



Simulation of the impact of pollution discharged by surface waters from agricultural areas on the water quality of Puck Bay, Baltic Sea

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Abstract

The paper presents the analysis results of the impact of pollution discharged by surface waters on the quality of the Puck Bay waters. Puck Bay is part of the Gulf of Gdansk and belongs to the Baltic Sea. The analysis was carried out using mathematical modeling. A numerical model of part of the Gulf of Gdansk was achieved, taking into account the current bathymetry and the shoreline shape. The pollutants inflow was assumed point-by-point at the mouth of the main watercourses: Plutnica, Gizdepka, Bładzikowski Creek and the Reda River. The hydrodynamic conditions in the Bay were adopted for several scenarios regarding wind speed and direction. In order to determine the velocity distribution, the Ekman model—dedicated to shallow coastal waters—was used. The spread of pollutants in the Bay's waters was determined by solving a two-dimensional, partial differential, advection–dispersion equation describing the migration of a non-degradable dissolved matter. The finite volume method was used for the solution. As a result, the extent of pollution in the Puck Bay area was obtained in relation to Natura 2000—the European Union's protected areas. Visible is the necessity of integrating these conclusions into measure aiming at the mitigation of eutrophic processes in the Baltic Sea. The results of this research may be extended to serve other bay regions adjacent to similar substantial agricultural activities.

Keywords Baltic Sea · Coastal waters · Pollution migration modeling · Puck Bay · WaterPuck

Introduction

The quality of coastal waters depends mainly on the pollution discharged along the tributaries of rivers (to a lesser extent surface runoff, secondary pollution resulting mainly from eutrophication and direct pollution—mainly oil and chemicals) (Clark 2001). The genesis of these pollutants is usually associated with the runoff of rainwater from developed agricultural catchments. This may be the cause of eutrophication and water hypoxia. The Baltic Marine Environment Protection Commission—the Helsinki Commission (HELCOM) has recommended the reduction of this type of pollution in the Baltic Sea (Backer et al. 2010; Conley et al.

2009, 2011), including for Poland. In the first place, however, this requires the recognition of the problem.

The Baltic Sea, surrounded by agricultural areas of industrially developed countries, is considered to be one of the most polluted seas in the world (HELCOM 2000, 2007). According to a special report (ECA 2016), currently 97% of the Baltic Sea area is eutrophicated. Eutrophication can significantly reduce the biodiversity of the sea, destroying the appearance of the coast and worsening the habitat of fish. The main sources of biogenic substances reaching the sea are loads transported by rivers, and direct discharges from the coast. Loads of pollutants in water account for 78% of the total nitrogen load and 95% of the total phosphorus load that enters the Baltic Sea. The presented report (HELCOM 2017) shows that the two most important sources of water loads of nutrients are dispersed sources, mainly agriculture (45% of the nitrogen load and 45% of the phosphorus load) and point sources, mainly municipal sewage (12% of the nitrogen load and 20% of the phosphorus load). In Poland, this problem particularly affects areas in the Gulf of Gdansk, where water exchange is impeded. Here, one main cause of poor water conditions is pollution supplied by the local

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watercourses and rivers from agricultural areas. In particular, this problem concerns Puck Bay, where surface water flows from agricultural areas of the Puck District (Fig. 1). The Puck Bay is classified as moderately contaminated with heavy metals. As in other Baltic regions, this is indicated by the coefficients of anthropogenic enrichment, with values as follows: Hg 3.1, Cd 2.0, Pb 2.4, Zn 3.1, Cu 2.1, Cr 2.2 (Kruk-Dowgiałło and Szaniawska 2008; Zalewska et al. 2015).

Materials and methods

Numerical model of the study area

Over the past 20 years, work has been carried out on modeling hydrodynamics and pollution migration in the area of the southern Baltic and the Gulf of Gdansk (Kowalewski 2001; Jedrasik 2005; Kowalewska-Kalkowska et al. 2007; Pырchła et al. 2016). The emerging models are mainly adaptation of ocean models, and their scale in the area of the Bay of Puck is insufficient for modeling on a local scale. For this reason a numerical model of part of the Gulf of Gdansk was made in order to analyze the impact of pollution from agricultural areas of the Puck District (Fig. 2). In addition to the watercourses from the Puck area, the largest Polish river, the Vistula, was included. The Vistula flows into the Gulf of Gdansk at its southern end, creating a delta at the estuary composed of: Vistula Przekop, Vistula Śmiała and

Vistula Martwa. In addition to the Vistula, several watercourses from adjacent catchments supply the Gulf, but their hydrographic role for the model is negligible (Kalinowska et al. 2018).

Puck Bay is the western branch of the Gulf of Gdansk in the southern Baltic Sea, separated from the open sea by the Hel Peninsula (Figs. 1, 2). The Polish Coastal Landscape Park covers a large portion of the Bay, while another part is a special protection area for birds and a popular place in Poland for water sports, especially kitesurfing. It is a shallow bay with an average depth of 3 m and numerous shoals not deeper than 1 m, which hampers the exchange of water in the Bay. For this reason, it is important to keep its waters clean and to prevent excessive pollution from the adjacent agricultural catchment located in the Puck District, drained by numerous rivers and springs (which is confirmed by research conducted in this area: Graca 2004; HELCOM 2007, 2017; Kruk-Dowgiałło and Szaniawska 2008; Łysiak-Pastuszek et al. 2004; Zalewska et al. 2015). The most important are: Plutnica, Gizdepka, Bładzikowski Creek, and the largest of them, the Reda River. A mathematical model of coastal waters in the area of the Bay of Puck was made, covering almost the entire Gulf of Gdansk (with bathymetry), including the estuary of the Vistula River (Fig. 2).

Meteorological conditions

The hydrodynamic conditions in the Gulf of Gdansk depend largely on meteorological conditions, mainly on the direction

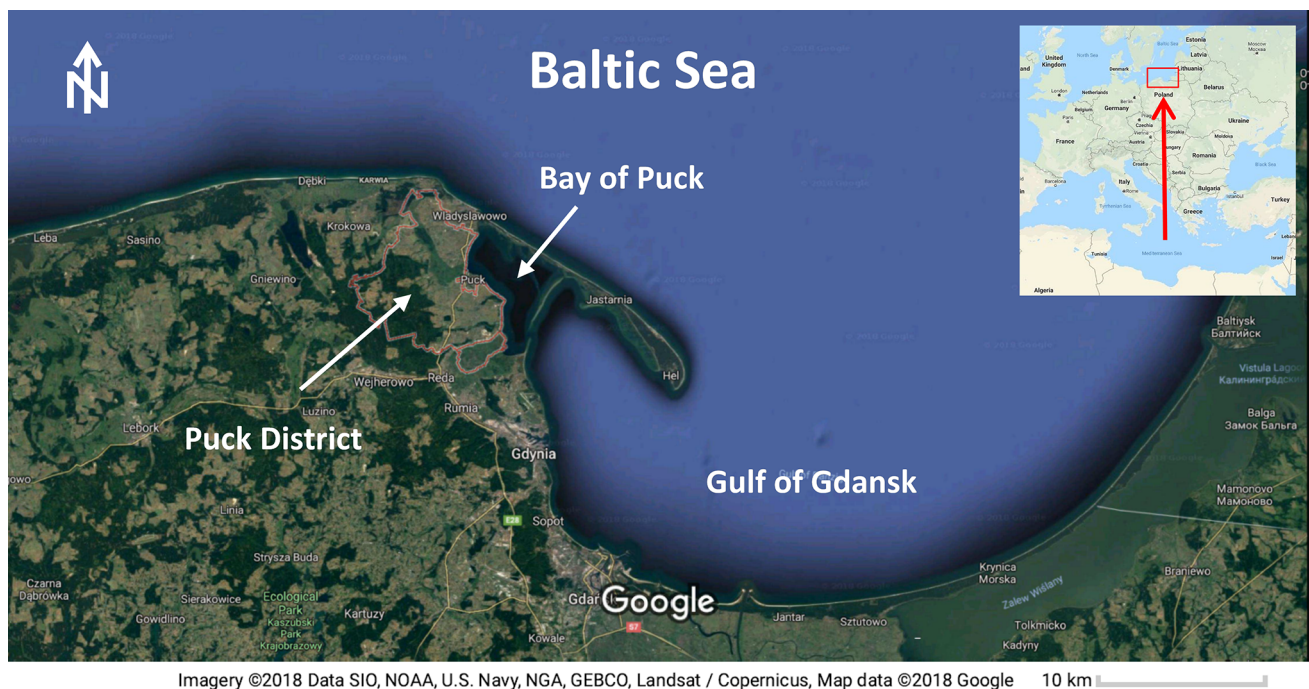
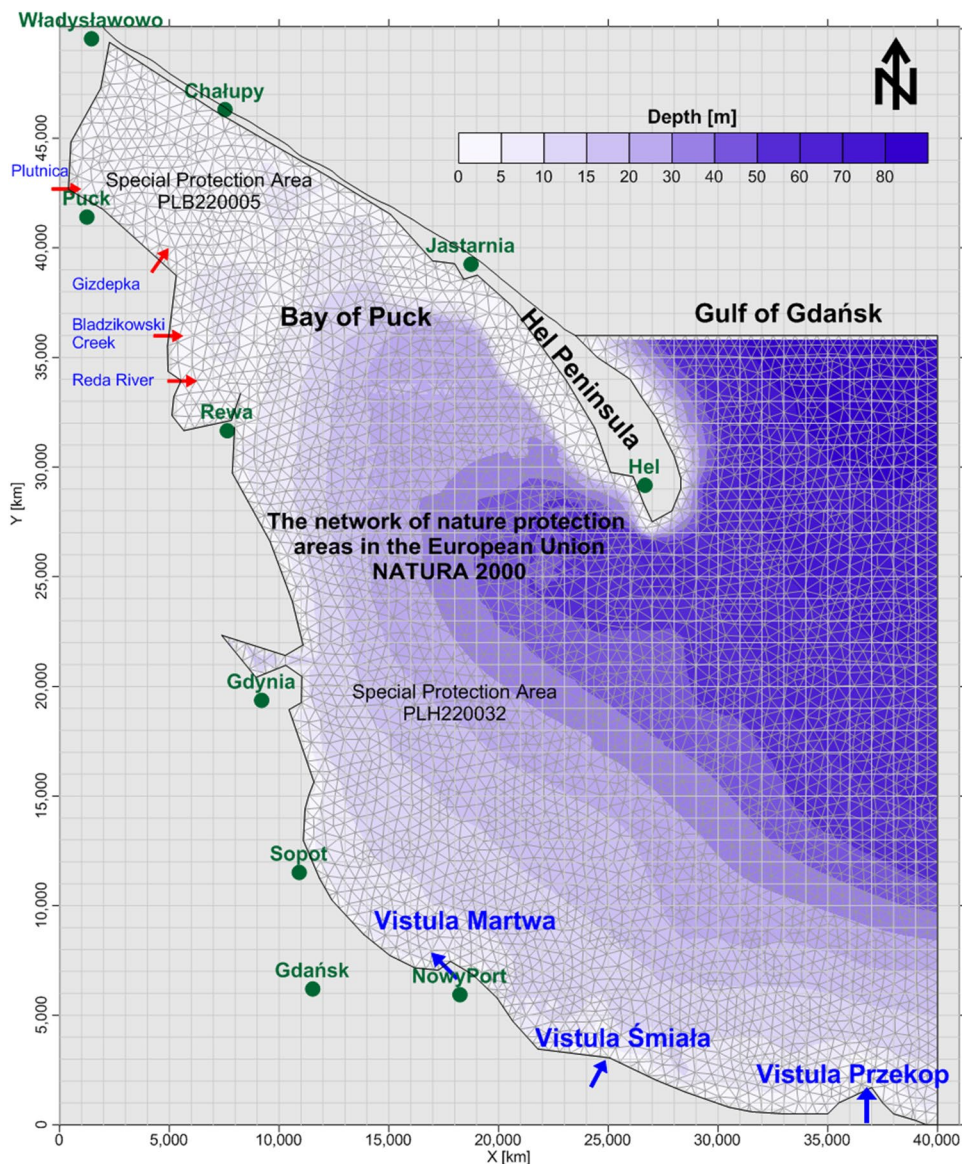


Fig. 1 Map of the study area (source: Google Maps, accessed 20 August 2018)

Fig. 2 Adopted mathematical model of coastal waters of the analyzed area



and speed of the wind. For the purpose of this study, meteorological data from the past 15 years were analyzed from a meteorological station located in Gdansk, near the analyzed area. Table 1 shows the average monthly wind speeds with the dominant direction. Additionally, Fig. 3 shows the wind rose plot from this period. As you can see, west winds prevail in this area. This fact influenced the adopted simulation scenarios. The average wind speed of $5 \text{ [m s}^{-1}\text{]}$ was used for calculations.

Model of velocity distribution

Mathematical modeling of the migration of pollutants in water areas requires solving two issues: determining the hydrodynamic conditions in the analyzed area (adopting the velocity distribution for specific hydrometeorological conditions) and then the simulation of pollutant migration (Szymkiewicz 2010). In the case of shallow water bodies (such as the coastal waters of the Bay), the most commonly used mathematical

Table 1 Wind statistics data from a meteorological station located in Gdansk

Month of the year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Dominant wind direction	W	W	W	WNW	NE	W	W	W	W	WSW	WSW	WSW	W
Average wind speed (m s^{-1})	5.5	4.4	5.4	5.5	5.5	5.2	5.0	4.5	4.4	4.2	4.5	4.6	4.9

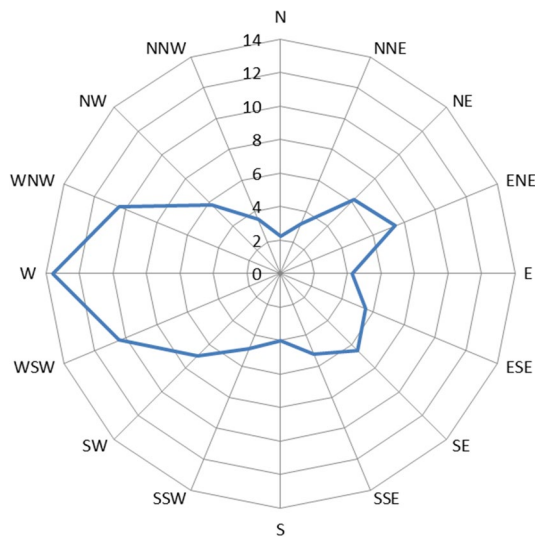


Fig. 3 Wind rose (wind direction distribution in %) from the past 15 years for the analyzed area

model is the two-dimensional model. Different approaches can be noted in this regard, the most developed in this area being the Shallow Water Equations (SWE) (Tan 1992). The SWE refer to the basic conservation equations in which the wind tension on the water surface has been determined to the extent of tangential stresses. More simplified approaches may be used where the effects of wind on the surface of water are taken into account in kinematics models (Zima 2018b). The most simplified are models that take into account the distribution of water velocity depending on meteorological conditions. The Ekman model belongs to this group (Welander 1957). It is recommended for shallow sea waters (Duke 2001). In this model, the components of the water velocity vector field are calculated based on the wind speed:

$$|\mathbf{u}| = 0.0106 \cdot |\mathbf{w}|_{10}^{1.5} \cdot h^{-0.5} \tag{1}$$

where $\mathbf{u} = (u_x, u_y)$ —two-dimensional vector of surface water velocity (m s^{-1}) (towards the wind), $\mathbf{w} = (w_x, w_y)$ —two-dimensional vector of wind velocity (m s^{-1}) at a height of 10 m, x, y —space coordinates (m), h —depth of water (m). By applying Eq. (1), the steady water velocity distribution for given wind conditions can be calculated.

Model of pollution migration

Water quality modeling requires the adoption of a model adequate to the complexity of the problem, and expectations in relation to the obtained result. Process-based (mechanistic) models allow one to simulate the majority of processes

to which pollution is subject (Waite 1984; Chapara 1994). Most of the processes (especially biological ones) reduce the concentration of the pollutants and improve the quality of water. This also affects the limitation of the area of their impact on the environment. The course of these processes very often depends on additional factors that are difficult to predict without very detailed data. Omitting them will allow the most unfavorable result to be obtained, i.e. the maximum impact on the environment. For this purpose, a two-dimensional, partial differential, advection–dispersion equation describing the migration (transport) of a non-degradable dissolved matter was used in the following form (Crank 1975; Sawicki and Zima 1997):

$$\begin{aligned} \frac{\partial(hc)}{\partial t} + \frac{\partial(hu_x c)}{\partial x} + \frac{\partial(hu_y c)}{\partial y} \\ = \frac{1}{h} \frac{\partial}{\partial x} \left(hD_{xx} \frac{\partial c}{\partial x} + hD_{xy} \frac{\partial c}{\partial y} \right) \\ + \frac{1}{h} \frac{\partial}{\partial y} \left(hD_{yx} \frac{\partial c}{\partial x} + hD_{yy} \frac{\partial c}{\partial y} \right), \end{aligned} \tag{2}$$

where t —time (s), c —concentration of dissolved matter (pollution) (kg m^{-3}), D_{xx}, D_{xy}, D_{yy} —coordinates of the dispersion tensor ($\text{m}^2 \text{s}^{-1}$). The coordinates of the dispersion tensor \mathbf{D} are defined as follows:

$$D_{xx} = D_L n_x^2 + D_T n_y^2, \tag{3a}$$

$$D_{xy} = D_{yx} = (D_L - D_T) n_x n_y, \tag{3b}$$

$$D_{yy} = D_L n_y^2 + D_T n_x^2 \tag{3c}$$

where $\mathbf{n} = (n_x, n_y)$ [1] is the directional velocity vector:

$$n_x = \frac{u_x}{|\mathbf{u}|}, n_y = \frac{u_y}{|\mathbf{u}|} \tag{4}$$

Longitudinal D_L ($\text{m}^2 \text{s}^{-1}$) and transverse D_T ($\text{m}^2 \text{s}^{-1}$) coordinates of the dispersion tensor (Eq. (3a–3c)) are described by the Elder formulas (Elder 1959):

$$D_L = \alpha \cdot h \cdot v * \quad 30 < \alpha < 3000, \tag{5a}$$

$$D_T = \beta \cdot h \cdot v * \quad 0.15 < \beta < 0.30, \tag{5b}$$

where $v *$ is the dynamic velocity (m s^{-1}). In this paper, the values of coefficients α [1] and β [1] were estimated based on available studies (Rutherford 1994; Wielgat and Zima 2016; Zima 2018a). The finally adopted values are $\alpha=300$ and $\beta=0.23$. These values were confirmed during the studies carried out earlier in wide and shallow rivers (Kalinowska et al. 2012).

Numerical method

Using Eq. (1), you can easily calculate the components of the velocity vector at any point in the area. In contrast, the simulation of pollutant migration requires the solution of the partial differential equation (Eq. (2)). In some cases, exact (analytical) solutions of this equation are available; in other cases, the equation must be solved numerically using computational methods. In this paper, Eq. (2) was solved using the Finite Volume Method (FVM) (LeVeque 2002), and a continuous area (domain) of the solution was discretized and covered with a mesh of triangular elements (Fig. 2). Applied to solve the unsteady transport equation, FVM refers to physical conservation laws on the level of control volumes. This can be described by the homogeneous hyperbolic equation (LeVeque 2002):

$$\frac{\partial(hc)}{\partial t} + \frac{\partial(hF_x)}{\partial x} + \frac{\partial(hF_y)}{\partial y} = 0; \tag{6}$$

therefore, fluxes (F_x and F_y) on the cell edges in Eq. (6) will also be in line with the directions of the orthogonal coordinate system (x and y). The form of the flux vector components [$\mathbf{F} = (F_x, F_y)$ ($\text{kg s}^{-1} \text{m}^{-2}$)] in the x and y directions will be as follows:

$$F_x = u_x c - \frac{1}{h} D_{xx} \frac{\partial c}{\partial x} - \frac{1}{h} D_{xy} \frac{\partial c}{\partial y}, \tag{7a}$$

$$F_y = u_y c - \frac{1}{h} D_{yy} \frac{\partial c}{\partial y} - \frac{1}{h} D_{yx} \frac{\partial c}{\partial x}, \tag{7b}$$

where the first part of the flux definition [$\mathbf{u}c$ ($\text{kg s}^{-1} \text{m}^{-2}$)] is the advection part of Eq. (2), and the remainder is the dispersion part of Eq. (2). This approach is a modification of the classic FVM theory obtained by the addition of two independent, additive fluxes (superposition property): advection flux and dispersion flux. As a result of the integration of Eq. (6) in each finite volume i and the application of the Gauss-Ostrogradski theorem, we obtain the following equation:

$$\frac{\partial(hc)_i}{\partial t} \Delta A_i + \oint_{L_i} (\mathbf{F} \cdot \mathbf{n}) dL = 0, \tag{8}$$

where ΔA_i , L_i —area (m^2) and length of the edge (m) of the cell i . The integral in Eq. (8) can be replaced by the sum of three components (for triangular cells):

$$\frac{\partial(hc)_i}{\partial t} \Delta A_i + \sum_{e=1}^3 (\mathbf{F}_e \cdot \mathbf{n}_e) \Delta L_e = 0, \tag{9}$$

where \mathbf{F}_e —numerical vector of flux ($\text{kg s}^{-1} \text{m}^{-2}$) (Eq. (7a, 7b)) estimation at the cell edge e and normal to this edge,

$\mathbf{n}_e = (n_{ex}, n_{ey})$ —unit vector [1] of the orthogonal coordinate system (x, y).

In order to determine the numerical fluxes \mathbf{F} (Eq. (7a, 7b)) by the cell edges in the advection equation, the second-order Lax–Wendroff scheme was used (Potter 1980). In the case of the dispersion part of the transport equation, the central differential schemes were used. In the method of integrating Eq. (9), it was assumed that the control area is the equivalent of a grid cell. This approach means that the values of components of the velocity vector \mathbf{u} are given in grid points and the functions of concentration c located in the central points of cells are unknown (Fig. 4). The calculation of intermediate values positioned between grid nodes (which are needed in determining the value of fluxes by individual cell edges) was determined by averaging the neighboring values. This approach was applied to the functions of concentration c , depth h and velocity vector components u_x and u_y .

The numerical derivatives in the global coordinate system (x, y) were determined by the following one-parameter family of minmod-like limiters ($r = \langle x, y \rangle$, m —time level) (Kurganov and Tadmory 2000):

$$\left(\frac{\partial c}{\partial r}\right)_i^m = \text{minmod}\left(\theta \frac{c_i^m - c_{i-1}^m}{\Delta r_{i-1}}, \frac{c_{i+1}^m - c_{i-1}^m}{\Delta r_{i-1} + \Delta r_{i+1}}, \theta \frac{c_{i+1}^m - c_i^m}{\Delta r_{i+1}}\right), \tag{10}$$

where θ —constant parameter [1]. In addition, two conditions must be satisfied: CFL condition and maximum principle (Kurganov and Tadmory 2000). The parameter $\theta \in \langle 1, 2 \rangle$. Note that $\theta = 2$ corresponds to the least dissipative limiter, whereas $\theta = 1$ ensures a non-oscillatory nature of the solution. In this paper $\theta = 1$.

Analyzing the fluxes \mathbf{F} between elements covering the continuous area of the solution, one can build a system of related differential equations in time. The second-order

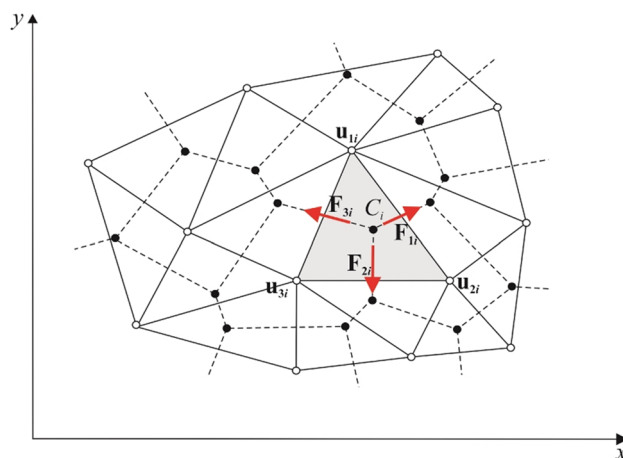


Fig. 4 Discretization of the domain into two-dimensional triangular cells and adoption of the parameters of the models used in the numerical solution

explicit Runge–Kutta method was used to solve the system of these equations (LeVeque 2002). Finally, we obtain in each element i a differential analog of Eq. (9) from which you can directly determine the function of c at the time level $m + 1$ (explicit scheme).

In order to obtain the solution, the distribution of surface velocity in the Gulf caused by wind stresses was adopted in accordance with the Ekman model (Eq. (1)). The inflow of pollution was assumed on the edge of the area (as a point), taking into account the multi-year average flow in all watercourses (streams, creeks and rivers) and a constant concentration of 100%. The pollution migration equation is a partial differential equation that describes the distribution of concentration in a given region over time. To solve this, additional conditions must be met: initial and boundary conditions. The initial condition in this case is the concentration of pollution in the domain at the beginning of the simulation (for $t=0$)— $c(x, y, t=0) = c_0$. The study assumed $c_0 = 0\%$, to achieve the purpose of the work described in the title. Additionally, boundary conditions should be defined at the edge of the domain. There were two types of boundary conditions. A Neumann-type condition was used on the impermeable edge (physical boundary), in the following form:

$$\frac{\partial c}{\partial n} = 0, \quad (11)$$

where Eq. (11) means that a normal mass flux to the edge is equal to 0. The application of this condition required the appropriate modification of the final version of the differential analog of Eq. (2). On the other hand, a Dirichlet-type condition was used on the permeable edge (mathematical boundary):

$$c = \text{const} \quad (12)$$

The application of this condition consists of adopting Eq. (12) directly in the computational node i .

Results and discussion

As a result of numerical simulations, the maximum distribution of concentrations of pollution flowing with surface waters into the area of the Bay of Puck was obtained (the inflow of pollutants with groundwater from a nearby aquifer is the subject of research conducted by Potrykus et al. (2018) and has not been included in this paper). The calculations were carried out for three wind condition scenarios resulting from meteorological data and the shape of the Bay: wind from the northwest (NW), southeast (SE) and west (W) by 5 m s^{-1} . The calculations were carried out until the pollution distribution was established (no less than 24 h). The results are presented in Fig. 5 (for the NW wind), in Fig. 6 (for the SE wind) and in Fig. 7 (for the W wind). The selection of

scenarios was made taking into account the most unfavorable conditions in terms of pollutant migration towards the nearest protected areas. The shape of the bay with respect to the wind direction (for this reason the scenario for NW and SE wind were adopted) and dominant wind direction (scenario for W wind) were taken into account. Simulation results obtained for winds from other directions did not show any threat of contamination of protected areas by pollutants flowing from the analyzed agricultural areas of the Puck District. In these cases, the pollutants were “pressed” towards the shore, and their range was limited. Unfavorable results were obtained in the case of the presented scenarios in Figs. 5, 6 and 7. In the worst case, the pollution reaching the sea connects and covers a large part of the Puck Bay waters. It spreads over an area of about 20 km along the shore and penetrates for a distance of about 10 km into the Bay (approaching the shores of the Hel Peninsula), affecting the Natura 2000 protected areas. Unfortunately, these results confirm the suspicions that in favorable hydrometeorological conditions, Natura 2000 sites will be polluted. This fact confirms the need to make a hydrodynamic model of the Puck Bay in order to accurately determine the impact of pollution from agricultural areas on coastal waters in region of Puck.

There is also the problem of validating the obtained results of numerical simulations. The properties of the applied numerical method of solving Eq. (1) are known in the literature (Kurganov and Tadmory 2000).

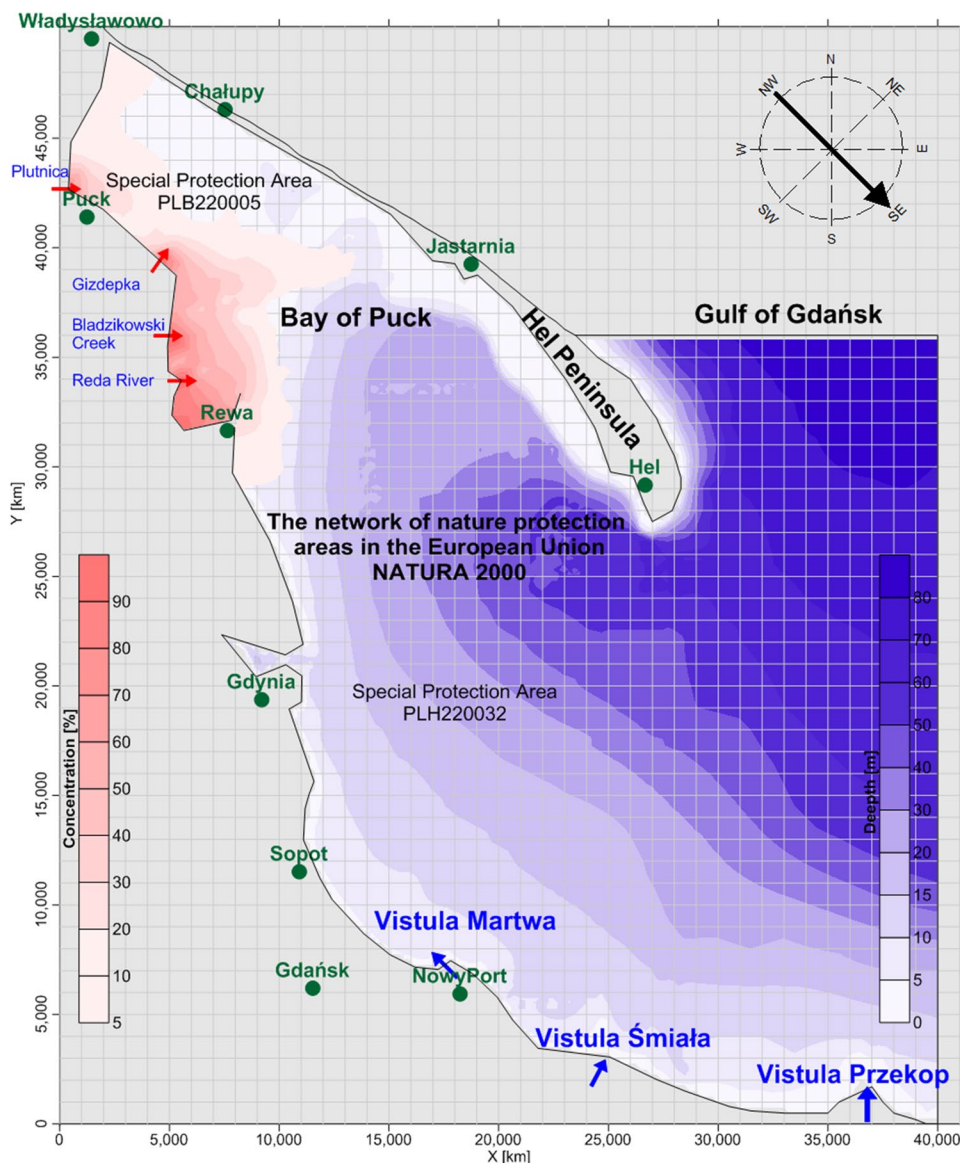
The applied model has also been positively verified in real conditions at (Wilegat and Zima 2016). At this stage of the work, using a simplified model of water circulation in the bay, the obtained results allowed to identify potential sources of contamination of nearby protected areas Natura 2000 and to determine the direction of further work on creating a model of the Puck Bay. In Puck Bay, research is carried out confirming the presence of biogenic substances of agricultural origin (Szymczycha et al. 2017a). However, further into the Gulf of Gdansk, nutrient concentrations are on an average level observed in the southern Baltic (HEL-COM 2017; Szymczycha et al. 2017b). This fact confirms the results obtained using the model proposed in this paper.

The analysis carried out concerns the migration of pollutants in the form of non-degradable dissolved matter. The comprehensive model will require taking into account the transport of substances in various forms, from dissolved to suspended.

Conclusions

The conducted research has shown that watercourses discharging water from areas adjacent to Puck Bay have a significant impact on the quality of its water and affect their

Fig. 5 Distribution of the concentration of non-degradable dissolved matter in the area of Puck Bay for the NW wind

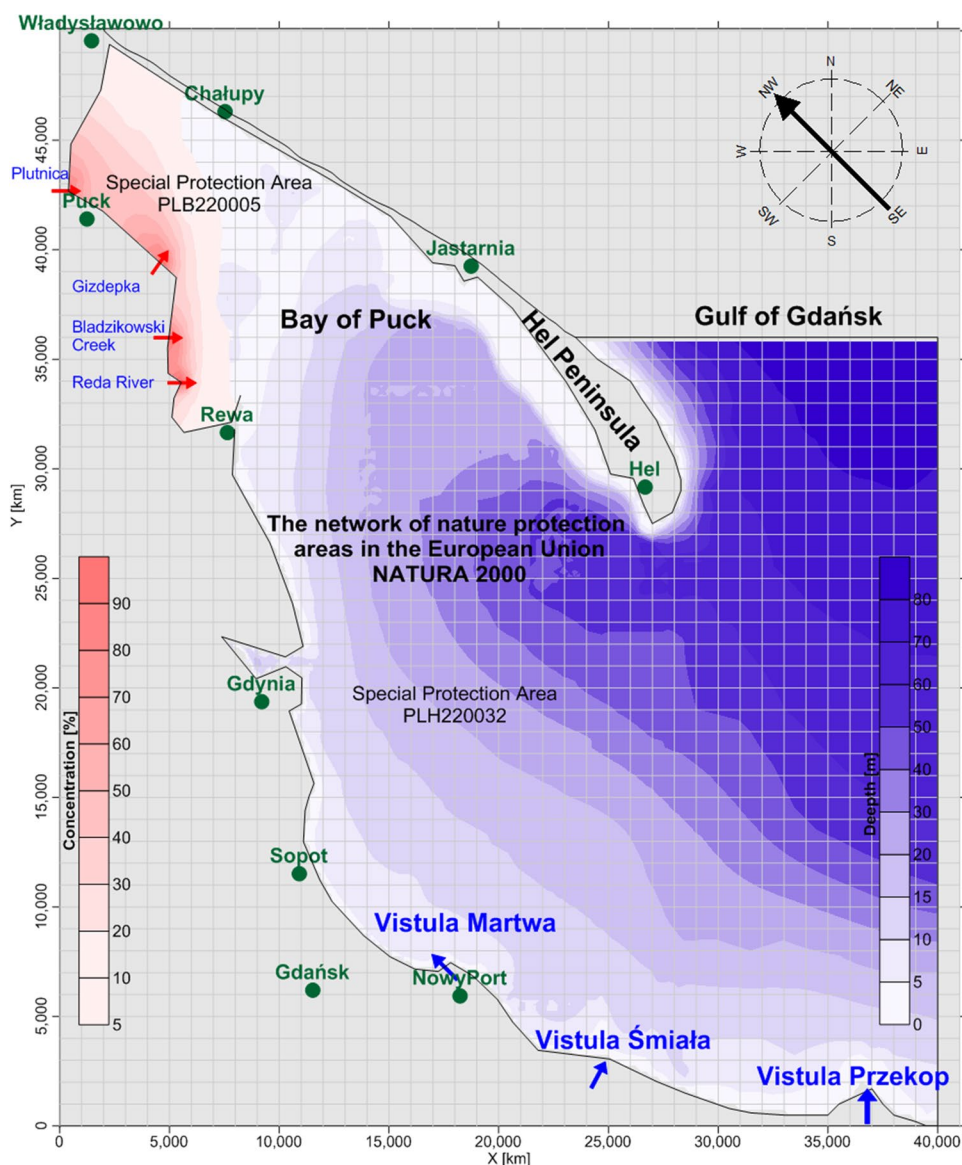


eutrophication. Taking into account the growing pressure of agriculture on the environment, an increase in the costs of the mitigation of eutrophic processes in the Baltic Sea is expected. In addition, the attractiveness for tourists of the Bay of Puck is decreasing.

The creation of a comprehensive model of the Puck Bay will require taking into account the type of pollution and many forms of their occurrence. The most visible effect of the eutrophication process is increased turbidity. It depends mainly on the presence in water of various insoluble inorganic and organic compounds of natural or anthropogenic origin, such as: particles of rocks and soils, compounds of iron, manganese, calcium and phosphorus, humic substances, plankton and higher microorganisms. The nitrogen compounds present in surface waters can be of organic and inorganic origin. Most often inorganic forms of nitrogen

appear, such as: ammonium nitrogen, nitrate nitrogen (III) and nitrate nitrogen (V). Planktonic organisms (phytoplankton, bacteria) can assimilate nitrogen from various chemical compounds (inorganic and organic), and some (e.g. cyanobacteria) also bind atmospheric nitrogen. The ammonium nitrogen (ammonia) present in surface waters comes from the biochemical decomposition of organic nitrogen compounds of plant and animal origin. Due to the biochemical decomposition of nitrogen compounds, ammonia is formed, present in water in the form of ammonium ions. In an aerobic environment, these ions transform into nitrates (III), which in the presence of Nitrobacter bacteria are easily oxidized to nitrates (V). However, in anaerobic conditions, the formation of nitrates (III) is combined with the reduction of nitrates (V). Total nitrogen is the sum of organic nitrogen and ammonium, nitrate (III) and nitrate (V) nitrogen,

Fig. 6 Distribution of the concentration of non-degradable dissolved matter in the area of Puck Bay for the SE wind



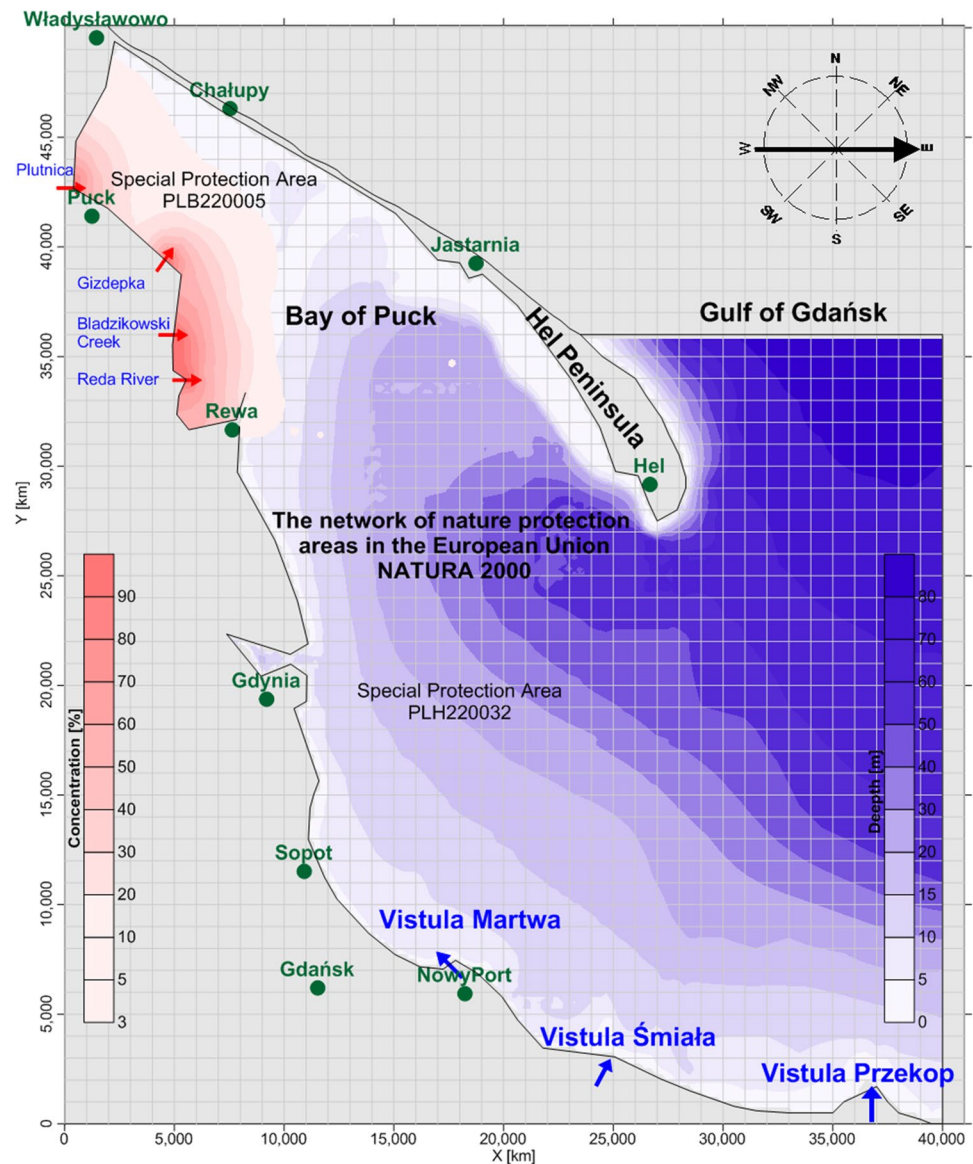
forming the sum of nitrogen inorganic forms (Ghaly and Ramakrishnan, 2015).

The phosphorus compounds, both organic and inorganic, including soluble and insoluble in water, exert a very strong influence on the eutrophication of surface waters. They come mainly from fertilizers, plant protection products and soil erosion. In an aqueous environment, phosphorus is in the form of phosphates (V) and is used in a form dissolved by aquatic organisms to build their own

cells. Insoluble phosphates form floating suspensions in water or occurring in bottom sediments.

These studies allowed only the formulation of the basic assumptions for the research project (in short called WaterPuck) supported by the National Centre for Research and Development within the BIOSTRATEG III program no. BIOSTRATEG3/343927/3/NCBR/2017. Under this program, a system to calculate the maximum allowable amount of fertilizers to be used on fields, together with the

Fig. 7 Distribution of the concentration of non-degradable dissolved matter in the area of Puck Bay for the W wind



determination of their impact on the environment of the Baltic Sea in the area of Puck Bay, will be created.

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Compliance with ethical standards

Conflict of interest The author declare no conflict of interest.

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