Operational water quantity management in a river basin

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Abstract The real-time water quantity management of complex water resources systems can be successfully supported by mathematical models. Since there were no models available for integrated water management on the catchment scale, a generally applicable model system for quantitative water management has been developed and adapted to the watershed of the River Ruhr in Germany. The first results attained with this model system in the Ruhr catchment basin show that it is a powerful tool for operational water quantity management and is able to simulate a differentially structured watershed with high anthropogenic impacts. The use of this model has enabled Ruhrverband to make crucial improvements and increase the objectivity of operational water quantity management.

Keywords Integrated modelling; real-time reservoir operation; river basin management; Ruhr river basin

Introduction

The protection and improvement of the status of aquatic ecosystems as well as the promotion of the sustainable use of water resources are among the main goals of the "EU Water Framework Directive". To achieve these objectives, river basin management plans with dedicated water quality measures are to be drawn up. For the effective development of such plans, computer models for integrated quantitative and qualitative management of water resources are highly useful. Since none of the available models can be adapted to different river basins, a model system for water quantity management has now been developed, as a first step, by the Ruhrverband in co-operation with the Institute for Water Resources Management at the University of Karlsruhe. This model can be used as an integral part of operational river basin management. It has been adapted to the watershed of the River Ruhr in Germany, and was implemented in July 2002. Before going into the details of the model it is necessary to provide a short introduction to the water management system in the Ruhr catchment basin.

Operational water quantity management in the Ruhr River Basin

A complex water management system has been operated by the Ruhrverband for more than 90 years. One of the major tasks of the Association is to provide drinking water for about 5.2 million inhabitants as well as process water for local industry in the Ruhr district, one of the most densely populated and highly industrialised areas of Europe (see Figure 1). A system of 14 reservoirs with a total storage capacity at present of 474×10^6 m^3 enables the Ruhrverband to maintain a fixed minimum runoff at critical cross-sections during dry seasons by replenishing the water taken directly from the river.

To convey an idea of the magnitude of the water quantities withdrawn from the River Ruhr, Table 1 shows the annual water abstractions and water losses, i.e. the amount of

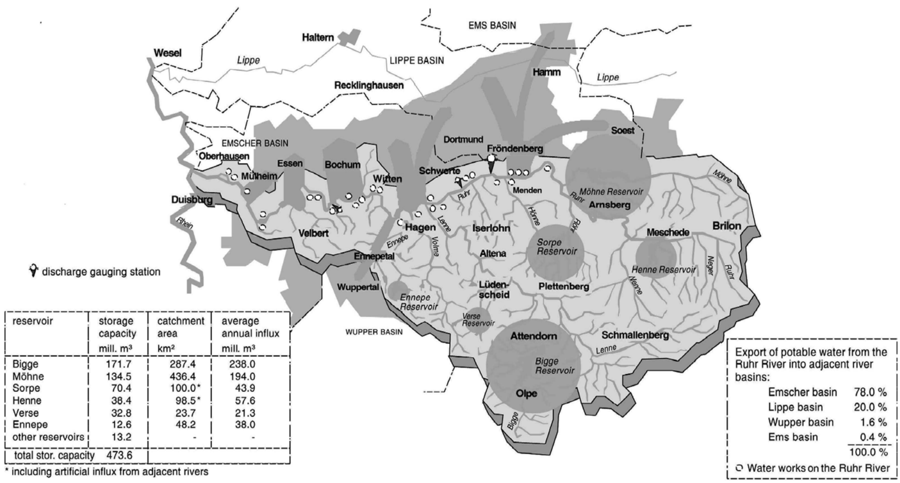

Figure 1 Ruhr catchment basin with water export and reservoirs

water exported to neighbouring catchment basins (cp. Figure 1); this amount represents a "loss" for the River Ruhr and had to be replaced by additional water supplied by the reservoirs during the period 1900–2000. It shows that, at times of highest water demand (e.g. 1975), 1.35 billion m^3 of water was withdrawn from the catchment basin per year. Even today, however, about 530 million m^3 of water is abstracted each year and about 270 million m^3 is pumped into the neighbouring catchment basins of the Emscher and Lippe Rivers, where coal mining and heavy industry historically exerted an enormous anthropogenic impact on the natural water supply structures.

On the other hand, low-flow situations periodically occurred in the River Ruhr, especially during the dry periods in the summer and autumn. Apart from creating water quantity problems, such low-flow periods caused tremendous hygienic problems: the region experienced frequent epidemics of malaria, typhoid and amoebic dysentery until the end of the 19th century.

To deal with these problems, a comprehensive water resource management system had to be established during the first decades of the 20th century. The basic objective of this system was to set up a regional "division of labour" by dividing water management tasks among the different river basins. The River Ruhr was assigned the task of providing a supra-regional supply of drinking water even for areas located within neighbouring catchment basins, such as the Emscher and Lippe rivers.

To maintain minimum runoff in the River Ruhr, the Association had to compensate for natural fluctuations in runoff, e.g. the differences between summer and winter, and make up for the water losses attributable to the above-mentioned water exports. The basic concept it developed to solve this problem was to build dams creating reservoirs in the

Table 1 Water abstraction and water losses in the Ruhr catchment basin

Year	Water abstraction (mill. m^3/a)	Water losses (mill. m^3/a)
1900	179	128
1925	545	287
1950	892	384
1975	1,031	397
2000	527	272
Max.	1,353	474

Sauerland, a mountainous area covered mainly by forests in the eastern part of the catchment basin. This idea attained legal status in 1913, when two water authorities were founded by special acts of the Prussian legislature: the Ruhr Reservoir Association (Ruhrtalsperrenverein) responsible for water quantity management and the Ruhr River Association (Ruhrverband) responsible for water quality management.

In this way, the integration of water quality and water quantity within the borders of a natural catchment basin was guaranteed from the beginning of the Association's history.

In 1990 these two authorities merged to form the present Ruhrverband. Since 1990 flood protection has been defined as the second major task of water quantity management. By flood protection we mean the use of the retention capacity of the reservoirs to reduce or even prevent flood damage in the cities along the River Ruhr and its main tributary, the River Lenne (see Figure 1).

In summary, it can be stated that water quantity management in the Ruhr river basin was historically focussed – and is in fact still focussed on – maintaining runoff threshold values during both low-flow periods and flood events.

Owing to its supra-regional character, the reservoir system is operated centrally from the headquarters of the Ruhrverband in Essen, which is up to 200 km away from the reservoirs. To operate such a complex system, the Ruhrverband needs a comprehensive hydrological information network with automatic data transmission and data visualization located in an Operation Centre at the headquarters of the Association.

Figure 2 presents, by way of example, a simplified overview of the present network of gauging stations to record surface runoff. With a total of 96 stations, this network has an above-average density of gauging stations. By way of emphasis, the control sections at which a certain minimum runoff has to be maintained, in conformance with statutory regulations, during daily water management operations are the gauging stations at Villigst and at Hattingen. Parallel to the network of gauging stations, there is a precipitation measurement network, with a total of 94 stations, operated in collaboration with the German Weather Service.

There is therefore now a closed information system in existence in the catchment area of the Ruhr via which all relevant system control data are conveyed just-in-time and with a high information density to the five local reservoir operation centres and the headquarters in Essen via long-distance data transmission. The data are then processed at an Operation

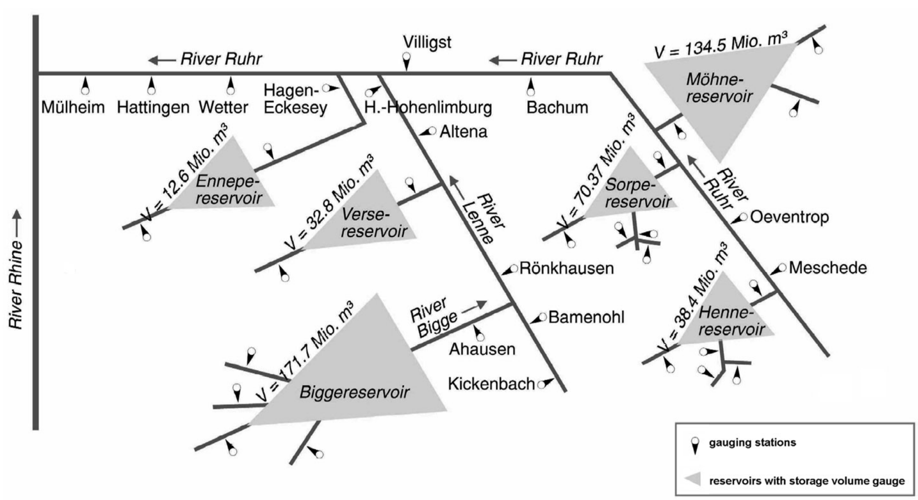

Figure 2 Measuring network for control and flow regulation of the reservoirs within the Ruhr catchment basin

Centre with the aid of state-of-the-art visualisation techniques and made available for the real-time control of the system (Morgenschweis, 2001).

As a result, information on the state of the system throughout the entire river basin is available in real time, allowing the Association to react immediately to any changes in the hydrological or meteorological situation. To optimise the operation of this complex system, the above-mentioned software system was installed at the Operation Centre in July 2002. The software system will continuously forecast the state of the system of the whole river basin for several days. These forecasts will be used to operate the reservoir system in real time to make crucial improvements as well as to increase the objectivity of operation.

The project has culminated in the development of a generally applicable system of hydrological models. The model concept and the first results are presented in the next sections.

Model for real-time river management

Modelling concept

On the basis of the above mentioned structures of the Ruhr catchment basin and the requirements of real-time operation, the model firstly has to achieve an adequate qualitative reproduction of the water management system. This requires the implementation of several system elements, which should be combined in modular fashion to simulate the complex system. The following modules have to be taken into consideration in the Ruhr catchment basin:

- river reaches
- reservoirs
- barrages
- gauging stations
- water withdrawals and inflows
- flow control structures between modules (e.g. pumps, weirs, water gates, etc.).

To fully comprehend the crucial processes affecting water quantity management in meso- or macro-scale watersheds, we have to break these processes down into daily or hourly time increments. In particular, the small storage volumes of barrages and canals and the wave deformation in rivers demand this kind of high temporal resolution. Computer models for the quantitative management of water resources are not designed for flood situations but rather for conditions characterized by low and medium discharge. For this reason, a flood routing calculation is postulated that simulates the associated flow velocities; the latter are a non-linear function of discharge. Nevertheless, the flood routing method has to be stable and applicable to real-time operation; this is why a hydrological and not a hydrodynamic calculation method is needed.

Finally, a model system designed for operational real-time management has to be user-friendly (Zagona *et al.*, 2000). This means that the model system can be operated via a graphical user interface for easy modification of the parameters and the control variables. In addition, automatic pre- and post-processing are required for fast data management and for analysis and visualisation of the model results.

On the basis of this concept, the water quantity management model RRM (Real-Time River Management) has been developed as a network flow model. It consists of a construction kit with a small number of modules. These modules can be used in various ways by modifying their parameters; a variety of system elements can thus be described with a limited number of modules.

Modules

The construction kit includes nodes and transport elements with different features which are interconnected to represent the topology of the river basin. In the following the methodology used in the most important modules is briefly described.

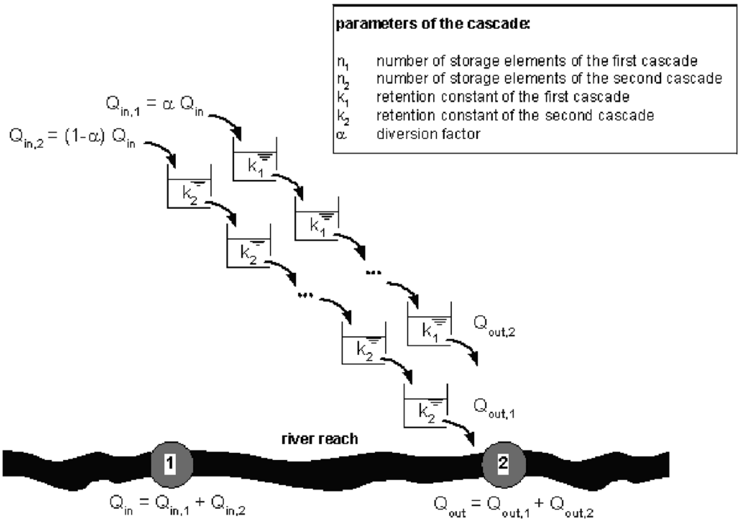

Figure 3 River reach module: double cascade model

River reaches. A modified version of the hydrological double cascade model has been implemented which takes account of the variable flow velocities under different flow conditions. The approach taken is shown in Figure 3. This figure depicts a river reach between the nodes 1 and 2. The inflow Q_{in} to node 1 is divided on the basis of the diversion factor a to the linear cascades. At the end of the reach both discharges are added to give the total outflow Q_{out}. The diversion factor α is used to produce flow velocities by means of the linear superposition of two cascades with different time lags.

An additional reason for applying the double cascade model is the possibility it offers of equipping the model system with a sophisticated updating procedure – the Kalman Filter – which requires the representation of the mathematical equations in the state space (Serban and Askew, 1991). The linear system of the double cascade model is suited for:

Canals and barrages. With respect to questions of water quantity management, the storage volumes of canals and barrages are so small that it is not necessary to calculate the effects of retention. Both system elements, canals and barrages, are computed with the equation for the conservation of mass. Only one module has been designed for the representation of both system elements.

Reservoirs. The wide variety of reservoir utilisation modes reflects the variability of reservoir release and withdrawal, which are characterised by dependencies on the state-of-system elements. To satisfy downstream boundary conditions (e.g. residual flows), an iterative calculation of the reservoir release is necessary. The physical process is described by the mass balance, neglecting retention effects. For further details refer to Brudy-Zippelius *et al*. (2002).

Model implementation in the Ruhr river basin

The operational water quantity management of the River Ruhr is an application of the model system developed for short-term forecasts with the derivation of the hydrological input from a deterministic watershed model. The water exports are forecasted by a fuzzy-logic model taking account of meteorological forecasts as well as the amount of water exported on the previous day and the actual weekday. The forecasted system states are used to determine the necessity of applying a separate flood forecast model. Total data

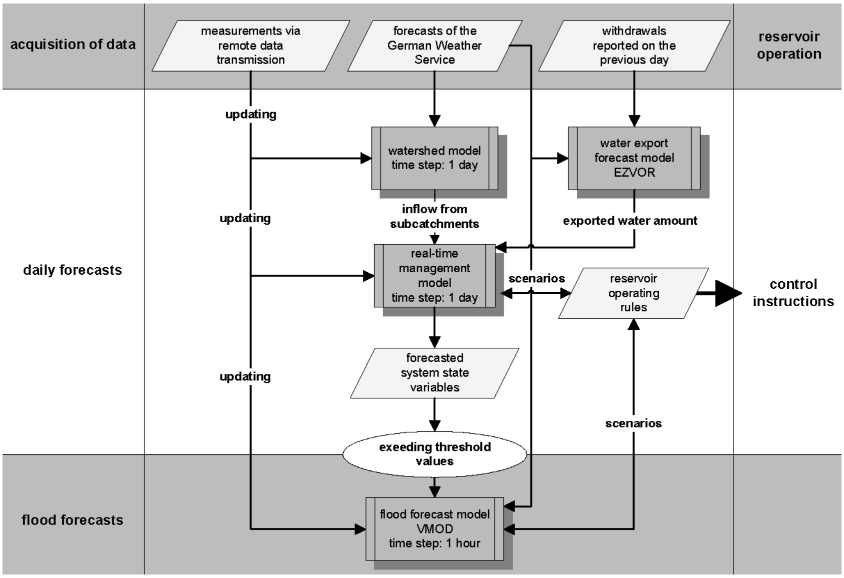

Figure 4 Overall concept for the water quantity management of the River Ruhr

acquisition has been automated to permit trouble-free real-time operation. Figure 4 shows the interrelationships in the management system of the River Ruhr.

Within the hierarchical flow structure of the River Ruhr, flood-routing is of prime importance. The modified double cascade model yields very good results, especially for low-flow situations, which are the kind of situations water quantity management is focused on. The calibration and validation of the model were carried out with historic data from the four water years 1992 to 1995 using the "split-sample test" (Klemeš, 1986). As is shown by the comparison of measured and calculated hydrographs at the Hattingen gauging station (cf Figure 5) situated 60 kilometres upstream of the mouth of the River Ruhr, the flood-routing method is suitable for the calculation of variable flow velocities. With regard to the anthropogenic impacts upstream of this gauging station (e.g. reservoirs, barrages, sewage plants, withdrawals, inlets, etc.), the model displays a high performance (Morgenschweis, 2001). On the other hand the results of model calculations during flood events proved to be unsatisfactory (cf Figure 5c); the daily time-step is obviously too rough. For this reason, flood forecasting will be carried out by a special model operating on an hourly data basis (Göppert *et al.*, 1998).

The model system enables the personnel involved to view river basin management as an integrated entity and to make decisions that take account of the state of the system at any time and place. The software system permits integrated water resource management; this means that solutions for individual management aspects – e.g. forecasts of water exports and real-time reservoir management in the basin of the River Ruhr – are connected and combined. This information can serve as the basis for advanced water quality modelling and water quality management in river basins.

Summary and outlook

The first results show that the RRM model system based on the generally applicable BEWASYS model is a powerful tool for operational water quantity management in the Ruhr catchment basin. It is able to simulate a differentially structured watershed with high anthropogenic impacts and to generate short-term forecasts for real-time system operation.

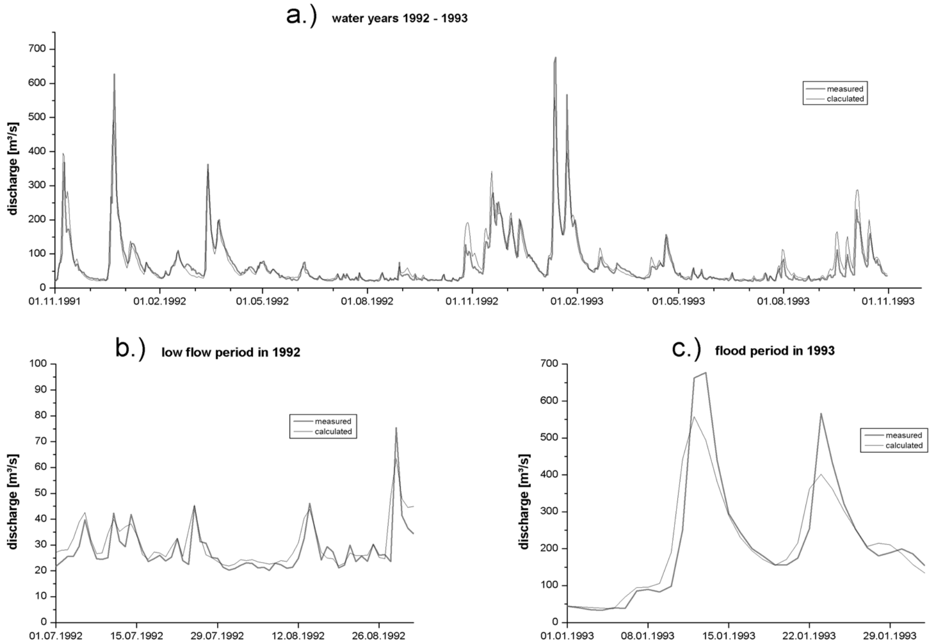

Figure 5 Comparison of measured and calculated hydrographs at the gauging station Hattingen a) entire water years of 1992 and 1993; b) low-flow period in 1993; c) flood period in 1993

The model system can be applied for prognostic long-term simulations as well as for operational short-term forecasts. The implemented flood-routing method, a modified double cascade model, is able to reproduce the variable flow velocities in river reaches, which have to be taken into particular consideration for low flow conditions. A suitable mathematical formula was chosen to permit the integration of a sophisticated updating procedure for real-time operation afterwards (cp. Refsgaard, 1997). Model interfaces were created so that the model system can be used as a tool for integrated river basin management encompassing water quantity and water quality aspects as required by the "EU Water Framework Directive".

The model system, which is also suitable for prognostic long-term simulations, has now been implemented for the water quantity management of waterways in eastern Germany. The excellent results obtained with the model system demonstrate the practicability of the modelling concept.

Because the input and output data of the model system are closely related to the spatial structure of a modelled river basin, an embedding of the management tool into a Geographic Information System (GIS) is provided. This facilitates the spatial visualisation of the system state of the entire river basin by the model user.

References

Brudy-Zippelius, T., Morgenschweis, G. and Ihringer, J. (2002). Water Quantity Management in River Basins: Methodical Developments. Proc. *5th International Conference on Hydroscience and Engineering ICHE-2002, 18–21 September 2002*, Warsaw.

Göppert, H.G., Morgenschweis, G., Ihringer, J. and Plate, E.J. (1998). Flood forecast model for improved reservoir management in the Lenne catchment, Germany. *Hydrological Sciences Journal*, **43**, 215–242.

Kleme?, V. (1986). Operational testing of hydrological simulation models. *Hydrological Sciences Journal*, **31**, 13–24.

Morgenschweis, G. (2001). Echtzeitbewirtschaftung eines Flussgebietes am Beispiel der Ruhr. *Wasserwirtschaft*, **12**, 575–581.

Refsgaard, J.C. (1997). Validation and Intercomparison of Different Updating Procedures for Real-Time Forecasting. *Nordic Hydrology*, **28**(2), 65–84.

Serban, P. and Askew, A.J. (1991). Hydrological Forecasting and Updating Procedures. Hydrology for the Water Management of Large River Basins. *IAHS Publ.*, **201**, 357–369.

Zagona, E.A., Fulp, T.J., Shane, R., Magee, T. and Goranflo, H.M.l. (2001). RiverWare. *Journal of the American Water Resources Association*, **37**(4), 913–929.