interpret</li> <li>- Translate major parameters into one indicator</li> <li>- Easy to calculate and interpret</li> <li>- Translate major parameters into one indicator</li> </ul>	<ul style="list-style-type: none"> <li>- Presents general groundwater quality and SWI</li> </ul>

**Table 8**  
Summary of performance of methods against internal (I) and external (E) factors and corresponding scores.

Method criteria	Complexity/simplicity			Representativeness (I)	Functionality		
	Input data (I)	Interpretation (I)	Independence (E)		Distinctiveness (I)	Integration in framework (E)	Interference (E)
TDS, EC, Cl <sup>-</sup>	Limited	Guidance	Needs supplementary	Limited	Share aspects	Basic block	Minimum
Hydrochemical ratios	Low	Need help	Needs supplementary	Fair	Share aspects	Direct	High
Seawater fraction	Limited	Guidance	Needs supplementary	Limited	Unique	Basic block	Minimum
Ionic deltas	Moderate	Need knowledge	Complementary	Fair	Share aspects	Possible	High
Saturation indices	Moderate	Need knowledge	Complementary	Fair	Unique	Possible	High
BEX and CAI	Low	Need help	Complementary	Fair	Share aspects	Direct	High
Hydro-chemical diagrams	Moderate	Need help	Standalone	Rich	Share aspects	Direct	Minimum
Stuyfzund method	High	Specialized	Standalone	Comprehensive	Integrative	Direct	None
GQI	Moderate	Guidance	Dependent	Comprehensive	Share aspects	Possible	Possible
GQI <sub>SWI</sub>	Moderate	Guidance	Standalone	Comprehensive	Integrative	Direct	Possible
Inference statistics	Varies	Varies	Varies	Rich	Integrative	Limited	Possible
Geospatial analyst	Varies	Guidance	Dependent	Rich	Unique	Direct	Varies

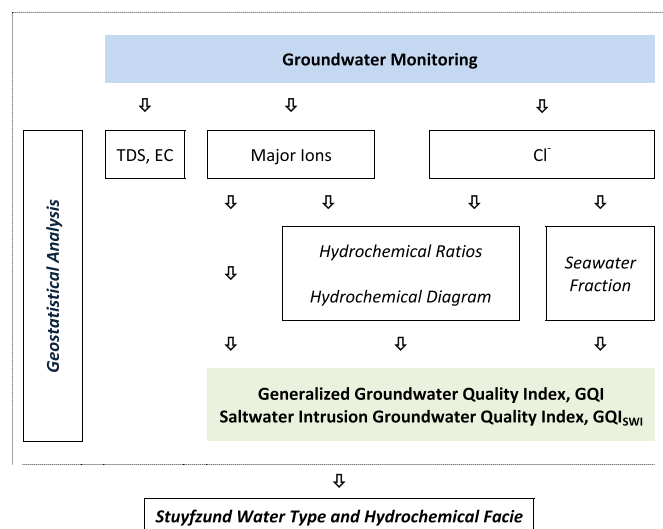
  


Fig. 8. Elements of proposed framework.

becomes handier if plotted temporally.

Put to test in a highly exploited heterogeneous coastal aquifer, this framework allowed the understanding of the spatio-temporal dynamics and impacts of SWI processes, provided a reliable baseline of the salinization status, and facilitated monitoring of the SWI impact over spatial and temporal domains while minimizing potential interferences by triangulating the results. As such, it aided in understanding that the occurrence and intensity of SWI in the pilot aquifer is shaped by multiple factors including the heterogeneous nature of the aquifer, the geologic characteristics (faults/flanks), and groundwater abstraction. Hence, the framework represents a starting point for planning and decision-making in strategic impact assessment towards improved groundwater management in coastal aquifers.

### 5. Conclusion

Common methods used in assessing the impact of SWI (saltwater intrusion) were examined to develop a novel effective assessment framework for managing coastal aquifers underlying densely populated urban areas. For this purpose, a qualitative assessment of complexity and functionality was first followed to select alternative methods that were tested and verified at an overexploited heterogeneous aquifer along the Eastern Mediterranean. A semi-quantitative CFA (complexity functionality assessment) coupling SWOT (strengths, weaknesses, opportunities and threats) and MADM (multi-attribute decision making) analyses was then developed and used to evaluate the effectiveness of various methods in scrutinizing the impact of SWI based on predefined criteria. Capitalizing on the characteristics of an indicator-index and its advantages, and complementing it with other indicators-indices to overcome associated uncertainties, provided a more reliable assessment framework of the intensity, ubiquity, persistence, and reversibility of SWI impacts. The framework of hydrogeochemical metrics (chloride, total dissolved solids (TDS) or electrical conductivity (EC) concentrations, the seawater fraction ( $f_{sea}$ ), the piper hydro-chemical diagram, the SWI specific GQI<sub>SWI</sub>, and the Stuyfzand's hydrochemical classification) coupled with geostatistical analysis was advanced to interpret complex groundwater quality data and examine the scale and magnitude of the impact of SWI and its dynamics in heterogeneous aquifers. Such a framework provides a platform for informed impact assessment and sustainable exploitation of coastal aquifers reducing the gap between SWI knowledge on one side and management needs for practice and implementation on the other. Efforts are on-going to further test this framework in other heterogeneous aquifers along the Eastern Mediterranean, to assess emerging saline aquifers moderately exploited for agricultural or domestic purposes.

While utilizing well established and commonly used techniques to assess SWI, this study presented a first attempt at examining these techniques in a systematic, transferable, repeatable and verifiable process through the development and application of qualitative and semi-quantitative criteria. Similarly, it is the first to apply SWOT and MADM analysis to SWI where 'fit for purpose' assessment techniques were identified based on functionality

and simplicity. In effect, this study has provided a systematic approach to the assessment of SWI and developed an effective assessment framework for managing coastal aquifers, including complex aquifers with data scarcity.

## Acknowledgements

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.eiar.2017.08.001>.

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