Salinity variations as an effect of groundwater seepage through the seabed (Puck Bay, Poland)

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Puck Bay
Salinity variations
Submarine
groundwater discharge

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Abstract

CTD vertical soundings carried out in 1992 and 1993 have revealed near-bottom salinity inversions in the deep part of Puck Bay. The general pattern of water circulation does not appear to explain the observed phenomena. In the authors' opinion it is a submarine groundwater discharge which influences the salinity regime, producing slightly less saline bottom water layers.

1. Introduction

The direct discharge of groundwater is one of the components of the water balance of marine basins. Until now this has been one of the least explored factors of the water circulation in the marine environment and has been estimated on a global scale (Zekster and Loaiciga, 1993). Groundwater discharge causes, for instance, changes in the physical and chemical properties of bottom sediments and sea water. The extent of these changes depends on the intensity of seepage and the differences between the physical and chemical characteristic of the ground- and sea water. The problem of submarine groundwater discharge has only occasionally been taken up in Poland (*e.g.* Dowgiałło and Kozerski, 1975; Kozerski and Sadurski, 1985). More detailed investigations have been carried out by Jankowska and Bolałek (1990) in Puck Bay. They have recorded aspects of groundwater, *e.g.* changes in sediment chemistry and the desalination of pore water. The present paper discusses the results of an investigation into the salinity changes of near-bottom waters caused by groundwater seepage in the SE part of Puck Bay (western part of the Gulf of Gdańsk).

2. Study area

2.1. Hydrological conditions

The study area is the deepest part of Puck Bay and is strongly influenced by the waters of the southern Baltic (Fig. 1). A major feature of its bottom topography is a trough running parallel to the Hel Peninsula. Open

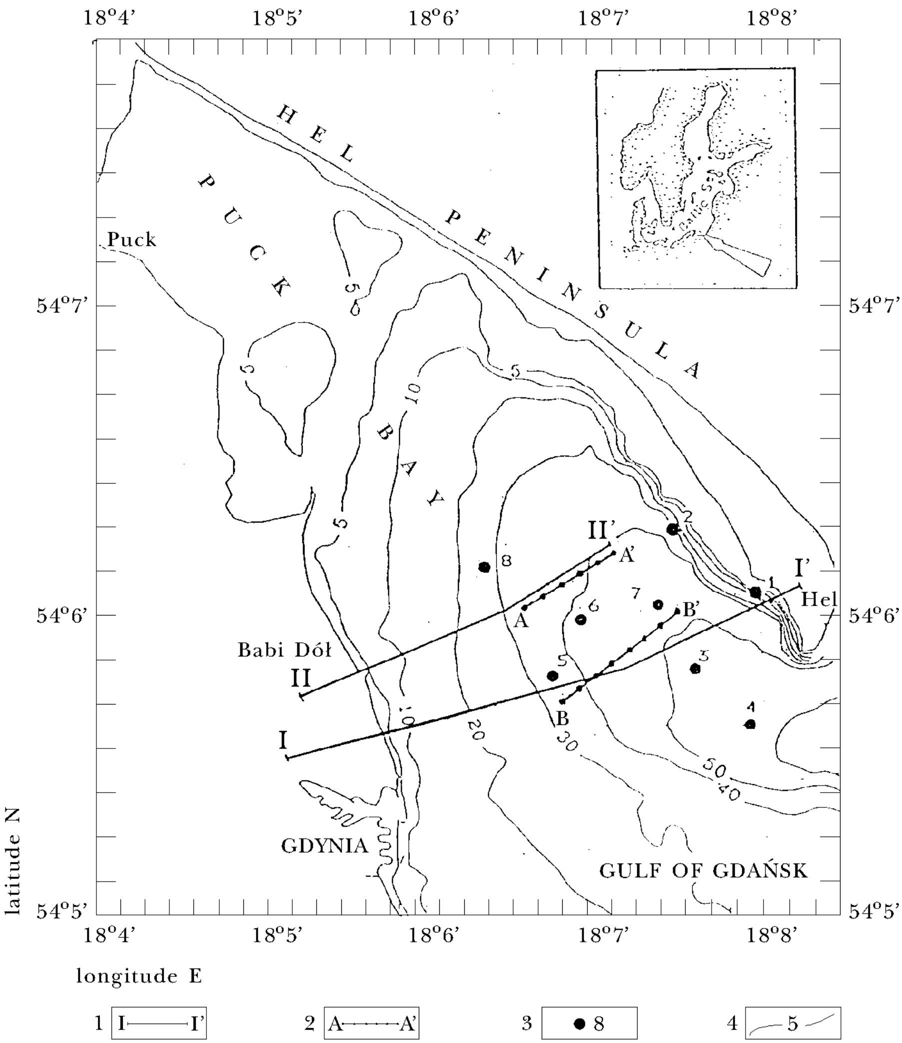


Fig. 1. The area of study. 1 – hydrogeological cross-sections, 2 – hydrologic transects, 3 – measurement station, 4 – isobaths

to the south-east with a maximum depth of over 50 m near the seaward end of the peninsula, the trough becomes gradually shallower in a north-westerly direction. The bottom gradient is steepest (*ca.* 1°–3.7°) in the area adjacent to the peninsula.

The salinity of the study area's waters is the same as that of the surface water in the Gulf of Gdańsk. The salinity, and also the temperature characteristics, display a distinct seasonal variability that is modified spatially by the bay's bathymetry, and by the anemobaric situation over the southern Baltic. The latter leads to intensive water exchange at all depths. When advection from the Gdańsk Basin takes place, water masses move up the trough and temporary salinity-temperature stratification occurs with a near-bottom pycnocline, which exists under conditions of decreasing temperature and increasing salinity.

It is convenient to describe the hydrostatic stability of the water layers in terms of the stability function. On the basis of this criterion, the water body of the deep part of Puck Bay can be divided into three layers: the surface and bottom ones are separated by an intermediate one at approximately 15–20 m, whose stability is poor in spring, summer and autumn, and neutral in winter. In spring and autumn it is the surface layer that is the most stable in the whole water body, in summer it is the bottom layer. In winter the water layers are the least stable. Generally, stability functions at a depth of about 20–30 m are less than zero and increase towards both surface and bottom (Nowacki, 1993).

2.2. The hydrogeological circumstances of the submarine discharge

The hydrogeological investigations carried out in the coastal zone of Puck Bay have revealed that the sea is the main drainage basin of terrestrial aquifers. The sea affects the directions of underground flow and models the regime of the piezometric heads (Bohdziewicz *et al.*, 1986; Dowgiałło and Kozerski, 1975). According to Cooper (1959) the nature, location and spatial extent of the discharge depend on how the hydrogeological parameters of the aquifer vary, its expansion below the sea bottom, the flow intensity, and the mutual relations between the piezometric had of the groundwater and the sea level.

The most important role in the hydrogeology of the study area is played by the upper Cretaceous, the Tertiary and the Quaternary groundwater horizons (Figs. 2, 3), which consist of fresh water with total mineralization from 150 to 300 mg dm^{-3}, occasionally slightly in excess of 400 mg dm^{-3}. The average chloride content ranges from 5 to 20 mg dm^{-3}. The groundwater temperature is stable and approaches the annual average air

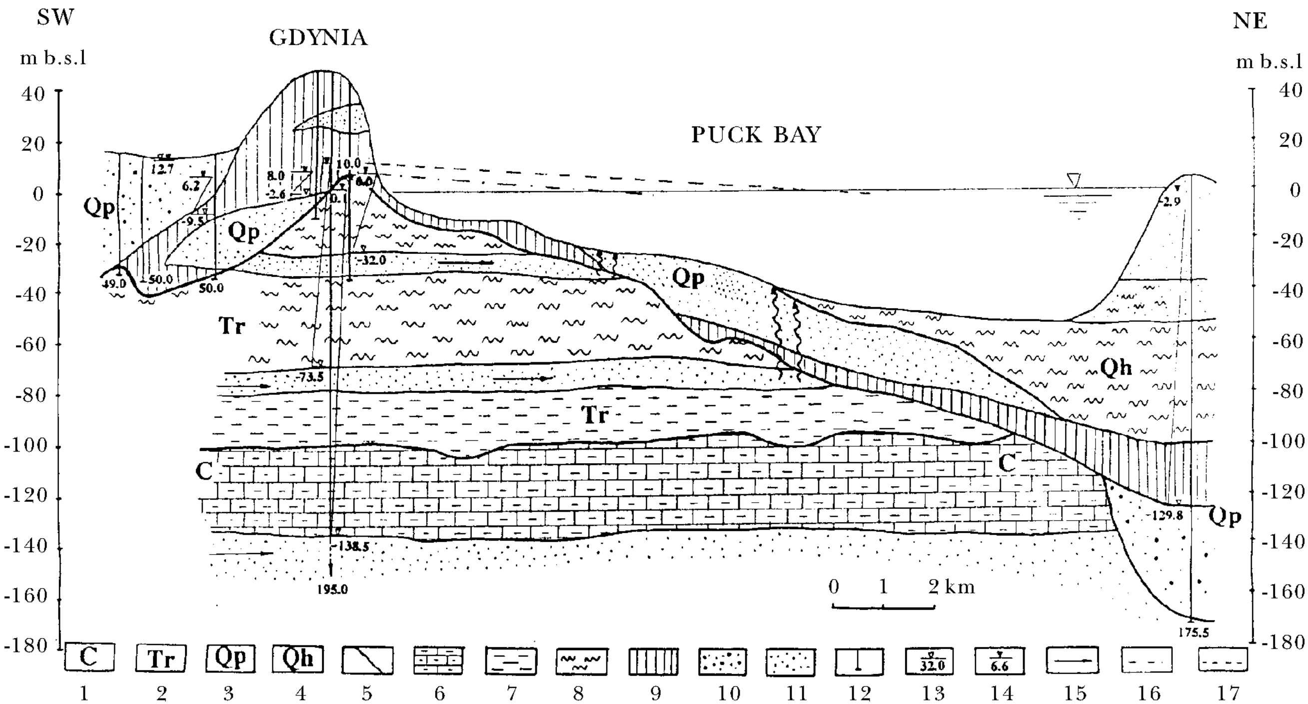


Fig. 2. Hydrogeological cross-section I–I′. 1 – Cretaceous, 2 – Tertiary, 3 – Quaternary-Pleistocene, 4 – Quaternary-Holocene, 5 – stratigraphic limit, 6 – marl, 7 – clay, 8 – silt, 9 – boulder clay, 10 – sand-gravel, 11 – sand, 12 – well, 13 – top of aquifer, 14 – piezometric groundwater level, 15 – direction of groundwater flow, 16 – piezometric level of the Miocene groundwater horizon, 17 – piezometric level of the Oligocene groundwater horizon

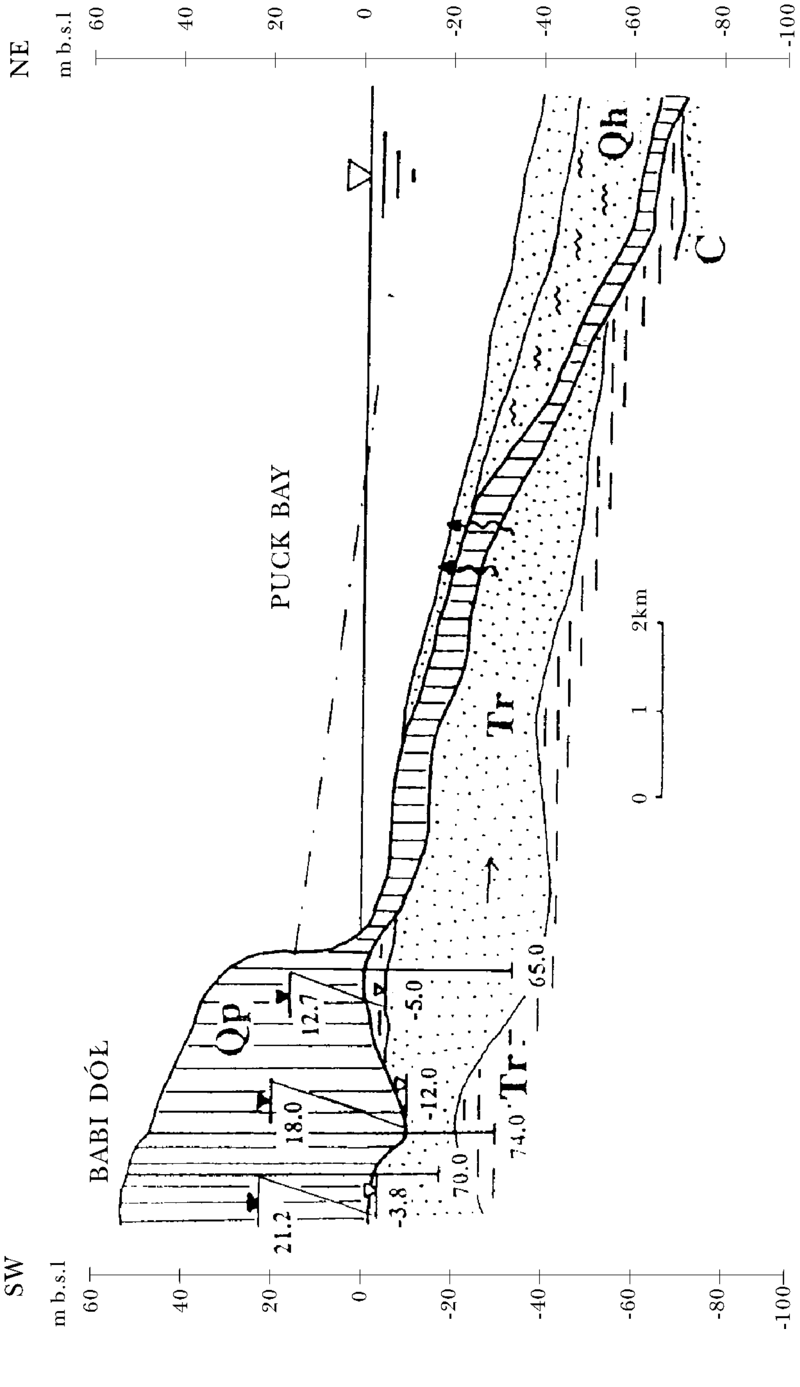


Fig. 3. Hydrogeological cross-section II–II′. Legend as in Fig. 2.

temperature (6°–7°C). Submarine groundwater drainage areas are simultaneously contact zones between fresh groundwater and salt sea waters. The existence of a drainage zone is indicated by changes in the salinity of the sediment-water interface due to large differences in the concentrations of chemical substances dissolved in the waters of both environments. The main component of sea water is the chloride ion. In Puck Bay its highest concentration is slightly more than 5 g dm^{-3} the average being 3.5–4 g^{-3}. These values are 100 times greater than those of the groundwater, which normally range from 5 to 20 mg dm^{-3} and rarely exceed 50 mg dm^{-3}.

The occurrence of groundwater has been quite well mapped on the land surrounding Puck Bay, but direct hydrogeological investigations of groundwater under the sea bottom are lacking. It was 1990 before continuous seismoacoustic profiling was completed (Jankowska *et al.*, 1992). The results of this study enabled the main lithological series to be distinguished and the occurrence of groundwater horizons below the sea bottom to be investigated.

The deepest freshwater horizon is made up of Upper Cretaceous waters belonging to the Coniacian, Santonian and Campanian. The top of the groundwater horizon occurs at *ca.* 140 m b.s.l. in Gdynia and at 95 m b.s.l. at Hel (Fig. 2). The Cretaceous groundwater horizon is generally isolated from the overlying horizons by impermeable or weakly permeable cover 20 to 60 m thick. On the Hel Peninsula the Upper Cretaceous sands are in direct contact with the Pleistocene sandy series and constitute a joint groundwater horizon.

The Upper Cretaceous waters are under a head of pressure. The primary water table is stabilized at *ca.* 3–8.5 m a.s.l. on the western coast of the Bay and at 1–4 m a.s.l. on the Hel Peninsula. Intensive extraction has brought about a cone of exhaustion encompassing the area of Gdynia and the adjacent part of the Bay bottom. A lowering of the water table has also been recorded on the Hel Peninsula. Recently the piezometric table has become stabilized slightly below sea level. It is probable that below the bottom of Puck Bay the piezometric surface has retained its primary character and is situated above sea level. In this case vertical percolation of the Cretaceous waters towards the sea bottom in zones of reduced thickness of impermeable or weakly permeable cover would be possible.

Younger groundwater horizons below the Bay bottom are bound to the Oligocene and Miocene sandy sediments. Two groundwater horizons usually occur: a lower one at 70–80 m b.s.l. and an upper one at 25–40 m b.s.l. Both are dissected by the Tertiary top and their outcrops under the seabed are covered by a relatively thin layer of boulder clays or by Pleistocene sands and marine sandy – silt deposits.

The waters of the Tertiary horizons are subject to variable pressure, depending on the hydrogeological parameters and range from 0.05 to 1.6 MPa. On the western part of the Puck Bay coast, at Gdynia, the Oligocene groundwater horizon stabilizes at 5 to 11 m a.s.l. and attains a maximum stabilization height of 7 m a.s.l. in the shore zone. The outflow of Tertiary waters from the terrestrial surroundings of Puck Bay is seaward. The respective average hydraulic gradients of the Oligocene and Miocene water tables are 0.001 and 0.002.

Because of the high lithological variability of the Tertiary aquifers, it may be expected that the piezometric heads below the seabed are different from those recorded in the terrestrial area. Analysis of hydrodynamic parameters such as piezometric head, height of water table stabilization and water table gradient reveals that the drainage zones of the Oligocene and Miocene waters extend *ca.* 9 and 4–5 km seawards respectively (Figs. 2, 3).

3. Materials and methods

Investigations into the hydrological structure of the water were carried out in 1992 and 1993, in the summer season (June, November). The locations of the measurement stations are shown on the map in Fig. 1. The conductivity (+/–0.1 mS cm^{-1}) and temperature (+/–0.05°C) were recorded for every 0.5 dB of pressure with an automatic CTD probe (Meerestechnik–Elektronik GmbH). These data were used to determine water salinity (+/–0.1 psu) and density in accordance with UNESCO algorithms. The figures in brackets represent the maximum measurement uncertainities. All soundings were carried out in good weather conditions at wind speeds below 5 m s^{-1}.

The lines of the AA′ and BB′ transects were chosen on the basis of hydrological criteria. They were oriented to follow the direction of groundwater flows perpendicularly to the expected zone of discharge. They are also approximately perpendicular to the bathymetrical contours. The other data were collected during monitoring cruises (Fig. 1).

The stability parameter (R_ρ) and effective Rayleigh number (R_{ef}) were calculated as follows (Turner, 1973):

$$R_\rho = \frac{\lambda \Delta T}{(\beta \Delta S)}, \tag{1}$$

$$R_{ef} = \frac{g\,(\Delta z)^3}{v\left[\frac{\lambda \Delta T}{k_t} - \frac{\beta \Delta S}{k_s}\right]}, \tag{2}$$

where

$\lambda = -1/\rho(\delta\rho/\delta T)$,

$\beta = 1/\rho(\delta\rho/\delta S)$,

ρ – density of water,
g – acceleration due to gravity,
k_s – molecular salt diffusivity,
k_t – molecular heat diffusivity,
v – kinematic viscosity,
ΔT, ΔS – the respective differences between temperature and salinity values at the extremities of a water layer of thickness Δz.

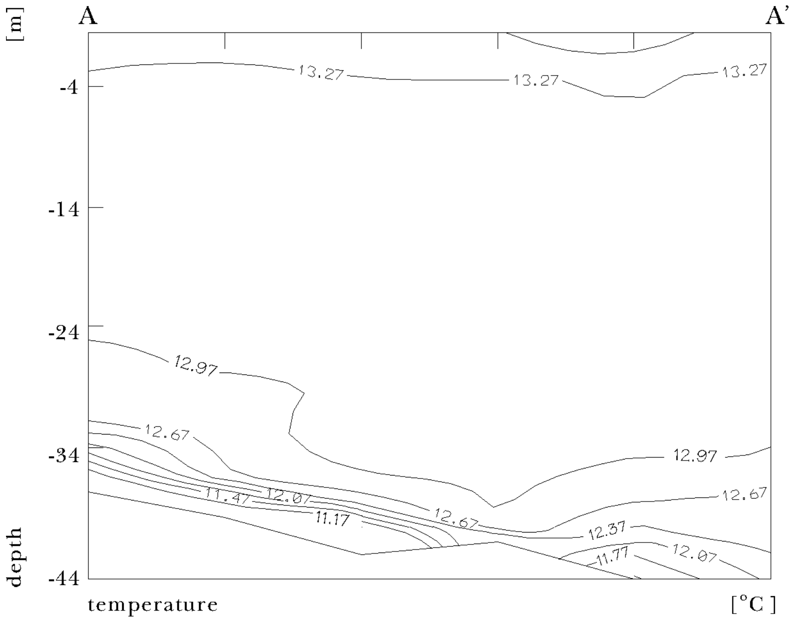
4. Results

A certain number of vertical profiles have revealed a salinity decrease in near-bottom water layers, the thickness of which varies from 4 to 20 m. The inversions can be divided into two types: one occurs when the hydrostatic stability is preserved due to a negative temperature gradient (transects AA′, BB′ and station 8), the other when salinity inversions take the form of pulsations appearing in the water layer below the thermocline (stations 3, 2, 7).

In the first case, the mean salinity of the near-bottom water layer is practically the same as the surface salinity, but is covered with more saline water. This is clearly seen in transect BB′ where the influence of the Gulf of Gdańsk waters is always stronger. The water layers are stable because of the sufficiently high temperature gradient (from –0.33 to –0.7 °C m^{-1}). The stability parameter (eq. 1) ranges from 1.16 to 2.68 in value. It is worth noting that on transect AA′ less saline water is observed in the western, shallower part and disappears at its deeper, eastern end (Fig. 4a), whereas on transect BB′ the situation is reversed, *i.e.* the less saline water is present in its deeper, eastern part (Fig. 4b).

Inversions of the second type (stations 3, 2, 7) occur in the bottom layer with neutral stability (uniform average salinity and temperature distributions) and in the thermocline. They appear on the salinity profiles as pulsations differing more than 0.1 psu from the mean salinity (Fig. 5). These pulsations have been determined with the use of a cosine filter (Fedorov, 1976) as the difference between the real and computed salinities at a given depth. The correlation coefficients between the temperature and salinity pulsations in the layers under consideration range from +0.32 to +0.78, indicating the presence of colder and less saline water intrusions in to the water column. It is probable that some of the observed salinity pulsations are associated with the upward movement of water, since local salinity inversions cause hydrodynamic instabilities with effective Rayleigh (eq. 2) numbers significantly exceeding the second critical number, equal to 50 000 (*e.g.* Druet, 1994).

a


A
A’
[m]
-4
-14
-24
-34
-44
depth
13.27
13.27
13.27
12.97
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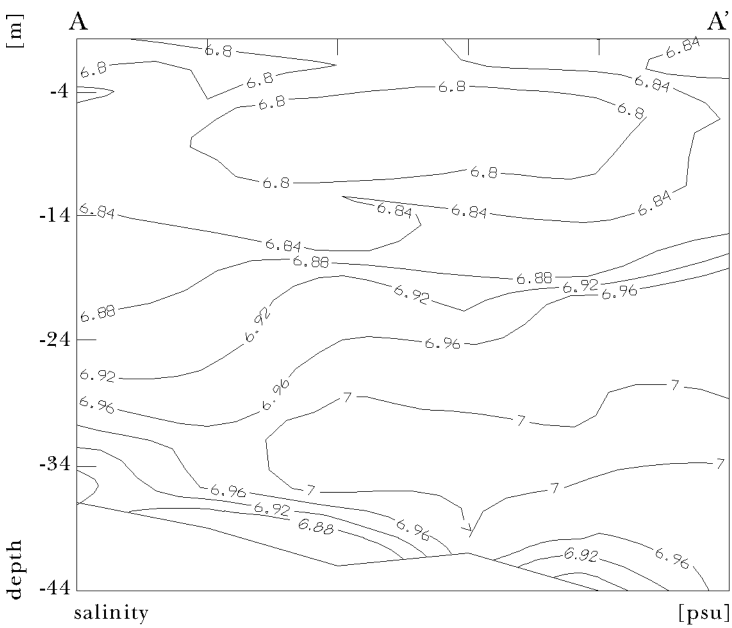
A
A’
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-4
-14
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depth
6.8
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7
salinity
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b

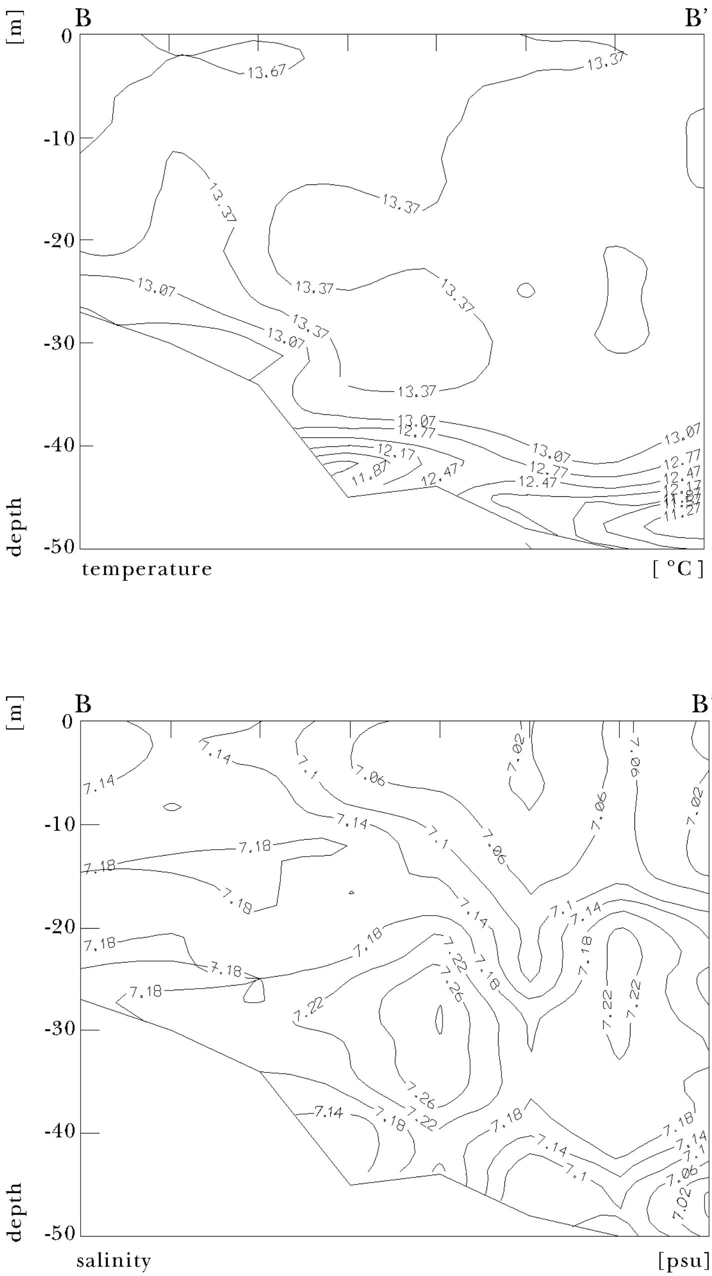

Fig. 4. Salinity and temperature distribution on the AA′ transect (a), on the BB′ transect (b)

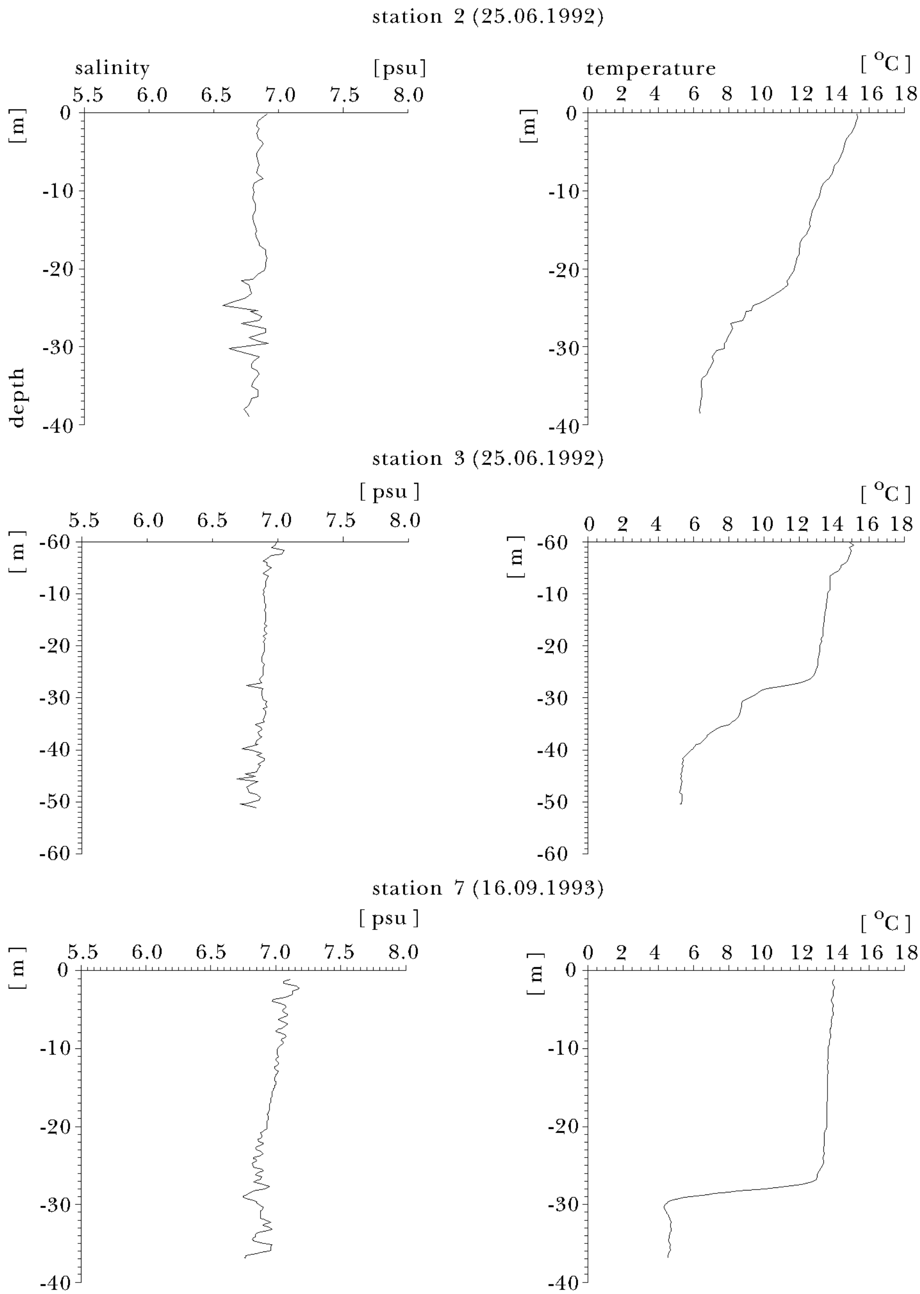

Fig. 5. Vertical salinity and temperature profiles at stations 2, 3 and 7

A salinity decrease of about 0.2 psu in the bottom layer was also recorded at station 1 on 29.06.92 when at the adjacent stations (2, 6, 3, 5, 4) no sa-

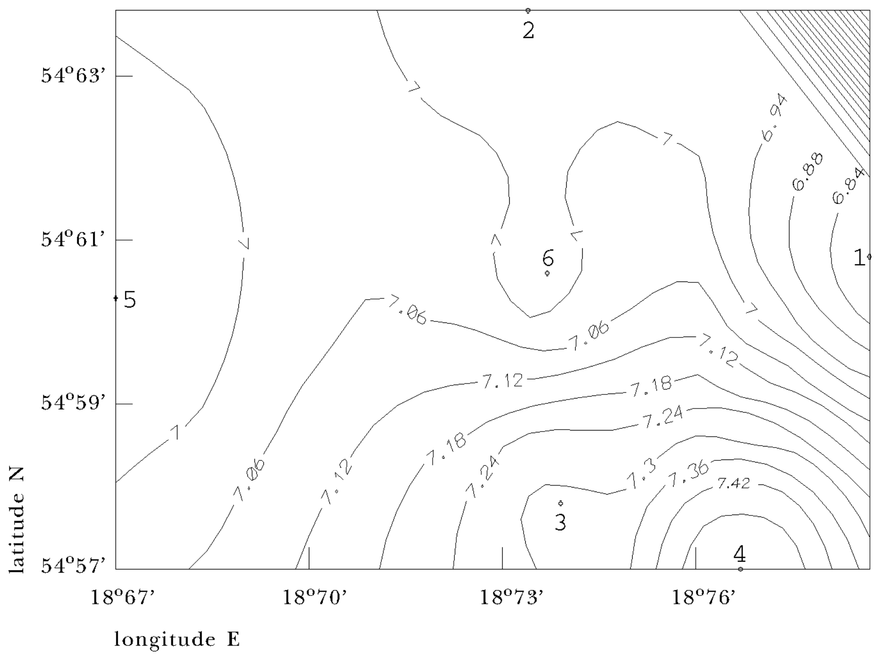

Fig. 6. Distribution of near-bottom salinity in the area around stations 1, 2, 3, 4, 5 and 6 (• – location of the stations)

linity inversions were registered. The distribution of the near-bottom salinity is shown in Fig. 6.

5. Discussion and conclusions

Our general knowledge of the hydrological and dynamic processes occurring in Puck Bay do not explain the observed phenomena. Taking into consideration the wind-induced water exchange in the Puck Bay region salinity distributions different from those recorded on the AA′ and BB′ transects might be expected. These measurements were made three days after a NW gale with wind speeds up to 12 m s^{-1}. Numerical simulation (Jankowski, 1984) has shown that such weather conditions must have caused a compensating bottom inflow of water from the Gulf of Gdańsk to Puck Bay. This should have resulted in a salinity increase in the bottom water layers.

It seems that the only obvious reason for the presence of the low-salinity water is submarine groundwater discharge. Such a concept would also provide an interpretation for the presence of less saline water layers below the pycnocline, as was the case at stations 2, 3, and 7.

The salinity distributions on transects AA′ and BB′ coincide with the locations of bottom zones where underground seepage can take place

(Figs. 2, 3). Thus the less saline water on transect AA′, at depths between 30 and 40 m, originates from the Miocene horizon and on transect BB′ from the Oligocene one. The intensity of discharge at the Puck Bay bottom depends on the permeability and thickness of the strata covering the aquifers, the lithological type of sediments and the hydrostatic equilibrium between fresh and sea water.

It is worth noting that the salinity deficiency recorded in Puck Bay is of the same order as that of a weak discharge occurring in the nearshore zone of seas, (see *e.g.* Johannes and Hearn, 1985).

The results show that recording the salinity variability in bottom water layers can be a useful method for locating sites of groundwater discharge in the sea bottom. For this kind of research it is necessary to use very sensitive devices with a high vertical resolution. Finally, it must be added here that measurements should be carried out under calm weather conditions because strong mixing processes could cause subtle salinity variations to disappear.

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