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Observations of presumable groundwater seepage occurrence in Puck Bay (the Baltic Sea)

by

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Abstract

We report the results of recent field measurements of seawater thermohaline structure and transparency carried out in early summer 2014 in Puck Bay. Near-bottom, less saline waters occurred almost in the entire study area. Their occurrence in the shallow part of Puck Bay was accompanied by an increase in the seawater transparency. The most likely explanation of these observations is a submarine fresh groundwater discharge.

Key words: Puck Bay, field measurements, water physical properties, groundwater seepage

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Puck Bay is a subregion of the Gulf of Gdańsk in the southern Baltic Sea (Fig. 1). Puck Bay and the Gulf of Gdańsk are separated from each other by the Hel Peninsula and are connected with each other in the south. The bay is divided into two parts: a deeper section with an average depth of 20.5 m, called the Outer Puck Bay, and a markedly shallower part with an average depth of 3.1 m, called the Puck Lagoon (Nowacki 1993a).

The two water bodies are separated by an underwater barrier (Rybitwia Sandbar) running from the Rewa Cape to the Hel Peninsula. During the year, some parts of the sandbar can protrude above the water. A passage is situated at each end of Rybitwia Sandbar: Głębinka at the southwestern end and Kuźnica Passage at the northeastern end. Water exchange between these two sections of Puck Bay occurs mainly through these passages, especially through Głębinka Passage (Nowacki 1993b) where the water depth is up to 6 m.

The field measurements were performed on board r/v *Oceanograf 2* from the 23rd to 27th of June 2014 at 5 stations located in the Outer Puck Bay, south of the Głębinka Passage, at one station located in the passage and two stations located in the Puck Lagoon (Fig. 1). Water transparency was estimated using an underwater visibility range of a white disk with a diameter of 0.3 m in the vertical direction (Secchi depth). Vertical profiles of salinity and temperature were measured with the use of an automatic Mini

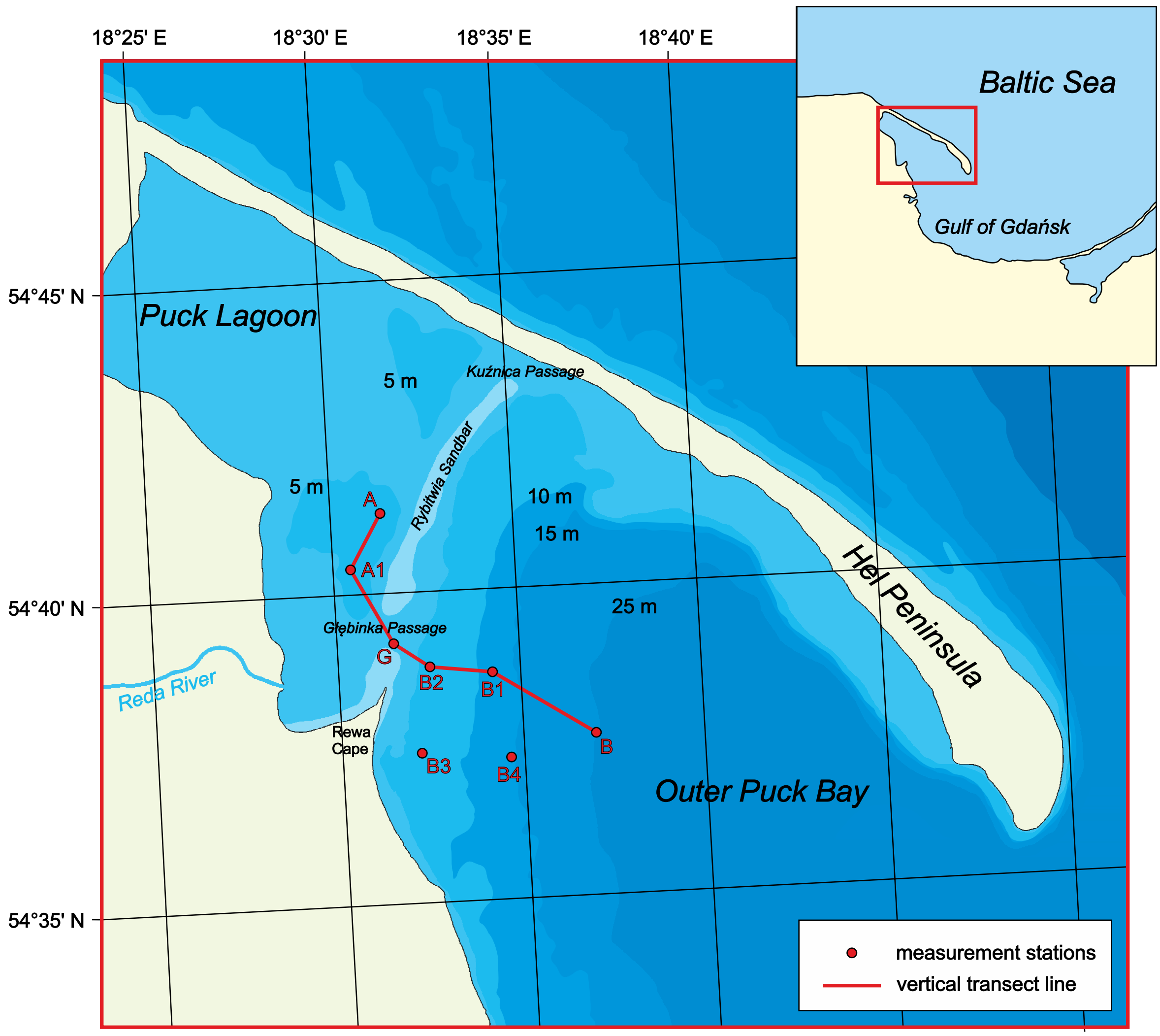

Figure 1

Study area

CTD Valeport probe with a depth interval of 0.5 m. Measurements were taken every day during midday hours (from 10 a.m. to 2 p.m. local time) at all stations, excluding A1, B3, B4 stations on the 23rd of June. As recorded in the ship's log, moderate, occasionally strong, north-west winds prevailed during the four days prior to data collection. Northern winds persisted throughout the entire study period. On the first day, the northwest wind of 7-10 m s^{-1} was observed. The next day, the wind speed was lower (5-9 m s^{-1}) but its direction remained the same. On the third day, the wind speed was still decreasing (4-7 m s^{-1}) and the direction changed to northerly. The last two days were characterized by mild (2-4.5 m s^{-1}) winds from the north and northeast. The decreasing wind speed was followed by a decrease in the choppiness of the sea surface, and the sea state according to the Pedersen scale ranged from 2 to 4° during the first day and from 1 to 2° during the last two days of the study period.

The Secchi depth ranged between 4 and 6 m. The Puck Lagoon was characterized by higher water transparency throughout the study period where the Secchi depth was never below 5 m, and on the 26th and 27th of June, it usually reached the bottom (6 m) (Fig. 2). The same results were observed in the Głębinka Passage during the same days.

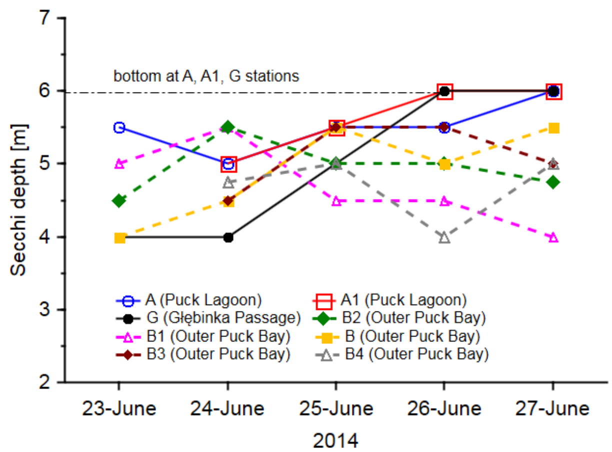

Figure 2

Water transparency estimated by the magnitude of the Secchi disk depth

The weather was improving during the field research, the insolation and the air temperature were increasing. Consequently, the seawater surface temperatures in the study area was also usually increasing (Fig. 3). Due to the faster heating of the water in the shallow areas, the highest temperature of 16.5°C was observed in the Puck Lagoon, whereas in the Outer Puck Bay, the temperature varied from about 14.5 to 15.5°C. At greater depths of the Outer Puck Bay, i.e. more than 20 m, the temperature decreased to about 13°C.

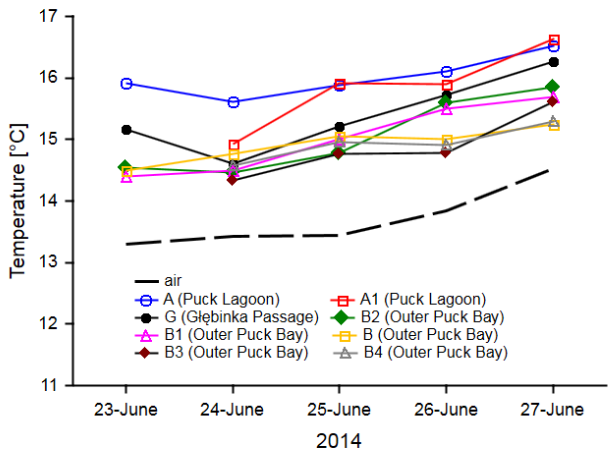

Figure 3

Daily average air temperature (data from the meteorological station located at the end of Hel Peninsula) and mean water temperature in the surface layer (0 -2 m)

The spatial distribution of salinity turned out to be untypical, particularly within the vertical transect from the Puck Lagoon (A, A1 stations) through the Głębinka Passage (G station) to the Outer Puck Bay (B2, B1, B stations) (Fig. 1) where less saline water was observed near the bottom. Such a salinity inversion occurred during the entire study period at the deepest station B (Fig. 4a, c, e, g, i). On the 23rd of June, a local decrease in the salinity (down to 6.97 PSU) as well as in the temperature (down to 13.8°C) was also noted near the bottom (~13 m) at the B1 station located between the Rybitwia Sandbar and the B station (Fig. 4a, b). The cold water (with temperature below 14.4°C) occurred near the bottom from the B1 station toward the entrance of the Głębinka Passage (Fig. 4b). A pool of less saline water (6.8 - 6.96 PSU) was also present in the surface layer of the Głębinka Passage. It was characterized by a lower visibility range (4 m of Secchi depth), therefore it may have drifted from the area by the mouth of the Reda river, which is the largest terrestrial source of

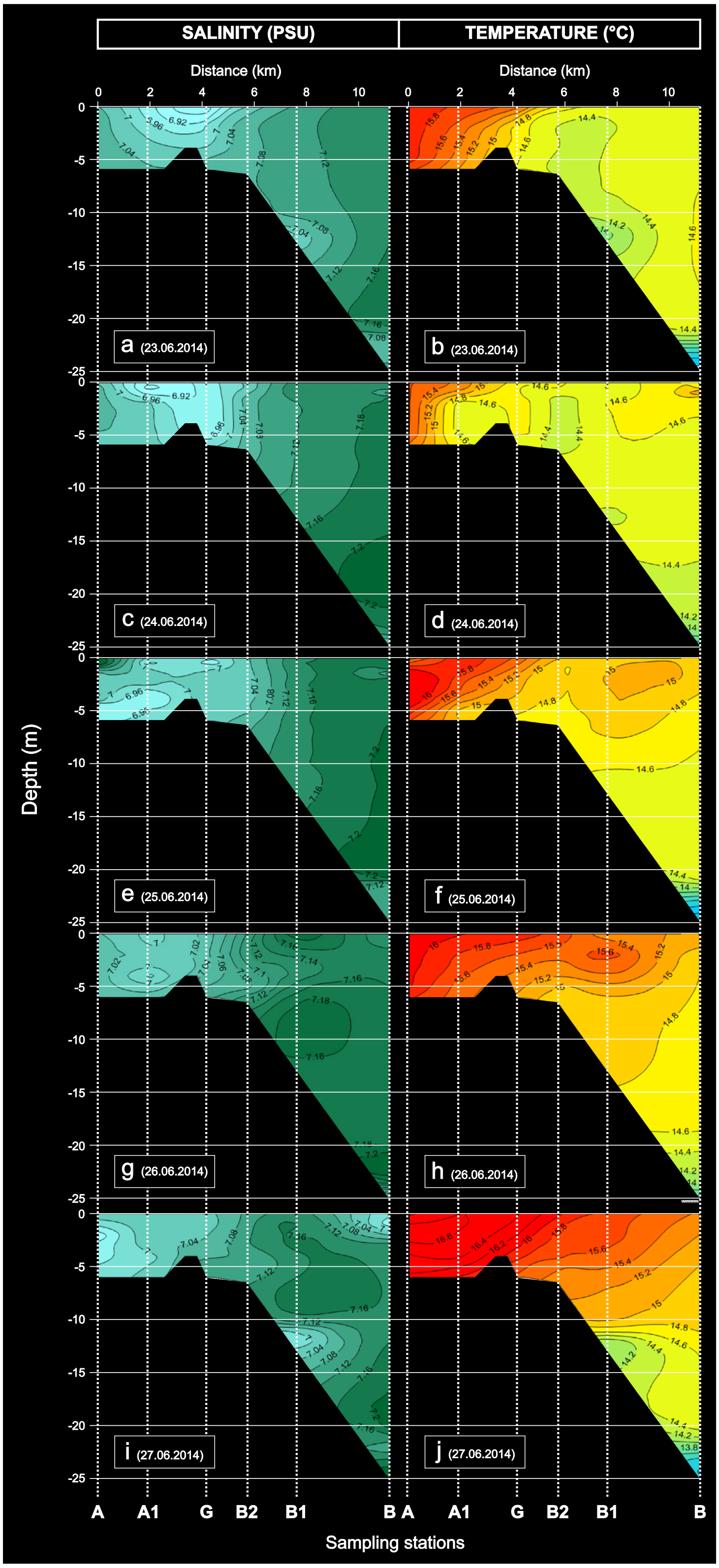

Figure 4

Spatial distributions of water salinity and temperature along the vertical transect connecting the sampling stations located in the Puck Lagoon and the Outer Puck Bay freshwater in the Puck Lagoon (Fig. 1). River waters are characterized by lower transparency (Krężel & Sagan 1987) and after being discharged into the lagoon, they often enter the Głębinka Passage (e.g. Szymczak & Piekarek-Jankowska 2007). On the next day (24th of June), the near-bottom water of lower salinity and temperature was not present at the B1 station (Fig. 4c). The isotherm pattern in the Głębinka Passage and its vicinity indicated that this water was transported to the Puck Lagoon through the passage (Fig. 4d). This explains the surface temperature decrease at the stations B2, G, A and low surface temperature at the A1 station on that day (Fig. 2). The circulation causing the motion of deeper waters toward the surface is characteristic of the upwelling phenomenon (e.g. Lehmann & Myrberg 2008). Hydrological manifestation of upwelling intrusion in the Puck Lagoon induced by winds from the northern sector has been reported previously by Matciak et al. (2011).

On the 25th and 26th of June, less saline (6.92-7 PSU) waters appeared near the bottom in the Puck Lagoon (Fig. 4e, g). Their volume must have been significant because it reduced the salinity within the entire water column. The northern winds caused the water outflow from the Puck Lagoon into the Outer Puck Bay. In consequence, the temperature in the surface water layer down to about 5 m south of the Głębinka Passage increased (Fig. 4f, h). On the 26th of June, a distinct subsurface intrusion of less saline water into the Outer Puck Bay was also formed (Fig. 4g). During these two days, the transparency of waters in the Puck Lagoon and Głębinka Passage increased (Fig. 2). On the 26th of June, the Secchi depth reached the bottom (6 m) at the stations A1 and G. The same result was obtained at the stations A1, G and A during the last day of measurements. On this day, near-bottom, less saline and colder water was noted once again at the B1 station in the Outer Puck Bay (Fig. 4i, j). At the remaining stations located in the Outer Puck Bay (B3 and B4) (Fig. 1), the salinity inversions occurred at the B4 station. The strongest one was observed on the 24th of June when the vertical thermohaline structure was very similar to those observed at the B1 station (Fig. 4a, b; Fig. 4i, j).

In the opinion of the authors, the unusual salinity patterns can be explained by a submarine fresh groundwater discharge. The hydrological structure of the area and the previous studies on salinity anomalies in Puck Bay seem to confirm this point of view (Piekarek-Jankowska 1994). There is no other natural process that could cause the occurrence of the least saline water at the bottom of the water column at a depth of 13 m or more. The occurrence of fresher waters with the highest transparency in the shallow Puck Lagoon could not have resulted from the influence of riverine waters because they contain a significant amount of suspended matter and hence they are turbid. On the other hand, it can be expected that the groundwaters undergo filtration within the aquifer (e.g. Davies-Cooley & Smith 1995) as well as when flowing through the bottom sediments. Therefore they can be more transparent than the waters of Puck Bay.

The groundwater seepage can intensify when the difference between the pressure in the underground aquifer and the pressure of the seawater column increases. It is enhanced by a decrease in the sea level. In Puck Bay, the water level decreases toward north during winds from the northern sector (NW, N, NE) (Nowacki 1993c). Such anemobaric conditions occurred several days before and during the whole study period. It is also worth mentioning that water temperature in the deepest layers at the B station was higher (ca. 13°C) compared to the long-term average of about 11°C (Nowacki 1993d). Higher temperature values within the observed ranges of temperature and salinity cause a decrease in the water density and therefore, in the pressure of the water column (e.g. Dera 1992).

Little is known about the impact of the groundwater discharge on the environment of Puck Bay. Assessment and evaluation of its significance is important because e.g. the Puck Lagoon is unique among Polish coastal waters in terms of biodiversity and the occurrence of underwater meadows (e.g. Opioła & Kruk-Dowgiałło 2009). From the reasons mentioned above, a sufficiently large seepage can lead to an improvement of water transparency, as it probably happened in the Puck Lagoon and the Głębinka Passage on the 26th and 27th of June. It is very interesting that during the growing season, the water clarity in the Puck Lagoon is often better than in the surface waters of the Outer Puck Bay (e.g. Matciak et al. 2011). This is unusual for a shallow, coastal and semi-enclosed reservoir. If the groundwater discharge occurs more frequently, it can be at least partly responsible for such conditions observed in this region.

On the other hand, it is suggested that a submarine groundwater discharge can be an external source of nutrients, organic compounds and metals which are the key factors in the initiation of phytoplankton blooms (e.g. Lapointe at al. 1990). Therefore it can be taken into account in the explanation of the bioluminescent algae blooms in the Puck Lagoon (http://hel.univ.gda.pl/aktu/2012/zatoka_swieci.html). In August 2012, the potentially toxic dinoflagellate *Alexandrium ostenfeldii* was the dominant species whose cysts can be found in the sediments of Puck Lagoon (J. Kobos & N. Hohlfeld, personal communications). The inflow of the potentially nutrient-rich groundwaters can transport these cysts into the seawater where they intensively grow.

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