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Excess seawater salinity in the Puck Lagoon, a shallow part of Puck Bay (southern Baltic Sea)

by

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Abstract

New detailed results on seawater salinity in the shallow part of Puck Bay (Puck Lagoon) obtained during the summer of 2020–2022 are presented. Water with salinity >7.5 $g \cdot kg^{-1}$, even up to 7.7 $g \cdot kg^{-1}$, occupied most of the lagoon area. The water in Puck Lagoon was clearly more saline than the water in the surface layer in the deep part of Puck Bay. A hypothesis is formulated that the observed increase in salinity in the Puck Lagoon was caused by sea surface evaporation when precipitation was distinctly reduced.

Key words: seawater salinity, Puck Lagoon, precipitation deficit, evaporation

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1. Introduction

Seawater salinity is an essential variable describing the state of seawater. Salinity strongly influences seawater density and, therefore, affects dynamical processes and the formation of water masses in the sea and ocean (e.g. Dera, 1992; Massel, 2010). The functioning of different marine ecosystems depends on the ability of fauna and flora to adapt to given salinity conditions (e.g. Smyth & Elliott, 2016). In inland seas and coastal water bodies (gulfs, bays, and lagoons), salinity is closely related to local water balance components such as river runoff, inflows from adjacent seas, precipitation, and evaporation. In the Baltic Sea, which is primarily subjected to river runoff (e.g. Leppäranta & Myrberg, 2009), the mean salinity level is low, but salinity is characterised by large variability at various space and timescales (Lehmann et al., 2022). Changes in water balance components result in changes in the salinity regime.

Recent investigation on hydrological conditions in the Puck Lagoon, a small water body on the southern coast of the Baltic Sea, carried out in the summer of 2020–2022 has revealed higher than expected seawater salinity. The results are presented in this study, and the possible reasons responsible for such a situation are considered.

2. Materials and methods

2.1. Study area

The Puck Lagoon is a shallow, northern part of Puck Bay, with an average depth of 3.1 m (Nowacki, 1993a) (Fig. 1). Puck Bay is the westernmost, semi-enclosed coastal region of the Gulf of Gdańsk in the southern Baltic Sea, separated from the waters of the open sea by the Hel Peninsula and connected to the Gulf of Gdańsk in the south.

The southern part of Puck Bay is markedly deeper, with an average depth of 20.5 m (Nowacki, 1993a). It is called Outer Puck Bay. The shallow and deep sections of Puck Bay are separated by an underwater barrier (Seagull Sandbar), running from the Hel Peninsula in a southwesterly direction and the Rewa Cape at the western coast of the bay (Fig. 1). A passage called Głębinka with a maximum depth of ~6 m is situated between Rewa Cape and Seagull Sandbar. The other shallower Kuźnica Passage, maximum depth ~1.5 m, is situated between the northeastern end of Seagull Sandbar and the Hel Peninsula (Nowacki, 1993a).

The hydrological conditions of Puck Bay are shaped mainly by inflows of marine waters and locally by surface terrestrial waters. Marine waters of the Gulf of Gdańsk flow into Puck Bay from the southeast. Land sources of freshwater, such as streams and a few small rivers, are situated at the western coastline. Most of the freshwater, including the largest river, the Reda, constituting 68% of the total runoff (on average 4.9 m^3 s^{-1}), is discharged into the Puck Lagoon (Cieśliński et al., 2022). In late autumn and winter, the waters of Puck Bay are well mixed, in Outer Puck Bay down to c.a. 30 m. The sea level is high, and Seagull Sandbar is covered by water, which facilitates water exchange between deep and shallow parts of the bay (Nowacki, 1993b). According to archival data, under such conditions, seawater salinity, about 7.6–7.7 g·kg^{-1}, is evenly distributed except for the area close to the river mouths, where it is lower (Nowacki, 1993c). Since spring, river runoff of the Vistula River, the largest river on the southern coast of the Gulf of Gdańsk, salinity in the surface layer of the gulf gradually decreases due to the spreading of riverine waters. The water from the Gulf of Gdańsk also enters Puck Bay, where surface salinity decreases as well, and an annual salinity minimum in Outer Puck Bay is observed in summer, on average c.a. 7.4 g·kg^{-1}. The spreading of water with lower salinity in the bay is stopped at the Seagull Sandbar, which in spring and summer usually protrudes above the water, and thus water exchange between the Outer Puck Bay and the Puck Lagoon can occur mainly through Głębinka and Kuźnica Passages. For this reason, seawater salinity in the lagoon in summer can be slightly higher than in Outer Puck Bay (Nowacki, 1993c).

2.2. Methods

Fieldwork was carried out during cruises of the r/v Oceanograf (University of Gdańsk) on the following dates: 23–24 June 2020, 30 August 2020, 30 June 2021, and 17 August 2022. A regular grid of 23 sampling sites with a 2 km × 2 km mesh, located in the Puck Lagoon, is presented in Fig. 2.

The automatic RBRconcerto CTD (Conductivity-Temperature-Depth) probe, and additionally the CastAway CTD probe on 17 August 2022 were used for vertical profiling of seawater properties. Due to navigational restrictions, measurements could not be performed at sampling sites Z1, Z2 in August 2020 and Z13, Z16 in June 2021. At reference sampling sites located in the Outer Puck Bay (Fig. 2), measurements were conducted using miniCTD Valeport probe. In 2020 and 2021, reference sampling sites were situated mainly near the entrances to the Głębinka and Kuźnica Passages to observe possible effects of water exchange between the two parts

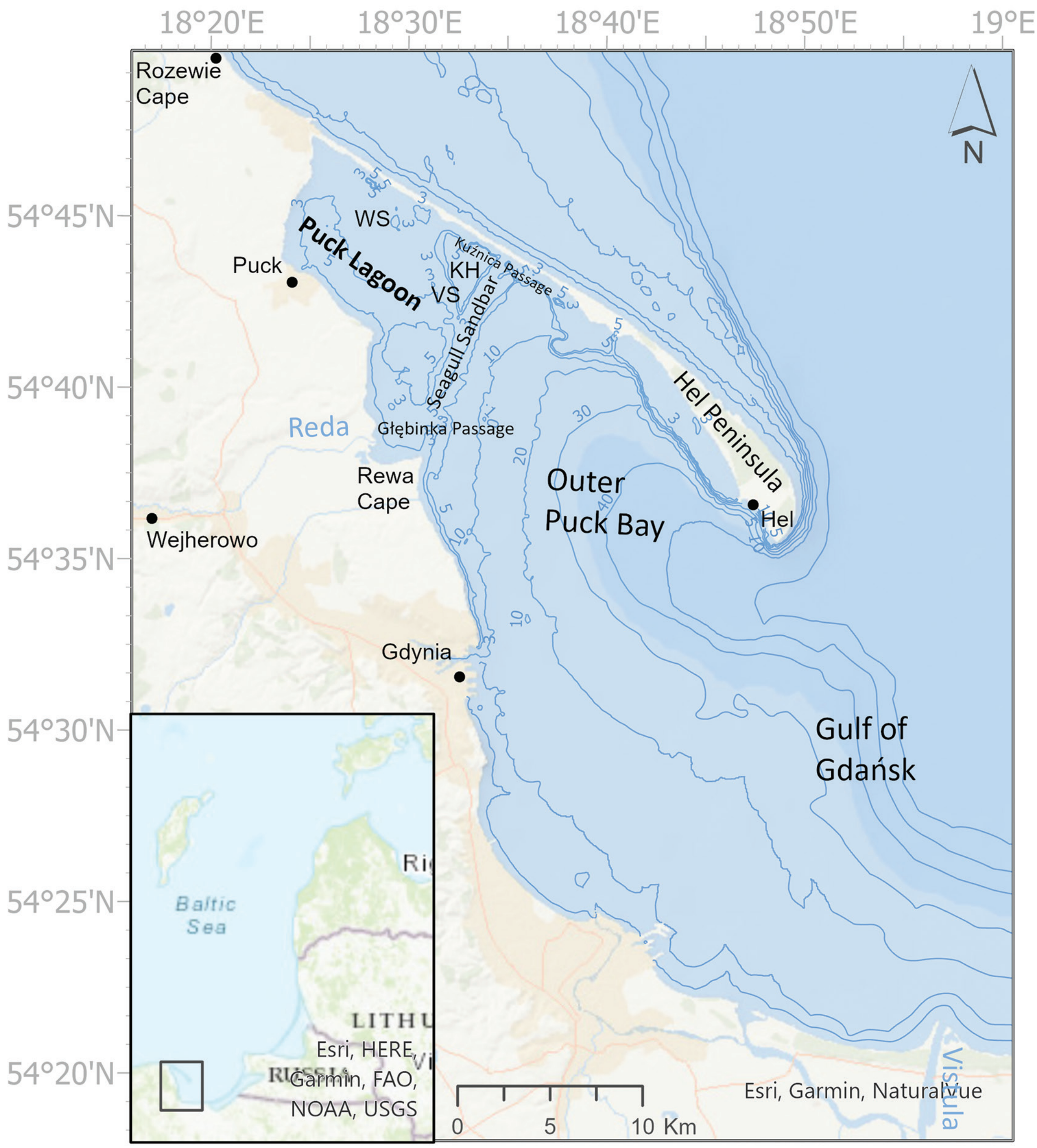

Figure 1

Area of the Puck Bay. The shallow parts are denoted as WS and VS; the deepest part is denoted as KH. KH, Kuźnica Hollow; VS, Virgin Sands; WS, Western Sands.

of the Puck Bay. In August 2022, a total number of 61 sampling sites covered almost the whole area of Outer Puck Bay. The locations of two of them (22, 33), for which measurement results in the water column are depicted in this study, are shown in Fig. 2. These results represent hydrologic conditions in the deep, central part of the Outer Puck Bay as a background for the observations in the Puck Lagoon. The seawater conductivity, temperature, and pressure were recorded from the sea surface to the bottom at a depth increment of c.a. 0.3 m. Based on these parameters, water salinity expressed in practical salinity units (PSU) was determined using a standard algorithm (Fofonoff & Millard Jr, 1983). There was a very good agreement between the salinity values obtained based on RBRconcerto and CastAway CTD probe data. The standard deviation of the salinity differences for surface and over-bottom data equaled 0.007 PSU. The salinity values in [PSU] were then recalculated to obtain absolute salinity expressed in [$g \cdot kg^{-1}$] for

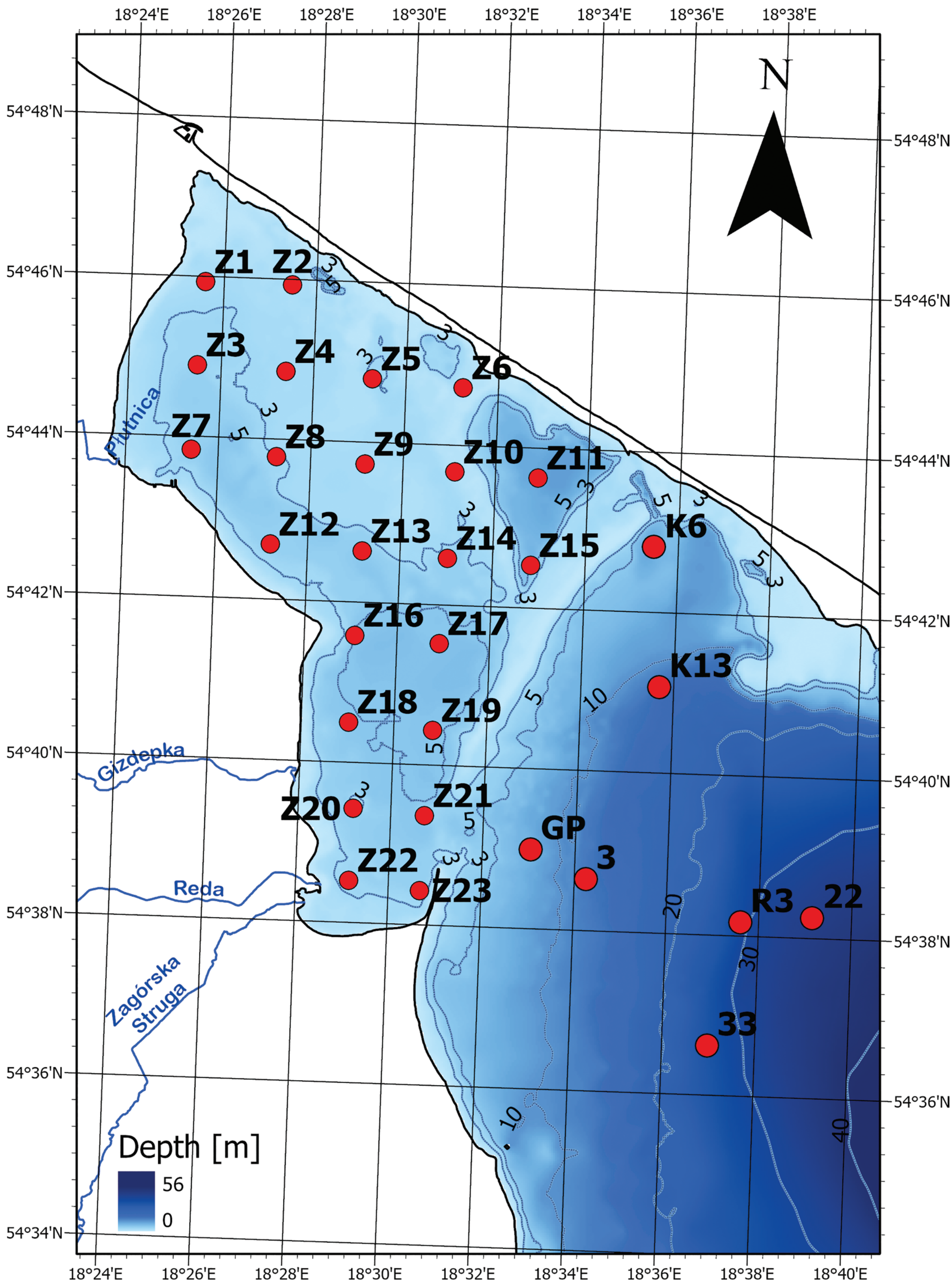

Figure 2

Locations of sampling sites in the Puck Lagoon and Outer Puck Bay during research in the summer of 2020–2022.

the case of Baltic waters (IOC et al., 2010). Previous systematic research on salinity in Puck Lagoon was carried out ~40–50 years ago, when seawater salinity expressed in [‰] was determined using the Mohr–Knudsen method (Klekot, 1980; Nowacki, 1993c). Archival salinity values cited in the text also represent absolute salinity, which was estimated based on old salinity values (IOC et al., 2010).

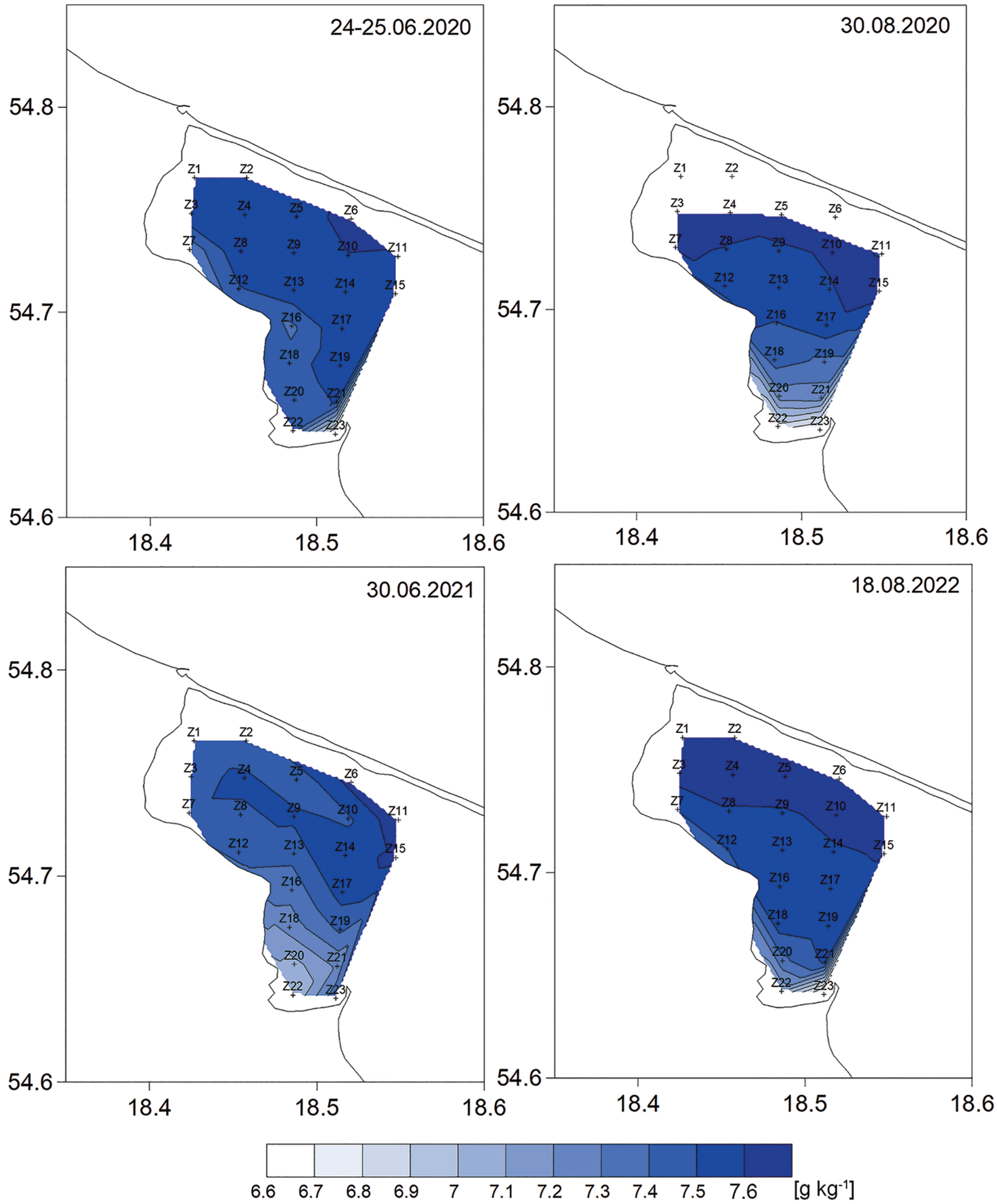

Figure 3

Spatial distributions of surface seawater salinity in the Puck Lagoon in the summer of 2020–2022.

Salinity vertical profiles were smoothed using a moving average of seven data points. Spatial horizontal distributions of seawater salinity in the study area were determined by triangulation with linear interpolation (Golden Software Inc, 2002).

3. Results

Due to the small depths in the Puck Lagoon basin, the water column was well mixed, and salinity mostly did not change from the sea surface to the bottom. Only near the Reda River was there a two-layer stratification, with water of distinctly lower salinity in the upper layer. Water with salinity ≥7.5 g·kg^{-1} usually occupied most of the Puck Lagoon area, that is, its northern, central, eastern, and even southeastern parts in June and August 2020 and August 2022 (Fig. 3). In June 2021, it covered a smaller area of the eastern and middle parts of the lagoon.

Some statistics of surface salinity values is given in Table 1.

The highest salinity values were in the range of ~7.6–7.7 g·kg^{-1}, except in June 2020, when they ranged

Table 1

Basic statistics of the surface seawater salinity [g·kg^{-1}] in the Puck Lagoon.

Date	Number of data	Mean (stand. dev.)	Minimum	Maximum
24–25.06.2020[a]	17	7.584 (0.035)	7.510 (Z21)	7.638 (Z6)
24–25.06.2020[b]	6	7.309 (0.246)	6.761 (Z23)	7.447 (Z12)
30.08.2020[a]	15	7.602 (0.056)	7.505 (Z13)	7.714 (Z3)
30.08.2020[b]	5	7.069 (0.281)	6.664 (Z23)	7.380 (Z16)
30.06.2021[a]	8	7.577 (0.061)	7.503 (Z4)	7.681 (Z11)
30.06.2021[b]	12	7.338 (0.157)	6.998 (Z22)	7.493 (Z10)
17.08.2022[a]	20	7.594 (0.057)	7.505 (Z12)	7.707 (Z2)
17.08.2022[b]	3	7.052 (0.302)	6.652 (Z23)	7.381 (Z20)

[a]For the dataset from sampling sites where salinity ≥7.5 [g·kg^{-1}].
[b]For the dataset from sampling sites where salinity <7.5 [g·kg^{-1}].

within ~7.55–7.6 g·kg^{-1} (Table 1). Generally, they were observed in the zone extending from Kuźnica Hollow, the deepest natural bottom depression in the Puck Lagoon (maximum depth c.a. 10 m), through the shallows of Virgin and Western Sands (c.a. 1 m of minimum depth), to the northern part of Puck Lagoon (Figs 1 and 3). Some salinity values were even higher than those observed in the surface waters of the southern Baltic Sea (Bornholm Basin), for example, ~7.6 g·kg^{-1} in August 2022 (original value of practical salinity used by permission of Cormano Sp. z o. o.). The southern part of the Puck Lagoon is directly influenced by the Reda River. There, the lower surface salinity values were noted. However, the lowest ones, in the range of ~6.6–7.0 g·kg^{-1}, occurred usually near the Rewa Cape (Z23) and once (30.06.2021) at sampling site Z22 located closer to the river mouth (Table 1).

At the reference sampling sites located in the Outer Puck Bay (Fig. 2), seawater surface salinity rarely exceeded c.a. 7.4 g·kg^{-1} (Fig. 4A). On 30 June 2021, it was elevated to c.a. 7.5 g·kg^{-1} at sampling sites K6 and K13 (Fig. 2) located near the Kuźnica Passage (Fig. 4A). High salinity values (~7.55–7.7 g·kg^{-1}), as observed in the Puck Lagoon, were noted below the homogenous surface layer even at the depth of 25–30 m (Fig. 4A). The increase of salinity down in the water column resulted from the advection of saline and cold water into Puck Bay from the Gulf of Gdańsk. The most distinct difference in surface seawater salinity between the two parts of Puck Bay was registered in August 2022 (Fig. 4B). In Outer Puck Bay, salinity ranged from c.a. 7.1 g·kg^{-1} to 7.4 g·kg^{-1}, while surface salinity in the Puck Lagoon was dominated by values in the range of 7.5–7.7 g·kg^{-1}. The salinity decrease in the surface layer of the Outer Puck Bay was caused by the migration of water from the area adjacent to the Vistula River mouth induced by the wind from the eastern sector before the fieldwork started.

4. Discussion

Previous studies on the Puck Bay hydrology did not report such a noticeable difference in salinity between both parts of the bay during summer. In 1969–1972, Klekot (1980) noted that in June and August, over-bottom water salinity in the Puck Lagoon could be as high as c.a. 8 g·kg^{-1}, which is even higher than the values reported in this work. It was suggested that under northern and western winds, surface water in the bay is pushed to the south and east, respectively, and compensating sea current from the Gulf of Gdańsk originating at greater depths and carrying more saline water gets into the Puck Lagoon. However, there were no data shown from the Outer Puck Bay or the Gulf of Gdańsk to support this idea. There are also no signs of such circulation in the vertical salinity profiles from the sampling sites south of Seagull Sandbar (Fig. 4A). A large number of data on salinity in Puck Bay were collected at the Institute of Oceanography of the University of Gdańsk during monitoring of the Gulf of Gdańsk between 1972 and 1990 (Nowacki, 1993c). Based on this material, it was found that in the summer, the mean surface salinity spatial distribution in Puck Bay revealed a plume of water characterised by salinity increase up to 7.5 g·kg^{-1} in the northern part of the Puck Lagoon (Nowacki, 1993c). This picture indicates the occurrence of water with higher salinity in the lagoon, but it is strongly different from the salinity surface distributions presented in Fig. 3.

There is also a simulation approach to the hydrology of Puck Bay developed within the WaterPUCK project (https://waterpuck.pl). The numerical model of seawater salt transport in the Puck Bay yields a reasonable approximation of the salinity field in the water body of the Outer Puck Bay, and discrepancies were noted in shallow waters, for example, near the Głębinka Passage (Dybowski

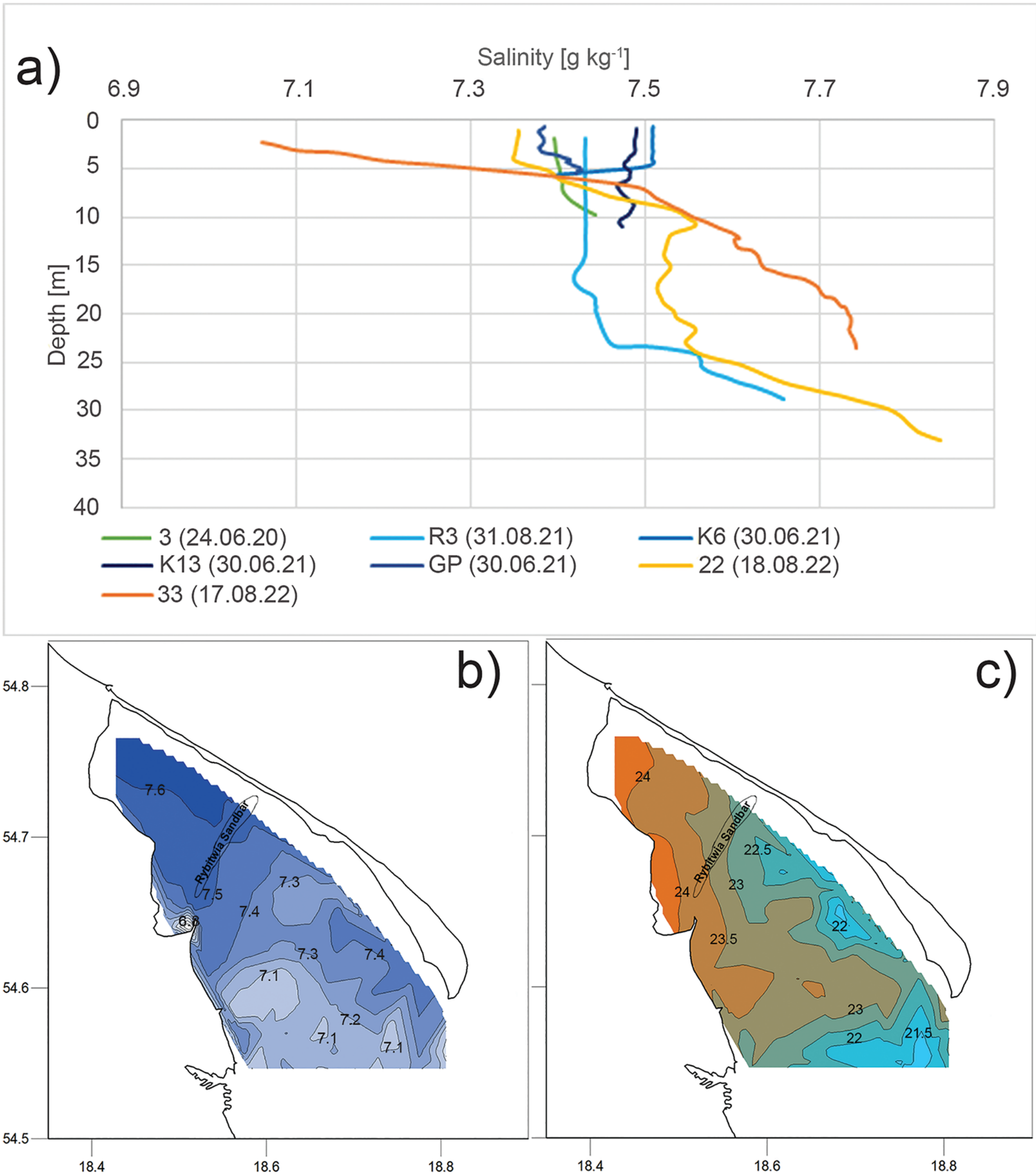

Figure 4

Vertical salinity variability at reference sampling sites in the Outer Puck Bay in the summer of 2020–22 (A). Surface seawater salinity [g·kg^{-1}] distribution in the Puck Bay on 17–19 August 2022 (B). Surface seawater temperature [°C] distribution in the Puck Bay on 17–19 August 2022 (C).

et al., 2019). However, the model results were not tested in the Puck Lagoon area. Visual inspection of the surface salinity distributions in the lagoon, presented at the WaterPUCK website for the days when the measurements were performed, revealed that modelled values strongly underestimate the real ones.

Precipitation and evaporation from the sea surface are basic components of the water budget. Climatological mean world ocean surface salinity and evaporation minus precipitation flux are highly correlated, and salinity changes over time, in significant part, can result from the alteration to evaporation and precipitation (e.g. Durack, 2015). Such a dependency is also observed during a year at some coastal seas and reservoirs (e.g. Liblik et al., 2024; Ratnawati et al., 2018). Precipitation over the sea results in the seawater salinity decrease. Precipitation over the land also affects seawater salinity because excess rainwater is discharged into the sea by rivers. The monthly sums on precipitation in the region of the Puck Bay were taken from meteorological coastal stations located at Rozewie Cape, in the town of Gdynia, and Hel (https://danepubliczne.imgw.pl/pl/datastore) (Fig. 1 and Table 2).

Generally, there was a distinct precipitation deficit in the summer of 2020–2022. Only in a few months was precipitation approximately similar to or even higher at certain stations than the long-run averages, as, for example, in June 2020 or in August 2021 (Table 2). Reduced precipitation was accompanied by a decrease in Reda River discharge. The monthly means of the river water flow at Wejherowo, ~10 km to the west from the river mouth (https://danepubliczne.imgw.pl/pl/datastore), were on average about 15% smaller compared to multiyear monthly means (Cieśliński et al., 2022). The occurrence of dry months (August 2020, June 2021, and August 2022) and higher salinity level, up to c.a. 7.7 $g \cdot kg^{-1}$, coincided, whereas, in June 2020, salinity was lower, up to c.a. 7.6 $g \cdot kg^{-1}$.

While precipitation and river discharge cause the dilution of seawater, evaporation acts in the opposite direction. Evaporation is more intensive when water is warmer (e.g. Eaglson, 1970). Due to shallow depth, the water in Puck Lagoon warms quickly. Heat transfer from the air to the water in this area can be efficient since there is usually no strong water dynamics (e.g. Dybowski et al., 2019). Therefore, in summer, the water temperature in the Puck Lagoon is higher than in the surface layer of the Outer Puck Bay (Nowacki, 1993c, Fig. 4C). Additionally, evaporation could also be enhanced in connection with global warming. It is considered that this process is responsible for the long-term growth of seawater temperature reported for the eastern part of Polish coastal waters, for example, at Hel (Świątek & Girjatowicz, 2019). Another factor intensifying evaporation in a shallow basin is increased roughness of its surface in comparison to deep water under the same wind conditions (e.g. Panin et al., 2006). According to the multiyear approach, evaporation exceeds precipitation in Puck Bay on average by ~10 $mm \cdot m^{-2}$ in summer months (Chlost & Cieśliński, 2022). In the light of precipitation data presented in Table 2, the advantage of evaporation had to be significantly larger than 10 $mm \cdot m^{-2}$. Therefore, evaporation seems to be the factor that should be considered responsible for the increase in seawater salinity. It could be expected that high salinity levels in Puck Lagoon are related to the occurrence of dry years in the Puck Bay region. According to Chlost and Cieśliński (2022), in the 1981–2015 period, dry years occurred irregularly, sometimes one after another. The seawater salinity increase in the Puck Lagoon was similar to that observed in Väike Strait, a shallow strait in the eastern Baltic Sea, where in June and August, evaporation caused the salinity to be in the range of c.a. 7.6–8 $g \cdot kg^{-1}$ (Liblik et al., 2024).

In summer, when the sea level is low and there are no severe windstorms, water exchange between the two parts of Puck Bay is hampered because of the presence of Seagull Sandbar (Nowacki, 1993b). In the absence of strong seawater flows through the passages, Puck Lagoon and Outer Puck Bay can be well isolated from each other and then the difference in seawater salinity becomes more pronounced. Such situations likely happened on 30 August 2020 and 17 August 2022, when salinity spatial distributions in the lagoon displayed a pattern with dominance of more saline water (Fig. 3). However, even when sea level is low, water exchange through the passages can be intensive, leading to distinct changes in salinity distribution in the lagoon. Probably, such an effect was observed at the end of July 2021, when the most saline water occurred in the eastern part of the lagoon at the entrance of the Kuźnica Passage, and increased salinity was also noted on the other side

Table 2

Monthly precipitation sums [$mm \cdot m^{-2}$] in the region of Puck Bay in the summer of 2020–2022 and the multiyear (2008–2024) average values (https://danepubliczne.imgw.pl/pl/datastore). Precipitation values in the months when seawater salinity measurements took place are in bold.

	June			July			August		
	Hel	Gdynia	Rozewie Cape	Hel	Gdynia	Rozewie Cape	Hel	Gdynia	Rozewie Cape
2020	**45.7**	**75.8**	**40.5**	35.6	27.9	65.8	**34.5**	**33.7**	**39.2**
2021	**17**	**7.6**	**5.5**	44.4	48.1	42.8	74.3	79.2	107.6
2022	35	24	10.5	84.2	36.5	66.8	**26.8**	**56.6**	**56.5**
Average (2008–2024)	49.9	40.5	43.1	90.0	67.3	80.8	62.1	46.0	72.3

of the passage in the Outer Puck (Figs. 3 and 4A). It seems that there was water outflow from the lagoon through the Kuźnica Passage. At the same time, there was an inflow of less saline surface water from Outer Puck Bay to the lagoon through the Głębinka Passage located at the other end of Seagull Sandbar. This inflow, together with freshened water near the Reda River mouth, was directed to the north, causing salinity decrease in the lagoon (Fig. 3). In this case, despite very low precipitation (Table 2), the impact of evaporation influence on seawater salinity was disturbed in a large part of the lagoon area by enhanced water circulation.

To sum up, it is suggested that the occurrence of seawater with increased salinity in the summer of 2020–2022 in Puck Lagoon mainly resulted from evaporation. The coastal shallow parts of the sea isolated to some extent from the open waters are particularly sensitive to changes in water balance components. Confirmation of this hypothesis requires further research combining salinity records and spatially expanded meteorological observations in the region of the Puck Lagoon.

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