DEVELOPMENT OF A GIS-BASED APPROACH FOR THE ASSESSMENT OF RELATIVE SEAWATER INTRUSION VULNERABILITY IN NOVA SCOTIA, CANADA

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ABSTRACT
Approximately 70% of Nova Scotians reside within 20 km of the coastline and many of the province's coastal regions are experiencing residential growth. In coastal regions of the province where municipal water service is not available (unserviced areas), private wells represent the only practical means of obtaining a water supply. It is estimated that over 90% of these wells intercept fractured bedrock aquifers. There are limited tools available, however, to groundwater managers and land-use planners for evaluating the sustainability of groundwater supplies in these unserviced areas, which are vulnerable to the effects of seawater intrusion. Seawater intrusion into coastal aquifers, driven by overpumping and rising sea levels, is therefore a key issue for water resource management in Nova Scotia.

Quantitative methods for vulnerability characterization cannot be meaningfully applied at the provincial scale due to the lack of available detailed hydrogeological data at this scale. A GIS-based approach for broadly evaluating the relative vulnerability of bedrock coastal aquifers to seawater intrusion in unserviced areas of the province was therefore developed. The approach uses available provincial spatial datasets, such as digital elevation models, civic address points and well logs data, to evaluate relative vulnerability based on the following derived criteria: distance to the coast, land slope, development density, non-residential groundwater use and static water level.

A provincial relative vulnerability map was produced using this GIS approach, and compared to available chemistry data. The map identifies areas that may already be experiencing seawater intrusion or are at greatest relative risk to additional groundwater withdrawals, sea-level rise, or decreased groundwater recharge. The map could be used by groundwater managers to help identify emerging seawater intrusion problem areas, to identify suitable coastal aquifer monitoring well locations and areas for more detailed quantitative analyses, and to help inform land-use planning decisions.

1 INTRODUCTION

Seawater intrusion (SWI) into coastal aquifers as a consequence of overpumping, coupled with the effects of climate change and sea-level rise, is a key issue for water resource management in the Province of Nova Scotia. Nova Scotia has over 10,000 km of coastline and approximately 70% of Nova Scotians reside within 20 km of the coast (Government of Nova Scotia 2005). It is estimated that over 50% of Nova Scotians living in coastal areas depend on groundwater as their primary source of potable water, and many of the province's coastal regions are experiencing residential growth, especially in suburban areas of Halifax (Figure 1) which experienced 7.5% population growth from 2006-2011 (Statistics Canada 2012).

The combined effect of eustatic and isostatic sea-level rise will produce an estimated 70 cm increase in relative sea level across Nova Scotia by 2100 (Forbes et al. 2009). Vasseur and Catto (2007) report that although precipitation is expected to remain the same or increase over the same period of time, the timing of precipitation events may contribute to an overall decrease in groundwater recharge in the province. This would result in a decrease in the availability of coastal groundwater and, along with projected increases in demand, especially during the summer months when groundwater levels are at their lowest, exacerbate the risk of SWI.

A study was recently completed under the Atlantic Regional Adaptation Collaborative (RAC) to provide an initial assessment of the potential impact of climate change on coastal aquifers in Atlantic Canada through a series of case studies consisting of site-specific field investigations coupled with groundwater modeling under various climate change scenarios. The location of the Nova Scotia case studies is shown in Figure 1. Historical documentation of SWI in Nova Scotia is limited to a handful of reports by the government and private consultants (e.g. H.J. Porter & Associates 1979; H. J Porter & Associates 1980, Cross 1980, Briggins and Cross 1995, CBCL Limited 2005). Based on the Atlantic RAC case study findings, Ferguson and Beebe (in prep.) reported that the province's aquifers are not very susceptible to SWI. Nova Scotia receives high rates of precipitation, and projected changes in recharge will have a minor impact on coastal aquifers over the range of hydraulic gradients observed in the province (Ferguson and Gleeson 2012). In addition, the low permeability of glacial till material overlying much of the province was interpreted to result in a high water-table slope, forcing

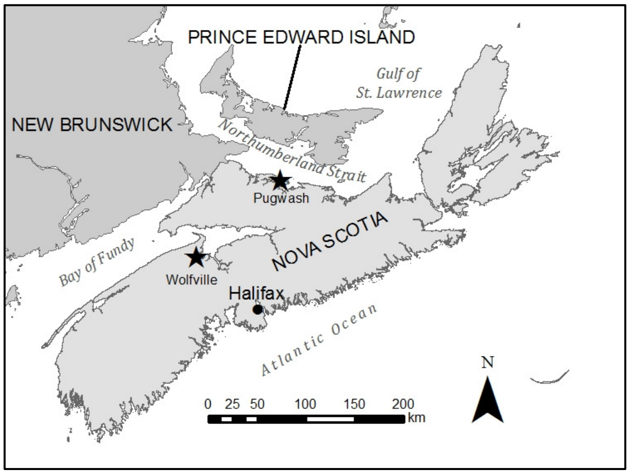

Figure 1. Location map showing Pugwash and Wolfville Atlantic RAC project sites

the freshwater-saltwater interface off the coast (Ferguson and Beebe in prep.). Key findings of the case study work under the Atlantic RAC also suggest that coastal aquifers are most sensitive to changes in groundwater withdrawals, highlighting the importance of managing water demand in coastal areas (Beebe 2011, Ferguson and Beebe in prep.).

1.1 SWI Vulnerability Characterization

Mapping the relative vulnerability of seawater intrusion throughout the province was proposed as a useful tool for managing SWI risk and prioritizing groundwater management activities. Quantitative methods of vulnerability characterization (e.g. Werner et al. 2012) cannot be meaningfully applied at the provincial scale due to the lack of detailed hydrogeological information available at this scale. The relative vulnerability of bedrock aquifers can be qualitatively characterized based on the hydrogeologic characteristics of the province's five major bedrock groundwater regions (Table 1). The province's bedrock groundwater regions are shown in Figure 2 and a detailed description of their hydrogeologic characteristics can be found in Kennedy and Drage (2009).

This approach, however, does not account for water use patterns and other site-specific information, and does not provide vulnerability characterization at the scale needed for land-use planning decisions. Qualitative vulnerability assessment techniques developed by others were reviewed (e.g. GALDIT, Chachadi and Lobo-Ferreira 2005), however, a customized tool tailored to the available spatial datasets in Nova Scotia was considered the most advantageous approach.

The adaptive capacity of the water user is an important consideration in SWI vulnerability characterization. Private well users have limited adaptive capacity because they have few low cost remedial options available to them if their water well becomes impacted by SWI. Remedial options might include the installation of a dug well or cistern system, modifications to the existing well or pumping configuration, water deliveries, reverse osmosis treatment, or water servicing. It is estimated that over 30% of Nova Scotians in coastal areas are supplied by private wells, and based on provincial trends over 90% of these wells are drilled wells intercepting fractured bedrock aquifers (Kennedy and Drage 2009). Reliance on private well water supplies in coastal areas is increasing in some parts of Nova Scotia. For example, 6 of the 10 subdivision applications received by the Halifax Regional Municipality over the past several years for new subdivisions serviced by private wells have been located within 1500 m of the coastline.

Table 1. Qualitative relative vulnerability assessment of major bedrock groundwater regions in Nova Scotia.

Groundwater Region	Bedrock Unit	Risk Characterization
Sedimentary (mostly siliciclastic units)	Cumberland, Fundy, Horton, Mabou, Morien, and Pictou groups	Extent of SWI can be more widespread due to higher hydraulic conductivity of sedimentary rock aquifers
Carbonate/ Evaporite	Windsor Group	Groundwater already associated with high TDS and often not suitable for consumption
Volcanic	Stirling and Fourchu groups, and North Mountain Formation of Fundy Group	Predominantly vertical fracturing may limit extent of SWI
Plutonic	All granitic bedrock types	Extent of SWI dependent on connectivity of water bearing fractures with seawater, lower hydraulic conductivity may result in more localized effects, although greater drawdowns in these rock types may result in increased upconing of seawater
Metamorphic	Meguma Supergroup, Georgeville Group	

There are few instruments available to water managers to evaluate the sustainability of groundwater withdrawals and manage SWI risk in these unserviced areas of the province. SWI vulnerability is also more difficult to characterize in these areas due to a lack of available well water chemistry and water level monitoring data relative to the extent of unserviced coastline. Nova Scotia currently has a total of 17 observation wells within 1500 m of the coastline and does not routinely collect private well chemistry data.

Although municipal groundwater supplies can be more susceptible to SWI than private well water supplies due to concentrated pumping of larger water volumes, areas serviced with municipal groundwater can be considered to have lower inherent risk because the resource is actively being managed by water utilities and subject to regulatory oversight, including monitoring protocols and routine chemistry analyses. Water utilities also have greater capacity to characterize risk and implement adaptive management (e.g. drill new wells farther inland) relative to private well users. Quantitative, physically based SWI assessment is appropriate for these systems (e.g. chemical fingerprinting, analytical/numerical modeling).

For these reasons the relative SWI vulnerability characterization work here focused on coastal bedrock aquifers located in unserviced areas of the province.

1.2 Study Objectives

The objectives of the study were to develop a simple GIS-based tool for broadly evaluating the relative vulnerability of bedrock coastal aquifers to SWI in unserviced areas of the province.

2 METHODS

2.1 SWI Indicator Map

Various indices of seawater intrusion were compiled and mapped within 1500 m of the coastline to help assess the potential extent of SWI in Nova Scotia. These indicators include groundwater chemistry data (such as chloride and bromide concentrations and ratios), water well drill locations where well drillers have reported encountering seawater, and areas where available reporting or anecdotal information have identified potential SWI.

For the purposes of the indicator map, chloride concentrations greater than 50 mg/L were considered to represent elevated levels above background. Kennedy and Finlayson-Bourque (2011) reported a median chloride concentration of 24 mg/L in the province's bedrock aquifers, with approximately 70% of the levels falling below 50 mg/L. In addition to SWI impacts, elevated chloride levels in groundwater in Nova Scotia have been attributed to sources such as road salt, on-site wastewater discharges and bedrock formation salt (e.g. halite bedrock units within the carbonate/evaporate groundwater region, Figure 2). A limited number of groundwater samples collected throughout the province also include measurements of bromide. The Br/Cl ratio has been used previously in Nova Scotia (e.g. Briggins and Cross 1995) and other jurisdictions (e.g. Snow et al. 1990) to effectively differentiate marine sources of chloride from road salt (e.g. halite). Br/Cl ratios of approximately 3.4×10^{-3} indicate chloride of seawater origin, whereas bromide tends to be present at lower concentrations in road salt, resulting in lower Br/Cl ratios.

2.2 SWI Vulnerability Map

2.2.1 GIS Approach

The assessment area was defined as a 250 m x 250 m grid within 1500 m of the 1:10 000 provincial coastline layer. The few documented cases of SWI in Nova Scotia are within 500 m of the coast, and therefore 1500 m inland from the coastline was considered to be a conservative distance for the relative vulnerability assessment. Key provincial spatial data layers were clipped to the grid and five variables considered to influence SWI vulnerability were derived from these layers (see Section 2.2.2 to 2.2.6).

The relationship between these variables and SWI vulnerability is conceptually illustrated in Figure 3 according to the Ghyben-Herzberg approximation, which relates the position of the saltwater-freshwater interface to the densities of freshwater and saltwater and the distribution of hydraulic head (Ghyben 1888; Herzberg 1901). This relationship predicts that the depth of the interface below sea level is equal to approximately 40 times the elevation of the water table above sea level.

Variables were classified and rankings were assigned to each grid cell. The rankings were summed to produce an overall SWI relative vulnerability map, which was then compared to available chemistry data to evaluate the reliability of the vulnerability assessment. Grid cells were compared based on a ranking relative to each other, and not upon a numerical indicator used to indicate a physical threshold. The ranking system for each of the five input variables is qualitative and based on a five-category defined-interval classification. The overall vulnerability ranking uses a three-category defined interval classification intended to generally classify SWI vulnerability into high, medium and low categories.

The GIS approach developed here is intended to be used as an indexing tool that can be readily re-applied to expanded or refined input spatial datasets as they become available. SWI vulnerability refers to the relative likelihood of an existing private well in a given area to be impacted by SWI, based on a simple treatment of factors known to influence SWI.

2.2.2 Distance to the Coastline

SWI risk is greatest near the coastline and decreases with distance inland (x, Figure 3). The distance from each grid centroid to the 1:10 000 coastline layer of the province was calculated, and the grid cell was assigned a ranking according to the criteria shown in Figure 4a.

2.2.3 Topographic Slope

Coastal aquifers with low hydraulic gradients are associated with increased SWI risk (i, Figure 3). Topographic slope was selected as a surrogate variable for hydraulic gradient since the bedrock water table in Nova Scotia tends to follow a subdued pattern of topography due to high precipitation rates and the presence of low-permeability surficial cover (Gleeson et al. 2011). The slope was calculated from the 20 m digital elevation model (DEM) of the province and grid cells were assigned a ranking according to the criteria shown in Figure 4b.

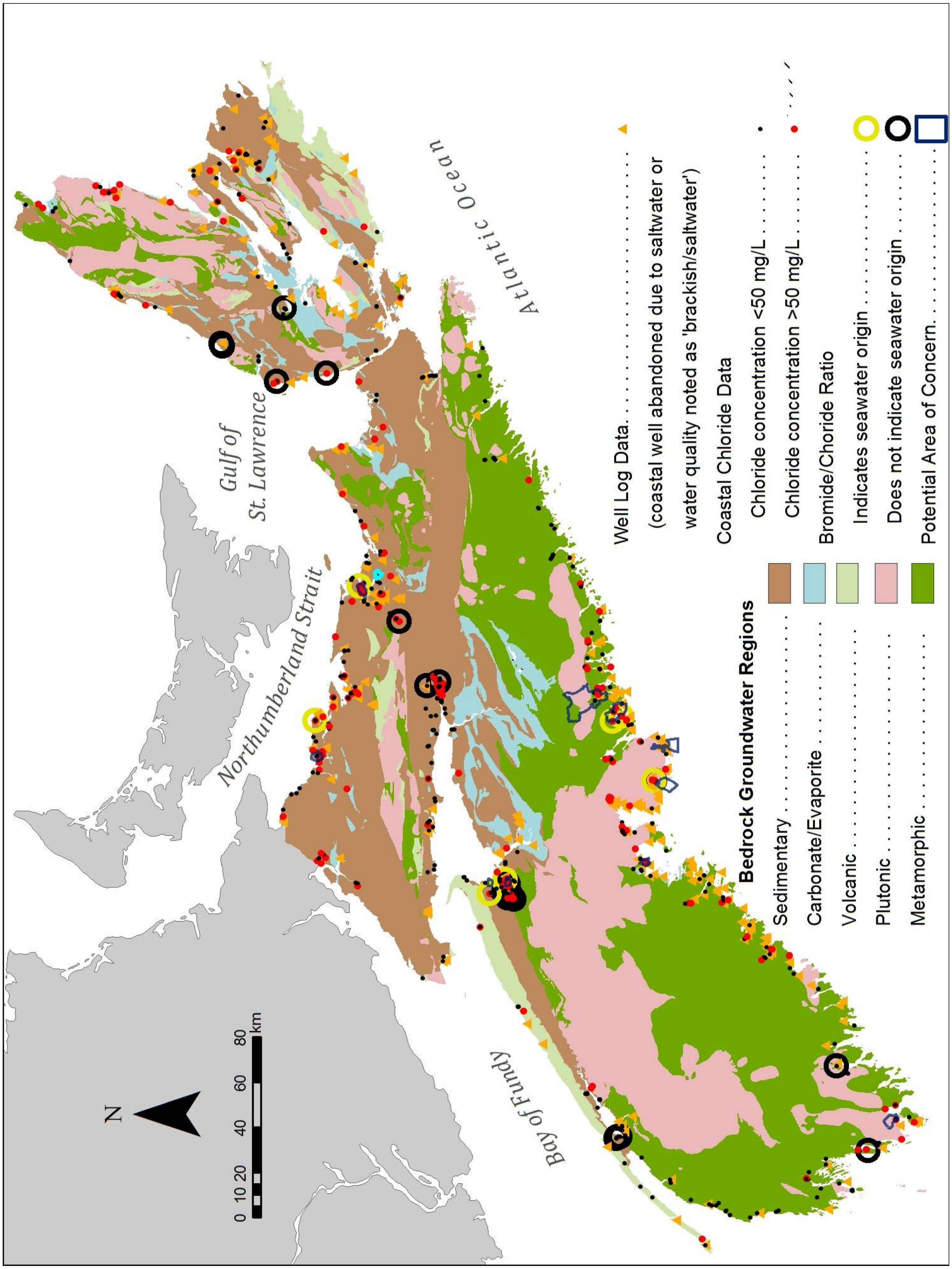

Figure 2. Map showing various indicators of potential seawater intrusion

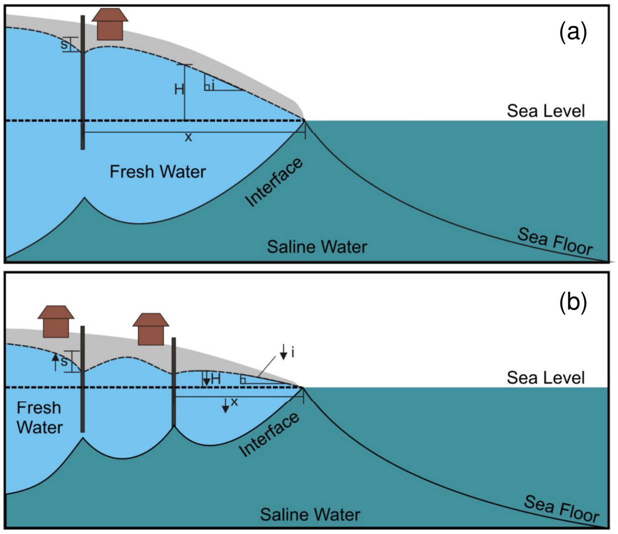

Figure 3. Conceptual illustration showing how vulnerability to SWI impacts can increase according to the Ghyben-Herzberg relationship. In (b), the water supply wells are at greater risk due to lower freshwater head above sea level (H) as a consequence of their closer position to the coast, a lower hydraulic gradient (i) and increased drawdown (s).

2.2.4 Civic Point (Residential) Density

Areas of intensive groundwater withdrawals have greater risk of SWI because increasing drawdown (s, Figure 3) will cause increased upconing of saline water according to the Ghyben-Herzberg relationship. Nova Scotia maintains a spatial layer of civic points throughout the province (Service Nova Scotia 2012). This layer was clipped to exclude civic points located within municipal water distribution zones, and the resulting civic point layer was used to indicate domestic groundwater use in areas not serviced with municipal water. A count was performed of civic points within each grid cell and rankings were assigned according to the criteria shown in Figure 4c.

2.2.5 Large Groundwater Users

In addition to concentrated domestic groundwater use, large non-domestic groundater users in unserviced areas can increase drawdown (s, Figure 3) and SWI risk. Nova Scotia maintains a spatial layer of large groundwater users and estimated daily withdrawal rates throughout the province (Kennedy et al. 2010). Daily non-domestic groundwater withdrawal rates were summed for each grid cell and classified according to the criteria shown in Figure 4d.

2.2.6 Water Level Elevation

An aquifer's susceptibility to seawater intrusion is influenced by pressure in the freshwater zone relative to sea level, since adequate freshwater pressure must be maintained to prevent SWI (H in Figure 3). Where the bedrock static water level is at or below sea level, SWI risk is greater.

Nova Scotia maintains a database of water well data, including static water level estimated by drillers during well construction (Nova Scotia Environment 2012a). Water wells located within the study area grid were filtered to exclude data with missing water level information. Moreover, the location accuracy of wells in the database is variable, and only well locations accurate to the property level were retained. The resulting data layer contained 8526 records, representing 15.5% of the total records located in the study area.

A ground surface elevation was assigned to each of these wells using the best available digital elevation model (DEM). Higher resolution LiDAR-derived DEMs (compared to the provincial DEM) were available in eight sub-areas of the province. The water level elevation was calculated as the depth to water level reported by the well driller on the log subtracted from the DEM estimated surface elevation. Where multiple wells were located within a grid cell, the minimum water level measurement was used for the vulnerability assessment. The more accurate water level elevation reported in provincial observation wells (Nova Scotia Environment 2012b) and pumping test reports superseded well log data where these data were available. Where water level data were sparse, the water level estimate predicted the water level in grid cells up to 500 m from the point measurement. Each grid cell was classified with respect to water level according to the criteria shown in Figure 4e.

2.2.7 Relative SWI Vulnerability

Relative SWI vulnerability was calculated as the sum of all five criteria to produce an overall score according to the criteria shown in Figure 5. Vulnerability was not calculated for cells with null water level measurements (i.e. no water level elevation estimate available).

2.2.8 Validation

A rigorous statistical validation of the relative SWI vulnerability mapping was not possible due to the limited availability of groundwater geochemistry data and confirmed cases of SWI in unserviced areas of the province. The results of the overall vulnerability mapping were compared to the SWI indicator mapping, however, to determine if there was general agreement between high vulnerability and existing indicators of SWI.

3 RESULTS

The SWI indicator map is shown in Figure 2. The map shows that many of the elevated chloride levels near the coast are located along the Atlantic coast in the south-central region of the province, and along the Northumberland Strait, where significant coastal populations exist and more groundwater information is available. The origin of the elevated chloride levels shown in Figure 2 is not known, although it should be noted that the median concentration of chloride in coastal regions (<1500 m from the coastline) is 43 mg/L compared to 15 mg/L for samples collected in the rest of the province. Areas where the bromide/chloride ratio is indicative of seawater intrusion to bedrock aquifers were identified in Prospect, Lawrencetown, Cow Bay, Wolfville, Canning, Pictou and Fox Harbour (Figure 2). Based on the data presented in the compilation map, suspected occurrences of SWI tend to be of local extent.

Figure 4 shows the results of the ranking of SWI vulnerability for the variables described in Sections 2.2.2 to 2.2.6. Figure 5 shows the relative SWI vulnerability

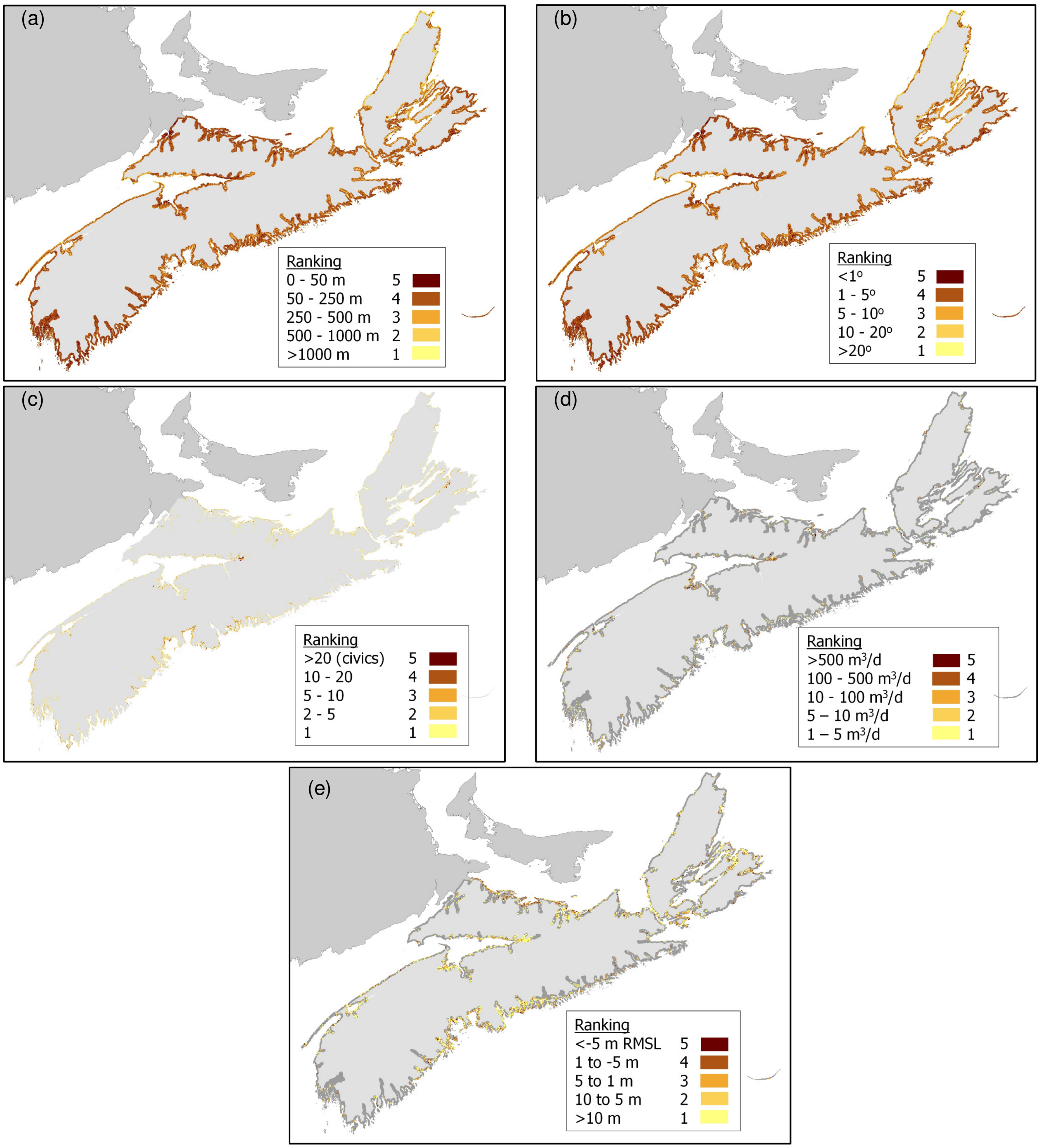

Figure 4. Input layers used to estimate overall relative SWI vulnerability, including (a) distance to the coastline, (b) topographic slope, (c) civic point (residential) density, (d) large groundwater users and (e) water level elevation relative to mean sea level (RMSL)

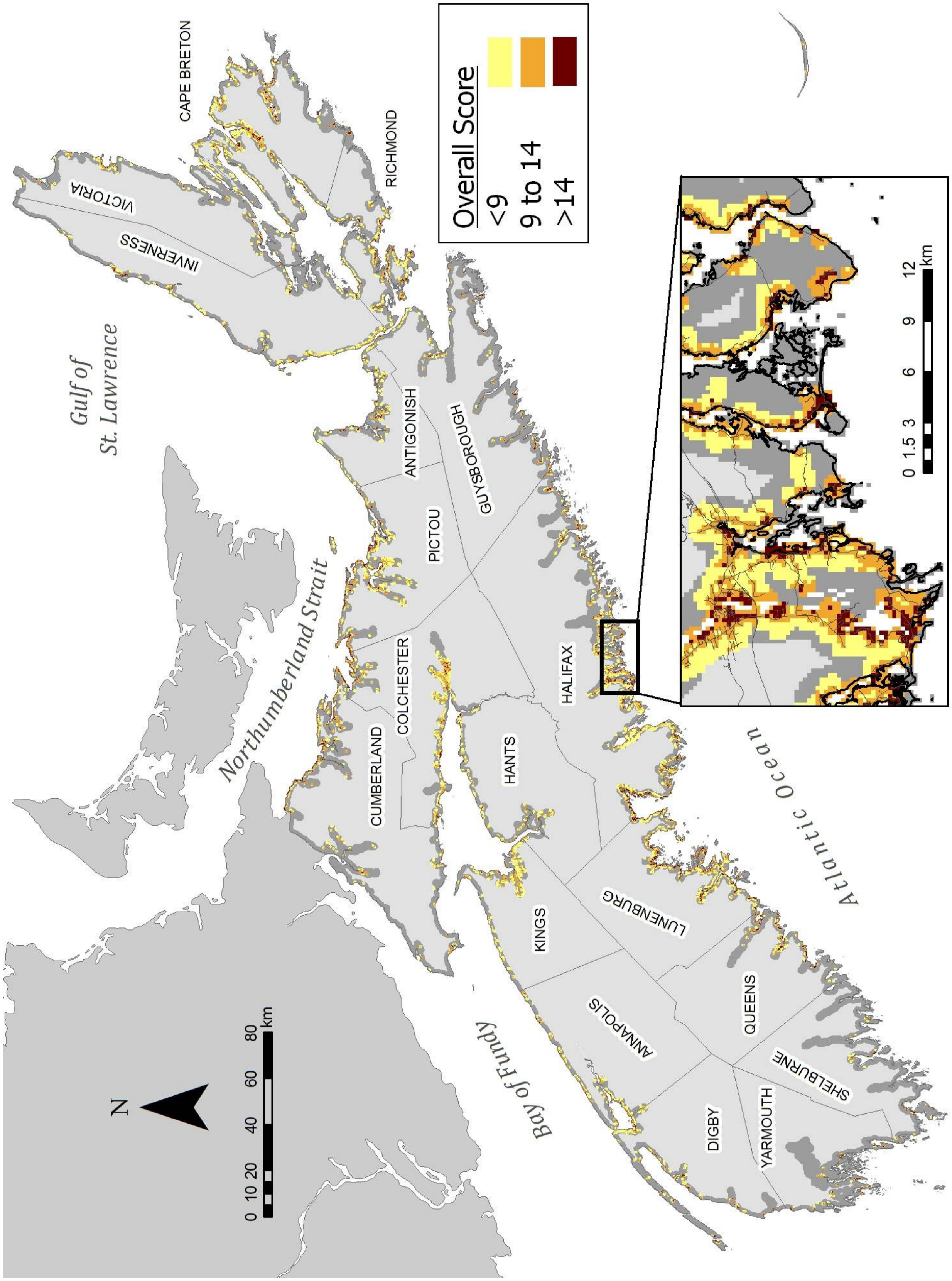

Figure 5. Overall relative SWI vulnerability map

map for the province. Since relative SWI vulnerability was calculated only for cells with water level information (e.g. calculated only for cells with water level information (e.g. Section 2.2.6), an overall vulnerability score was calculated for only approximately 26% (49,564 cells) of the total study area. Table 2 provides a count of the number of cells in each of the high, medium, and low vulnerability categories for the province and for each county. The south-central (Halifax and Lunenburg counties) and Northumberland Strait (Cumberland and Pictou counties) areas of the province had the greatest relative vulnerability based on a count of cells in the high vulnerability category. Table 2 also shows that 86% of the locations with Br/Cl ratios indicating SWI, and 55% of the locations where drillers have reported encountering seawater, were located in grid cells with a high relative vulnerability score.

4 DISCUSSION

Although recent work (Ferguson and Beebe in prep.) indicates that Nova Scotia's coastal aquifers are not especially vulnerable to SWI compared to many other coastal aquifer systems around the world, a large segment of the population in Nova Scotia relies on private wells intercepting coastal bedrock aquifers for potable water, and residential development (and groundwater use) in some coastal areas, especially in suburban Halifax, is growing (Statistics Canada 2012).

Table 2: Count of high, medium and low vulnerability scores broken down by jurisdiction (province and county) and compared to observed geochemical and well log data.

	Total Cells	Number of cells	Percent of total cells	Number of cells	Percent of total cells	Number of cells	Percent of total cells
		High		Medium		Low	
Nova Scotia	49564	4497	9%	20019	40%	25048	51%
Halifax	8926	1039	12%	3848	43%	4039	45%
Lunenburg	4266	592	14%	1869	44%	1805	42%
Cumberland	3403	421	12%	1595	47%	1387	41%
Pictou	3908	415	11%	1555	40%	1938	50%
Cape Breton	5111	408	8%	1973	39%	2730	53%
Colchester	3588	256	7%	1422	40%	1910	53%
Richmond	3220	244	8%	1442	45%	1534	48%
Queens	1236	175	14%	557	45%	504	41%
Guysborough	1683	161	10%	814	48%	708	42%
Digby	1649	142	9%	615	37%	892	54%
Inverness	2570	126	5%	791	31%	1653	64%
Victoria	1897	99	5%	585	31%	1213	64%
Antigonish	1684	98	6%	612	36%	974	58%
Yarmouth	625	89	14%	322	52%	214	34%
Kings	2290	75	3%	723	32%	1492	65%
Shelburne	510	74	15%	235	46%	201	39%
Annapolis	1475	43	3%	547	37%	885	60%
Hants	1523	40	3%	514	34%	969	64%
Drillers encountering saltwater[1]	96	53	55%	37	39%	6	6%
Br/Cl Indicating SWI	7	6	86%	1	14%	0	0%
Cl > 50 mg/L[1]	224	91	41%	97	43%	36	16%

1. Data intersecting the carbonate/evaporite groundwater region were excluded from the counts due to naturally occurring salinity

Prevention of SWI is critical because the adaptive capacity of private well users is limited. Since SWI is sensitive to groundwater withdrawals, careful water management is needed to prevent SWI, but water managers have limited instruments available for managing water demand and assessing SWI risk. Climate change effects, such as eustatic sea-level rise and changes to groundwater flow dynamics, can increase the severity of this risk.

The GIS-based relative SWI vulnerability indexing tool identified unserviced areas that may already be experiencing SWI or are at greatest risk to sea-level rise and additional withdrawals by new developments using private wells. The results of the assessment may allow land-use planners to target land-use controls and more detailed groundwater study requirements in areas of high residential growth and SWI vulnerability. Groundwater managers may use the results of the analysis to identify suitable coastal aquifer monitoring well locations and to help prioritize areas for more detailed risk assessment using quantitative physically based methods, such as well surveys, analytical and numerical modeling, and chemical fingerprinting. Effective utilization of the relative vulnerability mapping would require routine update and improvement of input data sets (e.g. higher resolution DEMs, new well logs, improved georeferencing of logs), and the development of suitable mechanisms for the regular transfer of the map information to users such as municipal planners and water managers.

It is difficult to evaluate the reliability of this approach as a relative vulnerability indexing tool. There was reasonably good spatial agreement between relative vulnerability and geochemical indicators of SWI and salinity problems reported by well drillers (Table 2). The collection of additional groundwater chemistry data (especially Br) and comparison of other geochemical indicators of SWI to the mapping would provide opportunities for a more robust evaluation of the approach presented here.

The relative SWI vulnerability assessment tool has a number of fundamental limitations and should only be used for broad relative risk characterization as a first pass analysis. The subjective indexing approach used in generating the relative vulnerability map lacks the theoretical translation of hydrogeological characteristics into SWI vulnerability. The approach could be refined by improved consideration of the local hydrogeologic setting (e.g. confined vs. unconfined aquifer types, hydraulic conductivity and bedrock fracture patterns). These types of refinements, however, are likely predicated on a more detailed understanding of the coastal zone hydrogeology of the province and how it relates to SWI vulnerability. If this knowledge is generated, however, it may be feasible to apply analytical SWI vulnerability indicators (e.g. Werner et al. 2012) at the provincial scale.

5 CONCLUSION

A GIS-based approach was developed to help broadly characterize SWI relative vulnerability in unserviced areas of Nova Scotia. The tool provides a preliminary assessment of relative SWI vulnerability in Nova Scotia based on factors known to influence the position of the seawater – freshwater interface. The spatial analysis can be readily repeated as new data become available. There was reasonably good agreement between indicators of SWI and areas identified as having medium to high vulnerability. The south-central and Northumberland Strait areas of the province appear to have the greatest relative SWI vulnerability based on the results of the mapping. Improvements to the quality and resolution of input data layers and refinement of the indexing approach are recommended to improve the reliability of the relative SWI vulnerability map.

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