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Identification of water quality changes in a water system – limitations and perspectives

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Abstract: From the abstraction point and the entrance of water in a Water System (WS) till its discharge back to the environment, water passes through a number of treatments and uses that directly affect its quality. The water quality changes several times while the water returning to the environment at a discharge point into the sea, a lake or a river has poorer quality compared to the water entering the system. All the parts of a WS should be integrated into one single model to assess the performance of the overall system for the development of design and control strategies assisting in its sustainable and cost effective management. Available models for the individual components have to be employed in order to develop the integrated tool. Problems that arise from this methodology are the increased data requirements together with incompatibility of state variables, processes and parameters used in different approaches.
For improved control and performance of a WS that includes the water treatment and waste water treatment processes a good knowledge of water quality at each part of the system is required.
Preliminary analysis of the available data shows an increase of the values in a number of quality parameters between the water source till the water treatment facility.

Key-Words: Water-quality modelling, water-quality processes, Athens Water System

1. Introduction

The Water System (WS) analysed and investigated for the purposes of the work presented in this paper consists of a number of different parts and components. The interest in analyzing a WS is that the different components influence the quality of water inside the WS in a non-uniform way. Dams, lakes, boreholes, open and covered channels, pipes and pumps, water and wastewater treatment plants, are typical parts of a WS.
In order to quantify the changes in water quality inside a WS it is imperative first to understand and quantify the influence of each and every component of the system and then integrate them to holistic model. Optimal management of the individual components of the system does not necessarily result in optimal performance of the entire system as interactions among the components can influence its overall behaviour. Therefore all the parts of the WS should be accounted for when investigating the overall change of quality parameters for the development of design and control strategies which will assist in sustainable and cost effective management. One of the main problems when developing an integrated model is the incompatibility between state variables, processes and parameters used in the different sub-models.
Water utility companies and environmental regulatory bodies around the world use water quality models for control and management of the water resources they are using. The research on water quality models is driven to a great extent by legislation and regulations and the 2000/60 WFD sets the perspective for EU applications. The Environmental Agency (EA) in the UK and the Environmental Protection Agency (EPA) in the USA are typical examples of environmental authorities that use and develop water quality models for planning improvements in catchment water quality. Typical examples are the SIMCAT, MIKE-11, QUASAR, QUAL2E. Still in most cases these models are focusing on watershed description and not on the WS. In the following sections the available methods and their limitations are discussed.

2. Water Quality modelling

2.1 Available methods

There is a long list of available quantitative techniques to assess the impacts and the fate of pollutants in water resources. These range from the basic mass balance concepts to sophisticated computed-based methods that can simulate hydrodynamics, dispersion and pollutant kinetics. Dynamic models involve the solution of differential equations, which formulate the relevant physical, chemical and biological mechanisms. Most of the available models have been developed for particular purposes and it is suggested that none of the models presented in literature can provide all the functionality required. Furthermore, all the models contain assumptions and limitations that need to be understood if meaningful interpretations of the model simulations are to be made. In most of the cases presented in literature the authors are interested in producing new variants of the original models or reviewing and comparing available models that can describe the changes of quality parameters in lakes, rivers and estuaries. A well documented review paper is given by [1] presenting the major models, currently in use, for describing water quality in freshwater river systems. There are also a number of studies on methods for describing the water quality changes in water treatment and waste water treatment plants ([2];[3];[4]; amongst others). There is a wide choice of parameters that can be found in the literature, but for the waste water treatment plants most of widely used models are designed to simulate parameters such as BOD, Ammonium and DO (sanitary determinants). The purpose is to set compliances levels for effluents from sewage treatment works and other discharges of organic waste.

Recently, the use of techniques like artificial intelligence to describe water and wastewater treatment plants are becoming increasingly popular due to their rapid development times, minimum information requirements, and ease of real-time implementation [9]. As it was presented by [5] the expert system approach is the most prevalent, but difficulties in acquiring and representing knowledge of the complex phenomena in these plants have led to the search for additional approaches. Fuzzy logic and statistical process control are used for formulating expert rules from plant historical operating data, but artificial neural networks, which can learn from examples, are believed to be a better solution for this task and for many additional problems encountered in the operation of the plants. Current and future utilization of neural networks in areas of water and wastewater plant modelling, expert rule extraction, fault detection and diagnosis, plant and instrument monitoring, dynamic forecasting, and robust control are discussed.

The selection of well-suited models in order to describe changes in water quality is an important task as it will define a number of parameters for the subsequent steps of the analysis and ultimately will influence - determine the implementation of the chosen approach.

However, there is lack in quality models for describing the entire course of water an in a WS. An interesting approach is presented by [3], [6], [7]. They couple a river water quality model with drainage and sewage system models.

For the work described here a similar approach is required. The whole WS should be integrated under a single model and the coupling of the numerous parts and elements of the WS is essential. Still the differences between the processes inside each component do not allow approaching this problem using the popular methodologies for water quality modelling.

2.2 Problems and limitations of integrated modelling

There are a number of problems encountered when developing an integrated model. First, the available quality models for each component of the WS use different variables to describe the aquatic system. Second, the hydraulic equations for the flow propagation in pipes, channels, tanks and reservoirs are non-linear partial differential equations and require complex numerical algorithms to solve. Third, is the size of the WS and its complexity. On top of this, there are numerous physical processes and parameters that require representation. This is translated to increased data requirements. The problems introduced by insufficient and inefficient data are critical for the development of the model as well as for the validity of the produced results. Data with different time step from various parts of the WS will limit the available options. Problems are also related to the use of different models for each component, making simultaneous simulations difficult to achieve.

Taking into account these problems and focusing on approaches that can solve them is a central task in the design of an integrated model. The complexity of resulting model should be supported by data availability.

The model choice also depends on the objectives of the analysis. The objectives can be distinguished in two categories: understanding / research and management and practice [8].

The limiting factor of data availability explains the popularity of hybrid/stochastic models [1]. These models provide the necessary statistical output for describing the changes of water quality parameters, but also they require relatively little data as they do not attempt to represent hydrochemical processes other than by as simple first-order decay rates.

The option of a conceptual representation of the entire WS will be investigated.

3. Water System (WS)

In order to describe the changes of the water quality parameters in each element of the WS it is essential to first analyse in detail all the elements that compose a WS.

A WS is a network consisting of a number of components that are connected to each other. The characteristics of each element, connection, connectors and practically everything that is included in the WS, is important information if a model is to be build to describe the processes in the WS.

The parts of a WS can be divided into four main groups:

- Elements of supply - those include the available ground water that is pumped, rivers, dams and lakes.
- Elements of transport – those include all the network connections, pipes, open and closed channels, return flows and pumps.
- Elements of treatment – those include all the water and wastewater treatment plants
- Elements of demand – those include all the uses of water, domestic, agricultural and industrial.

An example of a WS with all the above elements is given in Fig. 1.

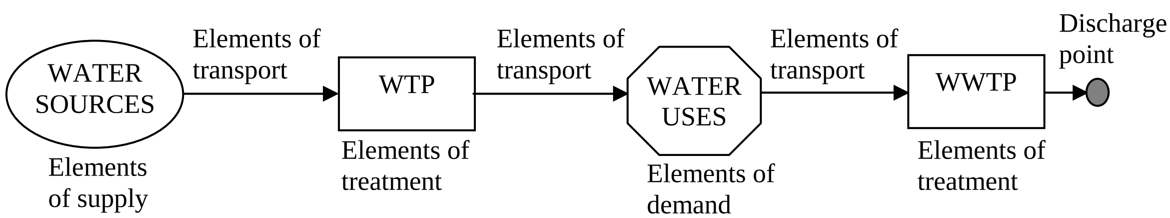

Figure 1. A typical WS that includes all the main elements

To minimise the problem of limited data required for describing each component, the WS should be divided initially into a series of grouped elements (if required) which are defined between the main junctions or user defined points. The connections (junctions) must be defined together with the physical parameters that define the extent of the system and reaction rates. A number of pre-selected points have to be defined to assist the course of the investigation.

Flow and quality data are entered for the main input of the system (supply elements), the main channels, and the pipes (transport elements) before and after the selected water treatment plants (treatment elements) and before and after the wastewater treatment plants (treatment elements). Mass balance equations that can provide useful information will have to be used for input-output analysis. Losses due to leakages and evaporation at the different parts of the WS will have to be estimated. At treatment and demand elements the mass balance will include the use of water.

A big advantage of this type of approach for describing the changes of quality parameters in the entire WS is the use of different models for each element or elements at each section of the WS without affecting the procedure of solving the entire system. Care should be put in the selection of variables. The selected variables should be meaningful and able to describe the changes in water quality in the entire WS. These variables ideally should come out of WFD catalog. These to a large extend are the basic monitoring variables. The typical parameters that are described by water quality models are Salinity (S), Chlorophyll a (Chl-a), Ammonia Nitrogen (N_1), Nitrate Nitrogen(N_2), Coliform Bacteria (E), Total Phosphorus (TP), Heavy metals (HM), BOD and DO. However it is advisable to use at least one variable that indicates the level of organic pollution such as TOC (Total Organic Carbon), BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand) and one indicating the level of Nitrogen (if possible both Ammonia and Nitrate).

4. Athens Water Supply Company WS

The current WS of Athens is quite extended and complex as it includes both surface and groundwater supply elements and spans in an area of approximately 4000 km^2. Athens WS supplies approximately 4.000.000 inhabitants with potable water, through an extensive network that includes 1.796.500 metered connections. There are four surface water sources (Table 1) and a total of 105 boreholes that provide water to the system

The WS incorporates four WTPs (Table 2), approximately seventy pumping stations, and the estimated length of the distribution network is 7,000 km. Leakages are estimated to exceed 20 % on average. The sewerage sector similarly serves 3.300.000 inhabitants, with a total network length of 5.800 km.

Table 1. Surface water sources of Athens WS

	Surface area (km^2)	Watershed (km^2)	Maximum capacity
Marathon	2,4	132	41 h m^3
Yliki Lake	25	2.423	590 h m^3
Evinos	3,5	350	140 h m^3
Mornos	18,5	560	780 h m^3

Table 2. Water Treatment Plants.

WTP	total water treatment capacity
Galatsi	540.000 m^3/d
Aharnon	800.000 m^3/d
Polydendri	300.000 m^3/d
Aspropyrgos	200.000 m^3/d

Table 3 WasteWater Treatment Plants

WWTP	sewage treatment capacity
Psittalia	1.000.000 m^3/d
Metamorfosi	24.000 m^3/d of cesspool waste
	20.000 m^3 /d of sewage

The main concern when trying to describe a WS of this size, is data availability. In order to fully analyse the changes of water quality parameters in each element or groups of elements, significant amounts of data are required. As it was impossible to obtain data for the entire WS, it was decided to try to describe the quality changes from one water source and one WTP. The effect of the processes in the WTP are also investigated.

5. Analysis of available data and discussion

The current available data are limiting the study to only one water source element, Mornos reservoir, and one treatment element, WTP of Aspropyrgos. The data from the reservoirs is of a monthly time step (one day per month – not average values) whereas the data from the water treatment plants and the distribution network is daily. To compare the parameter values from reservoir and the WTP, selection of the corresponding daily values while taking into consideration of the travel time (2-3 days) from reservoir to the WTP have been performed. As monthly time step has been used it has been impossible to monitor the changes of the quality parameters during a day. As the residence time at the different parts of the system varies from few hours to even days, the ideal time step to fully describe all the changes in each element of the WS is hourly. Furthermore there are long channels in the WS (more than 200km) where there is only one sampling point. Figs 2,3,4,5,6 show the variations of a number of parameters in three selected points in Athens WS. The first point (shown as MORNOS in the figures) is a monitoring point just after Mornos reservoir, the second point (shown as WTP ENTRANCE) is a monitoring point before the entrance at the WTP of Aspropyrgos and the third point (show as WTP EXIT) is a monitoring point after the WTP of Aspropyrgos at the beginning of the distribution network.

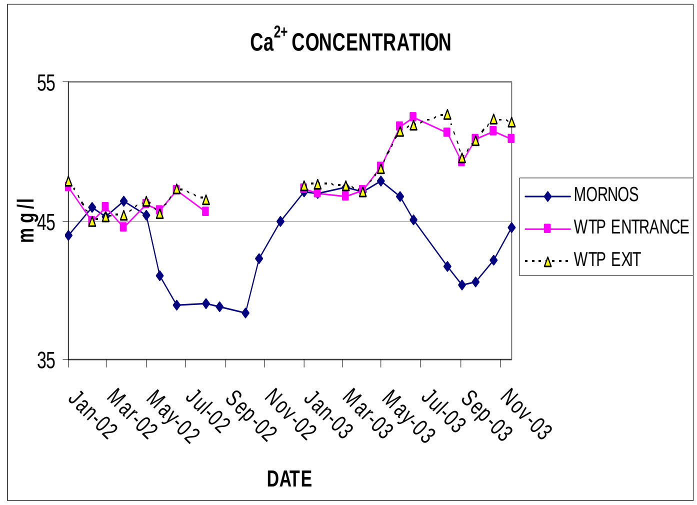

Figure 2. Variations of Ca^{2+} concentration

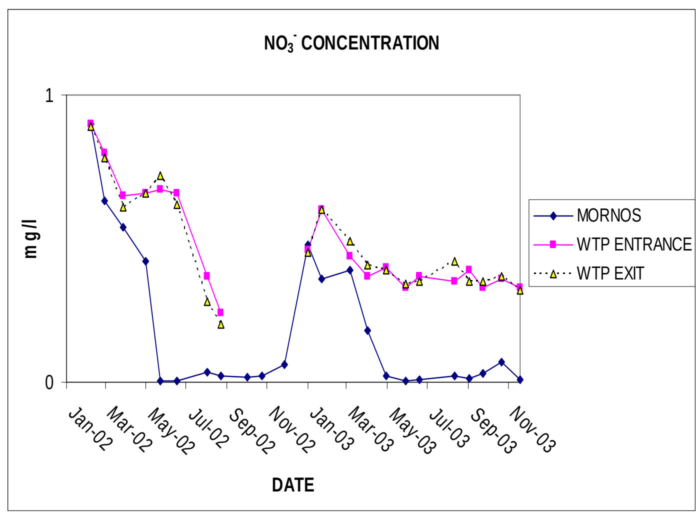

Figure 3. Variations of NO_3^- concentration

This set up allows the description of the effect of the elements of transport from Mornos reservoir to Aspropyrgos WTP as well as the effect of a treatment element (Aspropyrgos WTP) to water quality parameters. The parameters that have been used for the current investigation are Ca^{2+}, Cl^-, SO_4^{2-}, NO_3^- and DO. It can be seen in all figures that there are significant differences between the first and the third point in the WS. The changes of the selected parameters vary and the effect of each element should be identified. For Ca^{2+}, NO_3^- a significant difference is shown in Fig. 2 and 3 between Mornos reservoir and Aspropyrgos WTP. This implies that there is an effect of the channel and its surroundings (this is an open channel) that transfers the water to the WTP. As far as Ca^{2+} is concerned, the increase of concentration can be accounted to ground water rich in Ca entering the channel. The fact that increased Ca^{2+} concentrations are monitored during the summer period suggests that water from boreholes has been introduced to the system. NO_3^- increased values suggest that there is the possibility that the ground water entering the channel is rich in NO_3^- from fertilisers. However, as the channel crosses mountainous areas where agricultural activities are limited this hypothesis cannot be fully supported. An other possibility is nitrogen fixation in the parts of the channel close to Attica basin where the nitrogen concentrations in atmosphere are increased compared to the area around Mornos reservoir. In order to support this suggestion a pilot study should be organised to test this effect.

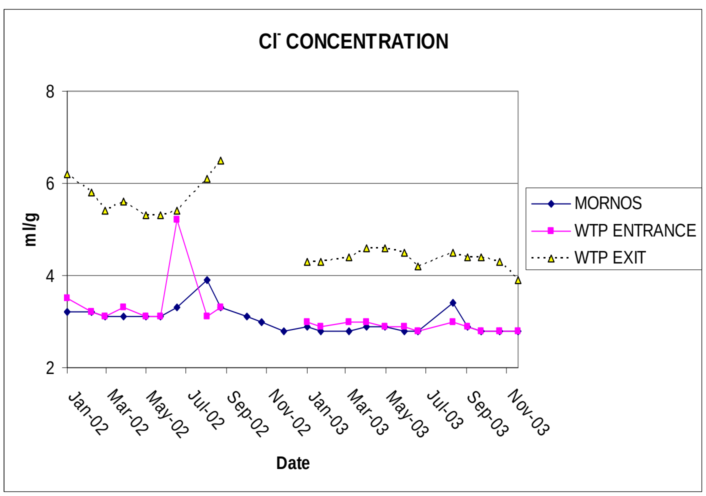

Figure 5. Variations of Cl^- concentration

Figs 5 and 6 indicate that there is a change in Cl^- and SO_4^{2-} respectively which can be accounted to the operation of the WTP where these chemicals are used in the treatment processes. There is an increase of SO_4^{2-} concentration for a long period in 2003 (May – Nov) at the entrance of the WTP that cannot be related to the operation of the WTP.

As shown in Fig 6, there is a seasonal variability in DO concentration, similar to NO_3^- variations, and a increase of the DO in the channel and the WTP. This can easily be explained by the aeration that takes place both in the channel and in the WTP because of the movement of the water and the treatment processes.

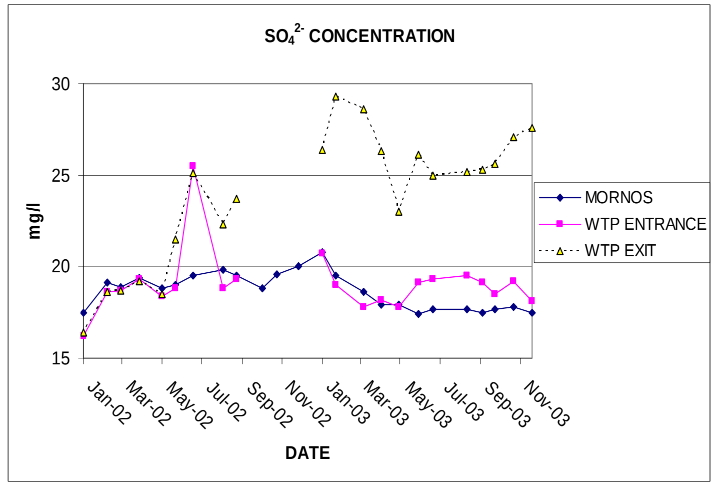

Figure 4. Variations of SO_4^{2-} concentration

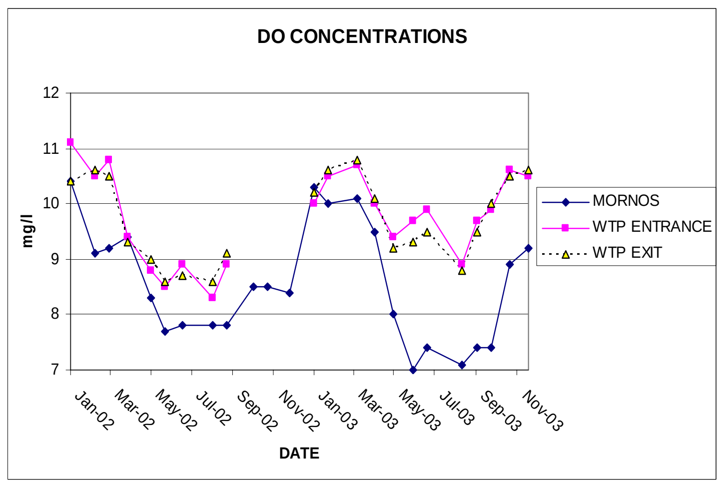

Figure 6. Variations of DO concentration

6. Concluding Remarks

This paper presents preliminary results of the investigation of water quality changes in Athens WS. The analysis indicate that it is possible to identify the changes in water quality parameters and indicate the effects of the different elements (elements of transportation and elements of treatment) analysed here. The following step will be the application of model that will be able to simulate the variation of the quality parameters. This will eventually provide the required information for improved control and management of Athens WS.

The work presented here is a simplified approach and it would be inappropriate to draw definite conclusions about the cause of changes that have been identified. Clearly a more extended range parameters and monitoring points at other elements of the WS are required. The aim would be to reproduce the identified changes and validate the hypothesis discussed in the previous sections.

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