A three-dimensional ecohydrodynamical model of the Puck Bay "EcoPuckBay" - a hydrodynamic part

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Abstract. A new method – 'Integrated information and prediction Web Service WaterPUCK' for investigation influence of agricultural holdings and land-use structures on coastal waters of the southern Baltic Sea is presented. WaterPUCK Service is focused on determination of the current and future environmental status of the surface water and groundwater located in the Puck District (Poland) and its impact on the Bay of Puck (the southern Baltic Sea) environment. It will highly desired tool for land-use and environment management. WaterPUCK combines several different components and methods such as retrospective analyses of existing monitoring data sets, in situ measures and the application of various models to estimate main mechanisms and threats responsible for the pollution transport from the agricultural holdings and land-use structure to the surface and groundwater and potential predictability of environment change of the Puck District and the Bay of Puck ecosystem. The WaterPUCK Service is constructed as part of the project with the same name 'WaterPUCK' (www.waterpuck.pl). Developed within the framework of this project, the model of the Puck Bay "EcoPuckBay" will be a three-dimensional ecohydrodynamical model of higher vertical and horizontal resolution that assimilates satellite data. EcoPuckBay model consists of active ocean, ecosystem and ice modules, coupled together with active land module (SWAT plus ModFlow) which provide data, such as freshwater inflow and nutrient discharge from rivers and ground, and passive atmospheric module which provide data such as weather forecasts from external sources (UM ICM). From the side of the open sea, boundary conditions will be fed from the three-dimensional model of the ecosystem for the Baltic Sea 3D CEMBS (www.cembs.pl). The model horizontal resolution is 1/960°, which corresponds to ca. 115 m grid. Vertically model is divided into 19 layers. The first of 5 layers is 0.4 meters thick. 3D EcoPuckBay model will generate 72-hour forecast which include currents, temperature, salinity and ice parameters. In addition, the model will forecast ecological parameters i.e. nutrients, pesticides, dissolved oxygen concentration and biomass of phytoplankton and zooplankton in the entire water column. Each of these variables will be calculated with a second-order advection-diffusion, partial differential equation.
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Keywords: 3D ecosystem model, hydrodynamic module, Puck Bay, Baltic Sea.

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1 Introduction

The Baltic Sea is a very difficult basin for numerical modelling. On the one hand, the mesoscale phenomena require the whole basin to be included, on the other hand – only very small spatial structures of bathymetry are of major significance for hydrology of the Baltic Sea. There is very strong vertical density stratification and the benthic zone is important for transportation of inflow waters. For the water balance, it is necessary to include rivers and precipitation. Due to all these elements, a proper spatial scale and long-term simulation are required to obtain a good projection of the real state of the Baltic Sea. Dzierzbicka-Glowacka and her co-workers published several papers respecting to modelling hydrodynamical and biological processes in the Baltic Sea, for instance: Dzierzbicka-Glowacka *et al.*[3, 4]. In 2011, the operational ecohydrodynamic model (3D CEMBS) was launched at the Institute of Oceanology PAS in the parallel version on the 2 km grid with rivers and the open boundary (www.cembs.pl).

Leaching of nutrients from agricultural areas is the main cause of water pollution and eutrophication of the Baltic Sea. A variety of remedial measures to reduce Nitrogen (N) and Phosphorus (P) losses from agricultural holdings have been taken in the past. However, knowledge about the risk of nutrient leaching has not yet reached many farmers operating in the watershed areas of the Baltic Sea. Nevertheless, the growing international consciousness on the need for water quality improvement has influenced the desire to expand knowledge and social awareness of environmental implications of water quality worldwide.

The research presented in this paper was conducted as part of the project on modelling of the impact of the agricultural holdings and land-use structure on quality of water in the Bay of Puck – Integrated information and forecasting Service "WaterPUCK" (Dzierzbicka-Glowacka *et al.*[5, 6, 7]).

The purpose of the project was to determine the current and future environmental status of surface water and groundwater quality in the Puck Commune and its impact on the Bay of Puck environment (Fig. 1). The most significant input of nutrients in the environment comes from agricultural source and surface structure usage e.g. sewers or drainage ditches. Therefore, objective of the project was to estimate the impact of nutrient loading by compiling the recent knowledge, factoring in the essential in situ measurements, and using advanced modelling. This paper presents an integrated, operational EcoPuckBay model of the Buy of Puck ecosystem for the hydrodynamic module (a first time) and examples of preliminary results.

The computing presented in this paper was processed by Tryton computer clusters at the Academic Computer Centre in Gdańsk (CI TASK).

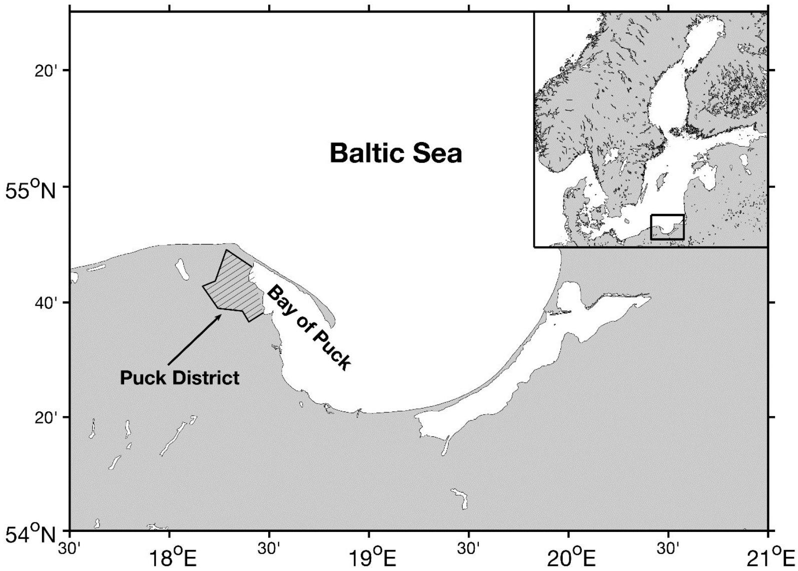

Fig. 1. Map of the Puck District and the Buy of Puck

2 Integrated Service WaterPUCK

Solutions to water access, land degradation, nutrient management and ecosystem services have to be developed in consideration of what influences the environment and communities across landscapes, not just what works influences the farm. Therefore, the main result of the project "WaterPuck" is Integrated information and prediction Service "WaterPUCK" developed by both improving the best available models and combining them with new models (Fig. 2).
Service WaterPUCK (Dzierzbicka-Głowacka *et al.*[5, 6]) is developed basing on SWAT (Soil and Water Assessment Tool, Brzozowski *et al.*[1], Taylor *et al.*[12], Zima[14]), groundwater flow model (based on Modflow, Jaworska-Szulc[8]), 3D ecohydrodynamic model of the Bay of Puck EcoPuckBay (based on the POP code, Dzierzbicka-Glowacka *et al.*[3, 4]) and integrated agriculture calculator called "CalcGosPuck" (Dzierzbicka-Głowacka *et al.*[7] and Ulén *at al.* [13]).

3 3D ecohydrodynamic model of the Bay of Puck EcoPuckBay

The model of the Puck Bay "EcoPuckBay" (Fig. 3) is a three-dimensional, ecohydrodynamic model of high vertical and horizontal resolution that assimilates in situ data measurements and satellite data. EcoPuckBay will determine the spatiotemporal changes in the quality of marine waters in respect to specific pollution indicators.

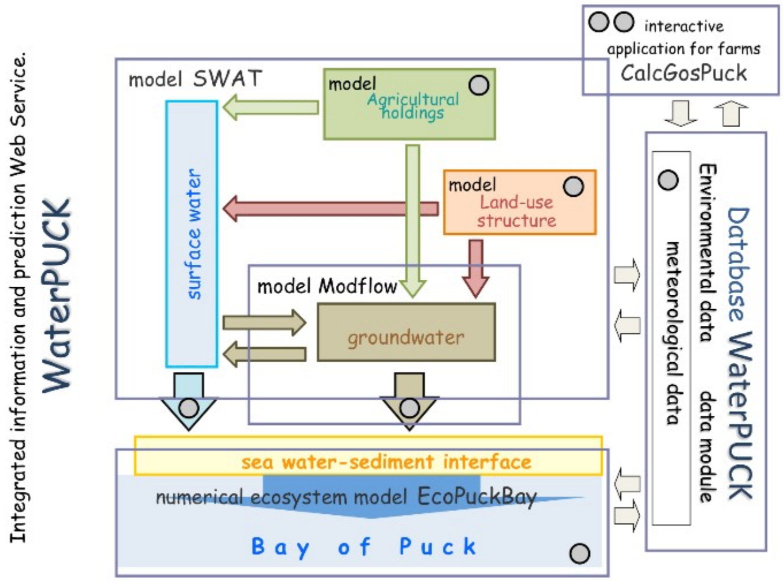

Fig. 2. The shame of water and contaminant fluxes covered in WaterPUCK.

EcoPuckBay is based on the POP code, the Parallel Ocean Program (POP, Smith and Gent[10]) from the National Laboratory in Los Alamos (LANL), which is derived from the global ocean model (Semtner[11]) with additional conditions for free surface (Killworth *et al*.[9]). It is consists of active ocean, ecosystem and ice modules, coupled together with active land module (SWAT plus ModFlow) which provide data, such as freshwater inflow and nutrient discharge from rivers and ground. It is a z-type model, meaning that the thickness of each layer will be identical for every cell and will be driven by the meteorological data. It will also be able to assimilate data from measurements. From the side of the open sea, boundary conditions is fed from the Baltic Sea 3D CEMBS model (www.cembs.pl) . The hydrological part of the model is describe the behaviour of a stratified basin by solving spatial derivatives in the spherical coordinates using the finite element method. It is able to solve momentum, continuity and hydrostatic equations; equations of state; and tracer transport equations.

It is responsible for calculating parameters such as water temperature, salinity and currents. The biochemical model will consist of a set of variables such as nutrients, phytoplankton, zooplankton, dissolved oxygen and organic matter. Each of these variables will be calculated with a second-order advection-diffusion, partial differential equation. The presented equation (1) describes the rate of change in the concentration of the variables in time and space, taking the source and loss functions into account:

$$\frac{\partial S}{\partial t} + (V + w_s)\nabla S = \frac{\partial}{\partial z}\left(K_z \frac{\partial S}{\partial z}\right) + \sum_{i=1}^{2} \frac{\partial}{\partial x_i}\left(K_{x_i} \frac{\partial S}{\partial x_i}\right) + F_S, \tag{1}$$

where S is each model variable, V (u, v, w) is the velocity vector, w_s is the sinking velocity of pelagic detritus, K_z and K_{xi} are vertical and horizontal turbulent diffusion coefficients and F_S is the biogeochemical source-sink term. F_S describes possible sources and losses of the diffusing substance in the space being studied. It is determined from knowledge of biogeochemical processes occurring in the marine environment and their mutual relations. The change in pesticide concentration will be calculated based on a similar equation. The pesticides are mainly introduced to the environment by being discharged from rivers and groundwater, and they are subjected to the process of sedimentation and bioaccumulation. In this work, the description of the hydrodynamic module is presented, only.

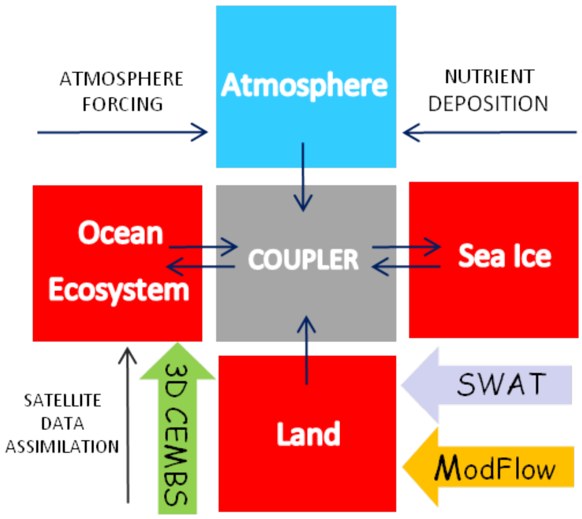

Fig. 3. Configuration of the 3D EcoPuckBay model

4 Description of the hydrodynamic module

The 3D EcoPuckBay model horizontal resolution is 1/960°, which corresponds to ca. 115 m grid. Vertically model is divided into 19 layers. The resolution in the five uppermost layers is 0.4 m. Below the 5th layer the thickness is gradually increasing to up to maximum of 5 m at 20 m depth

The initial state of the ocean model was prepared using temperature and salinity 3D CEMBS model data (Dzierzbicka-Glowacka *et al.*[3, 4]). 3D-CEMBS model is currently configured at approximately 2km (1/48°). The bottom topography is based on ETOPO1 1 arc-minute global relief model. The bathymetric data were interpolated to the model grid using the kriging method. 3D-CEMBS model domain is based on stereographic coordinates, but the equator of these coordinates is in the centre of the Baltic Sea (so we actually use rotated stereographic coordinates) and we could assume that shape of the cells is square and they are identical.

It is based on the Parallel Ocean Program – z-coordinate system model. The POP model is based on three-dimensional equations of motion with hydrostatics and Boussinesq's assumption. The adaptation required modifications in the code – we added extra energy dissipation based on a Smagorinsky-like viscosity and made modifications of the fresh water fluxes. The atmospheric data are from the UM model (provided by the Interdisciplinary Modelling Centre of the University of Warsaw). The horizontal resolution of the provided atmospheric data is 4 km. The model has passed the main stability tests and currently works properly.

Figures 4 – 7 show the modelled results from the 3D EcoPuckBay model. For example, distributions of the temperature (Fig. 4), salinity (Fig. 5), sea height (Fig. 6) and currents (Fig. 7) in the upper layer sea in Bay of Puck in May (for 10.05.2015) are presented.

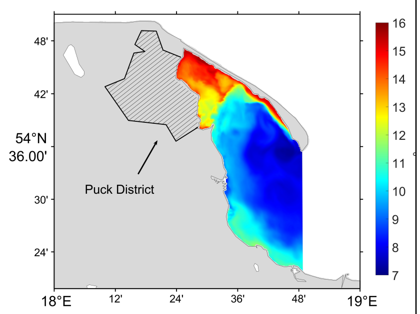

Fig. 4. Distribution of the sea surface temperature in Bay of Puck in May

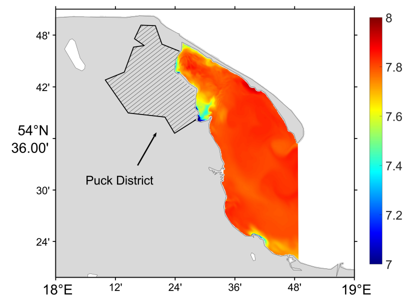

Fig. 5. Salinity distribution in the surface layer in Bay of Puck in May.

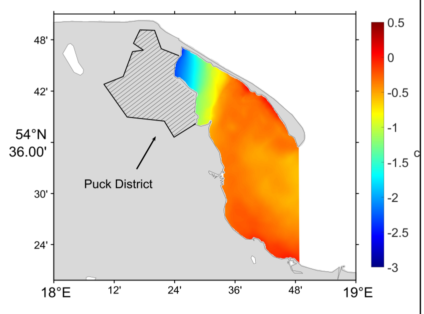

Fig. 6. Distribution of the sea surface height in Bay of Puck in May.

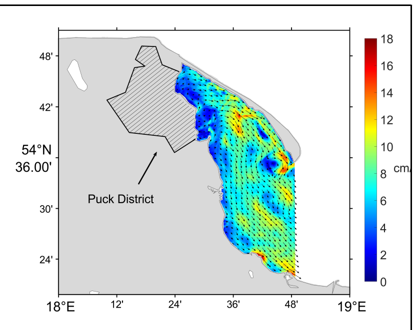

Fig. 7. Currents distribution in the surface layer in Bay of Puck in May.

Conclusions

To study the complexity of hydrophysical and biological processes in the marine environment, and the links between these processes, modern techniques, i.e. mathematical modelling and computer simulations are required. Although the field work provides the most reliable information on these mechanisms and processes, it requires comprehensive and costly in situ observations conducted under a variety of hydrological conditions for long periods of time. They are nevertheless essential for the collection of sufficient statistical data for an adequate diagnosis of the state of the environment and for forecasts.

The development of integrated approaches, such as monitoring measures and modelling, became an important tool not only for understanding the processes taking place in both inland and marine ecosystems but also for evaluating the impact of various land-use and climate scenarios on water quantity and quality at the basin scale (Conan[2]).

The main objective of this paper, i.e. development of a hydrodynamic module for the Bay of Puck model, was achieved in the following steps:

- adaptation of the 3D CEMBS model from IO PAS for the Bay of Puck, for the hydrodynamic module ;
- parametrization and calibration of the model ;
- compilation of bathymetry on the grid of the model;
- interpolation of atmospheric data for 6-hour forecast provided by the UM model from ICM UW;
- incorporation of rivers from SWAT model and precipitation;
- opening the boundary with the Baltic Sea;
- development of the model for the operating mode

The work presents the idea of a 3D ecohydrodynamic model of the Bay of Puck EcoPuckBay – a hydrodynamic part, which determines the main physical parameters of the environment: horizontal components of the velocity u,v and the vertical component of velocity w, pressure p, density , temperature T and salinity S of water. Variables will present on the website for 72-hour forecast are as follows: temperature, salinity, currents, sea surface height and ice area cover.

The 3D EcoPuckBay model (at present – the hydrodynamic module) is a suitable tool for studying the annual, seasonal, monthly and daily variability of environmental parameters in the Bay of Puck (the southern Baltic Sea). It can therefore be applied in the forecasting of ecological changes in the southern Baltic Sea. In order to assess the accuracy of the 3D EcoPuckBay model for the determination of parameters of the Bay of Puck ecosystem, the detailed comparison of the model results with measurements will be presented by us in a separate paper. The next step in our modelling work is to run the operational system for the 3D ecohydrodynamic model of the Bay of Puck EcoPuckBay with the assimilation of satellite and in situ data (a separate paper).

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