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Hydrophysical parameters of seawater in front of Ustka during the summer season 2013

Warunki hydrofizyczne obszarów morza na przedpolu Ustki w okresie letnim 2013

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Abstract: The article presents spatial distribution of hydrophysical parameters of coastal waters near Ustka, stretching towards the eastern part of Słupsk Bank which appeared there in July 2013. It covers studies of distribution of temperature, salinity and seawater density across the entire cross-section of the water depth. Additionally, directional distributions of the water flows recorded at Baltic Sea, as well as information on local wind speed and direction derived from numerical model of the atmosphere are presented. The resulting image of water density distribution across the entire cross-section of the water depth under steady conditions of stratification allowed determination of character and extent of river water distribution seawards of the Słupia River mouth during summer 2013

Keywords: Ustka Bay, Słupsk Strait, Słupsk Bank, Słupia River, Baltic Sea, hydrophysical parameters of the sea, sea currents, wind

Streszczenie: W pracy przedstawiono rozkład przestrzenny parametrów hydrofizycznych wody na przybrzeżnych akwenach przedpola Ustki do północnych zboczy wschodniej części Ławicy Słupskiej zarejestrowany w lipcu 2013 roku. W tym celu zbadano rozkłady temperatury, zasolenia oraz gęstości wody morskiej w całym przekroju toni wzdłuż przekroju Ustka - północny stok Ławicy Słupskiej. Dodatkowo przedstawiono rozkłady kierunkowe przepływów wody zarejestrowane w tym czasie na morzu, oraz informacje o kierunkach i prędkościach wiatru lokalnego z prognoz numerycznego modelu atmosfery. Uzyskany obraz rozkładu gęstości wody w całym przekroju toni w warunkach ustalonej stratyfikacji pozwolił na przedstawienie charakteru i zasięgu rozpływu wód rzecznych na przedpolu ujścia Słupi w okresie letnim 2013 roku.

Słowa kluczowe: Zatoka Ustecka, Cieśnina Słupska, Ławica Słupska, Słupia, warunki hydrofizyczne morza, prądy morskie, wiatr

Introduction

Coastal regions of the Baltic Sea located in the vicinity of the Słupia River mouth and the Ustka harbour form a clearly outlined bay jutting a few kilometres into the land. The name proposed for this formation is **Ustka Bay** (Rudowski and Wróblewski, 2012). To the north of it, between the land and the shallows of the Słupsk Bank, a deepening can be seen, which morphologically resembles a strait, and for which an unofficial name of the **Słupsk Strait** was accepted. Depth of the sea at the southern slope of the Słupsk Bank does not exceed 32 m. Next, seawards drops to a depth of 14 m b.s.l. (Fig. 1).

The above-mentioned areas have been thoroughly examined in terms of geological and geotechnical conditions (Cieślak et al., 1998; Gajewski et al., 1998; Florek, 2013), bathymetry and seismoacoustics (Gajewski et al., 2002; Rudowski et al., 2014) as well as morphology of the seabed (Rudowski et al., 2013). In this area, the **P16** monitoring point, which belongs to the network of the Polish measurement stations, is located. Hydrological, hydrophysical and hydrochemical measurements of the marine environment are performed here six times a year (Jakusik et al., 2013, CIEP, 2016). However, such information derived only from a single location does not provide grounds for drawing conclusions on spatial distribution of environmental parameters in the entire sea area located northwards of the Słupia River mouth. Hydrological conditions of these areas were presented in the publication issued by the Institute of Environmental Protection (Łysiak-Pastuszak and Zalewska, 2014), but it does not include the spatial distribution of seawater temperature and salinity as well.

As can be expected, water of the Słupia should have a noticeable impact on the state of the marine ecosystem between Ustka and the Słupsk Bank. Pollutions of the water catchment area are transported to the sea, which contributes significantly to the intensification of eutrophication process in the sea (CIEP, 2012). These coastal and transitional waters are the subject of current monitoring under the Water Framework Directive (Błaszczak, Kreft, 2008).

In Słupia there live numerous fish species, including *Salmo trutta* morpha *fario* and northern pike, the number of which has decreased over the past few years (Moczulska et al., 2006). Representatives of these species have also been found in its estuary. Study of size and range of river water distribution in the sea provides a sound basis for the performance of further stages of environmental studies of the coastal and transitional waters, i.e. chemical and biological measurements aimed at the formulation of an up-to-date assessment of marine ecosystems, including fish spawning ground areas. It is particularly important for the Słupsk Bank being located in close proximity, as well as the attractiveness of Ustka and the beaches near the Słupia mouth as tourist destinations, and environmental protection of the proposed special area of conservation (SAC) of the "The Valley of the Słupia River" habitat (dolinaslupi, 2016). The surveys conducted in the summer season (July) are connected well with implementation of the objectives stated above. Measurements of hydrophysical conditions across the entire cross-section of the water depth along a profile running perpendicular to the shoreline between Ustka and the Słupsk Bank, in order to gain knowledge on characteristic values of summer time seawater parameters in the studied sea areas, as well as of speed and direction of water flow in this region were performed. The obtained information can be helped to determine the range and character of distribution of freshwater from the river in the sea in summer time, as well as to investigate whether it had a noticeable influence on the area of the Słupsk Bank.

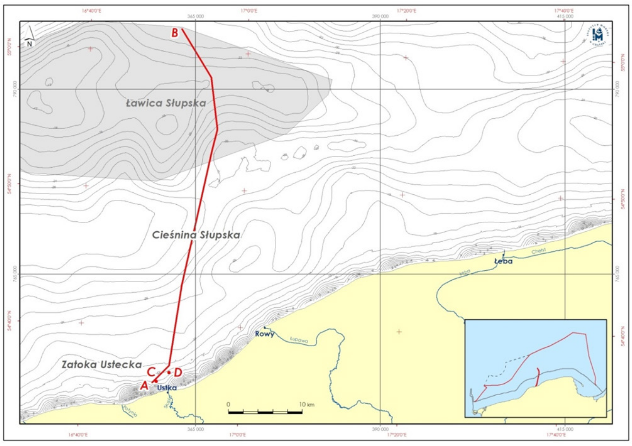

Fig. 1. Location of the AB cross-section between Ustka and the northern slope of the Słupsk Bank; C – place of currents recordings, D – the grid point of the UM atmospheric model, from which there were gathered data for wind parameters of above the sea surface, Cieśnina Słupska – the Słupsk Strait, Ławica Słupska – the Słupsk Bank, Zatoka Ustecka – the Ustka Bay

Tab. I. Characteristics of parameters registered by the STD/CTD SD204 SAIV probe (according to the manufacturer)

PARAMETER	ELECTROLYTIC CONDUCTIVITY	SALINITY	TEMPERATURE	PRESSURE
Range	0–70 $mS \cdot cm^{-1}$	0–40 ppt	-2–+40 °C	500 m
Resolution	0.01 $mS \cdot cm^{-1}$	0.01 ppt	0.01 °C	0.01 dbar
Accuracy	± 0.02 $mS \cdot cm^{-1}$	± 0,02 ppt	± 0.01 °C	± 0.01%

Environmental conditions of the studied area

The surveys presented herein were conducted in the Polish zone of the Baltic Sea, located in the central part of the coast along a profile leading from the port of Ustka to the northern slope of the eastern part of the Słupsk Bank's (the AB curve in the Fig. 1). They covered the area of coastal waters of the Ustka Bay, the parts of the sea characterized by greater depths (more than 30 m) between the Ustka Bay and the Słupsk Bank (i.e. the Słupsk Strait), and through the bank's eastern part they extended to its north-eastern slope.

The biggest river inflowing to the Ustka Bay is Słupia, the waters of which enter the sea via a funnel-shaped mouth in Ustka. The river is 138.6 km long, and its catchment areas cover an area of 1,623 km^2 (Augustowski, 1997). Flowing through the western part of the Pomeranian Voivodeship the waters collect pollution from the entire catchment area, which without a doubt has an impact on the quality of coastal waters in the whole considered region (Moczulska et al., 2006). It is feared that pollutions brought by the river water may also have a negative impact on the areas protected within the NATURA 2000 network located on the Słupsk Bank.

The course of the 20 m isobath is accepted as a marker of the northern border of the Ustka Bay (Rudowski et al. 2013, 2014), which next takes a shape of a deepening, extending north to the Słupsk Bank, defined herein as the Słupsk Strait. The northern boundary of the Słupsk Strait reaches the southern slope of the Słupsk Bank. Up to now, there is a lack of sufficient measurement data concerning this region of the sea, which could enable us to show the evolution of temperature distribution as well as degree and distribution of salinity on the surface and deeper to the bottom in different seasons of the year. Only very general information concerning the entire area of the Baltic Sea or different parts of it is available (e.g. Łomniewski, 1975; Augustowski, 1987; Majewski and Lauer, 1994; Jakusik et al., 2013; Łysiak-Pastuszak and Zalewska, 2014). In this regard, it should be also noted that basins of the Southern Baltic Sea are continuously and significantly influenced by waters characterized by a much higher salinity incoming from the North Sea via the Danish Straits. Additionally, the coastal areas, are also diluted by the inflowing rivers. Hence there appear diverse thermohaline conditions and noticeable areas with a clear-cut water stratification. Therefore, it is necessary to conduct regular monitoring of this region (Kałas et al., 2016).

Similarly, poorly identified, there are conditions of water dynamics which prevail in this sea area. It is generally assumed that along the southern coast of the Baltic Sea, in the coastal zone, there dominates a two-way water movement with flow from the west to the east that is much more abundant. This is caused by the winds blowing from the western directions, which prevail here throughout the year (Bączyk, 1968; Lorenc, 2005). Therefore, it is necessary to perform a methodical approach to the water flow measurements across the entire cross-section of the water depth.

Materials and methods

Hydrophysical parameters along the **AB** route, shown in the Fig. 1, were collected on 20 July 2013 (up to the 33rd km of the route) and 22 July 2013 (at the final part). During the cruise, at 53 points on the sea, distant to each other of 1 nautical mile, there were measured the following parameters: electrolytic conductivity, temperature, and salinity from the surface down to the bottom. Throughout the measurements, the weather conditions remained stable, which allowed to obtain homogeneous results of measurements of selected parameters.

The measurements were conducted by use of a STD/CTD probe (the SD204 model by the SAIV AS company) (Fig. 2) with a dedicated software for data processing called *MINISOFT SD200W*. Details concerning the measured parameters are presented in Tab. 1.

The probe was deployed each time at a speed not exceeding 0.33 m/s. Sampling interval was set at 2 s. Due to an intensive mixing observed in the water–air contact zone, gathered data from the surface layers of the sea (up to 2 m) were dropped in the analysis. Data concerning the actual depth at the place where the probing was conducted were resulted by the ship sonar.

For each of the performed probes there have been vertical profiles of water temperature, salinity and depth presented. All collected data were applied to chart vertical profiles of the studied seawater parameters across the entire route of the cruise (**AB**).

In the analysis, velocity and directions of water flows recorded in a location to the north-west of the Słupia estuary (16,821° E, 54,599° N – point **C**, Fig. 1) were taken into account from July 2014. The measurements were carried out, executed autonomously, in a continuous manner, by use of the AWAC 600 kHz acoustic Doppler current profiler manufactured by the Nortek company (Fig. 3), which was deployed on the seabed at a depth of 16 m. Water flow velocity components (cm/s) were measured throughout the entire cross-section of the water depth from the depth of 1 m above the seabed to the water surface (averaged for 1 m thick layers). Additionally, there were also parameters of the wave motion and water temperature recorded near the bottom. As the following step of the analysis, the values characterizing the water flow obtained in this manner were averaged for layers (each one was 4 m thick) starting from the water surface and moving down. What was achieved this way was information concerning the resultant horizontal water flow at various depths of the water column, with fine-scale fluctuations eliminated.

Fig. 2. CTD/STD probe (model SD204 by the SAIV AS company) used in the registrations

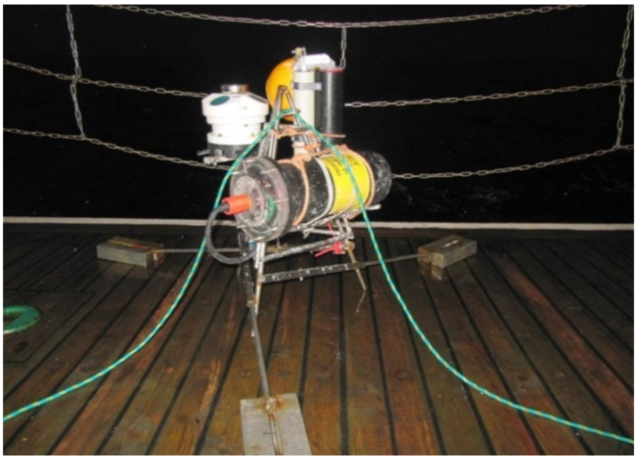

Fig. 3. The measuring system of the acoustic Doppler current profiler (ADCP) ready for deployment on the seabed, with the recording head, batteries and break release visible

As no meteorological registrations have been performed in the studied area, to get information regarding wind conditions above the sea surface for the period associated with the conducted measurements (July 2013), there were used numerical data of wind speed and direction based on forecast calculations of the mesoscale atmosphere model UM (*Unified Model*), run operationally by the Interdisciplinary Centre for Mathematical and Computational Modelling, Warsaw University (ICM UW) (Jakubiak, 2002), for the grid point (16.883° E, 54.627° N – point **D**, Fig. 1). As the conducted analysis of forecast reliability show, data obtained from the UM model calculations correlate well with the real conditions at the sea, and so they may be used for studies of actual wind conditions over different areas of the open sea with a good effect (Kałas, 2002, 2012).

Information on the river water inflow from the Słupia to the Ustka Bay were obtained from averaged monthly values of water flow as registered at the gauging station in Słupsk in the hydrological year of 2013 (Fig. 8) (IMWM, 2014).

Physical aspects of river water distribution in the sea

River waters flowing into the seawater are transformed and moved by forces connected with various mechanisms of advection and mixing with more dense water masses from the coastal zones of the sea. A detailed description of the mechanism governing these phenomena is included e.g. in a work by Hetland (2009). For a vertical cross-section of the area of fresh water distribution in the sea there can be distinguished a region of advection and a region with clearly predominating wind-mixing processes. In the first area, river water spreads over the surface of the sea together with the material it carries. In the marine environment, at the initial stage of water propagation, the layer of fresh water tapers off towards the bottom and its wedge extends in the top layer. Such a distribution is unstable and there occurs an intensive shearing mixing of waters (Hetland, 2005). Behind this zone, at a further distance from the shore, wind affects transformation of fluvial water more significantly (Fong and Geyer, 2001). The sketch presenting physical aspects of river water propagation in the sea across a vertical profile is presented in Fig. 4.

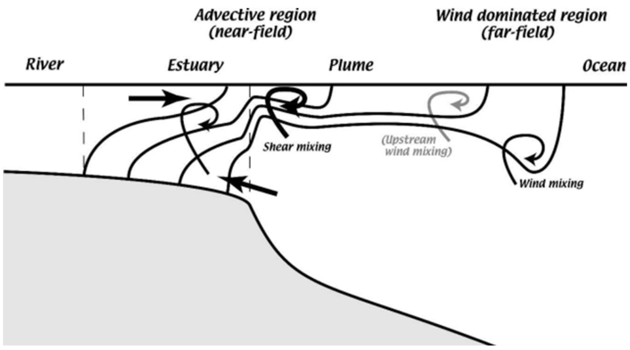

Fig. 4. Model of river water propagation across a vertical profile (by Hetland, 2005)

Results

The sea route (the **AB** cross-section, Fig. 1) at which the measurements were conducted starts about a mile to the north-west of the Słupia river estuary. Next, it crosses the Ustka Bay basin and the Słupsk Strait, goes through the eastern part of the Słupsk Bank and finally it reaches the northern slopes of the bank. It is about 46 km long. The greatest depth measured at a distance of about 33 km from the shore equals to 32 m. An outline of the relief across the studied section is presented in the Fig. 5a–5c.

Analysis of the water temperature distribution over the water depth and along the entire route demonstrates an evident impact of the seabed relief as well as distance from the coast on the intensity of water warming (Fig. 5a). What became clearly visible here is the typical thermal situation characteristic for the summer period when the phenomenon of upwelling does not occur (Lehman and Myrberg, 2008). In this case, the temperature of the surface layer of water is higher in the coastal zone than at the open sea, and masses of water with the lowest temperature remain in the deepest parts of the seafloor. It happens so because water gets heated much faster near the shore than at the open sea when circulation is poor as a result of wind affecting the surface of the sea. The highest values of temperature (19.9 °C at max.) occurred in the surface waters of the southern part of the **AB** cross-section, i.e. in a zone where isolines are distributed in a nearly vertical manner. From the 15th km of the profile on, in the direction of the Słupsk Bank, a horizontal stratification of the temperature distribution appeared. The warmest water was about 19 °C, and it could be found in the near-surface layer. Temperature dropped as depth increased, reaching the value of about 6 °C near the bottom, located at depths exceeding 30 m.

In the southern part of the **AB** section, river water mixes with seawater, and a zone characterized by clearly lower levels of salinity can be distinguished here (Fig. 5b). Measurements revealed that there i.e. 5.8 ppt occurred. The estimated impact of the river water on the seawater extends about 26 km from the Słupia estuary towards north, which covers the area characterized by the greatest depths. In this section, there can be distinguished two different zones of water mixing: a zone of advection located near the Słupia river mouth, and the located further seawards zone of intensive mixing associated with the impact of wind on the surface of the sea. The maximal values of water salinity, and simultaneously, of its density, were recorded over the bottom at the foot of the south-eastern slope of the Słupsk Bank. In this deeper sea region, salinity is relatively homogeneous down to the depth of 26 m, below which there cumulate more saline waters, with salinity levels of up to about 7.52 ppt at the depth of *ca*. 30 m. In the area of the Słupsk Bank, a layer of halocline occurs at a depth of about 14–16 m. In the upper layer, above the depth of 16 m, salinity is from 7.08 to 7.22 ppt. Below the halocline layer it is up to 7.28 ppt.

Distribution of conventional density of seawater resembles the one drawn for temperature and salinity (Fig. 5c). In the case of the studied section, these values varied within the range of 2.65–6.05. The lowest values of density were recorded in the southern part of the Ustka Bay, where an influence of the waters of the Słupia river can be easily noticed. The minimal level of density in this area was 2.65, while the highest ones occurred starting from the 30th km of the profile, at the foot of the Słupsk Bank's slopes, and they were up to 6.05.

Data obtained on the basis of the UM atmospheric model for speed and direction of wind blowing over the surface of the sea

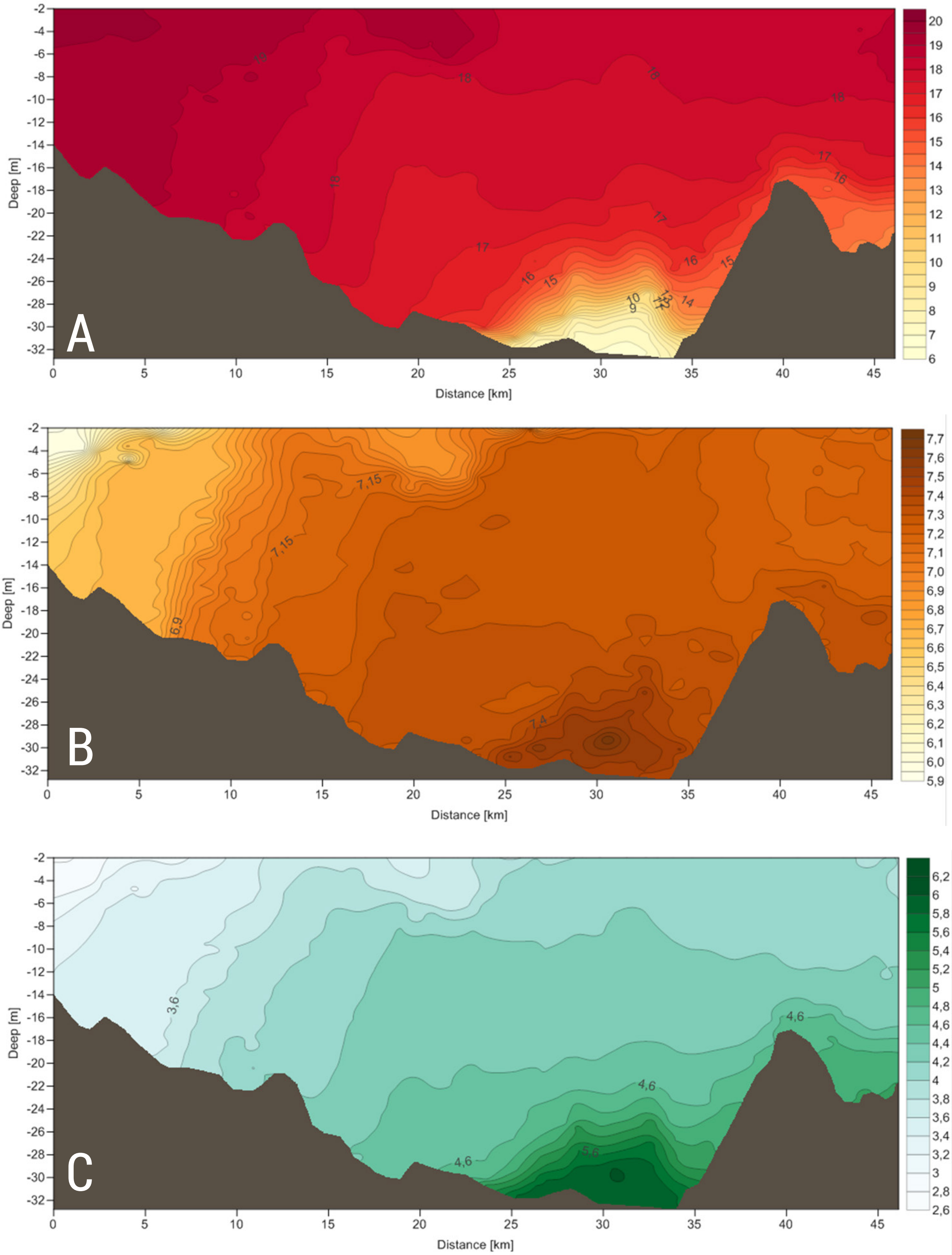

Fig. 5. Vertical cross-sections of temperature (a), salinity (b), and conventional density (c) of seawater obtained on the basis of in situ measurements conducted along the AB section.

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in June 2013, allowed drawing a description of the wind conditions that occurred at that time in the region of the Ustka Bay (the **D** point in the Fig. 1). As it is illustrated by the diagram (a direction rose), this is a place where a marked predominance of winds from the western sector was recorded (42%), with north and north-western winds also having their share (29%) (Fig. 6). There dominated a light wind (up to 5.5 m/s) amounting to 52% of cases, and a moderate one (5.5–7.9 m/s) – 27%. Quite strong (8.1–10.8 m/s) and strong (8.1–10.8 m/s) wind occurred less often, i.e. in 21% of registrations. No storm wind (exceeding 17.2 m/s) was noted. In this period, the average wind velocity was 5.2 m/s, and its maximal value reached 11.4 m/s. As is apparent, the wind conditions presented above were not favourable with respect to vertical mixing of water masses, and so the phenomenon of upwelling did not occur as well.

On the basis of data collected over a period of 1 month of recordings of velocities and directions of currents in the Ustka Bay conducted in July 2013 at the station located seawards of the Słupia river mouth, at a depth of 15 m (marked as **C** point in the Fig. 1) there were drawn characteristics of water flows presenting their dynamics and distribution of directions at various depths of water. They are depicted in the flow direction roses averaged for the subsequent 4 m thick layers of water measured from the surface down to the seabed (Fig. 7 a–d).

As can be seen, in the period in question in the near-surface layers of the sea down to the depth of 8 m, there largely dominated water flows directed eastwards (Fig. 7a and 7b). Below, at the depth of 12 m there was observed a greater share of the flow in the sectors associated with the north-eastern direction (Fig. 7c) which began to dominate as depth increased (Fig. 7d). Over the bottom there occurred an evident rise in the share of water flow faster than the ones recorded at shallower depths, whereas the maximal values are comparable to the ones recorded near the surface of the sea. This was reflected in an increase of the average water flow velocity (Fig. 7d).

Such an image of water dynamics recorded in the southern part of the measuring route in the period of time immediately preceding performance of surveys as well as in the middle of the surveys implementation says that propagation of the river water in the coastal sea areas was generally directed to the west, i.e. in line with the direction of sea currents dominating in this region (Kałas et al., 2010). This was fostered by the character of the sea surface wind field with domination of directions from the western sector. The key factor, however, is impact of the currents, which drive masses of the water body along the shore from the west to the east for most of the year in the coastal zone (Basiński, Żmudziński, 1988). The aerial photograph of the region of the Słupia river mouth also confirms this case (Fig. 8, from the Google Earth). The poorly differentiated anemobaric fields occurring in the summer season over the sea areas do not usually disturb this fixed characteristic of water flow.

Analysis of a spatial distribution of salinity in the coastal waters of the sea in the region connected with the Słupia estuary

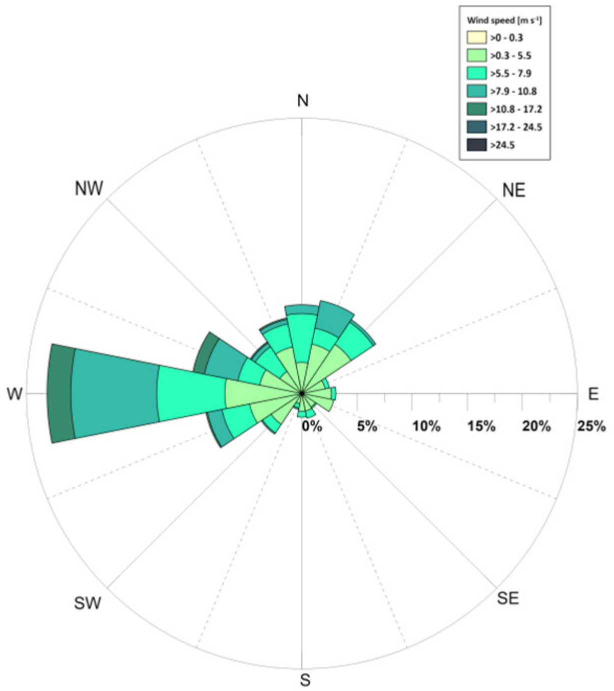
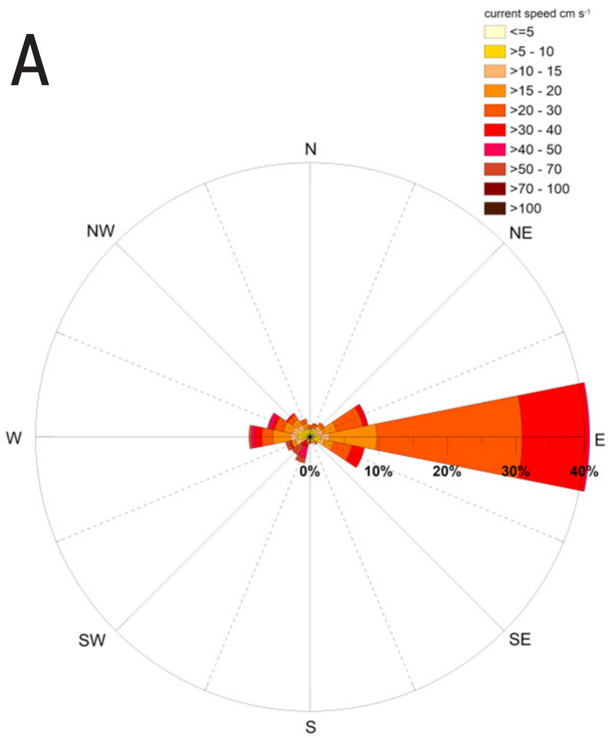


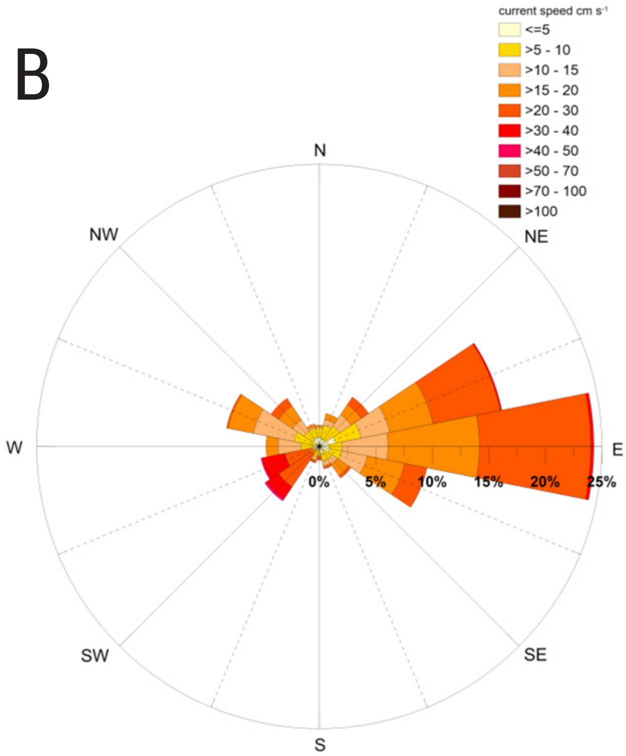
Fig. 6. Wind rose over sea in July 2013 in the region of the "Ustka Bay" (taken from the D point – Fig. 1)

requires that volume of fresh water inflowing from the river at the time is also taken into account. As no measurements of water flows are being conducted in the estuarial section of the Słupia River, in order to estimate the current volume of the water entering the sea, there was used the available information on daily average flows at the Słupsk gauging station (IMWM, 2014). The water gauge station in Słupsk is located at a distance of 31.6 km from the point where the river flows into the sea, and it covers 89.4% of surface of the water catchment area of the river (more accurate assessment of amount of river fluvial water entering the Ustka Bay may be obtained with use of data on water flow obtained from the Charnowo gauging station, located 11 km away from the estuary which covers 98.5% of the water catchment area) (IMWM, 1983). Data presented above show that to calculate proper volume of water which is brought into the sea by the Słupia River, it would be enough to increase the water discharge measured in Słupsk by 11%.

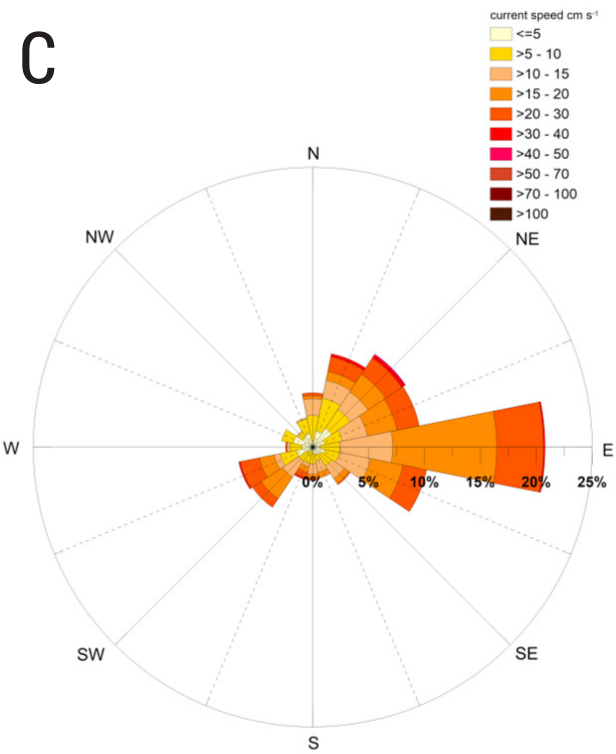
The course of annual changes in the daily average water flow of the Słupia river in particular months of the hydrological year 2013 (November 2012–October 2013) is presented in Fig. 9 by the blue bars. They were compiled with the estimated values of the average monthly water flows at the river mouth, with only the constant inflow of water from the river taken into account (red bars). We can observe here a high seasonal variability, e.g. in Słupsk the flow was 27.60 $m^3 s^{-1}$ in February, while in July it was only 9.69 $m^3 s^{-1}$, and the annual average was 14.76 $m^3 s^{-1}$. Because the measurements were carried out in the summer season, the volume of the river water entering the sea at that time of the year is the smallest in the year and almost twice smaller than in the winter season (during the period of meas-



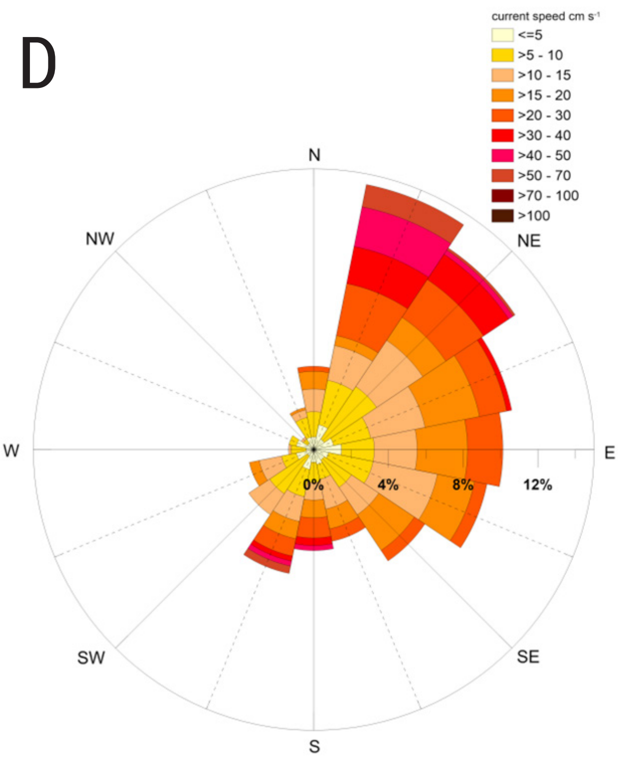
A. max. = 68.1 cm s^{-1}, mean = 22.7 cm s^{-1}



B. max = 42.2 cm s^{-1}, mean = 15.9 cm s^{-1}



C. max. = 40.9 cm s^{-1}, mean = 12.9 cm s^{-1}



D. max = 68.5 cm s^{-1}, mean = 15.1 cm s^{-1}

Fig. 7. Distribution of speed and directions of water flows at sea (point C, Fig.1) at the depths of 0–4 m (a), 4–8 m (b), 8– 2 m (c), and 12–15 m (d). Characteristic values of water flow's velocity are given.

urement performance, i.e. 20–22 July 2013, the daily average water flow was 10.2 $m^3\ s^{-1}$ in Słupsk and 11.3 $m^3\ s^{-1}$ at the river mouth).

Analysis of changes in the daily average water flows of the Słupia River based on data of the Słupsk water gauge station from the years 1984–2013 (IMWM, 2014 and earlier) allowed to determinate annual inflow of its waters to the sea over the past three decades (Fig. 10). Apparently, in 2013 this value (0.515 km^3) was below the average for the preceding 29 years (1984–2012) (0.548 km^3), and is one of the lowest values recorded over the studied three decades.

Summary and conclusions

Analysis of hydrophysical conditions of the sea across the entire cross-section of the water depth recorded in July 2013 along a section crossing the Ustka Bay, the Słupsk Strait, and the Słupsk Bank shows that the inflow of the fresh water from the Słupia River can have a visible impact on environmental conditions of seawater even up to the distance of 10 -15 nautical miles away from the shore (about 20 - 30 km). This situation can occur when stratification of seawater is stable and wind wave mixing is rather inconsiderable. The resulting images of distribution of hydrophysical parameters characterising this sea area reveal that process of mixing of water masses with various degrees of salinity follows a set order, in which there may be distinguished areas of water propagation and mixing generated by wind and wave motion.

It should be emphasized that the results presented herein have been derived from measurements conducted in the summer season, i.e. at the time of the year when inflow of river waters is the least intensive, and in 2013 it demonstrated one of the lowest levels recorded over the past three decades (1984–2013). It was concluded that in the period when the measurements described herein were being performed, the impact range of river water from the Słupia did not reach the area of the Słupsk Bank. It could have been observed affecting the surface of the sea only up to the region of the deepening (the Słupsk Strait) and near the foot of its slope. Values of seawater flow recorded from the surface to the bottom indicated that an alongshore movement of the water to the east was the dominating type of flow, which is consistent with directions of sea currents prevailing over the year in this region of the sea. It can be expected that in the other months of the year, when inflow of fluvial waters of the Słupia river is much higher, and when no strong winds over the sea surface during the longer period occur, the impact range of river waters on the sea may be discernible even at a greater distance from the shore covered by the Słupsk Bank area. However, further performance of such measurements is necessary to confirm this thesis.

In the studied area of the sea, there is clearly evident the influence of seabed relief and of depth of this region of the sea on distribution of hydrophysical parameters of water throughout the entire cross-section of the water depth. The most dense water could be found in the deepest layers of the water body. Layers of thermocline and halocline were at the depth of about 18 m. Thus fixed a stratification of water at sea is typical for the summer season.

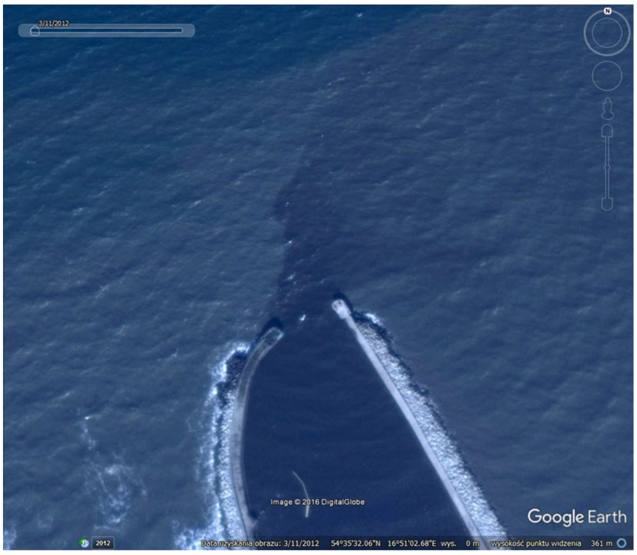


Fig. 8. Propagation of fresh water in the sea areas located northwards of the Słupia River mouth [March 11, 2012] *(source: Google Earth)*

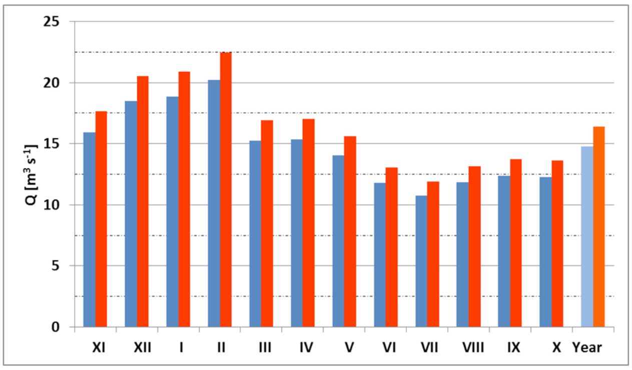


Fig. 9. The daily average water flow of the Słupia river in Słupsk in subsequent months of the hydrological year 2013 (blue) and estimated daily average water flow at the river mouth (red)

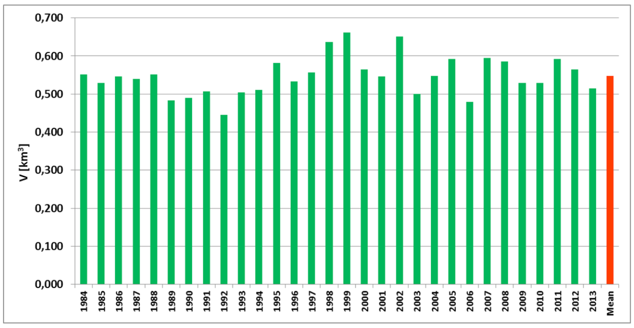


Fig. 10. Volumes of water outflowing annually from the Słupia river to the Ustka Bay in the years 1984–2013.

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