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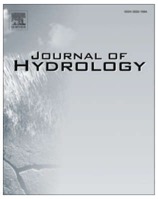

Research papers

# Assessing the risk of saltwater intrusion in coastal aquifers

J. Klassen, D.M. Allen *

Department of Earth Sciences, Simon Fraser University, British Columbia, Canada

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ABSTRACT

In coastal regions, the quality of groundwater can be compromised due to saltwater intrusion (SWI) caused by natural (sea level rise (SLR) and storm surge) and anthropogenic (pumping) hazards. The goal of this research was to develop and test an approach for assessing the risk of SWI in coastal aquifers. The Gulf Islands in British Columbia (BC) was the case study area. The vulnerability of the bedrock aquifers to SWI was assessed spatially by mapping hazards in combination with the aquifer susceptibility. Climate change related hazards, including SLR and storm surge overwash, were integrated into floodplain maps for each island using projected SLR data for 2100 in combination with estimated storm surge levels based on data collected over a forty year period. When combined with maps showing the density of pumping wells, coastal zones that may be at higher risk of SWI were identified for this particular coastal area of BC. Hazards due to pumping have the greatest influence on the vulnerability. Risk was evaluated spatially using an economic valuation of loss – here replacement of a water supply. The combination of chemical indicators of SWI and risk assessment maps are potentially useful tools for identifying areas vulnerable to SWI, and these tools can be used to improve decision-making related to monitoring and community development for coastal areas, thereby increasing resilience.

## 1. Introduction

About seventy percent of the world's population resides in coastal regions (Webb and Howard, 2011). Eight out of the ten largest cities in the world are located along a coast, resulting in a total of 2.2 billion people worldwide living 100 km from a coast (United Nations Atlas of the Oceans, 2010, 2013). Moreover, the population density in coastal regions is about three times greater than the global average (Small and Nicholls, 2003). Thus, currently there is a high demand for freshwater in coastal aquifers globally, which adds stress to the natural system (e.g. Barlow and Reichard, 2010; Bocanegra et al., 2010; Custodio, 2010; Steyl and Dennis, 2010; Werner, 2010; White and Falkland, 2010), potentially leading to water insecurity. In many parts of the world, however, groundwater information is lacking and monitoring networks are insufficient for identifying long term trends in groundwater quality and quantity. Moreover, the interactions between fresh and saline water in coastal aquifers involve complex density-dependent flow and hydrochemical processes that are inherently difficult and expensive to investigate and monitor (Werner, 2010). The already delicate hydrological balance that maintains the position of the freshwater-saltwater interface in a coastal aquifer will be impacted by climate change (Turner et al., 1996) as well as by an increased demand for freshwater in the future (Post, 2005). Therefore, approaches are needed to assess water security in coastal areas so that appropriate measures can be put in place to assure long term sustainability of the resource.

A range of approaches have been applied for assessing the vulnerability of coastal aquifers to saltwater intrusion (SWI) – the process by which a freshwater aquifer becomes salinized due to natural or anthropogenic stresses. Regional assessments typically have been carried out using some vulnerability indexing method, the most common being the GALDIT method (Lobo-Ferreira et al., 2007). Recognizing "the subjectivity and lack of theoretical underpinnings in converting hydrogeological characteristics into vulnerability to SWI", Werner et al. (2012) proposed a quantitative indexing approach, based on the fundamental theoretical principles of saltwater intrusion, to assess vulnerability. Rates-of-change in the wedge toe or sea water volume were used to quantify the aquifer vulnerability to various stress situations. They applied the method to a selection of case study areas for which a range of hydrogeological parameters were available. Ferguson and Gleeson (2012) similarly applied an analytical solution in combination with a geographic information system (GIS) to assess the vulnerability of coastal aquifers in the contiguous United States to groundwater extraction and climate change. Hydraulic gradients were estimated by dividing the maximum simulated water-table elevation by the distance to the coastline, and parameter values

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* Corresponding author at: Department of Earth Sciences, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada.

*E-mail address:* dallen@sfu.ca (D.M. Allen).

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were derived from the GIS synthesis or taken from the literature. At smaller scales, numerical simulations using density-dependent flow and transport models are commonly used to evaluate the responses of coastal aquifers to stresses (e.g. Sanford and Pope, 2010, among others). Numerical models offer perhaps the most robust means to evaluate the impact of stressors on saltwater intrusion; however, their application at large scales remains problematic. Sanford and Pope (2010) conclude that "even with current computer capabilities, accurate numerical simulations of concentrations within a regional-scale (many km) transition zone are computationally prohibitive". Thus, while the quantitative approaches are arguably improvements over the basic indexing methods, their application at a regional scale is limited because they rely on parameter estimates that often are not available in sparsely populated areas, and if they are, they carry a lot of uncertainty. Moreover, a high degree of expertise is needed to implement these methods, and therefore they may be cost prohibitive to implement. These limitations suggest that simpler indexing methods still have their place in vulnerability assessments, particularly for screening purposes, despite their lack of sophistication.

Most of the methods described above assess current vulnerability to SWI; some include SLR; some include changes in recharge; and some include pumping. Notably lacking is overwash related to storm surge. Ideally all of these natural (SLR and storm surge) and anthropogenic (pumping) hazards should be incorporated into vulnerability assessments. Furthermore, the consequence of salinization should be considered as this determines the overall risk.

Applying risk principles to environmental systems is a relatively new concept that continues to evolve (Peterman and Anderson, 1999; Dunn et al., 2012). In environmental geoscience, risk assessment has largely been applied to natural disasters such as landslides and earthquakes (Birkmann, 2006). Comprehensive risk assessment has not typically been applied to water related issues (Peterman and Anderson, 1999), and when it has, it is usually within a source water protection context. For source water protection, water resource vulnerability and contaminant pathways are identified and ways to manage and reduce risk are determined. Typically, however, source water protection focuses on chemical hazards that are related to land use (vertical transport of contaminants). For example, Simpson et al. (2014) developed a groundwater quality risk assessment approach in which the likelihood of chemical hazards (associated with different land uses) might be introduced at surface (due to spills or agricultural activities). The resulting maps showed risk to the aquifer spatially.

For coastal aquifers, however, contamination is associated with salinization due to SWI arising from (1) gradual landward encroachment of the freshwater/saltwater interface, (2) inundation, or (3) excess pumping. Salinization of the freshwater lens can occur from a variety of directions (over the top, from the side, or from below) and can impact the quality and quantity of freshwater (Fig. 1). These diverse salinization pathways require a different conceptualization of risk and an alternative approach for assessing risk to coastal aquifers (e.g. Holding and Allen, 2015a).

Landward encroachment of the saltwater-freshwater interface (Fig. 1) may occur for a variety of reasons, including a rise in sea level and a reduction in recharge. Sea level is currently rising due to changes in atmospheric pressure, thermal expansion of oceans, and melting of ice caps and glaciers. Global sea level is predicted to rise up to 0.6 m by 2100 (Nicholls et al., 2007); however, local SLR varies by region due to a combination of global SLR and local vertical land movements. In a coastal aquifer, a rise in sea level can lead to a reduction in the hydraulic gradient; particularly in coastal aquifers that are constrained by topography (Michael et al., 2013). A reduction in recharge due to lower precipitation in a warming climate will also reduce the hydraulic gradient (Holding and Allen, 2015a). A reduction in the hydraulic gradient lowers the flux of fresh groundwater toward the ocean and the interface responds by moving inland, causing SWI.

Storm surge is an abnormal rise in sea level that is associated with a storm event (Danard et al., 2003). Storm surge causes land erosion and flooding; when the surface becomes flooded, the saltwater can infiltrate into the freshwater lens from the land surface and cause localized salinization (Fig. 1). Storm surges vary in size based on the morphology of the coastline and the topography of the ocean floor (Stoltman et al., 2007; Debernard et al., 2002). The topography of the ocean floor influences storm surge because currents are obstructed by shallow waters and wave heights increase. The shape of the coastline may also increase the damage potential of storm surge because tidal energy can be focused, and wind and water funnelled to the shoreline (Romanowski, 2010; Christiansen, 2009).

SWI can also be exacerbated by pumping freshwater at high rates or by pumping numerous wells simultaneously (high well density locations) (Fig. 1). Pumping can cause the freshwater/saltwater interface to move inland by reducing the natural gradient to the sea (United States Geological Survey (USGS), 2000). Other mechanisms leading to salinization include upconing from depth due to pumping (Reilly and Goodman, 1985) and localized intrusion by reversal of the hydraulic gradient near the well or well field (Fetter, 2001). In fractured rock, saltwater has been shown to enter wells through discrete fractures (Allen et al., 2002).

This study was motivated by the need to undertake a screening SWI vulnerability assessment for the Gulf Islands in coastal British Columbia (BC), Canada. Most properties on the islands consist of a single dwelling, typically on a ¼ acre lot, serviced by a private well and septic system. The majority of dwellings are situated right along the coast or in small residential developments, which leads to bias in the distribution of data, where available. There are

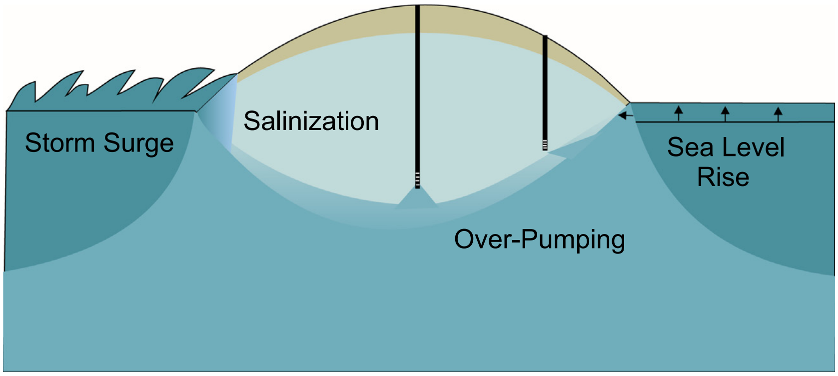

**Fig. 1.** Salinization due to sea level rise, storm surge and over-pumping of groundwater by pumping. The freshwater lens is shown in light blue. (For interpretation of the references to colours in this figure legend, the reader is referred to the web version of this paper.)