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A MODEL OF MATTER EXCHANGE AND FLOW OF ENERGY IN THE GULF OF GDAŃSK ECOSYSTEM - OVERVIEW

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Abstract

A conception of the ecological model of the Gulf of Gdańsk is presented. The model includes both the inflow of matter from land and the flow of energy into the environment of the Gulf. The model consists in submodels which solve the following issues: the inflow of solar energy into the sea surface, light penetration into the deeper parts of the sea, river advection, heat balance at the sea surface, production of organic matter, the spread of suspended matter as well as bacteria and three dimensional hydrodynamics. Configuration and short descriptions of these submodels are given.

INTRODUCTION

At the beginning of XXth century, physicists proposed the new philosophy of understanding of the world. Their conception is known as holistic or ecological approach and is in opposition to Cartesian analysts who suggested the pre-eminence of a part over the integrity. According to the holistic point of view, the environment should be perceived as a whole and any research which deals with only one constituent of the environment is not relevant.

In scientific investigations besides observations and laboratory experiments, the mathematical modelling has appeared as the new approach in studying the mechanisms of functioning of the nature. Modelling allows phenomena and

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processes to be simulated and then compared with measurements. Thus, the model can be verified and used for diagnostic or prognostic purposes. Such an approach has become a useful methodology in research on the nature as well as in making decisions concerning environment protection.

The ecological modelling combines physical, chemical and biological processes and their interactions in the marine environment (Nihoul 1975, Fransz *et al.* 1991, Blackford and Radford 1995). Physical processes include continual, extremely complicated motion of marine water described by equations of momentum, matter and energy. To chemical processes belong the interactions between compounds found on contact surfaces of different components of the biosphere. Biological processes are modelled taking into account physico-chemical conditions and trophic levels (Shuert and Walsh 1993). The ecosystem evolves due to the flow of matter and energy across its border surfaces (Baretta *at al.* 1995).

The Baltic belongs to contaminated seas. There are many cities along its coast which are the source of pollution, especially that the national economies of Baltic countries are well developed. The runoff from catchment, four times larger than this sea area, delivers huge load of contaminants carried by rivers. The shallow and narrow Danish Straits render the exchange of water between the Baltic and the ocean difficult. These factors among others caused such a dramatic change in the environmental conditions that the extensive ecological research became necessary. Presently, the investigations of the Baltic Sea ecosystem are very advanced. Their first stage concentrated on dissemitiation of monitoring. Currently, the ecological modelling is developing (Fennel and Neumann 1996, Suursaar and Astok 1996, Savchuk and Wulff 1996, Tamsalu 1996).

There are many ecological problems in the Gulf of Gdańsk, some of them are a result of long-term carelessness towards the environment. The problems with water quality and sanitary status of the Gulf have prompted the research project entitled*: A model of matter exchange and flow of energy in the Gulf of Gdańsk ecosystem.*

It was undertaken by the Institute of Oceanography at University of Gdańsk. Earlier research on the Gulf area covered only partial issues (Jankowski 1987, Jędrasik and Kowalewski 1993, Ołdakowski *et al.* 1994). The present studies deal with both physical and biogeochemical processes.

STRUCTURE OF THE MODEL

Structure of the model (Fig. 1) comprises three levels - submodels. At the first level, these models yield boundary conditions which are influenced by the atmosphere and land. They take into account the solar energy inflow into the sea surface, the heat balance at the sea surface and the runoff from land by rivers.

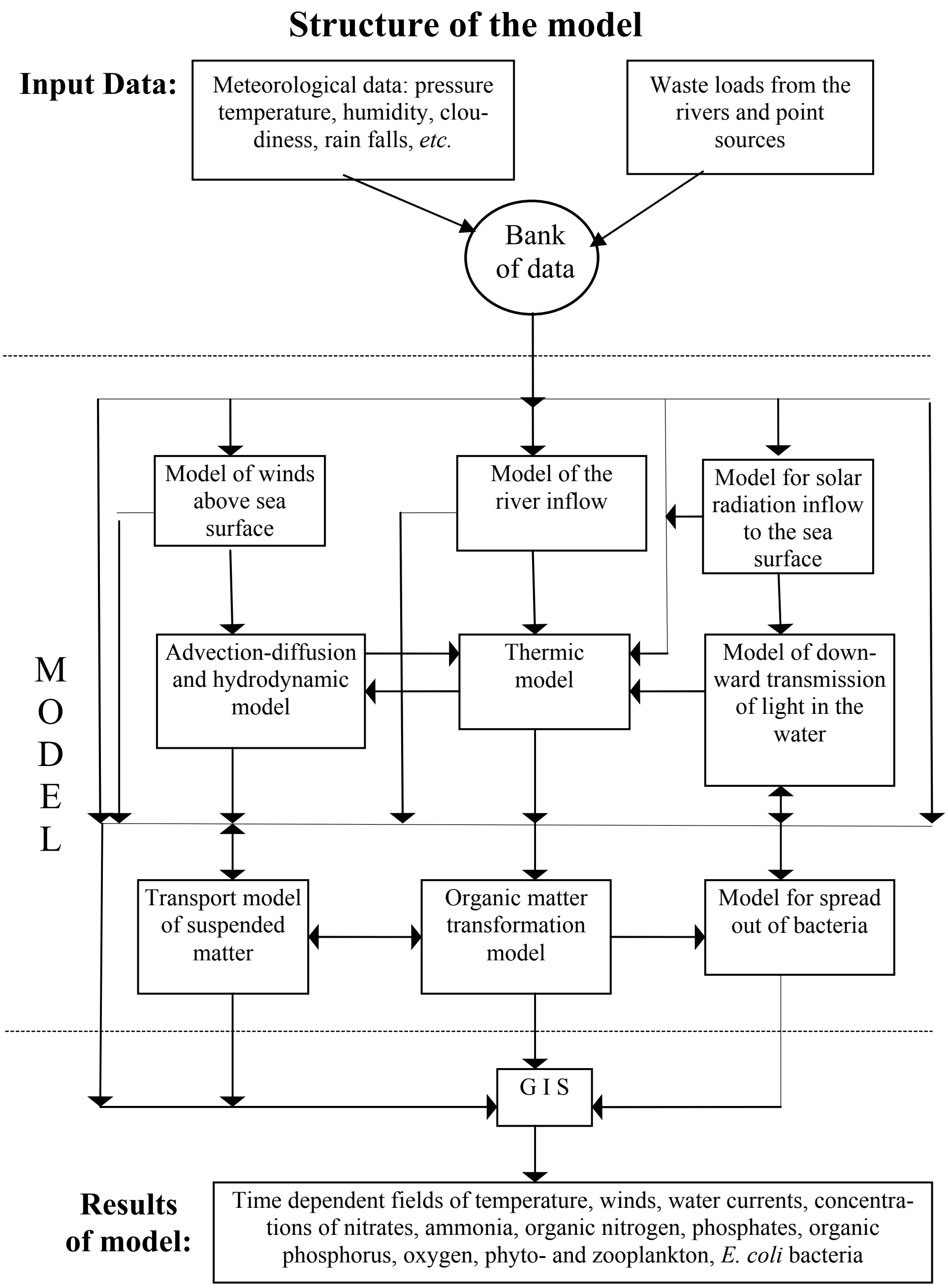

Fig. 1. Organisation and structure of the model of matter exchange and flow of energy in the Gulf of Gdańsk ecosystem

The model input of solar energy gives a field of solar radiation for any period of time for the Gulf of Gdańsk. It is based on planetary conditions (geographical situation, intensity of shortwave radiation), atmosphere state (absorption by gases and attenuation by aerosols) as well as meteorological parameters, *e.g.* cloudiness. The model of river discharges is based on the annual cycle of runoff parametrized for chosen rivers by Fourier series. The long-term observations of riverine outflows play a key role in this model. For some larger rivers, the thermal changes of river water were also parameterized.

At the second level of the submodels, physical processes in the water body are investigated, mainly the penetration of light into the water, turbulent transmission of heat and salinity as well as hydrodynamics including advection and diffusion. Light penetration in water is a natural consequence of the sea surface exposure on solar radiation. The model includes the transmission of light in clear water and the change of extinction due to contaminants or floating suspended matter found in the Gulf waters as well as substances brought about by biogeochemical processes.

The radiation balance and loss of heat resulting from evaporation and conduction at the sea surface delimit the heat fluxes as boundary conditions for turbulent transfer of heat. The thermal model describes spatial distributions of water temperature and their changes with time, particularly the seasonal cycle and phenomena associated with water freezing. The basic model describing the hydrodynamics is three dimensional and baroclinic, it covers effects of advection and diffusion. The hydrodynamics model is based on the Princeton Ocean Model (POM) (Blumberg and Mellor 1987) which deals with sea currents at many levels of depth.

The first level models (the external ones) deliver the fluxes of momentum, matter and heat which influence circulation in bathymetry. All processes involved in hydrodynamics are essential for another group of models - the third level models.

The third level group of models concerns biogeochemical processes, that is the production of organic matter, transport of suspensions and spreading of bacteria. The input of light, heat and nutrients must be known if primary production is to be predicted. The present model includes only the first trophic level, *i.e.* the primary production and zooplankton as a consumer. The motion of organic and inorganic suspended matter in both horizontal and vertical directions is specified by the transport model of suspension. Bacteria *Escherichia coli* discharged at the coastal zone pose a sanitary hazard. Therefore, the know- ledge about concentrations and paths of migration of these bacteria are essential to avoid health risk.

Arrows between the boxes (see Fig. 1) indicate associations and interactions between the submodels. Meteorological and hydrological parameters as well as loads of contaminants discharged by rivers or from other sources are necessary as an input data for the model. These input data are accesible at special data banks. The bank used for the development of the presented model contains the results of our measurements, the data obtained from Institute of Meteorology and Water Management in Białystok, Gdynia, Warszawa and Słupsk as well as the data obtained from the European Centre for Medium-Range Weather Forecasts (EC MRWF) in Reading, Great Britain.

The computations are performed for two areas simultaneously: the Gulf of Gdańsk and the Baltic Sea. The Baltic is covered by a numerical grid with the unit equal to 5 nautical miles, the Gulf - 1 nautical mile. The mouths of rivers, strips of shores or places of intensive man activity can be covered, if needed, by a finer numerical grid with higher resolution (Fig. 2). In the presented model, the open boundary conditions are taken into account. For presentation of the model results, the Geographical Information System (GIS) instructions have been adopted. The same method is used in the case of analyses of environmental changes.

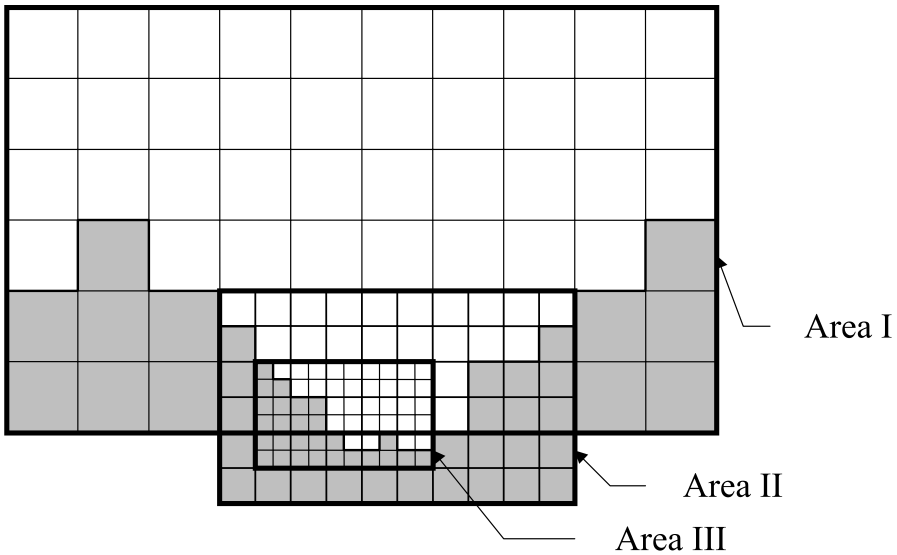

Fig. 2. The fine and coarse grid covering the estuary area of the Gulf of Gdańsk

A MODEL OF SOLAR ENERGY INPUT TO THE SEA SURFACE

This model enables determination of the flux or total dose of (direct + scattered) radiation from the visible light or another light spectrum in the range of 300–4000 nm. The initial data to the model include atmospheric pressure, water vapour pressure on the sea surface and cloudiness. The seasonal mean long-term values of ozone level and aerosol attenuation in the Southern Baltic area are also taken into account. It is assumed that the total solar radiation energy, for a given wavelength reaching the sea surface at a defined time period, can be presented in the following form:

$$Q = \int_{t_1}^{t_2} (E_s \cos\vartheta + E_d) dt \cdot T_{Ch} \quad , \tag{1}$$

where:
E_s and E_d, are the irradiance flux densities at the sea surface generated by direct and scattered in the atmosphere solar radiation, respectively; t, time; ϑ, distance to the solar zenith; T_{Ch}, the function defining the effect of mean cloudiness on irradiance transmission at a time interval t_2–t_1.

$$E_s(\lambda) = \frac{F_s(\lambda)}{\beta^2} T_R(\lambda) \cdot T_a(\lambda) \cdot T_{wv}(\lambda) \cdot T_{O_3}(\lambda) \cdot T_G(\lambda) \, , \tag{2}$$

where:
λ, wavelength; $F_s(\lambda)$, spectral density of the solar constant; $\beta = R_s/R$, factor defining the annual variability of the distance between the Earth and the sun (R and R_s are actual and mean distances between the Earth and the sun, respectively); $T_R(\lambda)$,...,$T_G(\lambda)$, functions of light transmission describing irradiance attenuation in the processes of molecular scattering, scattering and absorption by aerosols and absorption by water vapour, ozone and the most important constant gaseous components of the atmosphere, respectively.

$$E_d(\lambda) = E_{dR}(\lambda) + E_{da}(\lambda) + E_{dg}(\lambda) \, , \tag{3}$$

where:
$E_{dR}(\lambda)$, results from molecular scattering, $E_{da}(\lambda)$, results from aerosol attenuation and $E_{dg}(\lambda)$ results from multiple reflection between the sea (land) surface and the atmosphere.

$$Q = Q_c \cdot T_{ch} = Q_c \cdot (1 - 0.33 \cdot c - 0.37 \cdot c^2) \quad \text{for } \varphi < 57°\text{N} \, , \tag{4}$$

where:
Q_c, energy dose reaching the sea surface in the case of cloudless atmosphere, regardless of cloudiness; c, cloudiness in fractional form (fraction of cloud cover).

Considering the most important processes which take place in the atmosphere and which influence solar radiation on its way to the sea surface, the direct irradiance of the area perpendicular to solar beam incidence (at the sea surface) may be expressed as (2). It may be assumed that scattered radiation incident on horizontal area consists of three components (3). In the case of the Southern Baltic area, the effect of cloudiness on the amount of solar radiation energy reaching the sea surface was evaluated by means of the algorithm given in form (4). Details of this model can be found elsewhere (Krężel 1997).

THE WIND STRESS FORCING

The wind forcing is necessary to induce the circulation of water. In the presented model, daily wind stress fields are used. Their horizontal components are proportional to the square velocity of wind. The values of wind stress covering the Baltic region with spatial step 0.5 × 0.5 geographical degree for period 1994–96, have been obtained from the European Centre for Medium Range Weather Forecasts (ECMWF) in Reading, Great Britain. In the case of the area of the Gulf of Gdańsk these data were interpolated.

MODEL OF THE RIVER INFLOW

For the evaluation of daily river runoff reaching the Baltic Sea, the observations carried out for several years of the main rivers outflows are used. Annual runoff is parametrized by employing the Fourier series formula (5). The values Q_i and φ_i are determined by the nonlinear regression method. The Fourier formula for daily runoff based on the observation period 1971–1990 for the Vistula river in final cross-section may serve as an example (6). The equations for other rivers are presented elsewhere (Cyberski 1997).

$$Q(t) = Q_0 + \sum_{i=1}^{N} Q_{\mathrm{i}} \sin\left(\omega t + \varphi_{\mathrm{i}}\right), \tag{5}$$

where:

$Q(t)$, flow value on day t; t, number of days in the year (from 1 to 365); Q_0, mean annual discharge; Q_{i}, flow amplitude or temperature amplitude corresponding to T_{i}, N, number of harmonic components; φ_{i}, phase shift; T_{i}, periods expressed in days; $\omega = \frac{2\pi}{T_{\mathrm{i}}}$, frequency.

$$\begin{aligned} Q_{(t)} = {} & 1089 + 387 \sin\left(\frac{2\pi}{365} t - 0.126\right) + 190 \sin\left(\frac{2\pi}{182.5} t - 1.92\right) + \\ & + 176 \sin\left(\frac{2\pi}{121.7} t + 2.93\right) + 57.6 \sin\left(\frac{2\pi}{91.25} t + 0.969\right). \end{aligned} \tag{6}$$

MODEL OF THE LIGHT PENETRATION INTO THE WATER

Transmission of solar energy in the sea water is determinated separately for visible light (400–700 nm) and longwave (700–4000 nm) spectral bands. The irradiance within visible light spectrum reaching euphotic zone is used in primary production equations and it depends on chlorophyll concentration.

$$\frac{\int_{400}^{700} E(\lambda, z)d\lambda}{\int_{400}^{700} E(\lambda, z=0)d\lambda} = \exp(-k \cdot z), \qquad (7)$$

$$k = f(Chla), \qquad (8)$$

where:

k, diffusive attenuation coefficient for downward visible light irradiance; f, linear function of *Chla*.

$$\frac{\int_{700}^{4000} E(\lambda, z)d\lambda}{\int_{700}^{4000} E(\lambda, z=0)d\lambda} = \sum_{i=1}^{3} a_i \exp(-k_i \cdot z), \qquad (9)$$

where:

k_i, a_i, are diffusive attenuation coefficients for downward irradiance in longwave (700–4000 nm) spectral bands, their values are: $a_1 = 0.177$, $a_2 = 0.589$, $a_3 = (1\text{-}a_1\text{-}a_2) = 0.234$; $k_1 = 4.624$, $k_2 = 32.257$, $k_3 = 2.139$.

Functional dependence of longwave irradiance on depth allows one to include the warming effect in the process of heat diffusion and has a form (9). More information referring to this model is reported in (Matciak 1997).

THREE-DIMENSIONAL HYDRODYNAMIC MODEL

The three-dimensional, baroclinic Blumberg and Mellor model (Blumberg and Mellor 1987) was adopted to the Baltic conditions. The equations of this circulation model describe the velocity, surface elevation, temperature and salinity fields. The Reynolds equations of motion are (10 a, b). The continuity equation is (11). The conservation equation for temperature and salinity are given in (12). Using the temperature and salinity, the density is computed according to the equation of state (13).

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(K_M \frac{\partial u}{\partial z}\right) + A_M\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right), \qquad (10a)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K_M \frac{\partial v}{\partial z}\right) + A_M\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right), \qquad (10b)$$

where:

u, v and w, components of velocity vector; f, Coriolis parameter; ρ and ρ_0, *in situ* and reference water densities; p, pressure, K_M and A_M, the coefficients of vertical and horizontal momentum mixing.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0\,, \tag{11}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial z}\left(K_{\mathrm{H}}\frac{\partial T}{\partial z}\right)+A_{\mathrm{H}}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\theta_{\mathrm{T}}\,, \tag{12a}$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial z}\left(K_{\mathrm{H}}\frac{\partial S}{\partial z}\right)+A_{\mathrm{H}}\left(\frac{\partial^2 S}{\partial x^2}+\frac{\partial^2 S}{\partial y^2}\right), \tag{12b}$$

where:

T and S are temperature and salinity of water, respectively; K_H and A_H are vertical and horizontal heat and mass diffusivities for turbulent mixing of heat and salinity; θ_T, source of heat and salinity functions.

$$\rho=\rho(T,S,p)\,, \tag{13}$$

The boundary conditions at the free surface $z=\xi(x,y)$ include the wind stresses of momentum (14), and heat and salt fluxes (15). At the bottom $z = H$, the bottom friction stresses as in (16). The boundary temperature and salinity fluxes are assumed to equal zero. At the lateral boundaries (rivers), the temperature and salinity conditions are given by (17).

$$\rho_0 K_{\mathrm{M}}\frac{\partial u}{\partial z}=\tau_{0x}\,,\qquad \rho_0 K_{\mathrm{M}}\frac{\partial v}{\partial z}=\tau_{0y}\,, \tag{14}$$

$$\rho_0 K_{\mathrm{H}}\frac{\partial T}{\partial z}=H_0\,,\qquad \rho_0 K_{\mathrm{H}}\frac{\partial S}{\partial z}=0\,, \tag{15}$$

$$\rho_0 K_{\mathrm{M}}\frac{\partial u}{\partial z}=\tau_{\mathrm{b}x}\,,\qquad \rho_0 K_{\mathrm{M}}\frac{\partial v}{\partial z}=\tau_{\mathrm{b}y}\,, \tag{16}$$

where:

τ_{ox}, τ_{oy}, surface wind stresses; H_0, the atmospheric heat flux; S_0, salt flux; τ_{bx}, τ_{by} bottom stresses.

$$\frac{\partial T}{\partial t} + u_n \frac{\partial T}{\partial n} = 0 \ , \qquad \frac{\partial S}{\partial t} + u_n \frac{\partial S}{\partial n} = 0 \ . \tag{17}$$

At the moment $t = 0$ the initial conditions, that is velocities, are assumed to equal zero while in the case of temperature and salinity three-dimensional distributions based on field observations were taken. Other details connected with theoretical and numerical issues as well as modifications necessary to achieve conformity with local conditions were presented by Kowalewski (1997).

THE TEMPERATURE MODEL OF THE GULF OF GDAŃSK

The three-dimensional distributions of the water temperature and their evaluation are described by the conservation equation for the temperature (12a) and the boundary conditions (15) which are parameterized as heat fluxes by the method of heat balance. The resultant heat flux at the sea surface contains gains and losses of heat in a form (18). Fluxes of solar radiation H_s are available from the model of solar energy input to the sea surface (Krężel 1997). The longwave radiation includes the radiation from the water surface (19a) and the back atmospheric radiation (19b). H_L is the sum of these both constituents (19c). Losses of heat due to evaporation are described by the formula (20) while latent heat of evaporation L_e is expressed by (21). The sensible heat transfer depends on the difference of the water and air temperatures (22). The freezing point is an effect of cooling down of water and may be calculated according to Omstedt (1994) from equation (23). Then, the ice cover develops which can be described as (24). This H^*_{wl} flux consists of two components; the first one results from heat conduction from the atmosphere through the ice (25), the second from the upper boundary layer of the water (26). At the lateral boundaries, heat fluxes are caused by rivers and flows through the open boundary and are given in a form (27). Distributions of temperature resulting from wind driven advection when heat fluxes are excluded have been described in the paper by Jędrasik (1997).

$$H^* = H_s - H_L + H_e + H_{wt} \ , \tag{18}$$

where:
H_s, and H_L are shortwave and longwave solar radiation; H_e, loss of heat due to evaporation; H_{wt}, sensible heat transfer.

$$H_{Lw} = 5.23 \cdot 10^{-8} (273^{o} + T_w)^4 \ , \tag{19a}$$

$$H_{La} = -5.18 \cdot 10^{-13} (1 + 0.17N) \cdot (273^{o} + T_p)^6 \ , \tag{19b}$$

where:
T_p, air temperature; N, cloudiness.

$$H_{\mathrm{L}} = H_{\mathrm{Lw}} + H_{\mathrm{La}}, \tag{19c}$$

$$H_{\mathrm{e}} = c_{\mathrm{e}} \rho_a L_{\mathrm{e}} U \left(q_{\mathrm{p}} - q_{\mathrm{w}} \right), \tag{20}$$

$$L_{\mathrm{e}} = \left(595.9 - 0.54 \cdot T_{\mathrm{w}} \right) \cdot 4186, \tag{21}$$

where:

c_{e}, proportional coefficient; ρ_a, air density; U, wind velocity; q_w, the saturation specific humidity at the water temperature T_{w}; q_p, the saturation specific humidity at the air temperature T_{p}.

$$H_{\mathrm{wt}} = c_{\mathrm{e}} \rho_{\mathrm{a}} C_{\mathrm{pa}} U \left(T_{\mathrm{p}} - T_{\mathrm{w}} \right), \tag{22}$$

where:

C_{pa}, the specific heat of air.

$$T_{\mathrm{f}} = -0.0575 S_{\mathrm{o}} + 1.710523 \cdot 10^{-3} S_{\mathrm{o}}^{3/2} - 2.154996 \cdot 10^{-4} S_{\mathrm{o}}^{2}, \tag{23}$$

where:

T_{f}, freezing temperature; S_{o}, salinity at the freezing surface.

$$\frac{dh_{\mathrm{l}}}{dt} = -\frac{H_{\mathrm{wl}}^{*\mathrm{l}}}{\rho_{\mathrm{l}} L_{\mathrm{l}}}, \tag{24}$$

where:

h_{l}, thickness of ice; t, time; ρ_{l}, density of ice; L_{l}, latent heat of sublimation; H_{wl}^{*}, resultant heat flux under the ice cover.

$$H_{\mathrm{f}}^{\mathrm{l}} = \frac{\kappa_{\mathrm{Tl}}}{h_{\mathrm{l}}} \left(T_{\mathrm{l}} - T_{\mathrm{w}} \right), \tag{25}$$

$$H_{\mathrm{w}}^{*} = c_{\mathrm{ls}} \rho_{\mathrm{w}} C_{\mathrm{pw}} u_{\mathrm{w}} \left(T_{\mathrm{f}} - T_{\mathrm{w}} \right), \tag{26}$$

where:

$H_{\mathrm{f}}^{\mathrm{l}}$, heat flux due to conduction from the atmosphere through the ice cover; H_{w}^{*}, heat flux from the water; κ_{Tl}, coefficient of heat conduction through the ice; T_{f}, freezing temperature; T_{l}, ice temperature; T_{w}, water temperature under ice; C_{pw}, the specific heat of water; u_{w}, velocity of water under the ice; c_{ls}, proportional coefficient; ρ_w, density of water.

$$H_{\mathrm{advrz}} = \frac{V_{\mathrm{d}} T_{\mathrm{d}} - V_{\mathrm{o}} T_{\mathrm{o}}}{P_{\mathrm{dd}} \cdot \Delta t}, \tag{27}$$

where:

H_{advrz}, heat flux brought in by inflowing water; V_d and V_o are volumes of inflowing and outflowing water, respectively; T_d and T_o are temperatures of inflowing and outflowing water, respectively; P_{dd}, area of the cross-section; Δt, interval of time.

MODEL OF PRODUCTION AND DESTRUCTION OF ORGANIC MATTER

Following the concept of the Production and Destruction of Organic Matter Model (ProDeMo), four functional groups are considered in the present model: phytoplankton, zooplankton, detritus and nutrients. The phytoplankton may be divided into two or three subgroups: diatoms, flagellates and chlorophytes. Zooplankton is defined as the biomass of all organisms grazing on the phytoplankton. Detritus pool consists of all dead material which undergoes mineralization. Four macronutrients are considered: nitrate nitrogen, ammonium nitrogen, phosphate phosphorus and silicate silicon. The inorganic form of carbon has not been included into the model structure, since it is not a limiting factor for the growth of phytoplankton. Therefore, only the part of carbon cycle involving phytoplankton, zooplankton, detritus, is taken into consideration. The mass balance equations are closed for nitrogen, phosphorus and silicon. They contain production and destruction terms. The relation between them determines the growth or decay of state variable. The overall mass balance equations for state variables are:

PHYTOPLANKTON GROUPS

$$\frac{\partial[PHYT]}{\partial t} = \left(G - R - D_Z - \frac{V_s}{\Delta z}\right)[PHYT], \tag{28}$$

where:

t, time [d]; G, growth of phytoplankton [d^{-1}]; R, total respiration rate [d^{-1}]; D_Z, grazing rate by zooplankton [d^{-1}]; V_s, sinking velocity [$m\,d^{-1}$]; Δz, depth [m].

ZOOPLANKTON

$$\frac{\partial[ZOOP]}{\partial t} = \left(G_Z - R_Z - W_Z - L_Z\right)[ZOOP], \tag{29}$$

where:

G_Z, growth of zooplankton [d^{-1}]; R_Z, total respiration of zooplankton [d^{-1}]; W_Z, excretion by zooplankton [d^{-1}]; L_Z, natural mortality of zooplankton [d^{-1}].

DETRITUS

$$\frac{\partial[DETR]}{\partial t} = R\cdot[PHYT] + (1 - Z_{\mathrm{As}})\cdot Fr\cdot[PHYT]\cdot[ZOOP] + (R_{\mathrm{Z}} + W_{\mathrm{Z}} + L_{\mathrm{Z}})\cdot[ZOOP] - \left(M_{\mathrm{C}} + \frac{V_{\mathrm{sDETR}}}{\Delta z}\right)\cdot[DETR], \tag{30}$$

where:
M_{C}, mineralization rate [d^{-1}]; V_{sDETR}, sinking rate of detritus [$\mathrm{m\,d}^{-1}$]; Z_{As} assimilation efficiency.

Nutrients

There are two main processes influencing the concentration of phosphorus, silicon and different forms of nitrogen: mineralization and uptake by phytoplankton. In the case of nitrogen also nitrification and denitrification are included in the mass balance equations. Parametrization of the sorption-desorption process (equilibrium concept) is included into the phosphorus cycle. For example, the nitrogen cycle is described in the following way:

<u>Nitrate nitrogen</u>

$$\frac{\partial[N\_NO3]}{\partial t} = N_{\mathrm{Nitr}}\cdot[N\_NH4] - G\cdot[PHYT]\cdot a_{\mathrm{NC}}\cdot(1 - P_{\mathrm{NH4}}) - N_{\mathrm{Denitr}}\cdot[N\_NO3], \tag{31}$$

<u>Ammonium nitrogen</u>

$$\frac{\partial[N\_NH4]}{\partial t} = M_{\mathrm{N}}\cdot[N\_DETR] - G\cdot[PHYT]\cdot a_{\mathrm{NC}}\cdot P_{\mathrm{NH4}} - N_{\mathrm{Nitr}}\cdot[N\_NH4] + \frac{S_{\mathrm{N}}}{\Delta z}, \tag{32}$$

<u>Detritus nitrogen</u>

$$\frac{\partial[N\_DETR]}{\partial t} = R\cdot[PHYT]\cdot a_{\mathrm{NCPHYT}}(R_{\mathrm{Z}} + W_{\mathrm{Z}} + L_{\mathrm{Z}})\times[ZOOP]\cdot a_{\mathrm{NCZOOP}} - \left(M_{\mathrm{N}} + \frac{V_{\mathrm{sD}}}{\Delta z}\right)\cdot[N\_DETR], \tag{33}$$

where:
N_{Nitr}, nitrification rate [d^{-1}]; N_{Denitr}, denitrification rate [d^{-1}]; M_{N}, nitrogen mineralization rate [d^{-1}]; a_{NCPHYT}, nitrogen to carbon ratio in phytoplankton [-]; a_{NCZOOP}, nitrogen to car-

bon ratio in zooplankton [-]; P_{NH4}, preference ammonium over nitrate nitrogen factor; S_N, inorganic nitrogen flux from sediment [g m^{-2} d^{-1}].

DISSOLVED OXYGEN

In the case of dissolved oxygen, all processes involving this element, except reaeration, are taken into account in mass balance equations describing other state variables: primary production, nitrification, denitrification, respiration of living organisms, mineralization, consumption by sediment. For each of these processes, the specific proportionality ratios are applied. The reaeration is considered to be the function of current velocity and wind speed. All state variables as well as derived quantities are described elsewhere (Ołdakowski and Renk 1997).

MODEL OF TRANSPORT OF INORGANIC SUSPENSION

This model allows one to evaluate the concentration and rate of deposition of suspended matter as well as the extent of bottom erosion. It is based on the turbulent diffusion equation (34). Changes of the bottom level are connected with the erosion of the sediment and deposition of the suspended particles in the bottom boundary layer in the way (35). The results of this model are presented in the paper by Bradtke (1997).

$$\frac{\partial C}{\partial t} = \underbrace{-\frac{\partial(u \cdot C)}{\partial x} - \frac{\partial(v \cdot C)}{\partial y} - \frac{\partial(w \cdot C + w_s \cdot C)}{\partial z}}_{advection\ +\ settling} + \underbrace{+\frac{\partial}{\partial x}\left(D_H \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_H \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_V \frac{\partial C}{\partial z}\right)}_{diffusion} + F, \tag{34}$$

where:

C, concentration of suspended matter; u, v, and w, components of velocity along the axes: x, y, z; w_s, rate of particle sedimentation; $F = F_A + F_R + F_E + F_D$, fluxes of suspended matter; atmospheric input (F_A), river inflow (F_R), erosion of the bottom (F_E), deposition at the bottom (F_D).

$$\rho_s \frac{\partial h_s}{\partial t} = F_D - F_E , \tag{35}$$

where:

ρ_s, density of sediment; h_s, level of the bottom compared to the initial level.

MODEL OF PROPAGATION OF BACTERIA

To investigate the sanitary state of the coastal waters, bacteria of the *Escherichia coli* have been chosen as a marker organism. The ranges of their spreading depend on the advection and their survival. Survival of these bacteria is influenced by some environmental parameters and is described by the equation (36).

$$N = N_o e^{-Kt}, \tag{36}$$

where:
N, cel number of bacteria of *E. coli* after time *t* in days; N_o, the initial cell number bacteria of *E. coli*; *K*, mortality coefficient of *E. coli* bacteria [d^{-1}]; *t*, time [d].

The mortality coefficient has been established on the base of laboratory experiments. Its mean value has got the following form

$$K = 6.466 - 0.195\, t + 2.215 \cdot 10^{-7}\, t^2\, i^2, \tag{37}$$

where:
K, mean mortality coefficient; *t*, temperature; *i*, irradiance.

The results of these investigations show that the mortality is influenced by the water temperature and irradiance as described by a non-linear regression (37). These results can be found in the article by Królska *et al.* (1997).

MODEL OF NUTRIENT DISTRIBUTION IN THE GULF OF GDAŃSK

A series of temperature, salinity and nutrient measurements were taken in the Gulf of Gdańsk by Institute of Oceanography at University of Gdańsk during period 1981–96. The 35 stations were chosen at which regular or occasional measurements were carried out for the longest period of time. Based on these stations, at standard levels of depth, the Fourier series was formulated in a form (38). As an example can serve the temperature at station 122 localised at Puck Bay for which the formula has taken the shape (39).

$$E_p(z,t) = E_{po} + \sum_{i=1}^{N} E_{p_i}(z) \sin(i\omega t - \varphi_i(z)), \tag{38}$$

where:
$E_p(z,t)$, daily value of an environmental parameter *T*, *S*, or nutrients; E_{po}, mean annual value of an environmental parameter *T*, *S* or nutrients; E_{pi}, harmonic components of annual amplitude changes of an environmental parameter *T, S* or nutrients; φ_i, phase displacement in [d] for harmonic components of an environmental parameter *T, S* or nutri-

ents; $\omega = \frac{2\pi}{T}$, frequency; T, length of the year in days; t, day in the year; z, level of depth; N, number of components *e.g.* equals 3.

$$E_\mathrm{p}(z,t) = 9.23 + 8.67\sin\left(\frac{2\pi}{365}t - 133.62\right) + 0.91\sin\left(\frac{2\pi}{182.5}t - \right.$$
$$\left. + 0.393\right) + 0.39\sin\left(\frac{2\pi}{121.7}t - 101.61\right), \qquad (39)$$

For each selected station at the chosen level of depth, the annual courses of environmental parameters were evaluated by this type of Fourier series. In this way, they have become the first reference for simulations generated by our model. Other results are reported by Nowacki (1997).

CONCLUSIONS

The model consists of a set of interlinked submodels describing the physical and biogeochemical processes. The model dynamically simulates seasonal cycles of nitrogen, phosphorus and silicon which are forced by wind, irradiance, temperature and transport processes. This approach can be applied to low trophic levels which are very much determined by the abiotic environment, hydrodynamics, vertical structure of the water column, horizontal and vertical transport of nutrients. The results of the model include hindcast for 1994–96, that is for the period for which all the mentioned above processes have been simulated.

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