Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 70 (2014) 1441 – 1449

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

Prevention of discoloration events in water distribution systems

J. Rucka [a,*], J. Kovar [b]

[a] Brno University of Technology, Faculty of Civil Engineering, Zizkova 17, Brno 602 00, The Czech Republic
[b] Brno University of Technology, Faculty of Mechanical Engineering, Technicka 2896/2, Brno 616 69, The Czech Republic

Abstract

Mathematical modeling and simulation techniques represent powerful tools for optimizing the operation of drinking water supply networks. Water quality in the distribution systems is affected by the hydraulic regime in the network (Vreeburg, 2007). An incidental re-suspension of accumulated loose particles is the main cause of discoloration events in the network (Vreeburg, 2010). This article describes two technical tools that are being developed to help water utilities create and maintain programs for preventing the occurrence of discoloration events in their water distribution systems. The first of the two directly applicable tools is a portable measuring device that enables continuous measurement of hydraulic properties and water discoloration in the network. The other tool is a software application ADAM, which uses a non-data-hungry methodology based on a risk analysis approach and utilizes the author's previous experience with mathematical modeling of various water-supply networks. The probability of the presence of sediment accumulation in each pipe section in the network is estimated. Problems relating to uncertainty and poor input data quality are solved by the application of the FMEA/FMECA technique (Tuhovčák, Ručka, 2009). The analysis is performed using ADAM, the newly developed simulation software for hydraulic analysis of water supply networks. The tools presented in this paper have been developed under the framework of "Tools for prevention of water discoloration in water mains", the current national research project of the Technology Agency of the Czech Republic (registration number TA02020604), a brief outline of which is also presented in this paper.

Keywords: Water distribution system; discoloration; water quality; software; mathematical modelling; measurement

* Corresponding author. Tel.: +420-604794350; fax: +420-541147728.
E-mail address: rucka.j@fce.vutbr.cz

doi:10.1016/j.proeng.2014.02.159

1. Introduction

The issue of drinking water quality supplied by public water supply systems (WSS) has been at the forefront both in the Czech Republic (CR) and elsewhere. In recent years, the importance of not only water quality, but also the reliability of the distributed water quality has increasingly been recognized. This shift has been caused not only by legislative changes, but particularly by the changing attitude of drinking water consumers connected to the WSS, who perceive short-term negative fluctuations of water quality as less and less acceptable. This results in increasing number of customer complaints received by water companies. However, there are likely to be other reasons for this trend, such as the operating life of the water supply infrastructure across the CR, which is aging and has not been sufficiently renovated, and increasing prices of drinking water. Between 1994 and 2011, the price of drinking water charge in the CR increased on average from 0.38 EURO per cubic meter to 1.36 EURO per cubic meter (The Ministry of Agriculture of the Czech Republic, 2012).

The types of complaints received by water utilities broadly correspond with the findings of studies published abroad (Vreeburg, 2007). Majority of the complaints relate to cloudiness or water discoloration, whilst smaller percentage relates to insufficient water pressure. Whereas pressure management of the water supply networks is a relatively well-developed technical discipline with a series of proactive solutions, technical tools and means of problem solving, water quality optimization in water supply mains is a much more complex issue. There are many factors that affect the distributed water quality, for instance the hydraulic regime, distributed water composition or pipe material, but their impact on water quality has not yet been sufficiently quantified. Therefore, problems related to inadequate water quality in the supply network usually do not have simple solutions and require comprehensive approaches.

The trend in the customers' behavior described above is expected to become even more pronounced in the future. With this in mind, a new three-year research project has been initiated with the core objective of developing a preventative approach to the optimization of water quality in public water supply networks.

1.1 Research project TA02020604 – Tools for the prevention of water discoloration in water mains

The new three-year research project entitled "Tools for prevention of water discoloration in water mains" started in January 2012. The project is an applied research with the main aim to develop two specialized technical tools for the prevention of water discoloration events in water supply mains. The tools include a portable measurement device and a software application, which are described in detail below. The project is funded by the Technology Agency of the Czech Republic.

The research project coordinator is Brno University of Technology (BUT) in the Czech Republic, with a private company Provod as a partner. Provod are contributing financially and by providing further human resources. The project group also includes two major and one smaller water companies, which provide the case studies. The companies include Vsetín Waterworks, who manages 803km of water network, Brno Waterworks, who manage 1172km of water network, and Kateřinice Village with 9km of water network, respectively. The methodology and tools are being tested and verified using these three case studies chosen for their specific characteristics.

More information can be found on the project web pages www.vodabrno.cz, which are updated regularly and include the information in English.

1.2 Discoloration of drinking water in the Czech Republic

The legal requirements defining the tap water quality for public water use in the CR are based on the EU Drinking Water Directive 98/83/EC and are therefore similar to other EU countries. The Directive requires drinking water to be available not only in adequate quantity, but particularly in adequate quality. This means that the supplied drinking water has to have certain health standards, adequate taste and other properties including the level of discoloration. Czech legislation specifies the drinking water standard for discoloration at 5 NTU and 1 NTU for water treatment work outflow in case of surface water resources.

In the Czech Republic, the issue of discoloration has not yet been discussed frequently at scientific conferences. There are two reasons for this. Water companies are used to flush the water mains periodically as part of their routine maintenance set in their maintenance plan, which are not, however, based on any analysis such as the hydraulic analysis of water supply systems. Instead, they are based on the companies' empirical methods and experience of their staff.

Fig. 1 Case study Kateřinice – water main flushing

The presence, volume or thickness of sediment layer in the distribution network is not being monitored in routine water distribution processes. Therefore, the water companies base their management on the number of customer complaints that regard water quality, and this defines the frequency of the flushing. Water companies tend to manage the problem more frequently as a proactive measure if their supply areas experience periodic problems with water discoloration. Flushing of water mains is typically used to resolve the discoloration problems and is executed by opening the water hydrant and releasing water from the mains (Fig. 1). The volume and discharge of the flushed water is, however, not monitored during the process and the degree of discoloration is assessed visually only. No reports are produced to document the findings. Consequently, it is often not possible to audit the frequency of the past treatments. Water companies are neither obliged to inform the public or any institutional body about the discoloration incidents, nor to analyze the causes and impacts. A thorough investigation is carried out only for serious incidents with discoloration in the order of tens of NTU over a vast water supply area. These incidents are usually also negatively commented on by media. In most cases, there are no official statistical data or other detailed information. Water companies respond with considerable delay to discoloration events. There are neither any proactive measures implemented by water companies to help prevent inadequate discoloration, nor does the current legislation in the CR require them.

It is important to note that the analyzed water companies reported no major problems with discoloration incidents as they occur only in exceptional situations. This is caused by the physical circumstances under which the discoloration incidents arise, i.e. random events typically caused by an external intervention to the hydraulic regime of the network. Conventional municipal WSS have a typical daily and weekly hydraulic regime, which is at any moment in time of a day and in each pipe section of the network defined by its average, maximum and minimum flow and shearing stress, referred to as the demand pattern (Fig. 2).

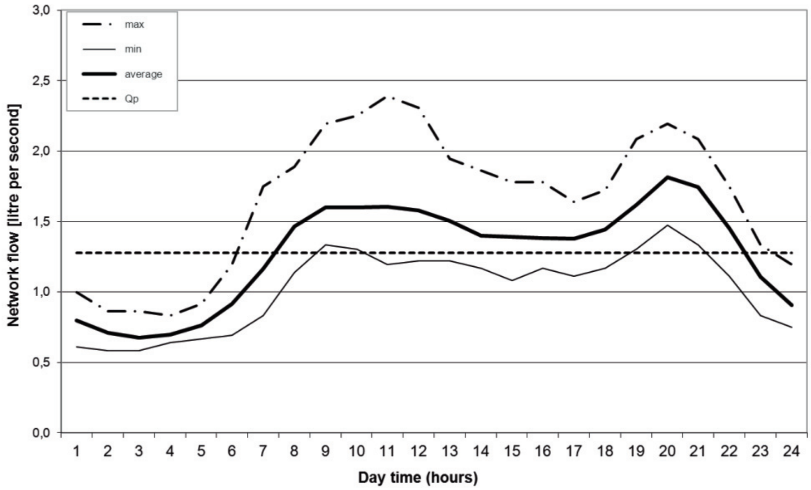

Fig. 2 Case study Kateřinice – demand pattern characteristic of the water supply system

In the timescale of several months, it is possible to consider the demand pattern nearly as constant (Fig. 3). The characteristic demand patterns of the water supply system are evaluated by applying statistical methods to flows measured continuously in a short time step for at least 3, preferably 4-5 months.

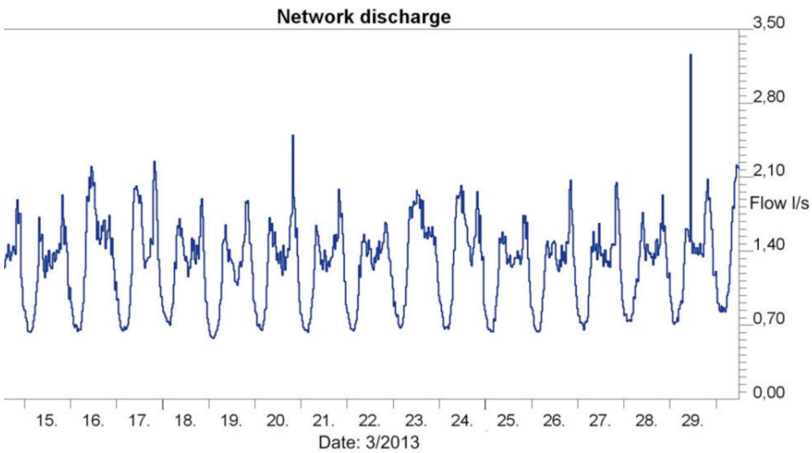

Fig. 3 Case study Kateřinice – long term network discharge monitoring

In some cases, the flow in the particular pipe section can increase and considerably exceed the typical maxima, which can result in re-suspension of accumulated sediments and the occurrence of a discoloration incident (Boxall, 2011; Husband, 2011; Vreeburg, 2010). The discoloration incident usually has a typical development: a rapid increase in water discoloration in a short space of time is followed by its slow decrease during several tenths of minutes until the pre-incident levels restored. Discoloration incidents can typically occur due to the following causes:

- Fire-fighting water demands,
- Testing of the hydraulic capacity of fire hydrants,
- Manipulation with the valves in water supply network,
- Seasonal peak demands, e.g. filling the swimming pools during the first warm weather spells at the beginning of summer,
- Burst failure in the water supply network,
- Poorly managed flushing.

According to the results of long term water quality monitoring undertaken by the Czech Ministry of Health during the period of 2005 to 2007, drinking water distributed by the public water supply in the CR does not exceed the legal standard of 5 NTU in 99.5% of tested water samples. This implies that only 0.5% of all the samples exceeded the legal limit for discoloration. Therefore, increased water discoloration is perceived as a temporal event caused by unexpected events and external interventions in the water supply network rather than as a persistent problem.

2. Risk analysis of drinking water discoloration – FMECA technique

The methodology for risk analysis of discoloration events in the WSS, which has been implemented in the software tool ADAM, utilizes a semi-qualitative technique of risk analysis termed Failure Mode, Effects and Criticality Analysis – FMECA. The FMECA technique is described in detail in the technical IEC Standard 812: “Procedure for Failure Mode and Effects Analysis (FMEA)”. Its implementation in the water supply sector is detailed in the authors’ previous publications (e.g. Tuhovčák, Ručka, 2008).

A brief description of the analysis is as follows: the water supply network is split during the development of the mathematical model into short segments of pipes so that each segment can be evaluated by a set of defined risk factors in a two staged process. Firstly, these risk factors enable the estimation of the probability of presence of sediments in each segment. Subsequently, the probability of the occurrence of hydraulic conditions that cause the re-suspension of the accumulated sediments can be estimated. The FMECA methodology specifically defines the evaluation matrix and categories for each of the evaluated risk factors. The total score is calculated for each segment of the network by means of sequential evaluation of the individual factors. Depending on the value of the total score, each segment is assigned a probabilistic category according to the following criteria:

- the probability of sediment accumulation in the pipe section,
- the probability of occurrence of a discoloration event.

The segment can be assigned one of four probabilistic categories ranging from K1, i.e. low probability, to K4, i.e. very high probability (Tuhovčák, Ručka 2009).

This method conveniently combines qualitative approach in the evaluation of factors that would otherwise be very difficult to evaluate or would require exceptionally time consuming and financially demanding collection of accurate values. However, the method enables the use of such accurate input information, if available. One of the crucial input data source for this method is made up of the results of the simulations performed by a detailed calibrated hydraulic model of the water supply network.

The factors that are analyzed to estimate the probability of sediment accumulation in the pipe section include the material of the water mains and its age, corrosion processes, quality of distributed water, hydraulic regime in the pipe section and standard of maintenance, for instance. The factors that are analyzed to estimate the probability of occurrence of a discoloration event are based mainly on hydraulic analysis and simulations in the hydraulic model of the network. The result of the analysis is a defined group of selected pipe sections of the WSS that have a significant impact on the hydraulic regime of the remaining site. This means that closing or opening of these pipe sections results in significant changes to the hydraulic conditions in the remaining segments. This implies that these specific pipe segments should be given due attention in the prevention of discoloration events particularly with regards to their technical condition and the manipulation of valves. Another important group are those sections of the pipe network that show sensitivity to changes in the network hydraulics. This means that their hydraulic regime is impacted more than in other parts of the network for instance by manipulation of the control valves elsewhere in the network or by increased water demand. Additionally, where these sensitive segments also tend towards sediment accumulation, they become critical in the development of discoloration events. Such segments are therefore called “causal pipe sections”.

The aim of the above-described analytical method is to seek out the pipe sections that may cause the discoloration events, and therefore are crucial from this point of view. These segments can be located by evaluating the risk factors of the individual sections of the pipes, but also on the basis of a detailed hydraulic analysis and simulation using a calibrated model of the water supply network.

A discoloration treatment plan is designed using the results of the risk analysis. Efficient approaches are set in order that the manipulation of the valves with the greatest impact on the hydraulic regime is optimized whilst avoiding any unnecessary changes to the regime. The pipe segments identified as causal pipe sections should be regularly cleaned from sediment in order to reduce the probability of a discoloration accident.

3. Technical tools for the creation of flushing programs

The design and application of plans for water discoloration management in water supply networks requires an appropriate technology, which allows the network to be analyzed and provide information about the risk of occurrence and propagation of the discoloration, identification of the hotspots, simulation of remedial measures and evaluation of their efficiency. It is also necessary to provide equipment for the monitoring of discoloration and hydraulic characteristics on the site. These tools are being developed as part of this research project and their brief description is provided below.

3.1. Portable measuring device

As explained above, a water discoloration management plan has to be preceded by the development of a detailed hydraulic model of the water supply network and its adequate calibration. The calibration data are collected by taking off a defined flow in several specific locations along the network, typically underground fire hydrants, whilst monitoring the decrease in hydrodynamic pressure not only at the monitoring points, but also in a hydraulically connected part of the network. The calibration process is the most time and effort consuming part of the model development. A very important factor impacting on the quality of the subsequent work and the results of the analysis is the accuracy of the procedures and the monitoring of the hydraulic characteristics.

Model calibration is considered satisfactory if a value of $\Delta p \leq 0{,}01$MPa is achieved, where Δp is the difference in hydrodynamic pressures under reference flow between the result of the hydraulic model and the measurements in-situ. Higher accuracy is usually not necessary and often not technically achievable due to the inherit accuracy of pressure sensors, the fluctuation of water level in storage tanks and other uncertainty in the input data (e.g. water main bedding depth).

Measuring tools that would allow the required accuracy at reasonable price are not readily available in the market. The appropriate measuring equipment was therefore constructed during the first year of the research project (Fig. 4).

One of the main factors in the construction of the measuring instrument was its future practical applicability in water supply operation. It is designed as a measuring extension that can be positioned on a common underground hydrant. The water flow can be regulated directly by the extension, not by means of a valve in the hydrant.

A common fire hosepipe with B75 ending can be used to direct the discharged water. The instrument is constructed from steel with welded joints in order to protect the equipment from damage during transport and installation. Once a one-off calibration of the flow meter in the extension is performed, no further adjustment is required. The instrument is ready to use. Its individual meters show directly the measured values on their displays and are powered by a battery without the need for an external electricity supply. A major advantage is the very low weight of the equipment. At only 12.3 kg the instrument can easily be transported and manipulated. The largest dimension of the measuring extension is 1250 mm.

The accuracy of the flow meter was calibrated and validated in the hydraulic laboratory of the BUT. The calibration was undertaken in pressure bore circuit. A standard underground hydrant was included in the circuit through which water was directed. The measuring extension was set on the hydrant. The calibration of the flow meter therefore took into account the impact of turbulences and deformation of the velocity field, which typically occur under high flow in the hydrant. The stilling pipe of the extension before the flow meter also includes flow rectifier that not only directs the flow parallel with the axe of the meter, but also prevents the sensors from damage by particles intruding from the water network. The flow meter, the pressure sensor and the tap connecting the discoloration meter are sited on the measuring extension so that they do not influence each other. The calibration process included the setting of the flow through the pressure circuit by pumps at frequencies gradually from $0.5\ l \cdot s^{-1}$ to $15.0\ l \cdot s^{-1}$. The flow measurement was undertaken by a couple of accurate electromagnetic water meters, which comply with the Czech standards set out in the Meter law 505/1990 Sb. As a result of the calibration, the measuring extension complies with the requirements for meters as defined by the Meter law 505/1990 Sb. and its parameters are as follows:

- Flow measurement – accuracy ± $0.1\ l \cdot s^{-1}$, flow range 0.5 to $15.0\ l \cdot s^{-1}$
- Pressure measurement – accuracy ± 0.0025 MPa, pressure range 0.0 to 1.0 MPa (limits may vary according to used pressure sensor)
- Turbidity measurement – in concordance with requirements of the standard EN ISO 7027:1999 Water quality – Determination of turbidity

Fig. 4 Portable measuring device

The accuracy of the instrument is satisfactory for the calibration of hydraulic models. Currently only one piece of the measuring extension exists. It has already been routinely used for the measurements in water supply networks for the purposes of other research activities of this project.

3.2. Software tool ADAM

The other tool, which is being developed under the project TA02020604, is the software application ADAM. The software is intended for water utilities as its end-users. The software is being developed on a professional basis in close cooperation with the BUT research team and an external software company. ADAM is a new desktop application, which is primarily designed for risk analysis of the occurrence and propagation of water discoloration in water supply networks, and for the production and management of discoloration management plans. Therefore, the software will enable the following:

- Design of new hydraulic models of water supply networks
- Import and editing of existing hydraulic models of water supply networks
- Hydraulic analysis of water supply networks including water quality modeling
- Risk analysis of the occurrence of discoloration
- Design and editing of discoloration management plans

The programming language chosen for the software development is C# (Windows), application type desktop. An important functionality of ADAM is to enable a dynamic upload of publicly available map layers such as Google maps, CENIA and mapy.cz, which allow working with the water supply network model with the map of the supply area in the background. The application will provide standard mapping tools such as distance measurement or elevation. ADAM will support the import of standardized file type inp (Epanet 2.0) and also additional import of supplementary information. This will use "live" connection with spreadsheets (MS Excel). The application is intended for OS Windows XP SP3 and later versions. The finalization of the software development and testing is scheduled for 2014.

4. Conclusions

Water quality analysis in water supply networks is an extremely elaborate and time-consuming process. The quality of the input data fundamentally determines the accuracy of the results. The authors of this paper therefore use a risk analysis approach based on the FMECA technique to analyze the occurrence of water discoloration, which enables a systematic analysis of the input data uncertainty. The technique is based on qualitative analysis of factors that cause the accumulation of sediments in water mains and their subsequent re-suspension. The hydraulic parameters of the individual pipe segments are obtained with assistance of a hydraulic model of the water supply network. These procedures are built into the newly developed software tool ADAM, which is being designed for the purpose of risk analysis of the occurrence of discoloration events in water supply networks. The analysis results in the identification of a discoloration risk category for each pipe segment. The results are displayed directly in the topology of the water supply network within ADAM, overlying a mapping background of the supply area. The results can be used to propose an optimized water discoloration management plan of the entire area (or pressure area).

A specially designed instrument, a portable measuring device, was developed in order to allow increased accuracy for the calibration of the hydraulic models and the discoloration management itself. The extension allows simultaneous measurement of pressure, flow and discoloration directly on the hydrants in the water supply network.

The methodology presented in this paper is being developed alongside with the two tools within the scope of the three year research project, the main aims of which include not only the development of these tools, but also their “real life” testing in water supply networks. For this reason, the case studies include two major water utilities and one small water company in the Czech Republic.

Acknowledgements

This research work is funded by the Technology Agency of the Czech Republic in the frame of the research project titled “Tools for prevention of water discoloration in water mains” - registration number TA02020604. The paper is also supported by the research project “Assessment of vulnerability of water-supply systems” – Reg. Nr. FAST-S-11-8. Additionally is this paper supported by European Regional Development Fund in the framework of the research project NETME Centre under the Operational Programme Research and Development for Innovation. Reg. Nr. CZ.1.05/2.1.00/01.0002, id code: ED0002/01/01, project name: NETME Centre – New Technologies for Mechanical Engineering.

References

J. Vreeburg, 2007. “Discolouration in drinking water systems: a particular approach”, Dissertation thesis, p. 184, Delft University of Technology, ISBN: 978-90-74741-91-0

J. Vreeburg, 2010. “Discolouration in Drinking Water Systems: The Role of Particles Clarified”, 1st ed., IWA Publishing, Aug 2010, ISBN: 9781843393757.

L. Tuhovčák and J. Ručka, 2009. “Hazard identification and risk analysis of water supply systems”, Strategic Asset Management of Water Supply and Wastewater Infrastructures, London UK, pp. 287-298, IWA Publishing, ISBN: 1-84339-186- 4.

L. Tuhovčák and J. Rucka, 2008. “Risk analysis concepts and methods - detailed methods”. In Proactive Crisis Management of Urban Infrastructure. 1. Brusel: COST Office; SINTEF, 2008. pp. 30-46. ISBN: 978-82-536-1003- 0.

P.S. Husband and J.B. Boxall, 2011. “Asset deterioration and discolouration in water distribution systems", Water Research, vol. 45, pp. 113-124

The Ministry of Agriculture of the Czech Republic, Water supply and sanitation CR 2012, Praha, 2012, www.mze.cz, ISBN 978-80-7434-079-6