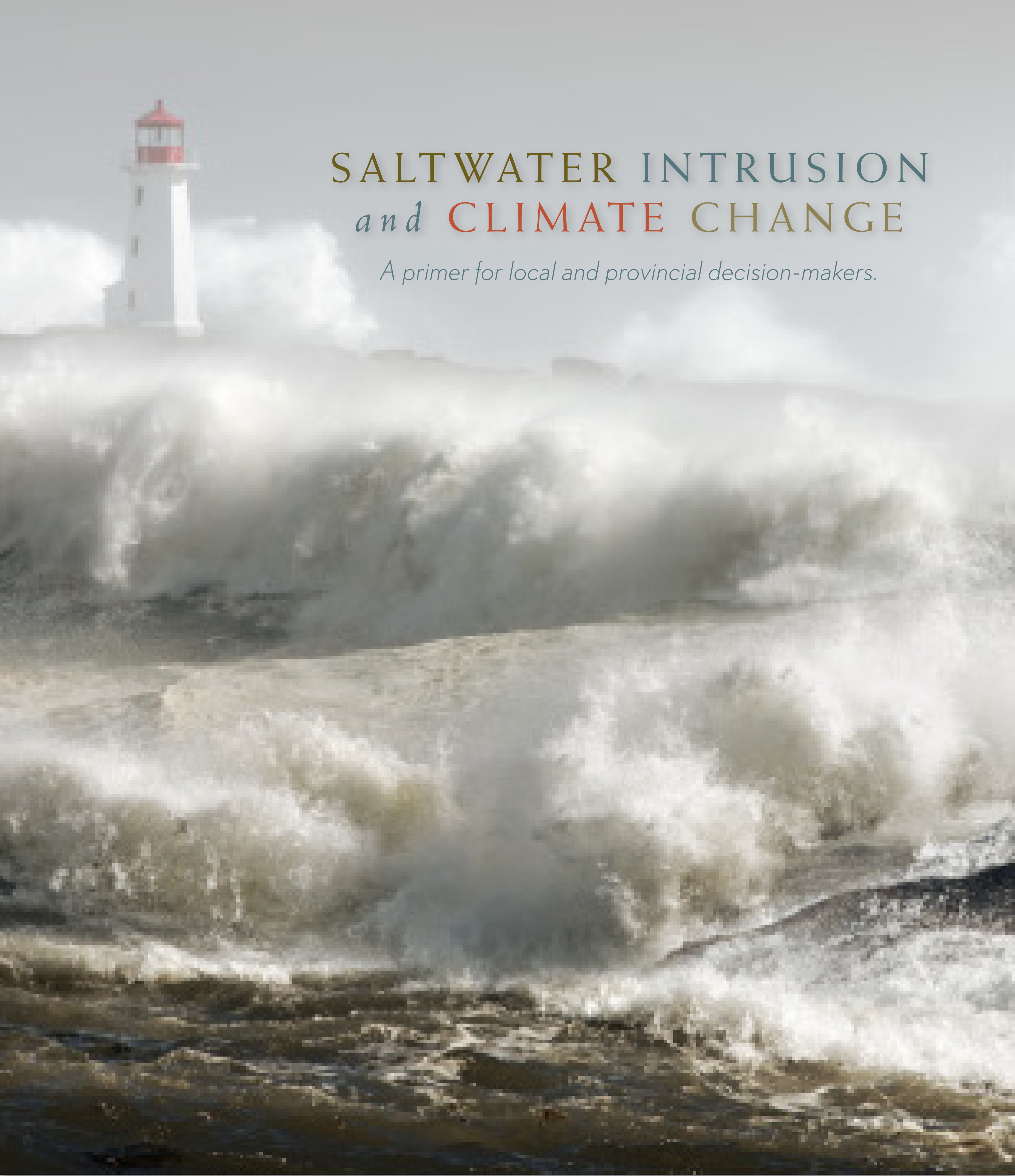
SALTWATER INTRUSION and CLIMATE CHANGE

A primer for local and provincial decision-makers.



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SALTWATER INTRUSION *and* CLIMATE CHANGE

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ACASA is a non-profit organization formed to coordinate project management and planning for climate-change adaptation initiatives in Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland and Labrador. ACASA is supported through the Regional Adaptation Collaborative, a joint undertaking between the Atlantic provinces, Natural Resources Canada, and regional municipalities and other partners.

SACCA est un organisme à but non lucratif formé pour coordonner la gestion de projet et la planification des initiatives d'adaptation au changement climatique en Nouvelle-Écosse, du Nouveau-Brunswick, Île du Prince Édouard et Terre-Neuve et soutenu par la collaboration pour l'adaptation régionale, une entreprise commune entre les provinces de l'Atlantique, Ressources naturelles Canada et municipalités régionales et d'autres partenaires.

This report is also available on the Internet at www.atlanticadaptation.ca

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EXECUTIVE SUMMARY

In coastal areas, fresh groundwater from inland sources mixes with saline (salty) groundwater originating beneath the ocean floor. The boundary between fresh groundwater and saline groundwater does not always remain in the same place and can often shift inland or seaward, depending on the conditions beneath the surface. When the fresh groundwater supply decreases (in the dry summer months, for example), the boundary can move further inland. Conversely, when the fresh groundwater supply increases (during wetter spring months), the boundary can shift seaward. When the mixing of saltwater with freshwater beneath the surface occurs in an area that was previously fresh, the process is referred to as saltwater intrusion (or seawater intrusion). Saltwater intrusion can become a problem when saltwater moves far enough inland that it "intrudes" into fresh groundwater sources such as wells.

Though saltwater intrusion is a naturally occurring process, it can also be influenced by human activity. When coastal communities use wells to pump fresh drinking water to the surface, it often makes the problem of saltwater intrusion worse. When more freshwater is pumped from the ground than groundwater can supply, as can often occur in densely-populated coastal areas, the well starts to pump water with an increased salt content. Once groundwater is contaminated with too much saltwater, the well or groundwater source can no longer be used for drinking water, and it often has to be abandoned altogether.

Saltwater intrusion is a problem for coastal regions around the world, including Atlantic Canada. Several studies have been undertaken in this region to learn more about the extent of the problem in specific locations; however, there has been only a limited amount of research in this area. Saltwater intrusion is expected to become a more serious issue as our climate changes. Sea-level rise, extreme weather events, coastal erosion, changing precipitation patterns, warmer temperatures, and the potential for increased freshwater demand could all increase the risks of saltwater intrusion. Greater knowledge of Atlantic Canada's vulnerability to saltwater intrusion, particularly under conditions of a changing climate, will be needed in order to plan adequately for the future.

Dealing with the issue of saltwater intrusion in Atlantic Canada will likely require greater scientific monitoring and assessment and regulatory changes.

Currently, the Atlantic Regional Adaptation Collaborative (RAC) of Natural Resources Canada has begun case studies in each of the four Atlantic provinces to examine the expected impact of saltwater intrusion in the context of climate change.

A primer for local and provincial decision-makers.

Contents

List of Figures

Key terms

ADAPTATION is action taken to prepare for climate change. This is different from mitigation, which focuses on reducing greenhouse gas emissions in an effort to reduce the extent of climate change.

An **AQUIFER** is a layer of rock beneath the surface that is able to hold useable amounts of water that can be pumped out by wells. The pores and cracks in the rock allow the water to be stored – and also to flow – making it possible for water to be pumped to the surface.

CLIMATE CHANGE refers to the gradual change in average weather conditions over time. The earth's climate does naturally experience variation over the long term, but human activity during the past 300 years has led to a sharp and unprecedented warming trend. Impacts of climate change include sea level rise, changing precipitation patterns, and more frequent and intense weather events.

An **ESTUARY** is a coastal body of water in which freshwater from a river system mixes with seawater.

The **SALTWATER-FRESHWATER INTERFACE** is the boundary (beneath the earth's surface) where saltwater meets freshwater. It is not a sharp boundary or line; rather, it is a gradual transition zone where water gets saltier as you move towards the sea. This zone is called the zone of dispersion.

HYDRAULIC HEAD refers to the height of groundwater above some reference point (often sea-level).

OVEREXPLOITATION refers to the action of removing water from the hydrologic cycle (e.g. pumping groundwater) faster than it can be naturally recharged.

PERMEABILITY refers to the ability of an object (in this case, a layer of soil or rock) to transmit water. A permeable object or layer (e.g. an aquifer) will allow water to pass through it, whereas an impermeable object or layer (e.g. clay) will not allow water to pass through it.

RECHARGE is the process by which the water in an aquifer is replenished. Typically in eastern Canada, aquifers are recharged primarily in the spring and to a lesser extent in the fall, when the amount of precipitation (and snow melt) exceeds the amount of evaporation; this excess water soaks into the ground and migrates to the water table.

ARTIFICIAL RECHARGE refers to the action of adding freshwater into an aquifer through man-made systems (e.g. recharge basins, injection wells).

SALTWATER INTRUSION is the process by which saltwater infiltrates a coastal aquifer, leading to contamination of fresh groundwater.

ZONE OF DISPERSION (see SALTWATER- FRESHWATER INTERFACE)

BACKGROUND

What Is Saltwater Intrusion?

Saltwater intrusion refers to the process by which sea water infiltrates coastal groundwater systems, thus mixing with the local freshwater supply. Groundwater is stored in the pores and fractures of rock beneath the surface, and the rock formations containing groundwater are referred to as aquifers (Barlow 2003). Aquifers are naturally replenished (or recharged) by way of precipitation (rain, snow) that seeps into the ground and eventually reaches the water table. The water table is simply the boundary between the upper portion of the ground that is only partially saturated with water (unsaturated zone) and the lower portion where all the pore spaces and fractures are fully saturated with water (Figure 1). The elevation of the water table at any point is often referred to as the "hydraulic head." Groundwater generally flows from areas of higher elevation (high hydraulic head) to lower elevations (lower hydraulic head), and the difference between these hydraulic heads is referred to as the hydraulic gradient. All other factors being equal, the bigger the difference in water table elevations between two points (i.e., the higher the hydraulic gradient), the faster groundwater will flow toward lower elevations.

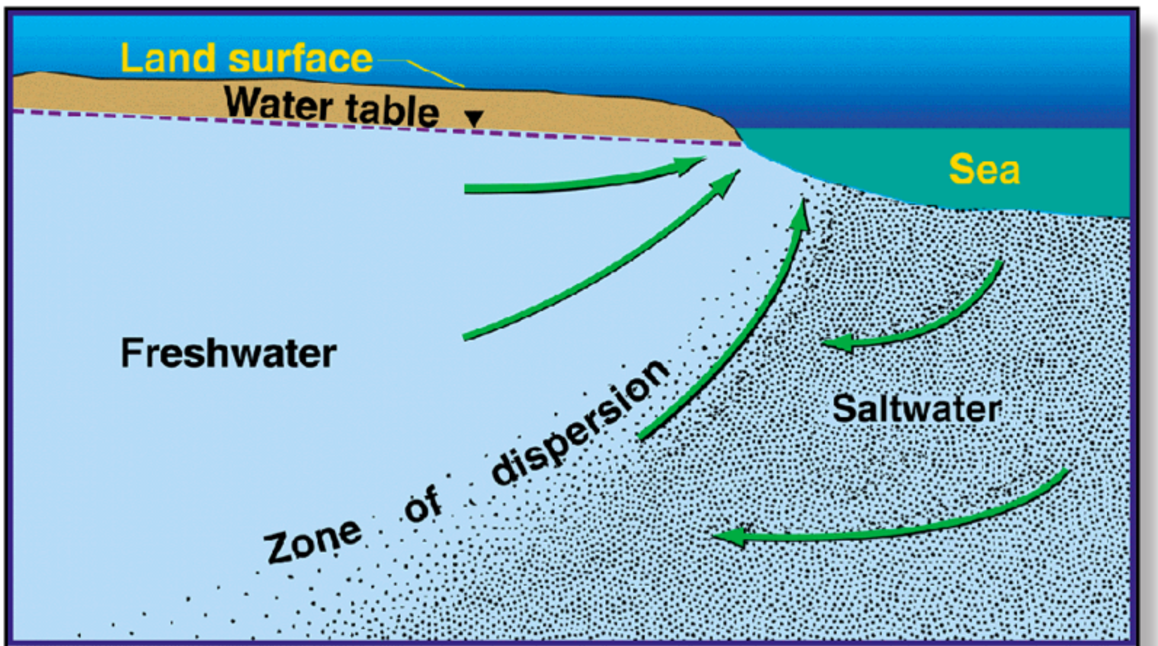

Figure 1. Groundwater flow and the zone of dispersion. The zone of dispersion marks the transition between seaward freshwater and landward saltwater. (Source: U.S. Geological Survey)

In coastal areas, the process of recharge causes groundwater to flow from inland areas with higher water-table elevations toward the sea at a lower elevation. Sea water, meanwhile, also saturates the ground along the coast, creating a boundary along which saltwater meets freshwater beneath the surface. Because saltwater is denser than freshwater, this saline groundwater may "intrude" beneath fresh groundwater, creating a saltwater "wedge" at the coastline. In addition to the local hydraulic and density gradients, the nature of this saltwater-freshwater interaction is controlled by numerous factors, including the characteristics of the aquifer (such as permeability and thickness) and the characteristics of any layers of rock underlying or overlying the aquifer (confining layers) (Barlow 2003). The resulting saltwater-freshwater interface is not so much a firm boundary as a transition zone (or zone of dispersion) reflecting changes in salinity (Figure 1).

What Is Saltwater Intrusion? cont'd

Saltwater intrusion occurs naturally in many areas but can become problematic when groundwater is withdrawn (pumped) from the aquifer; this reduces the hydraulic head in the aquifer, subsequently slowing or stopping the seaward flow of freshwater, which in turn allows saltwater to move further inland (Khublalryan et al. 2008). Excessive pumping of groundwater can also induce saltwater intrusion through "up-coning," when deeper saline waters from the underlying saltwater wedge are drawn toward a pumping well (Figure 2). In either case, a portion of the aquifer becomes contaminated with saltwater, thus compromising any nearby wells as viable freshwater sources (Bear and Cheng 2010). Other changes, such as reduced recharge (from less precipitation, for example) or increased sea level, can cause a similar landward shift in the location of the saltwater-freshwater interface, thus increasing the risk of saltwater intrusion (Barlow 2003).

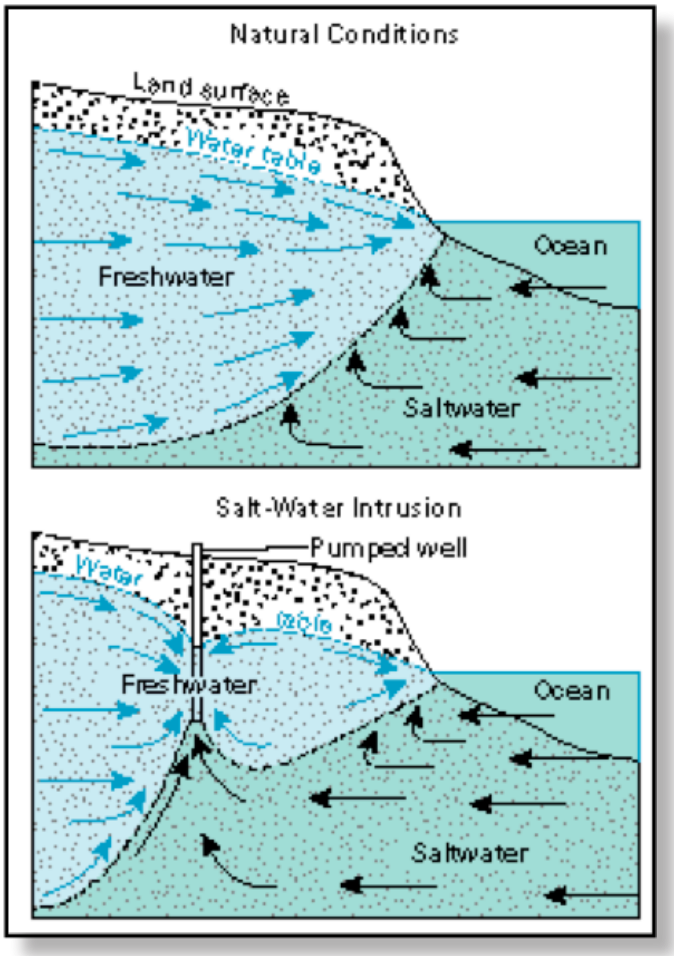

Figure 2.
Saltwater Intrusion. Fresh water withdrawal in coastal areas can result in reduced freshwater flow, resulting in increased landward saltwater flow. (Source: U.S. Geological Survey)

Demands on groundwater resources are particularly high in coastal areas. Coastal zones account for approximately 70 per cent of the world's population, often resulting in overexploitation of groundwater resources and, subsequently, increased risk of saltwater intrusion in those areas (Darneault and Godinez 2008). Indeed, in Atlantic Canada, overexploitation is the most common cause of saltwater intrusion (Cruickshanks et al. 1987, 45–54). More-densely populated coastal areas also usually have more-developed infrastructure. Such development can be problematic in two regards: first, large paved surfaces such as roads inhibit natural recharge of the aquifer (in nature, precipitation normally drains into the ground, replenishing the water supply) and, second, such developed areas are more prone to contaminating underlying water groundwater sources (Bear 2004). Sustainable exploitation of coastal aquifers, then, is critical to controlling saltwater intrusion and thus maintaining a long-term freshwater supply (Bear et al. 1999, cited in Darneault and Godinez 2008).

SALTWATER INTRUSION: *A Growing Problem*

Globally, saltwater intrusion has emerged as a significant issue for local governments. Coastal areas around the world [10] have been forced to address the issue of saltwater intrusion, and they will likely continue to address it in the context of a changing climate. Sea level rise, changing precipitation regimes and changing groundwater recharge rates may all influence the incidence of saltwater intrusion. Increased groundwater demand amid warming temperatures will also have a significant influence. While some elements are likely to have more direct impacts on saltwater intrusion (e.g., sea-level rise), others may have an impact in less direct ways (e.g., changing recharge regimes), depending on local conditions. In all cases, however, the dynamic subsurface interaction between freshwater and saltwater is both complex and influential, and is therefore deserving of close attention in coastal regions.
Several studies in Atlantic Canada have examined the prevalence of saltwater intrusion.

- New Brunswick: Saltwater intrusion was found to have occurred at Shippagan (NE New Brunswick), where lower freshwater heads on Taylor Island limit available supply (Brown 1971; Cruickshanks et al. 1987, 45–54), and at Richibucto (SE New Brunswick), where overpumping is the likely cause (Stapinsky et al. 2002). In Shediac Bay, some 50 km south of Richibucto, the location of the saltwater-freshwater interface has been studied, and the risk of saltwater contamination is considered low (Rivard et al. 2008).

- Nova Scotia: Saltwater intrusion was found to be occurring at Upper Lawrencetown, where low freshwater head resulted in a landward shift of the saltwater-freshwater interface, and a reduction or re-distribution of pumping was subsequently recommended (Cross 1980). Intrusion has also been identified at Pictou, most likely because of development and increased groundwater demand (Cruickshanks et al. 1987, 45–54).

- Prince Edward Island: PEI appears to be particularly vulnerable to saltwater intrusion (CCME 2010) and has been the subject of multiple saltwater intrusion studies. Saltwater intrusion has been identified at Summerside; it was found to be occurring as a result of the landward movement of the saltwater-freshwater interface from pumping (Tremblay et al. 1973). In general, however, saltwater intrusion on PEI seems to occur mainly as a result of natural conditions (Somers 2011) and has been found to occur even in areas where pumping is minimal. Tidal action and changing recharge rates, combined with numerous estuaries penetrating far inland, appear to increase susceptibility throughout the Island (Carr 1969). Despite low groundwater withdrawals, intrusion has been discovered at Eliot River (West River) (Carr 1969), York Point (central PEI) (van der Kamp 1981), and Souris West (Jardine 2011). At Rustico Harbour, a study was conducted to determine the location of the saltwater-freshwater interface in that area (Rivard et al. 2008). Its location was found to be highly variable within even short distances (e.g. at one location, the interface was not present at shallow depths, while only 400 metres away it was found to be 200 metres inland). For PEI, this variability, along with the Island's coastal population density and rising sea level (van der Kamp 1981), is likely to increase its vulnerability to saltwater intrusion in the future.

  Studies have also been conducted on PEI to investigate saltwater wells as a commercial fishery resource (Jacques Whitford 1990a) and to evaluate the potential impact of sea-level rise on such wells (Jacques Whitford 1999b). Currently, saltwater wells are used commercially at both Souris (Jardine 2011) and Victoria-by-the-Sea (Smith 2011).

A Growing Problem *cont'd*

- Newfoundland and Labrador: Little has been reported so far on saltwater intrusion; therefore, our knowledge of its risk is limited.
- Other Areas: On the nearby Magdalen Islands (QC), subsurface conditions appear to be strongly influenced by pumping activity, suggesting a high vulnerability to saltwater intrusion (Comte and Banton 2006).

Overall, saltwater intrusion in Atlantic Canada has been researched in a very limited manner, despite appearing poised to emerge as an unavoidable challenge for resource managers and planners—particularly in the context of a changing climate. Coastal areas in the Atlantic provinces will be among those most vulnerable to the effects of sea-level rise and, subsequently, to the increased threat of saltwater intrusion. Far greater knowledge of Atlantic Canada's vulnerability to saltwater intrusion will therefore be needed in order to plan adequately for the future. Further research into current saltwater intrusion dynamics will form an essential part of any attempt to assess how climate change may affect this process in the future.

Challenges, Adaptation Options and Needs

Any attempt to tackle the issue of saltwater intrusion will require a better understanding of the impacts of climate change as well as the pros and cons of the various available adaptation options.

Saltwater Intrusion and Climate Change

Climate change will affect everyone. Changing temperature and precipitation regimes, sea-level rise, more-frequent extreme weather events, and coastal erosion will be experienced around the world (IPCC 2007). The nature and magnitude of these changes will be different for different regions; therefore, knowledge about future climate trends specific to Atlantic Canada will be vital to effective preparation and adaptation in our region.

Changing Temperature and Precipitation Regimes

In Atlantic Canada, warmer temperatures and more precipitation are expected. While the impacts of such increases are not yet fully understood, these changes could certainly have an important effect on the recharge rates for coastal aquifers and, subsequently, the susceptibility of coastal wells to saltwater intrusion. The total annual recharge in Atlantic Canada seems unlikely to change significantly, but important seasonal variations could occur (Jiang 2011). Warmer temperatures, particularly in the spring and fall when most recharge occurs, could act to reduce the amount of freshwater input to the aquifer at those times of year. More precipitation in the winter could result in greater snowpack, thus increasing snowmelt and recharge in the spring. Furthermore, changing temperatures—particularly in the form of warmer summers—are likely to increase freshwater demand, leading to greater withdrawals (Jiang 2011). While the precise effect that changing recharge rates have on saltwater intrusion is unknown (Underwood and Ferguson 2009), the uncertainty surrounding future seasonal variations and changing supply/demand dynamics certainly highlight both the need for further research and the need to prepare for a range of possibilities.

Sea-level Rise

For coastal regions, no change is likely to have a greater impact than that of sea-level rise. Warming global temperatures will result in the thermal expansion of the world's oceans (warmer water bodies expand in volume), which, in combination with glacial melting, will lead to sea-level rise. Crustal subsidence, the process by which Atlantic Canadian provinces are currently "sinking," will also contribute to a relative rise in sea level. Sea-level rise is projected to occur at an alarming rate over the 100 years. The Intergovernmental Panel on Climate Change (IPCC) has predicted that by 2100, sea level will rise between 18 cm and 59 cm (IPCC 2007), though more-recent studies have calculated that sea-level rise is likely to be more than twice that amount (Rahmstorf 2010). Such changes are certain to affect coastal regions, with dramatic impacts on infrastructure, industries, residential properties, heritage properties, and commercial properties (McCulloch et al. 2002). A less direct—though perhaps significant—consequence of sea-level rise could be more-severe saltwater intrusion.

Saltwater intrusion occurs as result of the landward movement of sea water into the coastal aquifer. This landward movement is caused by a change in the freshwater and saltwater pressure gradients resulting from, among other factors

- Pumping (overpumping, in particular) of the aquifer (more freshwater leaving the aquifer results in decreased freshwater hydraulic head)
- Decreased recharge (less freshwater entering the aquifer results in decreased freshwater hydraulic head)
- Sea-level rise (increased volume of saltwater results in increased saltwater hydraulic head)

Sea level rise is likely to lead to increased risk of intrusion and well contamination (Figure 3). While the exact nature of this relationship—precisely how much risk will increase as a result of sea-level rise—is still not well understood (Werner and Simmons 2009), the need to prepare for such an eventuality cannot be ignored.

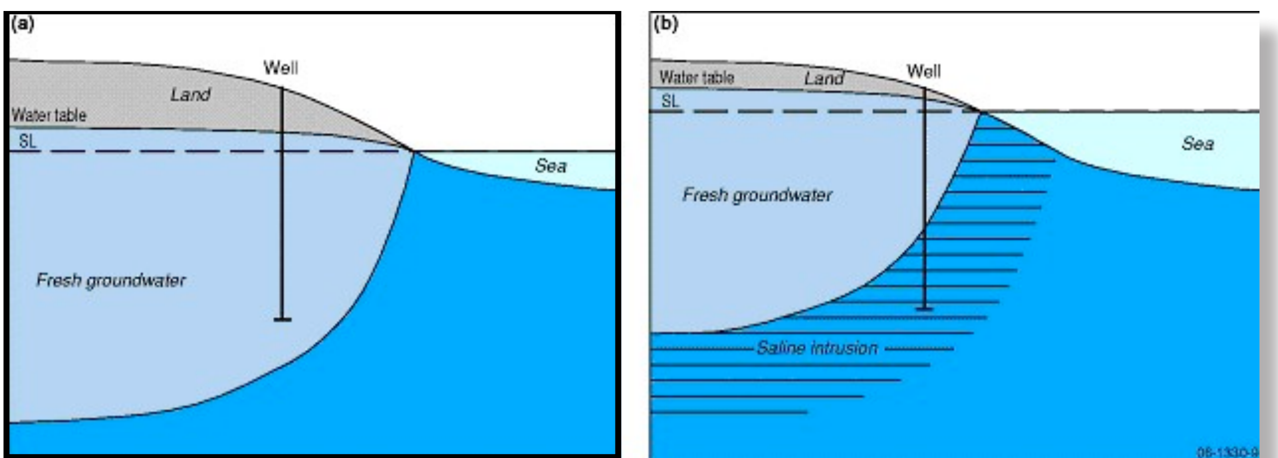

Figure 3. Sea-level rise and saltwater intrusion.

The location of saltwater-freshwater interface under static conditions (a) shifts landward under a scenario of sea-level rise (b), allowing saline water (saltwater) to intrude into the aquifer and contaminate a coastal well.

(Source: OzCoasts–Australian Online Coastal Information)

Extreme Weather Events

Climate change is likely to cause an increase in both the frequency and intensity of extreme weather events such as tropical storms and hurricanes (IPCC 2007). Combined with sea-level rise, this change is expected to bring more-frequent and intense storm surges to coastal areas (Figure 4), leading to saltwater flooding in the area of coastal wells (Van Biersel et al. 2007). Consequently, wells could be subject to both inundation and physical damage by storm surge. The duration of such inundation would likely be brief in the event of storm surge, and the risk of saltwater contamination would therefore likely also be short-lived (Somers 2011). Wells located in low-lying areas and other locations susceptible to storm surge will be particularly at risk.

Figure 4. Storm surge can lead to saltwater flooding near coastal wells and can also result in a landward shift of the freshwater-saltwater interface; both increase the likelihood of saltwater intrusion (St. Lawrence, NL, depicted here). (Source: Natural Resources Canada, courtesy of the Southern Gazette, Marystown, NL)

Heavy precipitation is another extreme weather event with a potential impact on aquifer recharge. If total amounts of precipitation remain relatively unchanged, yet come in fewer but more intense events, one possibility is that a higher proportion could be lost in the form of run-off (rather than being absorbed into the ground). This could result in reduced aquifer recharge, which would in turn lead to reduced freshwater hydraulic head and a landward shift of the saltwater-freshwater interface. Conversely, a recent study has shown that extreme weather events could in fact lead to more recharge than small events (Owor et al. 2009). Regardless, future changes to the precipitation regime are certain to impact aquifer recharge in some manner and will subsequently influence the movement of the saltwater-freshwater interface.

Coastal Erosion

Sea-level rise and more-frequent extreme weather events will in turn lead to increased coastal erosion (Figure 5), putting island communities, in particular, at risk (IPCC 2007). Similar to the effects of overpumping, decreased recharge, and sea-level rise, coastal erosion causes the shoreline to recede and the saltwater-freshwater interface to move further inland. Once again, this shift will allow saltwater to infiltrate more of the aquifer, increasing the likelihood of well contamination.

Figure 5.
Coastal erosion. Coastal erosion (Point Deroche, PEI, depicted here) allows seawater to infiltrate more of the aquifer beneath the surface, increasing the likelihood of saltwater intrusion.
(Source: D. Jardine)

Adaptation Options

To preserve groundwater sources in our coastal communities, it will be necessary to manage the threat of saltwater intrusion. Management strategies can generally be placed into three categories: monitoring and assessment, regulation, and engineering (Barlow 2003; Barlow and Reichard 2010), with the ultimate goal of preserving groundwater resources for current and future use (Bear 2004).

Scientific Monitoring and Assessment

Scientific monitoring and assessment form an essential starting point for effective management of saltwater intrusion. As particular aquifer dynamics can vary greatly from location to location, these tools give decision makers an in-depth, localized understanding of their coastal freshwater resources and enable them to make sound and informed decisions (Barlow and Reichard 2010). Water-quality monitoring networks have been established in various coastal areas of the United States, providing useful data about movement in the saltwater-freshwater interface; in essence, they serve as warning or detection systems of any landward flow of subsurface saltwater (Barlow and Reichard 2010; Barlow 2003). Although groundwater quality and quantity are monitored regularly in the Atlantic provinces through both provincial and federal programs, saltwater intrusion is not monitored specifically. To properly assess the threat of saltwater intrusion, however, specific monitoring programs (programs dedicated to monitoring movement of the saltwater-freshwater interface) are required. While salinity levels are measured by existing monitoring programs, elevated salt levels cannot necessarily be attributed to contamination from seawater; for example, increased groundwater salinity can be attributed to road salt, and therefore, proper assessment of saltwater intrusion requires monitoring of more-specific water chemistry (such as bromide ion) that is not associated with road salt. The reason for the lack of monitoring programs dedicated to saltwater intrusion in Atlantic Canada is likely because of both the low number of reported cases of saltwater intrusion in this region and the fact that the problems characterizing many areas in the United States (such as high population density, high groundwater demand, and overpumping) have yet to occur on the same scale in this region.

It is particularly important to emphasize the long-term commitment required for effective monitoring and assessment of saltwater intrusion. Again, elevated salt content within a well does not necessarily reflect intrusion; rather, active saltwater intrusion (characterized by a prolonged shift in the saltwater-freshwater interface) can be definitively identified only with numerous samples over a longer period of time (Barlow 2003). Such monitoring and assessment contributes to a thorough understanding of existing conditions in coastal aquifers and constitutes a necessary first step in determining both the severity of any saltwater intrusion and the best approach(es) in adapting to the impacts of climate change (Somers 2011).

Another essential tool in the assessment of coastal aquifer dynamics is that of scientific modelling. Modelling is a numerical way of conceptualizing the physical processes by which groundwater flows beneath the surface. Modelling helps identify the different factors (such as recharge) that influence groundwater movement. Models can be further enhanced to incorporate the effect of water density (e.g., salinity) on groundwater flow, and they can be adapted to identify conditions under which groundwater availability is optimized and saltwater intrusion is limited (Barlow and Reichard 2010). Specifically, these optimization models allow us to calculate favourable groundwater yields by identifying the pumping rates, well locations, and human interventions (such as artificial recharge) that are most efficient (Darnault and Godinez 2008; Ferreira da Silva and Haie 2007).

Regulation

A second group of coastal aquifer management strategies fit into the category of regulation, consisting of legislative action designed to ensure sustained water quality and quantity over the long term. Such action seeks to ensure the preservation of freshwater sources through both supply-related and demand-related policies (Giordana and Montginoul 2006). Supply-related policies seek to secure adequate groundwater supply by optimizing the locations and rates of withdrawals and by controlling land use and development around coastal aquifers. Demand-related policies seek to curb demand through economic and moral incentives.

Figure 6. Well relocation. Erosion leaves coastal wells vulnerable to saltwater intrusion as the freshwater-saltwater interface moves inland, occasionally necessitating well relocation. This well, located in Anglo-Tignish, PEI, demonstrates the need for prudence and foresight when drilling wells near the shoreline. (Source: D. Jardine)

With regard to supply-related policies, the natural choice might be to reduce pumping rates and, potentially, to relocate wells farther inland (Barlow 2003; Barlow and Reichard 2010) (Figure 6). In Newfoundland and Labrador (2002), for example, provincial legislation permits the government to establish private groundwater withdrawal rates in order to prevent the lowering of the water table and to reduce the threat of saltwater intrusion in coastal areas. Such action not only ensures water quantity by allowing coastal aquifers to recover; it also aids water quality by promoting the seaward shift of the saltwater-freshwater interface. Relocation of wells is made possible by optimization modelling, an ideal tool for identifying the best locations for groundwater withdrawal (Ferreira da Silva and Haie 2007). In the Atlantic provinces, there is currently no provincial legislation that explicitly regulates the proximity of wells to the shoreline. The development of such legislation could prove to be challenging, as coastal groundwater dynamics—and the prevalence of saltwater intrusion—can vary greatly from location to location.

Regulation *cont'd*

Land use is another important consideration in supply-related policy development. As groundwater is strongly influenced by above-ground activity, it is essential to include a land use management component in the management of subsurface water resources. Protection of groundwater sources through land use regulation (of, for example, property and infrastructure development, landfills, and hazardous waste storage) helps to ensure adequate aquifer recharge and to limit risk of contamination.

Demand-related policies focus on attempting to limit or reduce demand for groundwater. Water pricing is one such policy; it can be practical in that it a) assigns a specific value to a much-used resource and b) can serve as a cost-recovery mechanism to fund other management actions. While water pricing is useful in this regard, a potential drawback to consider is the detailed knowledge of water usage required to implement this policy (Giordana and Montginoul 2006). Other demand-related policies include water quotas, electricity quotas, and electricity pricing (to assign value to the cost of pumping). Demand can also be curbed through use of more-efficient irrigation systems, which can be encouraged through financial incentives to farmers, for example (Zekri 2008). Finally, demand-related policies may include an appeal to the moral responsibility of citizens. Examples of moral incentives include public education programs about water conservation, efficiency, and re-use (Barlow and Reichard 2010; Giordana and Montginoul 2006).

Ultimately, no one regulatory action is capable of solving every problem related to water quality and quantity in coastal aquifers. Indeed, the most successful water management actions are able to integrate both supply and demand-related policies (Barlow and Reichard 2010; Giordana and Montginoul 2006).

Engineering Techniques

A third group of coastal aquifer management strategies consists of various engineering techniques that can be employed as a way to adapt in the event of saltwater intrusion. They include artificial recharge, aquifer storage and recovery (ASR) systems, barrier systems, desalination, and blending (Barlow 2003; Barlow and Reichard 2010; Pool and Carrera 2010). The effectiveness of engineering techniques depends a lot on local conditions, and therefore not all methods listed below are necessarily appropriate or desirable in Atlantic Canada. To determine the suitability of any given measure would require further research and consultation.

- Artificial recharge consists of adding water to an aquifer through man-made systems (e.g., recharge basin, injection well) to increase the amount of freshwater and to control or prevent the intrusion of saltwater (Barlow and Reichard 2010; Pool and Carrera 2010). Water is stored at the surface in a permeable man-made basin, which allows water to percolate down through the ground into the aquifer. Though prevalent in other regions, including the coastal United States, artificial recharge has not been undertaken in coastal Atlantic Canada. It has been used inland at Edmundston, NB (Environment Canada 2011).
- Aquifer storage and recovery (ASR), a technique used successfully in the United States (Barlow and Reichard 2010), is a particular type of artificial recharge whereby freshwater is injected into the aquifer (through a well) during high-supply seasons (winter, spring) and then recovered (pumped to the surface) during low-supply seasons (summer, early fall).
- Barrier systems are subsurface in nature; they fall into two categories: physical barriers and hydraulic barriers (Pool and Carrera 2010). Physical barriers consist of a low-permeable material (such as steel or concrete) that acts to block the intrusion of saltwater into the aquifer. Hydraulic barriers consist of injecting freshwater and/or pumping saltwater to prevent the landward movement of the saltwater-freshwater interface.
- Desalination is the process by which salt and mineral content are removed from brackish water or seawater (Buros 1985). Desalination has become a more attractive option as the technology improves, costs decrease, and freshwater supplies become less prevalent (Barlow and Reichard 2010).
- Blending refers to the process by which desalinated water is mixed with freshwater from the surface (to an acceptable standard) to meet increasing demand for drinking water (Barlow and Reichard 2010).

While engineering techniques can prove effective in addressing problems of groundwater quality and quantity, they are generally more expensive, invasive, and site-specific than the adaptation options of scientific monitoring, scientific assessment, and regulation. In light of this fact, coupled with the fact that there is still much knowledge to be gained about saltwater intrusion dynamics in Atlantic Canada, engineering techniques should—at least initially—be passed over in favour of monitoring, assessment, and regulatory solutions.

NEXT STEPS

In Atlantic Canada, there is still a great deal to be learned about the hydrogeologic conditions that currently influence the prevalence and severity of saltwater intrusion. The natural occurrence of saltwater intrusion depends on site conditions and therefore does not necessarily take place to the same extent even at sites within close proximity. At some locations, the saltwater-freshwater interface may be found at a significant distance seaward from the shoreline, while at other locations it may extend a significant distance inland.

The occurrence of saltwater intrusion is also greatly influenced by human activity. Increased groundwater demand and subsequent pumping, in particular, can have significant effect on the landward movement of the saltwater-freshwater interface. Water demand in coastal regions, of course, is highly variable from location to location, further complicating attempts to assess vulnerability.

Finally, the continued impacts of climate change contribute an additional element of uncertainty. As sea-level rises and coastal erosion and demand for groundwater increase, the threat of saltwater intrusion is also likely to increase. The specific effects of these impacts are not certain, however, and are likely to be highly variable from location to location. Coastal erosion rates, for example, can be different within very short distances. Similarly, because soil characteristics vary from place to place, changing precipitation regimes may not affect recharge rates uniformly across the region. Such uncertainty highlights three notable voids currently inhibiting progress in our attempt to address vulnerability to saltwater intrusion in Atlantic Canada: the need for better data, the need for better collaboration, and the need for better planning.

Better Data

A better understanding of the existing conditions controlling saltwater intrusion and the potential impacts that a changing climate could have on those conditions is contingent on acquiring better data—and more of it. Long-term monitoring of the saltwater-freshwater interface, particularly at sites identified as potentially sensitive to intrusion, will increase the quality and quantity of data used to assess vulnerability to saltwater intrusion. Climate modelling is also an essential component of anticipating future changes. Increasing temperatures, changes to precipitation patterns (and, subsequently, recharge rates), rising sea level, and more coastal erosion are all expected to increase the severity of saltwater intrusion. The extent to which these changes influence saltwater intrusion is very site-specific, however, and has not been quantified in Atlantic Canada.

Better Collaboration

Equally important as the need for better data is the need to acquire and make use of those data as efficiently as possible. Formal and informal monitoring and assessment are often conducted by universities, community groups, various levels of government, and private citizens—each of which may bring a unique capacity for data acquisition as well as a unique perspective of the issue. University researchers, for example, might bring specialized expertise in fields such as hydrogeology. Community groups might offer a volunteer or low-cost workforce to conduct monitoring. Federal, provincial, or municipal government might bring the resources necessary to carry out long-term monitoring, and they may also facilitate the transition from monitoring and assessment to policy development. Private citizens, whose local knowledge and experience cannot be substituted for, offer the ability to recount occurrences of saltwater intrusion perhaps unknown outside the community. Unfortunately, however, there is often limited collaboration between these groups, leaving the potential for duplicated efforts, incomplete information, and other inefficiencies.

Better Planning

Better data and better collaboration, of course, form the foundation for better planning. To date, vulnerability to saltwater intrusion has perhaps not been a prominent cause for concern in Atlantic Canada. The inevitability of climate change and its impacts on natural coastal systems, however, prompts the need for long-term decision making that accounts for vulnerability to saltwater intrusion. Data of increased quality and quantity help to paint a more complete picture of existing coastal conditions, providing accurate and up-to-date information regarding coastal erosion rates, sea-level rise, temperature and precipitation trends, and the position and movement of the saltwater-freshwater interface. These data can assist in the areas of land use regulation and policy development, particularly regarding groundwater withdrawals and setback distances for coastal development.

ATLANTIC REGIONAL ADAPTATION COLLABORATIVE (RAC)

To date, few studies have been undertaken to evaluate the potential impacts of sea-level rise on Atlantic Canada's coastal groundwater supplies. Consequently, a sizeable knowledge gap exists regarding both the current extent and characteristics of saltwater intrusion and the possible timing and extent of saltwater intrusion in the future. Policy development and planning has therefore proven difficult. While much of the current work in this area focuses on the influence of climate change on saltwater intrusion, it is equally if not more important to develop first an improved understanding of current saltwater intrusion dynamics.

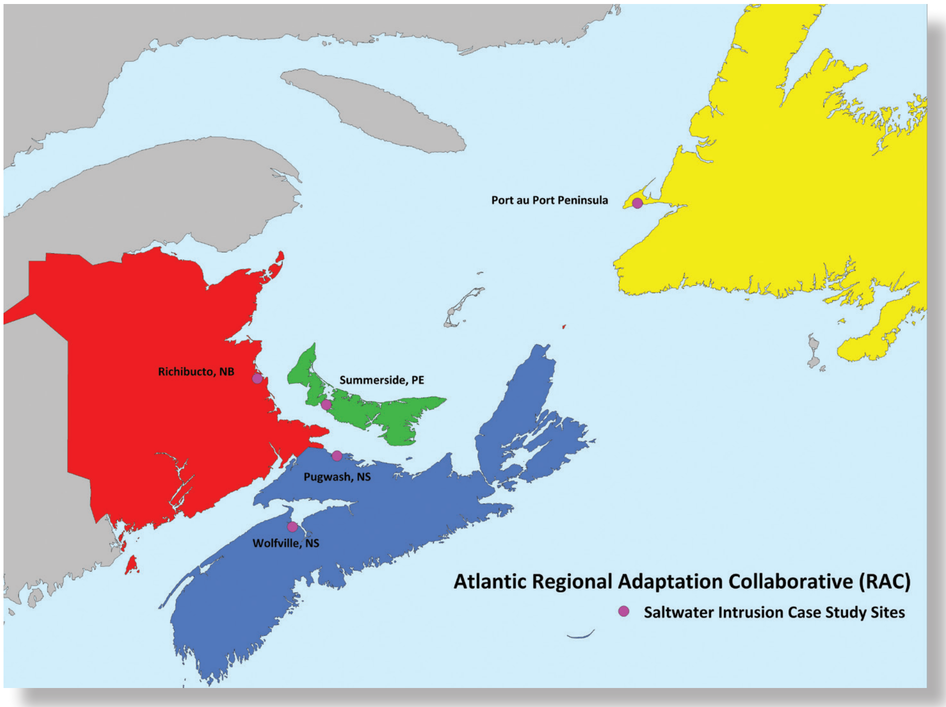

Figure 7. Atlantic Regional Adaptation Collaborative (RAC) Saltwater Intrusion Case Study Sites. Saltwater intrusion case studies have been undertaken at five sites within Atlantic Canada: Richibucto (NB), Pugwash (NS), Wolfville (NS), Port au Peninsula (NL), and Summerside (PE).

As part of Natural Resources Canada's Regional Adaptation Collaborative (RAC), case studies have been developed in each of the Atlantic Canadian provinces in order to better understand saltwater intrusion, along with the challenges and needs it presents. Case studies are being conducted at Richibucto, NB (Green et al. 2011), Pugwash, NS (Beebe et al. 2011), Wolfville, NS (Beebe et al. 2011), Summerside, PE (Hansen et al. 2011), and Port au Port Peninsula, NL (Adams 2011) to investigate existing conditions and the potential impacts of climate change on groundwater resources (Figure 7). Groundwater monitoring, geophysical surveying, geochemical analysis, and groundwater modelling under current and future conditions have been undertaken to this end. Collectively, these four provincial RAC projects are the first to assess the potential future impacts of sea-level rise on Atlantic Canada's coastal aquifers. They will form an important science-based foundation upon which future policy and planning can be carried out by local, provincial, and national governments that seek to adapt to current and future impacts of climate change.

LINKAGES AND KEY RESOURCES

Effective adaptation work will require collaboration in the areas of research, policy, and management. An open exchange of ideas, information, and resources between multiple levels of government (municipal, provincial, federal), academic institutions and research groups, community organizations, environmental associations, and others will be essential to successfully preparing for and adapting to the anticipated impacts of climate change. The list of linkages and key resources provided here should by no means be considered to be complete. Rather, this list can serve as a starting point for future working relationships aimed at achieving this valuable objective.

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