Journal of Hydrology: Regional Studies 3 (2015) 400–423

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

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

Simulating the impact of climate change on the groundwater resources of the Magdalen Islands, Québec, Canada

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ARTICLE INFO

Article history:
Received 28 May 2014
Received in revised form 16 December 2014
Accepted 18 February 2015
Available online 2 April 2015

Keywords:
Coastal aquifers
Seawater intrusion
Climate change
Magdalen Islands

ABSTRACT

Study region: This study is conducted in the Magdalen Islands (Québec, Canada), a small archipelago located in the Gulf of St. Lawrence.
Study focus: This work was undertaken to support the design of a long-term groundwater monitoring network and for the sustainable management of groundwater resources. This study relies mostly on the compilation of existing data, but additional field work has also been carried out, allowing for the first time in the Magdalen Islands, direct observation of the depth and shape of the transition zone between freshwater and seawater under natural conditions. Simulations were conducted along a 2D cross-section on Grande Entrée Island in order to assess the individual and combined impacts of sea-level rise, coastal erosion and decreased groundwater recharge on the position of the saltwater–freshwater interface. The simulations were performed considering variable-density flow and solute transport under saturated-unsaturated conditions. The model was driven by observed and projected climate change scenarios to 2040 for the Magdalen Islands.
New hydrological insights for the region: The simulation results show that among the three impacts considered, the most important is sea-level rise, followed by decreasing groundwater recharge and coastal erosion. When combined, these impacts cause the saltwater–freshwater interface to migrate inland over a distance of 37 m and to rise by 6.5 m near the coast to 3.1 m further inland, over a 28-year period.

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http://dx.doi.org/10.1016/j.ejrh.2015.02.011

1. Introduction

Sustainable groundwater supply for maritime coastal communities is a constant challenge due to the presence of surrounding seawater and its possible intrusion into freshwater aquifers. This challenge is even greater for island communities where there are no other sources of drinking water. This is the case of the Magdalen Islands, a small archipelago of 200 km^2 located in the Gulf of St. Lawrence in eastern Canada where 13,000 inhabitants depend entirely on groundwater for their potable water supply (Dessureault and Simard, 1970; BAPE, 2013). In this situation, one of the biggest threats for the water supply is the upconing of seawater into the freshwater supply wells. Saltwater upconing is especially serious because high salinity will force a well to be abandoned for a relatively long period as the upconed seawater slowly decays (Zhou et al., 2005). In the long term, this situation may occur due to over-extraction of freshwater in pumping wells or to changes in natural conditions induced by climate change.

While predictions of seawater upconing under various pumping conditions have been extensively studied in the context of water management (e.g. Dagan and Bear, 1968), the impacts of climate change, and more specifically the impact of sea-level rise, on saltwater intrusion has only gained interest recently. Recent studies have been conducted for both confined and unconfined aquifers at either specific sites (e.g. Sherif and Singh, 1999; Bobba, 2002; Green and MacQuarrie, 2014) or generic sites using parametric studies (e.g. Werner and Simmons, 2009; Webb and Howard, 2011; Ferguson and Gleeson, 2012) with a wide range of models including analytical solutions, numerical models using the Ghyben–Herzberg assumption, and fully coupled density-dependent flow and solute transport models.

The reported impacts of sea-level rise are highly variable because they depend on the site hydrogeological context, climate conditions and geometry of the aquifers, as well as on the selected boundary conditions. For instance, Werner and Simmons (2009) and Werner et al. (2012) have shown that flux-controlled systems, in which the groundwater discharge flux to the sea is constant despite the sea-level rise, are much less sensitive to sea-level rise than constant-head systems, where the inland boundary is controlled by groundwater abstraction and where the heads are prescribed. These conclusions are particularly relevant for small island aquifers (Morgan and Werner, 2014).

While sea-level rise is usually considered the main impact of climate change on coastal aquifers, other impacts can also be expected, such as coastal erosion and changes in precipitation and temperature, which may in turn impact evapotranspiration and groundwater recharge. The magnitude of these individual impacts is poorly documented and it is not obvious whether they will have a cumulative effect or will offset each other.

Recently, Green and MacQuarrie (2014) investigated the relative importance of projected sea-level rise, climate change effects on recharge and groundwater extraction rates on seawater intrusion in an unconfined sandstone aquifer located on the coast of the Gulf of St. Lawrence in New Brunswick. Their scenario, investigating the period between 2011 and 2100, is based on a decrease in groundwater recharge (40–85 mm/year), a sea-level rise (0.93–1.86 m) and a pumping rate increase (by a factor of 2.3) for 2100. Although the relative importance of the three factors changes according to the specific location, they found that sea-level rise had the least impact on seawater intrusion into shallow and intermediate aquifers. The effect of declining recharge was most significant at shallow to intermediate depths along the transition zone, while the impact of increased pumping rates was limited to the area close to the well and at the same depth of extraction.

Predicting the dynamics of a freshwater–saltwater interface can also be valuable for designing a groundwater monitoring network as part of a groundwater management strategy. For example, in 2007 the Quebec Ministry of Sustainable Development, Environment and the Fight Against Climate Change (MDDELCC) implemented an action plan on climate change in which Action 22 aims at maintaining a monitoring network to evaluate the impacts of climate change on groundwater resources (Government of Québec, 2008). Because of the specific hydrogeological context of the Magdalen Islands, the monitoring network should allow tracking the position of the freshwater–saltwater interface. Up to now, two different options have been considered for monitoring the interface: time-domain electromagnetic (TDEM) surveys and instrumented boreholes. This study should help to decide whether the expected changes are within the resolution of the TDEM method and if