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Modelling water quality in drinking water distribution networks from real-time direction data

S. Nazarovs, S. Dejus, and T. Juhna

Riga Technical University, Riga, Latvia

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Correspondence to: S. Nazarovs (nazarow@yahoo.com)

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Abstract

Modelling of contamination spread and location of contamination source in a water distribution network is an important task. The paper considers applicability of real-time flow direction data based model for contaminant transport for a distribution network of a city. Simulations of several contamination scenarios are made to evaluate necessary number of flow direction sensors. It is found that for a model, containing major pipes of Riga distribution system, sensor number decrease from 927 to 207 results in average 20 % increase of simulated contaminated length of pipes. Simulation data suggest that optimal number of sensors for Riga model is around 200.

1 Introduction

Development of comprehensive tools for contaminant transport simulation in water distribution network is a subject of scientific and engineering interest. A lot of work has already been done in this field by various authors, starting in the early 80's (Ostfeld, 2005), and research is still going on.

Research work in the field of contamination transport simulation is aimed in three main directions:

- Development of equations governing transport of contaminating agents, interactions with walls and reactions.
- Development of methods of solving the equations.
- Development of practical network models capable of predicting which parts of network can be affected once the contamination is spotted at some point of the network.

Many authors have focused their efforts on development of comprehensive mathematical models for various types of contaminants. There are studies carried out with the

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goal of modelling chlorine decay (Rossman et al., 1994; Clark et al., 1995; Ozdemir and Ger, 1999; Al-Omari and Chaudhry, 2001; Ozdemir and Ucak, 2002) and trihalomethanes formation (Clark, 1998; Elshorbagy et al., 2000; Li and Zhao, 2005) in water distribution networks. There is also much work done in the field of modelling bacteria spread and regrowth in water distribution systems. Digiano and Zhang (2004) developed a mechanistic model for bacterial regrowth. A mechanistic model with higher distinction between attached and bulk bacteria was also proposed by Munavalli and Kumar (2005). Mechanistic models for bacterial or chemical contamination have a significant drawback. The models are based on equation of hydraulics, in other words a hydraulic model is used to calculate flows and pressure distribution in the system. Precise modelling of hydraulics requires accurate information about water demand in each node of a network. Although estimates of demand loads, based on population density and typical consumption patterns, can be made, these estimations may not be applicable at small timescale like hours and minutes. Actual demands may fluctuate significantly at such a small timescale. In case of contamination is detected in the system, fluctuations of demand patterns will be caused by issue of public health notices and directives in the first place. Therefore precise calculations of flow magnitude in pipes at given time moment may be a virtually impossible task. Errors in flow magnitude calculations will lead to errors in contamination spread simulation results.

Besner at al. (2005) offered a more practical approach to seeking of contamination source. The idea is to gather statistical data on distribution system operation such as valve closures, repairs, consumer complains, water quality measurements. In case of contamination incident gathered statistical data can be used to backtrack events that occurred in the system prior to contamination, and, hopefully, indicate the contamination source.

Another example of an attempt to develop a practical tool for contamination tracking and source seeking has been presented by Davidson and Bouchart (2005). The authors suggested that area that will be affected in case of contamination incident is determined primary by flow directions in pipes rather than flow magnitudes. So, if

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real-time data on flow directions are available then it is possible to construct a connectivity matrix. There is no need to estimate demand loads. Connectivity matrix shows if there is a feasible flowpath between two selected nodes. The matrix also allows to see all upstream and downstream nodes for any selected node. Therefore if contamination is detected in a node, the connectivity matrix can show all downstream nodes that may be affected. This does not necessary mean that all downstream nodes will be contaminated, but the possibility of contamination of these nodes cannot be ruled out. In addition, connectivity matrix may indicate all upstream nodes that might be the source of contamination. Construction of the connectivity matrix requires real-time flow direction data. Real-time flow direction data can be collected by using flow direction sensors. The proposed technique provides the worst-case scenario of possible contamination spread.

However the major drawback of the technique offered in the paper by Davidson et al. (2005) is that real-time data may be insufficient due to limited possibilities of flow sensor installation. Insufficient flow data may result in too large possible contamination spread pattern.

2 Objectives and methods

Davidson and Bouchart (2005) consider applicability of their proposed approach for a small subdivision of a municipal water distribution network rather than for a whole city. This paper presents an attempt to test applicability of the approach proposed by Davidson and Bouchart (2005) to a whole water distribution network of the city of Riga (Latvia). The Riga network provides drinking water to approximately 700 000 inhabitants. The distribution network is mainly supplied with water by three water treatment plants.

It is clear that if real-time data on flow directions are available, it is possible to determine affected area more precisely. However Riga network includes more than 7000 pipes and it is not sensible to install a flow direction sensor on each of them.

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Splitting the network into distribution management areas (DMA) may be one of possible solutions (Fig. 1). Each DMA has flow direction sensors on every pipe connecting it with other DMAs. There are now flow sensors inside the DMA. Optimal choice of DMA size is a crucial part. The size of DMAs determines precision of the model and costs of sensor installation. The smaller the DMA size is, the more precise determination of the affected area is possible. However smaller DMA size leads to higher installation costs.

In this paper an effort is made to determine optimal size of DMA and to choose optimal number of flow sensors for Riga distribution network as well as to find best locations for sensor.

The point of installing flow direction sensors on the pipes is to find out the affected area in case one of the water treatment plants (or any other junction) gets contaminated. Although each water treatment part supplies water to a particular region of the city, flow patterns may change significantly due to issue of public health notices. For example, if one of the water treatment plants gets contaminated, citizens in the area, the plant supplies water to, will be warned and advised not to drink tap water. Water consumption in the area drops so flow direction in some pipes will be reversed thus allowing contaminated water to enter the areas normally supplied by the two other water treatment plants. Pipes where flow reversal is possible due to reduced consumption because of day-night cycle or health notices are the most sensitive parts of the network that may affect evaluation of contamination spread. This is the part of the water distribution network where water might be supplied from different treatment plants. To be sure in which direction the contamination will spread the sensors should be installed on these sites.

A model of Riga water distribution network developed by Rubulis et al. (2010) was used for simulations. The model includes 927 pipes and 574 junctions. The total length of the pipes in the model is 538 km. There are not included 80 % of pipes with diameter smaller than 200 mm (Rubulis et al., 2010).

Locations of the sensors were chosen as follows. First, flow direction sensors were placed in the model to create several DMA areas. Then the placement of sensors was

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optimized. For example, there were several sites in the network where the sensors did not serve their purpose in an effective way because of very close location to each other. To minimize the number of sensors installed, several optimization methods were used. First, there were sites in the network where a link splits into 2 links with the same flow direction and sensors were installed on both new links. For the sake of optimization, the two sensors were removed and a new sensor was installed on the first link prior the splitting point (Fig. 2a). On sites where two consequent sensors were installed, the one that was closer to a treatment plant, was removed (Fig. 2b). It goes without saying that careful consideration should be made before each optimization step.

Effectiveness of several sensor installation configurations was evaluated by running simulations of 3 different contamination scenarios.

Scenario 1: water treatment plant "Daugava" that produces about 50 % of drinking water in Riga city gets contaminated. Scenario 2: one of water reservoirs of Riga city water distribution network gets contaminated. Scenario 3: random node of the water distribution network gets contaminated. Locations of contamination sources in the hydraulic model are shown in Fig. 3.

Model simulations were run for all scenarios. The software calculated total length of contaminated pipes for each scenario assuming a flow direction sensor is installed on every pipe. Then sensors were removed from certain pipes thus splitting the network into DMA. Splitting the network into DMA increases the total length of contaminated pipes, as the software considers a DMA to be completely contaminated once contamination gets into it.

3 Results

Simulations were made for several number of sensors. Case studies with 57, 67, 160, 185 and 207 sensors were considered. Total contaminated pipe length was calculated for each number of sensors for every scenario. The relationship between the number of sensors and total contaminated length for each scenario is represented in the chart

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(Fig. 4). Normalized data and average data for all three scenarios are presented in Fig. 5.

The simulation results suggest that optimal number of sensors for Riga network is around 200. Further increase in sensor number has little effect on simulated contamination length. For Riga model, installation of 207 sensors allows splitting the network into 25 DMA areas. As mentioned before, sites where water provided by different treatment plant meets, are of special interest (Fig. 6). There are 67 such sites in Riga model.

The suggested DMA pattern for Riga network is shown in Fig. 7. Pipes with sensors installed are designated with triangles and marked in blue.

The obtained results demonstrate that number of sensors can be significantly reduced without major decrease of simulation results accuracy. According to Fig. 5, total simulated contaminated length on average increases only by about 20 % if number of sensors is reduced from 927 to 207 thus more than four times cutting costs of installation and maintenance. Probably, the optimal number of sensors can be found for distribution networks of other cities too by running simulations of several contamination scenarios for different number of sensors.

It should be also mentioned that flow direction sensors are relatively cheap and do not need sophisticated signal conditioning circuits. These properties of flow direction sensors allow reduction of costs compared to volumetric flow sensors.

4 Conclusions

Advances in communications technologies and increasing calculation power of computers made it feasible to collect with practically meaningful frequency flow and pressure data from a water distribution network. Therefore it became possible to model contamination spread as well as perform source location on the basis of real-time data. Real-time data-based model enables rapid determination of possibly affected area in case of detection of contamination as well and estimation of source location. However

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water distribution network of a city may consist of hundreds or even a thousand of pipes so installation of a flow and pressure sensor on every pipe and annual maintenance of sensors may be a large financial burden. Splitting the network into distribution management area allows to reduce number of sensors and usage of flow direction sensors instead of volumetric or velocity sensors helps to reduce installation and maintenance costs. Estimations show that for a city of a size of Riga (around 700 000 citizens) network can be split into 25 DMA areas that requires about 200 flow direction sensors. Number of sensors can also be reduced by optimizing location of sensors.

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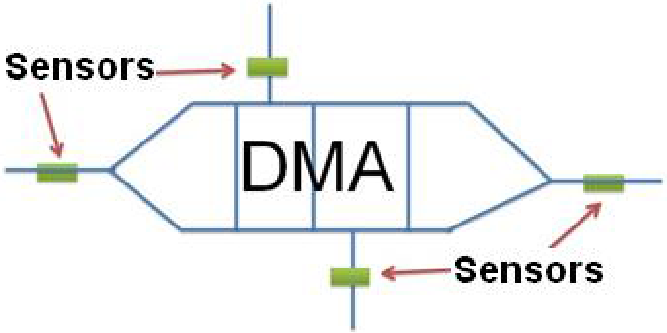

Fig. 1. DMA concept.

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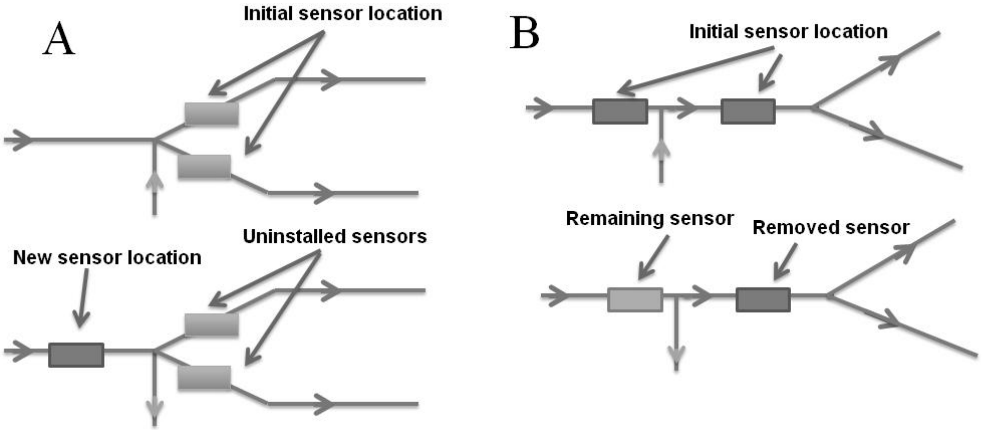

Fig. 2. Methods of optimization of number of sensors.

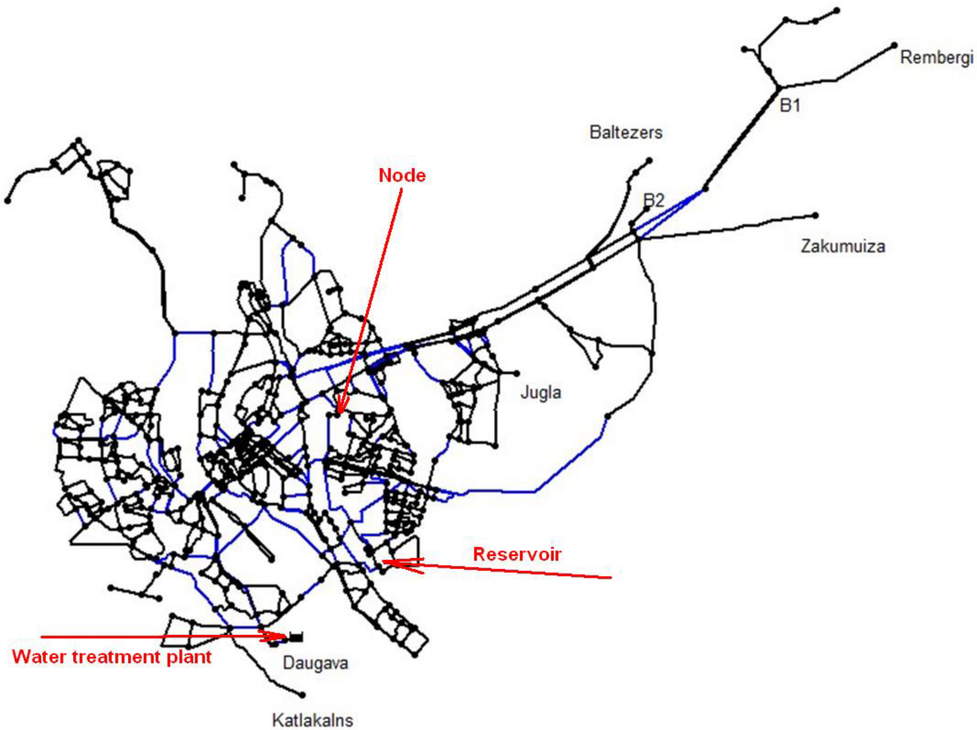

Fig. 3. Contamination sources for different scenarios.

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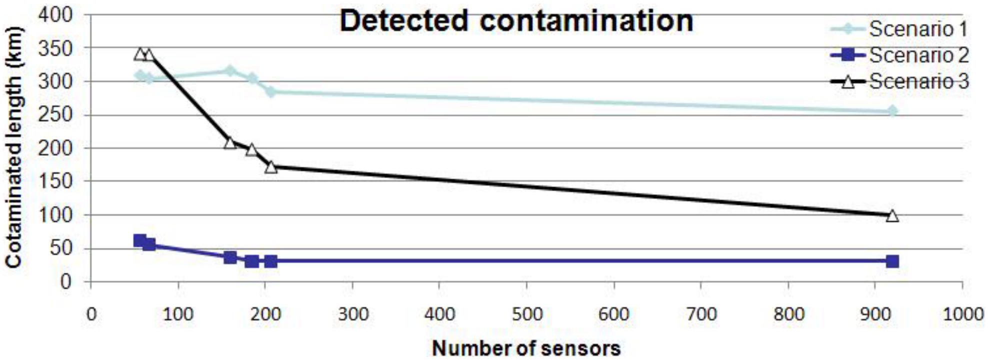

Fig. 4. Simulated contamination length for various numbers of sensors.

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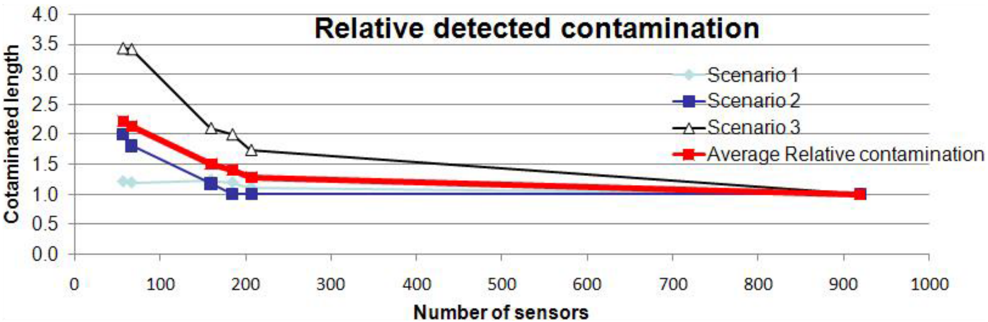

Fig. 5. Normalized contamination length for various numbers of sensors.

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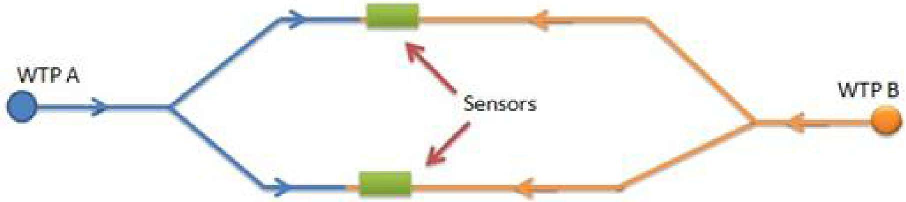

Fig. 6. "Collision" sites for water from different treatment plants.

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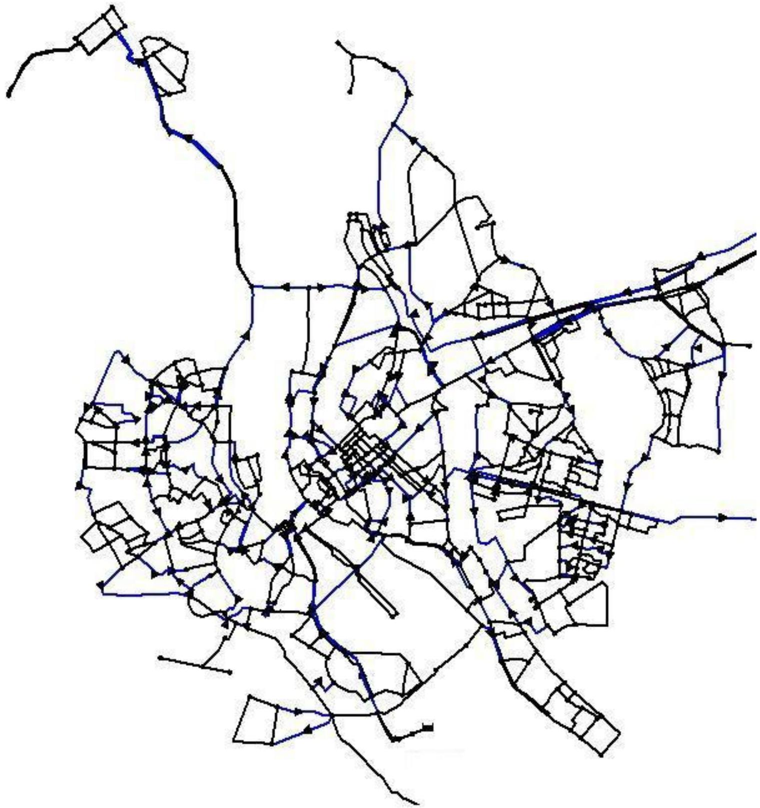

Fig. 7. Suggested DMA distribution at Riga water distribution network. Sensor installation sites shown in blue.