

Salt-water intrusion in Prince Edward Island

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The numerous saline estuaries situated throughout Prince Edward Island permit high tides to carry salt water a long way inland and to penetrate the bedrock aquifer. Very little groundwater consumption occurs around the banks of the Eliot River estuary, yet salt water has moved into the bedrock and created a large zone of diffusion. This salty water extends as far as 1200 ft inland and has penetrated to a depth of 185 ft. Beneath this salty water is fresh groundwater, which extends down to about 600 ft where it is underlain by salty water.

The salty water in the upper 185 ft of the aquifer is not separated from the fresh groundwater by a confining stratum, but is kept in this position by the higher head of the fresh groundwater. This head maintains a dynamic equilibrium with the heavier salty water. The effect of density in maintaining the position of a fresh and salt water front is not as important as has been previously thought.

Introduction

This report describes the position and the fluctuations of the zone of diffusion in the bedrock aquifer in a part of Prince Edward Island (P.E.I.) that has no large withdrawals of groundwater. A small area just west of Charlottetown, near the Eliot River estuary (locally known as the West River), was selected for this study (Fig. 1).

Zones of diffusion occur in aquifers situated along sea coasts. They are a mixture of fresh groundwater flowing out to the sea and sea water

flowing into the aquifer. Cooper *et al.* (1964) have shown in the Biscayne aquifer of Florida that a saline zone of diffusion is developed between lighter, fresh groundwater on top and heavier, salt water underneath. The zone has salt water circulating through it and is dynamically stable. Variations in ocean tides and in the rate of recharge due to seasonal and long-term fluctuations enable the sea water to penetrate the aquifer. It is diluted by seaward-flowing fresh water and is returned to the sea floor through the upper part

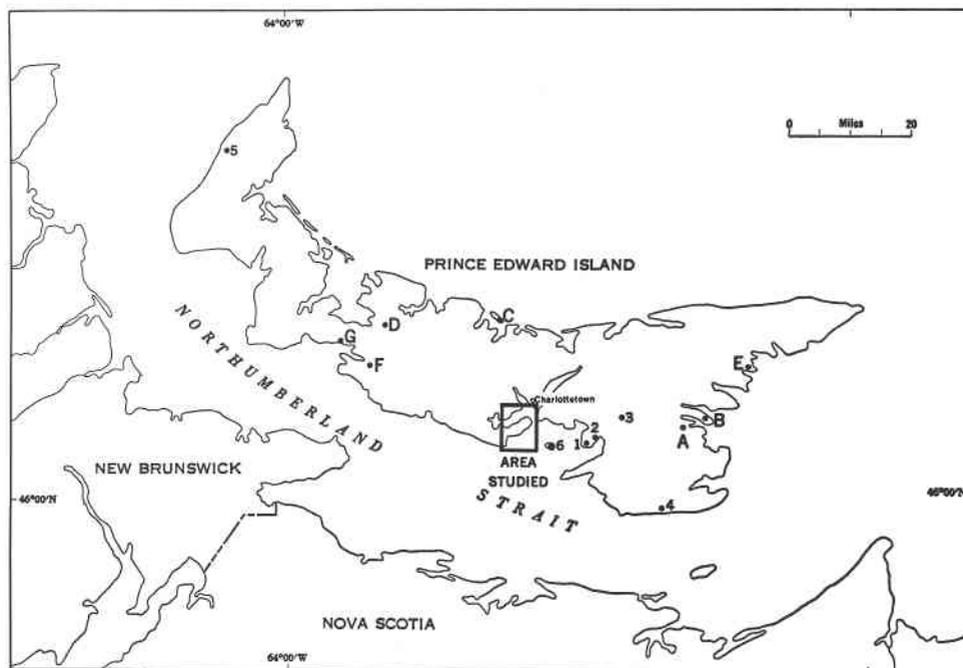


FIG. 1. Index map showing area studied and deep wells in Prince Edward Island.

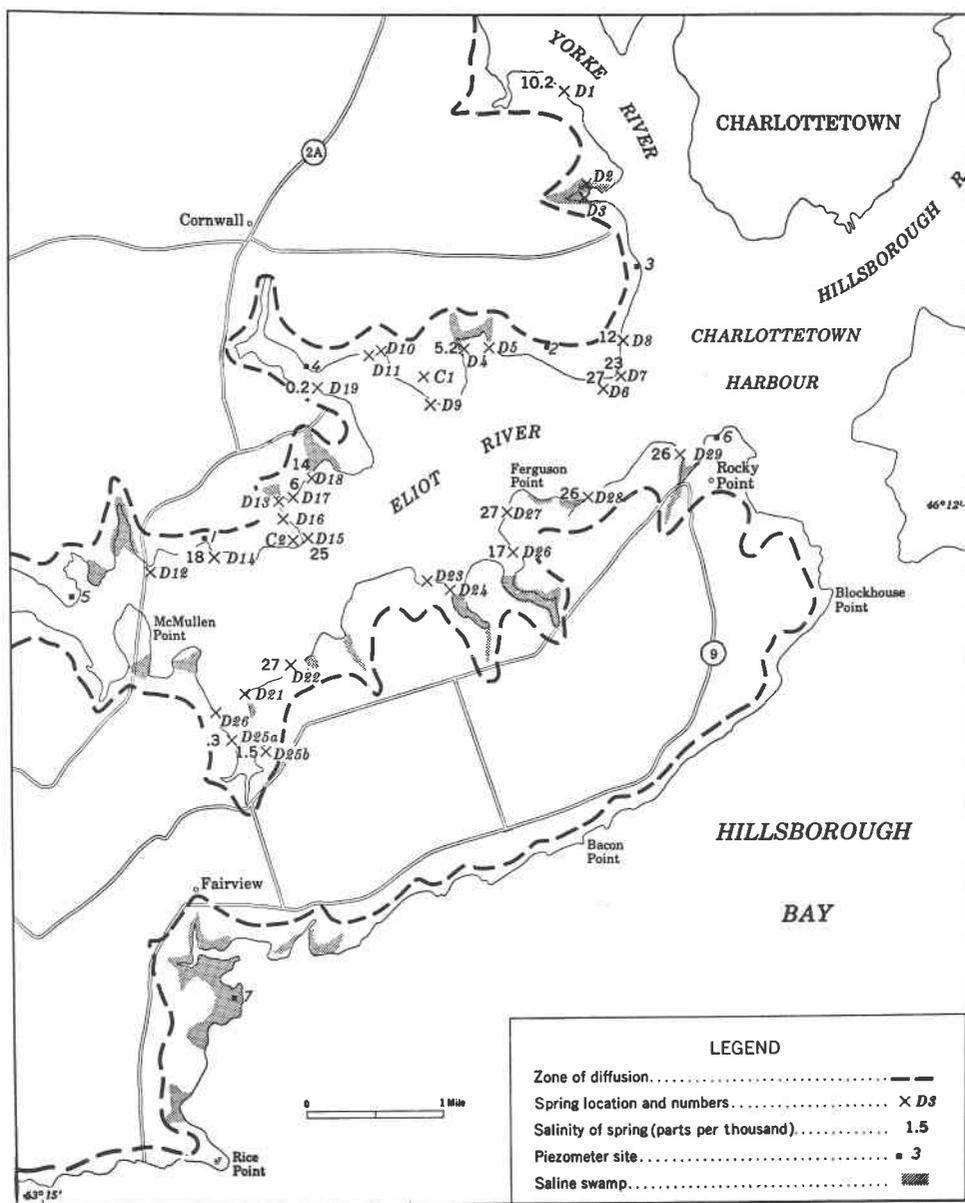


FIG. 2. Map showing the zone of diffusion.

of the zone of diffusion. The sea-water component of flow that is discharged is resupplied by more sea water flowing into the aquifer to the zone of diffusion. Thus, cyclic flow of sea water into and out of the aquifer is achieved.

The results of the studies in Prince Edward Island indicate that at the coast and around the edge of the estuary, the zone of diffusion extends

from sea level into the bedrock (Fig. 2) to a depth of 185 ft; underneath is a large fresh groundwater flow system extending to about 600 ft. Between these depths the zone of diffusion is displaced seaward. Sea water is present from 600 ft to at least 2000 ft. Active recycling of sea water with the tides only occurs in the uppermost part of the aquifer.

Hydrogeology

Geology

All of Prince Edward Island is underlain by nearly flat-lying terrestrial sediments of Pennsylvanian and Permian age. They are covered with a veneer of glacial drift generally less than 25 ft thick. The rocks are reddish brown, dominantly fine grained, and composed of massive and cross-bedded sandstone interbedded with channel fillings of siltstone, claystone, clay-pebble conglomerate, and breccia. Individual beds are lenticular and range in thickness from $\frac{1}{2}$ ft to 24 ft; the average thickness is 7 ft.

Because these sediments were deposited in a terrestrial environment as channel and flood-plain deposits, their types of bedding and structures are very similar. There is little variation in the mineralogical composition of these rock types and they have a common post-depositional stress history. These similarities in rock properties extend throughout Prince Edward Island and of course control the movement of groundwater. Thus the principles determined with respect to their hydrologic performance in one area can be applied to another part of Prince Edward Island without any appreciable error.

Fracture Flow

Hydraulic conductivity values determined from pump tests are a summation of fracture and intergranular hydraulic conductivity, whereas hydraulic conductivity values determined from cores using a falling head permeameter measure intergranular hydraulic conductivity only. The average of 32 values of hydraulic conductivity derived from pump tests of municipal wells situated throughout the island is 5.3 ft per day. The maximum intergranular hydraulic conductivity value determined from 13 cores taken from various depths below the water table in the Eliot River area is only 0.3 ft per day. Thus, most of the movement of groundwater occurs through the fractures rather than the pore spaces of the rocks.

A network of piezometers and open holes was drilled around the estuary. As drilling progressed, sudden losses of circulation occurred, denoting the presence of fractures in the bedrock. The depth of these fractures was recorded, but no significant correlation between depth and number of fractures was found. Fractures were noted in all rock types; however, the majority were found in sandstone. Of the 59 fractures recorded while

drilling, 47 (80%) were in sandstone strata; the remainder were in siltstone and claystone.

Water-yielding fractures occurred in sandstone, siltstone, and claystone strata. In dry spells, the fractures in the siltstone and claystone strata yielded water, but the fractures in the overlying and underlying sandstone strata were dry. This attests to the more rapid movement of groundwater in the sandstone and to the fact that the finer-grained strata yield groundwater more slowly.

The inclination of the fractures is vertical or subvertical. This permits rapid entry of precipitation into the bedrock. Lateral flow of groundwater occurs along the length of these fractures and along the bedding planes between the sandstone and the finer-grained rocks. Groundwater will often percolate down into the aquifer until it intersects an unfractured part of a siltstone or claystone bed. Then the groundwater flow is deflected laterally along the top of the poorly permeable strata. This flow produces springs, which are seen at the contact of different rock types.

No significant differences in groundwater movement were observed between siltstone and claystone. Thus, from the point of view of hydrogeology only two rock types, sandstone and mudstone, need to be considered. The term mudstone is used to include siltstone, claystone, or mixtures of both. Sandstone is a relatively good aquifer due to the greater abundance of fractures; mudstone has fewer fractures and is a relatively poor aquifer.

Hydrographs from 10 groups of piezometers, situated at various depths in both sandstone and mudstone units, indicate different fluid potentials, but all show similar responses to precipitation and evaporation. During pump tests the aquifer usually yields groundwater in a semi-confined manner. Because of these factors and because of the number and distribution of the fractures, it is evident that the interbedded sandstone and mudstone are connected by fractures to the ground surface. Thus, the strata are considered as one large interconnected aquifer.

Chemistry of Groundwater

In order to determine the chemistry of the groundwater all of the chemical analyses reported by Owen and Pollitt (1950), Pollitt (1952, 1953), and Brandon (1966) were examined. Samples that

were taken near the sea and had a high chloride content were believed to exhibit salt-water intrusion and were discarded; the remaining 122 samples were averaged. The average total dissolved solids (tds) content is 180 parts per million (ppm) and the average chloride content is 18 ppm. Groundwater containing a chloride content above 40 ppm suggests the presence of salt-water intrusion, especially if the well is located near the sea. Groundwater containing a chloride content over 100 ppm is considered to be contaminated with sea water and is considered part of the zone of diffusion.

Chemistry of Water from the Zone of Diffusion

Water from saline springs and piezometers penetrating the zone of diffusion was analyzed for its chemical constituents. The tds and the specific conductance in micromhos/cm (at 25 °C) were plotted against the chloride content in ppm (Fig. 3). Both the tds and the specific conductance

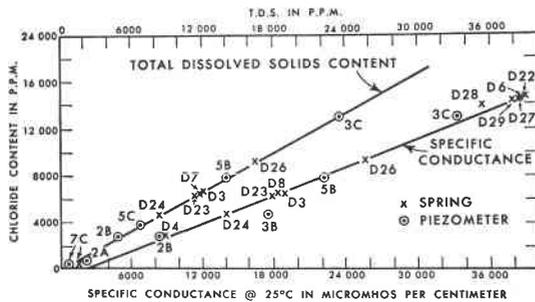


FIG. 3. Variation in specific conductance and total dissolved solids with chloride content for water in the zone of diffusion.

show a straight line relationship with respect to the chloride content. As the chloride content of the water in the zone of diffusion increases so do the tds and the specific conductance. This linear relationship, which previously has been observed by Visher and Mink (1964) and Gischler (1967), is due to the mixing of fresh water with sea water. If sea water is diluted with fresh water under laboratory conditions this linear relationship occurs. It also occurs in the geologic environment, for the chloride ions, unlike calcium, sodium, or sulfate ions, are unaffected by base exchange of reduction (Revelle 1941) as they pass through the bedrock and are diluted with groundwater. However, the specific conductance values below 2000 micromhos/cm and the tds below 500 ppm do not

vary linearly with the chloride content because of the large percentage of other ions in fresh groundwater. In this study many field measurements of tds were made with a portable conductivity bridge. Wherever the concentrations are above 500 ppm, they are considered to be mainly composed of sodium chloride and are referred to as "salinity" in this report.

Shallow Occurrence of Salty Water

Position of the Zone of Diffusion

The aerial extent of the zone of diffusion was determined by saline swamps and springs near the sea, and the thickness of this zone was determined with piezometers (Fig. 2).

(1) Swamps

Numerous saline swamps occur in the low-lying areas around the Eliot River. The yellowish brown vegetation characteristic of these swamps contrasts sharply with the vivid green vegetation developed in fresh-water swamps, and hence they are easily mapped. They occur at the mouths of the streams that flow into the Eliot River and as far inland as $\frac{3}{4}$ mile from the banks of the river.

At high tide the salt water percolates into the aquifer and at low tide some of it is returned to the surface of the swamp by groundwater flow. Thus, a zone of diffusion is developed. The presence of upward-flowing saline springs in these swamps indicates that the swamps are situated in a discharge area of the groundwater flow system.

(2) Springs

Saline springs occur not only in the swamps, but also in the adjacent headlands (Fig 2). They are found at the edges of the banks of the estuary and are often situated in the intertidal zone. Because their salinities were determined over a period of several days and at different tidal levels, they cannot be compared directly. Each of these springs has a small discharge, less than 5 gallons per minute, with the fresh groundwater component of the spring derived from the nearby banks adjacent to the estuary.

In the headland areas, wells have been drilled for cottage water supplies. Usually these wells are less than 40 ft deep and many are contaminated with salty water, even though some of them are 500 ft from the nearest saline spring or swamp. The fresh water in some of these wells indicates that, in the headland areas, there is a thin layer of fresh groundwater above the saline water. This

groundwater is derived from the nearest hills, does not occur in large quantities, and is subject to large seasonal fluctuations. Consequently the salt content in these shallow wells can vary considerably during the year.

In the adjacent swamps and lowlands there is no fresh water on top of salt water, for the groundwater has been discharged as springs at the base of the hills. Thus, the zone of diffusion extends farther inland in these areas than in the headland areas.

The presence of saline swamps and springs indicates that the zone of diffusion encroaches a considerable distance into the aquifer. It can be expected at shallow depths, around the estuary, when drilling at an elevation of less than 50 ft.

Considering that there is no heavy withdrawal of groundwater in the area, the extent of salt-water encroachment into the aquifer is surprising. Occasional discussions with drillers and cottage owners concerning other saline estuaries throughout the island have indicated this situation to be common. This means that at these shallow depths the groundwater flows through the zone of diffusion and is discharged to the sea as salty water.

(3) Piezometers

Piezometers were installed in groups of two or three around the estuary in order to determine the thickness of the zone of diffusion. They show a general increase in fresh-water head with depth, indicating that the banks of the river are part of a discharge area. The lowest heads in the groundwater flow system were found in the shallowest piezometers, which are closest to the estuary. The heads in 5 of the 15 piezometers installed, were 1 to 2 ft below the mean head of the salt water in the estuary, and nearly all of the heads in the piezometers are below the head of the salt water at high tide. Thus, salt water can readily flow from the river into the bedrock and create a zone of diffusion there.

In each one of these piezometers, the groundwater was sampled for salinity. Two complete sets of salinity values were collected from each piezometer between July 10 and 13, and July 18 and 20, 1967. Each set of salinities was collected on different days and at different tide levels during these days. Therefore, in a strict sense they are not absolutely comparable, but they do indicate a general trend.

The salinity values determined during the

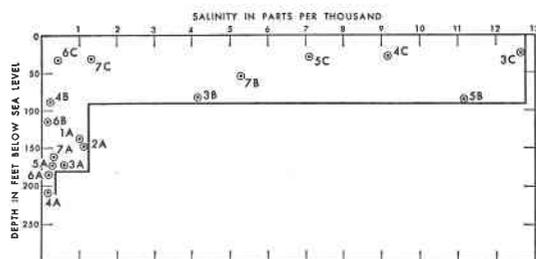


FIG. 4. Variation of salinity with depth in zone of diffusion.

interval of July 18 to 20 were plotted against depth below sea level (Fig. 4). A line was drawn enclosing all the values, to accentuate the variation with depth. The highest value of salinity, and the greatest range of salinity between piezometer filters, occurs in a region extending down to 95 ft below sea level. The average salinity in this interval is 5700 ppm. Below this, in the region from 95 ft down to 185 ft below sea level, the average salinity drops markedly to 580 ppm, and the maximum salinity is only 1100 ppm. Below 185 ft the average salinity is only 168 ppm, which is the tds content of fresh groundwater. Thus the zone of diffusion is about 185 ft thick and becomes progressively fresher with depth.

There are specific exceptions to this trend; for instance, piezometers 5B and 7B, at depths of 84 and 57 ft below sea level respectively, have higher salinities than their shallower counterparts 5C and 7C. These exceptions are due to the deeper piezometers (5B and 7B) being set in fractures, which permit direct infiltration of salt water, whereas 5C and 7C are not. In general though, the aforementioned trend holds true and was reinforced by the earlier set of readings, taken between July 10 and 13.

The change in salinity values between the samples taken on July 10 to 13 and July 18 to 20 was plotted against depth below sea level (Fig. 5). Although the samples from each piezometer were taken at different tidal levels, a trend similar to that shown in Fig. 4 is present. The change in salinity was greatest in the piezometers situated less than 35 ft below sea level and steadily decreases with depth. Again, there is marked decrease at 95 ft; below this depth a maximum salinity change of only 0.05 ppm was recorded.

Some of the piezometer filters are set in mudstone and others in sandstone, yet for similar depths no significant difference in salinity could be established. Thus the saline water appears to

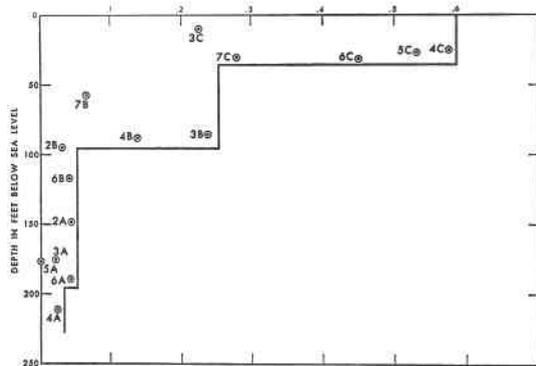


FIG. 5. Change in salinity between July 10-13 and 18-20 with depth.

be distributed fairly evenly throughout both rock types. Although fewer fractures occur in the mudstone beds than in the sandstone beds, enough fractures are present to permit continuous upward and downward flow across these beds.

Most of the saline water occurs in the first 95 ft below sea level and enough saline water occurs between 95 and 185 ft below sea level to be undesirable for human consumption. Below 185 ft, fresh groundwater is present.

The presence of fresh groundwater underlying salty water in an interconnected aquifer is due to the groundwater having sufficient head at this depth to prevent salt water from moving any farther into the aquifer. This condition is probably characteristic of areas of little or no pumping of groundwater. Since salt-water intrusion is rarely studied in such areas, this situation has seldom been reported in the literature.

(4) Zone of Diffusion in Pumped Areas

Salt-water intrusion is usually studied in areas where it has contaminated a well field. In these areas the fresh groundwater is generally reported to be sitting on top of the salt water, and the salt concentration in the zone of diffusion increases with depth of penetration. This is due to the wells intercepting groundwater outflow, causing a large cone of depression, which permits salt water to enter the aquifer, displacing the small remnant of lighter fresh groundwater upwards towards the surface. This has led to the idea of developing a well field by skimming groundwater off the top of the salt-water wedge with shallow wells (Chow 1964). In Prince Edward Island, however, the zone of diffusion becomes fresher with depth, and to obtain groundwater there, wells should be

cased through the salt water and drilled into the underlying fresh groundwater.

Compared with zones of diffusion in Florida and Israel the thickness of this zone (185 ft) in Prince Edward Island is great for an area having no heavy groundwater withdrawal. Near Miami, Florida, where heavy pumping has induced sea water inland, the zone is only 60 ft thick (Kohout 1964). Along the Coastal Plain of Israel, the zone is generally about 10 ft thick (Jacobs and Schmorak 1960). In Hawaii, Visher and Mink (1964) reported the zone to be about 850 ft thick in the Pearl Harbor district, where large quantities of groundwater are being withdrawn.

The development of a deep zone of diffusion in the Eliot River area is enhanced by the absence of confining beds and by the deep channel of the estuary. This channel has been cut down to a depth of 55 ft below sea level at one place, thus, the salty water in the estuary has access to a large area of suboutcrop. Conversely, off the coast at Bacon Point, the sea is less than 10 ft deep out to 2 miles off shore; there the vertical section of suboutcrop exposed to salty water is considerably less and a thinner zone of diffusion can be expected.

Fluctuations with the Tides

(1) Springs

One spring, number D4 (Fig. 2), is situated on a beach between high and low tide levels on the north shore of the Eliot River. It can be seen to flow up to a height of 8 inches above the beach level at low tide. Measurements taken from this spring as the tide receded revealed that the temperature and salinity declined steadily as the tide level dropped (Fig. 6). The salinity decreased from 28.0‰ (parts per thousand) to 4.3‰ and the temperature decreased from 54 °F to 47 °F. The temperature of the salt water was close to 60 °F and that of the groundwater about 42 °F. It is concluded that the water issuing from the spring is a mixture of groundwater and sea water coming from the zone of diffusion and that as the tide receded, more fresh groundwater and less sea water was discharged.

The direct response of the chloride content with the tide indicates that there is a transmission of sea water from the saline estuary in the bedrock to the spring with each tidal cycle. The remainder of the springs shown on Fig. 2 were sampled for salinity over a period of several days, and showed

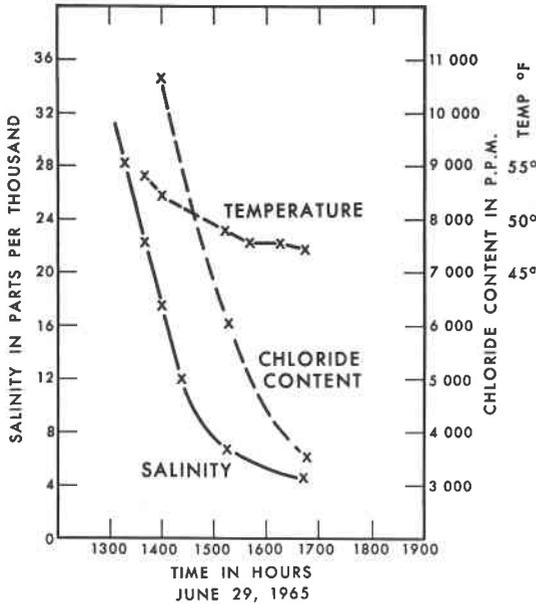


FIG. 6. Fluctuations in spring D4 with the tides.

a large range of salinities, suggesting that their salinities vary in the same manner as that of spring D4. These springs indicate fluctuations in the uppermost part of the zone of diffusion only.

(2) Piezometers

In order to study the effect of tides on the deeper part of the zone of diffusion, the variations in head and salinity of two piezometer sites (3 and 7) were recorded with the tidal fluctuations.

The head recorded in each piezometer is the point-water head, as defined by Lusczynski (1961). In an aquifer containing water of variable density, the point-water head has the density of the water entering the piezometer filter. This point-water head is measured with mean sea level as datum. In order to compare heads, the density of the water of each head should be the same, thus, each point-water head was converted to a fresh-water head according to the method explained by Kohout (1964).

The fresh-water heads vary sinusoidally with the tides (Figs. 7 and 8). The water from the deepest piezometers 7A and 3A is the lightest and has the highest head. It is this fresh-water head that maintains a dynamic equilibrium with the salty water and carries it back to the sea.

At both sites the salinity values did not fluctuate sinusoidally with the tides. The appearance of sudden highs or lows in salinities produces a more

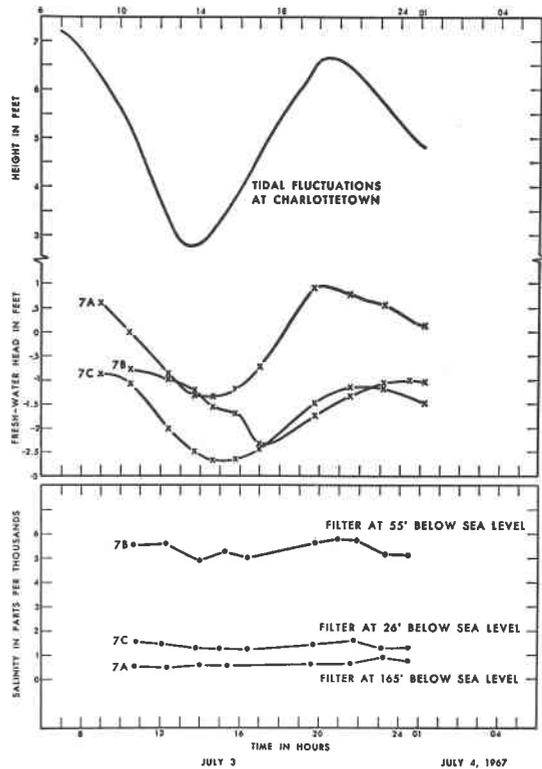


FIG. 7. Variations in head and salinity with the tides at site 7.

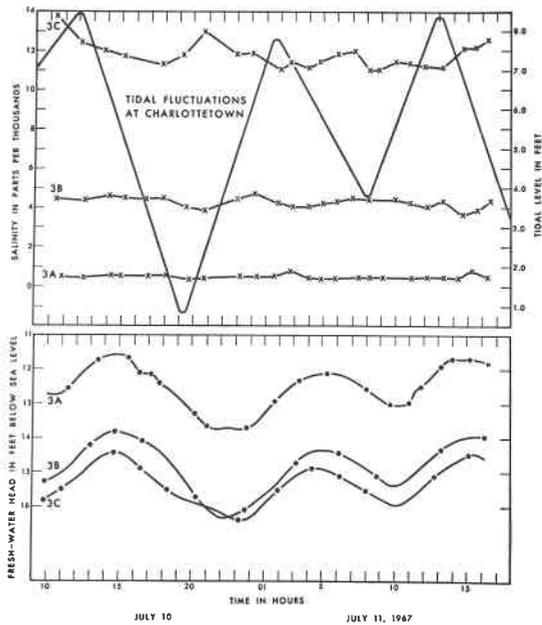


FIG. 8. Variations in head and salinity with the tides at site 3.

TABLE I
Variation of salinity with depth

Piezometer	Depth of filter (ft below sea level)	Average salinity (ppm)	Change in salinity (ppm)
3C	16	12500	2900
3B	93	4200	1000
3A	176	650	320
7C	26	1400	400
7B	55	5100	825
7A	165	700	300

complex pattern of fluctuation (Figs. 7 and 8). The piezometers with the highest salinities, 3C and 7B, fluctuate the most. The change in salinities of the piezometers is listed in Table I. At site 3, piezometer 3C has the highest salinity, which fluctuated between 11 000 and 13 900 ppm (a range of 2900 ppm), whereas 3B fluctuated between 3750 and 4750 ppm (a range of 1000 ppm), and the deepest piezometer, 3A, has the lowest salinity values, 820 ppm, and the smallest range 320 ppm.

At site 7, there is not a uniform decrease in salinity and range of salinity with depth, but the piezometers with the highest average salinities also show the largest range of salinity values. Piezometer 7B situated at 55 ft below sea level has an average salinity of about 5100 ppm and varied from 4800 to 5625 ppm, a range of 825 ppm. The deepest piezometer, 7A, has the lowest salinity, averaging about 700, and varying from 580 to 880 ppm, a range of 300 ppm.

The results indicate that the piezometers that have the highest salinity values also have the largest absolute range of salinity. These piezometers, 3C and 7B, probably have the best hydraulic connection with the salt water. The deepest piezometers, 3A and 7A, have the lowest salinities and the smallest salinity fluctuations.

(3) Discussion of the Observations

The springs and piezometers indicate that only near the surface of the estuary floor in the uppermost part of the aquifer does the salinity appear to fluctuate in a sinusoidal manner. This indicates direct transmission of salt water from the estuary into the aquifer and back with each tidal cycle. However, there appears to be no extensive recycling of salt water throughout the zone with each tide as Kohout (1964) reported in Florida. Presumably the tidal energy that drives the salt

water into the bedrock is dampened and distorted by the low permeability of the aquifer and by variations in the groundwater flow, so that its sinusoidal identity is no longer apparent. Thus the path of salt water moving into the zone of diffusion probably has a series of up and down movements with each tidal cycle as it progresses towards the piezometer.

The sinusoidal fluctuations in head are caused by a loading effect on the aquifer. This is transmitted immediately to the piezometer filter; there the load compresses the aquifer and the water, causing water to flow into the piezometer. As the load is reduced, the intergranular stress and the pore pressure are reduced, the aquifer expands, and the water in the piezometer pipe flows back into the aquifer. The result is a sinusoidal water-level fluctuation in the piezometer, with no significant change in the salinity.

Deep Occurrence of Salty Water

The deepest piezometer drilled near the Eliot River estuary is only 210 ft below sea level; thus, in order to get data concerning the flow system below this depth, it was necessary to obtain data from other parts of the island. Fortunately, the variations in geology and climate throughout the island are too small to make any significant regional difference to the hydrogeology throughout the island. So the deep well data can probably be safely integrated with the shallow data to present a composite picture of the zone of diffusion around the coast of the island down to a depth of 2000 ft.

Most of the larger communities obtain water from wells, many of which extend below 210 ft. Several such wells are located close to the sea (Fig. 1), and are listed in Table II along with their depth, chloride content, and total dissolved solids. All the groundwater in these wells has a chloride content and total-dissolved-solid content of fresh groundwater found in recharge areas farther inland.

The estimated pumping rate is recorded in Table II in order to give some indication of the amount of groundwater that does occur at this depth. From these pumping rates it is apparent that groundwater extends down to at least 500 ft below sea level, and that relatively high yields are obtained from these depths. Throughout Prince Edward Island the yield of a well generally increases with depth down to 300 or 400 ft,

TABLE II
Deep wells with fresh groundwater near the sea

Location of well	Well identification on Fig. 1	Date sampled	Estimated yield (g.p.m.)	Depth of well (ft)	Estimated depth below sea level (ft)	Chloride content (ppm)	Total dissolved solids (ppm)	Method of sampling
Montague Frozen Foods Ltd. Well No. 1	A	Feb. 27/63	464	600	440	3.2	144	by bailer at 150 ft
Georgetown No. 3 (B)	B	July 30/64	60	300	234	7.6	102	by pump
Rustico Island Park Seabrook Farm Ltd. Well No. 1	C	Sept. 10/62		300	275	20.9	173	by pump
Souris town Well No. 1	D	June 15/62	490	561	340	6.2	165	by pump
Central Bedeque	E	July 16/62	200	510	410	13.1	132	by pump
Summerside No. 6	F	Aug. 15/62		356	280	20.2	213	by pump
	G	Summer/62	600	555	535	18.1	191	by pump

NOTE: Average tds of fresh groundwater is 180 ppm. Average chloride content of fresh groundwater is 18 ppm.

suggesting the existence of relatively permeable zones at these depths compared with shallower depths.

The only data concerning the groundwater flow system beneath 500 ft come from old boring records of Ingall (1909), which are of a qualitative nature only. Five holes situated close to the sea (Fig. 1) were drilled by the Geological Survey of Canada to depths between 1630 and 2032 ft below sea level. According to Ingall the drilling was done with a churn drill, and when the flow of water into the holes made drilling too difficult, casing was installed to cut off the flow and to enable further drilling. The depth at which these flows were encountered was reported along with the taste as fresh, brackish or saline.

Hem (1959) reported that chloride concentration of 200 to 300 ppm in water containing an equivalent amount of sodium is enough to give a noticeable salty taste to most people. Thus, the "fresh" water reported by Ingall (1909) is assumed to have a chloride content of less than 200 ppm. Since chloride content in excess of 100 ppm is considered here to be indicative of salt-water intrusion, Ingall's "fresh" water could still be contaminated with salt water, but it is assumed that the fresh groundwater outflow dominates salt water inflow. No attempt was made to distinguish quantitatively between brackish and saline water. The main details concerning depth and taste of the groundwater are listed in Table III.

The five wells were situated in areas that have no heavy industrial use of groundwater today. The amount of groundwater withdrawal in these areas has not increased significantly since 1909. The main causes of fluctuations in the zone of diffusion that would have varied since then are the seasonal and secular changes in recharge. It is

assumed that these fluctuations have not significantly changed the position of the zone of diffusion.

In wells 1, 2, 3 and 5, salt water occurred at depths varying from 580 to 775 ft below sea level. Below these depths, only salty water was encountered. Thus, the base of the fresh water flow system occurs between 580 and 775 ft.

In well number 4, salt water was encountered at depths of 150, 400, and 490 ft below sea level, and considerable flows of fresh groundwater were encountered at 860, 900, 1380 and 1600 ft below sea level. The latter footage is the greatest known depth of fresh groundwater occurrence in these rocks. The fresh groundwater invariably occurred in the sandstone strata rather than in mudstone. Since the fractures in the mudstone at this depth are probably closed due to the weight of the overlying strata, they act as confining beds, separating the fresh water from the salt water. Similarly fresh groundwater occurs at depths of 900 ft along the coast of New Brunswick.

The greatest depth of the first occurrence of salt water (775 ft) is in well number 3, which is farthest inland. The shallowest depth of salt water, 31 ft, occurs farthest from land on Governor Island in Hillsborough Bay. This well (No. 6) was drilled to a depth of 1507 ft below sea level and no fresh water was encountered other than at 13 ft below sea level. This suggests that Governor Island is completely underlain by salt water, and that the deep fresh water flow system does not extend out this far from the mainland, but discharges upwards towards the floor of the sea before reaching Governor Island. It is not known how far the fresh groundwater extends seaward before it flows through the zone of diffusion and discharges onto the floor of the sea.

TABLE III
Depths of fresh and salty water
(obtained from deep borings)

Well No.	First appearance of salty or brackish water (ft below sea level)	Deepest appearance of fresh water (ft below sea level)
1	610	125
2	725	30
3	775	655
4	100	1600
5	580	420
Governor Is. Well No. 6	31	13

Synthesis

By integrating the information from shallow depths determined from the Eliot River area and the information from greater depths from other parts of Prince Edward Island, the variations of the position of the zone of diffusion with depth along the coast were determined, and are shown schematically in Fig. 9. The variation of the positions of the zone of diffusion can be readily grouped into three regions; the first extends from sea level to 185 ft below sea level, the second from 185 ft to a depth varying from 580 to 775 ft below

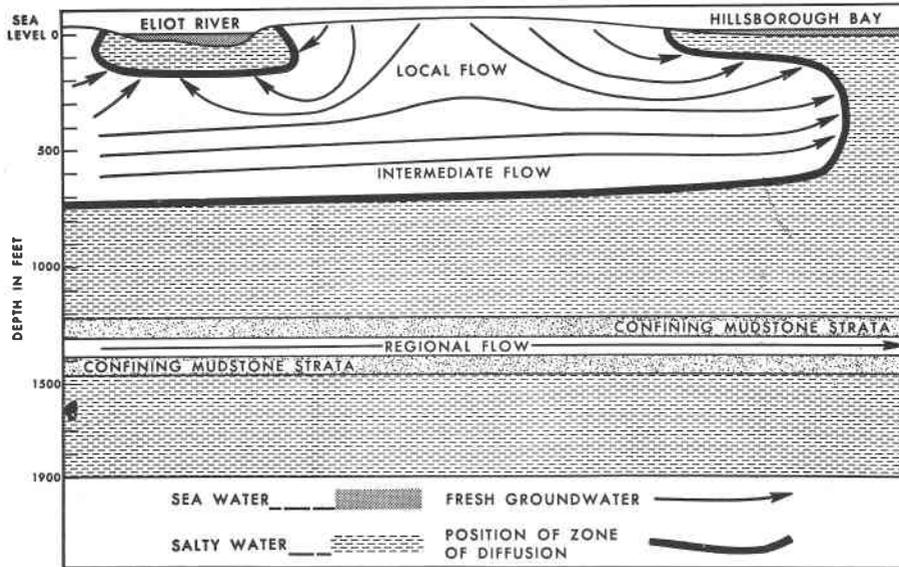


FIG. 9. Composite sketch of fresh and salty water in bedrock aquifers along the coast of Prince Edward Island.

sea level, and the third region extends beneath this depth. The position of the zone of diffusion in each of these regions is controlled primarily by the hydraulic conductivity of the aquifer and by the hydraulic gradient of the groundwater flow system. Upson (1966) concluded that the circulation pattern of the fresh water rather than the density of salt water controls the position of the zone of diffusion in the confined coastal aquifers of New York and New Jersey.

These three regions were related to three mutually dependent flow systems. In the first region the zone, which extends inland and downwards to 185 ft, has encroached upon the local groundwater flow system. This flow system has its recharge area in the hills on either side of the Eliot River and its discharge area along the banks of the river. Sea water is able to move inland at high tide; it has a higher head than the groundwater in the discharge area.

In the second region, below 185 ft, the zone of diffusion is displaced seaward by the large groundwater outflow from the intermediate flow system. This large outflow is related to the presence of higher groundwater heads and possibly to more permeable rocks at these depths. This flow system contains the most groundwater, because its recharge area comprises all of the area between the divide of the Eliot River basin and the hills immediately surrounding the Eliot River. It flows

under the river and discharges upward to the floor of the sea.

The third region extends from a depth varying from 580 to 775 ft below sea level, depending on the hydraulic gradient of the groundwater, down to at least 2000 ft below sea level. This region consists almost entirely of salty water and hence is part of the zone of diffusion. It is not known if salt water at this depth underlies the entire island. Locally fresh groundwater is encountered in this region down to depths of 1600 ft below sea level. There the groundwater occurs in sandstone strata and is confined from the surrounding salty water by mudstone strata. This groundwater probably originates from or near the divide of the basin and is considered part of the regional flow system.

Conclusions

- (1) Salt-water intrusion occurs under natural groundwater flow conditions in the bedrock aquifer, along the coastline, and along the saline estuaries of Prince Edward Island.
- (2) Groundwater discharges to the sea through this zone of diffusion as salty water. It does not discharge directly to the sea as fresh water. The saline springs of the zone of diffusion are at the end of the groundwater flow system.
- (3) The zone of diffusion adjacent to the local flow system becomes fresher as the depth of

penetration increases, until the fresh groundwater of the intermediate flow system is encountered. The position of the zone is kept in a dynamic balance by the hydraulic gradient of the intermediate flow system and by the hydraulic conductivity of the aquifer.

- (4) To develop large well fields near the sea, the groundwater in the intermediate flow system should be exploited. Thus, wells should be cased to keep salt water from the local flow system out of the wells. The concept of using a large number of shallow wells to skim off fresh water from the underlying salt water is not applicable here.

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