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An Integrated Approach to Water Quality Monitoring in Reservoirs, Aqueducts and Distribution Networks of Water Supply Systems

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Abstract: The use of state-of-the-art technology allows the continuous, automated and telemetric monitoring of different physical and chemical parameters that characterize water quality in water supply systems (reservoirs and aqueducts), with simultaneous monitoring of water flows driven by the external forces affecting reservoir circulation, including wind, heat transfer due to solar and atmospheric radiation, incoming river discharges, water withdrawal, etc. This can be achieved by combining in situ automated sensors installed in the reservoir, the incoming river(s), and at selected locations along the aqueduct from the reservoir to the respective treatment facility, with software that simulates in real time, the reservoir hydrodynamics, aqueduct hydraulics and water quality of the entire reservoir and aqueduct system, utilizing time series of the monitored parameters through a data assimilation scheme. This paper describes the possibilities offered by currently available technology for integrated water quality monitoring in reservoirs, open aqueducts and the distribution network of large water supply systems.

Key words: Water quality monitoring system, reservoirs, aqueducts, water supply system.

1. INTRODUCTION

The European Union (EU) has recognized the need for both the development of surface water monitoring programs in every watershed (article 8 of the EU Directive 2000/60, issued on October 23, 2000) and the adoption of special pollution prevention measures to protect surface water resources, especially in places where various pollutants pose a risk to human health (article 16 of the same directive). Measures to prevent contamination from these pollutants should aim at their gradual reduction, and the eventual elimination of the most hazardous of them.

It has long been recognized that regular monitoring of the physical, chemical and biological parameters characterizing water quality in rivers, lakes and reservoirs used for water supply is essential for protecting public health and assuring the long term reliability of these resources. The data collected from such monitoring: a) allow the early detection of changes and trends in water quality, b) provide the basis for the calibration of predictive water quality and ecological models, c) allow evaluation of alternative remediation strategies, and d) contribute to the advancement of the fundamental understanding of the behavior of these water bodies. In addition there is increasing pressure to develop the capability to provide early warning in the event of accidental or purposeful water contamination in any of the major components of a water supply system, i.e. the reservoir, the aqueducts, and the distribution network. An example of an effort to develop such a system is described by Clark et al. [1]. Systems for the detection of such low probability but high impact incidents must provide sufficiently early warning to allow the prevention of public exposure to the contaminants, and be able to identify the location of the contamination source. They must be accurate, reliable and affordable, sample at a reasonably high rate, cover all potential contamination threats and have remote operation [2]. Continuous water quality monitoring, in water supply systems, is necessary for other reasons too, such as, for example, for regulating land use around reservoirs, and for selecting proper treatment practices of raw water, depending on the quality of water conveyed from the reservoir trough the aqueduct to the respective treatment plant.

New monitoring technologies employing robotics, and advanced probes and sensors open new horizons in water quality protection. Also, the last two decades have seen a dramatic increase in the use of numerical simulation models in a variety of large water bodies. These models often focus on the prediction of production, transport, chemical and biological transformations of various pollutants, as well as and their impact on the aquatic environment. Hydrodynamic, water quality and ecological models are used interdependently to predict the impact of the presence and/or further introduction of nutrients, or other pollutants on an aquatic ecosystem. The major weakness of most simulation models is the lack of sufficient validation with field data, especially during critical short duration events, making thus many numerical simulations mere academic exercises.

Disadvantages of the conventional monitoring methods often used in lakes and rivers are: a) the small number of samples collected, giving rather limited coverage of the spatial (horizontal and vertical) distribution of the measured parameters, b) the low frequency and sometimes the aperiodic nature of such measurements, c) the absence, in many cases, of simultaneous monitoring of external forcing parameters (wind, solar radiation, inflows and outflows, etc) and flow field they generate, which, not only affects, but possibly, determines water quality, and d) their high cost.

The dynamic nature of large water bodies is the main cause of the variability of the physical, chemical, and biological processes (and parameters), which define water quality in them. Water samples from a small number of specific locations at a particular time may not necessarily be representative of water quality in the entire reservoir before, or after that time. These limitations can be overcome by going beyond the conventional approach and adopting some of the more recently developed monitoring concepts, such as those used successfully in meteorological and oceanographic studies that integrate many aspects of real-time monitoring and combine it with modeling. Integrated water quality monitoring systems are today commercially available and have been used in the ocean, lakes and rivers [3, 4, 5, 6, 7, 8, 9]. A similar monitoring system has also been proposed by the first author for operational use in water distribution networks covering the needs of small and/or large cities [10]. A similar proposal for developing and deploying a remote *in-situ* and on-line water quality monitoring system for the drinking water network of Salt Lake City has been put forward by Bahabur et al. [11, 12]. Also, the U.S. Environmental Protection Agency has developed a model that predicts the propagation of contaminants in networks, and is engaged in research on sensors and monitoring systems for measuring contaminants in distribution systems [13].

This paper describes the monitoring system envisioned for a large water supply system, such as, for example, the system that serves the metropolitan area of Athens (in Greece). Such a system may consist of one or more reservoirs and long conveyance works. For example, the Athens water supply system includes four reservoirs, Evinos with an operational reservoir volume of 113 Mm^3, Mornos (670 Mm^3), Yliki (580 Mm^3), and Marathon (34 Mm^3). These reservoirs are connected by about 177 km of canals and about 110 km of tunnels. The Mornos aqueduct, which connects the Mornos reservoir with the Aharnon water treatment plant, is the longest aqueduct of the system having 67.5 km of tunnels, 113.5 km of canals and 7.5 km of inverted siphons. The whole system has four water treatment plants with a total treatment capacity over 1.7 Mm^3/day. The distribution network (covering the Athens metropolitan area) has about 1.8 million metered connected customers serving about four million people. The network is approximately 7,500 km long, having about 1,800 km of primary water supply mains 400 mm to 1.800 mm in diameter, and 5,700 km of water distribution pipes with diameter up to 300 mm.

2. OVERVIEW OF THE SYSTEM

A complete monitoring system for a large water supply system must cover all its parts, i.e.

- supply sources, (reservoirs, rivers),
- conveyance works (open aqueducts, tunnels),
- (inner) distribution system.

The ideal integrated system for water quality management in water supply systems consists of three major components:

a) a system of continuous automated, telemetric monitoring of water quality and other parameters that affect water quality, e.g. meteorologic and hydrologic data,
b) computer models for the simulation of the recorded water quality, and other, not directly measured, parameters, and
c) a decision support system, including a database and other software for storing, processing and analyzing the collected data.

Several basic chemical and biological parameters are measured in all three parts of the system including pH, turbidity, dissolved oxygen, nitrates and nitrites, phosphates, total phosphorus, orthophosphates, heavy metals, total bacteria and coliforms. Additional water quality parameters unique to some parts of the system are addressed in the following sections.

The special models developed for each of the parts of the system should run in real time, and their calibration could be continuously updated with the aid of assimilation methods. The basic problems associated with the assimilation of data into mathematical models that simulate physical and/or biochemical processes are well understood today. Typical methods, as the "sequence" or the ''optimum interpolation'' technique, or schemes that utilize statistical errors depending on time and showing dynamic consistency may be used to maximize the precision of water quality simulation predictions. The combination of simulation software and an assimilation module can optimize the reliability of the model simulations.

The remaining of this paper, focusing on the first two components (monitoring and modeling) of the integrated water quality management system, is structured around the three major parts of a typical water supply system, that is, its reservoirs, aqueducts and the inner distribution network.

3. THE RESERVOIR MONITORING SYSTEM

A system of automated, continuous, telemetric reservoir monitoring may consist of one or more buoys anchored at selected stations in the reservoir, properly equipped with a small mast and instrumented to monitor basic meteorological data, (e.g. wind speed and direction, atmospheric pressure, air temperature, relative humidity and solar radiation), water level, water temperature and salinity/conductivity, the basic chemical and biological parameters, and chlorophyll a. If hydrodynamic circulation patterns in the reservoir affect its water quality, one or more Acoustic Doppler Current Profilers (ADCP) could be added to the monitoring system, either mounted at the bottom of the buoy(s), or placed at the bottom of the reservoir pointing towards the water surface, to provide water current profiles (magnitude and direction). Current profiles can also be obtained by mounting current meters along the buoy(s) anchoring line(s). Analytical instrumentation for determining the chemical oxygen demand (COD), total organic carbon (TOC), total bacteria and coliforms, as well as instrumentation for radioactivity may also be added to the monitoring system. First, the location of the monitoring stations in the reservoir must be based on any evidence of the spatial variability of various physico-chemical parameters of interest. This will provide an initial characterization of the system. It can then be changed as regular monitoring leads to better understanding of the reservoir system.

A comprehensive reservoir monitoring system must also include a station in each of the major river branches to monitor the water quality of the water flowing into each reservoir. In simple reservoirs systems one inflow station may be sufficient. The inflow monitoring stations must have instrumentation for recording the river stage, water temperature, salinity/conductivity, and the basic chemical and biological parameters.

If no meteorological station exists in the vicinity of the reservoir, then a meteorological station should be installed to monitor precipitation, wind speed and direction, air temperature, cloud cover, relative humidity and evaporation, quantities needed for estimating the direct surface runoff into the reservoir and water losses due to evaporation from its surface. It is also desirable to monitor short and long wave radiation for estimating heat fluxes at the reservoir surface.

A typical reservoir simulation model consists of two modules, a hydrodynamic and a water quality module. The first module simulates hydrodynamic circulation in the reservoir using as input inflow (direct runoff and stream flows, including controlled releases from upstream reservoirs) and outflow data, and data on external forcing, such as wind and meteorological parameters that control the heating and cooling of the reservoir. The dimensionality and complexity of the hydrodynamic module depends on the size, geometry and other characteristics of the reservoir. In many reservoirs, one-dimensional (in the vertical direction) models, incorporating parametric equations to describe key physical processes, provide an adequate description of reservoir hydrodynamics and can reproduce well the annual cycle of stratification and account for the effect of variable temperature inflows, density currents, thermal stratification, selective withdrawal, etc. An example of this case, are the reservoirs that have relatively simple geometry extending upstream of the dam along a single river. In other reservoirs, whose geometry is quite complex having multiple arms receiving water from different river branches, the use of a two-dimensional, or even a three-dimensional, model may be warranted.

The hydrodynamic module solves simultaneously the mass conservation, flow, temperature, and salinity equations, coupled through an equation of state for the water, most often on a Cartesian grid. In the most general case, multi-dimensional models may employ a curvilinear adaptive grid, which utilizes a σ-coordinate transformation in the vertical direction. The equations of motion include: a) horizontal advection-dispersion (and/or vertical convection) to account for density gradients caused by thermal or other stratification conditions, b) pressure gradients, c) a turbulence model to account for vertical turbulent mixing, d) the effects of surface wind shear stresses and bottom friction through proper parameterization, and (in fewer cases) e) the Coriolis effects (if significant).

Adaptive grids offer the flexibility of changing in time, especially near the reservoir boundaries, depending on whether the boundaries remain wet or dry, as the water level in the reservoir rises or falls (flooding and drying moving boundaries). In large reservoirs the hydrodynamic module may incorporate a spatially varying wind and atmospheric pressure field on the water surface, using appropriate boundary conditions at the open boundaries.

The water quality module solves the mass conservation equation for different compounds and parameters of concern, e.g. nutrients, heavy metals, suspended sediments and pathogens, accounting for chemical reactions where needed. It predicts the transport and transformation of the water quality parameters of concern by simulating the nitrogen and phosphorus cycles, the phytoplankton kinetics and the dissolved oxygen budget, accounting for their interaction with suspended and bottom sediments. The parameters simulated, by the water quality module, are physical (e.g. water temperature, pH, salinity/conductivity, turbidity), and chemical (redox potential, dissolved oxygen and BOD, nitrates, ammonia, inorganic and organic phosphorus-total phosphorus and orthophosphates). The water quality module may also account for other biological and ecological parameters, like bacteria (total and coliforms), phytoplankton (through the simulation of chlorophyll **a** or other relative indicators), zooplankton, etc. The water quality module is linked with the hydrodynamic module, through the velocity and temperature fields produced by the hydrodynamic module, which are used in the transport simulation of different chemical and biological parameters.

The simulation of the parameters that characterize water quality in a reservoir accounts through appropriate budgets for the conservative (or non-conservative) character of each parameter using appropriate kinetics (e.g. linear, first order, etc). It also includes photosynthetic and other biogeochemical processes, e.g. nitrification and denitrification, BOD reduction, adsorption-desorption of heavy metals and orthophosphates, phytoplankton growth (as algae-chlorophyll *a*) or the consumption of phytoplankton by the zooplankton, nutrient recycling, as well as the processes of deposition and resuspension of bottom sediments, and finally the bacterial decay. It also accounts for the reaeration of the reservoir.

The mathematical models of the reservoirs of a large water supply system should be developed in steps. First, the hydrodynamic module must be tested independently of the water quality module by checking its ability to reproduce well the annual stratification cycle and other hydrodynamic characteristics of the reservoir. The next step involves the development of the water quality module, testing first its ability to simulate the variability of dissolved oxygen, different forms of nitrogen, phosphorus and chlorophyll *a*, and subsequently incorporating other parameters if needed. The hydrodynamic and the water quality modules must have interfaces with appropriate data input and data processing sub-modules, and/or with a Geographic Information System.

The two main modules of a (typical) reservoir simulation model can use the data recorded by the instrumentation on the buoy(s) and the on-land station(s) through a scheme of data assimilation, to optimize their performance in terms of their ability to simulate the parameters of interest over the entire simulation field. The data assimilation system may include different schemes for the hydrodynamic module and the water quality module, given the different nature of the equations in each of these two modules.

The installation of the monitoring system in the reservoirs must be preceded by:

a) a systematic compilation, analysis and evaluation of all existing data regarding the specific reservoir(s), as well as an effort to organize and store these data in a database. This database must include data for each reservoir and its drainage basin, e.g. meteorological, hydrologic and water quality data, as well as information on actual or potential pollution sources in its watershed. This information must be subsequently used to develop and initial estimate of the pollution load that enters the reservoir, which will be used as input to the water quality model.

b) a water quality data collection program using conventional methods. This should include data collection at different locations and reservoir depths (and in the inflowing rivers), during both the dry season, especially during the period of thermal stratification, and the wet season. These data can provide an initial picture of water quality in the reservoir, which can support the detailed development of the model, and help design the continuous monitoring program, by facilitating the final selection of the number and location of the sensors (and/or buoys) that must be purchased and installed. Considering the dynamic nature of the reservoir-river system and its complex interaction with the surrounding watersheds, it is advisable to equip the monitoring stations with sensors for continuous, automated and telemetric monitoring of all basic water quality parameters that can be monitored. This can better satisfy the EU requirements regarding the quality of water in reservoirs, and particularly in those used for drinking water supply.

4. MONITORING SYSTEMS FOR AQUEDUCTS

A similar integrated water quality monitoring system is envisioned at selected locations along the open portion of the aqueducts (i.e. canals) of the water supply system. The monitoring stations for the open aqueducts can be similar to those for monitoring water quality in the rivers flowing into the reservoirs, and it can be installed on land. Each station should be equipped with a computer controlling different (monitoring) sensors and the corresponding transducers, and other electronic signal processing devices, such as amplifiers, filters, etc. The location of the monitoring stations must be selected based on consideration of the variability of different water quality indicators along the aqueduct, and to a lesser extent, based on secondary criteria, such as the topography of the area. Before the installation of the permanent monitoring stations, an initial evaluation of the water quality variability along the aqueducts can be made using conventional means during both the period of high water supply, e.g. in the summer, and during the rain season, taking into account the hydraulic characteristics of the open part of the aqueduct and the supplied flow rates. An effort must be made to determine to what extent the variability of the water quality is due to changes in the hydraulic characteristics of the aqueduct (friction, cross sectional geometry), and to what extent is due to local changes in the flow rate, or other factors, e.g. the local presence of algae. All these factors can influence the hydrodynamic dispersion of various (pollutant) substances that maybe found at any particular moment in the aqueduct. The selection of the monitoring locations, along the supplying aqueducts, can be also optimized using entropy principles [14].

At a typical monitoring station, along the aqueduct, water can be diverted either naturally, or with the aid of a small pump in an adjacent sump, to the side of the aqueduct for *in situ* sampling and further chemical analysis. A computer, along with various sensors and other driving electronic devices, can be placed in an adjacent portable container, or in a mobile unit that would serve as a small chemical laboratory and also assist in maintaining and validating periodically the performance of continuously recording instruments. The results of the quick chemical analysis can be either recorded locally on this computer, or they can be transmitted electronically to a central data collection and evaluation-control center.

A computer model can also be used to predict water quality along each aqueduct. This model can be much simpler than its counterpart for the reservoir, because of the much simpler hydraulics, transport and (physicochemical and bio-geological) transformation processes that affect the fate of pollutants and other substances in (usually 1-D) open aqueducts compared with those in reservoirs.

An important function of the monitoring system is to provide early warning in the event that water quality in the aqueduct is threatened by natural hazards, and intentional or accidental human activities. In order to improve the security of open aqueducts one must first assess their vulnerability to activities, such as the introduction of toxic chemicals or biological agents in the water.

The vulnerability assessment of an aqueduct to physical disasters and other threats should aim at determining ways that would help the responsible water agencies protect public health, as quickly and effectively as possible, by minimizing the anticipated risks and providing early warning in the event of a toxic contamination incident. This assessment must be comprehensive and should address several specific issues, as:

a) the probability of occurrence of specific threats to the aqueduct (and/or reservoir),
b) overlooked aspects of physical protection of the system,
c) ways to minimize the impact of potential physical disasters, new potential threats in view of various international crises (terrorism),
d) available protection systems and technologies for reservoirs, aqueducts and water treatment facilities,
e) differences in the response to natural disasters and terrorist activities, etc.

There are different methods for the detection of the presence of undesirable (chemical and biological) substances in open aqueducts. Besides the classical chemical analysis methodologies and the continuous recording (and analysis) of temperature, pH, conductivity and turbidity, other methods such as the "advanced chemical resolution-verification", the inverse analysis technique[15], or the monitoring of the behavior of the immune system of different organisms can be used. For example, an indicator of the presence of toxic substances in the water is the response of microorganisms with fluorescent properties, which are sensitive to these substances. Such microorganisms are certain fish (cyprinidae, e.g. carp), daphnia, copepods, etc. Monitoring the state of the health of these organisms requires sensitive sensors and advanced techniques of optical imaging, combined with appropriate computer models and response protocols of the monitored organisms, as well as other laboratory analyses. The methodology of monitoring the biological activity of the water of the aqueduct can be effective only in combination with the appropriate instrumentation and computer model(s), which of course can be part of the integrated water quality monitoring system [15, 16, 17, 18].

5. DISTRIBUTION NETWORK MONITORING

Monitoring of the water quality in the distribution network is achieved through a number of monitoring stations located at carefully selected parts of the distribution network, e.g. critical junctions of the network. The system of permanent fixed monitoring stations can be supplemented by self-contained mobile units, which could be moved to specific locations of the network, if needed.

The selection of the location of the monitoring stations is based on several criteria including the topography, the age of the distribution system, its hydraulic characteristics and density (km of conduits/km^2 network), the expected spatial and temporal variability of potential contaminant concentrations in the network, the residence time (or renewal period) of water within particular areas of the distribution system, and space considerations for placing the required instrumentation and equipment. Hasit et al. [19] discuss different methods for locating monitoring stations in water distribution networks including intuitive optimization and mathematical programming, and hydraulic/water quality network simulation methods.

Significant progress has been made, over the last few years, in the design and manufacturing of specialized sensors for real time automated water quality monitoring in water supply systems. ASCE [20] has recently compiled and published a database of commercially available and emerging technology water monitoring equipment. There are several sensors for automated and continuous monitoring of various quality parameters, as specified by the pertinent EU regulations. These parameters are associated with the physicochemical properties of water and its organoleptic characteristics, the presence of organic pollutants, pesticides and their transformation products, the presence of toxic substances and heavy metals, trace elements, nutrients, the presence of bacteria and, perhaps, of other undesirable substances (as polychlorinated biphenyls in ground water, and some other substances in waste waters).

The data collected at each monitoring station could be transmitted wirelessly to the data management center. Each station should be equipped with a computer, which facilitates the communication with the center.

There are several simulation techniques for water quality modeling in water distribution systems, some of which have been implemented in public domain or commercial software packages. An example of such model is EPANET [21], which simulates both the hydraulics and the water quality distribution in the system.

The distribution network monitoring system should be able to provide early warning on the nature and location of contaminants in the network and support the response to such threats. For example, it could be used to evaluate potential response actions to decide whether the contaminated pressure zone should be isolated, whether any hydrants should be opened to flush the system, whether any pumps should be turned on or off, etc. A calibrated real-time operated simulation model can be used to run alternative management scenarios in response to changing demand conditions in the aftermath of a contamination event.

Such systems can reduce human errors in the measurement chain, reduce costs and increase the ease of overall network maintenance. They can also improve water quality by identifying and eliminating stagnant water from the pipe network, adjusting various remotely controlled valves and chlorine levels in the entire distribution network.

6. CONCLUSIONS

The described monitoring system is viewed as an important element of an integrated approach to monitoring, simulating and managing water quality in reservoirs, water supply aqueducts, and distribution networks. Such a system should aim at providing the utility authority, responsible for the management of large-scale water supply systems, with means for quick and efficient environmental data collection, analysis, presentation/visualization and storage of both the raw data and their interpretation. It should be capable of simulating the most important physical, chemical, and biological processes and their interaction. This capability could be used, in conjunction with real time data, for water quality predictions throughout the entire system.

Such a system will meet the requirements of EU regulations and will provide a viable option for monitoring and managing water quality in reservoirs, supply aqueducts and distribution networks. Despite its obvious advantages, it has not yet been established internationally, but several groups work towards this goal. In Greece, besides some systems of limited monitoring capabilities, such a comprehensive system is not in use yet. Similar systems, but not as comprehensive as the system described in this paper, have been installed in the European Union, e.g. in Norway, Poland, and elsewhere for monitoring water quality. A proposal for such a comprehensive system in support of water quality management has been presented by the authors to the Athens Water Supply and Sewerage Company (EYDAP SA), which manages and operates the water supply system of the metropolitan Athens area in Greece.

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