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Using the Set Point Concept to Allow Water Distribution System Skeletonization Preserving Water Quality Constraints

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Abstract

Water distribution networks were included in the catalogue of critical infrastructures by different institutions as the European Council. One of the vulnerabilities of a water distribution networks consists of the contamination due to accidental or provoked events. Therefore, it is increasingly common to develop water quality models which allow the study of these threats. Many hydraulic models use algorithms with a high computational cost. Therefore, any strategy to accelerate these algorithms is an important contribution to the problem. This paper proposes a method to simplify branched areas of the network without losing information regarding water quality.

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Keywords: Water Quality Model; Skeletonization; Optimization

1. Introduction

For several years there is a growing concern about the state of the water supplied to the population. Once the water has been disinfected and drinkable, its quality deteriorates over time. That is, the longer it takes the water to reach the point of consumption, the worse quality. Machell and Boxall [1] confirm this statement through unperturbed flow routes within a real network.

Following the attacks that took place in New York (Sept. 11, 2001), Madrid (March 11, 2004,) and London (July 7, 2005) this concern increased further, including security against terrorist attacks in the operational protocols. Different countries adopted regulations to consider these attacks. This is the case of the Directive 2008/114/EC in the

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European Union [2], the National Infrastructure Protection Plan in the United States [3] or more recently the Regulation for Protection of Critical Infrastructures in Spain [4]. In all these cases, measures and procedures for the identification and designation of critical infrastructures were established.

The term "critical infrastructure" refers to an asset, system or part of it which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in the European Union as a result of the failure to maintain those functions [2]. All aforementioned regulations include water infrastructure (both drinking water and wastewater) in the catalogue of critical infrastructures.

One of the vulnerabilities of a water supply network is the quality of water supplied. Furthermore, there is a possibility that some event, accidental or provoked, makes the supplied water be unfit for human consumption. Therefore, it is increasingly common the usage of water quality models as well as the inclusion of water quality constraints in the project and rehabilitation protocols of water distribution networks. As is well known, the problems associated with networks design and rehabilitation are often solved by algorithms that seek for economic optimization of the works without sacrificing meet all constraints. This becomes the problem complex the use of heuristic, trial and error algorithms. These algorithms test multiple solutions and combine them with ranking, improving, and evolving methods. All these algorithms have as a common feature a high computational cost in terms of hours of simulation. Therefore, any strategy to accelerate these algorithms is an important contribution to the problem.

This work proposes a method for simplifying sectors of water supply network with branched or assimilated layout in order to trace their behavior regarding water quality in the most unfavorable conditions arise.

2. Methodology

Early studies of water quality in water distribution systems were limited to determining steady state conditions. For steady state, implicit methods that require matrix calculations for solving equations were used [5]. Subsequently, Boulos and Altman [6] proposed an explicit method for solving these same equations in steady state and non- reactive substances based on oriented graphs. As there was no reaction, it was not necessary to consider the effect of the reaction in the calculation, which is the case of fluorine, mixing, precedence and residence time models. Recently, Chung et al. [7] have extended the study of Boulos and Altman to include the possibility of chemical reactions that suffers a disinfectant within the water.

Since the emergence of EPANET [8], the use of software to complete the hydraulic calculation of water quality has been increasing. In these programs, dynamic water quality models are included. Thus, in the first version of EPANET Rossman et al [9] proposed a discrete volume element method for water quality modeling. Subsequently, Rossman and Boulos [10] made a comparative study in which they decided to change to the Lagrange time-driven method (LTDM). From this comparison were two important and conflicting conclusions: this method is more versatile for calculating a quality model, but requires more memory usage and can be potentially slower. This is due to the need to divide each line into smaller portions so that the reverse flow in a pipe may be reflected in the calculation of the quality. If water quality models are integrated into design programs (for example, letting the quality be a constraint) or into real time systems (RTC), the computation time may become even more important than numerical accuracy. In this case, it may be convenient to have a reliable, robust and fast water quality model.

In water system models, simplifying the network without losing representativeness in neither the hydraulic model nor quality model becomes especially interesting [11]. It is necessary to obtain an explicit and unique relationship between one point and another network so that if the simplification occurs, knowing the value of a quality parameter at one point, it will be possible to know the same parameter at the other.

This is the base of the set point curve concept. Set point curve can be defined as the minimum head or pressure required at a supplying node to ensure sufficient residual pressure at the worst consumption node in the network. This definition may be extended to the allowable concentration of pollutant at the supplying node so that a certain concentration threshold at any point in the network is not exceeded. This will allow performing the optimization of a project including minimum values of the chlorine concentration, maximum residence time and even maximum values of a harmful agent in the network. In the latter application, it will be possible to establish reaction times and possible effects over population.

The main problem lies in the quality model. This paper has taken EPANET hydraulic model as reference. The main difference between the hydraulic model and the quality relays on the treatment that EPANET makes of the time domain. The hydraulic calculation makes a quasi-static model, in which for each time interval the boundary conditions remain constants for later update before the next calculation. Thus, for most cases, the results are practically insensitive to the time interval used. However, in the case of water quality model EPANET makes a dynamic model in which the results depend on both the current and the previous time instant. In this case, the time step becomes very important and even has a limitation. The time needed for the water to go through the shortest pipe has to be shorter than the time step used by the water quality model. This makes the time scales are not equal. EPANET calculation supports looped networks which pipes with flow in both directions and the water quality model should allow these phenomena. Therefore, EPANET uses a Lagrange time-driven method. In this model, the concentration depends of the boundary conditions in an undetermined number of previous time intervals, making it impossible to use in the simplification.

This paper proposes replacing the LTDM with a plug flow based algorithm in pipes, simplifying the calculation of quality in exchange for imposing one direction flow in them. The latter is often a reality, especially when the objective is to simplify parts of the network with smaller pipes.

3. Water Quality Model

Zoppou [12] makes an excellent review of the equations that are involved in a quality model, as well as any of the methods used for resolution. Thus, the main equation, from which all others derive, is the equation of the advection and diffusion processes:

$$\frac{\partial}{\partial t}(A \cdot c) + \frac{\partial}{\partial x}(Q \cdot c) = \frac{\partial}{\partial x}\left(A \cdot D \cdot \frac{\partial c}{\partial x} \right) \pm S(x,t,c) \tag{1}$$

In the above equation, D is the molecular diffusivity and $S\ (x, t, c)$ a term representing the sources and sinks of the selected substance. In general, it is common to neglect the effect of diffusivity compared with the transport, which leads to:

$$\frac{\partial}{\partial t}(A \cdot c) + \frac{\partial}{\partial x}(Q \cdot c) = \pm S(x,t,c) \tag{2}$$

For a pipe and a time interval, the flow rate and its volume remain constant:

$$\frac{\partial c}{\partial t} + v\frac{\partial c}{\partial x} = \pm S(x,t,c) \tag{3}$$

In junction nodes, without storage, complete mixing behavior with no retention time is assumed. Thus, the above equation is reduced to a mass balance:

$$\frac{\partial}{\partial x}(Q \cdot c) = \pm S(x,t,c) \tag{4}$$

That is:

$$\sum_{j \in E_D} Q_j c_j + S(t) = \sum_{k \in S_D} Q_k c \tag{5}$$

As a result we obtain:

$$c = \frac{\sum_{j \in E_D} Q_j c_j + S(t)}{\sum_{k \in S_D} Q_k} \tag{6}$$

In equations (4) to (6), let E_D represent all the water lines supplying the node and S_D the pipes receiving from the node. Finally, as storage nodes present some residence time, they include a reaction term in the equation (5):

$$\frac{\partial}{\partial t}(\forall \cdot c) + \sum_{j \in E_D} Q_j c_j + S(t) = \sum_{k \in S_D} Q_k c \tag{7}$$

Once the hydraulic model has been solved, the node equations become explicit since concentrations in the previous instant are known. The problem focuses on the equations affecting transport in pipelines. If a pipe is treated as a linear reactor, there are two completely opposing reaction models. The complete mixing reactor model and the plug flow model. The complete mixing model assumes that pipes behave as a tank with a single inflow pipe (flow from the initial node) and an outflow pipe (the final node). In contrast, the plug flow model admits that there is no mixing between the different sections of the pipe.

4. Case Study

The proposed method has been successfully used in the D-Town network (see Fig. 1). This network is based on the Battle of the Water Network (BWN-II) [13]. BWN-II is an exercise that began in 1985 in the Water Distribution System Analysis Symposium, organized by ASCE Hydraulic Congress. For the WDSA 2012, the objective of the Battle consisted of optimizing the network taking into account economic, energy and water quality criteria. While this is an imaginary network, data are actual characteristics, both in terms of the precision and its reliability. In this case, restrictions affected the residence time. Hence, the source and sink terms, *S (x, t, c)* were limited to the calculation of the residence time:

$$\frac{\partial c}{\partial t} + v \frac{\partial c}{\partial x} = K \tag{8}$$

There was a need for simplifying the network and the proposed method was used. The network was reduced almost to half the original size. In Fig. 1 the network after simplification is presented, together with the detail of one of the parts whose results are studied in this paper.

4.1. Complete Mixing Model

The solution based on complete mixed reactor consists of two phases: mixing and reaction. First, we proceed to mix the flow from the initial node with the water within the pipe:

$$Q(t) \cdot \Delta t \cdot c_{IN}(t) + \left[A \cdot L - Q(t) \cdot \Delta t\right] c(t) = A \cdot L \cdot c'(t) \tag{9}$$

When complete mixing throughout the pipe is done, equation (8) will be in a given time step:

$$\frac{\partial c}{\partial x}=0 \quad \Rightarrow \quad \frac{\partial c}{\partial t}=K \quad \Rightarrow \quad c(t+\Delta t)=c'(t)+K\cdot\Delta t \tag{10}$$

In equation (10), K is a unit conversion factor and c an intermediate calculation variable that will not be stored. Thus, combining (9) and (10) is:

$$c(t+\Delta t)=c(t)+N\cdot\Delta t\cdot m(t)\cdot\left[c_{IN}(t)-c(t)\right]+K\cdot\Delta t \tag{11}$$

In the above equation, $m(t)$ is the coefficient of the demand pattern coefficient of the flow line (provided by the hydraulic model) and N the number of renewals of the volume of the pipe (inverse of the average residence time). This is calculated as the ratio between the volume and the average flow of the pipe in any time interval.

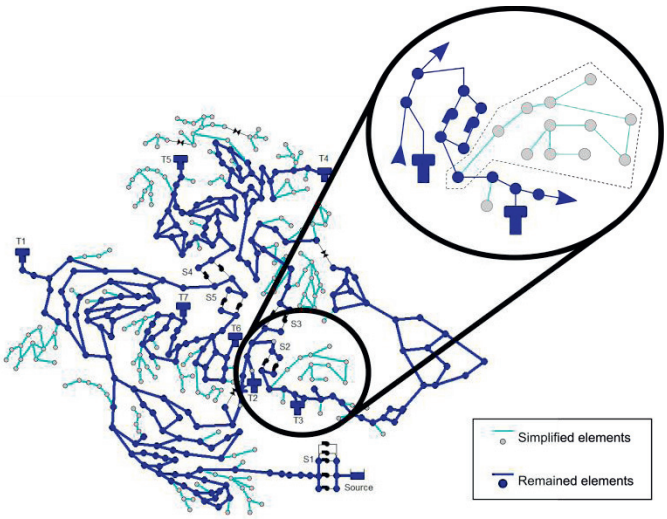

Fig. 1. D-Town Network (simplified pipes are shown in light blue).

4.2. Plug Flow Model

In the plug flow model, it is assumed that there is little change in the concentration in a given section of the pipe (transversal direction), but the will along the same (longitudinal direction):

$$\frac{\partial c}{\partial t}=0 \quad \Rightarrow \quad v\frac{\partial c}{\partial x}=K \quad \Rightarrow \quad c(L)=c(0)+K\cdot\frac{L}{v(t)} \tag{12}$$

Considering the travel time along the pipe, the water leaving the pipe through its end node entered the pipe at a previous time with a concentration given by:

$$c(L,t')=c(0,t)+K\cdot\frac{L}{v(t)} \tag{13}$$

where:

$$t' = t + \frac{L}{v(t)} \tag{14}$$

4.3. Results

Because of the relative complexity of the network and the algorithms used for optimization, both need a reduction in the number of variables to be optimized, the size of the network, and the time being used in each simulation. Hence, different simplification tools and different schemes for calculating the quality were tested. Complete mixing model smoothed the peak concentrations due to the mixing effect with flows with lower concentration. This was against the objective since it underestimated the effect of a potential contamination effect.

On the other hand, the plug flow, quasi-static model slightly anticipated peak quality values but the values for concentration were found to be virtually identical to those obtained by EPANET. For this reason, plug flow model was chosen as the tool for verifying the quality constraints. Fig. 2 shows the comparison of the results in one of the nodes that were simplified, corresponding with the simplified pipes highlighted in Fig. 1.

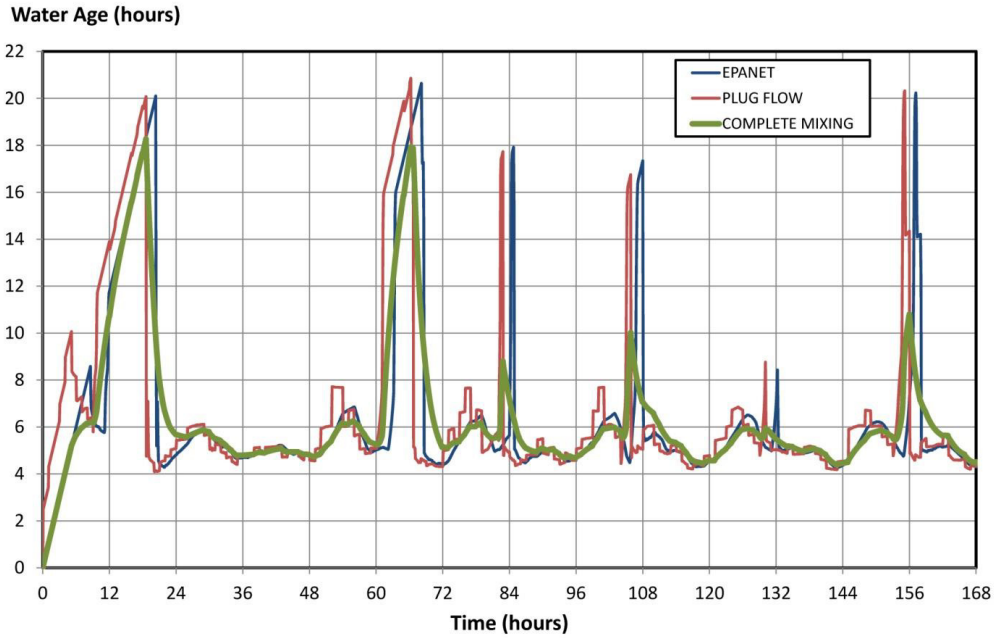

Fig. 2. Comparison among the three models studied: EPANET, Complete Mixing and Plug Flow.

5. Conclusions

A method to express unique and explicitly the concentration of a pollutant at a node that receives water from another was presented. The main advantage of this method consists of the possibility to reverse the calculation, that is, from a desired concentration at a point, determine the quality conditions necessary in another node to ensure such a concentration. The method is based on an explicit function, which accelerates calculations and hence can be included in optimization algorithms without penalizing the computational cost.

The method has the limitation that the pipes must be topologically ordered, i.e., the flow direction of flow through a pipe must be defined. This fact limits its application to branched areas of the network and overridden as water quality method for general purpose. The results have been successfully tested against the model built by EPANET and gives practically identical values for quality, although slightly offset in time.

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