MINERAL RESOURCES BRANCH

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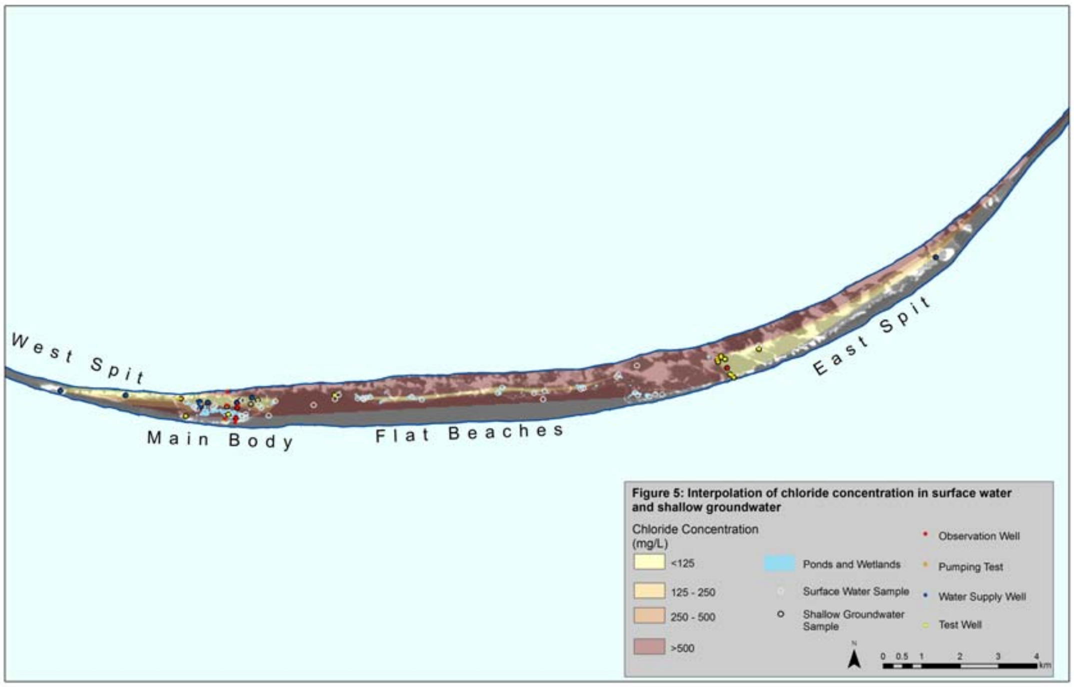


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*G. W. Kennedy, J. Drage and T. W. Hennigar[1]*

## Introduction

The freshwater resources of Sable Island were first assessed in the 1970s due to increasing interest in oil exploration and the concomitant need for potable water and sound management of the island's water resources. Assessment activities included test drilling, water-level monitoring, groundwater and surface-water sampling for chemical and bacteriological quality, pumping tests, and a geophysical survey. The findings and recommendations were released as an assessment report, which serves as a baseline understanding of freshwater resources on the island (Hennigar, 1976). A map showing the estimated locations of test holes, pumping tests, observation wells and resistivity surveys from the 1970s assessment work is provided in Figure 1 (inset). More recently, several environmental site investigations have taken place on Sable Island (e.g. Public Works and Government Services Canada, 1996; Stantec Consulting Limited, 2010; Conestoga-Rovers and Associates Limited, 2011), which have further contributed to the understanding of its groundwater quality and quantity. The objective of the current report is to compile and summarize available hydrogeological information in order to update our baseline understanding of the groundwater resources of Sable Island.

## Geology and Physiography

Sable Island, the emergent part of the Sable Island Bank, is a crescent-shaped series of dunes that is about 49 km long, up to 1.5 km wide and covers an area of 2984 ha; its maximum elevation above sea level is approximately 30 m (Applied Geomatics Research Group, 2011; Muise, 2012). For the purposes of studying its freshwater resources, the island physiography was divided into four sub-regions: the west spit, the main body, the flat beaches and the east spit (Hennigar, 1976; Fig. 1). The island, which experiences frequent changes in shape and size due to coastal geomorphological processes, is gradually migrating eastward (Byrne and McCann, 1993). The surficial geology is relatively homogeneous, consisting of more than 300 m of unconsolidated Quaternary-age sands (0.08 to 1.8 mm particle size) that were deposited as outwash materials during the last glaciation (Hennigar, 1976). This layer is underlain by 900 m of Tertiary-age sediment and 3400 m of Cretaceous-age sediment (Munro and Brusset, 1968 cited in Hennigar, 1976). A more detailed description of the geological setting of Sable Island is provided in Hennigar (1976).

Shallow ponds or wetlands occur where the depth of surface depressions exceeds the depth of the local water table or where surface water collects in poorly drained depressional features due to the low permeability of the benthic material (i.e. gyttja, a mud rich in partially decayed organic matter).

## Groundwater Occurrence and Flow

Groundwater occurs in the unconfined sands as a lens of freshwater that gently slopes from the central areas of the island toward its northern and southern beaches. Where there are barrier-dunes, the groundwater level may rise before dipping towards the coast (Public Works and Government Services Canada, 1996).

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The idealized profile of the freshwater lens can be described by the Ghyben-Herzberg relation, which relates the position of underlying seawater to the relative densities of fresh- and saltwater and the distribution of hydraulic head. The configuration of the lens aquifer of Sable Island was characterized in Hennigar (1976) based on a series of geophysical profiles completed in 1973. The location of two of the profiles is shown in Figure 1. The geophysical work found that the thickness of the lens aquifer ranges from 1 to 36 m and is separated from underlying saline water by a narrow zone of diffusion. According to the Ghyben-Herzberg relation, the predicted thickness of the freshwater lens could exceed 60 m in some areas of Sable Island, based on observed water-level elevation measurements (Public Works and Government Services Canada, 1996). The freshwater lens is likely not continuous across the island because in areas where the island elevation is low, overland flooding by seawater during storm surges would result in slugs of vertically infiltrating salt water. The freshwater lens is relatively stable east of the flat beaches where the island is wider and protected to the north and south by dune barriers. In the western area of the main body of the island (Geophysical Profile 1 in Fig.1), the lens has been described as distorted, becoming thicker towards the north beach (Hennigar, 1976).

Regional radial groundwater flow is directed towards the coasts (north and south beaches) according to the island's physiography, although barrier-dune structures may act as a flow divide at some locations, directing groundwater towards both the centre of the island and the adjacent coast (Public Works and Government Services Canada, 1996). At a more local scale, groundwater movement may be affected by the presence of ponds or wetlands.

A range of horizontal hydraulic gradients has been reported in site investigations, varying from about 0.001 to 0.01 according to local topographic gradients. Mean annual precipitation (1971-2000) is 1459 mm, mostly occurring as rainfall due to mild temperatures (Environment Canada, 2014). The infiltration capacity generally exceeds rainfall intensity, and hence there is little generation of surface water runoff, so that almost all rainfall recharges the lens aquifer or surface water (Hennigar, 1976). Groundwater levels respond quickly to recharge events, with the magnitude of the response depending on such factors as antecedent soil moisture and rainfall intensity.

## Groundwater Levels

Observation wells have been monitored on Sable Island for various periods between 1971 and 1990 (Table 1 and Fig. 1). Groundwater level trends were previously summarized by Hennigar (1976) and McIntosh (1984). Available groundwater level data show that the following occur:

1. There is a semi-diurnal water-level fluctuation ranging from 1 to 20 cm in phased response to tidal oscillations. Hennigar (1976) noted that this tidal influence occurs as much as 300 m inland, with the strongest response near the coast and a dampened signal inland.

2. There is a longer seasonal trend with low water-levels from August to October and higher levels from November to February. The annual range of water-level fluctuations is about 0.7 to 0.9 m, based on data from two longer term monitoring wells (i.e. Sable Island 016 and 017).

The two observation wells with the longest water-level records were digitized from the original charts and analyzed for trends. These wells were Sable Island 016 (RSI-TH19) and 017 (RSI-TH50), which recorded water-level data from 1971 to 1990 and 1975 to 1990, respectively, but each with a large gap in the data between 1976 and 1982. The trends for these wells are presented in the following sections. Note that these groundwater-level data are presented with respect to a mean sea-level datum (i.e. as metres

**Table 1.** Observation wells that have been monitored on Sable Island.

| Station Number | Well ID | Easting[1] | Northing[1] | Monitoring Period | Minimum Water Level (m asl[3]) | Maximum Water Level (m asl) | Maximum Range (m) |
|---|---|---|---|---|---|---|---|
| 042 | RSI-TH17 | 739676 | 4868933 | 1972 | -0.68 | -0.23 | 0.45 |
| 016 | RSI-TH19 | 739603 | 4868237 | 1971 - 1990 | -0.65 | 0.71 | 1.36 |
| 019[2] | RSI-TH27 | 739657 | 4868584 | 1971 - 1972 | Not assessed | Not assessed | - |
| 051[2] | RSI-TH45 | 739882 | 4868140 | 1972 | Not assessed | Not assessed | - |
| 052[2] | RSI-TH46 | 739886 | 4868174 | 1972 | Not assessed | Not assessed | - |
| 018 | RSI-TH47 | 739959 | 4868583 | 1972 - 1974 | -0.02 | 0.2 | 0.22 |
| 053 | RSI-TH49 | 739924 | 4868518 | 1984 - 1990 | Not assessed | Not assessed | - |
| 017 | RSI-TH50 | 739891 | 4868255 | 1975 - 1990 | -0.51 | 0.67 | 1.18 |

[1]Coordinates are expressed in NAD83, UTM Zone 20.
[2]Station number predicted based on gaps in provincial numbering sequence.
[3]asl: above mean sea level.

above mean sea level, m asl). Hennigar (1976) and McIntosh (1984) used a chart datum for water- level reporting for Sable Island, which was taken as 1.0 m below the mean sea level.

Due to the island's dynamic geomorphological environment, only two of the eight observation wells in Table 1 could be located by Hennigar (2013) in 2013; these are assumed to be RSI-TH49 (053) and RSI-TH50 (017) (Fig. 1). However, the wells were found to be inoperable due to sand accumulation. A review of historical water-level records found that the documentation, methodology and maintenance of the observation wells on Sable Island were inconsistent, which may affect the reliability of the interpreted trends.

The Mann-Kendall trend test (Gilbert, 1987) was used to determine whether a statistically significant trend was present for groundwater elevation at each well, based on a 95% confidence level. Note that 'statistically significant' means there is statistical evidence that there is a trend present, but does not indicate whether the trend is large or small.

The long-term groundwater-level data were compared to precipitation data for Sable Island (Climate Station ID 8204700; Environment Canada, 2014) (Figs. 2 and 3). A trend analysis for the period 1971 to 1990 showed a significant upward trend in annual precipitation, with a slope of about 12 mm/a.

## Sable Island 016 (RSI-TH19)

Between 1971 and 1990, the groundwater elevation for well Sable Island 016 averaged -0.11 m asl and had a range of -0.65 to 0.71 m and a seasonal fluctuation of about 0.9 m (Fig. 2). There is also a tidal fluctuation that is not apparent in Figure 2, although the hourly water-level data show a maximum peak-to-peak tidal amplitude of about 0.2 m. A trend analysis indicated a significant but small (11 mm/a) downward trend over the monitoring period. This observation well was located close to the south beach of the main body sub-region of the island, where transgression is on-going and could explain the downward trend (Fig. 1).

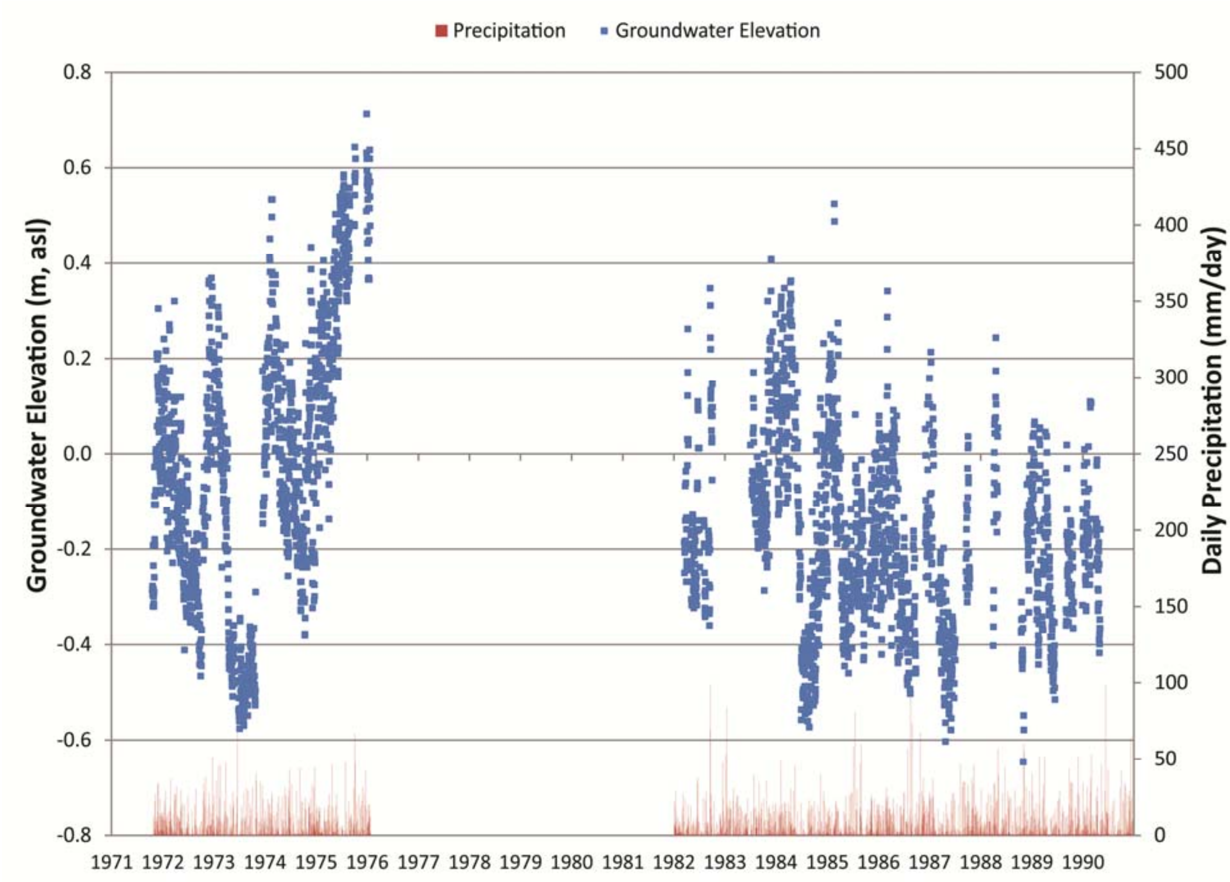


**Figure 2.** Groundwater hydrograph for Sable Island well 016 (RSI-TH19) during the period 1971 to 1990.

## Sable Island 017 (RSI-TH50)

Between 1975 and 1990, the groundwater elevation for well Sable Island 017 averaged 0.21 m asl and had a range of -0.51 to 0.67 m and a seasonal fluctuation of about 0.7 m (Fig. 3). A tidal fluctuation is not apparent in the hourly water-level data. A trend analysis found no significant trend between 1975 and 1987, but a decreasing trend (about 150 mm/a) was identified between 1987 and 1990. This observation well was located close to the south beach of the main body sub-region of the island, where transgression is on-going and could explain the downward trend (Fig. 1).

# Groundwater Quantity

Pumping tests were conducted as part of the 1970s baseline characterization work in test wells RSI-TH39 and RSI-TH40. The results of the tests are summarized in Table 2 and their location is shown on Figure 1.

Based on the pumping-test results, the hydraulic conductivity of the unconfined sand aquifer is estimated to be between $1 \times 10^{-3}$ m/s and $1 \times 10^{-2}$ m/s. The long-term safe yield is about 150 Lpm, based on the interpreted transmissivity values from the pumping tests and an assumed long-term available drawdown of 1 m. It should be noted, however, that this yield exceeds the test-pumping rate, and groundwater quality considerations, such as seawater intrusion, will be a critical factor in determining the safe pumping rate of any supply well developed on the island. Hennigar (1976) observed that a groundwater

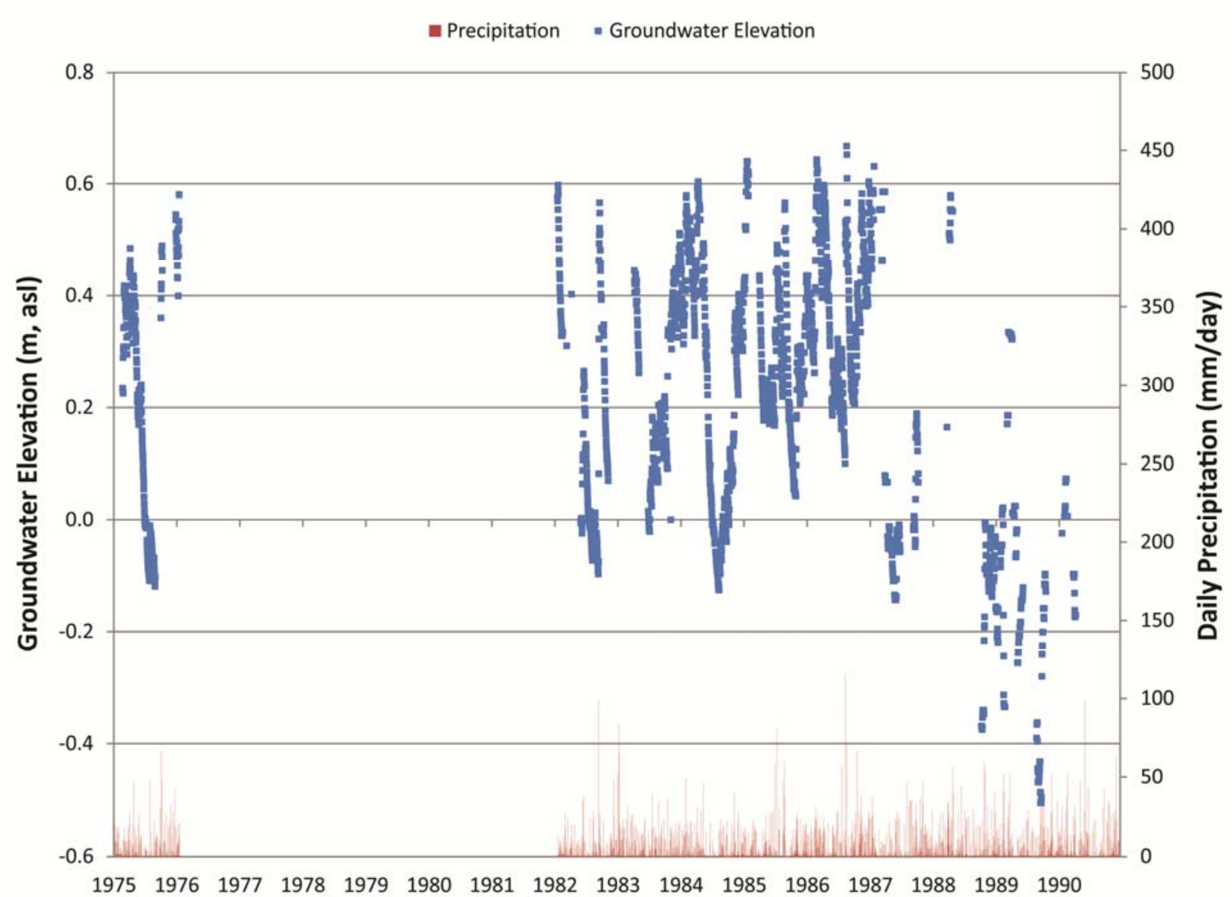


**Figure 3.** Groundwater hydrograph for Sable Island well 017 (RSI-TH50) from 1975 to 1990.

supply producing about 160 $m^3$/d (110 Lpm) should be feasible at locations where the freshwater lens is at least 3 m thick, the local geometry is favourable (inland of a barrier dune) and the well is far enough from the coast that the cone of drawdown would not intercept the lateral seawater-freshwater interface.

Assuming that runoff and groundwater use are negligible for Sable Island, a general formulation of the hydrological budget for the island is as follows:

$\Delta S = P - ET - Q_s$, where
$\Delta S$ = change in groundwater and surface water storage
P = precipitation
ET = evapotranspiration
$Q_s$ = submarine groundwater discharge to the ocean

The mean annual precipitation rate (1971-2000) used in the calculation was 1460 mm/a (Environment Canada, 2014), and the island area was estimated to be 2983 ha (Applied Geomatics Research Group, 2011). Assuming no significant changes in long-term groundwater and surface water storage on the island, the estimated magnitude of the main components of the water budget is summarized in Table 3.

## Groundwater Use

There are up to four active pumping wells on Sable Island (Conestoga Rover and Associates Limited, 2011). Three of the wells are located in the main body of the island, and the fourth is in the East Light

**Table 2.** Summary of pumping-test data for test holes RSI-TH39 and RSI-TH41.

| | RSI-TH39 | RSI-TH41 |
|---|---|---|
| Pumping Test ID | HAL-167 | HAL-168 |
| Easting | 738462 | 752426 |
| Northing | 4868755 | 4869773 |
| Well Depth (m) | 3.9 | 4.2 |
| Casing Diameter (mm) | 38 | 38 |
| Screen Length (m) | 0.9 | 0.9 |
| Screen Size | 10 slot | 10 slot |
| Date | August 8, 1972 | September 12, 1972 |
| Test Duration (hours) | 8 | 12 |
| Average Pumping Rate ($m^3$/d) | 164 | 164 |
| Transmissivity ($m^2$/d) | 447 | 462 |
| Storativity | 0.05 | 0.03 |
| Long-Term Safe Yield (Lpm) ($Q_{20}$)[1] | 148 | 153 |

[1]Long-term safe pumping rate for a well is calculated using the twenty-year safe-well yield calculation (Farvolden, 1959).

**Table 3.** Estimated hydrologic budget for Sable Island.

| Water Budget Component | Annual Water Volume ($10^7$ $m^3$) | Method |
|---|---|---|
| Groundwater recharge (P) | 4.35 | Mean total annual precipitation x island area |
| Evapotranspiration (ET) | 1.61 | Percent ET of mean P (POTEV Program: Thornwaite and Penman / Holmes and Robertson) (37%, taken from Hennigar, 1976) |
| Submarine groundwater discharge ($Q_s$) | 2.95 | Residual of P - ET |

Area (Fig. 1). AEB-16-PW2, constructed around 1982, is reportedly the second production well used to service the Environment Canada compound buildings, and it has the largest water use of the four water-supply wells on the island. DFO-05-PW2 services a building used by the Department of Fisheries and Oceans near the old West Light (this may be the well referenced as the West Light domestic well in Hennigar, 1976). Other water wells that reportedly have occasional use include one servicing the MT&T building near the West Light (MTT-PW1) and another servicing a building owned by the Department and Fisheries and Oceans near the East Light (DFO-01-PW1) (Conestoga Rover and Associates, 2011).

The relatively thin, unconfined freshwater lens is sensitive to large groundwater withdrawals. This is because a small decrease in groundwater level associated with pumping can result in upconing or lateral intrusion of seawater (a 1-unit decrease in water level corresponds to a 40-unit increase in seawater elevation, according to the Ghyben-Herzberg relation). The vulnerability of the freshwater lens aquifer to seawater intrusion is evident from early groundwater quality monitoring data, where elevated chloride levels (up to 220 mg/L) were attributed to concentrated pumping activity near the former Nova Scotia Department of Mines and Mobil Oil compounds in the west spit area (Fig. 1; Hennigar, 1976). However, recent water-level data (Stantec Consulting Limited, 2010) do not indicate regional aquifer drawdown in the area of highest groundwater usage, based on current pumping volumes from AEB-16-PW2 (although the water level and actual water use of the pumping well are not recorded). Water is returned to the freshwater aquifer via discharges from individual on-site wastewater treatment systems (Conestoga Rover and Associates Limited, 2011).

# Groundwater Quality

Available historical well-water chemistry data collected between 1971 and 2013 (Hennigar, 1976, 2013; Public Works and Government Services, 1996; Stantec Consulting Limited, 2010; Environment Canada, unpub. data, 2014) were compiled. A summary of representative well-water chemistry data for samples obtained from the freshwater lens aquifer is provided in Table 4. The chemistry is consistent with a shallow, unconfined groundwater-flow system in a coastal setting, and is generally described as low pH, very soft, naturally aggressive, sodium-chloride-type water, with dilute to moderate concentrations of TDS (total dissolved solids) and a tendency for iron and manganese to exceed the Guidelines for Canadian Drinking Water Quality (GCDWQ) aesthetic objectives (Health Canada, 2012).

A comparison of fresh groundwater and surface-water chemistry on a trilinear plot indicates that their chemistry is similar (Fig. 4a; Hennigar, 1976). A trilinear plot of groundwater chemistry samples collected between 1990 and 2013 (Fig. 4b) does not indicate a long-term change in water type compared to the 1970s water-sampling program.

Groundwater chemistry varies with depth according to the gradient from freshwater to underlying saline groundwater. Hennigar (1976) suggested that tidal oscillations produce mixing of fresh and saline water in the aquifer and that the zone of mixing or diffusion would be thicker in areas where the tidal response is greater. Groundwater chemistry can also vary spatially depending on the susceptibility of an area to seawater inundation by storm surges, and due to seawater intrusion (lateral intrusion or upconing of seawater) in response to groundwater withdrawals.

Chloride concentrations in surface water and shallow groundwater were spatially interpolated in ArcGIS (natural neighbour interpolation; Sibson, 1981) across the island using available water chemistry data collected between 1971 and 2013 (Fig. 5 [inset]). The trend of interpolated concentration generally followed topographic gradients. Shaded relief imagery derived from the provincial digital elevation model (Service Nova Scotia *et al*., 2013) is shown on the figure for comparison. Only a narrow band of chloride concentrations less than 125 mg/L is interpreted in the area north of the flat beaches, whereas the largest regions of the island showing chloride concentrations less than 125 mg/L are found immediately west (main body) and east of the flat beaches, indicating that they are less vulnerable to seawater intrusion or seawater flooding, and have greater potential for groundwater supply development. The GCDWQ aesthetic objective for chloride is 250 mg/L (Health Canada, 2012).

The long-term chloride trend in raw groundwater sampled at the Main Station pumping well between 1987 and 2013 (AEB-16-PW2; Fig. 6) shows a slight increase in concentration, although the current

**Table 4.** Summary of well-water chemistry data.

| | Units | GCDWQ Criteria | Minimum | Maximum | Median | Geomean | n |
|---|---|---|---|---|---|---|---|
| Alkalinity ($CaCO_3$) | mg/L | - | 2 | 110 | 12 | 9.6 | 33 |
| Bicarbonate | mg/L | - | 0.5 | 38 | 2 | 2.1 | 10 |
| Carbonate | mg/L | - | 0.05 | 5 | 0.275 | 0.20 | 10 |
| Calcium | mg/L | - | 0.3 | 37 | 6 | 5.2 | 34 |
| Magnesium | mg/L | - | 0.3 | 62 | 4.3 | 4.0 | 33 |
| Potassium | mg/L | - | 1.3 | 7 | 2.2 | 2.5 | 10 |
| Total Phosphorus | mg/L | - | 0.01 | 0.05 | 0.05 | 0.04 | 5 |
| Sodium | mg/L | 200 AO | 4.3 | 620 | 38.9 | 42 | 34 |
| Ammonia (N) | mg/L | - | 0.025 | 1.6 | 0.025 | 0.05 | 10 |
| Chloride | mg/L | 250 AO | 32 | 970 | 62.2 | 72 | 33 |
| Nitrate as N | mg/L | 10 | 0.01 | 5.6 | 1.48 | 0.66 | 28 |
| Sulphate | mg/L | 500 AO | 1 | 140 | 14 | 12 | 33 |
| Colour | TCU | 15 AO | 1.5 | 510 | 34 | 24 | 28 |
| Specific Conductance | µs/cm | - | 4.8 | 1000 | 264 | 233 | 34 |
| Hardness | mg/L | - | 12 | 308 | 32.15 | 33 | 32 |
| pH | | 6.5 - 8.5 AO | 4.5 | 8.9 | 6.125 | 6.2 | 34 |
| Total Dissolved Solids | mg/L | 500 AO | 15 | 1950 | 176 | 166 | 28 |
| Total Organic Carbon | mg/L | - | 0.25 | 28 | 7.95 | 5.9 | 10 |
| Turbidity | NTU | - | 0.5 | 100 | 8 | 6.1 | 27 |
| Arsenic | µg/L | 10 | 1 | 4 | 1 | 1.6 | 10 |
| Copper | µg/L | 1000 AO | 1 | 1080 | 5 | 18 | 10 |
| Iron | µg/L | 300 AO | 60 | 13100 | 874.5 | 1157 | 32 |
| Lead | µg/L | 10 | 0.2 | 250 | 4.55 | 4.6 | 10 |
| Manganese | µg/L | 50 AO | 4 | 2160 | 40 | 67 | 33 |
| Uranium | µg/L | 20 | 0.05 | 0.4 | 0.075 | 0.09 | 10 |
| Zinc | µg/L | 5000 AO | 14 | 3960 | 35 | 101 | 10 |

Only one representative raw well-water sample was used from each well for the summary statistics.
Only well water samples with a specific conductance value less than 1000 µs/cm were considered to be from the freshwater lens aquifer and were used in the summary statistics.
Non-detects were assigned a value equal to half of the detection limit.
AO: Aesthetic objective.

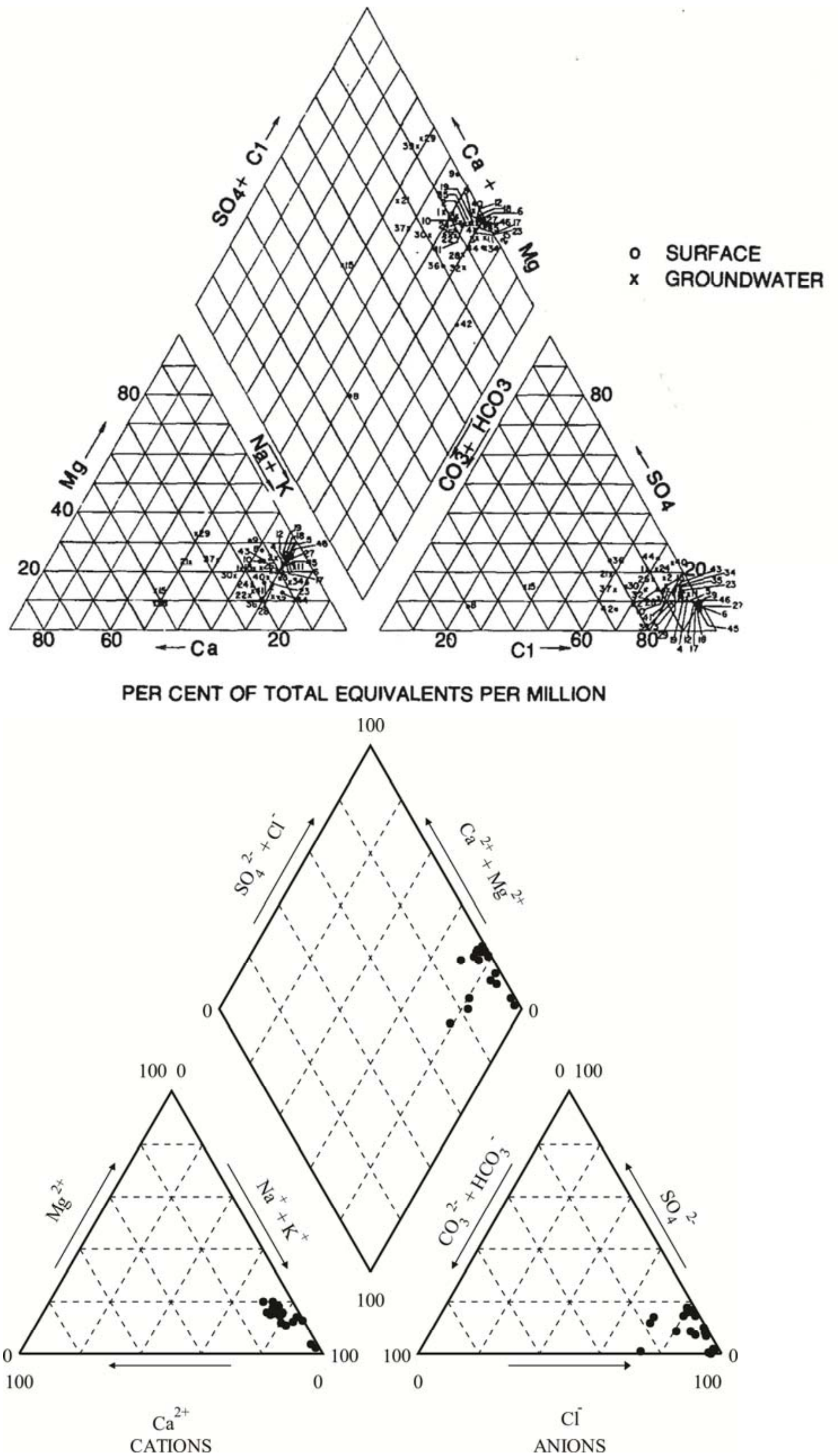


**Figure 4.** Trilinear plots of major ions from (a) water sampling between 1971 and 1974 (from Hennigar, 1976), and (b) groundwater sampling between 1990 and 2013.

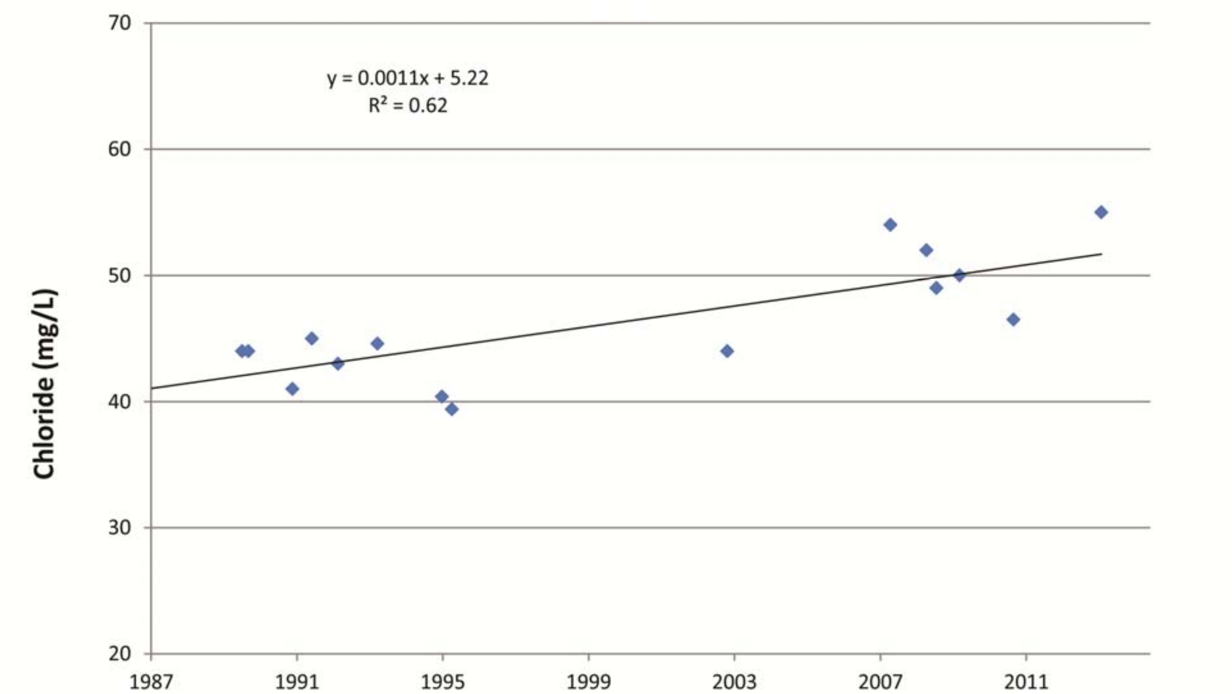


**Figure 6.** Trend in chloride concentration in drinking-water well AEB-16-PW2.

level of ~50 mg/L is well below the GCDWQ aesthetic objective of 250 mg/L. The increasing trend was statistically significant using regression analysis ($P < 0.01$).

Based on the findings of several environmental site investigations (e.g. Public Works and Government Services, 1996; Stantec Consulting Limited, 2010), the contaminants present in soil and groundwater on the island have not affected the groundwater quality of the two main drinking-water supply wells. Elevated concentrations of lead compared to GCDWQ criteria were detected in AEB-16-PW2 and DFO-05-PW2, which was attributed to aggressive water leaching the metal from plumbing fixtures (Public Works and Government Services, 1996).

# Summary

A review of selected information produced subsequent to the 1970s baseline investigation of water resources on Sable Island (Hennigar, 1976) shows that groundwater conditions are comparable, and so the study remains a suitable baseline reference. A slight increase in chloride concentration has been observed in the island's main production well over the past 30 years, and analysis of long-term water-level data in two observation wells shows a decrease in water level on the order of 5 to 30 cm, especially in the late 1980s towards the end of the available monitoring record. A possible reason for the decreasing trend is transgression in the area of the south beach. Based on island visitation and development patterns, it does not appear that groundwater use on Sable Island has increased. In areas of anthropogenic activities, local contaminant impacts to groundwater have been identified through environmental site assessment work, although existing drinking-water wells have not been impacted (Public Works and Government Services, 1996; Stantec Consulting Limited, 2010).

Due to the vulnerability of the groundwater flow system to intrusion and overland flooding of seawater, water-quality considerations are important factors in determining the safe yield for groundwater supply development. The geometry of the basin, distance to seawater and to potential sources of contamination, and thickness of the freshwater lens aquifer are important considerations in planning for the development of groundwater supplies on the island.

# Acknowledgements

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