

Spreading of brine in the Puck Bay in view of in-situ measurements

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ABSTRACT

Since autumn of 2010 in the north-eastern part of Poland underground gas stores are under construction by diluting salt deposits. A by-product of the technology applied is brine, which is discharged into the coastal waters of the Puck Bay (south Baltic Sea). In the pre-investment study a theoretical analysis of the mixing conditions in the near-field and far-field of the proposed installation was conducted. An extensive monitoring programme carried out since 2010 shows a good mixing of brine with the surrounding waters. Excess salinity due to the continuous discharge of brine estimated using data measured in situ is generally lower than permitted, i.e. not exceeding 0.5 psu in the near-field of installation.

INTRODUCTION

Increasing demands for gas storage capacity encouraged Polish Gas and Oil Company (PGNiG) to make use of salt deposits located in the north-eastern part of Poland, in the area bordering on the Puck Bay (the inner part of the Gulf of Gdańsk, South Baltic Sea), to create underground gas stores. A complex of 10 chambers (total volume of $250 \times 10^6 \text{ m}^3$) was designed for construction in Kosakowo, near Gdynia. Owing to local geological conditions, the chambers are created at a depth of 800-1600 m. The construction site (GSS, Figure 1) is located about 4 km away from the Baltic Sea coast. The drilling of boreholes and diluting of salt rock was proposed as a method of creating the chambers. Purified water from the treatment plant located in the vicinity (Dębogórze WWTP) is used for dilution purposes. For ecological reasons, the total volume of brine is limited to $300 \text{ m}^3/\text{h}$ while its saturation cannot exceed 250 kg/m^3 . The aim of this paper is to present results from the monitoring programme of brine spreading in the Puck Bay carried out in the years 2010-2017, in the context of theoretical analysis carried out in the pre-investment study.

THE STUDY SITE AND BRINE DISCHARGE SYSTEM

The Gulf of Gdańsk, situated in the south-eastern part of the Baltic Sea, is the area limited by the imaginary line between the Cape of Rozewie and the Cape of Taran (Figure 1). The Puck Bay is a shallow western sub-region of the Gulf of Gdańsk separated from the open sea by the Hel Peninsula. In the middle of the Hel Peninsula there is a shallow sandbank (called Rybitwia Mielizna) which divides the Puck Bay into two parts differing in circulation patterns: the eastern part, called the Outer Puck Bay (av. depth $\sim 20.5 \text{ m}$), and the western part, called the Puck Lagoon (av. depth $\sim 3 \text{ m}$). Currents in the region are generated mainly by wind and the accompanying water level variations in time and space. In addition, circulation in the Puck Lagoon is influenced by water exchange with the eastern part of the bay. Circulation patterns were described by Nowacki (1993) on the basis of occasional field observations of currents. It is quite well documented that water circulation patterns in the Puck Bay depend on the wind direction. The direction of surface currents is usually in accordance with the wind direction. The direction of bottom currents is frequently in

accordance with surface currents, although in the south-eastern part of the Outer Puck Bay the opposite current direction can be observed. Scarce field measurements of the currents are insufficient to present a detailed picture of flow patterns that are generated by spatially and temporarily varying wind conditions in the region.

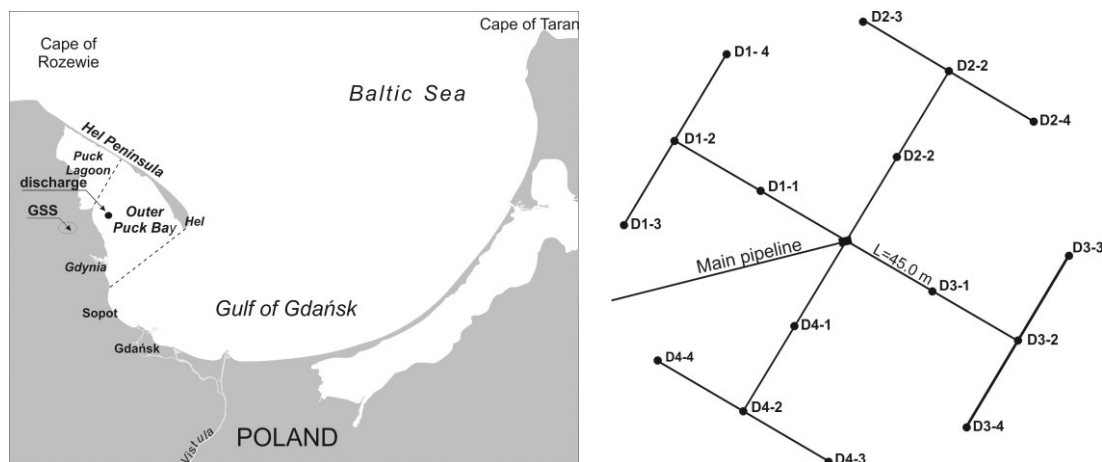


Figure 1. General view on the Gulf of Gdańsk, including the locations of the gas storage system (GSS) and the discharge system (left), and a general scheme of discharge system (right).

Water salinity in the Puck Bay is determined by interactions between marine and fresh waters. In the Outer Puck Bay, salinity is closely related to the inflow of more saline water from the Gdańsk Basin, predominantly through the bottom layer. In addition, the surface layer is modified by fresh water from the Vistula River. In the Puck Lagoon, salinity depends mainly on the intensity of water exchange with the Outer Puck Bay. The influence of small rivers is limited to their outlets.

The discharge system is located approx. 2300 m off-shore. It consists of 16 heads, each with 3 nozzles of 0.009 m diameter, distributed every 120° of circumference. The installation covers the area of 180x180 meters (Figure 1). Based on the pre-investment (Robakiewicz 2009) study brine is discharged 3 meters above the bottom at an angle of 45° to the ambient water. This system was designed to limit excess salinity to 0.5 psu in the near-field of installation.

THE MONITORING PROGRAMME

Execution of the monitoring programme was divided into two steps:

- **early-stage** (2010 – 2012), conducted to investigate the mixing of brine discharged into the coastal waters of the Puck Bay by a system of diffusers, and thus to verify theoretical assumptions made in the pre-investment study (Robakiewicz 2014, 2016).
- **basic** (2013 -), conducted to control the mixing of brine in the nearfield of discharge installation.

The analysis of the influence of brine discharge on the surrounding environment requires some general knowledge of hydrodynamic conditions in the region where the installation is located. To acquire such knowledge, in the early-stage of the monitoring continuous measurements of salinity, temperature, and water currents were carried out in two locations,

A and B (Figure 2), situated on the eastern and western sides of the installation. The measurements covered three periods, 13 October – 26 November 2010; 12 July – 26 August 2011; and 22 May – 9 August 2012, which represented three stages of brine discharge (early, intermediate, target) characterized by different brine saturation and density. Current meters equipped with conductivity and temperature sensors were installed 1 meter above the bottom. Sample results for those are presented in Figure 3. Water currents in the region are generated by wind. The measured flow velocity at a depth of 1 meter above the bottom was low, hardly ever exceeding 0.1 m/s. It is characteristic that the predominant flow directions were to the north and south, which resulted from the local bathymetry and configuration of the coastline. In the autumn of 2010 (the early stage), when brine was discharged for only a few hours a day, brine saturation was relatively low. At that time, the values of salinity in locations A and B were very similar, differing at most by 0.1 psu. In the summer of 2011, the amount of brine increased to 250 m³/h, and its saturation to 225 kg/m³. During periods of weak dynamics, salinity differences between the two gauges did not exceed 0.25 psu. In the summer of 2012, discharged brine reached the maximum permissible parameters (total discharge – 300 m³/h, saturation – 250 kg/m³). Under such conditions, the maximum salinity differences between the two gauges occasionally reached 0.35 psu. The variation in salinity observed over time represents not only natural salinity changes in the region, but also anthropogenic influence. On the basis of the data collected, natural variability can be estimated as 6.6-6.8 psu in the autumn of 2010, 6.6-7.0 psu in the summer of 2011, and 7.3-7.8 psu in the summer of 2012. In-situ measurements conducted in the years 2010-2012 confirmed earlier observations that a two-directional flow dominates in this specific part of the Outer Puck Bay. They also showed that under weak wind conditions, the local water currents were low, although at no time were they completely absent.

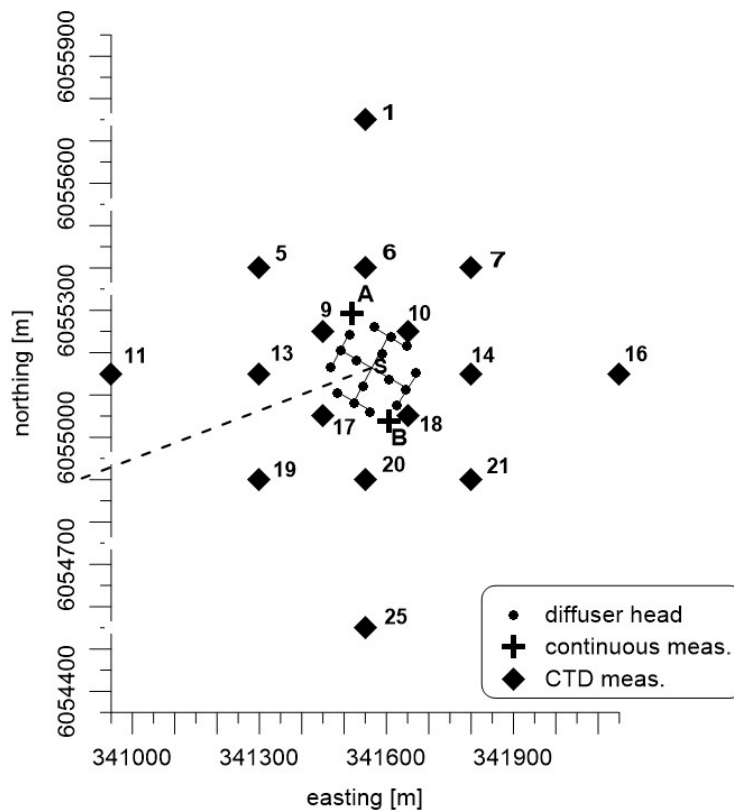


Figure 2. Location of points of the monitoring programme.

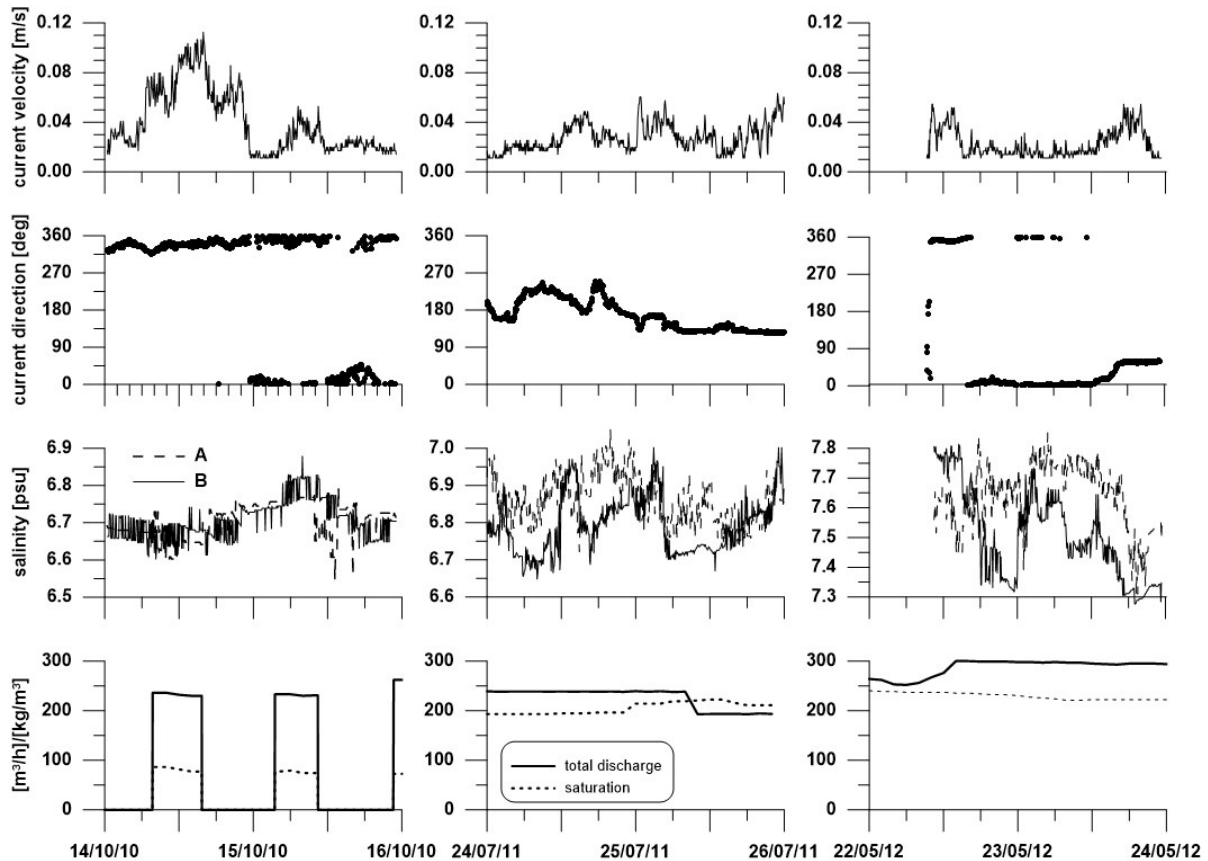


Figure 3. Continuous measurements in the early (left), intermediate (center) and target (right) stages of brine discharge – exemplary results.

The in-situ measurements of the spatial distribution of salinity in the nearfield of the installation started in October 2010. Up till now 42 series of CTD measurements were executed; in most cases they covered 17 verticals (Figure 2). To illustrate spreading of brine in the nearfield of installation two exemplary results, from the early (26.08.2011) and basic (23.10.2017) monitoring programme, are presented. Figure 4 shows spatial distributions of salinity in the bottom layer, and vertical profiles of salinity in chosen locations (S, 9, 10, 17, 18 – see Figure 2). It is very characteristic that in both cases salinity in the upper part of the water column is uniform (26.08.2011 – approx. 7.05 psu; 23.10.2017 – approx. 7.55 psu). Differences in salinity distribution in both cases are closely associated with wind conditions preceding the in-situ measurements, and natural salinity variability in the Gulf of Gdańsk. The first in-situ measurement (26.08.2011) was executed after a three day period of a very gentle wind (av. velocity - 2.5 m/s; predominant direction – SE), while in the second case (23.10.2017) more severe conditions were present (av. velocity - 4.7 m/s, predominant direction – S). In a consequence, in the second case local currents were higher and assymetric salinity pattern in the vicinity of installation can be observed. Differences in mixing conditions resulted in substantial differences in vertical structure of salinity in the chosen dates (see Figure 4 – bottom).

To confirm good mixing conditions of a single jet of brine with the ambient water detailed CTD measurements in the vicinity of a single head (D1-1, Figure 1) were carried out on 26 August 2011. They covered 71 verticals in an area of 17x17 meters (Figure 5 left). The position of each vertical was registered by a GPS gauge. During in-situ measurements, brine

saturated to 237.07 kg/m^3 was discharged through the D1 arm at a rate of $61.1\text{-}61.4 \text{ m}^3/\text{h}$, which means that the initial velocity at the nozzle was $22.20\text{-}22.45 \text{ m/s}$ (Robakiewicz 2016). On the basis of the CTD data collected, it is possible to determine the spatial distribution of the highest salinity values in measured verticals (Figure 5 left). In this distribution, three lines of salinity increase can be distinguished, tracing the three jets ejected from the D1-1 head. The above-mentioned distribution was used to select verticals for the AA cross-section through a single jet (Figure 5). The comparison of the estimated, theoretical shape of a single jet with its actual shape measured on 26 August 2011, shows good agreement in terms of the terminal rise height. The horizontal distance from the source of the jet to its outer boundary at the bottom appears to be underestimated, which can be related to the fact that a gentle water current ($\sim 0.04 \text{ m/s}$) was observed during the in-situ measurements.

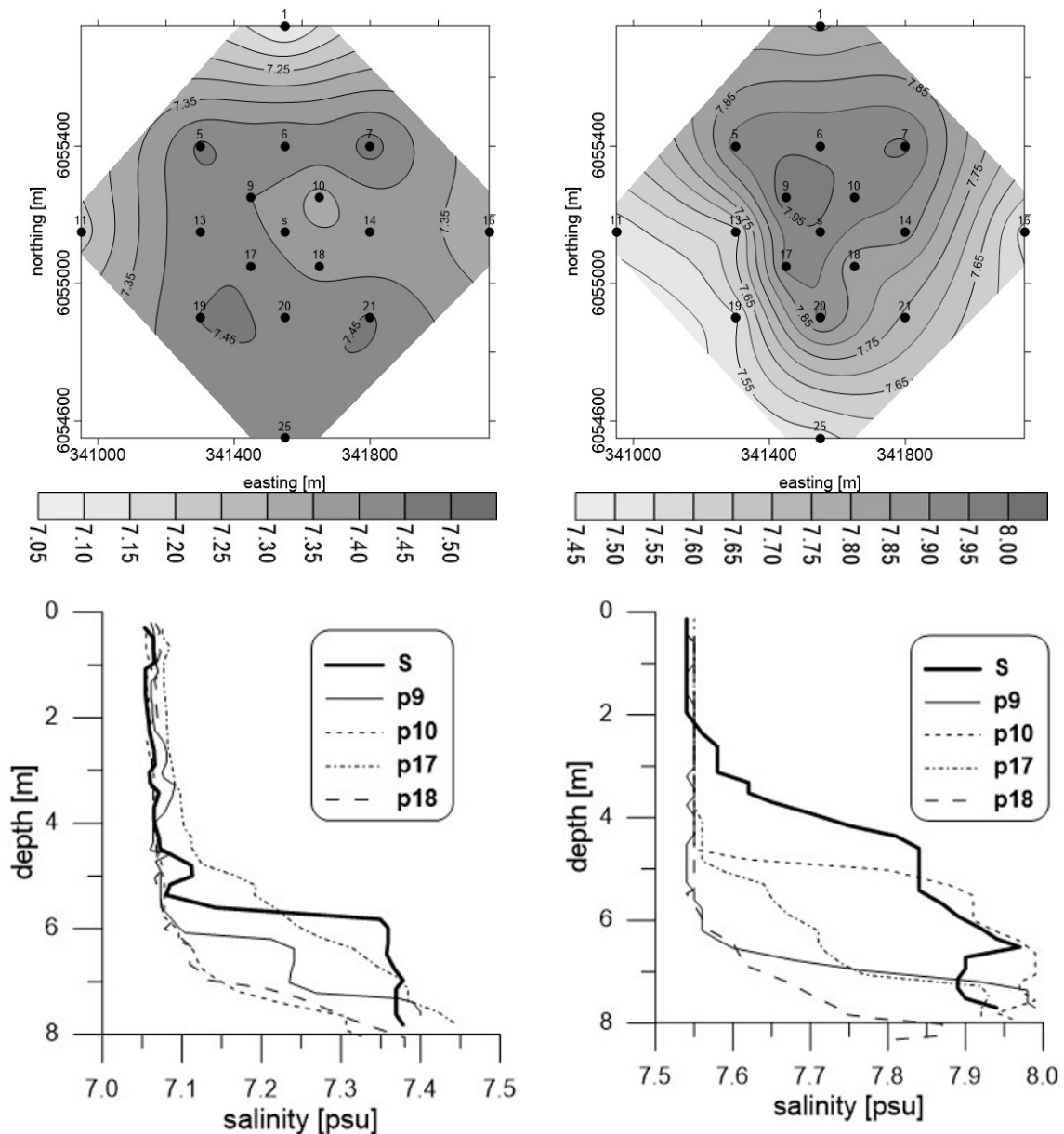


Figure 4. Salinity [psu] spatial distribution in the bottom layer (top) and profiles in selected verticals (bottom).

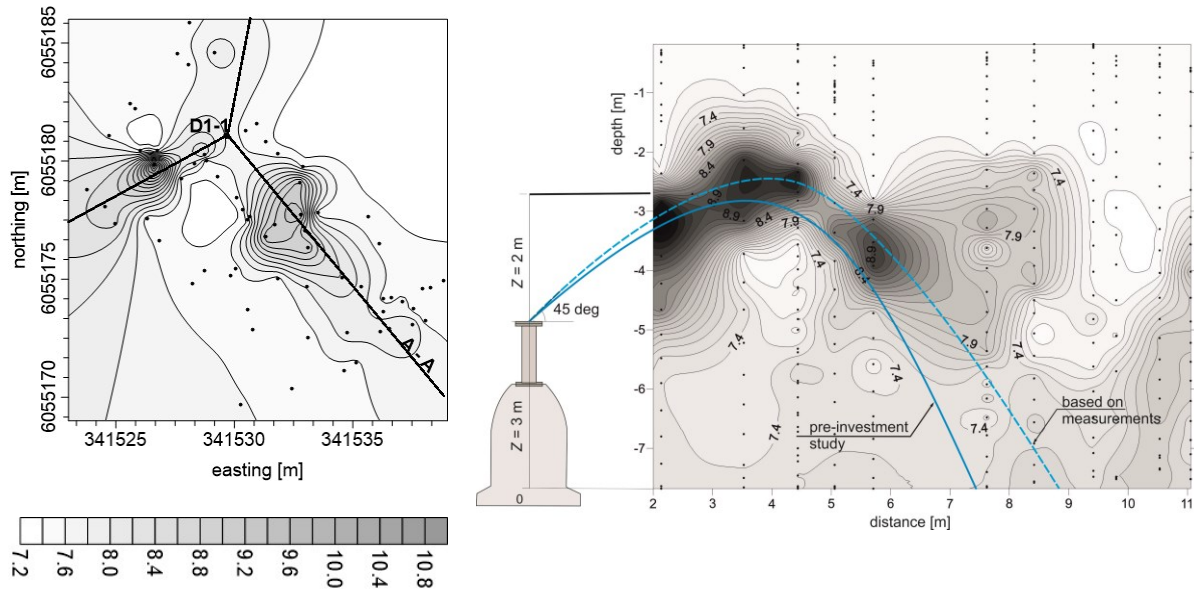


Figure 5. Spatial distribution of the highest salinity in verticals (left) and salinity in cross-section A-A in the vicinity of a single head carried out on 26.08.2011 (right).

DISCUSSION AND CONCLUSIONS

The extensive monitoring programme was carried out since the beginning of brine discharge into the Puck Bay. Continuous and short-term measurements confirmed significant natural variability of salinity in the Puck Bay region. Both, inflows of more saline water from Gdańsk Deep in the bottom layer, and traces of riverine water from Vistula have been registered. Measurements in the vicinity of a single head have shown that single jets introduced to the ambient water with high velocity mix intensively. In addition, the predicted trajectory of a single jet was confirmed by in-situ measurements.

Results from the monitoring programme confirm very good mixing of brine with the ambient water as predicted in the pre-investment study. They allow to conclude that the discharge system works in accordance with the obtained permission.

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