POLISH MARITIME RESEARCH 2 (102) 2019 Vol. 26; pp. 76-84
10.2478/pomr-2019-0027

NUMERICAL ANALYSIS OF AN IMPACT OF PLANNED LOCATION OF SEWAGE DISCHARGE ON NATURA 2000 AREAS – THE DEAD VISTULA REGION CASE STUDY

Piotr Zima
Gdańsk University of Technology, Faculty of Civil and Environment Engineering, Poland

ABSTRACT

This article presents results of an analysis of impact of a designed discharge of contaminated water into the Dead Vistula (Wisła Martwa) in the region of the Isthmus (Przesmyk) with the aim of determination of a possible effect of the pollution onto protected areas of Natura 2000 (bird habitats and sites, especially the Bird Paradise – Ptasi Raj) nature reserve. The analysis was conducted on the basis of the two-dimensional modelling of unsteady transport of non-degradable dissolved matter. To this end, a numerical model of a section of the Dead Vistula was worked out. Four scenarios of hydro-dynamical conditions (2 – for average weather conditions and 2 – for stormy weather conditions) were selected. To solving the equation of pollution migration the finite volumes method (MOS) was applied. Two localizations of contaminated water discharge outlet were considered, namely: the first from the side of Siennicki Bridge before the Isthmus and the other in the section of the Brave Vistula (Wisła Śmiała) downstream the Isthmus. The obtained results made it possible to assess positively the first localization of the designed discharge outlet. In the other case there is a fear that at unfavourable hydro-meteorological conditions a water pollution may happen over Natura 2000 protected areas.

Keywords: Numerical simulations, pollution migration, method of finite volumes, dispersion

INTRODUCTION

In Computer simulations of pollution migration in rivers are an important tool for aiding design projects in the scope of localization of sewage discharge outlets. They can be also used for analyzing dispersion of pollutants and their impact on receiving body waters and surrounding environment [20, 21]. This is especially important in the case of water areas close to protected regions for which a sewage discharge localization may form a threat of pollution. Unfavourable changes in water physical, chemical or bacteriological features may then occur due to introducing excessive amounts of inorganic and organic substances or water of an elevated temperature. Each of the factors (even in a small quantity) may unfavourably affects natural biocoenosis in water environment, that especially in protected regions may disturb homeostasis, i.e. a dynamic equilibrium in which the ecosystem remains [10]. The following anthropogenic pollutants of surface waters belong to the most frequently occurring [7]: pesticides, surface active substances, crude oil hydrocarbons, phenols, polychlorinated biphenyls and heavy metals (lead, copper, chrome, cadmium, mercury and zinc). Warm water (thermal pollution) is also a threat which may be especially dangerous for surface waters stagnant or slow running. Most of the anthropogenic water pollutants act toxically onto water organisms and some of them may be deposited in the ecosystem for a long time. For this reason it is important to correctly locate sewage discharge outlets and estimate their effect on a sewage receiving body. One of the methods to do it is to perform an analysis of such discharge by using computer simulation based on mathematical modelling.

Mathematical modelling of contamination spreading may be conducted in many ways [16]. The first phase of such

Fig. 1. Image of the Dead Vistula region with marked Natura 2000 protected areas and planned localization sites of contaminated water discharge outlets (based on: ortophotomap received from http://mapy.geoportal.gov.pl)

procedure is to work out a mathematical model of a considered object. Then, a mathematical model for description of factors affecting an analyzed process should be formed [19, 2]. In case of pollution migration it is necessary to combine into a functional whole at least two important elements: a water flow description model and pollution transport description model. The notion of "pollution" is related, in this case, to every factor which is discharge in an excessive amount to receiving body.

This paper presents an analysis of effects of designed sewage discharge to the Dead Vistula, performed with the use of numerical simulations. This case constitutes one of the concepts of localization of of the discharge and is an interesting issue due to dispersion conditions of the contaminated water. The analysis was focused on a site close to the marina and a specific pass in the Dead Vistula region, where water flow is very diversified spatially. Around the discharge site water flow direction depends on hydro-meteorological conditions. In the neighbourhood of the marina flow velocity ceases practically to zero forming dead zones of difficult exchange of water. Next, the water flows towards the pass in which due to the narrowing its velocity increases many times. Behind the pass there is a short section of the Brave Vistula with neighbouring terrain of Natura 2000 protected areas (bird habitats and sites, in particular, the nature reserve Ptasi Raj – Birds' Paradise) (Fig. 1). Close localization of the designed sewage discharge installations requires to perform an analysis of their effect on the protected areas.

The Dead Vistula is a part of the hydrographically complicated estuary which has been formed for the last centuries. (Fig. 1). The region is characteristic of mutual interaction of inland and sea waters. The Dead Vistula is connected to sea through two arms: the New Port canal and Brave Vistula. This fact significantly affects hydrodynamic conditions present in the Dead Vistula, in which water motion is determined first of all by sea states and blowing winds. An analysis of meteorological data recorded for the last 15 years showed that over the considered area the westerly winds of the mean speed of abt. 5 m/s dominate [22]. There were also observed winds of 15 and 25 m/s speed from this direction [8]. In this work the case of the easterly wind of 5 m/s speed was also taken into account, the significant case affecting the spread of contaminations in the area of potential sewage discharge localization sites.

MATHEMATICAL MODEL

In case of broad rivers the most frequently applied are flat two-dimensional models vertically averaged (in depth) in which a real flow area is represented by the two-dimensional flow in x-y plane [17, 15, 16]. The works associated with an analysis of contamination spreading require first of all to determine hydrodynamic conditions occurring in a receiving body. In rivers it can be achieved by determining velocity distribution as well as water depth (resulting from ordinates of bottom and water surface level). In this paper the results of simulation of hydrodynamic conditions in the considered area, carried out for a few extreme calculation scenarios, were taken into account acc. [22].The results were obtained from a simplified model by solving a modified Helmholtz equation [1], in which effect of wind generated stresses was taken into consideration. Four scenarios on hydro-meteorological conditions resulting from sea states and wind speed were assumed. For the conditions, the calculations of spreading the contamination in the form of a dissolved, permanent, non-degradable matter were performed. Localization of two potential discharge outlets in the considered section of the Dead Vistula (Fig. 1) as well as their impact on the neighbouring Natura 2000 protected areas were analyzed. The localization sites were selected based on an analysis of economic conditions for a potential industrial plant situated on a free industrial development area in this region.

THE ASSUMED SOLUTION SPACE AND SPEED DISTRIBUTION

In compliance with the assumed scope of the work the results of calculation of velocity distribution presented in [22] were used for simulation of pollution transport. There was assumed a numerical model with taking into account bathymetry of the section of the Dead Vistula from the cross-section at Siennicki Bridge up to the cross-section at Sobieszewo (abt. 8,5 km long) together with 2,5 km section of the Brave Vistula up to its outlet to the Bay of Gdansk. By making use of the available data on the measurement calculation cross-sections (20 transverse cross-sections of the river bed) the numerical model of the river bed along the considered section of the Dead Vistula was generated (Fig. 2). The bathymetry between the measurement cross-sections was generated by linear interpolation.

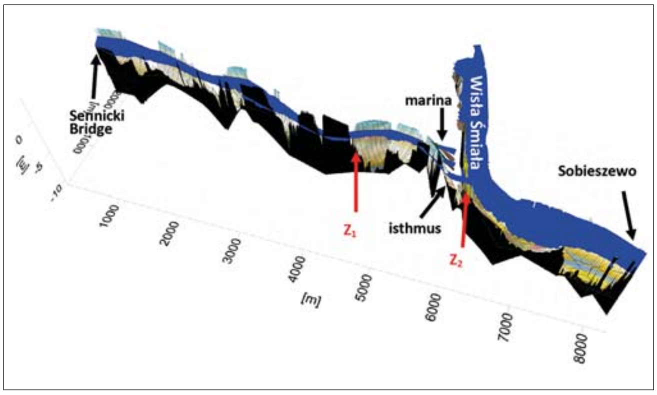

Fig. 2. Numerical model of the section of the Dead Vistula from Sobieszewo Bridge up to its outlet to the Bay of Gdansk together with the branch from the Watershed (Przełom) up to Siennicki Bridge (Z_1, Z_2 – planned sewage discharge localization sites)

In the publication [22] there were presented the results of hydrodynamic simulations for 4 hydro-meteorological conditions (for a given sea state, water level in the Dead Vistula as well as wind direction and speed – Tab. 1). The conditions (in the form of two-dimensional fields of water velocity and depth) were taken as input data to pollution transport model in order to determine their impact on water state in the receiver body and Natura 2000 protected areas. Two scenarios for the moderate conditions were assumed, namely: the easterly and westerly winds of 5 m/s speed and two scenarios for the extreme conditions – the westerly winds of 15 m/s and 25 m/s speed, respectively. The extreme conditions were assumed based on the available data from hydro-meteorological measurements and observations [8].

TRANSPORT EQUATION FOR DISSOLVED SUBSTANCE

Transport of indecomposable substance dissolved in two-dimensional space can be described by means of the following equation [3, 13, 14]:

$$\frac{\partial(hc)}{\partial t}+\frac{\partial(hu_x c)}{\partial x}+\frac{\partial(hu_y c)}{\partial y}=$$
$$\frac{1}{h}\frac{\partial}{\partial x}\left(hD_{xx}\frac{\partial c}{\partial x}+hD_{xy}\frac{\partial c}{\partial y}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(hD_{yx}\frac{\partial c}{\partial x}+hD_{yy}\frac{\partial c}{\partial y}\right) \quad (1)$$

where: t – time, x, y – spatial variables, h – depth, c – dissolved matter concentration, u_x, u_y – coordinates of the velocity vector **u**. The coordinates of the dispersion tensor **D** are defined as follows [5]:

$$D_{xx} = D_L n^2_x + D_T n^2_y$$
$$D_{xy} = D_{yx} = (D_L + D_T)\, n_x n_y \quad (2)$$
$$D_{yy} = D_L n^2_y + D_T n^2_x$$

where: n_x, n_y – the coordinates of the velocity field directional vector:

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

The longitudinal coordinates D_L and transverse ones D_T of the dispersion tensor (2) are described by the Elder's formula [6]:

Tab. 1. Overall characteristics of the assumed variants of hydro-meteorological conditions applied to calculations of spreading the pollution over the analyzed section of the Dead Vistula

Variant	Sea state	Wind		Average flow speed and direction in the cross – section at:							
				Siennicki Bridge		Sobieszewo		Brave Vistual (outlet)		The Pass (Isthmus)	
	[m a.s.l]	[m/s]	[–]	[m/s]	[–]	[m/s]	[–]	[m/s]	[–]	[m/s]	[–]
1.	0.00	5	← E	0.04	←	0.02	←	0.05	↓	0.25	←
2.	0.00	5	→ W	0.06	→	0.03	→	0.05	↑	0.28	→
3.	0.70	15	→ W	0.36	→	0.32	→	0.62	↑	1.51	→
4.	1.25	25	→ W	0.57	←	0.53	→	2.96	↓	1.02	←

$$D_L = \alpha \cdot h \cdot v^* \quad 30 < \alpha < 3000$$
$$D_T = \beta \cdot h \cdot v^* \quad 0.15 < \beta < 0.30 \tag{3}$$

where: v^* – the so called dynamic velocity acc. Prandtl, α, β – constants. In this work $\alpha = 300$ and $\beta = 0.23$ was assumed. The values were confirmed by investigations carried out earlier in broad and shallow rivers [9].

Eq. (1) formally expresses the mass conservation law for non-degradable matter (described by the mass concentration c) added to water solution. Time change of the solution component concentration c results from mass flow due to advection, mass motion against carrier molecules (diffusion) as well as dispersion (which results from the averaging along one of the variables, depth in this case). The taking into account additional effects (e.g. biological or chemical) makes it necessary to expand Eq. (1) by terms describing a loss or increase of dissolved substance mass (e.g. reaction equations). This is frequent practice in case of biodegradable substances, which – if applied – accelerates drop in concentration of organic contaminations and limits their spatial range. The omitting of the terms (especially in case of lacking information on factors affecting reaction rate of self-cleaning processes) makes it possible to assess maximum range of contaminations resulting from their analyzed discharge. Such approach was selected for purposes of this work.

METHOD OF SOLVING

In a general case the solving of Eq. (1) is possible only by means of numerical methods [16]. In this work the method of finite volumes (MOS) was applied. To integrate Eq. (1) in the two-dimensional space (x, y) it is necessary to transform a continuous area to a discrete one by replacing it with computational cells [11]. The assumed computational area (Fig. 2) was divided into square elements (cells), where $\Delta x = \Delta y$ (Fig. 3). The approach results in that values of the concentration c in the cell centre points (their centres of gravity), (at node i, j) are unknown, whereas values of the velocity vector **u** are given in the mesh points located in the cell corners (but having half-step values between step i and j). Intermediate values between mesh nodes (necessary in determining values of flow rates through particular edges) were calculated by averaging neighbouring values. It deals both with values of the concentration c and velocity vector components u_x and u_y.

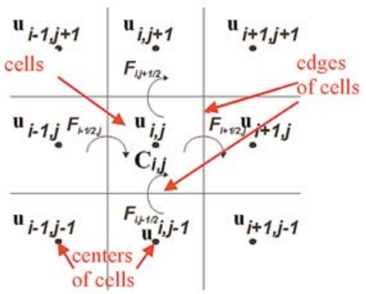

Fig. 3. Split of the computational area into two-dimensional cells and the assumed parameters of the models used for solving the equation of non-stationary transport of contaminations

The MOS applied to solving the equation of non-stationary transport of dissolved substance relates to physical laws of behaviour at the level of control volumes. It can be described by using the homogeneous hyperbolic equation as follows [11]:

$$\frac{\partial(hc)}{\partial t} + \frac{\partial(hF_x)}{\partial x} + \frac{\partial(hF_y)}{\partial y} = 0 \tag{4}$$

where: F_x, F_y – flow rates through computational cell edges, defined as follows:

$$F_x = u_x c - \frac{1}{h} D_{xx} \frac{\partial c}{\partial x} - \frac{1}{h} D_{xy} \frac{\partial c}{\partial y},$$
$$F_y = u_y c - \frac{1}{h} D_{yy} \frac{\partial c}{\partial y} - \frac{1}{h} D_{yx} \frac{\partial c}{\partial x} \tag{5}$$

To determine values of flow rates trough cell edges in the advection part of the Eq. (4) taken together with the flow rates defined by Eq. (5) the open scheme of Lax-Wendroff [12] was used. In the case of the dispersion equation the central differences schemes were employed. In the method of integration of Eq. (1) there was assumed that control area is equivalent to mesh cell. In the phase of hydro-dynamical calculations wind effect was taken into account in result of which velocity and depth distribution – an element of solution of Eq. (1) – was obtained.

Eq. (1) of pollution migration is a partial differential equation which describes distribution of their concentration over a given area in function of time. To solve the equation additional limiting conditions are to be fulfilled, namely: an initial condition and boundary conditions. In this case the initial condition is the contaminations concentration over the whole considered area in the beginning instance of simulation (for $t = 0$), i.e. $c\ (x, y, t = 0) = c_0$. In addition, two types of boundary conditions were assumed. At the impervious edge the Neumann's condition of the following form was used:

$$\frac{\partial c}{\partial n} = 0 \tag{6}$$

where Eq. (6) means that the normal flux of mass towards the area edge is equal to zero. In order to apply the condition it was necessary to modify the final version of difference analogue of Eq. (1). And, at the permeable edge the flux in the condition (6) was estimated on the basis of a result from the preceding step. In the discharge outlet Dirichlet condition was applied as follows:

$$c = const \tag{7}$$

The application of the condition consists in using Eq. 7 directly in the calculation node i, j.

To assure stability of the obtained solution the condition of Courant–Friedrichs–Lewy (CFL) had to be fulfilled [4, 18]:

$$\max\left(\frac{\Delta t^m}{\Delta x} \max_c |F_x'(c)|, \frac{\Delta t^m}{\Delta y} \max_c |F_y'(c)|\right) \le \frac{1}{8} \tag{8}$$

where: m – time level, Δt – time step, Δx, Δy – spatial steps (in x and y direction, respectively). At the determined spatial mesh dimensions Δx and Δy, the integration step over the time Δt, fulfilling the condition (8), was calculated.

NUMERICAL SIMULATIONS

The simulation calculations were carried out for 4 variants described in [22], namely: for the easterly wind of 5 m/s speed (Variant 1), the westerly wind of 5 m/s speed (Variant 2) as well as the extreme conditions – the westerly wind of 15 m/s speed (Variant 3) and the westerly wind of 25 m/s speed (Variant 4). Two sewage discharge localizations based on possible technical conditions for discharging the contaminations into receiving body were selected, namely: a) at the branch of the Dead Vistula from the side of the New Port of Gdansk, Z_1, and b) at the branch of the Brave Vistula, Z_2.

Next, the simulations of pollution migration were performed with the use of the assumed model. The calculations were carried out based on the square mesh of the sides: $\Delta x = \Delta y = 5{,}0$ m. The obtained results are presented in Fig. 4 through Fig. 7. The simulations were conducted independently for every discharge outlet and every condition variant (8 computational scenarios). In view of a significant distance between the discharge outlets and a lack of their interaction the results are presented in common figures for each of the variants. In each of the figures the spreading of contaminations is presented against the background of the velocity field. To reach the aim defined in the title of this paper the discharge was assumed in the form of the indecomposable substance of the maximum concentration $c = 100\%$ at the discharge outlet, and $c = 0\%$ in the receiving body. The calculations were continued up to the moment of reaching stable distribution of concentration values. In the analyzed cases duration time of this process did not exceed 24h. After that time changes in the spatial distribution of concentration values were practically unnoticeable.

Fig. 4 presents the results of sewage discharge simulation in the conditions of the slight easterly wind of 5 m/s speed at a moderate sea state. The wind causes a water flow from the side of the Bay of Gdansk through the section of the Brave Vistula, an inflow from the side of Przegalina, a westward flow through the branch of the Dead Vistula and an outflow towards the Bay of Gdansk in the region of the New Port of Gdansk. The maximum flow velocity appeared at the Isthmus and was equal to around 0,25 m/s. In these conditions the contaminations discharged to the Dead Vistula in the assumed localizations Z_1 and Z_2 migrate along directions of the water flow caused by wind and sea states. The flux of contaminations migrates from the point Z_1 towards Siennicki Bridge. The range of impact of the discharge is observed along the river side section up to abt. 0.5 km from the discharge point. In the conditions there is no threat of reaching the protected areas by the contaminations discharged from the point Z_1. A greater potential threat may constitute the discharge from the point Z_2. However in these flow conditions water current makes that the contaminations flux is carried away toward the Isthmus. There is a lack of an observable breaking-through of the contaminations flux into the section of the Brave Vistula towards the protected areas.

The slight westerly wind blowing with 5 m/s speed at a moderate sea state results in an almost different flow circulation in the Dead Vistula (Fig. 5). In the cross-section at the Brave Vistula outlet there is visible an outflow of 0,05 m/s speed towards the Bay of Gdansk. In the region of Sobieszewo there is observed a water flow of abt. 0,03 m/s velocity coinciding with wind direction. From the side of Siennicki Bridge a water inflow with abt. 0,06 m/s velocity is observed. As a result, an eastward water flow of 0,28 m/s velocity can be observed in the branch of the Dead Vistula close to the Pass. In these conditions the spread of contaminations is quite different from that in Variant 1. The pollution discharged to the Dead Vistula waters in the point Z_1 migrate towards

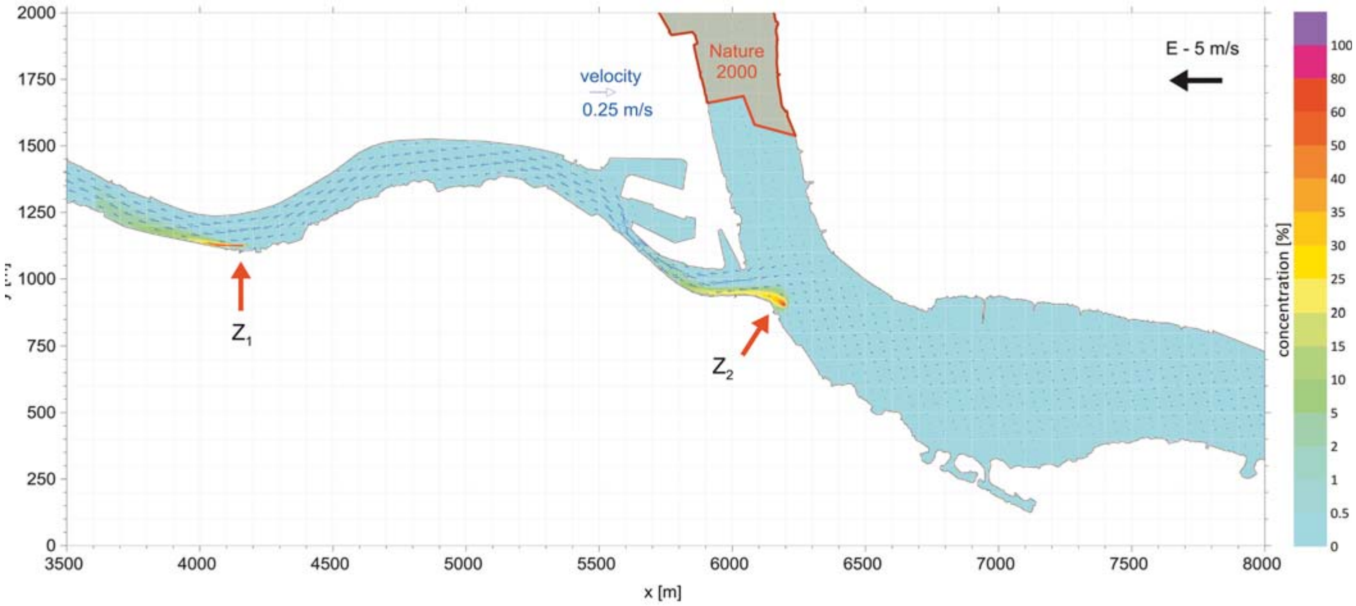

Fig. 4. Calculation results of spreading the pollution in the conditions of the easterly wind E – 5 m/s (Variant 1)

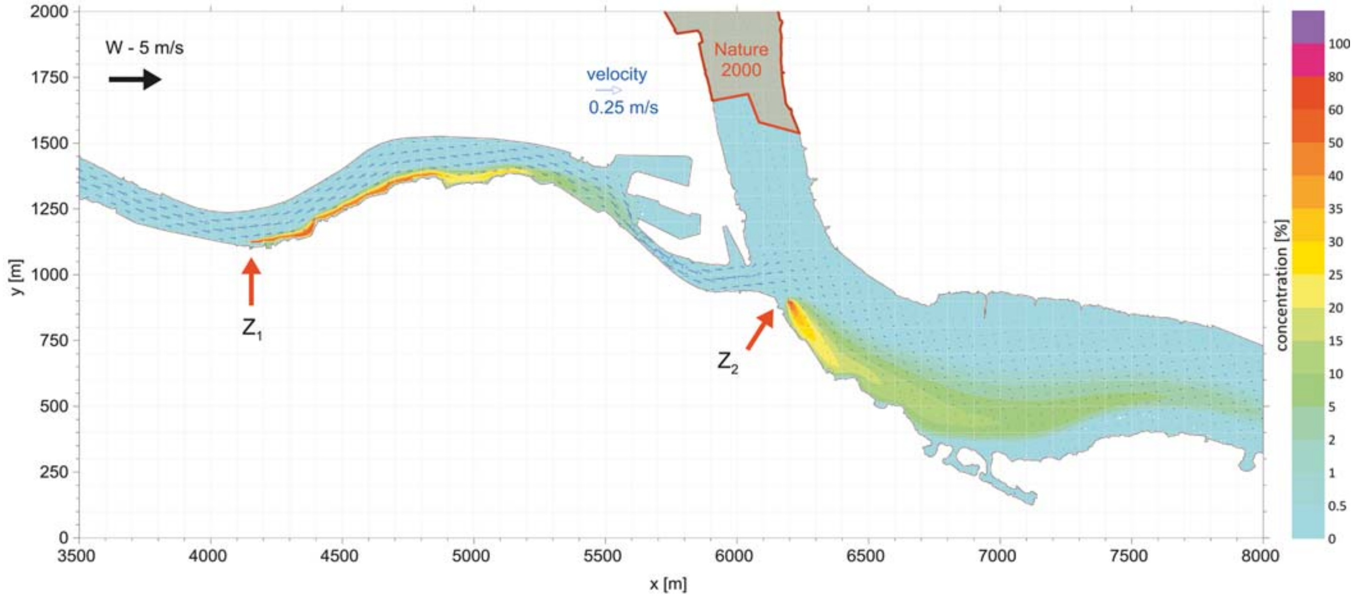

Fig. 5. Calculation results of spreading the pollution in the conditions of the westerly wind W – 5 m/s (Variant 2)

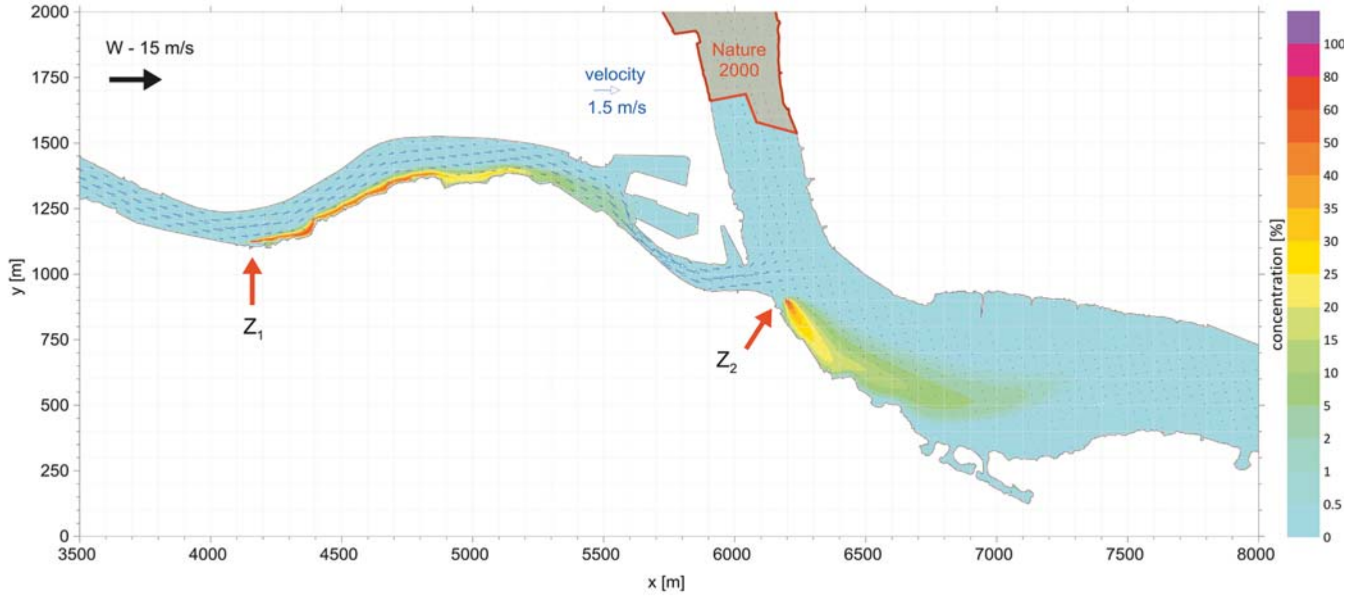

Fig. 6. Calculation results of spreading the pollution in the conditions of the westerly wind W – 15 m/s (Variant 3)

the Isthmus, and their range is observable along the river side section of abt. 2 km in length (practically up to the Isthmus itself). However no breaking – through of the contaminated water to the Brave Vistula and its migration towards Natura 2000 protected areas, occurs. In the case of the discharge from the point Z_2 the pollution migrate toward Sobieszewo along the 2.5 km river side section, i.e. in the opposite direction to the site of protected areas.

The successive two calculation variants were performed for the extreme hydro-meteorological conditions occurring in the region of the Dead Vistula. First, the simulations for the case of the westerly wind of 15 m/s speed were carried out, assuming an increase in the sea state by 0,7 m over the average (Fig. 6).

In the region of the Brave Vistula estuary the outflow of 0,6 m/s speed to the Bay of Gdansk then occurs. In the westerly branch of the Dead Vistula in the region of Siennicki Bridge an eastward flow (inflow) of abt. 0,3 ÷ 0,4 m/s speed occurs. In the easterly branch of the Dead Vistula in the region of Sobieszewo a faster eastward flow (outflow) of 0,3 m/s velocity can be observed. As a result, in the branch of the Dead Vistula a distinct eastward flow of the maximum velocity values of 1,5 m/s in the vicinity of the Isthmus appears. The bigger velocity makes that in waters of the Dead Vistula the pollution mixing processes proceed more intensive. In consequence, the range and concentration of the pollution changes. Also in this case, migration directions of contaminated water are

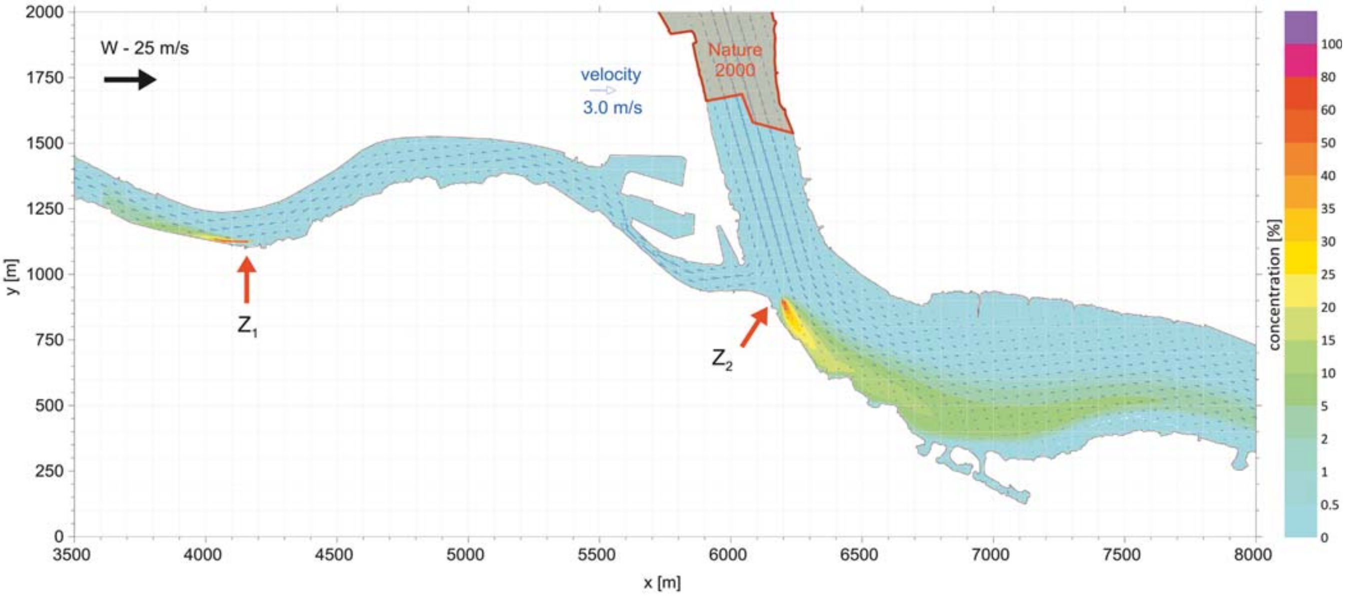

Fig. 7. Calculation results of spreading the pollution in the conditions of the westerly wind W – 25 m/s (Variant 4)

in line with those observed in the Dead Vistula branches. In this respect, directions of spreading the pollution are the same as in Variant 2. However the range of impact of the discharge in the point Z_1 reaches the section abt. 1 km long. In the case of the discharge in the point Z_2 its range is similar as that in Variant 2. There is a lack of noticeable breaking-through the flux of contaminated water towards the protected areas.

The last variant concerns the case of the westerly wind blowing with 25 m/s speed at the observed rise of sea state by 1,25 m [8] (Jasińska, 2002) over the average (Fig. 7). In such extreme conditions of the very high sea state and very fast westerly wind the flow conditions in estuaries change. Then in the region of the Brave Vistula an inflow of a very great velocity up to 3,0 m/s from the Gulf of Gdansk is observed. In the westerly branch of the Dead Vistula in the region of Siennicki Bridge a westward flow (outflow) of 0,5 – 0,6 m/s speed takes place. In the easterly branch of the Dead Vistula (in the region of Sobieszewo) a faster eastward flow (outflow) of abt. 0,5 m/s speed occurs. As a result, in the branch of the Dead Vistula a distinct westward flow with the maximum speed values of over 1,0 m/s can be observed in the vicinity of the Isthmus. The simulation of spreading the pollution from the designed discharge outlets is presented in Fig. 7. In view of the prevailing hydro-meteorological conditions their impact onto waters of the receiving body is slight and there is no potential circumstances to pollute the protected areas in question.

SUMMARY AND CONCLUSIONS

In the frame of this work there were performed computer simulations of migration process of pollution from two example localizations of industrial sewage discharge and their impact on the neighbouring Natura 2000 protected areas. The calculations were made for the section of the Dead Vistula between Sobieszewo and Siennicki Bridge together with the section of the Brave Vistula running to the Bay of Gdansk. Based on the available materials a numerical model of the considered river section was prepared. The model was supplemented with the data on water level position depending on hydro-meteorological conditions, presented in the work [8]. On the basis of the calculations given in [22]. 4 variants of hydrodynamic conditions were selected depending on wind direction and force and sea states (for the easterly wind E – 5 m/s, westerly wind W – 5 m/s as well as extreme conditions of the westerly winds: W – 15 m/s and W – 25 m/s). Next, the calculations of spreading the pollution from two selected sewage discharge localizations were performed for each of the assumed calculation variants. The results obtained from the computer simulations demonstrated that the planned sites of potential sewage discharge in the region of the Isthmus in the Dead Vistula could not cause migration of the contaminations into the Natura 2000 protected areas. A greater impact of the discharge can be observed for the moderate conditions (Variant 1 and 2). In the case of the stormy conditions the discharge range is more restrained due to intensification of their mixing processes in receiving body waters as well as the increased water flows. In the case of the discharge outlet Z_1 it may be deemed that no migration of the pollution towards the protected areas can happen.

However in the case of the discharge outlet Z_2 located in the branch of the Brave Vistula the conclusions are not so unambiguous. Though the simulations performed in 4 variants of hydro-meteorological conditions showed that a pollution of the Natura 2000 areas in the estuary section of the Brave Vistula could occur, but unfortunately it should not be considered impossible. If to assume that the water running through the Brave Vistula bed is directed towards the Gulf of Gdansk and is increased by the inflow from the Dead Vistula through the Isthmus, a water pollution from the discharge Z_2

will be possible to occur in the protected areas. However such case would be low probable because of hydro-meteorological conditions (a water outflow to the Gulf of Gdansk through the Brave Vistula and a simultaneous inflow from the Gulf in the region of the New Port of Gdansk) and also due to the fact that the section of the Dead Vistula from the side of Sobieszewo is separated from the Vistula Cutting (Przekop Wisły) by a closed lock. But, such scenario should be also taken into consideration as there is a connection through an open channel between the discharge region and protected areas. For this reason the localization of the discharge outlet in the point Z_1 is more favourable from the point of view of protection of Natura 2000 areas.

ACKNOWLEDGEMENT

This work is a part of the research project WaterPuck supported by the National Centre for Research and Development within the BIOSTRATEG III program No. BIOSTRATEG3/343927/3/NCBR/2017.

REFERENCES

1. Anderson J. D.: *Computational Fluid Dynamics. The Basics with Applications*, McGraw-Hill Inc., New York (1995), pp. 1–547.
2. Chapara S.C.: *Surface water-quality modeling.* MacGraw Hill Company, New York, (1994), pp. 1–884.
3. Crank J.: *The mathematics of diffusion*. Clarendon Press, Oxford, (1975), pp. 1–414.
4. Courant R., Friedrichs K. and Lewy H.: *On the partial difference equations of mathematical physics*, IBM Journal, (1967), pp. 215–234.
5. Czernuszenko W.: *Dispersion of pollutants in flowing surface water.* Encyclopedia of Fluid Mechanics, Surface and Groundwater flow phenomena. Houston, London, Paris: Gulf Publishing Company, 10 (1990), pp. 119–168.
6. Elder J.W.: *The dispersion of marked fluid in turbulent shear flow.* J Fluid Mech. 5, (1959), pp. 544–560.
7. Harrison R.M.: *Pollution: Causes, Effects and Control (5th ed.).* Royal Society of Chemistry, Cambridge, (2013), pp. 1–558.
8. Jasińska E.: *Hydrology and hydrodynamics of the Dead Vistula and Vistula Cutting*, (in Polish), Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Gdańsk, (2002), pp. 1–133.
9. Kalinowska M., Rowiński P., Kubrak J., Mirosław-Świątek D.: *Scenarios of the spread of a waste heat discharge in a river – Vistula River case study.* Acta Geophys 60 (2012), pp. 214–231.
10. *Laws E.A.: Aquatic Pollution: An Introductory Text (4th ed.).* Hoboken, NJ: John Wiley & Sons, (2017), pp. 1–760.
11. LeVeque R.J.: *Finite Volume Method for Hyperbolic Problems.* Cambridge University Press, New York, (2002), 1–578.
12. Potter D. E.: *Computational Physics*, John Wiley & Sons Ltd., Chichester (1980), pp.1–304.
13. Rutherford J.C.: *River Mixing.* Wiley, Chichester, (1994), pp. 1–362.
14. Sawicki J.M., Zima P.: *The Influence of Mixed Derivatives on The Mathematical Simulation of Pollutants Transfer.* 4th International Conference on Water Pollution, Slovenia, (1997), pp. 627–635.
15. Szydłowski M., Szpakowski W., Zima P.: *Numerical simulation of catastrophic flood: the case study of hypothetical failure of the Bielkowo hydro-power plant reservoir*, Acta Geophys 61 (2013), pp. 1229–1245.
16. Szymkiewicz R.: *Numerical Modeling in Open Channel Hydraulics*, Book Series: Water Science and Technology Library, vol. 83 (2010), pp. 1–419.
17. Tan W.Y.: *Shallow Water Hydrodynamics, Mathematical Theory and Numerical Solution for a Two-dimensional System of Shallow Water Equations*, Elsevier Oceanography Series, vol. 55 (1992), pp. 1–434.
18. Tannehill J.C., Anderson D.A. and Pletcher R.H.: *Computational Fluid Mechanics and Heat Transfer (2nd ed.),* Francis & Taylor, Philadelphia, (1997), pp.1–774.
19. Waite T.D.: Principles of Water Quality, Elsevier Academic Press, Orlando, (1984), pp. 1–287.
20. Wielgat P., Zima P.: *Analysis of the impact of the planned sewage discharge from the 'North' Power Plant on the Vistula water quality*, 16th International Multidisciplinary Scientific GeoConference SGEM 2016, Vienna, Book 3 vol. 3 (2016), pp. 19–26.
21. Zima P: *Mathematical Modeling of the Impact Range of Sewage Discharge on the Vistula Water Quality in the Region of Włocławek*. In: Kalinowska M, Mrokowska M, Rowiński P. (eds) Free Surface Flows and Transport Processes. GeoPlanet: Earth and Planetary Sciences. Springer, Cham, (2018) pp. 489–502.
22. Zima P.: *Modeling of the Two-Dimensional Flow Caused by Sea Conditions and Wind Stresses on the Example of Dead Vistula.* Pol. Marit. Res., vol. 97 (2018), pp. 166–171.

CONTACT WITH THE AUTHORS

Piotr Zima
e-mail: piotr.zima@pg.edu.pl

Gdańsk University of Technology
Faculty of Civil and Environment Engineering
Narutowicza 11/12
80–233 Gdańsk
Poland