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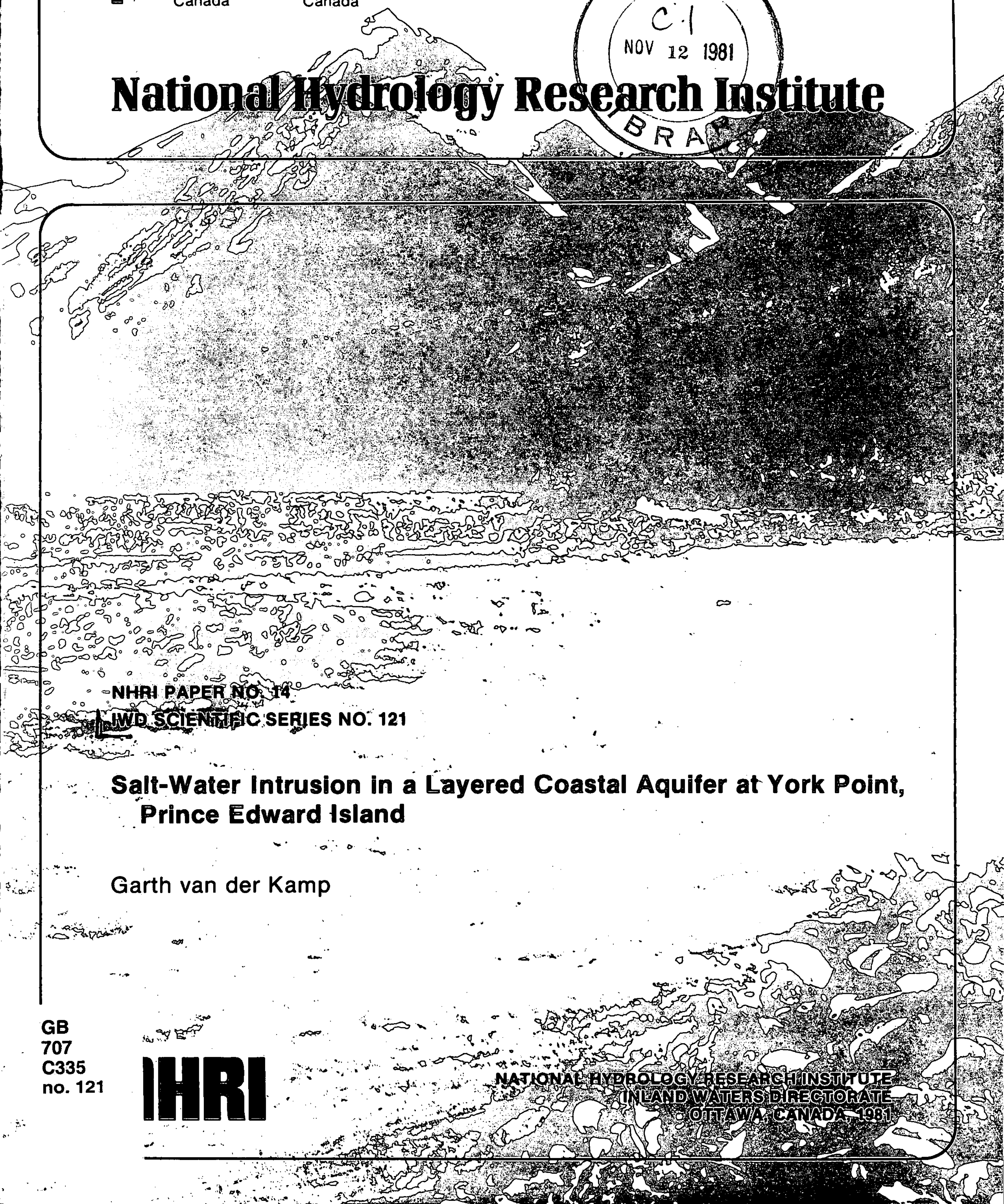

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Salt-Water Intrusion in a Layered Coastal Aquifer at York Point, Prince Edward Island

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Abstract

Detailed measurements of water levels and salinities have been carried out in a layered coastal aquifer, undisturbed by pumping, at York Point, Prince Edward Island. The position and movements of the sea water in the aquifer are analyzed in relation to density differences, and tidal, seasonal and secular changes of water levels. Separate "wedges" of salt water were encountered in each permeable layer. In the deeper beds, fresh water has been encountered in association with anomalously low heads. This phenomenon is at least in part due to the entrainment of salt water by the seaward flow of fresh water, but the rising sea level in the area can also lead to such an effect and, in fact, may have an important bearing on the pattern of salt-water intrusion at depth.

Résumé

On a mesuré de façon détaillée les niveaux d'eau et les salinités d'un aquifère côtier en couches, non perturbé par le pompage, de la pointe York (Île-du-Prince-Édouard). La position et les mouvements de l'eau de mer dans l'aquifère sont analysés par rapport aux différences de densité, au marnage, et aux variations saisonnières et séculaires des niveaux d'eau. Des «biseaux» distincts d'eau salée se retrouvent dans chaque couche perméable. Dans les lits plus profonds, l'eau douce rencontrée était associée à des promontoires anormalement bas. Ce phénomène est en partie dû à l'entraînement d'eau salée par l'eau douce descendant vers la mer, mais la hausse du niveau de la mer dans la région peut également produire un tel effet et, en fait, avoir une influence importante sur le mode d'intrusion de l'eau de mer en profondeur.

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INTRODUCTION

There is extensive literature on the problem of accounting for and predicting the position and movements of the interface between fresh and salt water in coastal aquifers (Szell, 1980). Modelling studies (Lee and Cheng, 1974; Mualem and Bear, 1974; Frind, 1980) have shown how the position of the interface in layered aquifers can be explained.

This study presents field data on water levels in an array of coastal observation wells and relates these data to salinity measurements. An attempt was made to observe the movements of the interface in response to tidal and seasonal changes of water level. The precision of the data is limited due to the effect of irregular fluctuations of sea level, but some tentative conclusions may be drawn.

Of particular interest is the possible effect of changing sea level on the pattern of salt-water intrusion. Most salt-water intrusion studies assume implicitly that sea level is constant, but it appears likely that a changing sea level may have an important bearing on the position of the interface in deeper formations (Perlmutter *et al.*, 1959; Kohout *et al.*, 1977; Collins, 1977). Data presented in this report indicate that the salt water in the deeper aquifers has not penetrated as far inland as would be expected on the basis of measured mean water levels. It is hypothesized that this effect may be related to the secular rise of sea level in the study area.

The discussion is based on measurements of water levels and salinities in an array of observation wells near the North River estuary at York Point, Prince Edward Island. A previous study of salt-water intrusion in the area indicated that at most places along the shoreline, brackish water in the shallowest aquifers overlies fresh water at greater depths (Carr, 1969). The present work is, in part, a further investigation of this anomalous condition through an analysis of the relationship between water level and salinity. Special attention was paid to the measurement and prediction of tidal fluctuations of water levels in the wells near the shore, since reliable determinations of seasonal fluctuations and yearly mean water levels were not possible unless the measured water levels were corrected for tidal effects.

Pumping of ground water in the study area is limited to scattered farms and cottages and may be assumed to have little influence on the overall flow pattern. The observation wells themselves are considered to have little effect on the flow within each separate aquifer unit and were grouted to prevent leakage through the aquitards. Thus, the observed water levels and salinities may be assumed to represent the natural undisturbed situation closely.

THEORETICAL CONSIDERATIONS

The Nature of the Interface

For present purposes, the term "salt water" will be used to refer to both the water of the adjacent sea or estuary and the essentially undiluted sea water in the formations. "Fresh water" will denote formation water that has no sea water mixed with it, and "brackish water" will denote water in the zone of dispersion where fresh and salt water are mixed.

Due to the effects of diffusion and dispersion, enhanced by tidal effects, there is no abrupt interface between fresh and salt water in the aquifer, but rather a gradual transition from fresh through brackish to salt water. The position of the zone of brackish water is governed by the heads and flows of the fresh and salt waters and, to some extent, by the mixing processes in the brackish water zone.

Heads and Flows of Fresh and Salt Water

The fluid pressure at any point may be used to define a freshwater head, h_f, or a salt-water head, h_s, as follows (see, for instance, DeWiest, 1965)

$$h_f = z + p/(\rho_f g) \qquad (1)$$

$$h_s = z + p/(\rho_s g) \qquad (2)$$

where z is the elevation of the point in question above an arbitrary datum, p is the fluid pressure at the point, g is the acceleration of gravity, and ρ_f and ρ_s are the densities of fresh and salt water, respectively. The heads, h_f and h_s, are also measured with respect to the arbitrary datum, which is most conveniently taken to be mean sea level and will be considered as such in the following discussion. Figure 1 is a sketch illustrating the definition of h_f and h_s. The salt-water head at any depth in the open sea can, for practical purposes, be taken as equal to sea level.

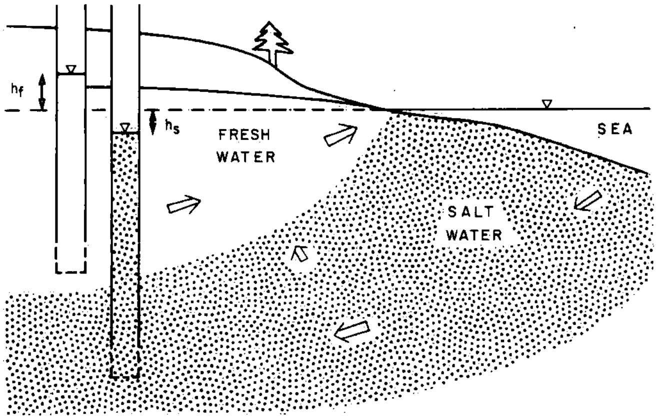

Figure 1. Heads and flows of fresh and salt water.

The freshwater and salt-water heads govern the flow of fresh and salt water, respectively. In Figure 1, for instance, the freshwater head is positive, so that the fresh water flows upward and out toward the sea, whereas the salt-water head is negative, so that there is a net landward flow of sea water. If the salt water in the aquifers is not moving, then the salt-water head will be equal to sea level everywhere in the portion of the subsurface invaded by salt water (assuming that porous membrane effects do not play a role). From (1) and (2)

$$h_s = \frac{\rho_f}{\rho_s}(h_f + \gamma z) \tag{3}$$

where

$$\gamma = \frac{\rho_s - \rho_f}{\rho_f} \tag{4}$$

The quantity γ is mentioned repeatedly in discussions of salt-water intrusion. For the York Point site, the estuary water has an average salinity of 26 500 ppm. For a mean temperature of 10°C, this gives $\rho_s = 1.020\,\rho_f$ and $\gamma = 1/50$.

Dispersion and Diffusion

Dispersion and diffusion effects can result in a wide zone of transition between fresh and salt water. Dispersion is much enhanced by the back-and-forth movement of water owing to tidal and seasonal fluctuations. This effect is further enhanced in a two-porosity medium such as a fractured porous sandstone where the flow takes place largely through the fractures, but most of the water is stored within the intergranular pores.

The existence of a zone of mixing implies an increased landward penetration of brackish water beyond the point to which the salt water would penetrate if the fresh and salt waters were immiscible. As has been shown by Cooper (1959) and Kohout (1960), however, a significant quantity of salt water is entrained by the freshwater flow and is discharged back to the surface. To use Cooper's expression, the salt-water wedge is "eroded" by the fresh water. Salt water enters the aquifer through the sea floor to replace the entrained water. This landward flow of salt water implies, by Darcy's law, a negative salt-water head at the interface. Figure 1 illustrates the effect. Detailed empirical studies of this phenomenon for the Biscayne aquifer in Florida showed that the landward flow of salt water owing to entrainment effects amounted to about one eighth of the seaward freshwater flow (Kohout, 1960). Numerical models of salt-water intrusion including the effect of dispersion have been developed for this case by Henry (1960) and Lee and Cheng (1974). Their results substantiate the existence of the entrainment effect.

Tidal Fluctuations of Water Levels

The water levels in wells near tidal waters are generally subject to tidal fluctuations induced by the tides in the nearby sea or estuary. The measured water levels must be corrected for such tidal effects if reliable information on mean water levels or seasonal fluctuations is required. As part of a more detailed study on tidal fluctuations in coastal aquifers (van der Kamp, 1973), the following straightforward and generally applicable method was developed for eliminating tidal effects from continuous or spot measurements of water level.

For periods of about one day, tidal fluctuations can be approximated if they are considered as the sum of a semidiurnal component with a period of 745 min and a diurnal component with a period of 1490 min. The tidal fluctuations in the sea can then be described by a function of the form:

$$\begin{aligned} W(t) &= A_s \cos(\omega_s t + \delta_s) \\ &\quad + A_d \cos(\omega_d t + \delta_d) \end{aligned} \tag{5}$$

where the subscripts s and d refer to the semidiurnal and diurnal components, A_s and A_d are the amplitudes, and δ_s and δ_d are the phase constants. The tidal fluctuations in a well can then be described by:

$$\begin{aligned} W(t) &= E_s A_s (\omega_s t + \delta_s - L_s) \\ &\quad + E_d A_d \cos(\omega_d t + \delta_d - L_d) \end{aligned} \tag{6}$$

where E_s and E_d are the tidal efficiencies and L_s and L_d are the phase lags for a particular well. The values of E and L can be determined by means of a least-squares fitting technique applied to several days of continuous water-level records, obtained simultaneously for the well and the nearby open tidal water. Measurements have shown that while A and δ vary from day to day, E and L remain relatively constant. On a daily basis, the approximations expressed by (5) and (6) are generally accurate to within 10 percent of the maximum tidal fluctuation. Once E_s, E_d, L_s and L_d have been determined for a particular well, the tidal displacement of the water level in the well at any time can be calculated through (6) if a continuous record of the tides in the nearby sea is available. It should be noted that irregular fluctuations of sea level also influence the water levels in coastal wells and tend to obscure the details of water-level changes in the wells owing to other causes.

DESCRIPTION OF THE YORK POINT STUDY SITE

Location

The York Point study site is situated on the south shore of Prince Edward Island beside the estuary of the North River. Its location is shown in Figure 2. This site was selected, in part, because previous work in the area had indicated a complex and unusual pattern of salt-water intrusion (Carr, 1969).

The available evidence indicates that the sea level in this area is rising relative to the land at about 30 cm per century (Dohler and Ku, 1970) and that the shoreline is receding by erosion and submergence at rates of up to 1 m/yr. To illustrate these trends, the coastline at about 5000 years B.P. (after Kranck, 1972) is also shown in Figure 2.

Hydrogeology

The geology of Prince Edward Island has been described by Frankel (1966) and Carr (1969). The bedrock consists of nearly flat-lying beds of sandstone, siltstone, claystone and conglomerate. Individual beds are lenticular and thin, with an average thickness of 2 or 3 m. The bedrock surface is covered with a thin layer of glacial drift generally less than 8 m thick.

A cross section of the hydrostratigraphy at the York Point site is given in Figure 3. For the purposes of discussing ground water flow, the siltstones and claystones are considered as mudstone, their common hydraulic characteristic being that they are much less permeable than the sandstones. The cross section shown in Figure 3 is a simplified rendition of the actual complicated conditions. However, the continuity of the main sandstone and mudstone units has been confirmed by pump tests.

The main sandstone aquifers have been numbered 1, 2 and 3 from the top down, as shown in Figure 3. Aquifer 2 actually consists of an upper and lower sandstone unit separated by a very thin and probably discontinuous mudstone layer. The positions of the observation well filters are also indicated. Each filter is referred to by number. For example, the number 4-2 would mean a well in cluster 4 open to aquifer 2. The well filters extend across most or all of the aquifer thickness. They may, therefore, have disturbed any existing vertical flow patterns within the aquifers. Since the vertical potential gradients within the aquifers are certainly very much smaller than those across the mudstone units that separate them, however, the disturbing effect of the wells on the flow pattern as a whole is likely to have been small.

Pump tests were carried out on all three aquifers, with wells 4-1, 4-2 and 4-3 serving as pumped wells, and various other wells, as observation wells. As might be expected from the irregular hydrogeology, analysis of the drawdown data leads to considerably different results for different observation wells. The average transmissivities and storage coefficients of the formations, determined from pump tests and slug tests, are given in Table 1. The transmissivity of aquifer 1 varies from the very high values of approximately 33 000 and 20 000 m^2/day at wells 1-1 and 4-1, respectively, to 35 m^2/day at well 6-1. Such a decrease of transmissivity with distance inland has been encountered elsewhere in the region in shallow aquifers near the shore (Carr, 1971; van der Kamp, 1973, p. 78).

Table 1. Hydraulic Characteristics of the York Point Aquifers

Aquifer	Average thickness (m)	Transmissivity, (m^2/day)	Hydraulic conductivity K (m/day)	Storage coefficient (dimensionless)
1*	4	20 000	5000	–
2	8	600	75	8×10^{-5}
3	6	37	6.2	3×10^{-5}

*The values quoted for aquifer 1 apply to the section near well 4-1.

The vertical hydraulic resistances of the mudstone aquitards could not be reliably determined because the finer details of the drawdown owing to pumping were obscured by irregularities of the tidal fluctuations in the wells. The mudstone unit between aquifers 1 and 2 is estimated to have a hydraulic resistance of about 1000 to 10 000 days, and the unit between aquifers 2 and 3 to have a resistance of about 1000 to 4000 days. The sandstones of Prince Edward Island have an average porosity of about 0.18 (Carr, 1971), a value which is probably also typical for the York Point aquifers.

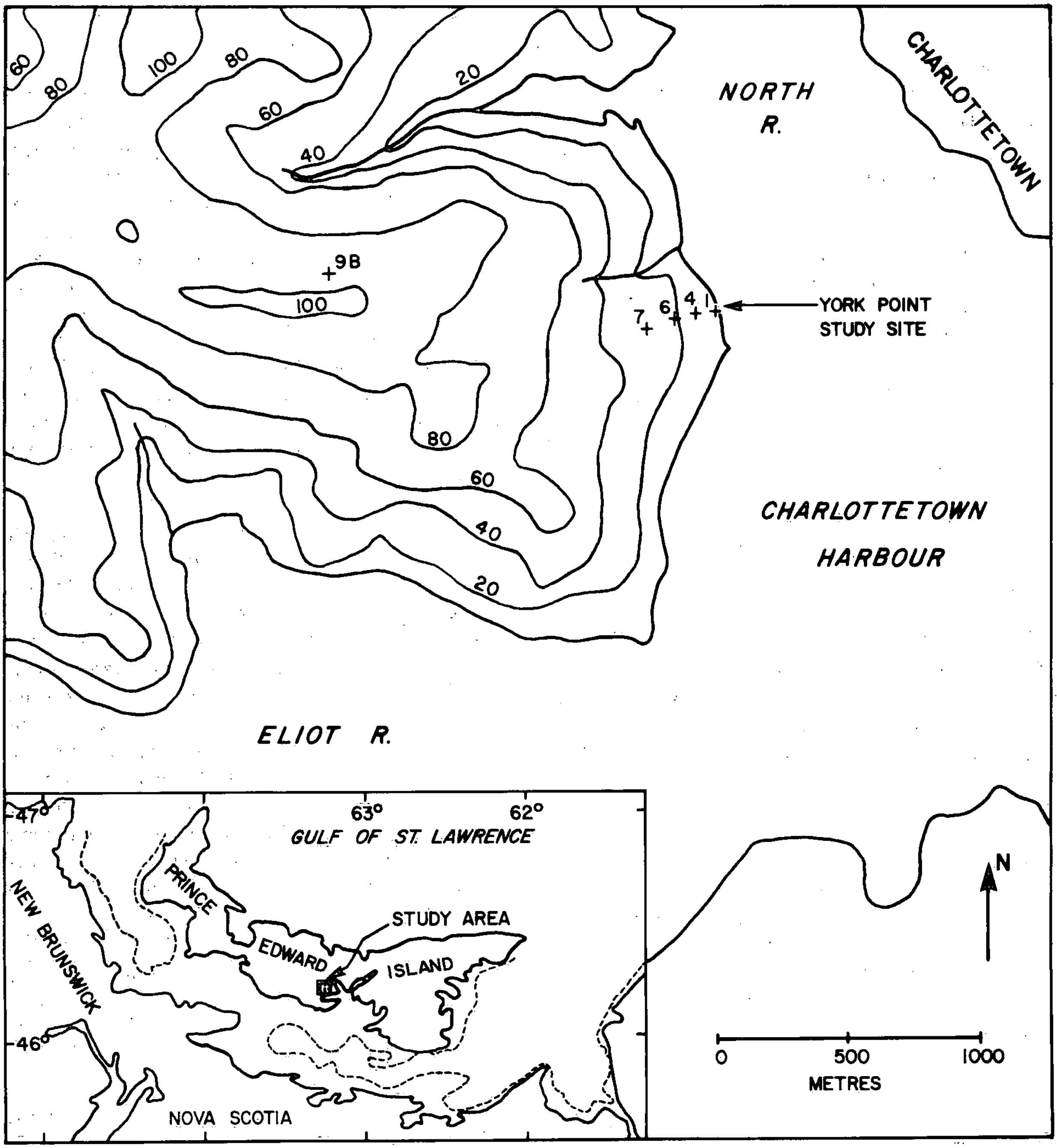

Figure 2. Location of York Point study site. Contour lines are at 20-ft intervals. The approximate location of the coastline at 5000 years B.P. is shown in the key map by a dashed line (after Kranck, 1972). Locations of observation well clusters are indicated by (+) symbol.

The Salt-Water Intrusion Pattern

Salinities of pore-fluid samples taken during the progress of the drilling in the summer of 1970 are also shown in Figure 3; the arrows in Figure 3 indicate the points at which the samples were taken. The values quoted are, for the most part, based on electrical conductivity measurements made on the spot, the salinity being defined as the weight of sodium chloride per unit weight of water (in parts per million) that would result in the observed conductivity. The electrical conductivity of fresh ground water in the area is generally such as to yield an equivalent salinity of 100 to 200 ppm. Thus values in this range indicate the limits of the intrusion of brackish water. Care was taken to ensure that the water sampled was representative of the formation water at the depth of sampling. The salinity values shown in Figure 3 may be subject to some error but they indicate clearly the general pattern of the salt-water intrusion.

The measured ground water salinities may be compared with the salinity of the sea water in the estuary near the York Point site, which varies little throughout the year and has an average value of 26 500 ppm. This result is based on 22 salinity measurements taken between April 13 and November 19, 1973, at the water surface and at the bottom of the main channel about 300 m offshore from the site (data courtesy of the Prince Edward Island Environmental Control Commission).

An important feature of the observed intrusion pattern is the existence of separate "wedges" of brackish water in each main aquifer unit. This overall picture did not change significantly during two years of observation. Such multiple-tongue intrusion patterns have been reported elsewhere (e.g., Jacobs and Schmorak, 1960; Collins and Gelhar, 1971). In fact, the observed pattern bears a marked correspondence to the theoretically expected pattern in layered aquifers described by Mualem and Bear (1974). The position and movement of the brackish water in the aquifers will be analyzed further below in relation to observed water-level changes.

Another noteworthy aspect of the intrusion pattern is the large horizontal extent of the zone of brackish water, which is about 200 m in aquifer 1 and probably much more in the lower aquifers. This dispersion effect may be due to the tidal motions in the aquifers. Frind (1980) has shown that it is enhanced if the overlying aquitards are highly impermeable.

Tidal Fluctuations

Water levels in all the observation wells at the York Point site are subject to tidal fluctuations induced by tides in the adjacent estuary. The maximum water-level fluctuation in the estuary is about 3 m and the tides are a mixed type, containing both semidiurnal and diurnal components. A continuously operated tide gauge at Charlottetown, about 3 km distant, provided data for the tidal fluctuations in the estuary.

For the wells at York Point, E_s, E_d, L_s and L_d were determined by means of the least-squares fitting technique mentioned earlier, applied to at least four separate days of continuous water-level records. The results are shown graphically in Figure 4 as a plot of L and ln E vs. distance inland from the mean tide mark. These values were used to eliminate tidal displacements from the observed water-level

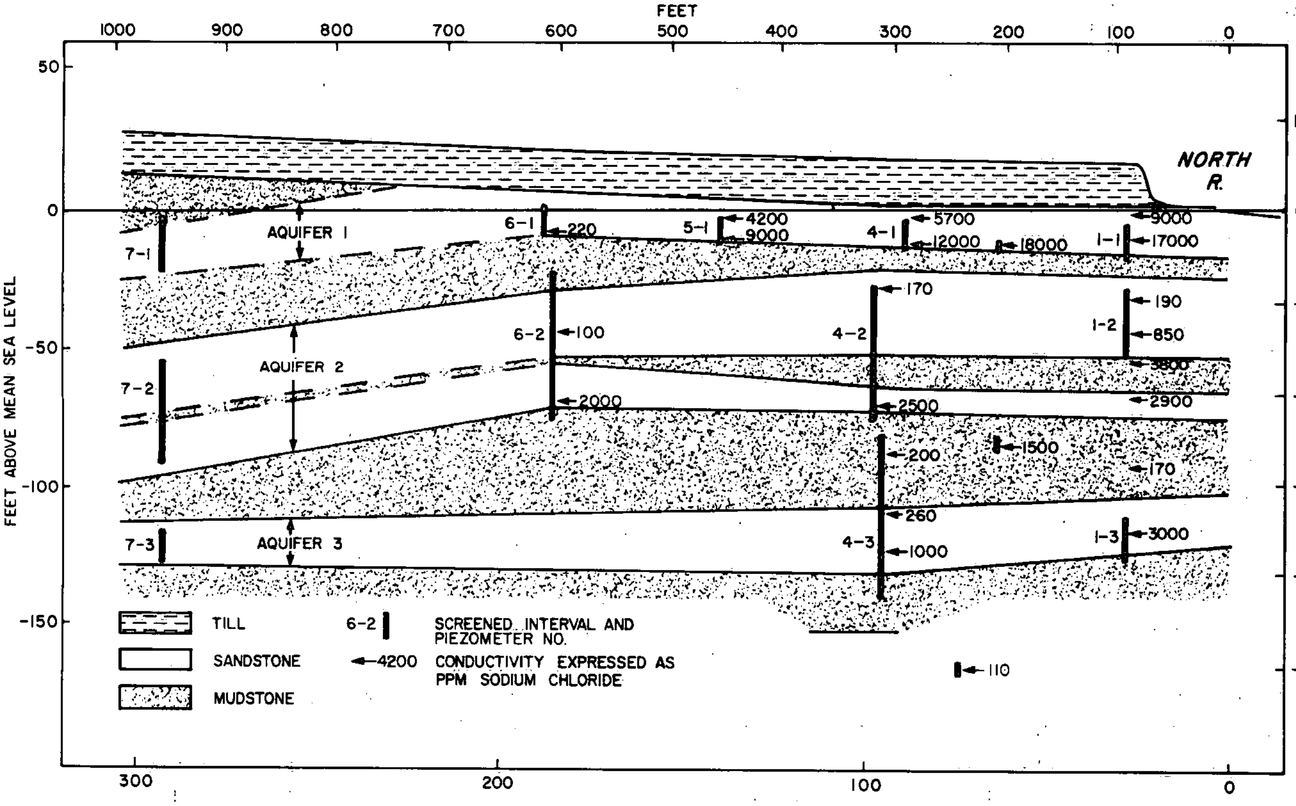

Figure 3. Hydrostratigraphy and salinities encountered during drilling at York Point in 1970. The three measurements at about 60 m inland are based on water samples taken in 1970 from wells drilled in 1967.

changes during pump tests (van der Kamp, 1973, p. 60) and from the instantaneous water levels that were measured once a month.

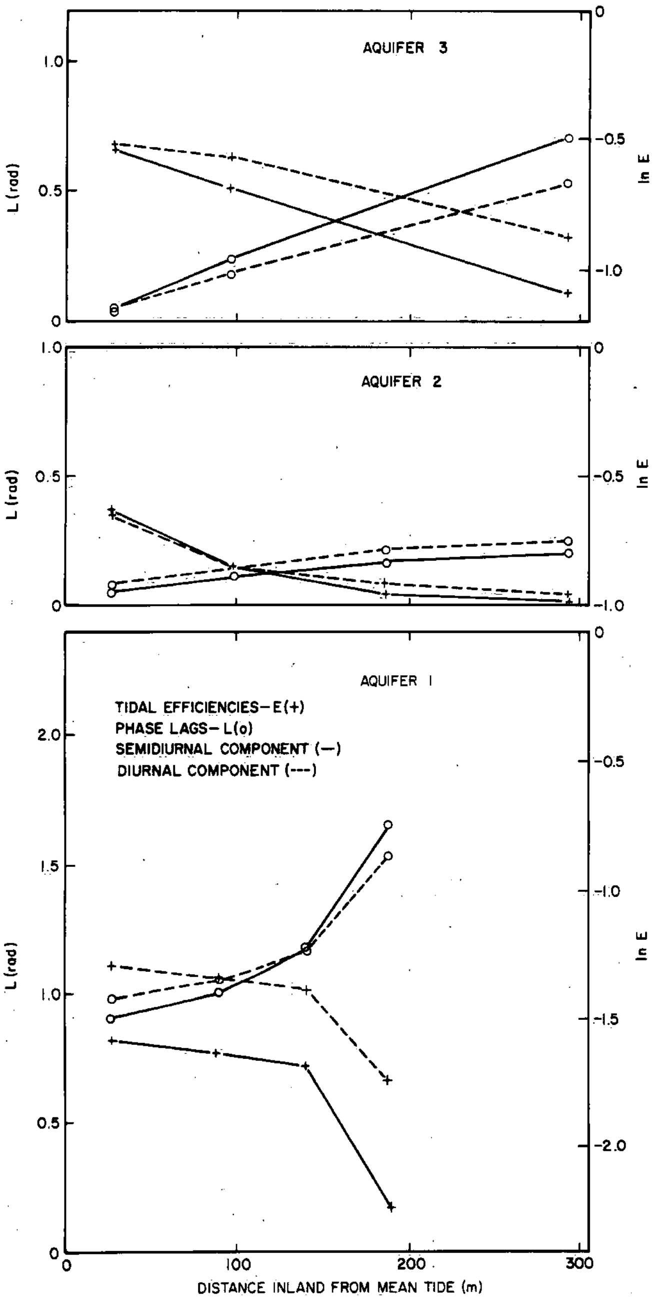

Figure 4. Tidal efficiencies and phase lags for the semidiurnal and diurnal components in the three aquifers at York Point.

Tidal fluctuations induce back-and-forth movements of the water in the aquifers. Under favourable circumstances, these movements may result in measurable fluctuations of salinity within the zone of brackish water. Tide-induced fluctuations of salinity were measured in aquifers 1 and 2 by means of a continuous recording of the electrical conductivity of the water near the bottoms of the wells. The salinity at the bottom of well 4-1 during a three-day period is presented in Figure 5 together with the water level in the well. The fluctuations of salinity in the well are seen to correspond closely to the water-level fluctuations. During a pumping test on well 4-1, salinity fluctuations of the pumped water varied with water level in much the same way as for the observations shown in Figure 5. Wells 1-1 and 5-1 in aquifer 1 showed similar fluctuations. The observed salinity fluctuations in aquifer 2 were smaller and irregular and were probably largely due to vertical movements of water in the wellbores. Significant fluctuations of salinity were observed in aquifer 1 probably because of the extremely high hydraulic conductivity of this aquifer, which is about 5000 m per day at well 4-1.

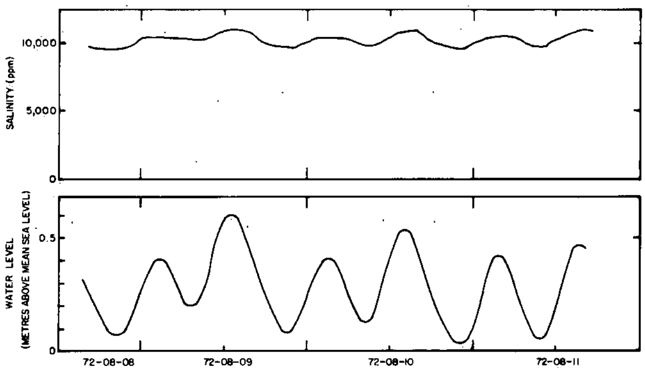

Figure 5. Tidal fluctuations of water level and salinity in well 4-1 at York Point.

In general, the observed tidal fluctuations of salinity are small, and no important error is introduced if the influence of the tidal motions on the observed salinities is disregarded.

Seasonal Fluctuations

In an attempt to monitor seasonal changes in the wells at York Point, water levels and salinities were measured once a month from February 1971 to September 1972. The measured water levels were corrected for tidal displacements by the method outlined previously. The results indicated that remaining irregularities, probably largely due to barometric effects and irregular fluctuations of sea level, could be as large as 0.30 m or up to 20 percent of the total tidal fluctuations in the wells. This "noise" obscured all but the gross outline of the seasonal fluctuations. The salinities were obtained from water samples taken at specified depths. Here again, the "noise" amounted to 20 to 30 percent of the total salinity, probably because of vertical flow and mixing of water within the wells, tidal fluctuations and small errors in sampling depth. Some of these monthly measurements are presented in

Figure 6 as three-month running means to bring out the main features of the seasonal changes.

All of the water levels are given with respect to mean sea level, as determined from the Charlottetown tide gauge records for the period September 1, 1971, to September 1, 1972. Wellhead elevations were determined by measuring the elevation above the level of the sea at the nearby shore at a given time. The level of the sea at that time was later obtained from tide gauge records. Two such leveling surveys were done and the results agreed to within 0.8 cm.

Figure 6A gives the water levels in a piezometer about 1500 m inland and at about 2 m below sea level (piezometer 9B; see Figure 2 for location). Figure 6B is a plot of the monthly mean sea levels at the Charlottetown tide gauge. These two parameters are, in effect, the independent boundary conditions governing the seasonal flow changes

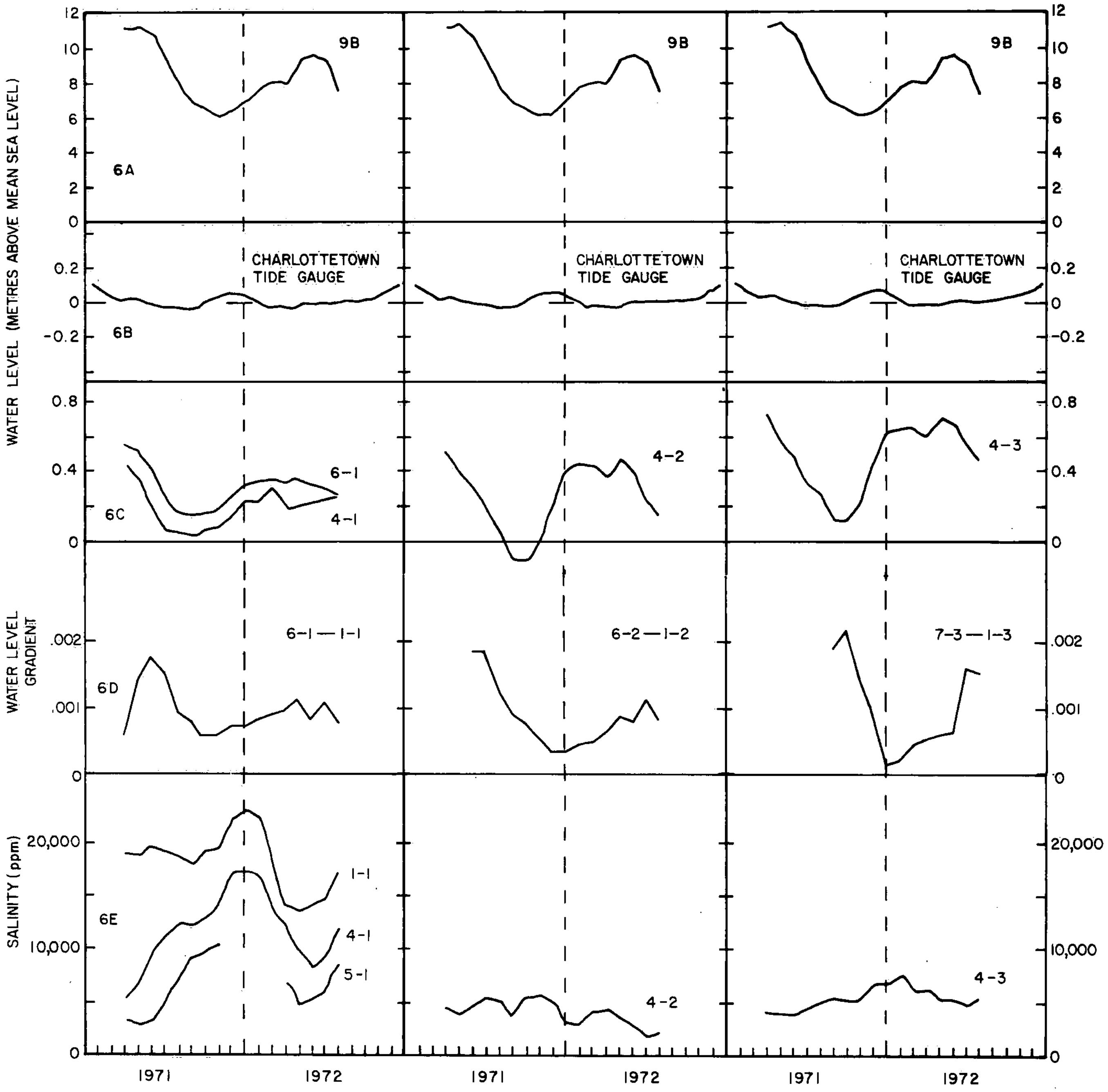

Figure 6. Seasonal fluctuations of water levels, three-month running means of monthly measurements, water-level gradients, and salinities at York Point.

in the coastal aquifers. They are also plotted as three-month running means. Figures 6C and 6E, respectively, present the water levels and salinities for various wells. Figure 6D shows the average water-level gradients for the three aquifers, between the two wells indicated.

In spite of the "noise" in these data, the main features of the seasonal fluctuation are clear. In particular, large seasonal fluctuations of salinity were recorded for the topmost aquifer, but the records for the deeper aquifers show no clear seasonal salinity fluctuations, although the seasonal water-level changes for these aquifers are larger. The salinity fluctuations in the top aquifer lag considerably behind the water-level fluctuations in the wells. However, the lowest salinities occur approximately at the same time as the highest water levels in piezometer 9B farther inland.

With respect to a yearly cycle, the water-level gradients appear to be distinctly out of phase with the water levels. The lowest gradients occur three to four months after the lowest water levels. Also in the top aquifer (aquifer 1), the salinity changes appear to be almost in opposing phase with the gradients.

These results for seasonal movements suggest a complex interaction between heads and flows of the fresh and salt water. If the system were in quasi-static equilibrium throughout the yearly cycle, then the heads and gradients would be in phase with each other and the salinity would be in opposing phase (the highest salinity would occur at the time of lowest heads and gradients). Such a relation may approximately fit the higher permeable top aquifer, but not the deeper aquifers.

Yearly Mean Water Levels and Salinities

Although the results of the monthly measurements are not reliable enough to permit a detailed description of the seasonal movements, they do permit a fairly reliable determination of the yearly mean water levels and salinities. The relationship between these two parameters can explain, to some degree, the mechanisms of the salt-water intrusion.

The mean values of salinity, water level, and freshwater and salt-water heads calculated from the monthly measurements for the period September 1, 1971, to September 1, 1972, are summarized in Table 2. The water level, heads and sampling depth are all relative to mean sea level during the same period, as determined from the records of the tide gauge in Charlottetown. The monthly water-level measurements were individually corrected for tidal effects before they were averaged.

The salinities were determined by the laboratory analysis of water samples taken by means of a bailer, 75 cm long. For samples with high salinity, the salinity was determined from the electrical conductivity of the sample. For low-salinity samples, the chloride concentration was determined by means of titration. These values of chloride content are shown in column 5 of Table 2. Salinity estimates based on these values are given in parentheses in column 4.

Table 2. Mean Values of Salinity, Freshwater Head and Salt-Water Head, September 1, 1971, to September 1, 1972

Well	Distance to mean tide mark (m)	Sampling depth (metres below mean sea level)	Mean salinity (ppm)	Mean chlorides (ppm)	Mean water level (metres above mean sea level)	Mean h_f (metres above mean sea level)	Mean h_s (metres above mean sea level)
1-1	28	2.7	18 000		0.15	0.18	0.12
4-1	89	2.4	12 800		0.18	0.20	0.15
5-1	139	2.4	8 600		0.22	0.23	0.18
6-1	187	2.4	(<200)*	20	0.28	0.28	0.22
7-1	292	0.3			1.6	1.6	1.6
1-2	28	8.2	(300)	140	0.20	0.20	0.04
4-2	97	7.6	(540)	210	0.22	0.22	0.07
		13.7	(1 900)	1120	0.22	0.23	-0.05
		19.8	3 700		0.22	0.24	-0.16
6-2	185	13.1	(<200)	15	0.31	0.31	0.05
		19.2	(<200)	10	0.31	0.31	-0.07
7-2	292	17.6			0.37	0.37	0.01
1-3	29	35.4	6 600		0.36	0.52	-0.18
4-3	96	24.4	(810)	440	0.46	0.47	-0.02
		30.5	(1 060)	590	0.46	0.49	-0.12
		36.6	5 600		0.46	0.51	-0.22
7-3	292	37.2			0.59	0.59	-0.15

*Salinity estimates based on chloride values are given in parentheses.

The freshwater head, h_f, was calculated from the measured mean water level with an allowance made for the salinity of the water in the well above the sampling point. The salt-water head was calculated from the freshwater head by means of (3) using the relations

$$\rho_s = 1.020\ \rho_f \text{ and } \gamma = 1/50$$

The mean salinities and freshwater and salt-water heads, as summarized in Table 2, are probably somewhat affected by vertical movements within the well screens. However, one feature is clear; in the two deeper aquifers, fresh or slightly salty water was encountered in association with negative salt-water heads. It follows that if the flows are governed by Darcy's law, there must then be a net landward flow from the sea toward the points at which negative heads were measured. In other words, there must be a landward flow of salt water in the deeper aquifers, entering the aquifers through the sea floor. This interesting conclusion will be considered further below.

The relationship between head, salinity and depth for the shallow aquifer is more normal; in fact, the heads are somewhat high for the measured salinities. Possibly, foreshore effects play a role here because, throughout the tidal cycle, the beach remains saturated with near-salt water up to well above the low-tide level.

The landward flow of sea water in the deeper aquifers can be explained, at least in part, as the result of entrainment through dispersion. As mentioned earlier, Kohout (1960) showed that for a shallow limestone aquifer in Florida, the flow of salt water owing to entrainment by fresh water was approximately one eighth of the freshwater flow. A similar effect certainly plays a role for the York Point aquifers, as indicated by the wide zone of dispersion and the discharge of brackish water along the shoreline (Carr, 1969).

Variations of annual rainfall could also have an important effect on the position and movement of salt water in the coastal aquifers. In particular, if the period in question, which is September 1, 1971, to September 1, 1972, were exceptionally dry, ground water levels inland would be lower than normal and a temporary landward movement of the salt water front could ensue. Data on water levels inland are sparse. Water-level data for piezometer 9B are shown in Figure 7, but the records are incomplete. It appears that the mean water level in 9B was not significantly below normal during the period in question. The average annual precipitation at the Charlottetown Department of Agriculture research station, about 5 km distant, is 1086 mm. During the period in question, the total precipitation was 997 mm, and for the previous one-year period, 1203 mm. Some landward movement of the salt-water front may therefore have been induced by the below average rainfall during the period of observation.

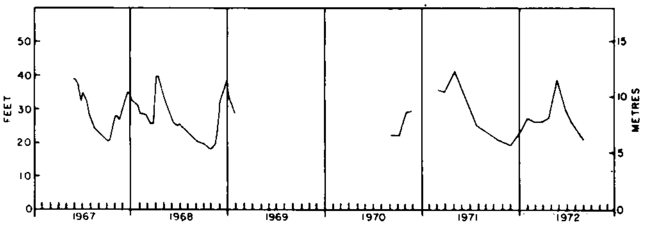

Figure 7. Water level above mean sea level in piezometer 9B near York Point.

There is another possible effect which certainly cannot be disregarded, namely that of the rising sea level in the region. Kranck (1972) indicates that in the Northumberland Strait area, the sea level has risen by about 20 m in the last 5000 years, an average rate of 40 cm per century. From an analysis of tidal records between 1938 and 1967, Dohler and Ku (1970) found an average rise of mean sea level at Charlottetown of 0.0097 ± 0.0011 ft/yr (30 ± 3 cm per century). Thus, there is good evidence that sea level in the area has been rising relative to the land at 30 to 40 cm per century for the last few thousand years. To illustrate this trend, a plot of yearly mean sea levels at Charlottetown since 1938 is presented in Figure 8 (data after Marine Environmental Data Service, 1974). Also indicated in the figure is the mean sea level between September 1, 1971, and September 1, 1972, which is the level used in this report. A steadily rising sea level implies that the salt water in the aquifers must be steadily penetrating farther inland because of both the coastline recession and the increasing head of the sea water.

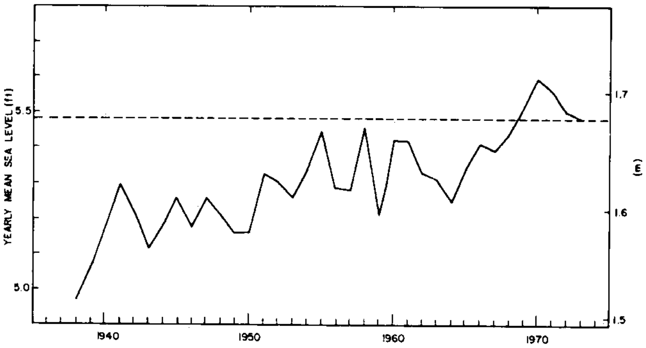

Figure 8. Yearly mean sea levels at Charlottetown, P.E.I. (after Marine Environmental Data Service, 1974). The dashed line indicates the mean sea level for the period from September 1, 1971, to September 1, 1972.

There are then two processes that can result in a continuous landward flow of salt water: entrainment of brackish water through dispersion and landward movement of the salt-water front owing to rising sea level. The relative importance of these two processes will depend on the strength of the seaward freshwater flow in comparison with the landward flow of salt water owing to the moving salt-water interface.

It is a general property of ground water flow systems in a fairly homogeneous hydrogeologic setting that the strength of the flow decreases with depth. It is to be expected therefore that the strength of the seaward freshwater flow and the associated entrainment of salt water will, in general, decrease with increasing depth. On the other hand, the displacement flow associated with a landward movement of the salt-water front depends largely on the porosity of the material at the front and should decrease only slowly with depth. Consequently, the effects of the rising sea level must predominate below some critical depth.

The hypothesis that changing sea level may be an important factor in the pattern of salt-water intrusion at depth is not novel. Perlmutter *et al.* (1959) suggested that the rising sea level is a possible explanation of fresh water associated with anomalously low head in a deep aquifer under Long Island, New York. More recently, Kohout *et al.* (1977) hypothesized that a rising sea level may explain the presence of fresh ground water under the continental shelf off the east coast of the United States. In the Netherlands, it has long been recognized that present-day distribution of fresh, brackish and salt ground water is, to a large degree, the result of geologic processes dating back to the beginning of the Pleistocene Epoch (Van Dam, 1976). The essential point is that salt-water intrusion is a slow process and that a static equilibrium between present-day water levels and the present-day intrusion pattern can rarely be assumed. For instance, Frind (1980) showed that for salt-water intrusion in an aquifer-aquitard system, the time required to attain equilibrium may well be of the order of decades or centuries.

It is possible that in very deep aquifers, the rate of intrusion of salt water does not keep pace with the rise in sea level and the recession of the coastline. In such cases, fresh water in the aquifer may become virtually entrapped below salt water at lesser depths and be effectively cut off from significant recharge. This effect offers an alternative explanation for the observation by Carr (1969) that along the south shore of Prince Edward Island, salt water in the shallowest aquifers generally overlies fresh water at greater depths. Carr suggested that this anomalous pattern of salt-water intrusion is due to strong freshwater discharges at depth. High heads observed in some deep piezometers near the shoreline may indicate the existence of such strong deep flows. If fresh water is encountered at depth at any particular location along the coastline, the question of whether it is entrapped water or part of a deep flow system could be answered through direct determination of the heads at that depth. If its salt-water head is negative, i.e., below mean sea level, then the water is probably entrapped.

This discussion of salt-water intrusion in relation to rising sea level may be of importance for ground water developments near the coast. If the fresh water at depth is associated with a deep but active flow system, it can be exploited indefinitely with careful management. If, on the other hand, such fresh water has been trapped by rising sea level and is without significant recharge, then it must be viewed as a nonrenewable resource which may be quickly depleted if intensively developed.

SUMMARY

Observations on the position of the salt water in a layered coastal aquifer have been described and analyzed in terms of the basic theory of salt-water intrusion. The most important results are listed below.

When a coastal aquifer consists of a number of different horizontal beds with widely differing permeabilities, a multiple salt-water intrusion pattern may develop. Separate "wedges" of brackish water will invade each of the most permeable beds. In the present case, three distinct intrusion "wedges" were encountered within the first 40 m below sea level.

Changes of salinity of the water in the aquifers owing to tidal and seasonal fluctuations tend to be small except in the highly permeable shallow aquifers.

Analysis of the yearly mean water levels and salinities indicates that there is a net landward flow of salt water in the deeper York Point aquifers. Part of this flow is undoubtedly due to entrainment of salt water by the seaward freshwater flow. However, the rising sea level in the area must also result in a landward flow of salt water and this effect probably predominates at depth. The rising sea level may also result in deep fresh water becoming entrapped below salt water.

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