Application of a comprehensive decision support system for the water quality management of the River Ruhr, Germany

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Abstract With increasing human activities and water quality deterioration within river basins, the problem of water quality management is playing an increasingly important role. Quality management can be realized through control measures having various economic and water quality implications. To facilitate the analysis of available management options, a comprehensive decision support system (REgional WAter Quality and Resources Decision Model (REWARD)) was developed, which represents many sides of the problem. The implied models of REWARD are capable of describing the hydrological, chemical and biological processes occurring in a river/reservoir system (or within a waste water treatment plant), while incorporating economic considerations within the decision model segment. The example problem was to provide quantitative support in formulating feasible, effluent based water quality management strategies for the upper 90 km section of the Ruhr River (a tributary of the River Rhine) in Germany.

INTRODUCTION

Great water resources projects show periodicity of investigations and research intensity in the different fields. For example, comparing the number of "new" water quality models (WQMs) published in the 1970s, 1980s and 1990s, one can detect a decreasing trend. In analysing the reasons, the following limitations should be mentioned:

(a) In the water resources field, there is relatively limited manpower for development of models and methods.

(b) The formerly developed WQMs are sometimes imperfect representations of the real world. The bio-geochemical components of the existing models are more or less generally formulated, but show variation between simple and more complex models. Models are either too simple or too complex. From a management point of view the simple linear models are preferred, however a precise process description needs complex ecological models (often with a large number of parameters subject to calibration). Although the calibration of complex models (with appropriate computing technology) is possible, it is rarely provided by a statistically reliable quantity of data.
(c) The existing models are more or less case dependent, considering the formulation of the boundary conditions and programming requirements.

(d) WQMs have soft character because observations of the phenomenon with scarce data (it is the "normal" case) are uncertain. Handling data and modelling uncertainties and coordinating their analysis with the parameter estimation are key steps in the applications of WQMs.

(e) Most of the existing WQMs do not allow continuous hypothesis testing and selection of different appropriate methods with a high level of flexibility.

To override the problems listed above and facilitate the analysis of available quality management options, a comprehensive PC-based decision support system was developed which focuses mainly on the above mentioned limitations. The example problem was to provide quantitative support in formulating appropriate water quality management strategies for the upper 90 km section of the Ruhr River (a tributary of the River Rhine; \( \approx 2000 \text{ km}^2 \) catchment area) in Germany (Fig. 1) that drains a part of the Ruhr industrial area and provides a source of potable water supply of more than 400 000 m\(^3\) day\(^{-1}\).

In the past decades, due to legislative and economic changes, intensive efforts were made to improve water quality by construction of several waste water treatment plants (WTPs) (11 municipal WTPs in the investigated reach), and at the same time some major industrial polluters ceased operations. Nowadays the water quality requirements are satisfied for most of the "traditional" parameters such as BOD, DO, \( \text{O}_2 \) etc., and loads for non-traditional components (e.g. AOX) were also greatly reduced. In the same period of time the ambient water quality standard cannot be met for ammonia nitrogen at the current level of emission and considerable algae development can be observed on the downstream reach of the Ruhr that indicates the need for further improvement of the water quality.

**ELEMENTS OF THE COMPUTER-AIDED SUPPORT SYSTEM: REWARD**

The implied models of REWARD are capable of describing the hydrological, chemical and biological processes occurring in a river/reservoir system (or within a waste water treatment plant). The linked water quality model consists of three main parts. The basic
framework of the model is established by the water quality transport model. This model determines the changes in constituent concentrations due to the hydrodynamic influences of advection and dispersion and due to the bio-geochemical reactions. The two other main parts of the model are the hydrodynamic and the bio-geochemical components.

WATER QUALITY TRANSPORT MODEL

In REWARD there are two approaches included in solving the transport equation on the basis of the simplified turbulent dispersion equation.

(a) Multiple-box model in which the object (river, channel, lake, etc.) is divided into a set (unlimited number) of completely mixed volume elements (tanks). Concentration is determined in each element by simple mass balance (integral of the turbulent dispersion equation (TDE)). This results in an ordinary differential equation for each state variable reducing the original TDE by spatial averaging to a set of zero-dimensional versions. REWARD takes into consideration discharges, withdrawals, dams as well as the sediment compartment attached to each reactor.

(b) An alternative to (a) is the application of the continuum approach by difference equations also available in REWARD.

Increasing resolution of the spatial description, however, allows one to solve complex bio-geochemical sub-models, but it is very difficult to formulate case-independent models in a flexible way. In this paper particular attention is paid to the river models for which the 1-D description can be applied. In this case a direct connection can be found between the solution methods (a) and (b) (Levenspiel & Bischoff, 1963). The key parameter is the Peclet number ($Pe$) which is directly related to the number of tanks ($n$). This similarity can be demonstrated by comparing the concentration response to the unit mass impulse described for the mass balance equations of the tanks-in-series model (equation (1)) and for the 1-D TDE (equation (2)) (Fig. 2). From Fig. 2 it can be concluded that the application of the tanks-in-series model employs the implicit dispersion as a surrogate for the actual dispersion of the reactor. Based on this philosophy a procedure was developed that relates to equation (2) with the Peclet number to achieve an equivalent dispersion (and the length of reactors $Dx$) for the tanks-in-series model that ensures appropriate description of the advection and dispersion. To illustrate this procedure there are several available results of dye experiments for the River Ruhr. Figure 3 shows the dye hydrograph measured 9.6 km downstream from the instantaneous injection point (under low flow conditions) (Morgenschweis & Nusch, 1990). The curve computed with equation (2) was fitted to this hydrograph, resulting in a reactor length of 215 m.

HYDRODYNAMIC MODELS

The application of the hydrodynamic models (1-D, 2-D; steady state or dynamic models) producing output data for the water quality models is problem dependent. Focusing on river basin management, REWARD describes the water motion along a reach by the well-known St Venant equation that can be solved numerically, as a function of the initial and boundary conditions. Using the full momentum equation, boundary conditions
\[ f(n) = \frac{C}{C_0} = \frac{n}{(n-1)!} \left( \frac{t}{t'} \right)^{n-1} \exp\left( -\frac{t}{t'} \right) \]  

(1)

\[ f(Pe) = \frac{C}{C_0} = 2 \sum_{n=1}^{\infty} \frac{\mu_n (\frac{Pe}{2} \sin \mu_n + \mu_n \cos \mu_n)}{\left( \frac{Pe}{2} \right)^2 + \mu_n^2 + Pe} \exp \left[ \frac{Pe}{2} \left( \frac{\mu_n^2}{Pe} \right) t \right] \]  

(2)

\[ \frac{1}{n} = \frac{2}{Pe} (Pe - 1 + e^{\mu \nu}) \]  

(3)

Fig. 2 Concentration response to the unit mass impulse achieved by the tanks-in-series model and the dispersed flow reactor (\( t' = V/Q \), residence time, \( V \) = volume of the individual tank, \( Q \) = flow out of the tank, \( C_0 = M/n V \), \( M \) = mass of injected tracer, \( n \) = number of tanks, \( Pe \) = Peclet number, \( L \) = length of reactor).
Fig. 3 Hydrograph of dye concentration: measurement (Morgenschweis & Nusch, 1990) and computation with equation (1) resulting in appropriate segmentation ($D_x = 214 \text{ m}$).

BIO-GEOCHEMICAL MODEL COMPONENT

There are different types of water quality models included in REWARD, which are associated with different levels of complexity and input requirements. For example, in cases where organic pollutants are the cause of the river water quality problems, the simple Streeter-Phelps model or the more complex QUAL II model can be used. Complex models with flexible structures are also available. Selection of models can be menu driven or provided by the system as default dependent of the defined problem. Recognizing the fact that processes occurring within biological treatment plants and those influencing river self-purification can be described theoretically by identical models, a well-known complex model (developed by a task group of the IAWPRC (Dold & Marais, 1986)) was applied in REWARD. The basic model capable of describing the C-oxidation and N-cycling and promoted for use in design and operation of biological treatment plants, was further developed to predict the P-cycling and several physical processes (settling, re-suspension, sorption, re-aeration, etc.). It is noteworthy that process description in treatment plants and in rivers within the same framework is a new research perspective in river basin modelling.
FORMULATION OF CASE-INDEPENDENT PROBLEMS

Boundary conditions (which distinguish the real cases) and hydrological tree defining flow paths, can be formulated through a user interface which allows one to use the system without any knowledge of the actual performance of the system. The entry to the system data and model bank is driven by a map viewer program which helps to identify (or define) the system's basic map and computation objects and to manage data processing (Fig. 4). Maps (and data files storing mapped information) can be created by any GIS program. REWARD can read and process output information from GIS. Data necessary for computation are attached to a computation unit (CU). The starting step in the system development is the definition of the computation units as well as the connection (flow paths) between unit processes. A CU can be defined as a channel, river, lake, filter etc. Based on the type defined, the system automatically selects the corresponding hydrodynamic and water quality models. Objects communicate (send and receive data) with each other. The connection of objects (and determination of their rank in the system hydrological tree) is realized by a graphical program. REWARD builds a water resources system by the inclusion of the following objects:

- **1-D object**: tanks-in-series or single reactor with appropriate shape of cross-section (applied for modelling of channels, rivers, reservoirs, settling tanks, etc.);
- **2-D object**: storing data for finite difference models;
- **Nodes without storage capacity**: for river junctions and hydrological inflows;
- **Pseudo-reactor**: which has no storage capacity or residence time. This object helps in creating object constructions (or other simpler objects as equation nodes with storage capacity).

CALIBRATION, HANDLING UNCERTAINITIES

Model complexity increases with the number of state variables and reaction terms, and, as complexity grows, so do the number of model parameters and the quantity of data required for the calibration. Parameters to which the model is not sensitive do not influence the model performance and the quantity of data needed for the calibration. Therefore proper classification of parameters into *sensitive* and *not sensitive* clusters is an essential step in the model identification. For this purpose modification of the well-known Hornberger-Spaer-Young (HSY) (Beck & van Straten, 1983) method was applied, which is, in fact, a black box experiment providing probability distributions for the parameters, rather than optimal values. The essential idea of the HSY method is to make repeated computations using inputs (parameters, load data, forcing functions, etc.) selected at random from populations which have the same statistical properties expected of each particular input (e.g. uniform *a priori* probability distribution for the parameters $f_0(P(i))$ in Fig. 5). Parameters belonging to acceptable Monte Carlo scenarios performed determine *a posteriori* distributions ($f(P(i))$, see Fig. 5) for each of the parameters. Because of the normally scarce and uncertain water quality data, an acceptance window (Fig. 6) was defined for each (measured) output of the system. In this sense the objective function defined ($S$) provides a frequency measure of accepted (or rejected) output values. Using such stochastic input disturbances it is customary both to determine the response of the system to the highest accepted values of the objective function
Fig. 4 Entry points to the model data: (a) - map, (b) - hydrological tree, (c) - object data bank.
Fig. 5 Calibration and sensitivity analysis in REWARD.
(S_0 = S_{\text{max}}), and in addition, to investigate a possible range of values of the inputs computed from the lower accepted values of the objective function (S_0 = S_{\text{min}}). The first case corresponds to the traditional calibration process resulting in a unique set of parameters, while the second is a sensitivity analysis of the inputs (parameters).

**CASE-STUDY: RIVER RUHR**

As a first step in the analysis, the calibration procedure and sensitivity analysis of the parameters were achieved based on the HSY method. The behaviour definition was obtained corresponding to quality data for longitudinal profiles measured for several "traditional" state variables (DO, BOD, O_2, NO_3-N, NH_4-N, Cl) of the model under low flow period in 1986. Measurements both for longitudinal profiles and external sources were repeated practically every month under different flow, load and temperature conditions that provide data for verification of the model. A simplified version of the modified IAWPRC model was tested in which the phosphorus sub-model was excluded. The model used the steady state version of the hydrodynamic model. In spite of the drastic simplification, there were 15 parameters subject to calibration. Surprisingly the HSY method filtered out 7 of them. The remaining "sensitive" parameters are associated with the growth, death and sedimentation of heterotrophic bacteria, the hydrolysis and sedimentation of particulate organic matter. Results show, beside parameter stability, acceptable agreement between measurements and computations for most of the measurement periods and state variables (an illustrative result is shown in Fig. 7(a) for BOD). With the help of the calibrated model, an extensive analysis of further policy improvements was then achieved. As initiated by the local water authority, an effluent based approach was checked by the model. The goal of this analysis was to control whether the required minimum levels of waste water treatment result in acceptable ambient water quality. Figure 7(b) shows the present situation for NH_4-N under low flow conditions and with the introduction of the new effluent standards. It can be seen that the model predicts acceptable water quality for this scenario. It is noteworthy that
Fig. 7 (a) Calibration of the bio-geochemical model for BOD measurements; (b) Water quality scenarios for the NH$_4$-N (under low flow conditions): (i) present conditions; (ii) after introduction of the new effluent water quality standards (AWS = ambient water quality standard).

this policy, resulting in the best available technology for each waste water treatment plant, is a simple, but not necessarily, cost-effective alternative. However other management strategies focusing on the target level of the ambient water quality can also be evaluated by the model.

REFERENCES


