Environmental Impact Assessment Review 67 (2017) 10–22

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

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

G. Rachid, M. El-Fadel*, M. Abou Najm, I. Alameddine

Department of Civil & Environmental Engineering, American University of Beirut, Lebanon

ARTICLE INFO

Keywords:
Coastal aquifers
Saltwater intrusion
Impact assessment

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

* Corresponding author.
E-mail address: mfadel@aub.edu.lb (M. El-Fadel).

http://dx.doi.org/10.1016/j.eiar.2017.08.001
Received 6 February 2017; Received in revised form 1 July 2017; Accepted 5 August 2017

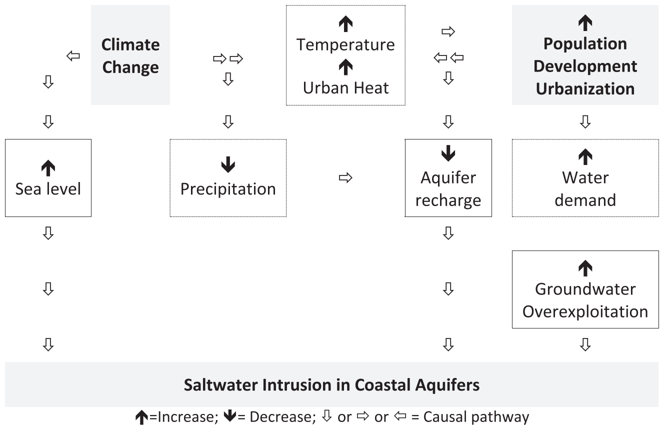

Fig. 1. General dynamics of saltwater intrusion driving processes. ↑ = Increase; ↓ = Decrease; ⇩ or ⇨ or ⇦ = Causal pathway.

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.

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. Concurrently, 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 asses 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 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. *relatively specialized, specialized, highly specialized*)
	Accessibility and availability	Relative level of accessibility/availability and feasibility in terms of requirements for sampling and analysis; challenges (i.e. *feasible/expensive; readily accessible/challenging*)
	Decision makers friendly	Ease of use by decision makers (i.e. *easy, medium, complex*)
Functionality	Output of the method	Level of contribution to understand the different aspects of SWI (spatial distribution, geochemical reactions, hydrochemical facies etc.) (i.e. *limited, varies, wide*)
	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*)