Saltwater Intrusion and Coastal Aquifer Sustainability

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ABSTRACT
Saltwater intrusion along coastlines has been a serious problem in several areas in North America and around the world. With sea level rising every year, saltwater intrusion is becoming a prominent problem in coastal aquifer sustainability. It is suspected that coastal groundwater supplies in Nova Scotia have the potential for saltwater intrusion, but this possibility has not been clearly defined or studied. In this study, the current distribution of salinity in selected environments in Nova Scotia are examined and predictions of future salinity distributions are made with numerical models using probable future sea levels and groundwater recharge rates.

RÉSUMÉ
L'intrusion d'eau de mer est un problème grave dans plusieurs zones côtières en Amérique du Nord et autour du monde. Avec la montée actuelle du niveau de la mer, ces intrusions sont devenues un problème majeur pour la durabilité des aquifères littoraux. Les réserves côtières d'eau souterraine en Nouvelle-Écosse pourraient être l'objet d'intrusions d'eau de mer, mais cette possibilité n'a pas été bien définie ou étudiée. Dans cette étude, la distribution actuelle de la salinité en Nouvelle-Écosse est examinée et des prévisions de distributions de salinité sont faites à l'aide de modèles numériques utilisant des estimations des futurs niveaux de la mer et taux de recharge d'eau souterraine.

1 INTRODUCTION

Saltwater intrusion is a well-documented phenomenon that affects coastal aquifers worldwide (Barlow and Wild, 2002; Calvache and Pulido-Bosch, 1996). Essentially, saltwater intrusion is the effect caused by saltwater encroaching into a coastal aquifer, creating a saltwater wedge within the coastal aquifer. Groundwater is linked to seawater through the saltwater/freshwater interface. When sea level changes, the interface position will change accordingly. If sea level rises, the position of the interface will move inland, which can cause several problems with water quality of coastal aquifers (Melloul and Collin 2006; Mercer et al 1980). Documented cases of sea-level rise in the Maritimes show that the rate of sea-level rise has increased in the past century (Environment Canada, 2006).

Several studies have noted that the elevation of the interface does occur rapidly when affected by surrounding surface systems (Giambastiani et al 2007). When a groundwater-fed surface system is present, the rapid elevation of the interface is caused by the increased stream flow and decreased rate of change of the surrounding aquifer water levels (Masterson and Garabedian, 2007). Other observations have noted that the subsurface geology of the area can have a retarding effect on the dynamics between the interface and sea level. Confining units cause a lag in equilibration between the two water bodies, creating a dynamic equilibrium (Feseker, 2007). In some instances, it may take over 10 000 years for the interface to equilibrate to the current sea-level conditions (Person et al 1998; Pope and Gordon 1999).

2 PAST RESEARCH

Climate change has come to the forefront of research groups throughout the scientific community (Church et al 2001, Bates et al 2008), focusing on topics that extend from carbon dioxide production to glacier mass loss. One of the main effects of climate change that has a direct link to saltwater intrusion is the increase in sea level rise in some areas, along with increased precipitation. According to the IPCC Technical Paper VI (Bates et al 2008), sea-level rise is projected to extend areas of salinization of groundwater in coastal environments. The effect of sea-level rise is attributed to thermal expansion, which accounts for 70-75% of sea level rise, melting of the world's glaciers and ice caps, and mass loss from Greenland and Antarctic ice sheets. Rates of sea level rise have increased since the past century. The average rate of sea level rise for the 20th century was 1.7 +/- 0.7 mm/year and the projected rate for the 21st century is expected to exceed this rate. Since this change in rate is spatially variable, some areas will have a drastic increase in sea level rise whereas others will experience sea level fall. An estimate of total sea-level rise for the next century for the Maritimes has been reported to be 50 to 59 cm +/-35 cm (Environment Canada 2006).

Dynamics of the saltwater/freshwater interface have been studied extensively via several types of methodologies ranging from site-specific observation (Person et al 2003; Pope and Gordon 1999) to numerical modelling (Bachu 1995; Simmons et al 2001). The dynamics of the interface are important to be aware of for proper interpretation of the results of this study.

Conclusions from Masterson and Garabedian's 2007 study included a rapid elevation in interface position with a surface water dominant system, caused by the interaction with a nearby stream. The seawater intruding inland caused the water table to rise, increasing stream flow and rate of interface rise. Along with these types of effects the surrounding environment can have on the position of the interface, subsurface geology has also shown strong control over saltwater/freshwater position.

A study done by Pope and Gordon (1999) demonstrated this lag through the discovery of freshwater below sea sediment near Nantucket Island. The lag was created through the presence of aquitards within the subsurface geology that slowed the inland migration of seawater. The lag causes a disequilibration between the interface position and the current surrounding conditions; the current conditions may not be reflected by the interface position. This lag has also been documented as being the result of glacial effects (Person et al 2003).

3 METHODOLOGY

The model was made in Modflow 4.2.1 and used the module SEAWAT. SEAWAT Version 4 is a module that has been incorporated into Modflow 4.2.1 by coupling MODFLOW with the module MT3DMS to simulate variable-density groundwater flow (Langevin and Guo 2006). The actual module SEAWAT is designed for the simulation of multi-species solute and heat transport in conjunction with other numerical models such as Modflow 4.2.1 (Langevin and Guo 2006).

3.1 Model Description

Components of the model were of a generic nature, yet had a tie-in to reality with boundary conditions based on realistic values for Nova Scotia. The boundary conditions of the model were of that of a generic coastal aquifer, with some reference to the topography and general geology of the Annapolis-Cornwallis Valley area provided by Geological Survey of Canada (2007) aside from rate of recharge. The only two components that were changed during the modeling process were: rate of recharge, and rate of sea level rise. Values for these boundary conditions, were based on data from the IPCC (Bates et al 2008, Church et al 2001), climate data for the surrounding area, and, in some instances, data from Nova Scotia Environment.

Once the model was established, small to significant changes were made in accordance to information from past research (Bates et al 2008, Church et al 2001) to include sea level rise and change in the rate of recharge to note any change in the position of the saltwater/freshwater interface. The change of the components occurred both singularly and dually, making three scenarios come out of the modeling process; recharge rates change only, sea-level rise only, and both change simultaneously.

Throughout the entire modeling process, interpretation and re-evaluation occurred for all aspects of the model. By applying the model to sections of the Nova Scotia shoreline and changing the rate of recharge and sea level rise accordingly to each new area would allow for the generation of a map of Nova Scotia that indicates areas of increased risk of saltwater intrusion.

3.2 Simulation of sea-level rise and recharge

The study consists of three scenarios that differ from each other by the difference of incorporating changes in sea-level, and recharge. Recharge was changed dramatically in each scenario to demonstrate the changes in the saltwater/freshwater interface caused by extreme recharge changes. Recharge and sea-level will be based on information from the IPCC (Bates et al 2008, Church et al 2001), and climate records from Atlantic Canada. The initial boundary conditions for the three scenarios are described in Table 1.

Table 1: Initial boundary conditions

	Scenario 1	Scenario 2	Scenario 3
Constant sea concentration	35 000 mg/L	35 000 mg/L	35 000 mg/L
Hydraulic Conductivity	0.00001 m/s	0.00001 m/s	0.00001 m/s
Rate of recharge	Variable from 0 mm/yr to 2500 mm/yr	Variable from 0 mm/yr to 2500 mm/yr	Steady at 250 mm/yr (same as steady state model)
Sea-Level Rise	0 m	0 m to 0.3 m	0 m to 0.3 m

Each scenario had two separate models: a steady state model and a transient state model. The steady state model had the same boundary conditions of the three scenarios, except for it had a steady recharge rate of 250 mm/yr and no sea-level rise was incorporated. This steady state model was used for each scenario and was run to a dynamic equilibrium to establish initial conditions for the following transient state model. Within each scenario there were eight different cases. These cases differed in the amount of increase or decrease that was applied to the rate of recharge. The transient state models were modified for each run; increased recharge, decreased recharge, no sea-level rise, and significant sea-level rise. Sea-level was modeled to rise 0.3 m within 100 years (estimated from Bates et al 2008, Church et al 2001).

4 ANALYSIS

The extent of the saltwater intrusion was analyzed via the concentration changes seen at four different points along the flow path. The points vary in distance from the coastline: 825 m, 1330 m, 1980 m, and 2450 m. All points are at the depth of 37.5 m at the end of the modeling timeframe (Figure 1). The orange circles indicate the points where concentrations were measured for analysis. A quick survey of the data suggests there are many wells at these distances, yet the points are essentially arbitrary.

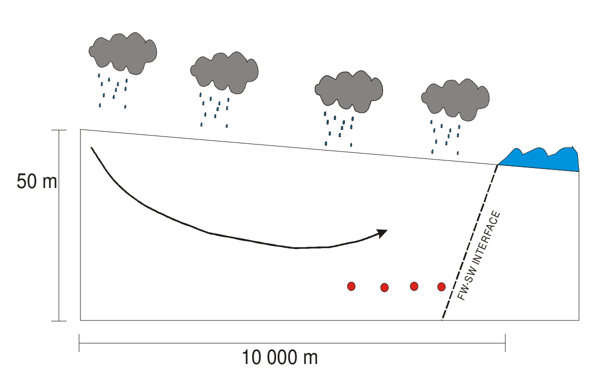
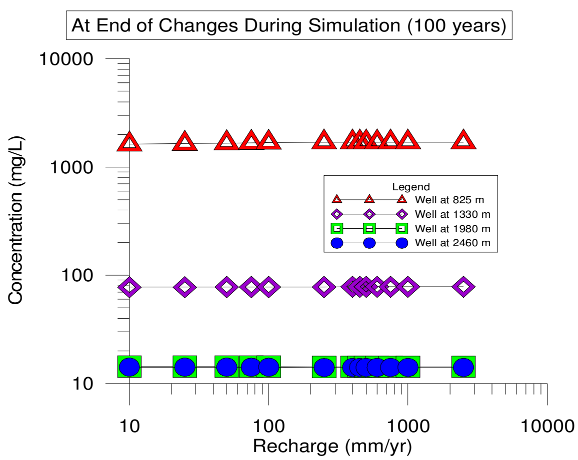
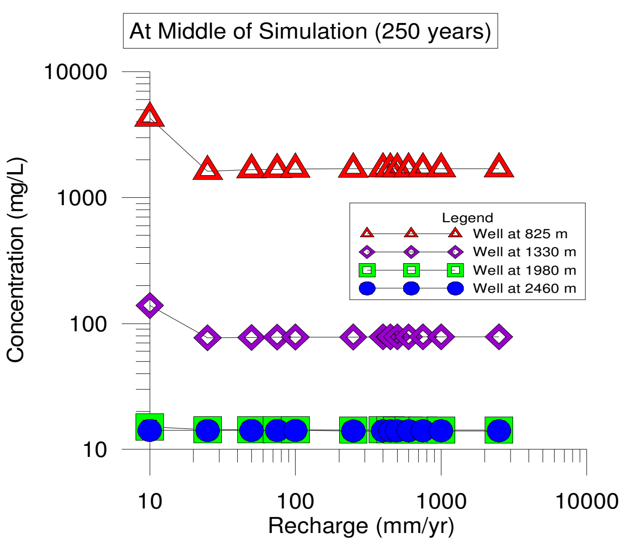
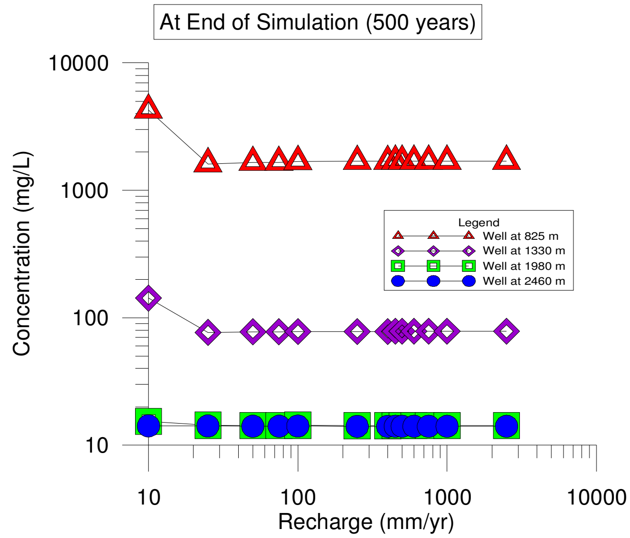


Figure 1: Schematic of the model.

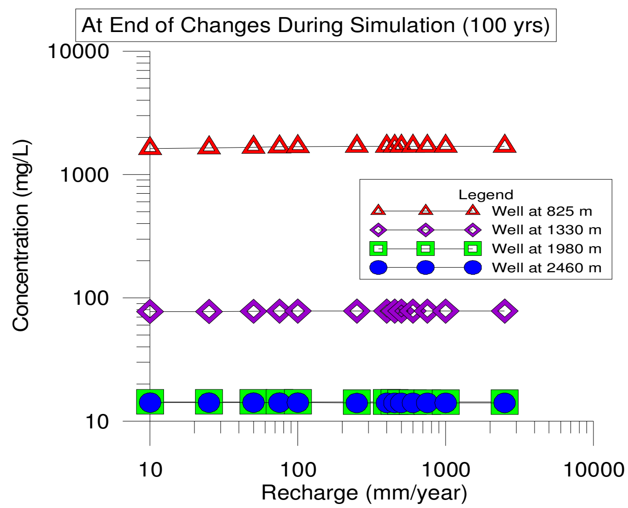
The area of constant concentration is found at the right end of the schematic. The constant head region on the right is representative of the sea, with a concentration of 35000 mg/L of salt. The hydraulic conductivity is set at 0.00001 m/s.

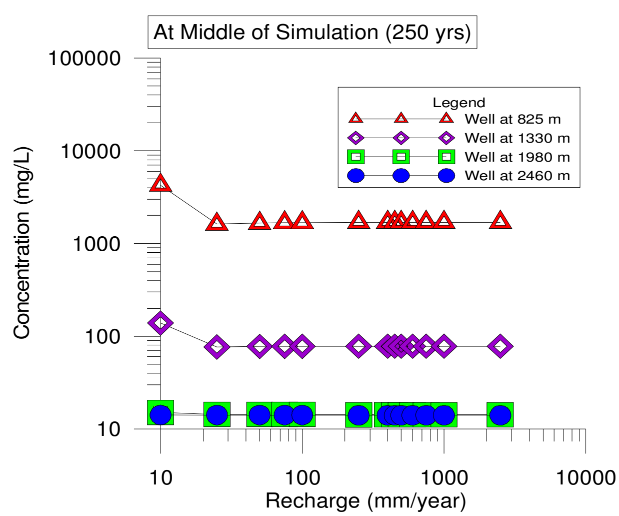


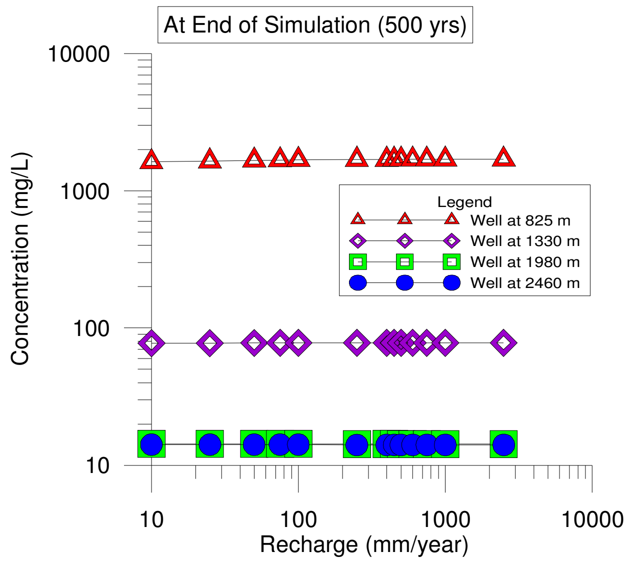




Figures 2a, b, and c: Results from Scenario 1, no sea-level rise.







Figures 3a, b, and c: Results from Scenario 2, incorporating sea-level rise and change in recharge.

Scenario 3 is slightly different from Scenarios 1 and 2 simply because there is no change in any of the boundary conditions except for sea-level rise. It demonstrates the effectiveness of sea-level rise with a magnitude of 0.3 m over 100 years.

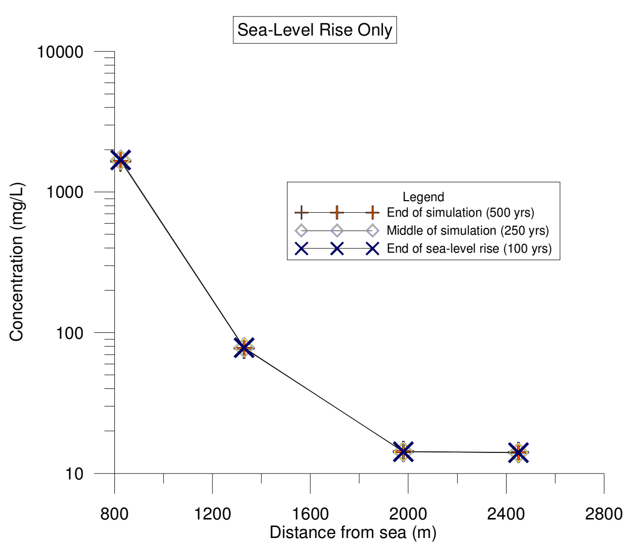


Figure 4: Results from Scenario 3, incorporating only sea-level rise with a constant rate of recharge of 250 mm/yr.

As shown in Figures 2a through c, 3a through c, and 4, recharge and sea-level rise have a slight control over the extent of saltwater intrusion seen in a coastal environment in extreme events. Where recharge is decreased from the initial value of 250 mm/yr to the extreme value of 10 mm/year, the extent of intrusion increases dramatically. Incorporating sea-level rise to all cases again induces the extent of the intrusion (Scenario 2). These changes in saltwater intrusion are only seen when there are extreme changes in recharge rate. Even with a change in magnitude of recharge from 250 mm/yr to 2500 mm/yr does not cause the saltwater/freshwater interface to move sea-ward. Figure 5 (see below) shows the different extents of intrusion for Scenario 1 with a recharge of 250 mm/yr with no sea-level rise and with sea-level rise. Clearly, when sea-level rise is incorporated into the model, saltwater intrusion is extended. The question now becomes: is the extension of saltwater intrusion significant.

5 DISCUSSION

5.1 Recharge and Sea-level Rise Effects on Saltwater Intrusion

Although the effect of varying recharge rates has been considered previously (e.g. Henry, 1964), it has not, at least to our knowledge, been considered in the context of climate change. As previously stated, when either increased or decreased, recharge will cause the extent of saltwater intrusion to decrease or increase, respectively. This phenomenon is seen even without sea-level rise. When sea-level rise was not incorporated within the model, and the only boundary condition that is changed when moving from the steady-state model to transient model was recharge, the changes in the extent of saltwater intrusion are minor, on the order of approximately 1 m in the scenarios examined in this study. The effect of sea-level rise slightly enhances or diminishes the effect of decreased or increased recharge respectively. With this stated, the data also suggests that the changes in recharge need to be dramatic for any significant change in the position of the saltwater/freshwater interface to occur.

5.2 Coastal Aquifer Sustainability

Although only minor changes in salinity are expected due to climate change, these shifts could have serious repercussions to coastal communities. Salinity is already an issue for several Nova Scotia communities and increases in salinity due to climate change could exacerbate this problem. However, given the magnitude of the changes in salinity due to changes in recharge and sea level, it appears that groundwater extraction is a larger issue. There are numerous options for managing this issue for larger public supplies, including relocation of wells or drilling multiple wells, but few options exist for small private users. Once a well is drilled or dug on private property, it is usually too expensive to move the well if it becomes contaminated with saltwater and limited options in terms of where it can be moved. As shown in Figure 6, the majority of the population of Nova Scotia resides near or on the coastline, making saltwater intrusion a probable problem for several communities within the province.

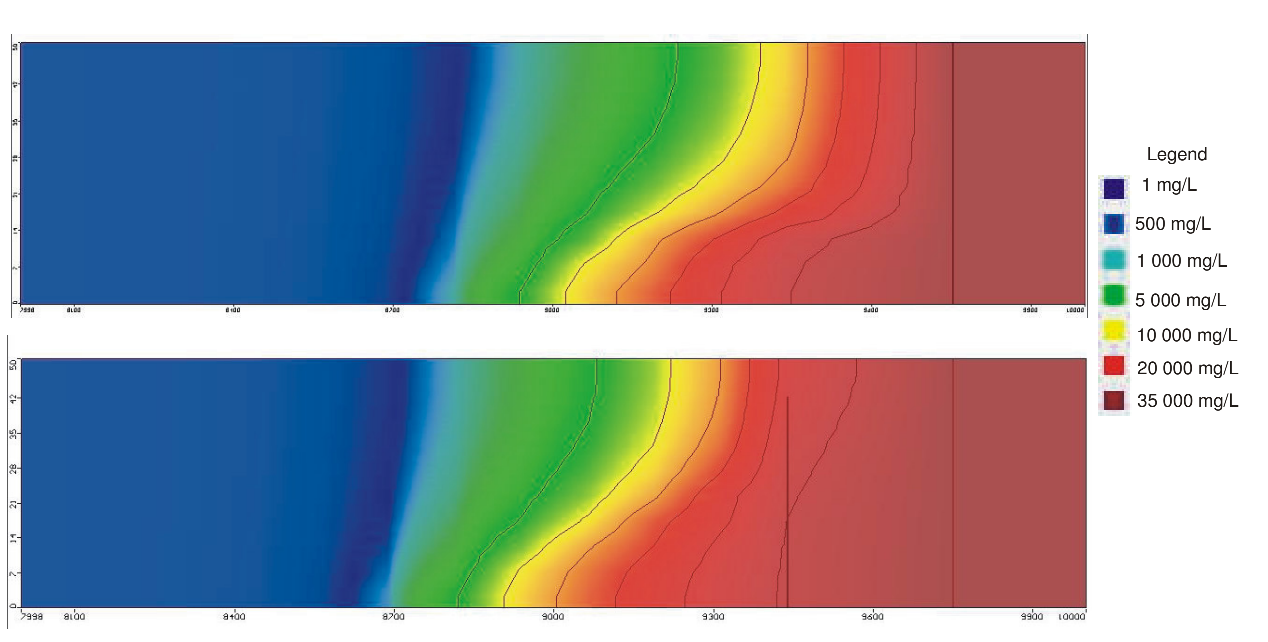


Figure 5: Shows the extent of saltwater intrusion for Scenario 2 when the rate of recharge is 250 mm/yr with sea-level rise (top cross-section) and without sea-level rise (bottom cross-section).

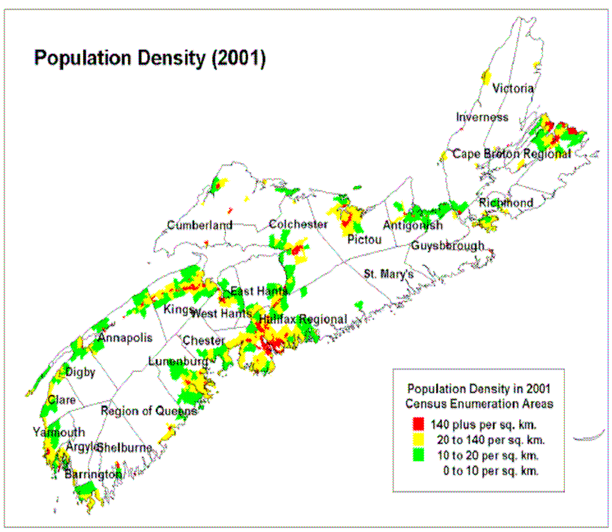


Figure 6: Map of Nova Scotia showing the population density of the province (from Service Nova Scotia).

6 CONCLUSION

Saltwater intrusion along coastlines of Nova Scotia has potential to be a significant issue because the province is almost completely surrounded by the ocean and much of the population and water wells are located on the coastline. Rates of recharge and sea-level rise will have a clear, yet not very significant effect on the extent of saltwater intrusion a region will experience. More information is needed to conclude how saltwater intrusion will affect areas in the future, particularly when including use of groundwater as a municipal water resource, and the rate of pumping that is used to extract the water.

7 ACKNOWLEDGEMENTS

The authors would like to thank NSERC for providing funds for the work done on the project; and Nova Scotia Environment for providing assistance with finances and data.

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