Papers

Water mass exchange between the Gulf of Gdańsk and the Baltic Sea*

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Water exchange
Baltic Sea
Gulf of Gdańsk
Numerical model

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Abstract

On the basis of the results of H-N models of steady wind-driven circulation in the Baltic Sea a general picture of water movements in the Gulf of Gdańsk is discussed. Depth profiles of the current speed components at the open boundary (Rozewie – Taran) complete the spatial scheme of the water mass exchange between the Gulf of Gdańsk and the Baltic Sea. The results presented in the paper were calculated for the case of the homogeneous sea water and for the homogeneous field of winds blowing from the directions, W, N, NW, and NE.

1. Introduction

The Gulf of Gdańsk has a wide and deep connection with the southern Baltic, which is not without influence on the hydrological regime of its waters. The determination of water dynamics in the Gulf, based on hydrodynamic numerical (H-N) models [3, 9], carried out so far, shows that the Gulf cannot be treated as a separate area as far as its water circulation is concerned. The field of currents of the Gulf is a continuation of such a field in the southern Baltic. This fact makes it more difficult to determine the water exchange between the Gulf and the Baltic Sea and estimate the balance of biogenic and chemical deposits carried into and out of the Gulf by water. The problem could be solved if a series of buoys with current meters and other instruments for measuring various hydrological parameters were installed at the boundary of the open Gulf for a longer period of time. Such an undertaking would be extremely costly and difficult to realize for technical reasons. Therefore, model-based investigations could be of some help in the evaluation of the water exchange between the Gulf and the Baltic.

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The present paper explores this problem, aiming at showing the outline of water exchange dynamics between the Gulf of Gdańsk and the Baltic Sea on the basis of H-N models of steady wind-driven circulation in the homogeneous Baltic Sea.

2. Materials and method

In the past few years, the determination of water circulation in natural sea reservoirs with the help of H-N models was quite successful. For the Baltic Sea we have a series of H-N models which describe wind-driven circulation, both, in the stratified and homogeneous sea [1 - 8, 10, 11].

The present paper is based on the H-N model worked out in the Institute of Oceanology of the Polish Academy of Sciences in Sopot [1, 2, 4] or, to be more precise, on the results obtained with its help for case of currents induced by a homogeneous wind field in the homogeneous Baltic Sea [1]. We shall not go into the details of the above-mentioned model; the reader may consult the relevant paper by the author [2]. This model gives the fields of currents on a numerical grid with a space step of $2\,h = 10$ nM. The distribution of nodes of the numerical grid in the Gulf of Gdańsk is presented in Figure 1. Due to the considerable space step of the

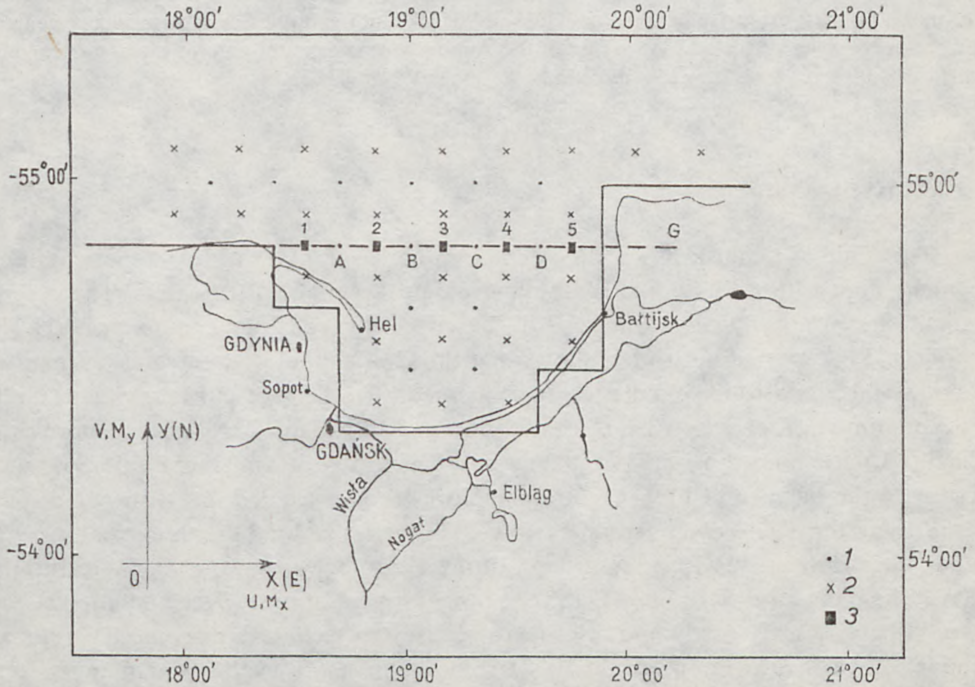


Fig. 1. Distribution of the nodes of the numerical grid in the Gulf of Gdańsk
1 – nodes, in which current vectors were calculated; *2* – nodes, in which mass transport vectors were calculated; *3* – nodes, in which mass transport components M_x, M_y were calculated

numerical grid, the shoreline and topography of the Gulf's bottom are presented in a simplified manner.

The results of calculations of mass transport and sea level obtained for a homogeneous wind field over the Baltic [1] as well as the algorithm for calculating the wind velocity described in [1] will be used in this paper. On the basis of these, we shall determine the currents at the surface and at the bottom of the area, as well as at depths of 25 and 50 m; we shall also estimate the vertical profiles of current speed components at the Gulf boundary line. The arbitrary open boundary between the Gulf and the Baltic Sea was assumed to be the line connecting Cape Rozewie with Taran (line G in Fig. 1). The magnitudes calculated with our H–N model are inscribed in a cartesian coordinates system whose origin is on the free surface of the area, and the OX axis is directed eastwards; the OY axis is directed northwards, and the OZ axis – vertically upwards.

The results presented below were calculated for W, N, NW, and NE winds with a constant speed of 10 m/s and a strong westerly wind with a speed of 20 m/s. It should be added that due to the linear design of our H-N model, the results for winds with opposite directions are the same except that the direction (sense) of mass transport and current vectors should be reversed. When modelling the circulation for strong winds, the influence of river discharges on the shape of the field of currents and mass transport in the Baltic Sea is small [2, 3]. Therefore, river discharges were neglected in our considerations of current dynamics for winds with speeds of 10 and 20 m/s, and the Baltic was treated as a closed area.

In our H-N model, in which the mass transport method was used [2], the shoreline is approximated by a broken line and constitutes a vertical wall. Water depth close to the shore-wall is several meters, depending on the localization of the wall in relation to the actual shoreline and the actual topography of the sea-bed in this area.

3. A general picture of water circulation in the Gulf of Gdańsk

Integral circulation is represented in our model by the field of mass transport whose vectors for the selected wind directions in the nodes of the numerical grid are presented in Figure 2. The components of mass transport represent the transport of mass in a unit of length ($g \cdot cm^{-1} s^{-1}$) in an elementary section made by two perpendicular lines passing from the surface to the bottom, with the distance between them equal to one space step of the numerical grid 2 h. Thus, schematic charts of mass transport in Figure 2 give us a general picture of the horizontal movements of water masses in the Gulf and the water exchange between the Gulf of Gdańsk and the southern Baltic.

For the westerly and the NW wind, both 10 m/s (Fig. 2b), the water masses are transported into the Gulf along the western coast (Helska Spit) and exit along the eastern coast. An extensive cyclonic whirl, connected with a similar gyre in the Baltic, is created, covering the whole area of the Gulf.

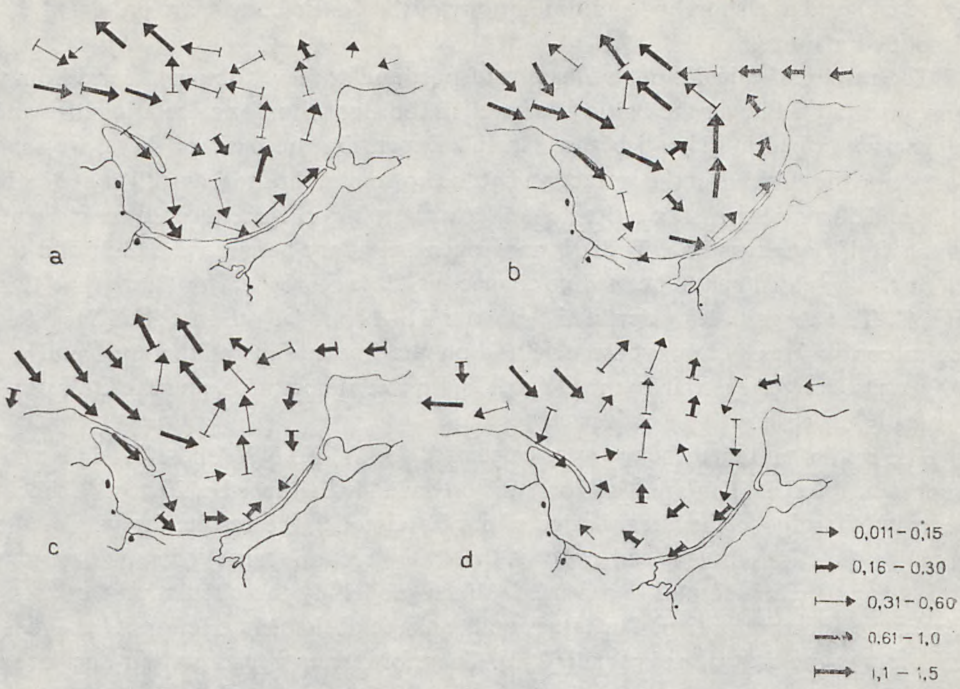


Fig. 2. Mass transport vectors ($\times 10^5$ g·cm^{-1} s^{-1}) for the different winds a–W, 10 m/s; b–NW, 10 m/s; c–N, 10 m/s; d–NE, 10 m/s

For the northerly wind (10 m/s), the cyclonic eddy is not as extensive and does not cover the whole area of the Gulf. At the eastern shore, a less intensive anticyclonic eddy developed, also carrying water masses into the Gdańsk basin. In the central part, both eddies meet and carry water out of the Gulf (Fig. 2c).

In the case of the NE wind (10 m/s), the field of integral circulation looks different. An anticyclonic eddy developed, covering almost the whole of the Gulf of Gdańsk. A weak cyclonic eddy is present in the north-western part of the Gulf (Fig. 2d). It constitutes a transitory dynamic system between the two anticyclonic eddies, one covering the Gulf and the other covering the Baltic Sea and visible only in part near Cape Rozewie.

A comparison of mass transport fields presented in Figure 2 with the fields of currents for the whole Baltic Sea [1] indicates clearly that there is a close relationship between the integral circulation of the Gulf of Gdańsk and that of the Baltic.

We shall now consider exemplary fields of currents at selected depths: at the surface, at the bottom, and at 25 m and 50 m (Figs. 3 and 4). A general observation may be made that for the W, N, and NW winds, the vector fields at all depths are cyclonic (Fig. 3). The characteristic feature of current fields for these wind directions is the occurrence of strong currents in the near-surface layer ($z=0$ and $z=25$ m) close to the western shores of the Gulf (the Hel Peninsula). They reach the following speeds: 36.2 cm/s (W, 10 m/s), 89.9 cm/s (W, 20 m/s), 22.8 cm/s (N, 10 m/s), and 39.3 cm/s (NW, 10 m/s). In the case of the N and NW winds, the current components

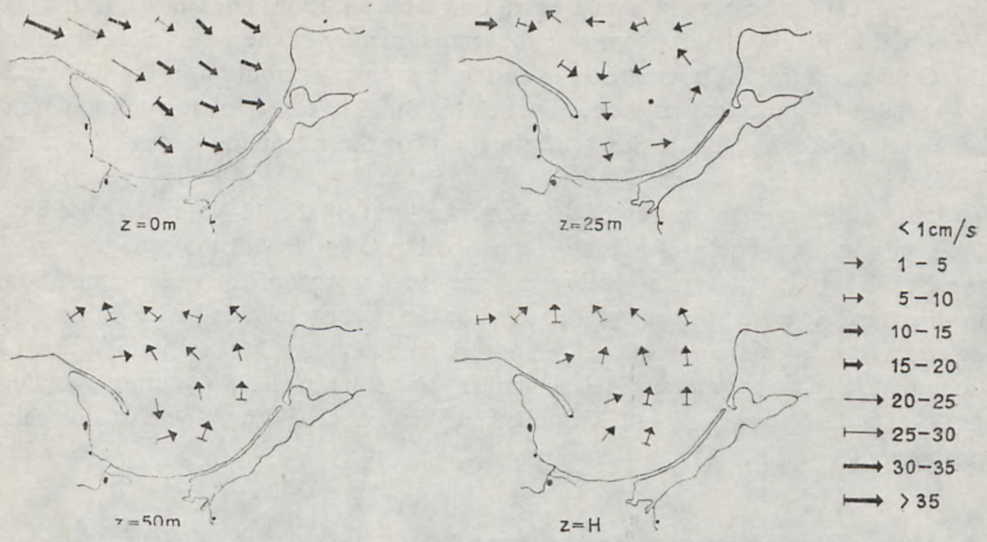


Fig. 3. Current vectors (cm/s) at selected depths for the wind W, 10 m/s

along the Helska Spit occur also at the remaining depths. It may be said that along the western coast of the Gulf (along the Hel Peninsula) a boundary layer, characterized by an intensification of flow. is formed; in the case of the northerly wind it reaches the bottom.

The current field for the NE wind (10 m/s) is of a different character (Fig. 4). The distribution of current vectors at all levels is not as varied as for the remaining wind directions. The currents are weaker and their maximum values at the surface

Fig. 4. Current vectors (cm/s) at selected depths for the wind NE, 10 m/s

equal 16.6 cm/s. There are also no areas of flow intensification. The charts of currents presented in Figure 3 and 4 complete the spatial picture of the water circulation in the Gulf of Gdańsk. A comparison of surface currents distribution in the Gulf and in the Baltic [1] indicates that the current fields in the Gdańsk basin are a continuation of such fields for the Baltic Sea. The situation for the remaining depths is similar (cf [2]).

Due to the large space step of the numerical grid of the H-N model used and the resulting schematic presentation of the shoreline contour and the topography of the Gulf's bottom, we cannot observe specific local aspects of the water circulation in this area. However, this is not essential for the purpose of this paper. For a full determination of mass and current transport fields in the Gdańsk basin, calculations with a space step several times smaller should be made. The author's model [2, 3] or a developed model of Kowalik and Wróblewski [9] may be used for this purpose.

4. Flow distribution at the open boundary of the Gulf of Gdańsk

Using the calculated values of mass transport, we can estimate the size of flow of water masses flowing perpendicularly (direction N-S) and parallelly (direction W-E) towards the open boundary. The boundary line is designated by G in Figure 1. For individual boundary segments whose length equals the space step of the numerical grid 2 h we have:

Table 1. Values of the water mass flow component $Q_x(\times 10^{11}\ \mathrm{g \cdot s^{-1}})$ for each space step of the open boundary of the Gulf of Gdańsk

Wind	Speed [m/s]	Index of the segment of the Gulf's open boundary				
		1	2	3	4	5
W	10	1.165	0.473	−0.314	−0.252	−0.019
N	10	1.088	0.697	−0.196	−0.273	−0.057
NW	10	1.595	0.828	−0.360	−0.372	−0.027
NE	10	−0.054	0.158	0.082	−0.015	−0.054
W	20	2.608	1.052	−0.878	−0.765	−0.060

Table 2. Values of the water mass flow component $Q_y(\times 10^{11}\ \mathrm{g \cdot s^{-1}})$ for each space step of the open boundary of the Gulf of Gdańsk

Wind	Speed [m/s]	Index of the segment of the Gulf's open boundary				
		1	2	3	4	5
W	10	−1.402	−0.050	0.065	0.439	0.948
N	10	−1.693	0.026	1.017	0.956	−0.298
NW	10	−2.189	−0.019	0.763	0.983	0.459
NE	10	−0.206	0.052	0.670	0.363	−0.883
W	20	−3.071	−0.096	0.170	0.957	2.041

$$Q_x^i = M_x^i \cdot 2\mathrm{h}, \tag{1}$$

$$Q_y^i = M_y^i \cdot 2\mathrm{h}, \tag{2}$$

where:

$i = 1, 2, 3, 4, 5$ – subsequent index of the segment (node) of the open boundary;

M_x^i, M_y^i – components of mass transport along the OX and OY axes, respectively;

Q_x^i, Q_y^i – values of water mass flow for the i-th segment of the open boundary, parallelly and perpendicularly to the boundary line, respectively.

The calculated values of Q_x^i and Q_y^i for particular wind directions are presented in Tables 1 and 2. They characterize the movement of water masses within a given segment of the open boundary, depending on the wind direction. The changes in the value of mass flow along the boundary reflect the changes in the integral circulation at a place where the Gdańsk and the Baltic basins meet.

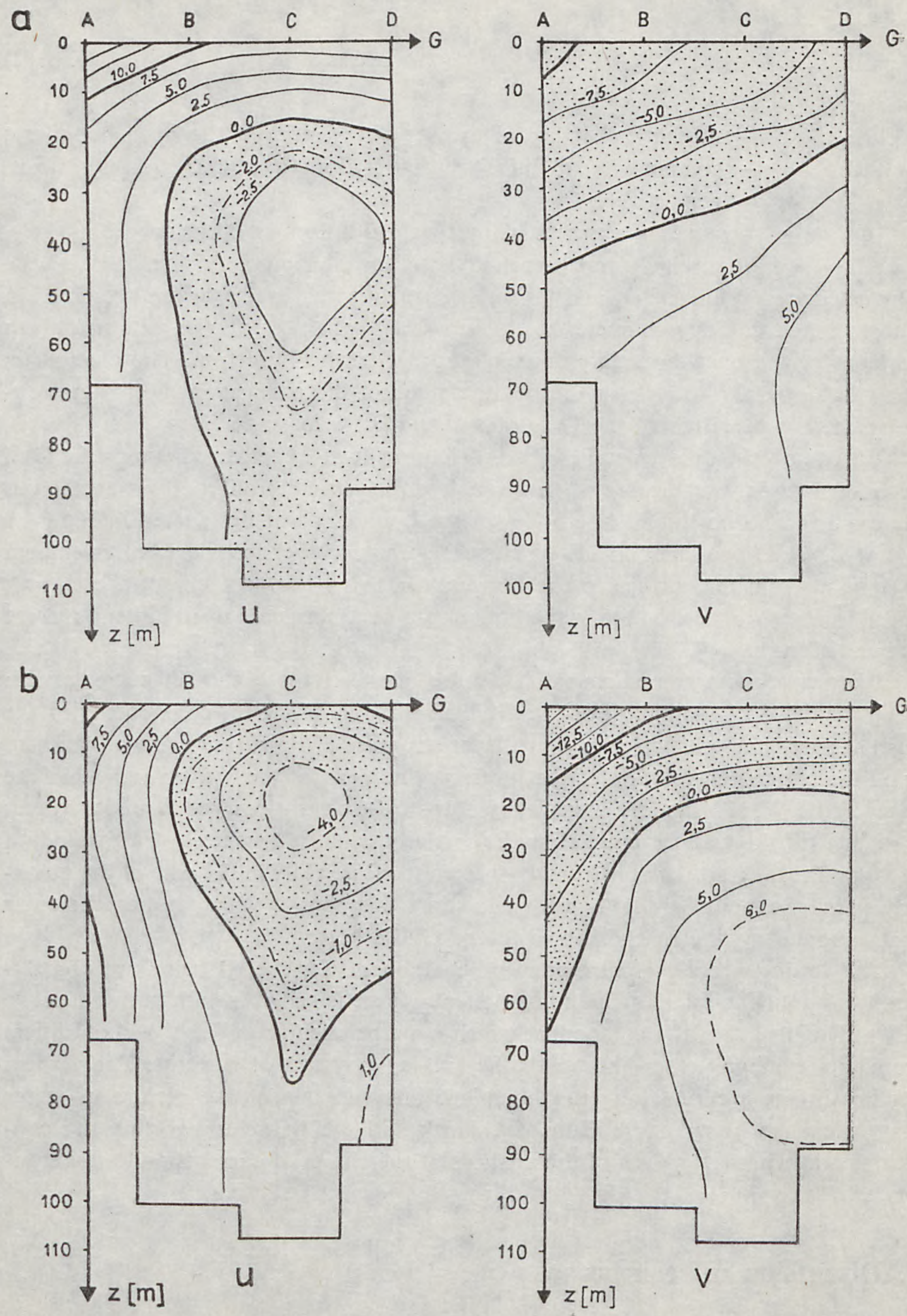
We can obtain a more detailed spatial picture of water exchange between the Gulf of Gdańsk and the Baltic Sea when we analyse the vertical profiles of wind velocities components. To do this, in the nodes of the boundary line designated in Figure 1 by A, B, C, D the components of current speed for each profile were calculated every 5 m from the surface to the bottom. On this basis, isotachs of the current speed in a vertical section along the boundary line for selected wind directions were drawn (Fig. 5a – d).

We have thus obtained a spatial picture of the changeability of currents with depth at the open boundary of the Gulf of Gdańsk. For both components of the current speed there is basically a two-layer structure of flow; however, for different wind directions, the relation of the layers in the plane of the section varies. In the case of the W, NW, and N winds (Fig. 5a – c), a clearly marked boundary layer is visible off the western coast. For the westerly wind, it reaches down to a depth of 40 m, for the north-westerly wind – down to 60 m. Only in the case of the northerly wind the boundary layer with a distinct component which is perpendicular to the boundary line reaches down to the Gulf's bottom.

The vertical profiles of current speed components for the NE wind are of a different nature (Fig. 5d). For both components, there is no layer with more intensive flows. The profile of the component which is perpendicular to the V section differs from the remaining cases and upsets the two-layer system of currents. The vertical profiles in the section along the boundary line supplement the picture of water mass exchange between the Gulf of Gdańsk and the Baltic, supporting the conclusions drawn on the basis of the analysis of the charts of currents and mass transport.

5. Discussion and conclusions

The schematic charts of mass transport and current vectors at several depths, presented in this paper, give some idea of the general picture of the field of steady circulation in the Gulf of Gdańsk and, on this basis, of water mass exchange between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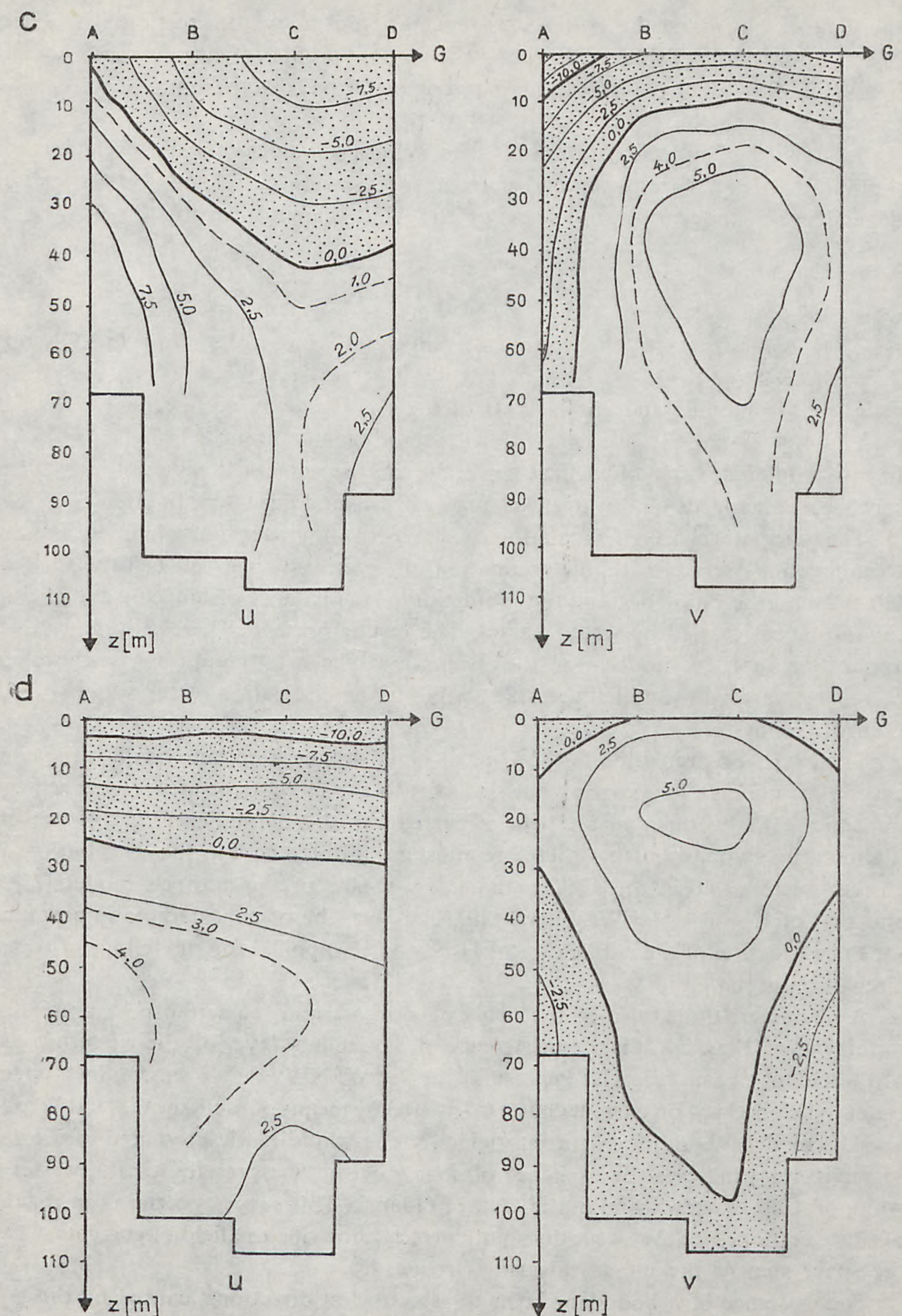

Fig. 5. Depth profiles of current speed components (cm/s) in the vertical section along the open boundary for the different winds
a – W, 10 m/s; b – NW, 10 m/s; c – N, 10 m/s; d – NE, 10 m/s

the Gdańsk basin and the Baltic Sea, depending on the wind direction. The values of water mass flow (Table 1 and 2) and the vertical profiles of current speed components (Fig. 5a – d) at the open boundary complete the spatial picture of water mass exchange in the southern Baltic.

It should be emphasized that the given numerical values of water exchange and the values of mass transport and current speeds were calculated for the chosen dependence of tangential wind stress on the wind velocity over the sea [1 - 3]:

$$\tau_x^s = \gamma w w_x; \quad \tau_y^s = \gamma w w_y, \tag{3}$$

where:

τ_x^s, τ_y^s – components of the vectors of tangential wind stress along the OX and OY axes;

w, w_x, w_y – module and components of the wind velocity vector;

γ–($3.25 \cdot 10^{-6}$ g·cm^{-3}) – coefficient of aerodynamic drag.

In case a different value of coefficient γ is chosen, the numerical values of mass transport, current speeds, and water exchange will be modified accordingly.

The schematic charts of circulation caused by the homogeneous wind field presented above may serve for the determination of water exchange between the Gulf of Gdańsk and the Baltic Sea and the estimation of the balance of biogenic and chemical substances carried by water masses. The results presented here may find direct application in H-N models for the evaluation of coastal conditions at the open boundary, used when modelling steady wind-driven circulation of the waters of the Gulf of Gdańsk.

The charts of circulation in the Gulf of Gdańsk presented here confirm the conclusion of investigations carried out so far as to the direct dependence between the dynamics of its waters and the field of currents in the Baltic Sea [3, 9]. However, it should be emphasized that there are substantial differences in the distribution of current vectors within the Gulf obtained by means of the author's model [2, 3] and that of Kowalik and Wróblewski [9]. They may be of considerable importance for the evaluation of the correctness of H-N models applied for modelling of water circulation in the Gulf.

A characteristic feature of the fields of currents and mass transport presented in this paper (Figs. 2 – 5) is the occurrence of a boundary layer off the western coast of the Gdańsk basin (the Hel Peninsula) for the W, NW, and N winds. Such effect is not to be observed on current charts calculated by means of the Kowalik and Wróblewski's model [9], although current fields for the whole Baltic presented in Kowalik's paper [5] indicate the existence of strong currents, especially for the westerly wind, off Cape Rozewie and in the Gulf of Gdańsk. This suggests certain drawbacks of those authors model since it does not correctly describe the field of currents when the space step of the numerical grid is reduced.

The existence of a boundary layer for some wind directions, caused by the positioning of the Helska Spit in the Gulf of Gdańsk, results from the analysis of the dynamics of water mass movements depending on the wind direction, the configuration of the shoreline, and the bottom topography of the area. In the author's paper [3], the H-N model [2] with the space step of the numerical grid 2 h = 2 nM was used for the evaluation of wind flows for westerly winds with speeds of 10 and 7 m/s. A clearly visible intensification of the current field along the coast of Hel was obtained. A comparison of the results of calculations with the results of measurements made by Wojewódzki [12] showed considerable agreement not only of the directions but also of the values of current speeds, especially off the Helska Spit, where the currents were the strongest.

Taking into consideration the above remarks, it may be said that the problem of the determination of currents in the Gulf of Gdańsk remains open and further investigations are needed. On the basis of the author's H-N model [2, 3] and the results of this paper and paper [1], steady circulation in the Gulf of Gdańsk for the basic wind directions was calculated, assuming the space step of the numerical grid as 2 h = 2 nM. The results of these investigations, presenting in a complex manner the problem of water circulation in the Gdańsk basin will be the subject of the next paper by the author.

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