Water quality modelling to support the operation of the Kakhovka Reservoir, Dnieper River, Ukraine

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Abstract The model system that comprised 1D, 2D and 3D water quality models was developed and implemented for the main water bodies of the Kakhovka Reservoir and Lower Dnieper to evaluate the environmental effect of various reservoir operation and water management scenarios and also to analyse consequences of the accidental pollution of the reservoir. These models have been tested using the monitoring data for 1984-1988 and 1998. It was shown that the significant factor for the Kakhovka Reservoir is the rate of the nutrient sources from the cities around the reservoir and nutrients flux into the reservoir from the up-stream reservoirs rather than from Dnieper inflow discharge. The simulation of the water quality of lower Dnieper and Dnieper-Boog Estuary shows that the distance of the intrusion of the salt wedge into lower Dnieper linearly depends from the discharges from Kakhovka HPP for the discharges in range 600-4000 m^3s^{-1}.

Keywords Water quality models, water management, Dnieper River, Kakhovka reservoir.

Introduction

The Kakhovka Reservoir (18 km^3) is the largest in the Dnieper Reservoir "Cascade"(Fig. 1). The water regulation is restricted by limitations a.o. water release from the Kakhovka Reservoir should not be less than 500 $m^3\ s^{-1}$ because of environmental concerns in the downstream reach of the Dnieper River as well as in the Dnieper-Bug Estuary. The latter one starts at 100 km downstream from the Kakhovka dam. In order to reveal the possibility for lifting the restrictions and to obtain a more flexible reservoir operation practice, an integrated study was conducted including advanced water quality modeling in Kakhovka Reservoir, Lower Dnieper, Dnieper-Bug Estuary and Ingultes River.

A set of models have been developed and applied for completing the decision support system. These models have two main objectives: (i) evaluation of the environmental and ecological effects of various reservoir operations and water management alternatives with focus on scenarios of low flow regime; and (ii) implementation of non-structural measures for emergency management of the Kakhovka reservoir. The complex model system, that include 1D, 2D and 3D models, now assists the decision-makers in analysing the effect of different reservoir management alternatives. The system is also used to prepare emergency management schemes for cases of sudden pollution from high-risk industries, which are active in the vicinity of the Kakhovka Reservoir, along the Lower Dnieper River and on the shore of Dnieper-Bug Estuary.

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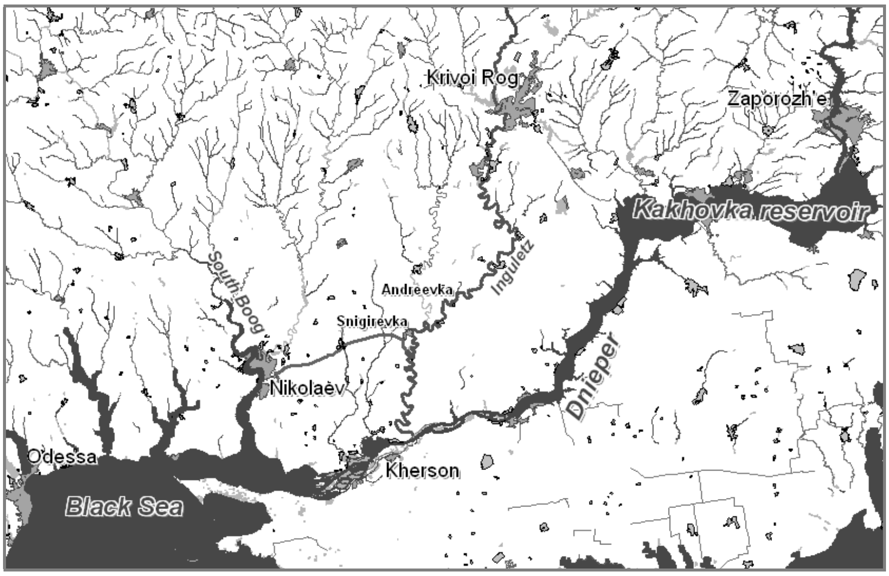


Figure 1. The map of the Kakhovka Reservoir and Lower Dnieper.

2. Models

The model system includes:

(1) One-dimensional model of the Ingulets River for analysing the effect of water releases from Kakhovka Reservoir on the pollution propagation from the mining area in Krivoy Rog through Ingulets to the Dnieper River and further down.

(2) Two-dimensional vertical/longitudinal model of the lower part of Dnieper River from Kakhovka Reservoir to the Dnieper-Boog estuary.

(3) Three-dimensional hydrodynamic and environmental model for the Kakhovka Reservoir and the Dnieper-Boog Estuary.

The Inguletz River modelling system allows making simulations of hydrological regime and pollutants dispersion in the Inguletz river system including part of the lower Dnieper from the Kakhovka HPP to Kherson. The 1-D river hydraulic and water quality model is a modification of the model RIVTOX (Zheleznyak et al., 2000). The model describes river flow hydraulics on the basis of the 1-D Saint-Venant equations and pollutant transport using the 1-D advection–dispersion equation.

The two-dimensional, transversely averaged hydrodynamics and water quality model CE-QUAL-W2 (Cole and Buchak, 1994) is used to analyse the effect of reservoir operation on the salt-water intrusion from the Black Sea and to evaluate the necessary water transport for the maintaining of appropriate water quality the lower Dnieper. The following parameters are calculated: elevation of the free surface, longitudinal horizontal velocity, vertical velocity, the temperature, salinity, suspended solids and water quality parameters (dissolved oxygen, algae, phosphates, ammonia nitrogen, nitrate nitrogen, mineral carbon, pH, carbon dioxide and BOD).

The three-dimensional THREETOX/WASP model (Margvelashvili et al., 1999; Iritz et al., 1999) includes a hydrodynamic module for calculating in-stream temperature and salinity fields, module for calculating processes of the estuary eutrophication as well as modules for the calculation of the transport of suspended sediments and toxic substances. The nutrient cycling or eutrophication submodel is functionally equivalent to the U. S. Environmental Protection Agency's WASP5 model (Ambrose et al., 1994). The submodel simulates the transport and transformation reactions of up to eight state variables that can be considered as four interacting systems: phytoplankton kinetics, the phosphorus cycle, the nitrogen cycle, and the dissolved oxygen balance.

3. Results of simulations

3.1 Kakhovka Reservoir

The 3D model THREETOX/WASP was set up for the Kakhovka Reservoir. It was calibrated and verified using available hydrological and water quality data (1984-1988). Distribution of BOD correlates well with the phytoplankton distribution. Oxygen is intensively produced in the reservoir due to production by phytoplankton and re-aeration.

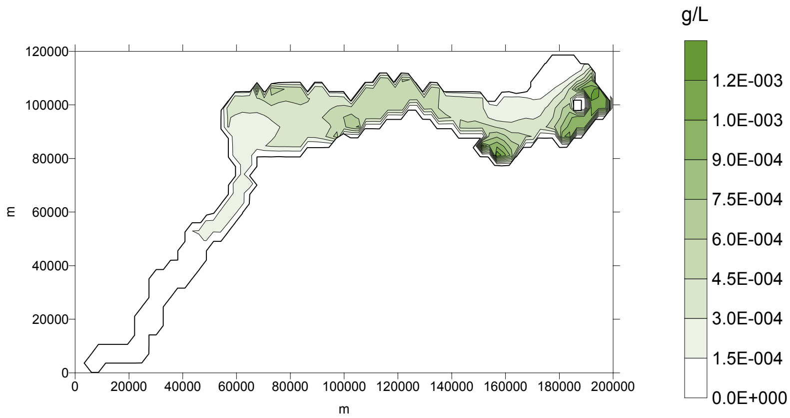


Figure 2. Simulated concentration of phytoplankton (carbon equivalent) at the surface of Kakhovka reservoir in July 1986.

The simulated period 1984-1987 includes a year with extremely low water discharge through the Kakhovka HPP (1984) and years with average and high discharge. The 3-D simulation of reservoir water quality showed that the influence of the water discharge on the general hydrochemical parameters (e.g., BOD, DO) not is particularly significant. The measured and simulated results demonstrate higher values of BOD in summer periods during low discharge (1984), however, during the summer period in other years, the BOD concentration has approximately the same magnitude. The simulated concentration of DO has had almost the same minimum value during the entire period, independent of the highly varying discharge levels. As it was demonstrated (Figure 2) maximal concentration of phytoplankton is reached in the central and north – east part of the reservoir as well as in shallow coastal embayments of the KWR. Distribution of BOD correlates well with the phytoplankton distribution. Unlike BOD, the correlation between oxygen and phytoplankton distribution is not pronounced. Analysis of the measured data and simulated results showed that the discharge from Kakhovka HPP not is among the main factors that determine the algae concentration in the reservoir.

3.2 Lower Dnieper and Dnieper-Boog Estuary

A set of simulations of water quality was carried out for Lower Dnieper and Dnieper-Boog Estuary using 2D and 3D models. Both models have been tested on the basis of the processing of the large amount of the monitoring data for 1984-1987 and 1998. A specialfeature of the Dnieper-Boog estuary is the deep (12 m) and narrow ship channel from the Black Sea to the Nikolaev and Kherson cities. Salt water from the sea penetrates into the Dnieper and South Boog lower reach. It is clearly visible in Figure 3, where comparison of the calculated and observed surface and bottom distribution of salinity are given. The figures show the ability of the model to reproduce the complicated pattern of water quality parameters in the DBE.

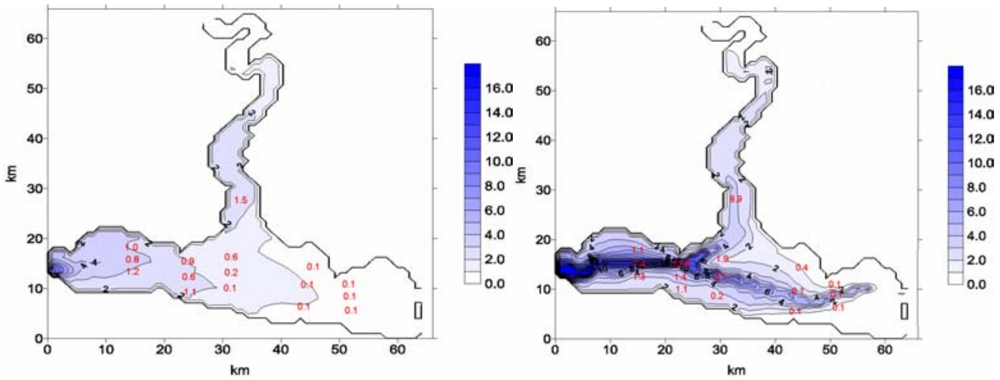
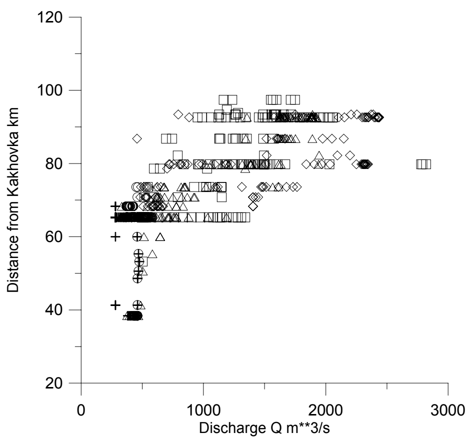


Figure 3 Calculated vs. measured salinity distribution at surface (left) and bottom (right) of Dnieper-Boog Estuary in June 1998. The data of the joint USA-Ukraine expedition survey are used.



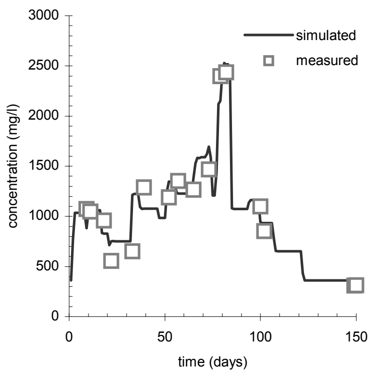
The simulation by 2D model of the water quality in lower Dnieper and Dnieper-Boog Estuary shows that the distance of the intrusion of the salt wedge into the lower Dnieper linearly depends on the discharge from Kakhovka HPP only for discharges in the range 600-4000 m^3s^{-1}. For discharge lower than 450 m^3s^{-1}, a significant salt intrusion can reach as far upstream as the Ingulets river mouth during spring conditions. The distance, however, of the intrusion does not depend linearly from the HPP discharges in this range (Fig. 4).

Figure 4 Calculated distance of salt wedge head from Kakhovka HPP vs. Dnieper discharge

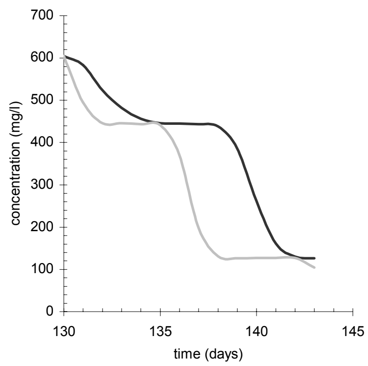
For low discharges the distance of the intrusion is influenced by the river bed topography upstream of Kherson, where deep basins divided by sills are located along the river. Filling of these basins by salt water leads to quick propagation of the salt wedge. Therefore, looking on the salt intrusion criteria, Kakhovka HPP discharge should not be reduced below 450 m^3s^{-1} during spring when a combination of meteorological factors could lead to long distance salt intrusion up to Ingulets river. The oxygen field is closely connected to the salinity field because the salt wedge maintains the stable stratification that inhibits turbulence mixing and prevents ventilation of deep layer of the estuary. Other parameters of water quality depend on the salinity and oxygen distribution in different ways. The most sensitive are NH4 and NO3 whereas dependence of BOD and PO4 on the Kakhovka HPP discharge was relatively weak.

3.3 Inguletz River

The main environmental problems of Ingulets River are technologically required releases from the mining water reservoirs located near the Krivoy Rog city (Fig. 1). The pumping station located in the Snigiryevka village connects Inguletz river with the Oktyabrskoe reservoir – a source of fresh water for Nikolaev.



a)



b)

Figure 5 Simulated and measured concentration of chlorides in the Ingulets at .Andrjevka (269 km from the river mouth) since 9 December 1997 (a) and chlorides concentration in Ingulez upstream the river mouth under two scenarios of the water discharges through the Kakhovka dam (b).

The operational use of the modeling system is necessary to predict propagation of the contaminated water in Ingulets and to find the most ecologically efficient discharge modes of the Kakhovka HPP to accelerate the propagation of the contaminated water in lower Ingulets and Lower Dnieper. The model was calibrated on the basis of measured data (Fig. 5a). This effect of discharges from Kakhovka is studied on the basis of the data on the Ingulets contamination in winter-spring 1998. The calculations were provided on the basis of the on the measured discharges from Kahovka HPP in range 2500-3000 m^3s^{-1} during 130-145 days after the starting date of the release 9.12.1998, and on the basis of the modified scenario when the discharge in this period was reduced to 500 m^3s^{-1}. This change in hydraulics parameters of the river gives the result that at day 137 from the start of the contamination release, the peak of the concentration for the Kakhovka low discharge scenario will be 30 km downstream of its position for measured discharges scenario. This leads to a 3 days difference in the time-lag of the release of the significant (more than 400 mg/l) chlorides concentration through the river mouth (Fig.5 b).

Conclusions

The model system comprising 1D, 2D and 3D water quality models was developed and implemented for the main water bodies of the Kakhovka Reservoir and Lower Dnieper to evaluate the environmental effect of various reservoir operation and water management scenarios and also to analyse consequences of the accidental pollution of the reservoir. These models have been tested on the monitoring data from the period 1984-1987 and 1998.

The 3D simulation of the Kakhovka reservoir water quality shows that the influence of the water discharge on the hydrochemical parameters not is a dominating factor. More significant is the rate of the nutrient sources from the cities around the reservoir and the nutrient flux into the reservoir from the up-stream reservoirs via the Dneprovsky HPP dam.

The 1D simulations of the Ingulets – Lower Dnieper system shows that it could be recommended to decrease the discharge through Kakhovka HPP to 500 m^3s^{-1} during the period where the waste water peak arrives at the junction of Ingulets and Dnieper. In this way it is possible to accelerate the propagation of the pollutants in lower Ingulets.

The main conclusion that could be made on the basis of the simulation study is that a reduction of the Kakhovka discharge below 400 m^3s^{-1} leads to a reduction of the dissolved oxygen concentration at the bottom layers of the main river channel. These results show that discharges in the range of 400-300 m^3s^{-1} could not damage the ecosystem except when the duration is shorter than one week.

The results of the simulations show the ability of this complex model system, that includes 1D, 2D and 3D models, to assist the decision-makers in analysing the effect of different reservoir management alternatives.

Acknowledgements

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