MODELING DISTRIBUTION SYSTEM WATER QUALITY WITH HYDROSIM MODEL

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Abstract: Simulation of the water quality in water distribution networks is an internationally accepted tool for the plan and the design of new systems and the evaluation of old ones in order to keep the drinking water clean and wholesome. Directive 98/83/EC has established specifications for the basic and preventive parameters and also, for the priority dangerous substances in drinking water. This Directive explicitly mentions that the parameter values should be maintained at the point of human consumption and not at the entry point of the network (water intake). The current valid technical specifications in Greece (Presidential Decree 696/1974) do not contain any prevision for simulating the hydraulic behavior of water distribution systems and neither for the drinking water quality analysis. Thus, while there is a long list of qualitative parameter values for drinking water, there is no institutional provision for the investigation during the design of a drinking water distribution network for the effect of the network design philosophy (network shape, simple or multiple water intake etc.) on the qualitative characteristics of the drinking water. It is well known that water quality in distribution networks is continuously changing. Therefore, the only way that these values can be examined and adjusted in advance is the simulation of the water quality in distribution networks for real or hypothetical conditions (scenarios) utilizing dynamically varying modeling programs. For this purpose the software package HYDROSIM was developed which is coded in Visual Studio .NET 2003 utilizing the source code of EPANET 2 which is a free software of Environmental Protection Agency (E.P.A.). The purpose of this research paper is the investigation of the effect of the design philosophy of a water distribution network on the qualitative characteristics of the drinking water and suggestions on improving the current specifications for the design of water networks in Greece.

Key words: chlorine decay, water age, distribution system, drinking water, water quality model.

1. INTRODUCTION

The objective of any Water Distribution System (WDS) is to provide water to the consumer in the proper quantity and pressure but also in the proper quality in terms of flavor, odor, appearance and sanitary security. Consequently each drinking water company has to maintain a very good water quality in the whole distribution system. This goal is not easily obtainable due to the geometric complexity of the network, the complexity of the network connections, the different functional regulatory systems, the temporal and spatial variations on the water demand and the reactions between the various substances contained in the water and also, the reactions between the water and the internal wall of the pipes (Wu 2006).

In practice, the combination of conventional methods of treatment and disinfection of drinking water gives very good results as far as it's quality (USEPA 2001). Traditionally chlorine is used as a disinfectant (USEPA 2001; Munavalli and Kumar 2003). However, the disinfection of drinking water with chlorine, while reducing the risk of pathogenic infections, may be a chemical threat to human health due to disinfection residuals and their Disinfection By-Products-(DBPs) (Sadiq and Rodriguez 2004). Specifically, chlorine presents some problems that make its management difficult. The Regulatory agencies establish stingent standards for the residual chlorine in the water and in any place in the network so that consumers are protected from pathogenic infections. However, chlorine decays due to decomposition in natural water with time and therefore enough quantity of disinfectant should be added to the water system but not at a high concentration in order to avoid problems in taste, odor and creation of DBPs.

For the continuous monitoring of water quality, sampling is carried out in appropriate places which plays an important role in minimizing the risk of supplying unsatisfactory water quality for public health. However they provide only a limited picture of water quality, because the sampling is carried out at specific points, and can not be used for predicting future conditions or the execution of «what if» analysis because of its limited coverage and high cost (Wu 2006).

The complex dynamic behavior of water quality and the various physical, chemical and microbiological processes taking place simultaneously in a WDS have induced scientists to use simulation models of water quality for the investigation of temporal and spatial evolution of disinfectant substances in WDS (Clark et al. 1993; Rossman et al. 1993; Boulos et al. 1995; Islam and Chaudhry 1998; Fernandes 2002).

The purpose of this work is to investigate the effect of the design of a water supply network in the quality of drinking water and suggest improvements on the current standards for drinking water network studies in Greece.

2 THE CURRENT LEGISLATION IN GREECE

The standing technical specifications in Greece for studies of water supply systems were formed in 1974 (Preferential Decree 696/74, Articles 204 - 207) which is 35 years ago without any improvement or correction. During this period a lot of progress was made in water network design, computers, hygiene of drinking water, etc. Furthermore, these specifications, do not follow international standards and practices, as opposed to the institutional framework for water quality for human consumption, since they do not refer to the obligation of creating the operation model of the WDS and make no reference whatsoever concerning the investigation of system reliability, nor in examining the characteristics of the network (geometric form, water intake locations, hours of pumping, etc.) to ensure good drinking water quality.

Regarding human consumption water quality Drinking Water Directive 98/83/EC (DWD) is incorporated in national law by virtue of Joint Ministerial Decisions (JMD) 2600/21-06-2001 and 38295/22-03-2007. The above legislation instruments follow a parametric approach that determines the standards for the most common substances that can be found in drinking water and are based on the examination and follow-up of the conformity in the numerical models of quality of water based on the samples that they are taken with a specific process (frequency, places of sampling etc.) The inspections aim at ensuring that the network water is safe and wholesome. These instruments establish three levels of control that is to say: (a) check monitoring, the aim of which is to provide, in a regular basis, information on the organoleptic and microbiological quality of the water supplied for human consumption and information on the effectiveness of drinking water treatment (particularly of disinfection), where it is used, in order to determine whether or not water intended for human consumption complies with the relevant parametric values laid down in DWD, (b) the audit monitoring, the aim of which is to provide the information necessary to determine whether or not all of the DWD's parametric values are being complied with and (c) the additional monitoring, which is realized in special cases for specific pathogenic bacteria and micro-organisms.

However, even though the Greek legislation in force clearly defines the quality limits of drinking water and the way of inspection, in practice there are a lot of shortcomings in its application, due to: (a) lack of suitable organization and personnel of the water supply undertakings, (b) shortage of economic resources for the confrontation of expenses for water treatment and inspection and maintenance of water supply systems, (c) lack of alternative water supply sources, which forces the drinking water companies (Municipal Water and Sewerage Companies etc.) to supply the network with water which does not always meet the standards in force, (d) lack of infrastructures for the required samplings and analyses according to the national and international models etc.

With Administrative Instructions (Circular) /39511/06-04-2005 of Ministry of Health and Social Solidarity the places of sampling and laboratory tests are specified at predetermined points of the distribution network from the water intake to the consumer faucet according to the corresponding follow-up program in which the sampling points should be reported. More specifically, for the sampling points it specifies that a percentage should be from stationary places (pump rooms, storage tanks and places with preexisting problems) and the rests should be taken accidentally from busy points (hospitals, schools, apartments etc.) and places with a high probability of pollution danger (branches, vacuum points etc.). The Joint Minesterial Decision (JMD) 5673/1958 establishes: (a) as basic method of disinfection of drinking water the chlorination (Article 2 (1)), (b) the imported quantity of chlorine in the network should be such that the residual of free chlorine is 0.20 mg/L (Article 3 (1)) and (c) the chlorination should be carried out so that its action is at least 20min from its introduction in the network till the uptake of water from the consumer (Article 3 (4)). It is marked that the newers JMD 2600/21-06-2001 and 38295/22-03-2007 does not specify limits for the residue of free chlorine.

3. HYDROSIM SOFTWARE

Using a well-designed hydraulic and water quality model may be an important approach for simulation of hydraulic and dynamic behavior of water quality for all elements of a water network, since the qualitative parameters of water in a drinking water network are time dependent, since water supply and pressures are constantly changing. Thus, the only way to examine in advance and regulate with safety these parameters is the simulation of the water quality of the network using dynamic models (Liou and Kroon 1987; Clark et al. 1993; Rossman et al .1993; Boulos et al.1995; Islam and Chaudry 1998; Fernades 2002). The use of these models in a real WDS makes it possible to predict the concentrations of disinfectant substances in each point. In this work HydroSim (Vantas 2007) was applied, which has developed in a Visual Studio. NET 2003 and for the calculations the source code of EPANET2 version 2.00.10 (EPANET 2 Programmer's Toolkit) was incorporated, which is written in ANSI C, was developed by USEPA and is software whose source code is distributed free (public domain software) (Rossman 2000). In EPANET2 for hydraulic calculations followed the method of Todini and Pilati (1987), while the analysis of water quality, method TDM (Lagrangian Time - Driven Method) (Liou and Kroon 1987). HydroSim performes dynamic simulation of hydraulic behavior of water and change the quality of a pipeline under pressure, which may consist of pipes, junctions, pumps, valves, valves and storage tanks or locations without water to limit the size or the complexity of the network. HydroSim simulates, also, the flow of water in each pipe, the pressure at each node, the amount of water in tanks and qualitative characteristics (age, origin and concentration of substances) for a predetermined period of time and steps.

4. APPLICATION

To investigate the effect of the design of a water supply network on the quality of drinking water, the network of Figure 1 was used which in the past was studied by Clark et al. (1995), Vasconcelos et al. (1997) and it is used as an sample problem for the software EPANET (Rossman 2000). This network has a very oblong shape, consisting of 92 nodes, 2 water supplies (river and lake), 3 tanks, 2 pumping stations, 117 pipelines and should provide at least 3 atm water pressure. In the network the consumption was considered to vary with time periodically during the day. For most nodes the consumption of water was considered to be for domestic use. As model of daily consumption was considered the model of a typical Greek city (Lamia) (Vantas 2007).

The Greek legislation in force does not specify maximum and typical values for the residual chlorine, but indicates that its value should be such that no problems should exist, a concentration of chlorine equal to 0. 20 mg / L was selected at water entry points and at least 0.05 mg/L residual chlorine (NWQMS 2004), within the network, in order to achieve disinfection. The Kinematic model chosen was first-order with a rate coefficient of K_b = - 0.5 hr^{-1} and was assumed that no reactions take place in the pipes, so the concentration of residual chlorine is written (Rossman

2000): $C = C_o \exp(-0.5\ t)$, where C = concentration [M/L^3] at time t [T], C_o = concentration [M/L^3] at time t_o. Mixing was considered to take place instantaneously and completely in the storage tank (full mixing model) (Rossman et al. 2003). The time step for hydraulic solution was 1 hr and for simulating the water quality was 5 min.

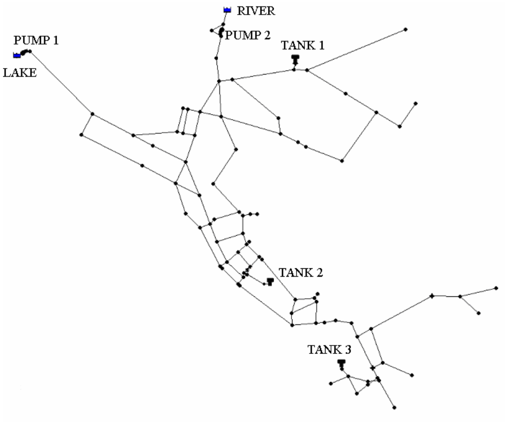


Figure 1. Network schematic

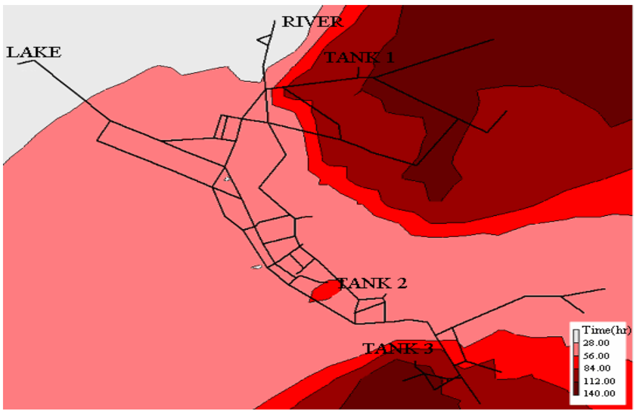
4.1 Regulation of initial chlorine dose at the water entry points

From the simulation of the network of Figure 1, it was found that it works without problems from a hydraulic point of view. In order to investigate the effects of the initial dose of chlorine to the water entry points to the system (Pump 1 and Pump 2) and the age of residual chlorine at the ends of the network, successive simulations were carried out for different initial doses. Residual chlorine (Table 1) at the ends of the network and the age of the water in the network and in the storage tanks were determined (Figure 2)

Table 1.Initial and residual chlorine

Initial chlorine (mg/L)	0.2	0.3	0.4	0.45	0.50
Minimum chlorine residual (mg/L)	0.02	0.03	0.04	0.05	0.06

It can be deduced from Table 1 that for a minimum value 0.05 mg / L residual chlorine at the ends of the network the initial dose of chlorine at entry points of the network has to be 0.45 mg / L which is almost twice the value of 0.20 mg / L set as the maximum permissible limit. On the other hand if the initial dose is 0.20 mg / L, then the minimum value in residual chlorine is 0.01 mg / L or 5 times less than the minimum allowable. Figure 2 shows that the water remains in the network long enough and particularly there are areas (dark brown) in which the age of the water exceeds 7 days.



Σχήμα 2. Values of water age in the network under examination

The substantial large values of the age of the water in the network are due to the long time of storage in the water tanks. The minimum and maximum values observed for the age of water in the tanks after 1000 hr time of simulation, is for the Tank 1 from 2.9 to 4.6 days, for the Tank 2 and Tank 3 from 1.0 to 3.1 days and 2.5 to 5.3 days, respectively. Note that the large resident time of water in tanks degrades water quality, because it favours the creation of disinfection by-products and does not allow retention of residual chlorine at sufficient levels for adequate disinfection.

4.2 Possible solutions to the problems

In order to maintain the residual chlorine within the permissible limits 0.05-0.20 mg / L and taking into account the specific characteristics of the network, such as the oblong shape, the location and number of tanks, the locations of water intakes and the number and the hours of pumping operation we should to reduce: (a) the age of water in tanks and in the network and (b) the excessive chlorination.

a. *Water age reduction in the tanks and the network*

To confront with this problem, different maximum water levels (MWL) were given in Tank 2 for which Pump 2 stops to operate and the age of the water was calculated in all three tanks (Figure 3). Observing Figure 3 we can see that the MWL in the Tank 2 for which the water in all three tanks have the lowest age is 3.75 m. Comparing the age of water obtained for the three tanks for water level 3.75 m at Tank 2 regarding to an original water level of 6 m, it was found that reduces the age of the water by 21%, 48% and 38% for tanks 1, 2 and 3 respectively and therefore the initial choice of a water level of 6 m in the Tank 2 was the worst as far as the age of water in tanks.

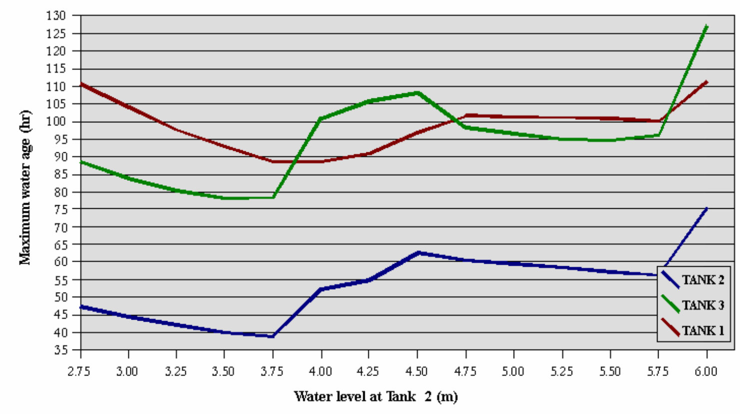


Figure 3. Water age in Tanks 1, 2, 3 as a function of water level in Tank 2.

Then the operation of Pump 1 (15hr) remained stable, but we changed the start time from 0.00 am, which was the original design, to 3.00 am and then to 6.00 am. It was found that changes to the start time of pump 1 have no influence on water age in the tanks.

In a similar way for different values of MWL in Tank 1 and M.W.L of 3.75 m in Tank 2 (previous case) the age of water was determined in the other tanks and concluded that when MWL in Tank 1: (a) is from 8 to 10 m, age does not affect the water in any of the tanks, (b) is less than 8 m, the age of water in the Tank 1 increases rapidly and for values <3 m water is effectively stationary (too many years in storage tank), (c) is from 6 to 8 m age in the water Tank3 increases up to 140 hr and lower prices of M.W.L stabilize it at 100 hr. Finally removing Tank1 shows that the age of the water in tanks 2 and 3 is 24 and 96 hr respectively.

Then M.W.L was held constant in Tanks 1 and 2 at 10 and 3.75 m (previous cases) respectively, and the age of the water was determined in the tanks for various values of MWL of Tank3. It was found that when MWL in the Tank3: (a) is from 7 to 12 m, no changes occur in the age of water in all tanks, (b) is from 4 to 7 m, the age of the water increases rapidly in the Tank3 and for values less than 4 m the water in Tank3 is practically stationary and (c) varies throughout the range of the above values, the age of the water in tanks 1 and 2 remains constant. Finally, removing Tank3 shows that the age of the water tanks1 and 2 are 93 and 38 hr respectively

Apart from the above cases the following cases were examined briefly: Case I - Elimination of Tank 1 and Tank 2: Significant reduction of the water age of Tank 2 (24 hr), and at the ends of the network (41 hr). Case II - Increase of the volume of Tank 2: The alleged removal of Tank 1 and Tank 3 in which total volume of water stored is 7.030 m^3 means that to restore the balance of water we should increase the volume of water stored in the Tank 2 from 4.910 m^3 to 11.940 m^3. Choosing a MWL in Tank 2 equal to 3.75 m causes a significant reduction of the age of water in this tank (34 hr) and at the ends of the network (41 hr).

b, Reduction of excessive chlorination:

The following cases were examined for better chlorination of the system:
(a) Regulating of Pump 2 so MWL at Tank 2 is 3.75m: It was assumed that the introduction of chlorine to the system is to pump stations 1 and 2 and the initial dose of chlorine is 0.20, 0.25 and 0.30 mg / L. It was found that the residual chlorine at the ends of the network is 0.03, 0.05 and 0.07 mg / L respectively. Therefore, to achieve a minimum residual chlorine of 0.05 mg / L to 0.25 mg / L of chlorine should be added to the network head chloride, which is more than the permitted (0.20 mg / L), which will affect consumers who are in the region of water intake and pump stations 1 and 2. (b) Adding 0.20 mg / L of chlorine in pumping stations 1 and 2 and 0.15 mg / L in Tank1 and Tank 2. .This case was found to produce allowed residual chlorine levels (0.05 and 0.20 mg / L) (Figure 4). (c)Removal of Tank1 and Tank 3 and proportional increase of the volume of water tank2 in order to meet the total water volume stored and chlorine input to the network in positions of pumps1and 2 in a quantity of 0.20 mg / L. It appears that the amount of chlorine throughout the network is within the allowable limits (0.05 - 0.20 mg / L) (Figure 5).

Although several assumptions and simplifications for the network under examination were made it was found to have a fairly complex operation and the results of the changes that were made could not be predicted from the beginning. It is obvious that the process described refers to the design stage of a water supply network and after its construction the process should be repeated for the calibration of the parameters. .

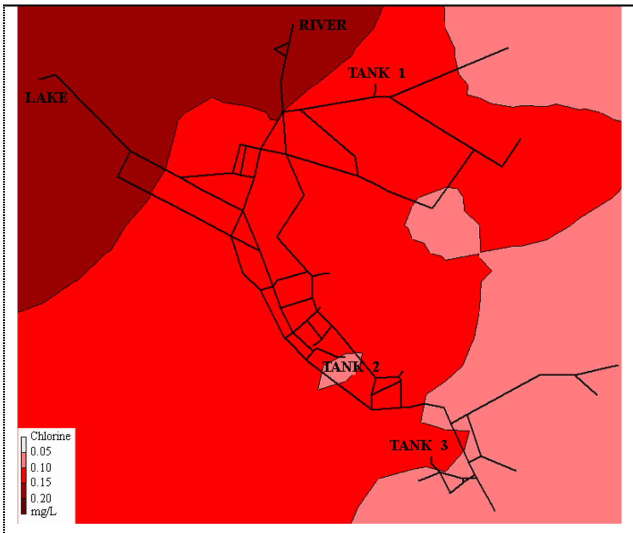
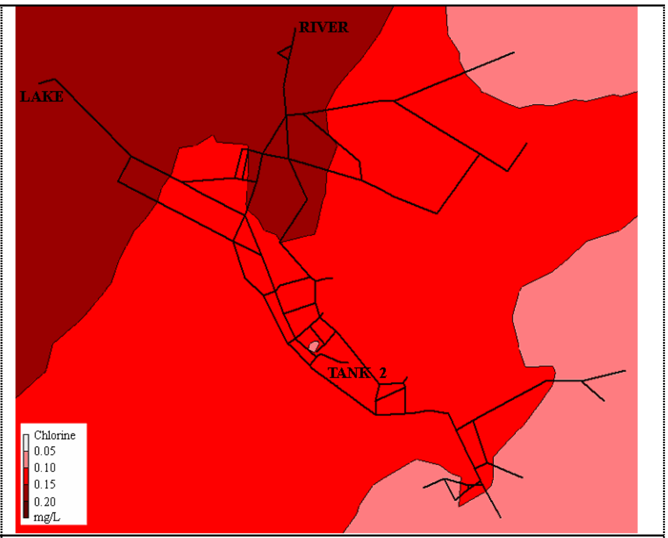


Figure 4. Residual chlorine for an initial dose of 0.20 mg/L in Pump2 and Tank 1 and Tank3



Σχήμα 5 Residual chlorine for an initial dose 0,20 mg/L in Pump 2 and in and Tank 1 and Tank 3 and icrease of the volume storage of Tank 2

5. CONCLUSIONS

Models that predict water quality in distribution networks can ensure safe lifelong basis consumption of drinking water at the point of consumption with continuous monitoring of the water quality and simultaneous regulation of disinfection. The use of models for simulation of water quality can be used to: (a) to assist water agencies with limited funds to manage their water networks. (b) To identify causes of problems in water quality and find managerial solutions that can be easily employed (regulation of pumping operation, setting the level of tanks, etc.) and thus have low cost. (c) Reduce disinfection by-products by reducing the age of the water in network and minimize the use of disinfectants without further pre-treatment of the water to remove organic substances. (d) Create emergency scenarios, such as contamination of the network, and investigate the optimal treatment.

It was found that for the optimum water disinfection of a drinking water network we should :(a) Minimize the initial dose of chlorine. (b) Reduce as much as possible the age of the water in the network and tanks. (c) Make appropriate choices for the positions of chlorination equipment, in order to achieve reduction of the initial dose at the head of the network, uniform distribution of residual chlorine concentration and minimum use of disinfectants. (d) Regulate the operation of pumps (duration, starting and stopping times) and carefully determine the active volume of the tanks (to avoid or minimize water stagnation in the tanks).

As far as Greece is concerned the main problem is the absence of technical specifications for the creation of models for new or existing drinking water networks, since the Presidential Decree 696/74 does not contain any specifications. It is proposed, therefore, to adopt new technical standards for studies concerning: (a) new drinking water networks (b) expansion of existing networks and (c) reviewing of existing networks, taking into account the progress of science in water network design, computers, hygiene of drinking water, GIS etc. These standards should, together with the hydraulic study of the system, provide a simulation study of water quality, disinfectants substances, age of the water in the network and tanks for the different consumption conditions at the beginning and at the end of life of the project, but also at intermediate intervals (eg every ten years) and finally a study of the reliability of the network (pipelines, pumping stations, etc.).

While the existing institutional framework for the quality of drinking water is considered generally satisfactory we have the opinion that it should: (a) Increase the number of unwanted substances and provide parametric values for them since the list of priority substances in Decision 2455 / 2001/EC contains 24 new toxic substances. (b) Establish maximum and minimum concentration of residual chlorine in a water network and avoid the use of the term "no problems" which is vague. Finally, it is proposed that the responsible stakeholders (Municipalities, D.E.Y.A. etc.) see after the creation of models for their networks connected with GIS, as experience has shown that several D.E.Y.A. in our country, given the age the networks, do not know the exact geometric and hydraulic characteristics of their networks and therefore face different management problems.

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