Operational modelling for pollution control in coastal areas: experiences from continuous operation in the Elbe estuary

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Abstract

The high spatial and temporal variability of dynamical processes in aquatic environments requires appropriate monitoring and forecasting methods and strategies. The combination of necessarily spotlike measurements with precise circulation and transport models is the basic idea of operational modelling to cope with these requirements. Under the EUREKA-EUROMAR umbrella the OPMOD project (OPERational MODelling of Regional Seas and Coastal Waters) has been performed by 11 European institutions. Existent modelling and measurement techniques were combined into a flexible operational tool for a wide range of environmental monitoring, navigational support, decision-making, and pollution control tasks. Major objectives of OPMOD systems are the routine monitoring of application areas as well as shortterm forecasting in cases of natural or man-made hazards like oilspills or storm surges.

In 1994 an OPMOD system became operational on a routine basis for the tidal estuary of the Elbe river and the dynamically complex port region of the City of Hamburg. Experiences of the routine operation of this system are described in this paper. Furthermore the system is used as a contribution to the MAST 3 project PROMISE (Pre-Operational Modelling in the Seas of Europe).

1 Motivations for Operational Modelling

In most shelf, coastal and estuarine areas as well as in many limnic regions the spatial and temporal variability of the dynamical processes requires appropriate monitoring and forecasting methods and strategies. Typical coherency scales for example for circulation and transport processes are in the range of 10 to 100 meters in the horizontal space domain and from some minutes to some hours in the
time domain, respectively. Even quasisynoptic and intensive measurements cannot resolve these processes. Therefore fully three-dimensional, non-linear prognostic models are necessary. Furthermore transport processes and the prediction of water levels, currents, waves, spill-behaviour, and various other processes can be described by numerical models on a high quality level.

The combination of continuously operating monitoring networks and numerical models to an operational system is a powerful tool for the observation and shortterm forecast of the dynamical situation and distribution of hydrographic and environmental parameters in the area of investigation.

2 General Concept

The OPMOD system was designed as a flexible and modular concept which allows the adaptation to many applications in a large range of objectives in marine and more generally aquatic technology, monitoring, and management by relatively simple modifications or extensions. Besides the operational approach it also allows off-line operation for case studies and specific analysis. Additional and external models and software can be applied to the internal system-concept and incorporated upon user’s specifications.

The combined system consists of autonomous measurement stations, telemetric equipment for data transfer, computer periphery, and the corresponding model, display, and technical software. The scientific software includes the current and transport calculations and the correlation of measurement and model data within the system.

Additionally software for data acquisition, data handling, and data representation have been developed to improve the respective model's performances and flexibilities.

The results produced by the system may act as a database for the identification of data gaps and measurement requirements allowing the optimization of survey procedures, tracklines, and station spacing positioning as well as precise level corrections of bathymetric and other survey data.

The development work was carried out in the EUREKA framework within the project OPMOD, which commenced in 1989 as a cooperation of 11 participants from 8 countries. It aims at applications from regional seas to river systems and lakes.

3 Model Characteristics and Requirements

The core of the system is the current model based on a three-dimensional prognostic baroclinic FD-scheme to solve the nonlinear Navier-Stokes equations (see Duwe et al. [1]). The semi-implicit numerical algorithm uses the Boussinesq approximation, is a multi-level scheme in the vertical dimension and can resolve vertical turbulence from constant approximation to full 3D $k-\epsilon$-scheme approximations. The system is driven by a few representative measurements provided by continuously processing field stations or monitoring networks. These measurement stations require small maintenance efforts combined with longterm stability
and high resolutions. In the case of forecasts boundary conditions are derived from operational meteorological models and efficient hydrological prognosis (e.g. tidal constituents).

The circulation model resolves the appropriate coherency scales and shows longterm stability and operability. It calculates the actual state as well as short-term forecasts of the governing parameters and processes (e.g. waterlevels, currents, salinity, temperature, density).

Besides the circulation model additionally designed spill and transport modules can be invoked upon necessity which are fed by the results of the circulation model. For the transport either finite differences (flux corrected transport) or Lagrangian tracer techniques are used which offer a high accuracy and show the necessary flexibility for individual definitions of items and characteristics of substances (e.g. hydro-chemical and biological interactions, decay and accumulations, sedimentation and erosion, etc.). They are either incorporated into the system or operating in stand-alone units which are connected via data links.

The models have been verified in a number of very different applications in coastal waters, shelf seas, and rivers (see e.g. Nöhren et al. [2], Pfeiffer et al. [4], Sündermann et al. [5]).

4 Area of Application

In 1992 the German OPMOD system became operative with a real application to the tidal estuary of the Elbe river and the dynamically complex port region of the City of Hamburg.

The morphology is rather complicated with large tidal creeks and flats, intersected by some islands and sands and a deep navigational channel leading from the North Sea to Hamburg. The dynamical processes are governed by the tide yielding complex co-oscillations and non-linear deformations of the tidal wave when progressing riverup. In the outer regions local wind-induced circulation patterns may occur. The brackish water zone is characterized by partially and temporarily strong baroclinic influences (i.e. density influenced flow patterns). The upper part of the area includes the Hamburg Port which is located in and around a branching and re-merging area of the river forming complex systems of strongly tidally influenced port bases, junction channels, and waterways.

5 The Basic Model System and Information Network

A three-dimensional baroclinic circulation model covers the area of the tidally influenced part of the river Elbe from Geesthacht to the river mouth west of Cuxhaven. The horizontal resolution of the model is 250 m and the average vertical one 1.5 m. At the seaward boundary values from the North Sea/German Bight forecast model system of the German Hydrographic Authority are applied. Wind forcing is taken from the meteorological forecast models operated by the German Meteorological Office.
In this basic model a barotropic model is embedded covering the area of Hamburg port. The higher horizontal resolution of 50 m is required to resolve and simulate the complex circulation in the river branches and canals as well as the narrower river sections east of Hamburg.

If not provided by the basic model with 250 m horizontal grid the input data for the current model (water level, water temperature, wind, etc. for boundary conditions and verification purposes) are supplied from the measurement stations of the port authorities and of the Environmental Authority of Hamburg. The latter is operating five monitoring stations on the river Elbe and in the harbour area evaluating water quality by measurement of temperature, oxygen content, alkalinity, conductivity, and radioactivity.

Additional connections exist to the monitoring devices of the measurement system established in the EUREKA-EUROMAR MERMAID project in the Elbe river. In this context a significant improvement in the reliability of links with the external measurement data and model forecast sources was experienced by the extensive use of network facilities both internally (workstations connected via ethernet) and externally (internet connection).

Generally the transport and spill models are driven by the results of the circulation models. Lagrangian schemes which have the advantage of low numerical diffusivity and give better possibilities for formulation and incorporation of sources, sinks, and intra-ensemble interaction are used. Turbulent diffusion, wave action, and other parameterized formulae or bulk parameters are usually represented by Monte Carlo schemes and random walk methods. For more details see e.g. Pfeiffer and Duwe [4].

The transport models can be operated either as an integral part of the system or as stand-alone systems on personal computers with the input data transferred or accessible via a local network. They are invoked either automatically or on user’s request and control whenever required.

### 6 System Control

A major part of the OPMOD systems are peripherical programs and software tools for configuration, installation, maintenance, communication (intra-system and with the user), real-time and multi-process control, automatic data processing, automatic control of the model’s performance and quality. The general system operation control is depicted in figure 1. The programs and system tools are usually not accessible and generally not interesting for the user. However, the system provides user shells as interfaces and menus which are graphically supported.

Thereby user-defined operations like online displays, animations, plotting, archiving, further evaluation of data and model results, setup of transport models are controlled.
Figure 1: General scheme of an OPMOD system
7 Experiences from Routine Operation

Intensive research and optimization work of numerical schemes and models, process and case studies have been done and are still ongoing in other project and research activities to support the development of the OPMOD system. Tests comprised the reaction of the model to noisy non- or only slightly smoothed data as they might be delivered by the interfaced measurement stations. Other model tests comprised the long-term stability and predictability of the model by hindcasting longer (some weeks to months) periods. This is an essential requirement for operational applications. The circulation models fully proved thereby their long-term stability, predictability, and operability. The simulation of estuarine dynamics in the Elbe estuary has shown a nature-like behaviour of the brackish water zone and temperature variation in the area (see e.g. figures 2 and 3). The quality of the model results was in the range of the error margins of field measurements and short-term meteorological forecasts. Figures 4 and 5 depict the corresponding distributions of current speeds whose detailed and reliable forecast is essential for determining turbulent mixing and dispersion as well as for sedimentation/erosion investigations.

8 Conclusion and Outlook

The OPMOD system for the Elbe estuary is able to produce routinely and permanently the actual state as well as daily 24 hours forecasts of relevant hydrographic parameters for the area of application. Thus the system has proven its reliability as a tool for continuous monitoring of the aquatic environment. It has a wide range of applications e.g. the monitoring and management of surface waters (synoptic information, forecasts, control and monitoring of effluents, determination of origin of detected oil spills), application in the offshore industry (prediction and hindcasts of spills, safety and risk analysis, etc.), or for navigators (e.g. on-line information for ship’s operation, integration into electronic mapping). Due to its modular design the system offers high flexibility to the requirements of individual users and allows the integration of specially applied modules and the coupling with monitoring networks already in operation or with models and evaluation procedures made available by other institutions.

The OPMOD system is envisaged to include other German coastal and estuarine areas and can be included into larger scale monitoring and forecast areas covering the German Bight and the Southern North Sea. The connection with the larger-scale operational model of the North Sea of the Bundesamt für Seeschifffahrt und Hydrographie (BSH) has already provided useful experiences to enable a generalization of the approach to the coupling of small- and larger-scale model systems within GOOS activities.

Furthermore the experiences made within the OPMOD project are a valuable contribution to the MAST 3 project PROMISE (Pre-operational Modelling in the Seas of Europe). This project aims at collecting high resolution comprehensive data sets which will be used to test pre-operational models including all aspects from data links, real-time monitoring devices and national data centers.
Figure 4: Example of an output: Current speed distribution in the surface layer close to high water; same area and time as in fig. 2 (darker colours denote higher velocities).

Figure 5: Example of an output: Current speed distribution in the surface layer close to low water; same area and time as in fig. 3.
Figure 2: Example of an output: salinity distribution in the surface layer close to high water; area near Cuxhaven (lighter colours denote brackish water).

Figure 3: Example of an output: salinity distribution in the surface layer close to low water; same area as in fig. 2.
and improve these model systems. Main focus of PROMISE is to quantify the rates and scales of exchange of sediment between the coast and the near-shore zone and, thereby, to enable subsequent application of this experience to other coastal areas and for broader management applications.

The model system is applied to the Sylt-Rømø Bight and the coastal regions near Holderness (UK) in the North Sea.

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