WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

GUIDANCE MANUAL

The Wat-Qual Consortium

Researching Water Quality in Drinking Water Distribution Systems

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Introduction

The Wat-Qual Consortium: Researching Water Quality in Drinking Water Distribution Systems

Safe drinking water is paramount for the health and wellbeing of all populations. Unsafe drinking water can contain pathogenic microorganisms and/or chemicals that can make people immediately unwell or can potentially cause serious illness over prolonged exposures. Drinking water systems in the developed world are successful in providing this resource to millions in a safe and efficient manner, however, there are instances where drinking water quality and therefore user safety has been compromised.

Within the EU, water is extracted from surface and groundwater sources and treated to comply with EU drinking water standards under the Water Framework Directive and Drinking Water Directive. The water is then circulated through the drinking water distribution system (DWDS) to end users, during which time its quality may deteriorate. The rate and extent of DWDS water quality degradation is influenced by: background water chemistry and treatment including presence of a disinfectant residual like chlorine; the design of the network; the age and configuration of the pipe infrastructure; the hydraulic conditions of operation including customer demand patterns; maintenance activities like flushing; and procedures for repairs.

While all water utilities must comply with EU Water Framework Directive and Drinking Water Directive requirements for specified water contaminants, many features of operation are not dictated by these regulations such as choice of treatment processes, procedures for maintenance activities, and hydraulic operations of the DWDS. Each water utility has its own sets of national standards and utility-specific procedures, many of them traditionally passed on and not always based on scientific evidence. Some of these typical practices, like flushing, may improve water quality in certain cases but the potential also exists that these activities can impair drinking water quality, resulting in regulatory violations and even waterborne disease.

Across the water industry, it is not clear what practices are most successful at ensuring clean drinking water under different conditions. Furthermore, localised issues concerning infrastructure design, historic protocols and national regulation make it challenging to identify and implement best practices across Europe. This project bridges the gap between science and practice, involving water utilities and researchers from multiple locations across Europe along with third-country expertise, to examine DWDS operational practices and use scientific research approaches to better understand the water quality impact of different interventions.

Summary

The multidisciplinary Wat-Qual consortium was led by The University of Sheffield (UK) and includes participation from 10 countries spanning academic and industrial institutions:

- Brno University of Technology (Czech Republic)
- Construcciones Y Canalizaciones (Spain)
- Delft University of Technology (Netherlands)
- DVGW-Technologiezentrum Wasser (Germany)
- Institut national de recherches en science et technologies pour l'environnement et l'agriculture (France)
- KWR Watercycle Research Institute (Netherlands)
- Norwegian University of Science and Technology (Norway)
- N.V. PWN Drinkwaterbedrijf Noord-Holland (Netherlands)
- Stichting Waternet (Netherlands)
- Università degli Studi di Pavia (Italy)
- Universitat Politecnica de Valencia (Spain)
- University of Arizona (USA)
- University of Belgrade (Serbia)
- University of California Santa Cruz (USA)
- University of Cincinnati (USA)
- University of Colorado (USA)
- University of Exeter (UK)
- Vodovod i kanalizacija (Serbia)

Several aspects of DWDS practices were selected for evaluation because of their significant links to water quality degradation:

- Flushing (led by Peter Schaap, PWN)
- Chlorination (led by Prof Vanessa Speight, University of Sheffield)
- Maintenance and repair activities (led by Dr Mirjam Blokker, KWR)

The project coordinator was Prof Vanessa Speight, University of Sheffield, assisted by the work package leaders and Prof Enrico Creaco, Università degli Studi di Pavia, who coordinated training activities.

Conclusions/ future research needs

The consortium completed more than 40 months of researcher secondments between pairs of partnered institutions in different countries and crossing from academia to industry, per the funding scheme requirements.

The research conducted resulted in more than 20 conference presentations and 10 papers, plus a special issue of the journal Water on distribution system water quality (https://www.mdpi.com/journal/water/special_issues/Drinking_Water_Distribution).

Links to further material

https://www.sheffield.ac.uk/civil/wat-qual

Authors names: Vanessa Speight

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

The Value of Sharing Experiences Across Countries

A Personal Account

During the closing workshop of Wat-Qual I got the feeling that all the participants, looking back at the last two years, were very enthusiastic of the outcomes of the project, not only for the resulting scientific production but also for the human and personal experience itself.

I myself had the opportunity to join the project, spending two months in the Netherlands as hosted researcher by PWN and KWR, while I was in my first year Postdoc in Pavia. For this reason, I would like to highlight the strengths of this experience from the perspective of an early career researcher.

A hard problem for young researchers is to start creating a network of collaboration with other researchers across the countries, in order to get feedbacks, support, better knowledge, etc. In that context, presenting at conferences can be helpful, but not always enough, given the high number of people participating and the short time available. Furthermore, the tendency is to develop great ideas without taking into account how to practically implement them in real life or without having the opportunity to work with real case studies and/or real data. In this context, Wat-Qual gave a big contribution bridging the gap between the young scientific world (researchers that just started to build their career) and the senior researchers and non-academic world (water companies) all across Europe. Indeed, based on my personal experience, I really appreciated the possibility to work closely together with experts of the Dutch water sector, which brought me to a more practical view for my scientific work. At the same time, I found extremely valuable also the possibility to easily get in touch and spend time with researchers with high expertise in different related topics. Sharing ideas and results with them during seminars or even during coffee breaks was very helpful, allowed me to speed up the research, to get a lot of useful feedbacks and to broaden my knowledge.

Also important to mention, it is the value of having the opportunity to travel (with an economical support), to experience for a while a deep immersion in a different culture and to make new friends that could be one day your future colleagues.

In general, Wat-Qual contributed to share knowledge and practices going beyond the geographical and cultural boundaries, connected people and created opportunities that may have never existed otherwise, creating the unexpected even for starting a new life. Indeed, in my specific case, the country that hosted me one year ago as a visiting researcher is now my new home and since May I am a scientific researcher in KWR, happily working in the same team that supported me during my Wat-Qual visit in the Netherlands.

Authors names: Claudia Quintiliani

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

The Value of Hosting Secondment Visitors

As a Water Cycle Company, students regularly visit for shorter or longer periods and work on all kinds of subjects. We hosted a Serbian duo from the University of Belgrade. These young professionals have very independently introduced theory to practical application.

Summary of best practices/tools/approaches

The aim of the secondment visits was to test an algorithm on the Waternet drinking water network. In the past few years, a group at Faculty of Civil Engineering at the University of Belgrade has been focused on the development of multi-objective network sectorization algorithm – WATer Network Clustering (WATNC), and on more efficient algorithms for the simulation of network hydraulics (loop-flow based method for hydraulic analysis). Within the scope of this research, they have applied and tested this application of the WATNC algorithm in its current state on a real network, allowing for further development of the WATNC in cooperation with the Waternet company. Additional network sectorization objectives, important for the efficient operation of the water distribution system, could be included, such as system flushing performance and maintenance efficiency.

The nice thing about this exchange was a non-classical solution by entering into a commitment with possibly all kinds of European institutions / universities. This type of project offers the opportunity to look beyond national borders and as a hosting organization, it was a nice challenge to identify a good practical subject to explore. As host, we had set the criterion that a well-thought-out plan had to be prepared in advance. After all, a kind of internship / job shadowing programme would require a lot from our colleagues in the supervision and such a project would not add value for us, since there are enough (university) students in the Netherlands who we could find to participate for a short or longer period.

It was nice to see that young professionals could find their way relatively easily in an organization such as Waternet; the largest water company in the Netherlands with over 2,000 employees. This fact also immediately indicated that the secondment visitor form of entering into a working relationship did not fit as standard in our protocols. The students remained "day visitors" in our systems for a long time. We have accepted this somewhat awkward situation so that the practical work would not suffer. Many Dutch colleagues have no great difficulty expressing themselves in English. Because of this, the visitors were included in all kinds of secondary activities (drinks, farewell reception, team events and even the Christmas gala of young Waternetters). It was very nice to be able to offer this opportunity in an already closely regulated western world.

The accommodation in and around Amsterdam requires some creativity; or there is nothing available or way too expensive. So our solution has become a combination of some travel time and sharing of an Airbnb. But this "problem" was known in advance, but should be something to take more into account in the future when setting the financial compensation for the visitors.

Conclusions/ future research needs

All in all, participating in this project was a great time and experience and I was happy to be able to contribute.

Links to further material

https://www.waternet.nl/

Authors names: Arne Bosch

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Impacts of Flushing

Characteristics of fine sediments in water supply network

Due to the effects of many different processes, fine particles are present in water supply networks and settle in the pipeline under favourable conditions. These particles may originate from the external environment or they may be directly formed in the water supply network. The sediments gradually settle in those sections of the network with low velocity. Here the particles form a fine layer of material, which creates excellent conditions for microorganisms to flourish, contributes to a faster decrease of disinfectant residual, and can lead to aesthetic failures in drinking water quality. Moreover, when the hydraulic conditions change when the sediment in the water resuspends, turbidity events occur and consumers complain.

This material in the pipeline is constantly moving. Its quantity at a particular place and time is the result of the action of hydraulic forces, corrosion processes, complex biofilm processes on the pipeline walls and the ingress of pollution from the external environment. Some of these particles are created in the network by corrosion and biological processes. Other material gets into the pipeline during pipe failures and repairs, the mass of which can greatly exceed the mass of particles that enter the network from the water source. Microorganisms and higher organisms also live in sediments, which also affect water quality.

In our research, controlled flushing of several selected water supply networks was performed, during which samples of heavily polluted water containing sediment were taken. This sediment was then subjected to chemical and microbiological analysis. It is necessary to understand the basic properties of this material to quantify the risks posed by the occurrence of a spontaneous discoloration event in the water network or the implementation of a controlled flushing. The information about the individual sediment types can also be used to calibrate the newly developed software tools to simulate the movement and accumulation of sediments in the water network. These analyses are indispensable to be able to focus flushing actions at those locations in the water network where there is a high probability of sediment accumulation, thereby maintaining the water network effectively.

Summary of best practices/tools/approaches

The most important findings are related to the identification and implementation of sampling points for sediment material. When monitoring water quality in the water network, the choice of place for drinking water sampling must reflect the specific purpose of the sampling.

1. For the needs of operational monitoring of the water quality the current practice is to draw water at the consumer's tap, which fulfils regulatory requirements to verify the quality of the water at that location. However, when analysing the quality of water in the water supply network, the consumer tap is not the optimal sampling point, as microbiological quality of the drinking water may be affected as it passes through the connection pipe and the plumbing. To investigate the differences in the water quality between the water main and the service connection, we created several specialized sampling points on our case study water supply network. Similar to consumer taps, underground fire hydrants are also not the correct place to take samples for this purpose because they are susceptible to contamination from the hydrant vault.

Fig. 1 Newly created sampling points for monitoring the microbial water quality on the water supply network, placed on the service connection very close to water main and before the plumbing

2. For the requirements of sediments sampling during a flushing event, a flowing fire hydrant is the best place to take samples.

Fig. 2 Taking samples of fine sediments during a flushing event

Fig. 3 Samples of the dirty water from the supply system during the flushing event

Conclusions/ future research needs

Research needs to be directed towards better understanding of fine sediments characteristics and optimization of water mains maintenance.

1) A catalogue of characteristics of fine sediments is needed, including properties of fine sediments as determined by their origin, their formation and their composition. To be able to reliably predict their creation and movement in the water supply network in the future, it is necessary to know the sediment properties first. However, such research is time-consuming, laborious, and expensive. Therefore, it would be appropriate to create a catalogue of different types of sediments and their properties, which could be subsequently used by individual water companies.

2) A better understanding of the ability of pathogens to survive and proliferate in the sediment is needed. Fecal pathogens are currently indicated by the presence of *E. Coli*. During our field work, we flushed several water supply networks and found *E. Coli* in many samples of sediments. There is low probability that all these systems were contaminated with *E. Coli* in recent days prior to sampling. Thus, it is important to know how long *E. Coli* can survive in the water supply network sediments and if it can flourish under those conditions.

Links to further material

Vreeburg, J. (2007). "Discolouration in drinking water systems: a particular approach." Netherland: Gildeprint BV Enschede. ISBN 978-90-74741-91-0.

Douterelo, I., Husband. S., BOXALL, J.B. (2014) "The bacteriological composition of biomass recovered by flushing an operational drinking water distribution system. " Water Research (54), 15, doi:10.1016/j.watres.2014.01.049

Authors names: Ing. Markéta Rajnochová

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Active corrosion

In a large part of older drinking water distribution systems (DWDS), cast iron is used as the main pipe material. Unprotected (unlined) cast iron is subject to corrosion and can be an important source for particle production in the network, resulting in high complaint and fouling rates. Flushing in DWDS with high percentage of unlined cast iron introduces risks related to damaging the scales that protect against active corrosion. The corrosion tubercles reduce the inside diameter of these pipes and high flush volumes can create forces that will damage relatively weak scales. Active corrosion is a continuous process that can take a long time to end once it has started.

Summary of best practices/tools/approaches

When flushing in cast iron pipe areas, it is advisable to analyse the strength of the scales before starting with extensive flushing action. Damaged pipes can bleed iron and related corrosion products for a long time, resulting in discoloured water complaints. While there are no easy interventions that can quickly end active corrosion other than pipe replacement, phosphate dosing and pH control can help rebuilding the desired scales.

Active corrosion is a continuous process so when water travels with a low flow, large amounts of corrosion byproducts can enter each package of water. During high demand peaks, the local accumulation of particles will be minimised as they are carried farther downstream. However, during low demand times and especially during the night, an increase of turbidity in areas with active corrosion can often be seen.

Best practice is conducting online turbidity monitoring prior to flushing:

- Select a dead end, or create a dead by closing a valve, preferably fed by a larger diameter main or loop.
- Place an online turbidity meter on the main and record the normal, background turbidity for a couple of days.
- Flush the selected pipe with the desired flow and continue to monitor the turbidity variation for a few days. If possible, measure pressure at the beginning and end of the pipe, so an actual internal diameter and/or roughness can be calculated using the headloss.
- If the pipe scales are disturbed and active corrosion begins, use a lower flushing velocity at the next location with similar pipe material. Determination of desired flushing velocity can also be done starting with a low flow, measuring turbidity for a couple of days and increasing flow stepwise, with every step monitored for a couple of days.

It is always advisable to flush with a low flow when unsure about strength of the scales on the pipe wall. Removal of particles will take place at all velocities so it is not strictly necessary to reach a given flushing velocity threshold, especially if that velocity might damage the pipe scale.

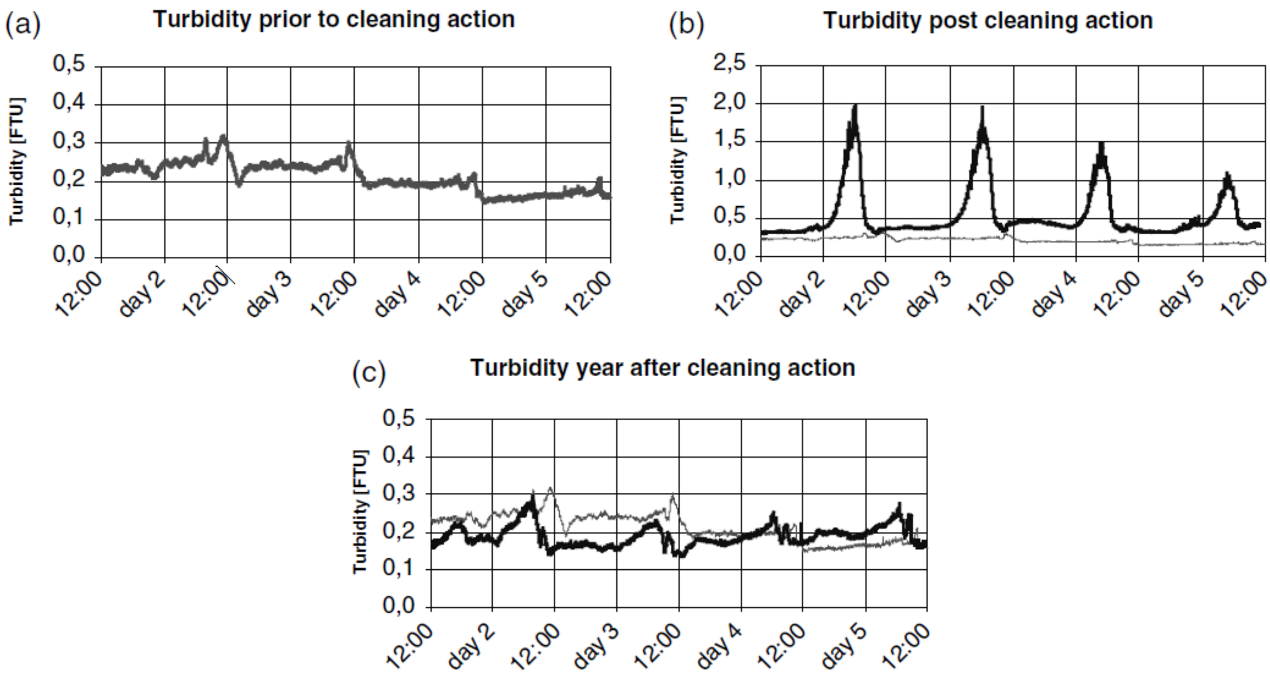

Figure 3 Turbidity in cast iron main: (a) Prior to cleaning; (b) Post cleaning action, upper curve (red line is original turbidity); (c) year post cleaning

Conclusions/ future research needs

Be aware with flushing areas with unprotected cast iron pipe as damaging the scales can lead to large problems afterwards. It is always advisable to flush with a low flow when unsure about strength of the scales on the pipe wall.

Links to further material

Vreeburg, J.H.G., Schaap, P.G. and van Dijk, J.C. (2004), "Particles in the drinking water system: from source to discolouration", Water Science and Technology, Vol: 4, (5-6): 431-438.

Authors names: Peter Schaap

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The value of monitoring during flushing

Drinking water distribution systems (DWDSs) will foul over time due to accumulation of particles from treatment, corrosion, and related processes. This accumulation needs to be removed, most often by flushing the DWDS. While flushing is a standard practice, it can be time consuming and wastes precious water resources. Flushing can be either reactive (after customer complaints or water quality regulatory sampling failures) or proactive/preventive. The ideal approach for an asset manager is to optimize costs and maximise benefits of flushing through flushing only the necessary locations at only the necessary times. To facilitate this approach, good system knowledge and careful tracking of system performance information is vital. Furthermore, given the significant effort and resources that are used during flushing, there is value in expending a small, additional effort to collect additional information before, during and after the flushing event to contribute to the knowledge base about the DWDS.

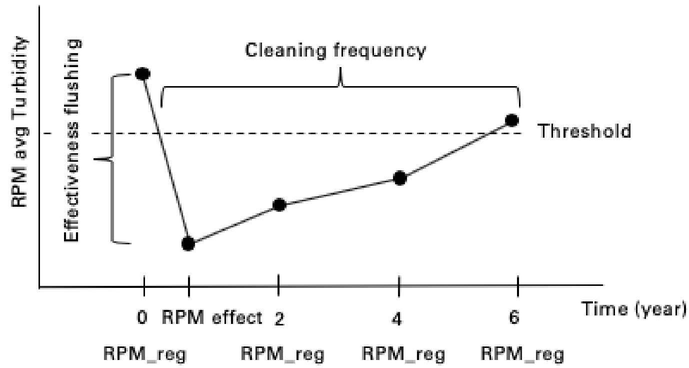
Summary of best practices/tools/approaches

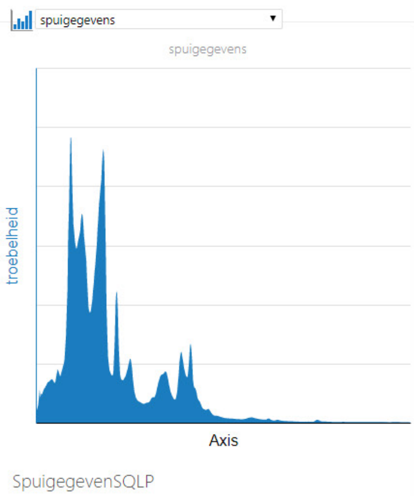
Conducting flush programmes throughout the DWDS is a very intense activity, in terms of labour, disruption, water losses and ultimately cost. Taking advantage of this work within the DWDS as an opportunity to collect additional data about the flushing process will generate information for future system optimisation.

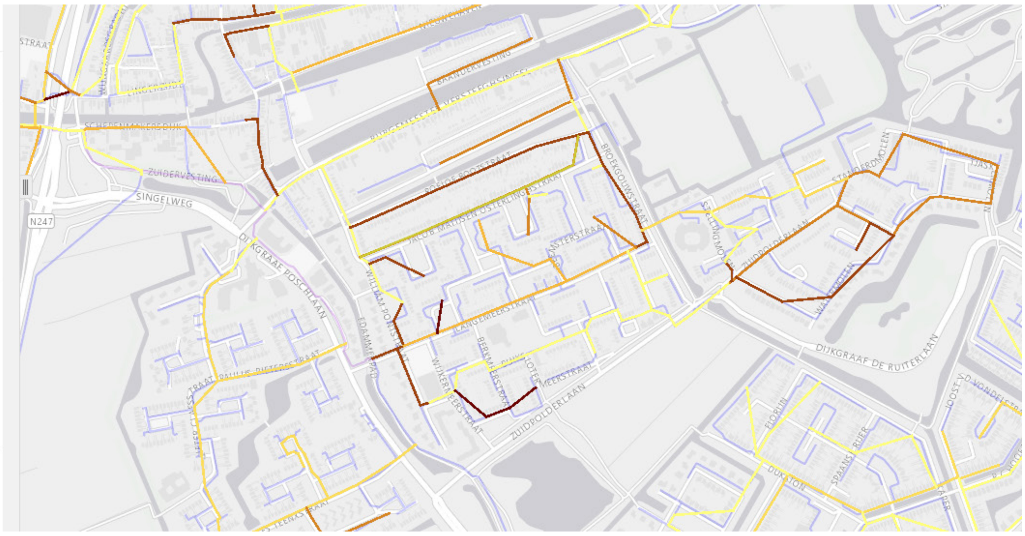
Before flushing		During flushing	After flushing
Collect	**Additional measurements**	**Collect**	**Evaluate**
• CC dirty water, taste and odour • Lab analyses (Turb, Fe, Mn)	• Periodical RM • Active corrosion turbidity measurement	• Online turbidity • Grab samples (Turb, Fe, Mn, TSS, VSS, particle counting) • Flow • Pressure	• RPM effect measurement • Active corrosion turbidity measurement

To identify the best locations for flushing, the spatial analysis of customer complaints and related water quality parameters such as turbidity, taste and odour across DMAs or service areas is useful. Setting a threshold, for example 1 customer complaint (CC) about discoloured water per 1000 connections, will help prioritize areas of greatest need. This prioritisation can also be strengthened with results from the regular monitoring about the particulate accumulation characteristics such as the Resuspension Potential Method (see RPM fact sheet). By repeating testing like the RPM on a 1-2 yearly basis, insight into the appropriate cleaning frequency for specific areas can be developed. Furthermore, conducting tests like the RPM after flushing will give allow tracking of the effectiveness of the flushing programme over time.

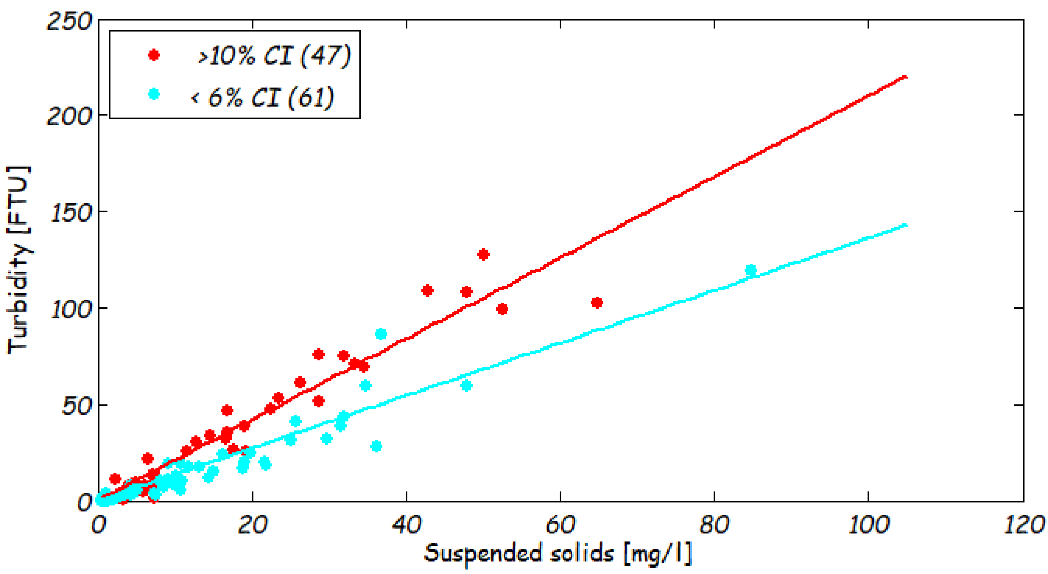
Monitoring turbidity using online measurements or grab samples during flushing gives insight in particle accumulation over the flush trajectory. This type of monitoring data will reveal if there are specific pipes/areas with high turbidity peaks or if the particles seem to be homogeneously distributed. Turbidity monitoring results can be plotted as a GIS layer showing pipes with high potential discolouration risk. By targeting these high-risk pipes periodically with low flow flushing instead of flushing the whole DMA, the discolouration risk can be managed with lower effort and cost.







Analysing grab samples taken during flushing will give insight into the type of particle material using measurements of suspended solids and total organic carbon. A high concentration of inorganic material as part of the suspended solids can indicate active corrosion, while a high concentration of organic material indicates biological processes as a source for particles.



Conclusions/ future research needs

Large flushing programs provide an opportunity to examine and evaluate a DWDS, which justifies the additional effort related to collecting data. At the very least, an assessment of the effectiveness of flushing should be determined. Monitoring the turbidity and flow during flushing will give help to identify the location of hot spots for material accumulation while the analysis of the particle characteristics gives insights into the nature and extent of the fouling.

Links to further material

Schaap, P. G. and Blokker, E. J. M.: Carefully designed measurements provide insight into sediment build-up in drinking water distribution systems, CCWI 2011 Urban Water Management: Challenges and Opportunities, Exeter, 2011.

Blokker, E. J. M., et al. (2011). Comparing the fouling rate of a drinking water distribution system in two different configurations. CCWI 2011 Urban Water Management: Challenges and Opportunities, Centre for Water Systems, University of Exeter, Exeter.

Authors names: Peter Schaap

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Critical Shear Stress

Entrained in distributed water is a constant low-level background concentration of particulate material. Two key processes have been identified whereby this material accumulates resulting in different discolouration risks. For each process there is a critical shear stress that if exceeded can cause mobilisation of material, leading to customer observable discolouration. By understanding these critical values, drinking water distribution system (DWDS) managers can manage operation and intervention strategies to reduce discolouration and associated water quality risks and safely remove material to increase system resilience.

Summary of best practices/tools/approaches

For a discolouration risk to exist there must be a store of material that if mobilised results in high and hence observable concentrations of material being entrained in the bulk flow. Two processes whereby material accumulation may occur are shown in Table 1. Although both processes are shear stress defined, they have different properties, occur in different network locations and have different management approaches.

Accumulation process	Network location	Discolouration magnitude	Potential no. of customers affected	Risk management strategies
Cohesive material layers (PODDS concept)	Ubiquitous	High (Extensive, event dependent)	High	• Reduce loading (e.g. treatment) • Cleaning (e.g. swabbing, jetting) • Hydraulic conditioning/flushing
Deposits/ sediments	Low flow zones	High (Localised: 1. Tidal 2. Oversize 3. Dead ends)	Low (but recurring)	• Passive flushing • Network design (e.g. dendritic, reducing diamiter, self cleaning) • Network flow management

1. Cohesive layers occur throughout DWDSs whereby particulate material present as low background concentrations comes into contact with boundary surfaces and becomes attached. Material layer development is biofilm mediated, with continuous adaptation to local conditions and material composition reflecting the supplied water quality. On a day-to-day basis, only material with a shear strength greater than daily peak shear stress at that point in the network can remain attached. This critical shear value is therefore location dependent and any shear stress in excess, either planned or unplanned, will cause mobilisation. The higher the excess shear stress above the critical value, the greater the response with more material being mobilised at a faster rate. Given that material layers are present in all pipes, this risk is ubiquitous and hence consequences will depend on downstream population served with larger pipes impacting higher numbers of consumers. Discolouration

levels are typically low magnitude but, depending on pipe lengths affected, can have long durations. Corroding assets exhibit the same layer behaviour, but contribute additional metals resulting in layers with higher metal concentrations and also impacting downstream networks as bulk water quality is deteriorated.

2. Material deposition leading to sediments occurs in network specific locations where flows are sufficiently low to allow particle self-weight forces to overcome inertial forces, i.e. effectively laminar regimes where Reynolds number < 2100. The flow at which this settling will occur can vary depending on network material characteristics (size, density). Primary deposition locations include dead-ends and tidal points (zones with low flow in looped networks).

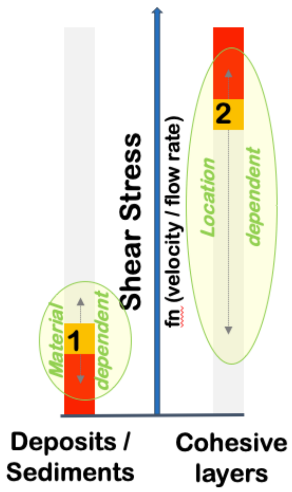

Figure 1 Discolouration material accumulation processes and discolouration risk. Understanding of τcritical values (1 & 2) required for management of discolouration issues highlighted. Material accumulation (hence risk) occurs in red zones.

At locations where daily peak flow is insufficient to generate turbulent conditions, the required transition value becomes a critical operational shear stress as any increase above this will mobilise sediments. As typically only short lengths of pipe are affected, responses maybe short duration with only a limited number of consumers impacted. If DWDS hydraulics operate in a consistent and repeating pattern, material accumulation can occur rapidly at deposition locations, leading to high magnitude events and recurring issues.

Best practices for discolouration and network resilience managment requires (Figure 1):

A. Identification of risk type / location

B. Determination of critical shear stress (τcritical);

- For Deposits/sediments, τcritical (1) is a function of localised material characteristics and applied hydraulics.
- For cohesive layers, τcritical (2) is defined as the typical (daily/weekly) peak value at which no pipe wall material is mobilised.

C. Best practices to manage discolouration can be broadly classified to address the two accumulation process;

- Prevent sedimentation e.g. flushing, network flow variations, such as periodic valve operations to manage flow rates/directions.
- Condition networks, such as by controlled incremental increases in shear stress to manage layer accumulated material, with the outcome being increased network resilience.

Conclusions/ future research needs

Understanding of critical shear stress values can inform best practices to manage networks and safeguard water quality. To achieve this goal, good monitoring and modelling of DWDS hydraulics is required to identify where sedimentation zones may occur and determine critical shear stress.

Links to further material

I. Sunny, S. Husband, J. Boxall, J., (2019). Impact of Hydraulic Interventions on Chronic and Acute Material Loading and Discolouration Risk in Drinking Water Distribution Systems. Water Research, https://doi.org/10.1016/j.watres.2019.115224.

II. Prediction of Discolouration in Distribution Systems (PODDS), www.podds.co.uk

Authors names: Stewart Husband

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Controlled flushing of water supply networks — practical approach

The water supply network deserves at least the same attention that is traditionally given to water resources and water treatment plants. Even if the highest quality drinking water from the water treatment plant enters an old, poorly designed or improperly operated water network, the resulting quality of the water at the place of consumption can be highly variable. Controlled flushing is one way to ensure that drinking water maintains its required quality throughout the transport from the source to the point of consumption. In some specific situations, controlled flushing is the last and only way to achieve this goal.

It is practically impossible to prepare for the flushing without the use of hydraulic simulation models. Each flushed water system has its own local configuration which must be adapted to prepare for and implement flushing. Before working out the flushing plan, it is necessary to understand the given water supply network very well, to verify the current method of its maintenance, to evaluate the existing problems and to carry out a hydraulic analysis and subsequent risk analysis. Without this preparation, performing a controlled flushing of the water network cannot be considered as a safe and beneficial operation.

Summary of best practices/tools/approaches

The purpose of controlled flushing is to remove sediment from the water supply network and to do it: (1) completely, (2) safely, to manage and maintain the hydraulic behaviour of the water supply network throughout the flushing process, (3) efficiently with minimum movements between the hydrants and (4) with minimal impact on consumers. As the controlled flushing is a hygienically significant operation, it is advisable to consult on the plan with the relevant regulatory authority in advance.

It is necessary to carry out a risk analysis of the possible negative consequences of poor flushing performance. It is also necessary to define preventive measures to eliminate these risks in advance. Possible risks include:

1. Temporary water pressure loss
2. Loss of control of water quality in the network, resulting in extensive uncontrolled discoloration events
3. Incomplete removal of accumulated sediment from the network
4. Hydraulic transients (possibly resulting in pipe bursts)
5. Ingress of dirty water
6. Worsening of the active corrosion processes in metal pipelines with high flushing velocities.

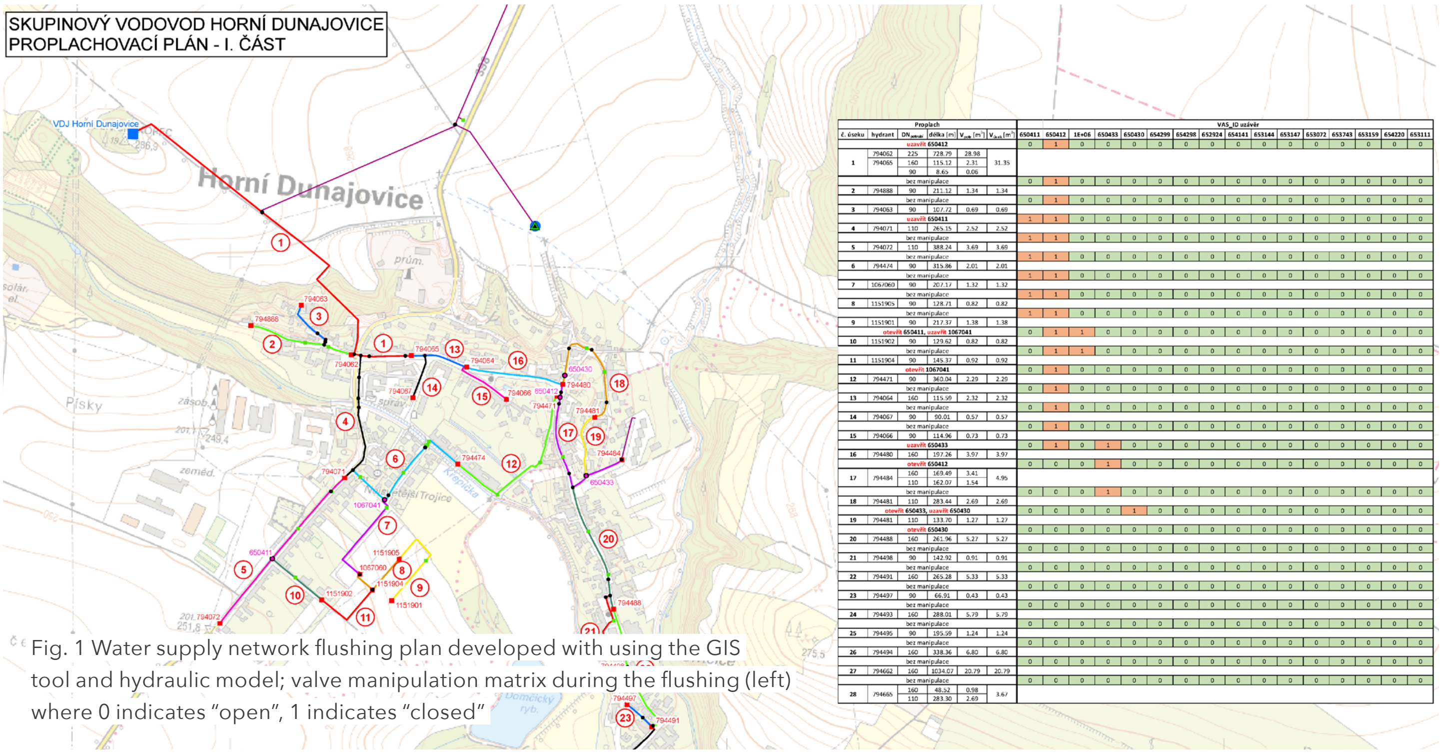

Fig. 1 Water supply network flushing plan developed with using the GIS tool and hydraulic model; valve manipulation matrix during the flushing (left) where 0 indicates “open”, 1 indicates “closed”

Fig. 2 Sampling the water from the supply system during the flushing event

Fig. 3 Material flushed out from the pipes

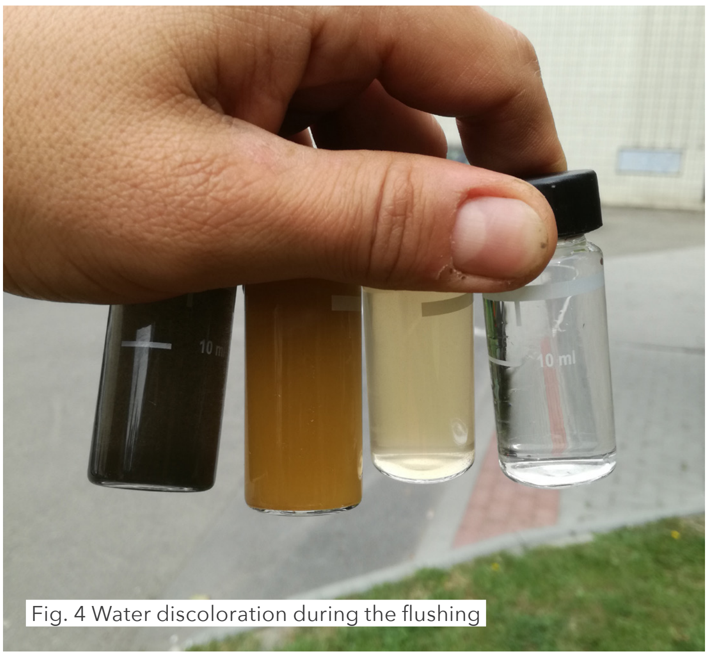

Fig. 4 Water discoloration during the flushing

Conclusions

During the research activities in the field and consultations with colleagues from PWN water company in the Netherlands some interesting information were found. Among the most important are the following ones:

1) The sediment still moves in the water supply network even during the very low velocities,

2) Underground hydrants are the risky parts of the water supply network. Special care must be taken when handling them, as there is a risk of intrusion of contamination into the water mains from these locations.

3) Fine sediments are not uniformly distributed over the cross-sectional height of the pipe. At the bottom of the pipe, water can have a higher turbidity than at the top. This differential should be taken into the account when: 1) sampling for turbidity measurement in water supply networks, especially for online turbidity measurement 2) when designing self-cleaning networks, 3) when designing and constructing water connections.

4) In water networks without the chlorine-based disinfectant residual, it is advantageous to maintain a strong and stable biofilm in the pipeline, which may act as a "probiotic" to prevent the proliferation of pathogenic organisms.

Knowledge gaps and further research needs

Additional research needs to be directed towards understanding fine sediments and optimization of water mains maintenance, including:

1) Software tool for simulation of sediment formation and movement in the water supply network – it is not possible to estimate the formation and movement of sediments in the water supply network without a software tool based on a hydraulic solver (e.g. Epanet). Thus, there is a need to develop such a support tool, not only to prepare the flushing plan but also to optimise the flushing operations across different operating conditions. Those pipes that are at higher risk of sediment accumulation need to be flushed more frequently that the rest of the network.

2) Sedimentation rates for various types of sediments – in case of unexpected discoloration event occurrence, the dirty water can moves throughout the water supply network. If the sedimentation rate is better understood, a risk-based approach to managing discolouration risk could be implemented.

3) Linkages between measured turbidity and the mass of sediment – one key operational question is the frequency of flushing required for particular areas of the network. In current practice, water utilities are able to measure turbidity of the water entering the network and at specific locations. From the turbidity measurements, the ability to more accurately calculate sediment mass would be helpful in understanding accumulation across the network.

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Authors names: Ing. Jan Ručka, Ph.D. and Ing. Tomáš Sucháček

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Flushing Planning

The appearance of discoloured water in drinking water distribution systems (DWDSs) is one of the most common subjects of customer complaints (Vreeburg & Boxall, 2007). Although these complaints are often addressed in a reactive manner, in the last decade the focus is being shifted towards prevention or discoloration risk management.
To manage the discoloration risk in the DWDS, water utilities should plan and implement activities that can prevent the occurrence of the discoloured water. Typically, discoloration risk assessment is based on turbidity measurement data. Once a critical value of turbidity has been exceeded, a plan of network cleaning activities (or operations), like water flushing, is developed and implemented in the affected parts of network. In order to improve the efficiency of flushing planning (FP), a support graph-based algorithm can be employed.

Summary of best practices/tools/approaches

A flushing plan defines a series of flushing operations used to flush the pipes in a DWDS zone. A single flushing operation includes 1) the necessary valve manipulations for isolation of the pipes to be flushed, and 2) the actual flushing of the pipes connecting the clear water front and the hydrant. In respect to the country where the water utility operates, different guidelines are applied for the design of the flushing operations. For example, in the Netherlands, typically only pipes ranging in diameter from 50 mm to 150 mm are flushed. The minimal flushing velocity is 1.5 m/s, while the duration of each operation should be such that a minimum of three water volume turnovers is achieved in the pipes. The length of each flushing operation is governed by the available pressure head and the flushing head loss.

Commonly, flushing plans are derived manually. However, to optimize the process of the WDN flushing planning, a graph-based FP algorithm can be used. Such FP algorithm has been developed within the present research program. In general, the FP algorithm should be customized to comply with the appropriate guidelines used in each water utility. However, the main steps of the algorithm will remain the same.

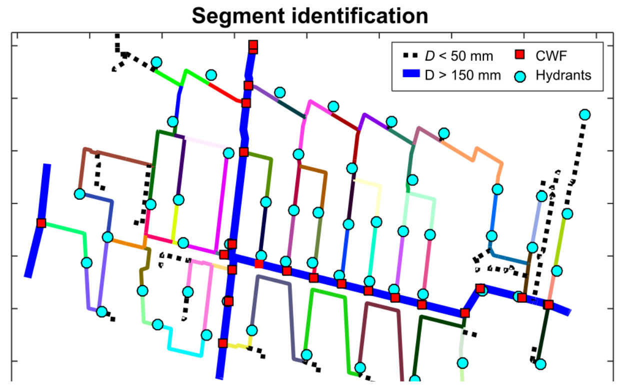
The input for the FP algorithm can be an EPANET model of the affected zone of the WDN. Roughness of the pipes should be determined through model calibration prior to the application of the FP algorithm.

The main steps in the FP algorithm are summarized below:

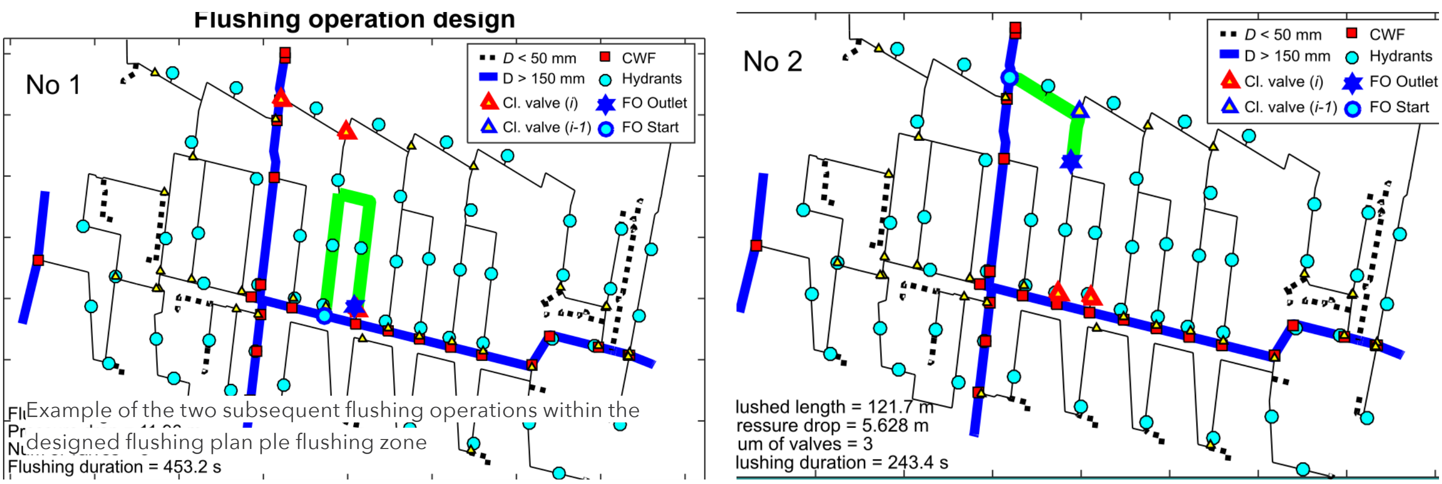
1. *Pre-processing of the EPANET model* – Detection of the target pipes in the affected zone of the network, based on the diameter criteria. Identification of the flushing outlets/hydrants. Identification of the clear water fronts.
2. *Identification of the flushing segments* – Flushing segments can be treated as the building blocks for the flushing operation. Flushing segments are defined as pipes connecting a clear water front inputs with hydrants, or pipes connecting two hydrants. Basic graph search algorithms, like Depth First Search (DFS), can be employed for this task.
3. *Design of the flushing operations* – A pool of possible flushing operations (from each clear water front input) is designed according to the appropriate flushing guidelines. Each flushing operation is a

made of one or more serially connected flushing segments. Appropriate valve manipulations must be identified for each flushing operation. Recursive DFS can be used in this step.

4. *Design of the flushing plan* – A suboptimal combination of the flushing operations, for the affected zone, is defined (minimal number of flushing operations and valve manipulations).



Identified flushing segments (in different colors) within the example flushing zone



Example of the two subsequent flushing operations within the designed flushing plan ple flushing zone

Conclusions/ future research needs

Design of flushing plans and related operations can be automated and optimized with the help of the graph-based FP algorithm. An EPANET model of the affected zone (part of the network that should be flushed) is used as the input. The design of each flushing operation, within the flushing plan, must be conducted in compliance with the local guidelines.

To allow for the unbiased valorisation of the achieved efficiency improvement, automatically generated flushing plans need to be compared with the existing flushing plans. The number of flushing operations and valve manipulations, alongside the total cost of the flushing activities, can be used as the parameters for this comparison.

Links to further material

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Authors names: Damjan Ivetić, Željko Vasilić

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Modelling of particulate matter transport in DWDS

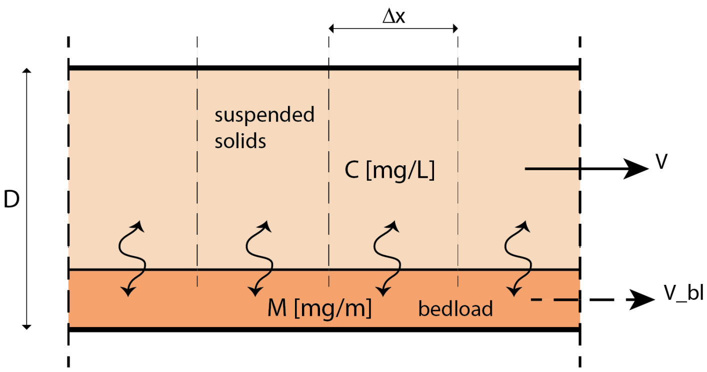
Modelling of particulate matter transport in drinking water distribution systems (DWDS) provides additional tools for optimization of flushing programmes and their planning, as well as better network design and sectorization. A new model, compatible with the EPANET environment, has been proposed and tested for this purpose. The model has been fully implemented in the 3DNet, GIS-based hydroinformatic tool. The model predicts the spatial distribution of particulate matter in DWDS and resulting discoloration risks.

Summary of best practices/tools/approaches

In order to model the distribution of particulate matter in DWDS, several important processes and mechanisms should be addressed:

1) Suspended particle transport,
2) Particle settlement,
3) Bedload transport, and
4) Particle resuspension.

Significance of each above mechanisms depend strongly on the short-term hydraulic conditions in the pipe, quantified by the dimensionless shear stress value. Depending on the actual value of the shear stress (based on EPANET hydraulics), a different set of transport equations is solved along the pipe.



Schematic representation of implemented mechanisms of the particle transport in the water distribution pipe.

Model application in the 3DNet environment.

Conclusions/ future research needs

The developed model potentially provides a valuable additional tool for better design and maintenance of DWDS in respect of discoloration issues. Further research is required to investigate sources of particulate matter, its mathematical description and model implementation. In addition, prevailing types of particulate matter are site specific and should be further investigated.

Links to further material

Van Summeren, J. and M. Blokker (2017). "Modeling particle transport and discoloration risk in drinking water distribution networks", Drink. Water. Eng. Sci., 10, 99-107.

Authors names: Nenad Jaćimović

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

Discolouration modelling tool: *Aquarellus*

In many countries, the main reason for customer complaints on drinking water quality is the occurrence of discoloured water at the tap. Water utilities take measures that are in part effective to reduce discolouration events: improving treatment processes to reduce the load of particulate matter that enters the distribution network, implementing self-cleaning networks (becoming more common in the Netherlands), and executing cleaning actions.

Commonly, the main sources of information to predict discolouration risks in drinking water distribution systems (DWDSs) are customer contacts and turbidity measurements. An example of the latter is the comprehensive and systematic measurements that PWN water company has conducted for many years in the Netherlands. Results from repeated cleaning actions on the same pipe sections suggest that that hydraulics is the driving force in the transport of particulate matter and contaminations can occur in a repetitive manner.

From these understandings, the wish originated to develop a numerical model that predicts how fast and where in the network particulate matter develops. Successful predictions can help optimize cleaning procedures, e.g. by adding target flushing actions at high risk locations or identifying effective turbidity measurement locations.

Summary of best practices/tools/approaches

KWR has developed the tool *Aquarellus*, based on the principles of particle settling, bed load transport, and resuspension (Van Summeren & Blokker, 2016) (Figure 1). To achieve numerical accuracy of the modelled transport processes requires a high numerical resolution and therefore long calculation times. This limits the practical application of the tool to networks of only a few km's and further development is required to shorten the calculation times.

The potential to obtain faster calculations was demonstrated by the Wat-Qual participants from Brno University of Technology. They accommodated the same theoretical framework as *Aquarellus* in a visualisation platform 3DNet and demonstrated that using a lower numerical resolution allows for faster calculations and how optimization tools can be used to find the input parameters that best fit turbidity measurements.

The University of Sheffield has developed the Variable Discolouration Model (VCDM, a continuation of the PODDS model), which assumes that matter attaches to pipe walls to form a cohesive layer which remobilises by erosion at high shear stresses. The model has been successfully validated for transport mains in the UK.

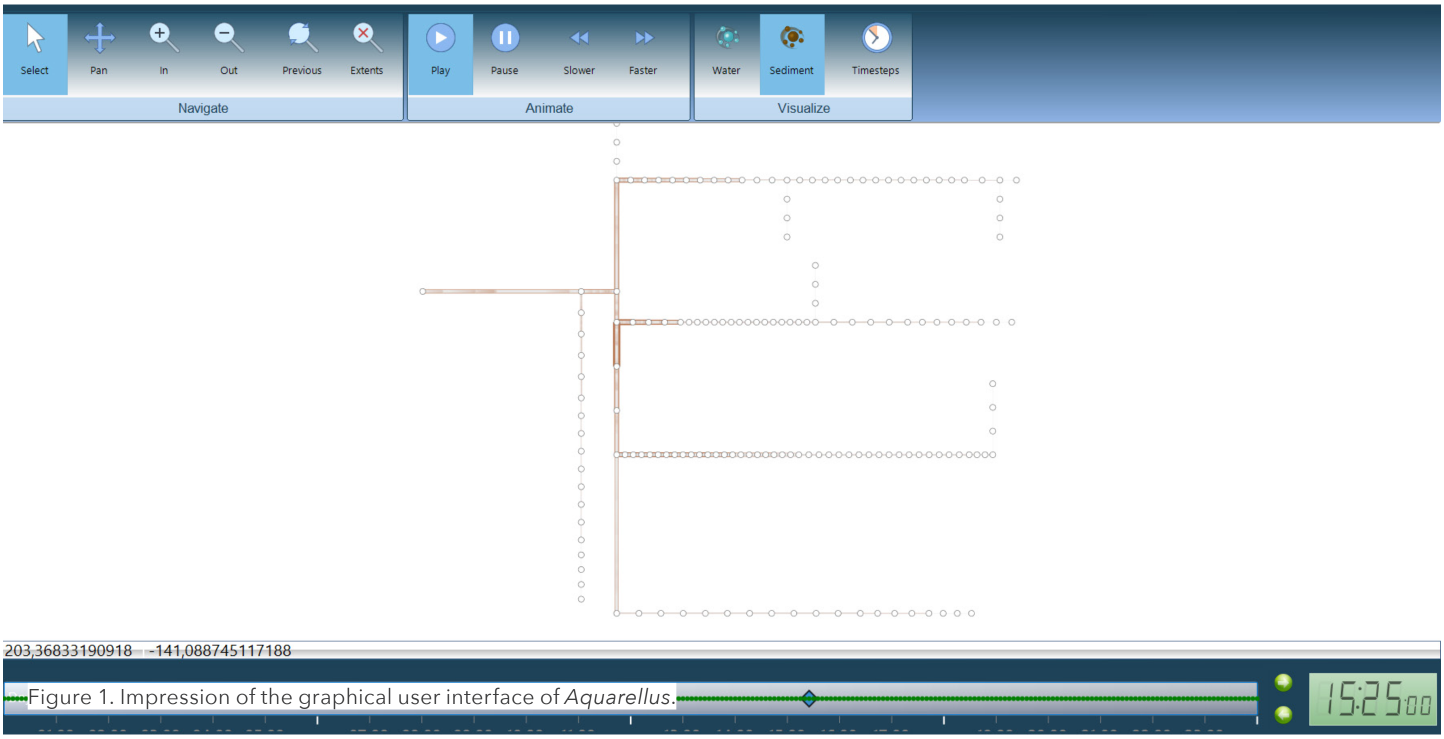


Figure 1. Impression of the graphical user interface of *Aquarellus*.

Properties of particulate matter can differ among DWDS across different countries, and even among supply zones within a DWDS. Because of their influence on particle transport, it is important to identify these particle properties for the successful application of predictive models. Several experiments have been performed aimed at determining the (distribution) of particle sizes (Figure 2) and gravitational settling velocity from flushing samples.

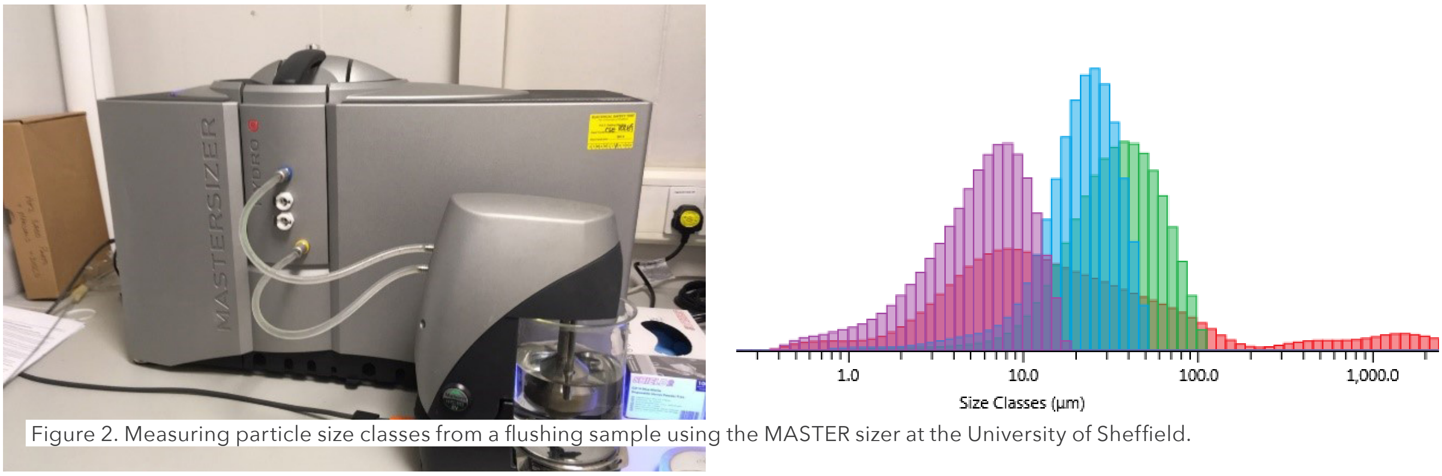


Figure 2. Measuring particle size classes from a flushing sample using the MASTER sizer at the University of Sheffield.

WAT-QUAL

Conclusions/ future research needs

While initial development of *Aquarellus* is now complete and this provides a valuable tool, there remain future research needs that include:

- meeting end user constraints on the practical applicability of the tool (such as reducing calculation times);
- determining particle properties using lab and/or field measurements to obtain relevant input parameters for *Aquarellus*;
- validating the model by comparing numerical results to (turbidity) measurements in real distribution systems.

Links to further material

Van Summeren, J. & Blokker, M. (2017). Modeling particle transport and discoloration risk in drinking water distribution networks, Drink Water Eng. Sci. 10, 99-107.

Authors names: Joost van Summeren

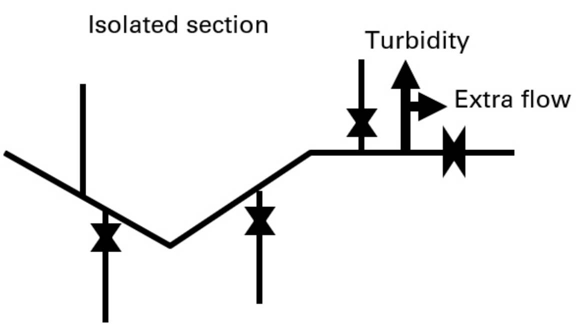
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

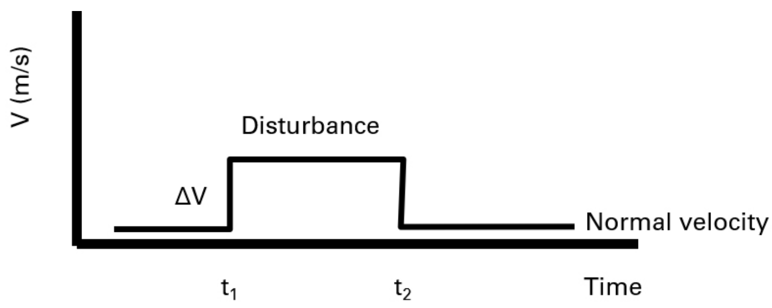
Resuspension Potential Method to Assess Discolouration Risk

Irrespective of the origin, the presence and mobility of particles in a water distribution system determines the discolouration risk. Customer complaints are an important identifier for discolouration risk but they are not suitable as a measure to quantify the risk: they are not reproducible or reliable and moreover they occur too late. By the time customers complain, the discoloration risk is already too high. To evaluate the discolouration risk, a uniform measurement method is needed. The Resuspension Potential Method (RPM), based on measuring the capability of the particles in a network to resuspend by a standardized disturbance and create visually noticeable turbidity levels, in widely in use in the Netherlands to address this need.

Summary of best practices/tools/approaches

The RPM is a uniform method to assess the discolouration risk in a specific main. By closing valves, a pipe length is isolated and prepared for a measurement. Opening a hydrant with a standardized flowrate creates a disturbance that is reproducible. In the Netherlands, a disturbance of 0.35 m/s (in a Ø100 mm this is 2,78 l/s) is used as standard. The duration of the test is standardized at 15 min, leading to a pipe length of 315 m measured. The turbidity is measured over the hydrant, using an online monitor or with grab samples. The results of this test help to select the high priority areas to flush by characterising the particle accumulation.

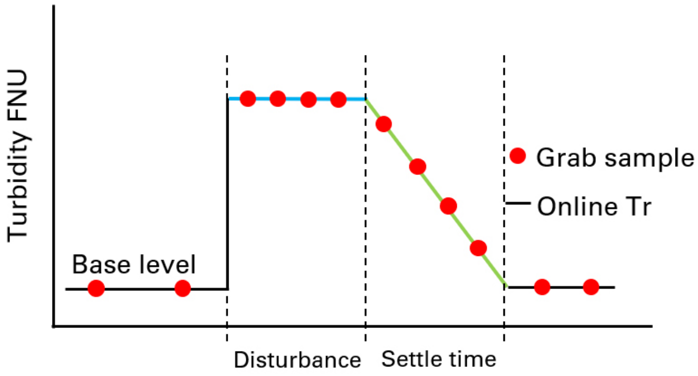




The power of the RPM is in its reproducibility and flexibility; conducting the measurement at every location in the same way creates the opportunity to compare locations, municipalities, DMAs, and service areas with each other. The comparison also works well over time, for example pre- and post- flushing to establish a measure for the effectiveness of the flushing process. It is also flexible, in height, length of the disturbance and interpretation of the turbidity, you can create your own standard.

The measurement is preferably conducted with an online turbidity meter that can measure at an interval of 1-10 seconds. Grab samples taken during standardized moments (for example 3, 6, 9 and 12 minutes of the disturbance) can also be used. Average turbidity is typically used a measure for discolouration risk. The RPM can be extended with a base level measurement and a settling period, giving additional information about the settling properties of the particles and therefore on the discolouration risk.

All the water companies in Netherlands are currently using the RPM, with their own thresholds for fouled locations, all depending on selected interpretation of turbidity. However, on the density of the measurements across a network there is more consensus, with most companies conducting on average 1 test per 12.5-15 km of pipe.



Conclusions/ future research needs

RPM is a uniform method to measure the fouling of individual pipes, and can be implemented across DMAs, municipalities and service areas to prioritise the need for flushing. It is a powerful and flexible tool.

Links to further material

Vreeburg, J.H.G., Schaap, P. and van Dijk, J.C. (2004). Measuring discoloration risk: resuspension potential method. Proceedings of the IWA Leading Edge Conference, Prague, 1–3 June 2004.

Vreeburg, J. H. G. (2007). Discolouration in drinking water systems: a particular approach. Ph.D. thesis report.

Authors names: Peter Schaap

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Prediction of Discolouration Events using Machine Learning

Water discolouration is an important issue in water distribution systems (WDSs). Although improvements have been made to reduce the risk of discolouration, discolouration is still largely dealt with by water utilities in a reactive way (Blokker, 2010; Cook et al., 2015). This note presents a new, machine learning (i.e. artificial intelligence) based turbidity forecasting methodology capable of predicting discolouration events, hours before these take place. This method, in turn, enables a more proactive approach to managing and reducing the risk of discolouration.

Summary of best practices/tools/approaches

The physically based turbidity prediction models are still rare. An example of such a model validated on a real WDS is the Prediction of Discolouration in Distribution Systems (PODDS) model by Husband and Boxall (2016). This model was developed for the cleaning of single pipes with minimal invasive action required. However, due to unknown pipe conditions and discolouration material build up rates, this model requires a hydraulic model with onsite model calibration before each use making it unsuitable in the context of continuous (rather than individual event based) turbidity prediction. The Variable Condition Discolouration Model (VCDM) builds upon the PODDS model and is capable of emulating material erosion and regeneration in pipes over time (Furnass et al., 2014). However, the VCDM is currently unverified as it requires repeated site-specific turbidity events for model parameter calibration and a calibrated hydraulic model to track the turbidity response.

As opposed to this, the turbidity prediction model presented here makes use of machine learning, i.e. it is developed directly from observed data on flows, turbidity and other system data. This approach overcomes the need for developing and calibrating a detailed hydraulic or any other physically based model.

Two separate data modelling approaches were taken, a direct prediction approach and a classification approach. The direct prediction approach for turbidity predicts the turbidity at a given location in the WDS at a specified period of time in the near future. The classification approach turbidity model predicts if the turbidity will be above a preselected threshold value, again at a given location and time in the near future (thus indicating the likely occurrence of a discolouration event).

An example of the direct turbidity prediction model for a real trunk mains system in the UK is given in Figure 1. This model was developed using Artificial Neural Networks. The model takes flow and upstream turbidity observations as an input to predict turbidity at the downstream location several hours into the future (output). As it can be seen from Figure 1, relatively accurate turbidity predictions are possible this way. Having said this, the other, classification-based approach, which is based on the Random Forest machine learning technique turns out to work even better and can, in this particular case, indicate the occurrence of a discolouration event with up to 6 hours lead time.

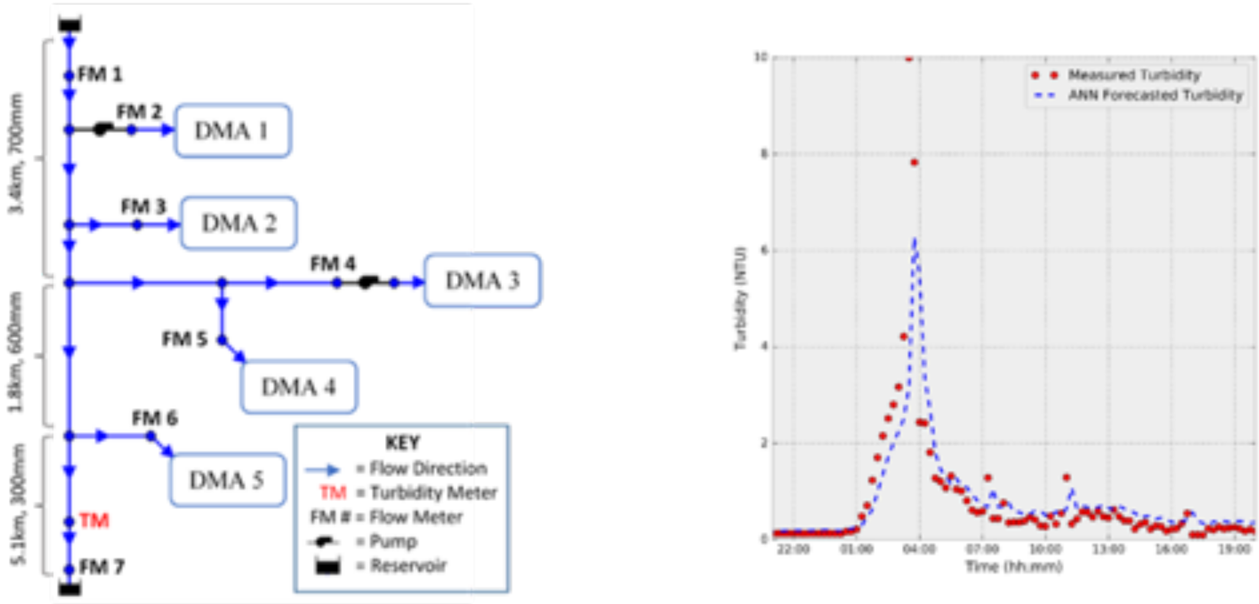


Figure 1: Forecasted turbidity (right figure) for the analysed real system in the UK at the downstream 'TM' location (left figure)

Conclusions/ future research needs

Predicting turbidity and assessing discolouration risk is still a challenging task. Building physically based models alone is unlikely to solve the problem of accurate turbidity/discolouration predictions. Machine learning and data-driven models have the potential to offer an alternative approach where the machine (i.e. a computer) can learn relevant patterns in data and build predictive models from it. Still, data-driven model on its own is unlikely to solve the challenge of accurate turbidity / discolouration forecasting either. The two approaches should be merged in the future in a suitable way thus building on the strengths of both physically based and data driven approaches.

Links to further material

Meyers, G., Kapelan, Z. and Keedwell, E., (2017), "Short-Term Forecasting of Turbidity in Trunk Main Networks", Water Research, vol. 124, 67-76., doi: 10.1016/j.watres.2017.07.035.

Authors names: Prof. Zoran Kapelan

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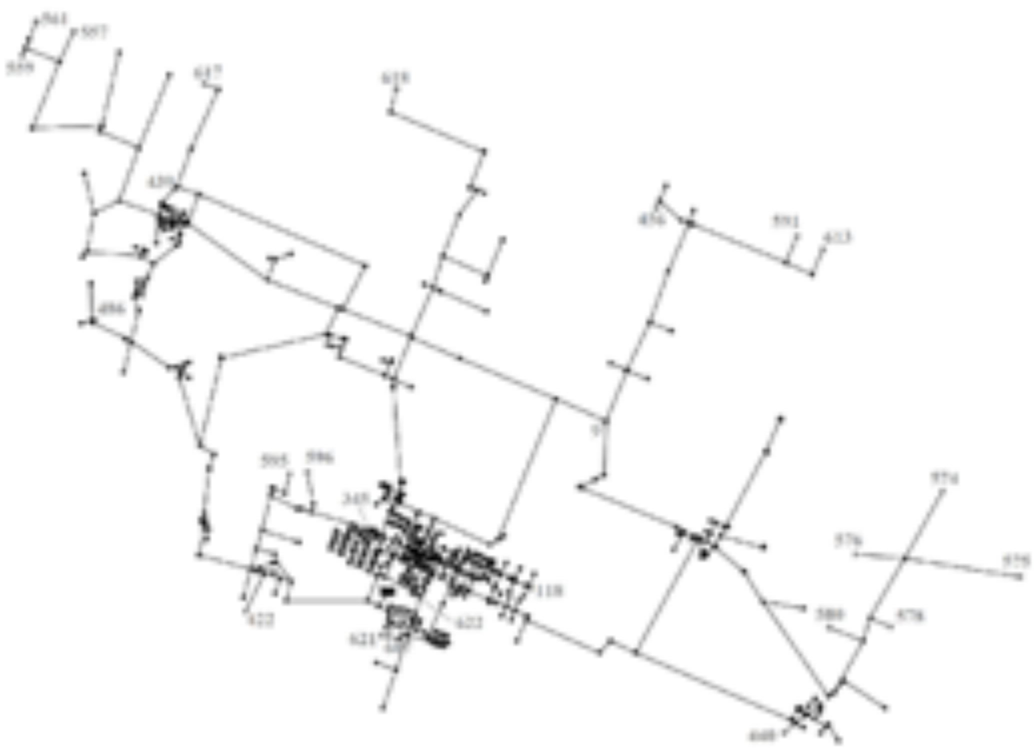
Low-flow/ trickle-flow flushing

In many European countries, water utilities must comply with minimum desired values of disinfectant (e.g., chlorine) concentration at all network nodes. Low flow velocities and high retention times in proximity to dead ends can prevent meeting of these minimum concentrations. The use of very high disinfectant concentrations at the source(s) or the installation of numerous disinfectant booster stations in the network may not suffice to solve this issue. A simple and cost-effective solution lies in installing a small tap at the hydrant site close to each critical dead-end and in leaving it dripping with the suitable water discharge to prevent water stagnating.

Summary of best practices/tools/approaches

Though this solution has never been tested on the field, its effectiveness has been corroborated by numerical simulations, the results of which are reported in Avvedimento et al., 2019. The resulting increase in water waste, around 2.5%, is marginal compared to leakage.



Layout of the network serving a town in Northern Italy with about 30,000 inhabitants. Grey nodes represent the critical dead ends with disinfectant residuals below the minimum desired value prescribed by the guidelines.

The following list of actions can be put into practice.

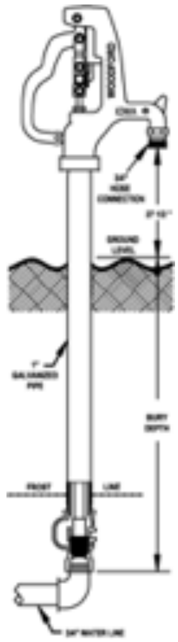
1) Identify the critical dead ends in a network (through numerical simulations or through field measurements of disinfectant residual concentration).

2) Install a tap in proximity to the hydrant.

3) Open gradually the tap until the outflowing water meets the desired value of disinfectant residual. The required flow can also be simulated with the network model.

The following pictures give an idea of the installation suitable for obtaining the trickle-flow at the hydrant site.

Site of a typical dry-barrel hydrant, in which a pressurized section of the pipe upstream of the orange boot at the bottom of the riser could be tapped. The riser is dry.



To obtain the trickle-flow, water utilities may want to install a device like the one shown upstream of the orange boot at the bottom of the riser.

Conclusions/ future research needs

A solution based on dripping hydrants is proposed to tackle the issue of low disinfectant residuals at dead-ends. Where hydrant sites are unavailable at critical dead-ends, dripping can be obtained at users' taps with similar positive effects. Thanks to incentives (i.e. grants for the installation of water reuse technologies), water utility managers may persuade users to store the lost water at remote nodes to be used for irrigation or other purposes.

Future research will be developed to optimize the solution described above in combination with the installation of disinfectant booster stations.

Links to further material

Avvedimento A., Todeschini S., Giudicianni C., Di Nardo A., Walski T. and Creaco E. (2019). " Modulating nodal outflows to guarantee sufficient disinfectant residuals in water distribution networks." Journal of Water Resources Planning and Management, submitted.

Authors names: Enrico Creaco

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

Self-cleaning networks

By designing networks in such a way that particulate matter does not accumulate over time, but instead is removed regularly by the increased shear stresses during every day peak demands, the discolouration risk can be kept low. The benefits are decreased cost of network installation (20%), decreased cost of network cleaning (100%), and increased customer satisfaction. There is no decrease in continuity of supply. Something to consider is the available hydrant capacity.

Summary of best practices/tools/approaches

In The Netherlands all 10 drinking water utilities are building their new networks according to the self-cleaning principles. This means all pipes in the streets, with a diameter < 160 mm are designed this way.

1. The layout is a branched structure (no closed loops).
2. The branch is connected to a looped backbone of 160 mm or larger pipes; the valves are located on the backbone.
3. The diameters are smaller towards the end; fitting the expected maximum peak demand and selecting a diameter that will then lead to ca. 0.2 – 0.25 m/s flow velocity.
   a) Expected peak demands are determined with SIMDEUM.
   b) This leads to diameters of PVC Ø110 mm, 63 mm and 40 mm pipes.
4. There are no dead ends. The last part of the branch is connected as a flowing end to the last customer.
5. Required hydrant demand is taken into account during the design phase. A capacity of 30 m3/h is possible on a Ø63 mm pipe. Large hydrant capacities may be possible on larger diameters, thus hydrant locations can influence the pipe trajectory / layout of the branch.

Example of network design with PVC (110, 63) and PE (50, 40) pipes and hydrants


PVC Ø63 mm to a hydrant, after that smaller PE pipes leading into a customer connection through a flowinng end.


Network of pipes and hydrants

Dutch drinking water utilities have discussed at length with fire departments on required hydrant capacity. New build areas, with modern fire codes, and standard housing heights can do with 30 m3/h. High rise buildings and special buildings such as hospitals or shopping centres require special higher capacities.

Design tools are available. The latest development is an automated CAD design tool to determine both layout and pipe diameters (Geowater).


Image/video caption

Conclusions/ future research needs

The Dutch drinking water companies have embraced this approach. For applications abroad some steps may be required. The self-cleaning (design) velocity of 0.2-0.25 m/s will depend on the water quality, and may be different for chlorinated water. This needs to be tested. This can be done in an existing network (of non-corroded pipes), possibly with the need to temporarily close some valves.

Also, a good estimate of daily peak demand needs to be determined for the supply area in which one wants to build a self-cleaning network. SIMDEUM can be used for this.

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Authors names: Miriam Blokker

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.778136.

Impacts of Chlorination

WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

The Impact of Disinfection Practices on Water Quality in Distribution Systems

Chlorination of drinking water, first pioneered in 1902, is used by some water utilities as a primary (at the treatment works) or secondary (within the drinking water distribution system, DWDS) disinfectant to control pathogenic microorganisms in the water. However, in 1974 disinfection by-products such as chloroform were found in disinfected water, formed by the reaction of chlorine with naturally-present organic matter, and these compounds are now known to be carcinogenic and are regulated.

At present, many countries still use chlorination to maintain a residual level of disinfectant at the point the water reaches the user as a safety barrier throughout the entire DWDS. However, some countries including Switzerland, the Netherlands and Germany, have moved to a DWDS operational configuration where residual disinfection is not utilised. Water utilities in these countries focus on advanced treatment to minimise concentrations of biodegradable material and thus inhibit microbiological growth, along with robust design and operation of their DWDS (Rosario-Ortiz et al., 2016). So the situation exists in Europe where neighbouring countries employ significantly different approaches to meet regulatory requirements yet little work has been done to understand the benefits and disadvantages associated with these approaches, to facilitate knowledge sharing among water utilities and researchers, and to identify best practices that could benefit all countries.

Summary of best practices/tools/approaches

One of the largest differences between different water utilities can be their practices around disinfection (chlorination). While some utilities do not use chlorine in the DWDS, others use varying concentrations and different forms, including free chlorine and chloramine (chlorine combined with ammonia). The targets for ideal chlorine concentration at the extremities of the DWDS vary between utility and there is little agreement among researchers about the true extent of microbial inactivation and biofilm growth control that is provided by different levels of chlorine. The presence of chlorine may impact not only the community of microorganisms present in DWDS biofilms but also their ability to be mobilised during flushing and their infectivity.

The use of chemical disinfectants also poses health risks in the form of disinfection by-products, which are formed by the reaction of chlorine with natural organic matter present in the water. Many of these compounds have been identified as carcinogens and are regulated in drinking water. However, much is still not known about the full extent of these compounds and their health effects and this uncertainty has been a significant driver in the choice to eliminate chlorine from DWDS in several countries (Speight et al., 2019). Non-chemical disinfectants like ultraviolet light may also play a role in maintaining water quality in the DWDS in future (Linden et al., 2019).

Water quality parameters including organic carbon content, metals including corrosion by-products, and inorganics concentrations can all react with disinfectants during travel in the distribution system and, as is the case for all chemical and microbial reactions, temperature plays a key role.

In a DWDS, customer demands for water dictate flows to a large extent and, along with the system configuration and operation, dictate the length of travel time, or water age, during which disinfectant reactions can occur. Therefore, a variety of interrelated factors, many of which are still poorly understood, contribute to the challenge of managing disinfectant residuals and related microbiological water safety in DWDS.

While this project was primarily concerned with disinfectant residual in DWDS, similar reactions resulting in loss of chlorine can take place in household plumbing. The understanding of the impact of plumbing materials, construction techniques, and water use on drinking water quality within buildings is a growing field of research.

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Authors names: Vanessa Speight

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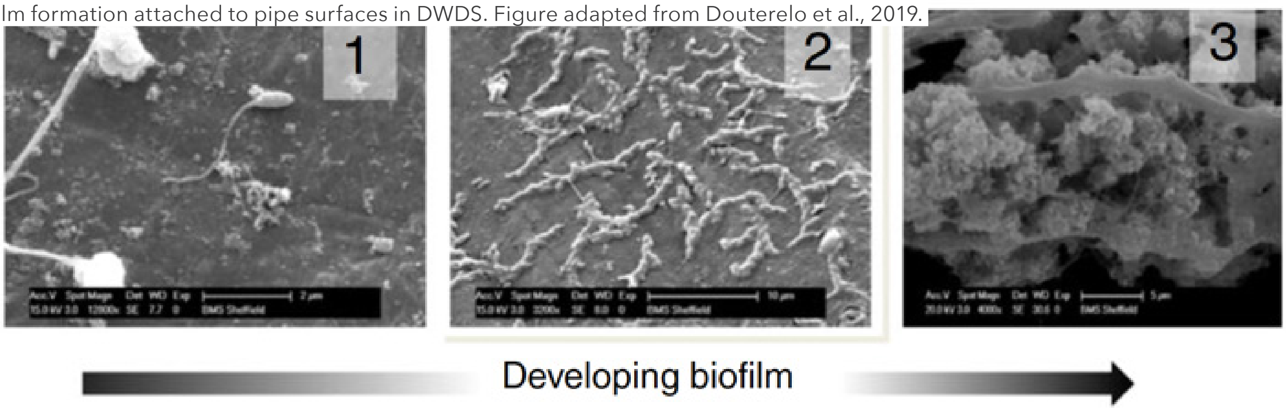
WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Biofilms and temperature

Despite the oligotrophic conditions inside the pipes, and the presence of a disinfectant residual used in some countries such as the UK, it has been widely demonstrated that drinking water distribution systems (DWDS) harbor microorganisms. The predominant form of microbial life in these systems are biofilms that develop on the inner pipe surfaces. Biofilm formation can lead to a large number of problems in these systems, including deterioration of the pipes, water discoloration or they can act as a reservoir of pathogens that can affect and modify water quality.

Biofilm formation attached to pipe surfaces in DWDS. Figure adapted from Douterelo et al., 2019.



Summary of best practices/tools/approaches

DWDS, and as a consequence their microbiome, are exposed to a large number of biotic and abiotic factors that surround them. For example, it has been demonstrated that pipe material or hydraulic conditions have important effects on the formation and development of biofilms in DWDS. Another factor that can modify these communities is temperature. Temperature in DWDS depends on the ambient ground temperature and its variation can produce important changes in these systems:

1. Temperature changes can modify processes occurring in DWDS, affecting the physico-chemical parameters or endothermic reactions such as solubilization, degradation, evaporation or dissolution. For example, the amount of chlorine used as a disinfection residual decrease at higher water temperature, lowering its effectiveness as a limiter of microbial growth.
2. Microbial growth rates are affected by changes in temperature, tending to be higher in warmer environments. Thus, an increase of temperature in DWDS can enhance the microbial growth in these systems.
3. In addition to growth, metabolic rates of microorganisms are also affected and depend on temperature. These metabolic rates include different biotic factors and processes such as respiration, fermentation, decomposition or degradation of different compounds, for example disinfectants, nutrients or contaminants.

4. The affinity of microorganisms for substrates also depends on the temperature. This affinity means that at different temperatures, the adhesion of microorganisms to the walls of the pipes can change. Together with the increase of microbial growth rates, the higher adhesion can lead to more developed biofilms, which could produce more DWDS problems related to biofilms such as discoloration or obstruction of the pipes.
5. Temperature can produce changes on biofilms microbial structure and composition. Different temperatures can benefit different groups of microorganisms, making them more competitive. This effect will increase the abundance of the more competitive groups, allowing them to displace others that could even be removed from the community. Therefore, different temperatures could lead to:
   a. Changes in the type of microorganisms that are part of the biofilms.
   b. Changes in the richness, dominance and diversity of DWDS microbial communities.
6. Increase of pathogens present in DWDS. Different species of pathogenic microorganisms are present in DWDS. Temperature changes could favor these pathogens, leading a greater occurrence of them in drinking water and resulting adverse impacts on human health.

Conclusions/future research needs

Temperature is an important factor that can affect biofilms in DWDS in different ways, many of which can compromise water quality. Due to the current processes of global climate change, which will cause changes in the temperature of DWDS, more research is needed to understand how the increase of temperature will affect the microbiome of these systems. This knowledge will help water companies to adapt and create new strategies to control microorganisms and preserve water quality in DWDS.

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Authors names: Carolina Calero Preciado & Isabel Douterelo

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Link between Weather and Water Consumption

Case study of the Netherlands

This note presents the analysis of the link between water consumption and weather in the Netherlands. Understanding this link is important for a number of reasons including the ability to do improved forecasting of water demands but also to better understand the likely changes in water quality in water distribution systems, which is very much driven by the advection process and hence influenced by demands.

Summary of best practices/tools/approaches

A lot of research has been dedicated to the drivers of water consumption, with the weather being consistently found in the literature among the factors that are used in order to explain demand variability. The work presented here focuses on the Dutch case.

The data analysed comes from 9 locations in the Netherlands, all with different household and societal characteristics (Table 1). The aggregated consumption of all houses in each location was recorded using smart meters at 1-minute intervals, from 1 July 2016 till 31 July 2017, by the Evides Water Company. The household and socio-economic characteristics of each location were derived from data publicly available from the Dutch Bureau of Statistics.

Locations	Description	Number of houses
1	Luxurious homes with gardens, mainly senior citizens	115
2	Terraced houses with gardens, mixed family composition	142
3	Luxurious homes with gardens, many double-income households	109
4	Luxurious homes with gardens, mainly double-income households and families with children	138
5	Apartments, mainly double-income households and families with children	–
6	Senior citizen flats	125
7	Luxurious terraced houses	112
8	Cheaper apartments, low-income households	117
9	Cheaper terraced houses with garden, mainly families with children	119

Table 1. Summary of Dutch Households with Recorded Water Consumption

Weather over the same time period recorded at the Rotterdam weather station was obtained and used in the analysis. Six weather variables: the maximum temperature (°C), global radiation, precipitation amount and duration, relative humidity and potential evapotranspiration were analysed.

The water consumption data was divided into a number of different groups using seasons (summer, spring, autumn, and winter), type of day (weekday, weekends and holidays) and time of the day (morning, afternoon, evening, and night consumption). For each data segmentation category and each weather variable, a model was fitted that described the best fit between consumption and a weather variable for each day in the data.

The results obtained show that link between weather and water consumption does exist in the Netherlands (see Figure 1). Air temperature and radiation have the largest influence on consumption, followed by relative humidity. No strong correlations were identified between water consumption and the precipitation amount or duration. In terms of different properties analysed, the results showed that households in countryside locations, as well as houses with gardens and affluent residents during summer and spring evenings of working days are the ones whose water consumption is most affected by changes in the weather.

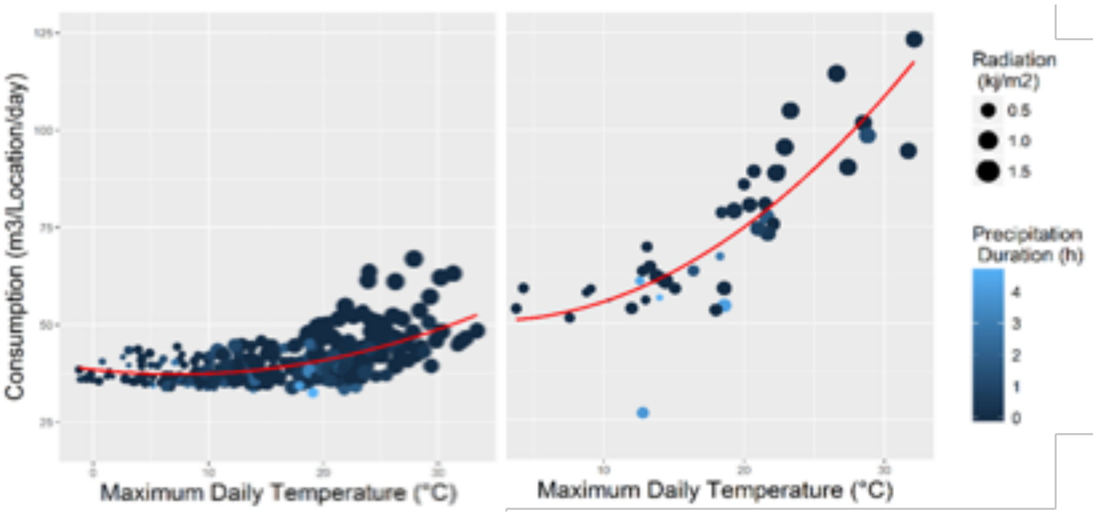

Figure 1. Correlation between maximum daily temperature and average daily consumption for all locations and days (left) a nd autumn evenings during working days for Land 4 (right).

Conclusions/ future research needs

The results obtained show that link between weather and water consumption exists in the Netherlands. However, this link still needs to be better understood. This will require collecting and analysing more detailed data on micro-components (i.e. individual water uses) of residential, commercial, industrial and other water users.

Links to further material

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Authors names: Zoran Kapelan and Maria Xenochristou

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

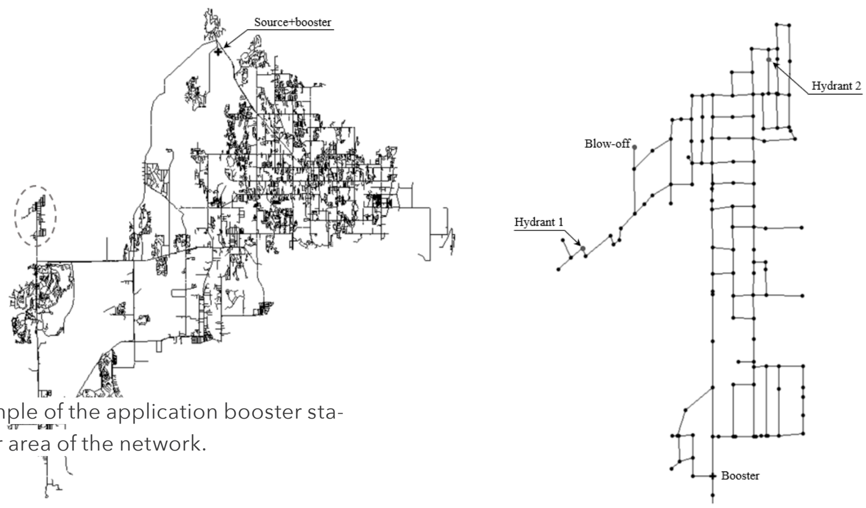
Maintenance of Disinfectant Residual through Booster Stations and Hydrant Operation

Maintaining a minimum disinfectant (typically chlorine) residual throughout a drinking water distribution system (DWDS) is an important task for public health. This issue becomes more complex in large and complex networks made up of numerous branches and dead ends, where low flow conditions and long residence times cause excessive chlorine decay. The operation of hydrants combined with disinfectant booster stations can improve DWDS water quality while requiring lower chlorine doses at the source. Booster stations facilitate suitable chlorine concentrations in the core of water distribution networks by adding disinfectant at distinct locations. Hydrants can be opened in proximity to critical nodes increasing the flow distribution and, hence, chlorine residuals.

Summary of best practices/tools/approaches

In the absence of field measurements, one approach for deriving indications of water quality in a DWDS consists of running a hydraulic/water quality model of the system. With the model, a system operator can estimate residual concentrations in the future under different operating conditions, which could include a change in water demand or a different chlorine decay rate.

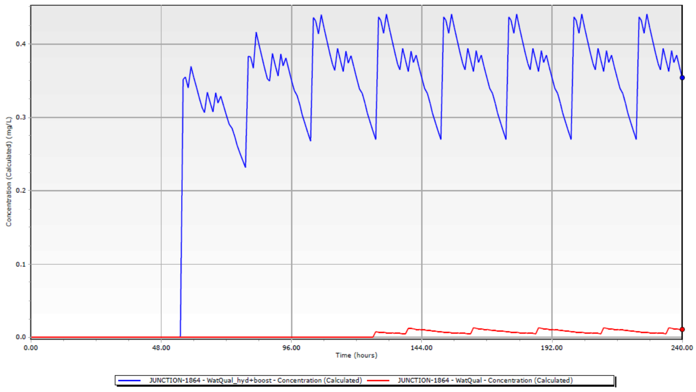
In a preliminary study, the combination of low flow through hydrants (or blow-offs) and chlorine booster stations was tested on a small area of a real network, with the goal of increasing the residuals of 62 nodes that show a chlorine concentration below the minimum threshold of 0.2 mg/L as required by the European regulation (98/83/CE).



Network layout and example of the application booster station-hydrants in a smaller area of the network.

A combination of opening hydrants at intermittent times (e.g. 10-15 L/s per day), a blow-off flowing all day long (e.g. 163 L/d) and adding an additional chlorine dose through a booster station (e.g. 2-3 mg/L), was able to meet the minimum concentration threshold, as shown in the following figure for a dead end node of the network.

Blow-offs with low flows all day long are needed in those dead-end nodes for which the use of periodic hydrants would be ineffective to solve the problem. Otherwise periodic hydrants flushing is preferred.



Chlorine concentration of the dead end node before and after the implementation of the solution, respectively in red and blue colors.

Conclusions/ future research needs

Preliminary water quality simulations show the effectiveness of booster station and flowing of hydrants in maintaining residuals throughout a network. Future work will extend the solution proposed to the entire network in order to optimize both chlorine dose at booster stations and hydrant operational settings.

Links to further material

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Authors names: Enrico Creaco, Stefania Avvedimento, Dominic Boccelli

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Biofilms and current state of knowledge

Microorganisms in drinking water distribution systems (DWDS), particularly biofilms (Figure 1) attached to infrastructure surfaces, govern critical processes impacting water quality and safety. Biofilm and material accumulation on pipes surfaces are affected by site-specific properties such as source water, pipe material and hydraulic regimes (Douterelo et al., 2014). The latest molecular microbial tools and techniques applied to these engineering systems have increased the understanding of DWDS ecology.

Summary of best practices/tools/approaches

Water utilities use standard culture-dependent methods, embedded in regulations, to monitor the microbial quality of drinking water. Culture dependent methods are convenient monitoring tools given that they are simple to perform and low cost. However, culturing methods are time intensive with water utilities waiting days for results and they account for less than 1% of the total microbial diversity in a sample (Douterelo et al., 2014). To circumvent the limitations of culture-dependent techniques in characterising the actual microbial diversity, molecular methods can be applied in DWDS to detect and quantify microorganisms.

Molecular methods are based on the information contained in nucleic acids (DNA/RNA) and are useful to monitor ecological dynamics in DWDS (Figure 2). Molecular techniques such as Next Generation Sequencing (NGS) are becoming more accessible and affordable for researchers and water utilities and will allow for the development of new monitoring tools and diagnostics of failures in DWDS. The used of this NGS methods in combination with environmental monitoring, has facilitated detailed investigations into microbial community, composition, and structure in DWDS (Douterelo et al., 2018). The main findings in DWDS that this holistic approach has generated can be summarised as:

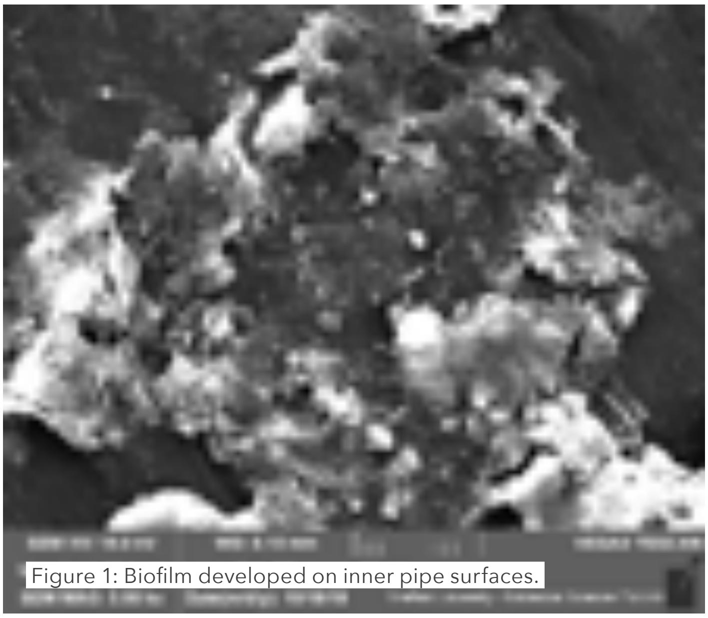

Figure 1: Biofilm developed on inner pipe surfaces.

1. Microbial biofilms demonstrate adaptation to specific network features and respond to system changes.
2. Pipe material and source water (groundwater vs. surface water) can influence microbial composition of biofilms.
3. Core microbial community members are found in DWDS with different characteristics. Most of the differences in the microbial community composition are generally due to less abundant species.

Conclusions/ future research needs

Future research should use integrated approaches to improve understanding of drinking water microbiology, combining a range of techniques, to link microbial diversity and activity to understand the relationship between microorganisms and DWDS function.

This work highlights that the study of biofilms and the use of new approaches such as environmental metagenomics are critical for strategy development to control microbial risks in DWDS and to provide water utilities with effective management strategies.

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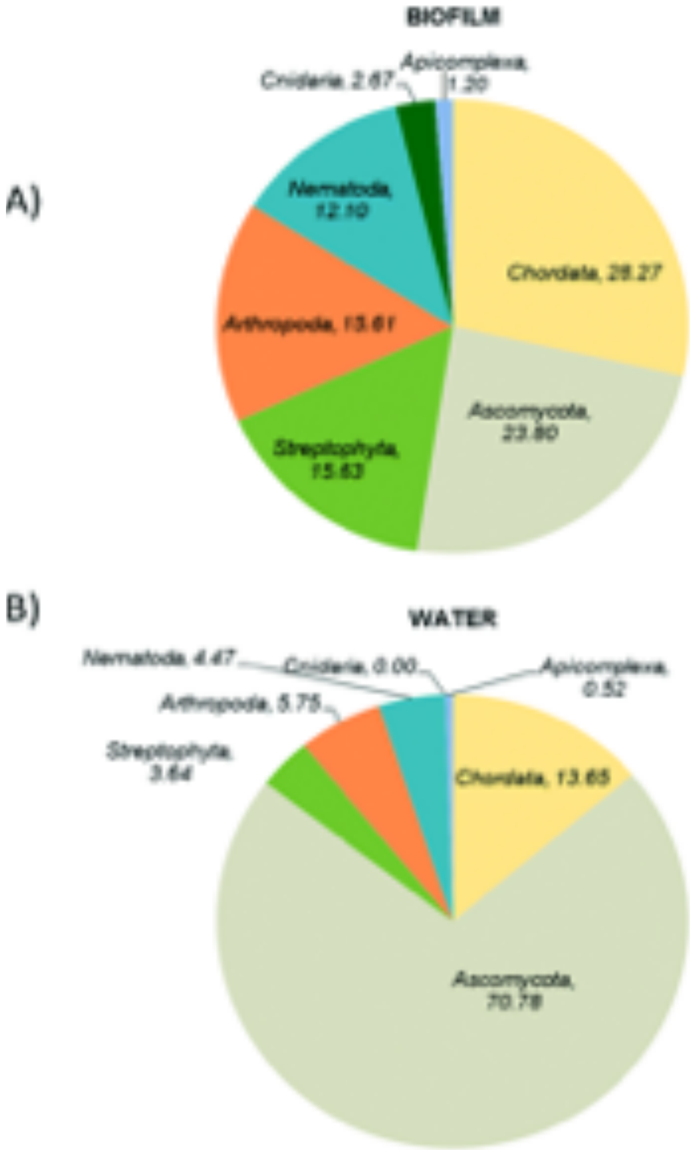

Figure 2: Taxonomic analysis of eukaryotes in the ground water supplied systems A) biofilm and B) water. From Douterelo et al., 2018.

Authors names: Isabel Douterelo

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Impacts of Maintenance/ Repair

The Impact of Repairs on Drinking Water Quality in Distribution Systems

External processes pose a threat to water quality during distribution. These external threats include contamination when the network is broken (pipe breaks or leaks) or under repair, corrosion from metallic pipes, and changing temperatures due to the soil conditions that the water is being transported through.

Best practices on designing the system with greater resilience to improve response strategies to ensure normal operation as smartly as possible are on one end of the spectrum, i.e. when things go wrong. Prediction of pipe breaks and prevention of active corrosion are on the other end, i.e. preventing things from going wrong. In the middle lies the operational considerations: performing repairs well and monitoring system performance to detect external threats, either using sensors to measure changes in water quality or to identify leaks and pipe bursts quickly. As distribution systems age, the degradation in pipe condition can lead to deterioration of drinking water quality and increased need for repair.

Maintenance and repair activities often represent the only time that the distribution system is exposed to the outside environmental conditions and thus are an opportunity for contamination to enter the system. Safe and hygienic practices for pipe rehabilitation and repair are required yet there is often little scientific evidence to support the selection or implementation of best practices.

Authors names: Miriam Blokker

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Event management and event response planning

Response to water network failure events (e.g. pipe bursts, contamination) plays a crucial role for a water utility when it comes to minimising negative impact on their customers (e.g. supply interruption, low pressure) as well as cost associated with addressing these events. Currently, response planning is carried out by utilities based on operators' experience without any automatism introduced in the decision-making.

Furthermore there is still need for 1) improved impact assessment in near real-time after events (e.g. real performance indicators used in the water industry, including discolouration potential), 2) more realistic selection of operational interventions, 3) effective exploration of the operator's proposed response strategies together with the automatically generated ones and their respective impact and 4) improved visualisation of response strategies and their resulting impact to the operators.

In this study, an overall response methodology that aims to fulfil the above need is proposed. The new response methodology is also integrated into an interactive decision-support tool aiming to enable operators make quick and informed decisions after the localisation of an event.

Response methodology

The response methodology consists of the following main steps: Step 1) initial impact assessment (i.e. before any intervention is implemented), Step 2) a solution is proposed by the operator and Step 3) an optimal solution is generated by using optimisation.

Note that these three steps do not need to be necessarily carried out in a sequential manner. The following three-stage routine is followed in each of the three steps: Stage 1) the operator inputs information/parameters into a decision-support tool, Stage 2) hydraulic simulations are carried out and the impact for each solution is calculated and Stage 3) the calculated impacts are visualised. The response methodology steps and stages are shown in Figure 1.

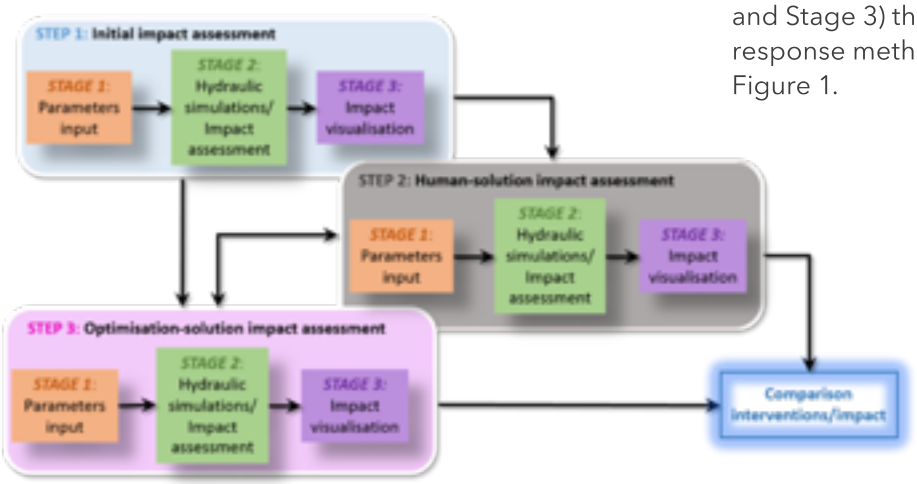

Figure 1: Response methodology steps and stages

The following impact indicators are used in the response methodology: 1) Average Minutes Supply Lost (AMSL), 2) Average Minutes Low Pressure (AMLP), 3) Undelivered Water (UW) and 4) Discolouration Risk Increase (DRI). The first three indicators are calculated for different customer types, namely: residential, commercial and sensitive (i.e. schools and hospital). The new response methodology is implemented into a decision-support tool entitled the Interactive Response Planning Tool (IRPT). IRPT links MATLAB software to the EPANET Programmer's Toolkit to execute the hydraulic simulations. It also links to Quantum Geographic Information System (QGIS) software to visualise the spatial distribution of impact on a map as well as to MS Excel for the visualisation of the numerical graphs. An example of implementation of the methodology into the IRPT is shown in Figure 2.

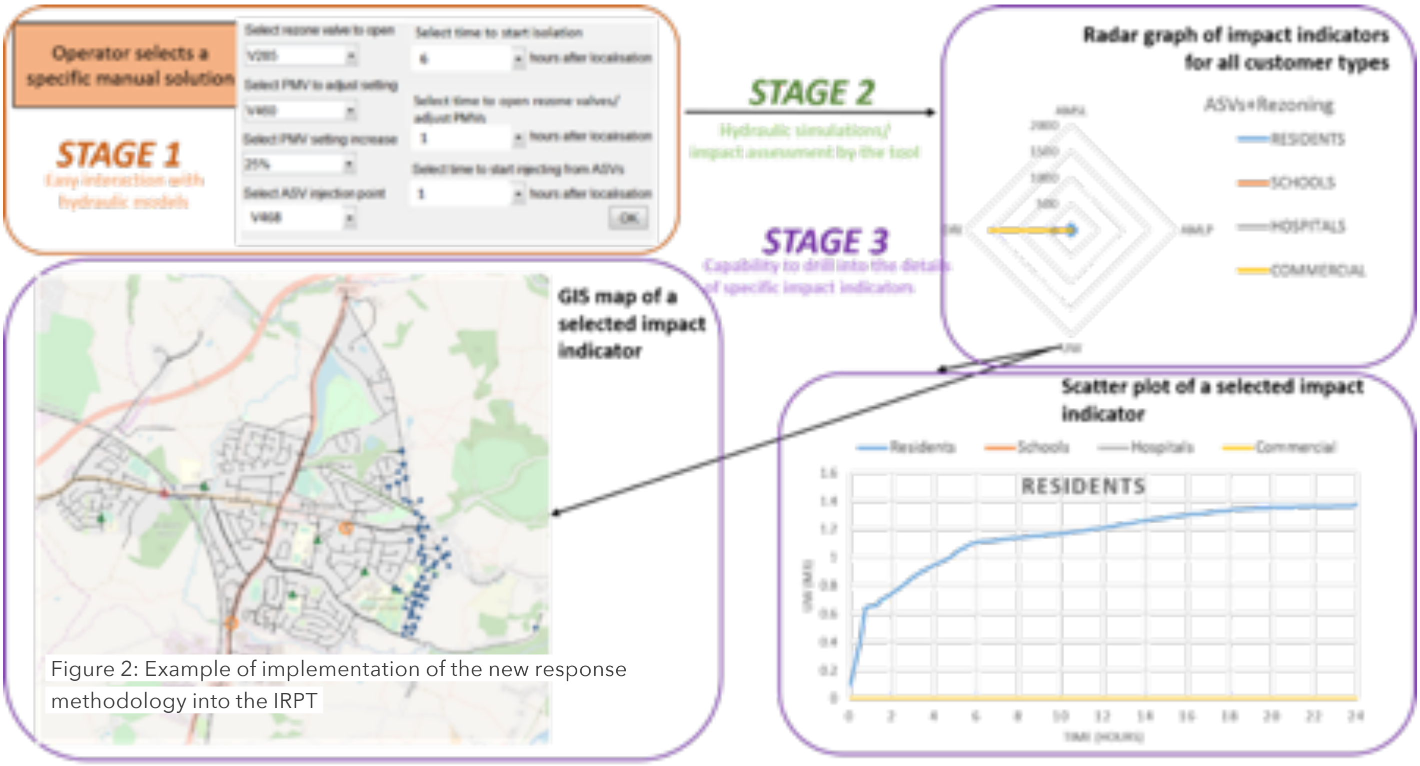

Figure 2: Example of implementation of the new response methodology into the IRPT

Conclusions/future research needs

The above methodology has been applied on a real water distribution network in Cheshire, England for an assumed pipe failure event. The results show that IRPT can support operators on calculating/visualising the impact and cost of manually-proposed solutions in near real-time (i.e. some minutes after event localisation). IRPT also identifies optimum response solutions (although still not in near real time) and also enables comparison between manually proposed and optimum solutions to identify the final best response strategy. Future work will focus on identifying optimum solutions in near real-time as well as improving visualisation of impact and cost for quicker and more accurate decision-making.

Authors names: Eirini Nikoloudi, Prof Zoran Kapelan

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

Pipeline Testing Before Commissioning – Requirements in 2 Case Study Locations

All work on a drinking water distribution system (DWDS) connected with the interior of the pipeline poses an increased risk of water contamination and could jeopardize hygienic safety. This risk exists even in the case of planned works such as construction of new parts of the water supply or reconstruction or repairs of existing lines. For all DWDS, therefore, in the event of any intervention in the pipeline and its subsequent re-commissioning, it is necessary to maintain certain safety principles that minimize the risk of subsequent distribution of microbiologically insufficient water.

Pressure tests and pipeline disinfection are therefore carried out before the water pipeline is introduced into operation. The purpose of these pressure tests is to verify the integrity of the pipeline and its resistance to internal overpressure. The purpose of flushing and disinfecting the pipeline after repair work is to flush out any impurities that may have entered the pipeline during the repair work.

Summary of best practices/tools/approaches

In the Czech Republic, the pressure test is carried out according to the requirements of the Czech technical standard CSN 75 5911 Pressure tests of water and irrigation pipelines, in effect since 2007. This standard specifies the requirements for the preparation, performance and evaluation of the pressure test. In the Czech Republic the (I) sectional test and (II) overall test are distinguished.

The value of the testing pressure (pz) of sectional pressure test depends on the material of the pipe:

$pz = 1.3 \cdot p_{p,max}$ [MPa]
for pipes made of plastic, asbestos-cement

$pz = 1.5 \cdot p_{p,max}$ [MPa]
for pipes made of steel, cast iron, glass, fiberglass or prestressed concrete, etc. (except reinforced concrete)

Pp,max is the maximum allowable overpressure determined according to the standard for the pipe material and fittings used on the water pipe section. The test is successful if the pressure drop is not greater than 0,02 MPa (or 0,03 MPa for asbestos-cement, reinforced concrete and pre-stressed concrete pipes) and if no visible water leakage is detected.

In Spain, the pressure test is carried out according to the requirement of the European Union DIN EN 805 Water supply - Requirements for systems and components outside buildings, in effect since 2000, or to the requirement of the Ministry Order of July 28th, 1974 approving the General Technical Prescriptions for drinking water supply piping.

DIN EN 805 sets the value of the testing pressure (STP) which is related to the maximum determined pressure (MDP):

STP = MDPc + 0,1 [MPa]

STP = 1,5 · MDPa or STP = MDPa + 0,5 [MPa]

(the smaller of the two values is selected)

Where MDPc is the calculated maximum pressure and MDPa is the set value.

European requirement makes no distinction between the segment test and the overall test.

Pressure decrease during this test should not be higher than 0,02 MPa for cast iron, steel, concrete and plastic pipes, or 0,04 MPa for fiber-cement and concrete pipes without steel sheath.

Pressure tests run according to Ministry Order of July 28th, 1974 approving the General Technical Prescriptions for drinking water supply piping are as follows:

$pp = 1.4 \cdot p_0$ [MPa or bar]

Where pp is the testing pressure and p_0 is the pressure in operating conditions (its range is 0.2 to 0.5 MPa). Test duration is 30 minutes and the pressure gradient in time from p0 to 1.4·p0 cannot be higher than 1 kg·cm^{-2} per minute. (1 kg·cm^{-2} = 0,98 bar)

The pressure test is successful if the pressure loss is not higher than square root (pp/5).

Sectional pressure test and disinfection of water pipes PE 150. For disinfection NaClO2 was used.
Testing pressure: 8 bars. Chlorine concentration in testing water: 310 ppm.

Conclusions/ future research needs

Pipeline disinfection is normally a part of pressure tests. When carrying out planned repairs, where the pipeline is disinfected and pressure tested, sufficient time must be taken to ensure that the tests are carried out to the proper extent, not shortened, and carried out on all sections concerned. Any possible microbiological accidents that may occur if the flushing of the pipeline to be replaced should be avoided.

Links to further material

DIN EN 805. Water supply - Requirements for systems and components outside buildings. 2000.

Ministry Order of July 28th, 1974 approving the General Technical Prescriptions for drinking water supply piping. (in Spanish)

Czech technical standard. CSN 75 5911 Pressure tests of water and irrigation pipelines. 2007.

Authors names: Jana Novakova

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Sectorisation of drinking water distribution systems

Sectorisation of drinking water distribution systems (DWDSs) into District Meter Areas (DMAs) is a proven measure for proactive leakage and pressure control. Improved contamination spread control is another possible benefit, as parts of the network become isolated. Sectorisation of DWDS must be designed carefully, as required network interventions can endanger water supply and pressure distribution. Complexity of the real life DWDS results in many different alternatives in which network sectorisation can be done. Sectorisation of DWDS into an optimal system of DMAs is a hard task to achieve, especially for the existing and continuously operating DWDS. Beside general criteria (e.g. DMA size, network length), the sectorisation process should be driven by case-specific criteria such as the required number of feeds, fire flow regulations, etc.

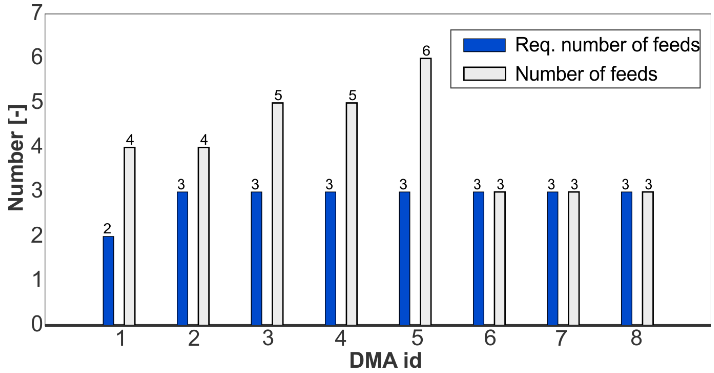
Summary of best practices/tools/approaches

A District Meter Area (DMA) is a distinct hydraulic area of the DWDS, separated from the rest of the supply system by isolation valves, with one or more metered inlets and outlets. Every DWDS is unique in its topology and characteristics and key sectorisation objectives so there is no common procedure for sectorisation of DWDS into DMAs but rather a series of guidelines provided by the different water and other authorities (e.g., Farley, 2001). Sectorisation solutions are usually obtained by "trial and error" conducted by a local expert, familiar with all the DWDS specifics. A more formal approach to the sectorisation problem that enables investigation of alternative sectorisation solutions for large DWDSs while adopting local design criteria is presented here.

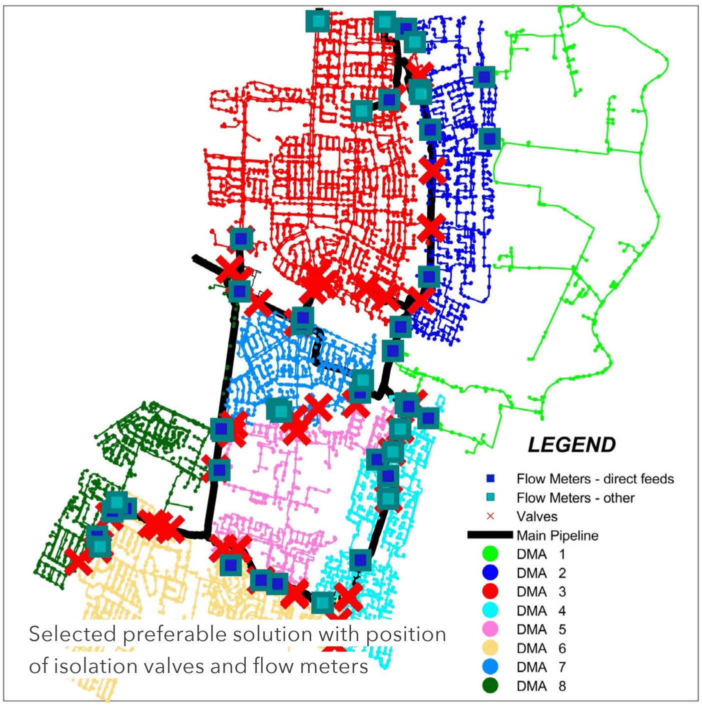
The automated sectorisation algorithm requires a calibrated model of the DWDS in consideration (in a form of an EPANET input file). The minimum investment for field implementation and maintenance of the same level of DWDS operational efficiency are adopted as the two main design criteria. The algorithm has four (4) general stages:

1. Pre-processing stage – all relevant data are obtained from input file and prepared for the following stages,
2. Network clustering stage – Clustering is done based on a novel Uniformity index metrics (Vasilic, 2018) which drives the clustering process and identifies clusters,
3. DMA creation and evaluation stage – The narrow set of clustering solutions is selected, based on the Uniformity index value (U), for the following hydraulic analysis. Each clustering solution from the set is subjected to genetic algorithm (GA) optimization to yield the near optimal locations for placement of isolation valves and flow meters, converting clusters to DMAs. Feasibility of the solution is imposed through several penalty functions used within the objective function (OF), penalizing each solution with a proportional penalty value (C_iP_i):
   $OF = Cost + \sum C_i P_i$
   The objective function is minimized in the optimization procedure. The solution is deemed to be feasible if: a) network pressure is within the predefined range (pmin-pmax) and b) the number of direct DMAs' feeds is greater than minimum required for the corresponding DMA size.
4. Selection of preferable sectorisation solution – The decision maker can choose preferred solution among number of feasible solutions.

The described sectorisation algorithm was tested on a part of Amsterdam's DWDS – Amstelveen, for which input data was supplied by Waternet. The investigated part of the network is fairly large (12 479 links, 11733 nodes and average consumption of 145 L/s) and the algorithm was able to identify a set of feasible sectorisation solutions in a computationally efficient manner, which in turn enabled exploring alternative sectorisation strategies by changing the input parameters.



Comparison of required and achieved number of direct feeds for each DMA in selected solution



Selected preferable solution with position of isolation valves and flow meters

Results are conveniently exported to Google Earth

Conclusions/ future research needs

The sectorisation algorithm is a decision support methodology valuable to practicing engineers who are commencing implementation of a sectorisation strategy in DWDS. General sectorisation criteria are supported as well as the required number of direct feed lines to DMA (subject to local guidelines). Future development should address adding sectorisation criteria such as design for fire flows, specific water quality parameters (e.g. chlorine), and design for security.

Links to further material

Farley, M. (2001). Leakage Management and Control : A Best Practice Training Manual, 1–169. Retrieved from https://apps.who.int/iris/bitstream/handle/10665/66893/WHO_SDE_WSH_01.1_eng.pdf?sequence=1&isAllowed=y

Vasilic, Z., Stanic, M., Kapelan, Z., Prodanovic, D. and Babic, B. (2020): Uniformity and Heuristics-Based DeNSE Method for Sectorization of Water Distribution Networks, Journal of Water Resources Planning and Management (accepted, waiting publication –doi: 10.1061/(ASCE)WR.1943-5452.0001163)

Authors names: Zeljko Vasilic, Damjan Ivetic

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Online Sensors for monitoring water quality

Water quality is typically monitored using classical chemical/physical parameters such as electrical conductivity, turbidity, temperature, and pH. In recent years, there have been numerous technical developments in online sensors. These advances enable the monitoring of parameters that in the past could only be analysed in the laboratory. This fact sheet gives an overview of current monitoring methods.

Summary of best practices/tools/approaches

Figure 1 divides the available technologies into four classes of sensors: biomonitors, traditional, spectroscopic, and biological.

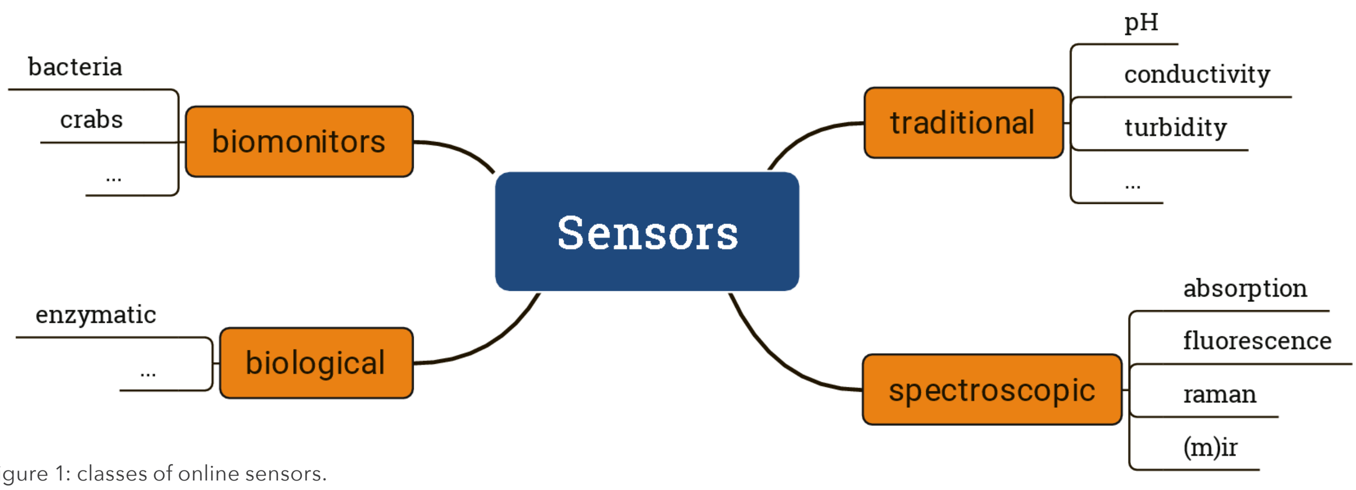

Figure 1: classes of online sensors.

In addition to the traditional physical/chemical sensors there are several new developments.

Biomonitors are based on the principle of monitoring indicator organisms and are used to detect water quality changes that can be detrimental to health. The organisms that can be used include crabs and fish, whose movement patterns are analysed, and bacteria, whose fluorescence is monitored.

Biological sensors detect the bacterial concentration. This detection can be done non-specifically, as is the case with flow cytometry (determination of total cell counts) or specifically using enzymatic reactions (determination of coliform bacteria, E. coli). Flow cytometry is becoming more established (Switzerland and other countries). Methods that are more specific are still in the trial phase and often lack the sensitivity for use in drinking water.

Spectroscopic sensors are based on absorption, fluorescence or scattered light measurements (Raman spectroscopy). Especially in the field of process analytics in the chemical industry, these methods are established due to their comparatively high selectivity (NIR, Raman). In the drinking water sector, however, UV/VIS absorption is more commonly used, with which parameters such as dissolved organic carbon (DOC), turbidity and nitrate can be estimated. Fluorescence is also used in the monitoring of surface waters for the determination of chlorophyll.

Figure 2: UV/VIS absorption probe.

Conclusions/ future research needs

With the sensor classes shown in Figure 1, numerous parameters can now be recorded. In certain individual cases, trace substances can also be detected (e.g. BTEX compounds in the µg/L range using UV/VIS absorption). Research is still needed to increase the selectivity (biological sensors) and sensitivity in general (e.g. biological sensors, Raman spectroscopy). Many sensors do not have sufficient sensitivity to prove defined limit values for compliance with WHO or national regulations (e.g. limit values for microbiological parameters). Currently, they therefore have a pure indicator function.

Links to further material

Wagner, M. et al. (2017): Online-Sensoren: Überwachung des Rohwassers bis zum Trinkwasserverteilungsnetz. In: Zukunftssicherer Betrieb von Wasserversorgungsanlagen, TZW-Schriftenreihe. Band 75.

https://www.resiwater.eu/publications/

Authors names: Martin Wagner

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WAT-QUAL WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS

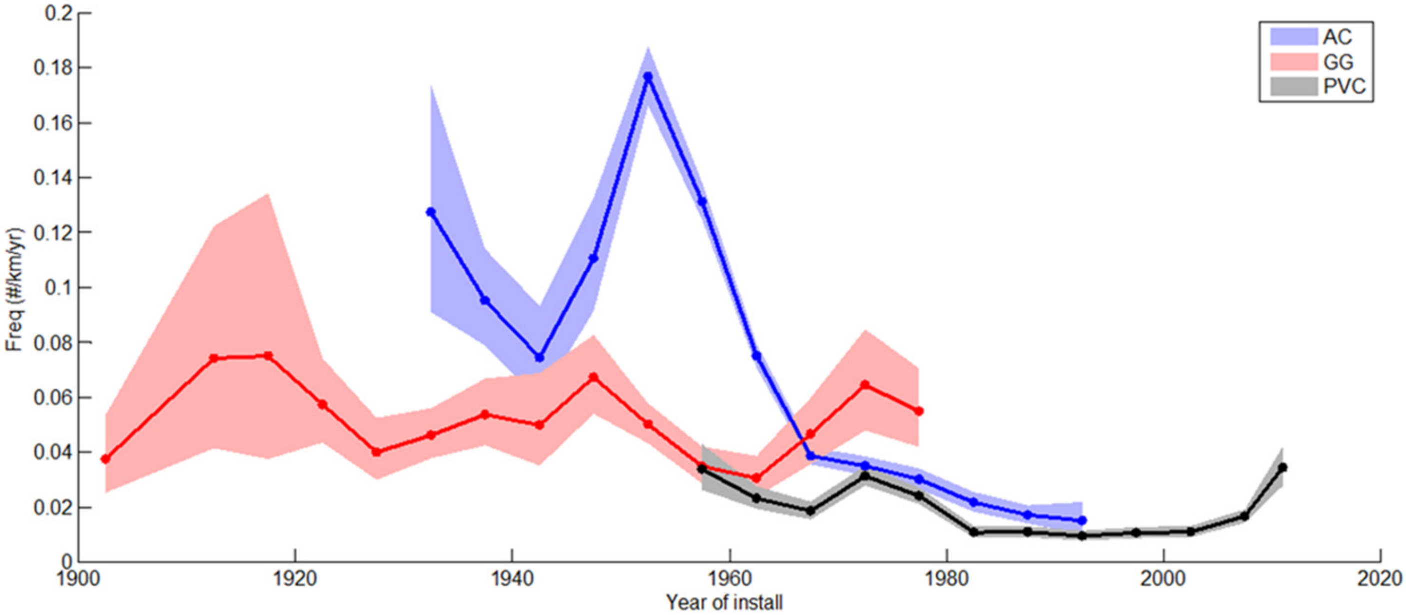
Pipe burst rate prediction

Pipe bursts cause water loss, customer minutes lost (CML), repair costs and possible burden or damage to surrounding environment. Moreover, pipe bursts mean the - otherwise sealed - drinking water distribution system is open and therefore constitute a risk of water quality being compromised. Assessing, modelling and predicting the burst rate provides a way to quantify the state and performance of the distribution network. Short-term prediction helps with prioritizing renewal projects to optimally increase network performance. Long-term prediction helps a utility to make informed decisions about preparing for the deterioration of their infrastructure.

Summary of best practices/tools/approaches

In the Netherlands and Flanders, eleven drinking water utilities collaborate to predict the performance and burst rate of their distribution network. The following four activities are key, both in the utilities' activities and in the joint research that KWR performs with them:

- Failure registration – failure registration is a top-down measurement of the condition and performance of the distribution network. Dutch water utilities register every case of unforeseen maintenance. In each case, the nature of the failure (e.g. failure mode, probable cause), the properties of the main (e.g. age, material) and its context (e.g. surrounding infrastructure, soil type) are recorded. Nine Dutch utilities collaborate in sustaining a collective database of uniformly registered failures, Ustore, so that data may be shared and statistic inference about the performance of specific types of mains can be based on data of good quality and quantity.
- Condition assessments – condition assessments provide detailed information on the physical state and condition of specific pipes. The Dutch utilities currently mainly perform tests on pipes taken out of the ground (exit assessment), for instance to further evaluate failure causes and to construct a more detailed image of the state of the network. Many Dutch utilities are performing pilots with non-destructive, in-line inspection techniques, so that they may know the condition ahead of maintenance or renewal. The Dutch utilities are supporting the development of an autonomous inspection robot that will continuously perform inspections on new parts of the network.
- Condition modelling – condition models provide a means to translate information about the physical properties of mains and their environment to knowledge about main condition and the expected burst rate. Ideally, these models are fed with data from condition assessments and validated with data from failure registration. Condition models are an essential tool to extrapolate the condition (and its uncertainty) of mains for which only partial information is available. Eight Dutch utilities have recently started using the condition model Comsima, embedded in the larger context of their decision support software.
- Risk assessment – expected burst rates primarily help Dutch utilities to prioritize their maintenance and renewal. To this end, extensive decision support is used to identify the mains which pose the highest risk to performance (risk = burst rate * burst effect). In their joined research programme, the Dutch utilities have taken the first steps to include possible effects regarding contamination due to maintenance in this assessment.



Failure rates of asbestos cement (AC, blue), cast iron (GG, red) and PVC (black) pipes. Based on failure registration data of Dutch water utilities.

Conclusions/ future research needs

Getting a good estimate of the physical state of the drinking water distribution network and translating this to a pipe burst rate prediction requires substantial effort in the way of data collection. Building up databases of historic failure data and condition assessments is arduous, costly work that will only truly start paying of once a certain critical mass of data is accumulated. The Dutch water utilities have started with this in the past decennium, and are now starting to reap the rewards. Now that the typical failure rates of specific groups of pipes are starting to become quantifiable, the utilities more and more turn their attention to the prediction of failure probabilities of individual pipes. This will only increase the need for detailed data on the pipe and its environment, and calls for more detailed condition models that are able to take more location specific influencing factors into account.

Links to further material

Van Thienen, Maks and Yntema (2016) Robots inspecting drinking water pipes. H2O water matters 2. Available at: http://www.h2o-watermatters.com/?article=2016123.

Vreeburg, Vloerbergh, van Thienen and de Bont (2013) Shared failure data for strategic asset management. Water Science and Technology: Water Supply 13:1154-1160.

Wols, Moerman, Horst and van Laarhoven (2019) Prediction of Pipe Failure in Drinking Water Distribution Networks by Comsima. Proceedings 2018. Available at: https://www.mdpi.com/2504-3900/2/11/589.

Authors names: Karel van Laarhoven

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