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Prediction and Management of Water Quality in Water Storage Reservoirs

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Abstract: Water quality is one of the main characteristics of water storage reservoirs. It must be taken into account when planning and using water resource systems. That is why more mathematical models and information systems are developed to control and manage water quality. Processes in an aquatic ecosystem are complex, and they depend on different abiotic and biotic parameters, including interrelations with the environment. Modeling approaches for all relevant abiotic and biotic parameters, with ihtiofauna as the highest level in the trophic chain of aquatic ecosystem, and its application to a real water storage reservoir, are presented in the paper. Management of water quality depends on operational efficiency and reliability of all activities related to the observation and assessment processes. A part of the information system (Information System for Observation and Monitoring the 'dam-reservoir' system), that deals with water quality is described in the paper. It applies three classifications for water quality assessment, as well as the fuzzy logic approach.

Keywords: Water quality, Water storage reservoirs, Mathematical modeling, Water quality assessment

1. INTRODUCTION

Available water resources can be described by three factors determing location, water quality and quantity. These factors vary in time and space, and generally do not satisfy demands for water. In that case complex water resources systems are the solution. The most important elements of these systems are water storage reservoirs. They can deal with irregular temporal distribution and, when combined into a system, can manage the spatial distribution.

Water quality is one of the main characteristics of a water storage reservoir, even when its purpose is other than human water supply. Already in the planning stages water quality has to be simulated and predicted (water treatment processes depend on future reservoir water quality). If predicted quality is not satisfying some changes or precaution measures must be implemented (such as increasing or decreasing normal water level, eliminating shallow areas, controlling nutrient inflow, protecting the chatchment). In this paper we describe the main processes (abiotic and biotic) in a water ecosystem and the modeling methods that can be used to predict water quality.

There was no adequate procedure in Yugoslavia to store and process the observed water quality parameters. That is why the Information System for Observation and Monitoring the 'dam-reservoir' system was created. Some components of this system are described later in the paper.

2. PROCESSES IN RESERVOIRS AND THEIR MODELING

Damming the water flow and filling the water storage reservoir create an entirely new ecosystem. This new ecosystem passes through the process of succession - a phenomenon of successive changes within the structure of the biocenoses. The newly created reservoir is a "young system", with low nutrient concentration and low organic production. The consumption of oxygen is also low, so the water is almost saturated by it, and the reservoir is in oligotrophic state. Increasing nutrient concentrations in the reservoir increases biological production. Populations of phytoplankton, zooplankton and other organisms increase, as well as the ecosystem biodiversity. As a consequence the process of reservoir aging starts. Water quality changes, and the reservoir shifts into next trophic states (mezotrophic and eutrophic). The process of

successions goes on to the final stage, when quasi-stable biocenoses are formed. When the biocenosis becomes stabilized and gets in balance with the biotope it is called the climax stage. It is characterized by balanced interactions maintained by a complex system of feedbacks - positive and negative.

Water quality models can be, generally, classified into three groups: (1) models of abiotic processes; (2) models of biotic processes and (3) integrated (coupled) models, which consider all relevant abiotic and biotic processes in the ecosystem.

Main processes treated with water quality models are similar and can be classified as:
- physical processes: hydrodynamics and temperature changes;
- chemical processes: variation of dissolved oxygen and nutrient concentrations;
- biological processes: dynamics of phytoplankton, zooplankton and fishes.

Hydrodynamic regimes, which are usually simulated in water quality models, include: flow and circulation patterns, mixing and dispersion and density distribution (as a function of temperature, salinity and suspended solids concentrations) over the water column. Water quality predictions are very dependent upon the hydrodynamic simulation. Despite this dependence, the modeler is often forced to make a trade-off between acceptable degrees of detail in water quality simulation vs. hydrodynamic simulation. It is due to cost or other restrictions. Therefore, it is desirable to select the simplest model that satisfies the temporal and spatial resolution required for water quality and/or ecosystem simulation.

Water temperature is one of the most important water quality parameters. All chemical and biological processes (dissolved oxygen concentration, biochemical oxygen demand, chemical-biological reactions, phytoplankton and zooplankton dynamics) depend upon this parameter. So, it is very important to consider it as a part of a water quality model and to simulate it with the highest possible accuracy.

Temperature changes in the water body depend on different effects of inflows, outflows, heat generated by chemical-biological reactions and heat exchange with the stream bed. But the dominant process is the atmospheric heat exchange at the water surface. Although there are numerous models, transfer of energy that occurs at the air-water interface is handled in one of two ways: 1) energies are calculated from meteorological data and used directly to establish the surface energy balance, or 2) meteorological data are used to calculate the equilibrium temperature.

Beside the temperature, water quality in reservoirs mostly depends on dissolved oxygen concentration. Generally, well-oxygenated water is considered to be of good quality since it supports aerobic processes such as respiration, which results in the release of carbon dioxide to the water. In contrast, low or zero dissolved oxygen concentration leads to anaerobosis in which fermentation is the major energy production mechanism – a process which releases reduced gases such as methane (CH_4), hydrogen sulphide (H_2S) and ammonia (NH_3) into the water. Not only may these gases cause a smell and taste of the water, but they may be also toxic (H_2S is extremely such). Furthermore the total ecosystem of the water body may be drastically altered.

Dissolved oxygen modeling depends on the complexity of the overall ecosystem model, i.e. on water quality parameters considered. Most generally, concentration of dissolved oxygen can be calculated as the difference between sources (atmospheric exchange at the water surface, photosynthetic production, inflow and exchange with other oxygen layers by diffusion), and sinks (respiration of all biological species, decomposition, decay (nitrification), outflow, etc.).

Certain elements in the water are referred to as nutrients because they are essential to the life processes of aquatic organisms. Primary production (algal grow) is usually limited by the concentration of a certain nutrient, and consequently all higher trophic levels depend on it. The major nutrients of concern are carbon, nitrogen, phosphorus and silicon. Other micronutrients such as iron, manganese, zinc, copper, molybdenum, and so on, are usually present in quantities adequate to meet the biochemical requirements of the organisms. Water quality models usually include only concentrations of relevant major nutrients, mainly nitrogen and phosphorus.

Algae are important components of water quality models. Algal and nutrient dynamics are closely linked together since nutrient uptake during algal growth is the main process that removes dissolved nutrients from the water, and algal respiration and decay are major components of nutrient recycling. Also, algal processes can cause diurnal variations in dissolved oxygen due to photosynthetic oxygen production during the daytime combined with oxygen consumption due to algal respiration

during the night. Seasonal oxygen dynamics may also be closely tied to algal dynamics, since the respiration and decomposition of algae that settles below the photic zone is often a major source of oxygen depletion.

Zooplankton is included in water quality models primary because of their effect on algae and nutrients. Algal and zooplankton dynamics are closely tied through predator – prey interactions. Nutrient dynamics are also influenced by zooplankton - directly, because zooplankton excretion is an important component of nutrient recycling, and indirectly, because of the effects that zooplankton has on algal dynamics.

These interactions are particularly important for long-term water quality simulations in lakes, since both, algal and zooplankton densities may change by orders of magnitude over periods of several months.

Two general approaches have been used to simulate algae and zooplankton in water quality models: (1) aggregating all algal (zooplankton) species into a single constituent (for example dry biomass), or (2) aggregating the algae (zooplankton) into a few dominant functional groups. Obviously, the second approach simulates processes in aquatic ecosystem more realistically, because it includes seasonal dynamics of different groups of algae and zooplankton. However it requires determination of numerous constants, coefficients and rates, which in many cases can be obtained only by field investigations. In water quality models algal and zooplankton dynamics are usually simulated using the first approach. According to that approach algal and zooplankton dynamics are governed by the processes of growth, respiration, excretion, predatory and nonpredatory mortality.

Fish are the highest level in trophic chain of aquatic ecosystem. Although very important, they are rarely included in water quality models. The main reason is the complexity of their dynamics, different homeotypical and heterotypical coactions and influences of abiotic parameters, algal and zooplankton dynamics. Water quality models that include fish use simpler types of biotic models. They are usually based on mutual influences of individuals within the same population – homeotypical coactions, and influences among different species – heterotypical coactions.

Different fish species, depending on their specific physiological characteristics, can be used as bioregulators for establishing optimal biocenosis and water quality. There are a few examples of good and inadequate fish management.

Positive examples are reservoirs Slano and Krupac (Montenegro, Yugoslavia). Both are formed at altitude of 600 m a.s.l., which is the zone of Barbell (*Barbus barbus*) and Graylings (*Thymallus thymallus*), and other fish belonging mainly to the *Salmonidae* family. In Krupac reservoir two species are detected: *Parasalmo gairdneri* and *Salmo trutta m. fario*, and in Slano reservoir - four species: *Parasalmo gairdneri*, *Salmo trutta m. fario*, *Salvelinus alpinus* and *Phoxinus phoxinus* [Kazic et al., 1989]. In both reservoirs dominant (over 80%) is *Parasalmo gairdneri*.

Reservoir Vlasina (Serbia, Yugoslavia) is an example of inadequate fish management and water quality degradation, caused by uncontrolled fish introduction [Ostojic and Simic, 1994]. In this reservoir for many years the stable state was maintained with three fish species: *Salmo trutta m. fario*, *Salmo letnica* and *Phoxinus phoxinus*. Introduction of *Perca fluviatilis fluviatilis* (perch) destabilized the system, and the lake degraded both in terms of fishery and water quality.

3. INFORMATION SYSTEM

Water quality in reservoirs can be maintained in desired quality limits, only with rigorous and continuous monitoring and simulation of water quality parameters. Unfortunately, that problem is not adequately treated in Yugoslavia. To mitigate this problem we have created the Information System for Observation and Monitoring the 'dam – reservoir' system. This information system provides: 1) automatic data control, even in the phase of data input, 2) fast data management and water quality assessment, 3) centralized data collection, 4) fast access and data overview.

Water quality and trophic levels are determined according to three classifications: 1) the OECD classification, that defines the trophic state based on three water quality parameters: turbidity measured by Secchi disc, total phosphorus concentration and Chlorophyll-a; 2) Carlson's classification, that uses the same three parameters for calculating trophic state index (TSI) [Carlson, 1997]; 3) legal classification in Yugoslavia: "Regulation on classification of interrepublic water flow, international water flow and coastal sea water in Yugoslavia" (standard YU classification), which is the. Water quality is divided into four classes, starting with the highest water quality (class I) water that can be used in natural

condition, to the water that can be used only after rigorous water treatment (class IV). This classification incorporates fifteen parameters, of which eight are numerically defined. Water is classified according to the worst observed parameter. Seven parameters are considered in the information system: suspended matter, pH value, dissolved oxygen, biochemical oxygen demand after five days, chemical oxygen demand, dissolved matter and concentration of Escherichia coli.

Beside this classical approach water quality, in the information system, can be determined using the fuzzy approach (further: fuzzy YU classification), [Milanovic, 1998]. Main reason for creating this new fuzzy classification is the fact that according to standard YU classification small changes of concentration of one water quality parameter can cause significant changes of overall water quality. This happens when concentration is near the boundary one, when small changes cause transition of water quality parameter into the lower class (e.g. when concentration of dissolved oxygen changes from 8.2 to 7.8 mg O_2/l, and all other parameters are in the class I, water passes from class I to II - see Figure 1a). However, in reality, such small deviations of water quality are usually omitted, and water is kept in the higher class, only with some appropriate comments added.

Another reason for fuzzy approach is the values of the boundary concentrations. These values, although defined in the YU classification, are under permanent discussion. They slightly differ in different classifications, so they are not so strict, and a flexible approach for defining them would be more appropriate.

Fuzzy theory gives us a mathematical method to treat these problems. In this approach, water classes are defined as fuzzy sets with flexible boundaries rather than binary sets, with 0/1 (belongs / does not belong) degrees of membership.

For each water quality parameter input membership functions are defined. They consist of four fuzzy sets, representing four water quality classes. An input membership function defines a fuzzy sets by mapping crisp inputs from its domain (all possible concentrations of water quality parameter) to degrees of membership (from 0 to 1). An example of an input membership function for dissolved oxygen is presented in Figure 1b.

After applying fuzzy rules and the center of gravity defuzzification method for singleton output membership function, water classes are defined. Fuzzy rules are written in such a way that small changes of water quality do not affect overall water quality (class), but the significant ones - do. The significance of changes is defined through input fuzzy sets, and its fuzziness. According to this method the legal procedure for water quality classification is generally satisfied. Exceptions are only the cases when insignificant water quality degradation occurs.

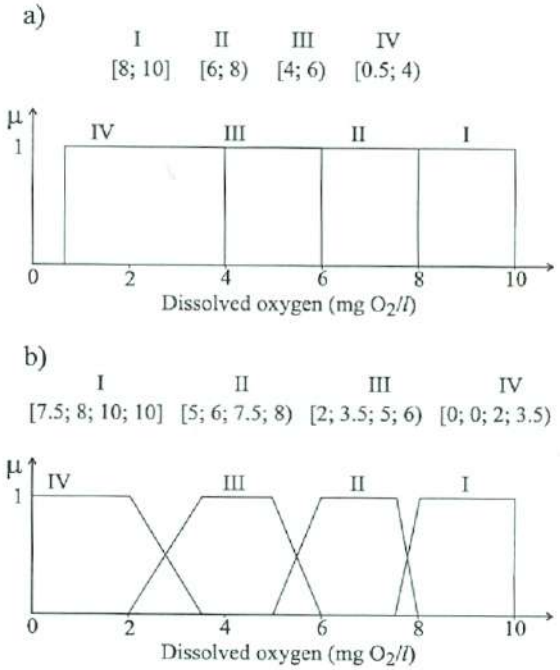

Figure 1. Water quality classes for dissolved oxygen concentrations: a) standard YU classification, b) fuzzy YU classification

4. EXAMPLE

The Information System and the water quality mathematical model based on WASP 5 model (developed by EPA, Ambrose et al. [1993]) and supplemented by zooplankton dynamic, were used for the example of Barje reservoir. For the purpose of modeling, the reservoir was divided into 8 segments (3 epilimnion segments (1, 4, 7), and 5 hypolimnion segments), with advective and dispersive transport between them (Figure 2).

Figure 2. Barje reservoir segmentation

Boundary conditions were defined for the upstream boundary segments (7 and 8). They were specified for each simulated water quality parameter (ammonia nitrogen (NH_3), nitrate nitrogen (NO_3), inorganic phosphorus (PO_4), phytoplankton, carbonaceous biochemical oxygen demand (CBOD), dissolved oxygen (DO), organic nitrogen (ON) and organic phosphorus (OP)), as time depending concentrations.

It should be mentioned that certain assumptions were made, because data was insufficient. As a part of standard water quality assessment some parameters included in the model were measured four times a year, in summer.

The concentrations of water quality parameters, that were not measured and are necessary for the simulation (CBOD, ON, OP), were determined using the relations between those parameters and the measured ones (Bowie et al. [1985], Ambrose et al. [1993], Henderson-Sellers [1984]). Using the correlation between the stream flow and concentration of the parameter, time depending concentrations for the investigated year were reconstructed. It was presumed that concentrations of the water quality parameters for which the correlation could not be established were constant during each month.

Diffuse waste loads were not included in simulation as there was no measured data.

Concentrations of simulated water quality parameters were compared with the observed (measured) values. Field investigations were performed at four locations: two locations near the dam (near the water intake structure and on the other side of the dam), the middle of the reservoir and the end of the reservoir (inflow of Veternica river into the reservoir). The most important location is near the water intake structure (the location where water for municipal water supply is taken), so measured and simulated concentrations for that location were compared. That location belongs to the segment 1.

Simulated dissolved oxygen concentration is minimal in late summer in hypolimnetic segments. Its concentration corresponds with observed (measured) values (Figure 3), and does not decrease below 6 mg O_2/l, so anaerobic conditions do not occurs. This can be explained by the rigorous reservoir bottom cleansing before filling the reservoir, by good quality inflow water, and by strict protection of nutrient loadings in the chatchment area.

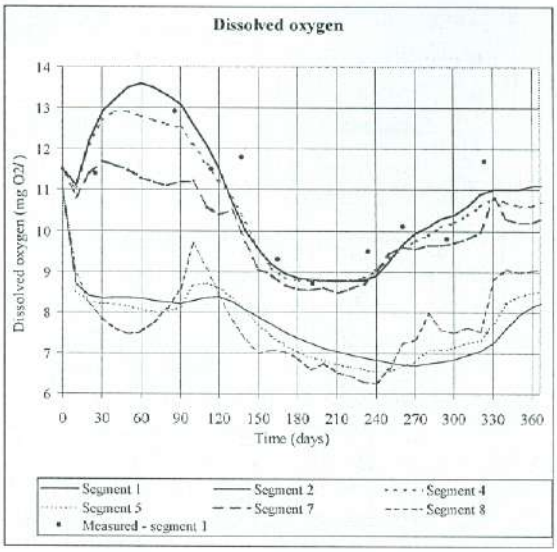

Figure 3. Dissolved oxygen concentration

Simulated nitrate concentrations were between 0 and 0.38 mg $N\text{-}NO_3/l$ and well matched the data. Its concentration decreased in segments and during periods when phytoplankton concentration increases. Total phosphorus concentration changes in a similar way, with mean annual value in epilimnetic segments equal to 0.026 mg P/l. Unfortunately, this parameter was not measured, neither for the inflow water nor in the reservoir, so the results of simulation could not be verified for water quality parameter.

Phytoplankton simulation expressed in term of chlorophyll a corresponded well to observed data (Figure 4). Phytoplankton concentration decreases at the end of May. The main reasons were probably the decrease of nutrient concentration and turbidity and increased settling velocity, caused by changing the outlet level (from 334 m a.s.l. to 361.5 m a.s.l.). It was returned to the previous level in August, when phytoplankton concentration increased (second maximum). Unexpectedly high concentrations of phytoplankton occur in November. Probably this may be because of very high precipitation during the end of October and in November. During that period agricultural land was cultivated and fertilized. Surface flow, as a consequence of precipitation, probably brought phosphate into the reservoir. That caused expansive growth of phytoplankton. Unfortunately, this assumption was not verified because phosphorus concentration in the reservoir was not measured. As previously mentioned, diffuse waste loads were not included in the simulation, so the simulated concentrations are different from the measured results for the end of the simulated year.

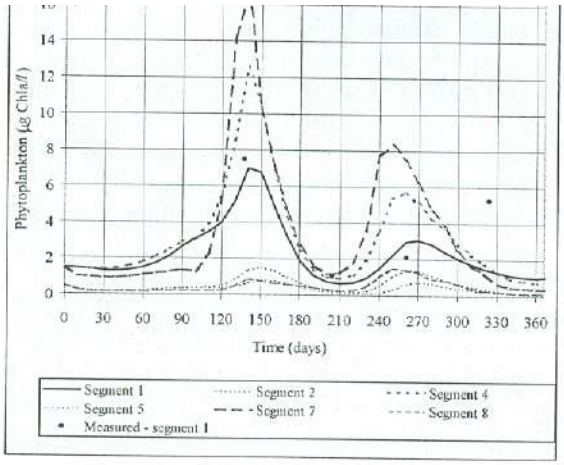

Figure 4. Phytoplankton dynamic

On the bases of simulated and observed water quality data, the trophic state was defined. According to the OECD and Carlson's classification Barje reservoir was in oligotrophic and mezotrophic state, or in classes I and II according to the YU-classification. The segments near the dam (the deepest part of reservoir) were mostly oligotrophic, the quality was decreasing towards the upper part of the reservoir, and the worse quality - mezotrophic state - was in the very upper end of the reservoir, which is its shallowest part. This was expected, and is common for water storage reservoirs.

5. CONCLUSIONS

Monitoring, modeling and assessment of water quality in Yugoslavia is not adequately treated. Therefore, the Information System for Observation and Monitoring the 'dam - reservoir' system was created. This information system, supported by more rigorous legal regulations, would increase the operational efficiency and reliability of all activities related to the assessment of water quality in reservoirs.

Mathematical modeling of water quality can give us a certain "advantage" over the nature. That enables timely reactions for water quality protection. But the complexity of mathematical models used for water quality simulation should be adjusted to needs and available input data. The most complex models should include both abiotic and biotic parameters (phytoplankton, zooplankton and ihtiofauna). Dynamism of biotic components is complex and models should include interrelations between biotic parameters, their can be determined by field investigations.

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