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Submarine groundwater discharge (SGD) to the Baltic Sea

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1. Introduction

Submarine groundwater discharge (SGD) is one of the water pathways connecting land and ocean in the global water cycle. Moreover it has been recently recognized as important factor influencing coastal zone [5]. In comparison with easily seen and typically large point sources surface of water inputs (e.g. rivers and streams), which are gauged and well analysed, estimations of groundwater inputs are much more difficult due to lack of simple mean to gauge these fluxes [28]. Groundwater in many areas has become contaminated and therefore is a source of nutrients, trace metals, organic compounds and radionuclides.

Hence it is important for the marine geochemical cycles of elements and may cause an environmental deterioration of coastal zones.

SGD to the coastal area usually occurs as a slow diffuse flow but can be found as a large point sources in certain terrain. What is more low flows of groundwater are typically temporally and spatially variable, complicating efforts to characterize site-specific flow regimes.

“Submarine groundwater discharge” exist in two well-known meanings, first includes fresh groundwater discharge, second includes recirculated water seepage [42]. However, nowadays the most popular definition for SGD is “any and all flow of water on continental margins from seabed to the coastal ocean, regardless of the fluid composition of driving force” [4].

Importance of SGD

Many studies have been performed concerning SGD [5, 43]. At Figure 1 it is showed locations of the studies: east and west coast of United States, South America, Hawaii, Europe, Japan and Oceania.

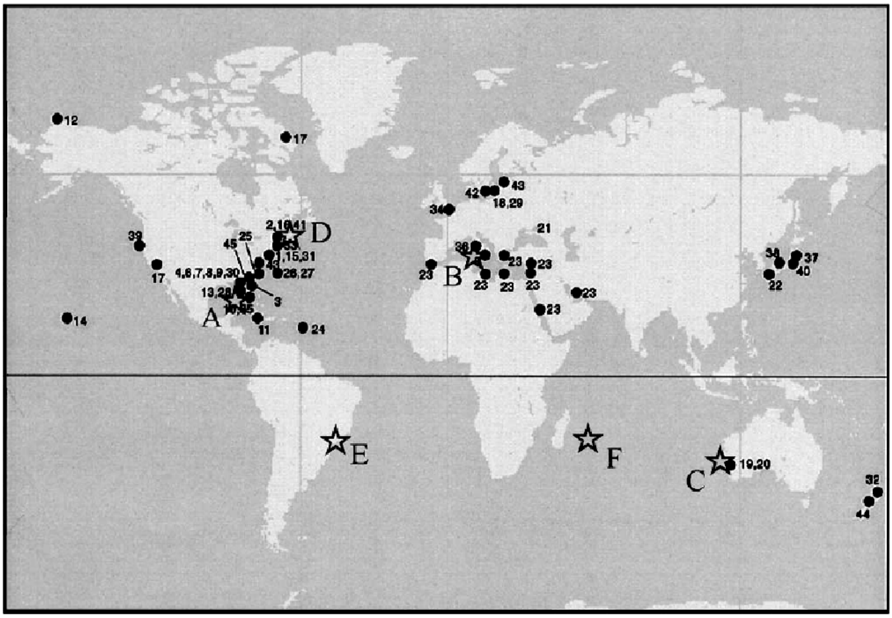

Fig. 1. Locations of published study sites concerning SGD. Sites labeled “A” through “F” are locations where SGD assessment intercomparisons have been carried out. Site “A” was an initial experiment in Florida [3] and “B” through “F” represent the five experiments reported by Burnett et al. [5]. The numbers refer to 45 sites where SGD evaluations were identified by Taniguchi [43]

Rys. 1. Położenie miejsc badań dotyczących podwodnego dopływu podziemnego, dotychczas opublikowanych. Miejsca oznaczone A÷F to lokacje, w których dokonano ocen porównawczych podwodnego dopływu podziemnego. A to początkowy eksperyment na Florydzie [3] a B÷F to pięć eksperymentów opublikowanych przez Burnetta i in. [5]. Numery odnoszą się do 45 miejsc gdzie podwodny dopływ podziemny był badany przez Taniguchiego [43]

Results of some of these studies show ecological impact of groundwater flow into coastal zones. Valiela et al. [45, 46] proved that groundwater inputs of nitrogen are critical to the overall nutrient economy of salt marches. Corbett et al. [10, 11] concluded that groundwater nutrient inputs are nearly equal to nutrient input via surface water in eastern Florida Bay. While Krest et al. [20] claimed that nutrient load of groundwater discharge to the Pacific off California that is higher than from all South Carolina rivers. Lapointe et al. [22] suggested that groundwater flow into Florida Keys may be main factor for initiating the phytoplankton blooms observed there. It is obvious that SGD may have great ecological significance. On occasion even greater that river runoff.

2. Methods used to measure SGD

The most important step in quantifying chemical influence of SGD on a coastal area is determining the amount of water discharged there. This is a rather difficult challenge because groundwater flow is temporally and spatially variable. Moreover the sites of SGD are difficult to approach. There has been developed many techniques/methods of qualitative and quantitative measurements of SGD. Each of them has its advantages and disadvantages and has proven to show specific features of SGD. That is why at any particular site, with determining SGD, we should use as many methods as possible. There are three general methods: direct measurements; piezometers; natural tracers; theoretical analysis and numerical simulations. Within the last few years some new methods of SGD measurements have been developed, some of them, like infrared thermography seem to be an important tool for indentifying and quantifying SGD. Infrared imaging is only used for identification of the location and spatial variability of SGD by using the temperature difference between surface water and groundwater [28].

Direct measurements

Seepage meters

Measurements of groundwater seepage rates into coastal waters are often made using manual or automatic seepage meters.

Manual seepage meters

Manual seepage meter was first developed by Israelsen and Reeve [16] to measure water loss from irrigation canals. Lee [23] designed a seepage meter constructed from steel drum (208 L volume), which form a chamber with one end opened and put into sediment while the other end has a sample port with plastic collection bag (Figure 2).

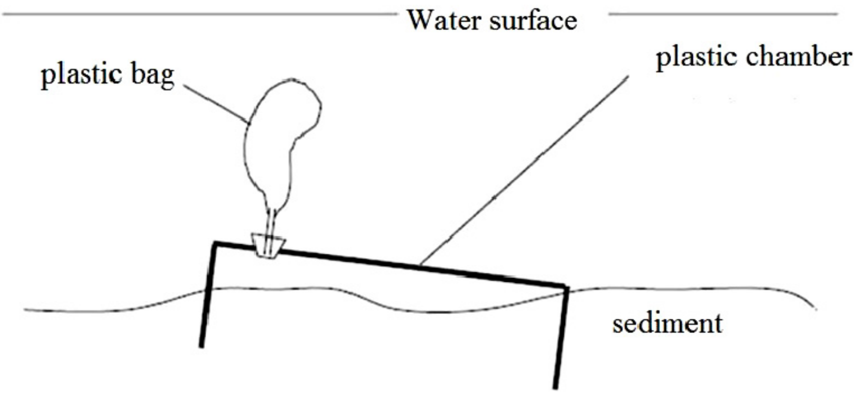

Fig. 2. "Lee-type" manual seepage meter [23]
Rys. 2. Ręczny miernik wysięku „typu-Lee" [23]

Groundwater seeping through the sediment will displace water trapped in the chamber forcing it up through the port into the plastic bag. The change in volume of water in the bag over a measured time interval provides the flux intensity. Operation of seepage meters is simple, but they are very sensitive to wave disturbance and currents [7, 38]. Moreover, they only sample a small flow area and this is a reason why so many seepage meters are needed to characterize the spatial variability at most sample sites.

Automatic seepage meters

Since various types of automated seepage meters have been developed, it is possible to obtain the groundwater discharge rate automatically and continuously. Automatic seepage meters include such technologies as: heat-pulse method [40], continuous heat [42], ultrasonic [29], and dye-dilution [39]. The advantage of these seepage meters is that they can be left in place for some days or even weeks and they will produce data without manual intervention. In the other hand disadvantage is that they require very calm environment [15].

Methods based on both manual and automatic seepage meters are working relatively well [44], but they always should be complemented with other methods.

Piezometers

Multi-level piezometers nests are used to measure the groundwater potential in the sediments at several depths [14]. With knowledge of the aquifer hydraulic conductivity, one can calculate the SGD rate into the ocean by use of one dimensional form of Darcy's Law:

$$q = -K\mathrm{d}h/\mathrm{d}L$$

where:
q is Darcian flux (groundwater discharge volume per unit area per unit time),
K is hydraulic conductivity,
$\mathrm{d}h/\mathrm{d}L$ is the hydraulic gradient in which h is hydraulic head,
L is distance.

The serious disadvantage of piezometers is difficulty in obtaining representative values of hydraulic conductivity, which usually varies. Nevertheless, piezometers nests are often used together with seepage meters to estimate hydraulic conductivity from observed seepage rates and the hydraulic gradient [1, 41].

Natural tracers

The main reason why natural tracers are used to quantify SGD is that their appear in high amounts in groundwater and present an integrated signal while entering the marine water column [24]. However using natural tracers for quantifying SGD require knowledge that all the other tracer sources and sinks are evaluated.

Over a past few years many SGD studies have utilized natural isotopes: ^{222}Rn [3, 7, 11, 26] and ^{223,224,226,228}Ra [9, 19, 24] for measurement groundwater. Moreover ^{3}H, ^{4}He have also been used in recent SGD studies [8, 27].

Theoretical analysis and numerical simulations

Since the past 40 years hydrogeologic models have developed and become interesting tool for understanding SGD. Numerical hydrogeologic models simplify key factors in aquifer systems and enable analysis of groundwater and saline water movement under varying conditions, which is not possible to measure by other methods. First description of groundwater seepage rate distribution through lakebeds using numerical models were made by McBride and Pfannkuch [25]. Bokuniewicz [2] used this description and developed an analytical solution for SGD. Since then many numerical models were invented but they all need experimental data to determine the location and strength of SGD.

3. SGD studies in the Baltic Sea

The Baltic Sea is one of the largest brackish water bodies in the world. Baltic total surface area is 375,000km^2 and drains the area of approximately 1,720,000 km^2. The Baltic Sea is divided into five basins: the Bothnian Bay, the Gulf of Finland, the Gulf of Riga, the Baltic Proper and the Danish Sounds.

In the Gulf of Finland, the Eckernfőrde Bay and the Gulf of Gdańsk SGD studies have been performed [6, 12, 13, 17, 18, 21, 30÷37, 47÷49]. The Gulf of Finland belongs to eastern part of the Baltic Sea and is on the junction of two main geological basement structures, the Russian Platform and Baltic Shield. Above these structures are sedimentary rocks from Precambrian to Quaternary. The overlying glacial sediments vary between gravel, sand and clay. The Eckernfőrde Bay is 17 km long and 3 km wide inlet of Kiel Bay placed in the western Baltic Sea. Glacial and post glacial sediments and subsurface tertiary deposits determine the morphology of the bay. The Gulf of Gdańsk and the Puck Bay (part of the Gulf of Gdańsk) is in the southeastern Baltic Sea. The hydrogeological condition of the Gulf of Gdańsk is not well identified, however seismic-acoustic investigations showed that the Quaternary sediments are 25 m thick and the roof of the Cretaceous formations is located at the ordinate form 108 m to 135 m below mean sea level.

In the Gulf of Finland the studied area was divided into four geological-hydrogeological zones. To measure SGD Zekster's methods were used. The results of SGD studies from zones are presented in Table 1. The total amount of groundwater discharge to the Gulf of Finland was 0,6 km^3/year. Discharges from zones were different, the greatest were from southern zone (4) and the smallest from the northern zone (1). The amount of chemical substances value (Csd) was determined to 335t/year, which is more than chemical substances contained in the river runoff discharged to that particular part of Gulf.

Table 1. Results of groundwater discharge investigation in different zones of the Gulf of Finland [47]
Tabela 1. Wyniki badań zrzutu wód podziemnych w różnych strefach Zatoki Fińskiej [47]

Zone Number	Length-Width of zone (km)	Surface of zone (km^2)	Value of dis-charging groundwater (m^3/year)	Load of chemical substances dis-charge (CSd) (t/year)	Specific com-pounds
1	180-2.5	450	34.058	6.8	Rn
2	110-20	2.2	1666.51	33.2	Fe
3	75-20	1.5	113.529	90.823	Heavy metal. organics. petroleum compound
4	180-50	9	340.588	204.352	NO_3^-
Total	555- -	13.150	654.685	335.175	-

The Eckernfőrde Bay was monitored for SGD using many methods for the period 1991-2001. Mainly methane and salinity measurements were made for 1991-1994 and for 1998-2001 generally water and sediment sampling. ^{222}Radon. ^{226}Radium and methane analysis. The Bussmann [6] studies shows that SGD activity increases methane concentrations in the bottom and surface water. The lowest bottom water salinity was 2.9 ‰. From Schluter [36] studies it may be inferred that in Eckernfőrde Bay ^{222}Rn seems is a suitable tracer for SGD. whereas ^{226}Ra showed no apparent trends. This feature different from other coastal regions [3, 24]. Basing on ^{222}Rn activity it was estimated that discharge rates were in the range of $37\cdot10^6$ to $337\cdot10^6$ m^3/year .

In the Gulf of Gdańsk (Figure 3) the groundwater discharge was identified [12, 13, 21, 31÷34]. Measurements showed an unusual vertical distribution of temperature and salinity in the SGD region there. Similar observations had been made in Puck Bay. Chemical measurements were also made.

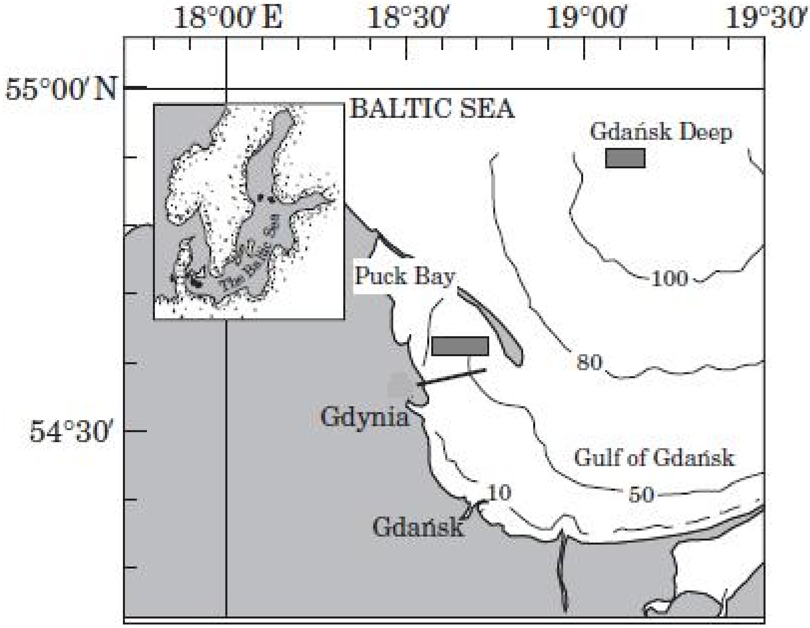

Fig. 3. The study areas in The Gdańsk Basin: Gdańsk Deep and Puck Bay [13]
Rys. 3. Obszary badań w Basenie Gdańskim: Głębia Gdańska i Zatoka Pucka [13]

The increase in concentration of nitrate and phosphate with the water column was observed.

There have been also made estimations about a hole flow of SGD to the Baltic Sea. First Zekster [49] than Peltonen [30] estimated the volume of SGD entering the seawater balance. As reported by Peltonen [30] the volume of groundwater discharge into the Baltic Sea equals about 4.4 km^3/year which is about 1% of total fresh water flow.

3.1. Chemical characteristics of SGD from the Puck Bay (recent findings)

In 2009 studies concerning SGD in the Puck Bay have been continued [48]. The main aim was to find groundwater seepage, than characterize its geochemical composition. One research cruise on a research vessel Sir Albrecht Penck during summer and one campaign near the shore line of the Hel Peninsula in spring have been carried. There has been found one area with groundwater impact into the Gulf of Gdańsk and other area near the shoreline of the Hel Peninsula. The water samples were collected using bathometers, seepage meters and piezometers. Several chemical analysis were done using Multi 34i-meter., ICP-MS, spectrophotometer and HyPerTOC analyser with UV/persulphate oxidation and non-dispersive infrared detection. The limits of detection of applied methods are smaller than the measured concentrations by an order of magnitude The limits are also substantially smaller than variations of the measured concentrations.The precision of the results is as follow: <3% for the measured nutrients, <8% for the measured metals, <2% for DOC and DIC, and <1% for pH and salinity.

The salinity profiles from the SGD impacted area and non impacted area differs at the Gulf of Gdańsk (Figure 4). In the impacted area salinity profile we may see two decrease in salinity in the top and bottom of the water column. The low salinity on the top is due to a heavy rain and bottom.

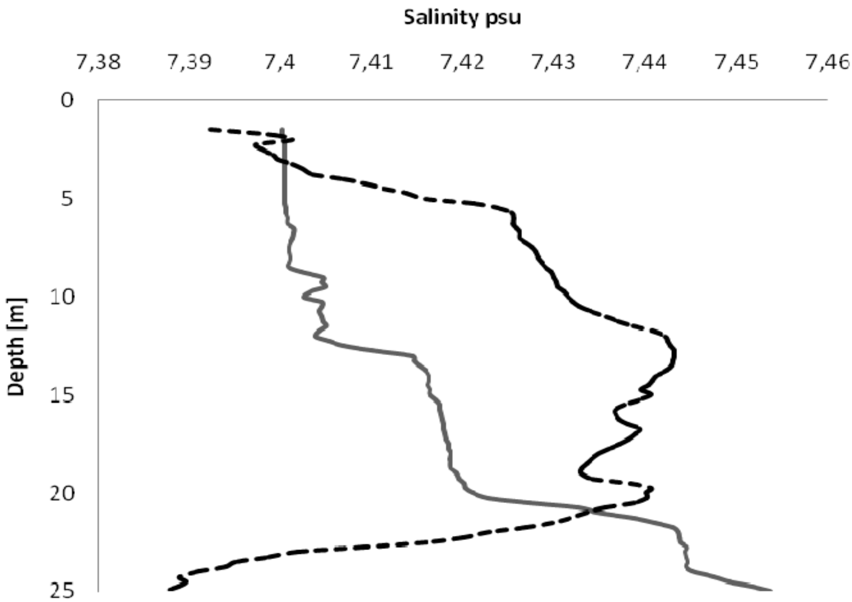

Fig. 4. Salinity profiles at a non-impacted – continous line and an impacted area – discontinuous line from the Gulf of Gdańsk

Rys. 4. Profile zasolenia w obszarze bez wpływu – linia ciągła i z wpływem – linia przerywana w Zatoce Gdańskiej

It was also observed that some trace metals concentrations in groundwater samples are larger than in saline water samples (Figure 5).

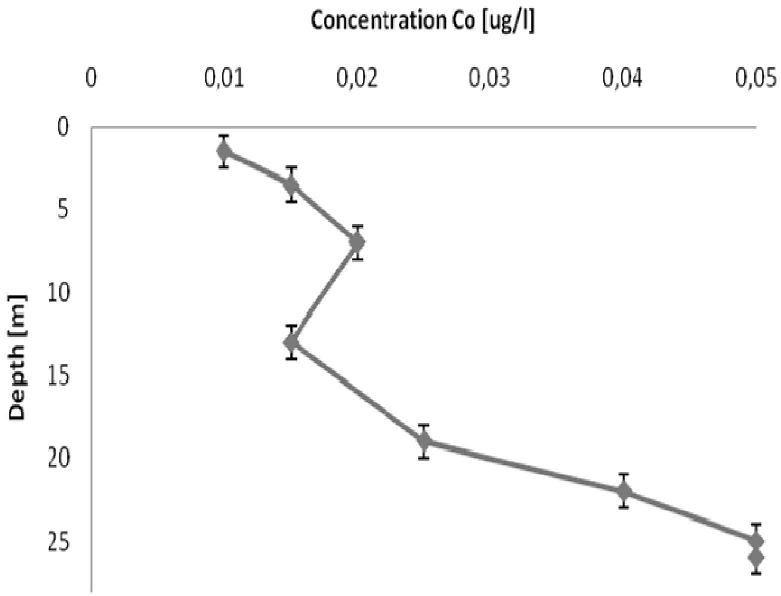

Fig. 5. Cobalt concentrations in water column from groundwater impacted area in the Gulf of Gdańsk
Rys. 5. Stężenia kobaltu w słupie wody w obszarze wpływu wód gruntowych w Zatoce Gdańskiej

In the area near the shore line of the Hel Peninsula we took water samples from seepage meters and piezometers. The saline profiles from two piezometers are presented in Figure 6. The analysed water samples from piezometers and seepage meters show the relationships between the salinity and pH (Figure 7). It may be caused by high amount of DIC in groundwater samples. On the other hand the groundwater samples have lower amounts of DOC than saline water.

The lowest and highest concentration of some chemical compounds in the water samples are presented in Table 2.

More studies are needed to be done to better understand the SGD phenomena and its impact on the Puck Bay.

Table 2. Characteristics of concentrations of some chemical compounds from water samples from the Hel Peninsula
Tabela 2. Charakterystyka stężenia niektórych związków chemicznych w próbkach wody z Helu

Chemical compounds	The lowest and highest concentrations
NH_4^+	1.12-19 [umol/l]
NO_3^-	0.12-0.8 [umol/l]
NO_2^-	0.09-0.5 [umol/l]
SiO_2	7.6-43 [umol/l]
PO_4^{3-}	0.01-18.8 [umol/l]
DIC	30-59 [mg C/l]
DOC	3.1-6.2 [mg C/l]

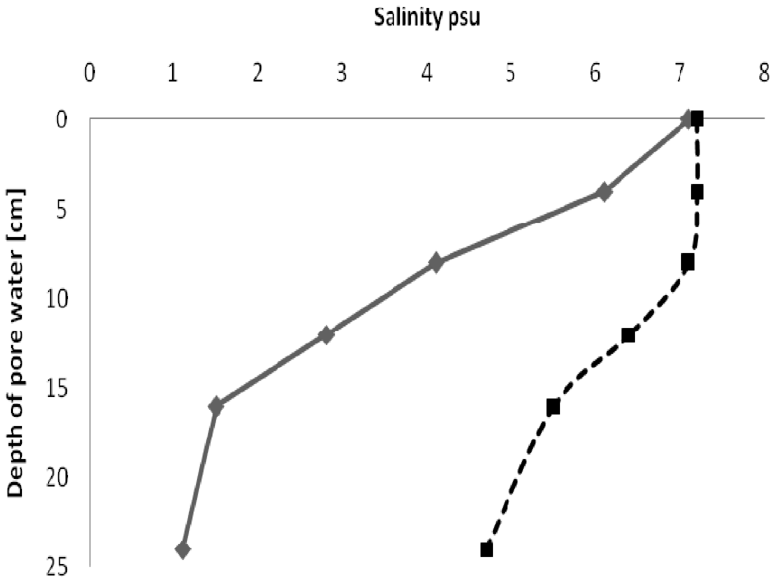

Fig. 6. Salinity profiles from pore water samples, impacted area – continuous line, less-impacted – discontinuous line
Rys. 6. Profile zasolenia w próbek wody porowej, obszar wpływu – linia ciągła, obszar mniejszego wpływu – linia przerywana

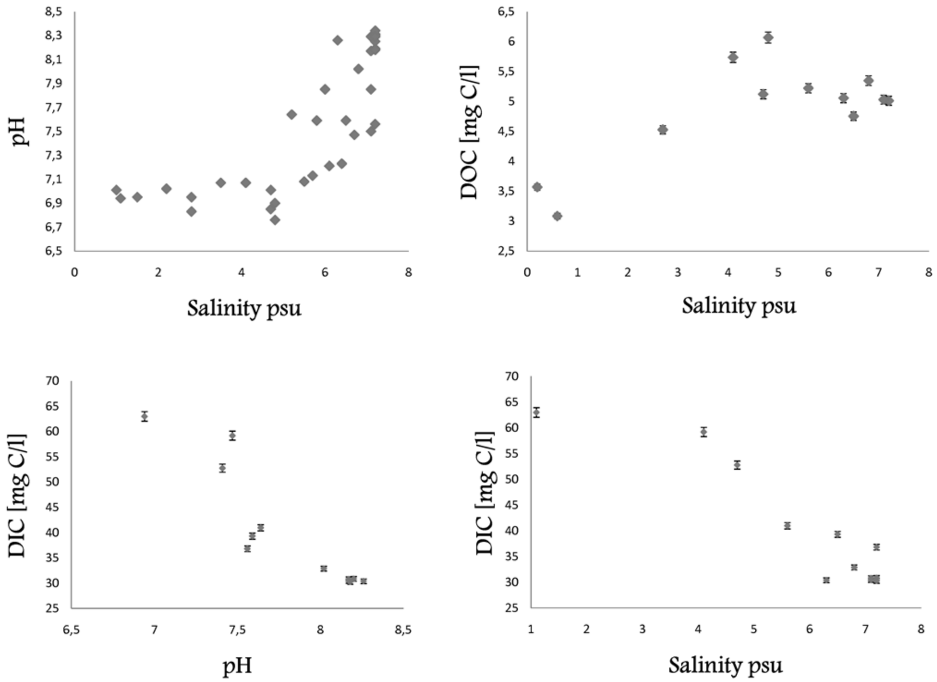

Fig. 7. Relationships between salinity and selected properties of water samples collected at the impacted and non-impacted sites in the Hel Peninsula

Rys. 7. Zależności między zasoleniem i wybranymi własnościami próbek wody pobranych w obszarach wpływu i obszarach bez wpływu na Helu

4. Conclusions

In the Gulf of Gdańsk the areas of Submarine Groundwater Discharge impact were identified. These discharges causes the local decrease in salinity and pH. The wide range of concentrations of nutrients. DIC and DOC were identified. These fluxes of chemical compounds may cause the deterioration of coastal zone of The Puck Bay.

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Podwodny dopływ podziemny do Morza Bałtyckiego

Streszczenie

Dopływ wód podziemnych do środowiska morskiego jest obecnie postrzegany jako istotny szlak wymiany masy pomiędzy lądem i oceanem. Cechuje go znacząca przestrzenna i czasowa zmienność, w porównaniu do spływu rzecznego, co utrudnia jakościową i ilościową charakterystykę dopływających substancji. Dopływająca woda podziemna i zawarte w niej substancje (związki organiczne, substancje biogeniczne czy metale) wpływają w szczególności na przemiany geochemiczne w wodach przybrzeżnych. Badania dotyczące dopływu wód podziemnych do środowiska morskiego są prowadzone na świecie, w tym na Morzu Bałtyckim od wielu lat.

Podjęto też badania dotyczące dopływu wody podziemnej – wody wysiękowej do Zatoki Gdańskiej. Próbki wody są pobierane za pomocą batometrów, kolektorów wody wysiękowej i piezometrów, a następnie analizowane. Ustalono że, wody wysiękowe zawierają substancje biogeniczne, rozpuszczony węgiel nieorganiczny oraz metale śladowe w szerokich zakresach stężeń. Otrzymane wyniki stężeń badanych komponentów wody korelują z zasoleniem i pH.

Dalsze badanie zjawiska dopływu wód wysiękowych i ich charakterystyki jest niezbędne dla lepszego zrozumienia zasad funkcjonowania ekosystemów morskich oraz określenia niebezpieczeństw zagrażającym im, związanych z dopływem dużych ilości substancji toksycznych.