Experimental studies on the biofilm growth and sediment accumulation within drinking water distribution networks

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Abstract
Primary aim of the paper is to outline the methodological achievements for the investigation of complex processes of secondary water quality deterioration in water supply network of large distribution systems.

The results of the multiple year projects were obtained in two experimental fields; samples were analysed during network flushes and cleansing as well as a pilot was built and run for 2 years. Results of the flushing were investigated in details both in terms of flushing efficacy as followed by the water quality parameters and microscopic investigation. Parallel to the on-site investigations and following analyses a pilot system was designed and constructed containing various pipe diameters, flow velocities and pipe materials all characteristics to the real urban system of Budapest. Within the pipe system we maintained constant flow velocities and feed the actual water to be supplied to the real system. Regular monitoring was conducted to investigate the aging processes, the rate of biofilm formation, sedimentation patterns and corrosion processes. The pilot also contains artificial surfaces for bacterial colonization that are regularly removed following an appropriate exposure time (every quarter year). These artificial substrates were investigated using light microscopic techniques to establish data on the rate of biofilm formation and to provide estimates on developing biofilm thickness and porosity. For the in-situ investigation of the experimental pipe system endoscopic technique was also used to detect sediment formation points and to assess sediment formation rates depending on the applied flow rates within the given pipeline.

The results of the investigation are aimed to provide predictions for the operator to optimize the regular O&M works (i.e., flushing sites and frequencies) to prevent secondary water quality deterioration within the water supply system.

Keywords
Biofilm; corrosion; sedimentation; water quality deterioration

INTRODUCTION

A principal aim of every water supplier is to provide safe drinking water in the desired quantity and quality. To achieve this goal the waterworks all around the world utilize ample resources to clean the water produced according to the relevant regulations and standards. There is however another challenge the suppliers are facing: the water produced and treated has to be transported to the costumer, preferably without any undesirable changes in the quality. So it is obvious that the quality of the distribution network has a serious impact on the quality of the service provided by the waterworks.

Maintaining the quality of the water in the distribution system is ensured by a twofold procedure: introducing a disinfecting agent in the water and ensuring a suitable clean environment within the distribution lines. The disinfectant ensures that the distribution network will not be the source of secondary contamination. However, the pipe network can be the source of not only biological, but physical contaminants also, in extreme cases even quenching the effectiveness of the disinfectant present in the water.

The method used to clean the distribution network (with diameters between DN80 – DN 100) is regular flushing. The frequency of flushing is determined by the "best practice" established on the experience gained during the multiple decades of operation. Budapest Water Works (BWW) supplies water since 1868, accumulating considerable amount of experience in every aspect of the operation of water distribution systems over the years, including the flushing frequency too. This experience however is based on conditions that drastically changed over the past few decades. The considerable increase in the service costs and the technological advances resulted in drastic decline of water consumption over the last two decades. The climate change influences in a yet unknown way the properties of the water produced, and the available sources of water are subject to a previously unknown and very diverse anthropogenic loads. It is imperative to develop a methodology for handling the aspects of water supply industry that were based on empirical experiences, because the suppliers will not have the luxury of a 100 years to adapt to the changes described above.

This paper presents the methodology used to examine the biofilm developed and the sediment accumulated in the distribution network. We examined the aging of the biofilms and the dynamic of the sediment accumulation following flushing, aiming to determine the time when the biofilm growing over the pipe walls and the sediment accumulated will become mobilized, as this is considered to be the critical time frame when the flushing becomes a necessity.

METHODOLOGY

During the research of the processes resulting in secondary contamination we focused on several areas. We examined the quality and quantity of the suspended materials removed from the system during flushing, conducted experiments regarding the monitoring of the growth and aging processes of the biofilm developed on the surface of the pipe walls as well as the mobilization potential of biofilm layers. Both of these areas required different experimental, measurement and data processing method, the presentation of which is beyond the scope of the present paper, so after a short description of each method used we present an in depth analysis of the results obtained from the water distribution network flushing experiments. Moreover, as the different areas covered are in a strong connection with each other, we present the relations between the conclusions reached based on the different areas analyzed under the scope of our research – without a detailed presentation of the results. The following experiments and measurements were conducted within the scope of our research and development project.

Investigation of pipes obtained from water supply network reconstruction

One focus area for our research was the measurement of the biofilm thickness developed over the pipe walls, and we conducted laboratory experiment to determine the potential abrasion and wash off the biofilm layers developed over the years of standard operation of the distribution network. The results of these experiments are not detailed in this paper.

Experiments with the Distribution Network Model Device (DNMD)

The device constructed at BWW's pumping station at Káposztásmegyer (Budapest, Hungary). It was designed with regard to its size and operation to emulate the biological, chemical and physical processes present in the water distribution network. It provides the opportunity to conduct various experiments and measurements regarding the biofilm development and aging, as well as the sediment accumulation over the network without the need to disturb the operating distribution network. The DNMD consists of pipes with different material (ac: asbestos cement, HPE: hard polyethylene) and diameter (DN 80, 100, 150), fitted with two sampling points for each section, and its operation mimics the operation of the real network (see Figure 1.). An array of artificial substrate was fitted in special frameworks to be inserted in the distribution network model device (DNMD). These artificial substrates present no considerable hydraulic obstacle in the pipes while provide us with the opportunity to analyze the biofilm development process over time.

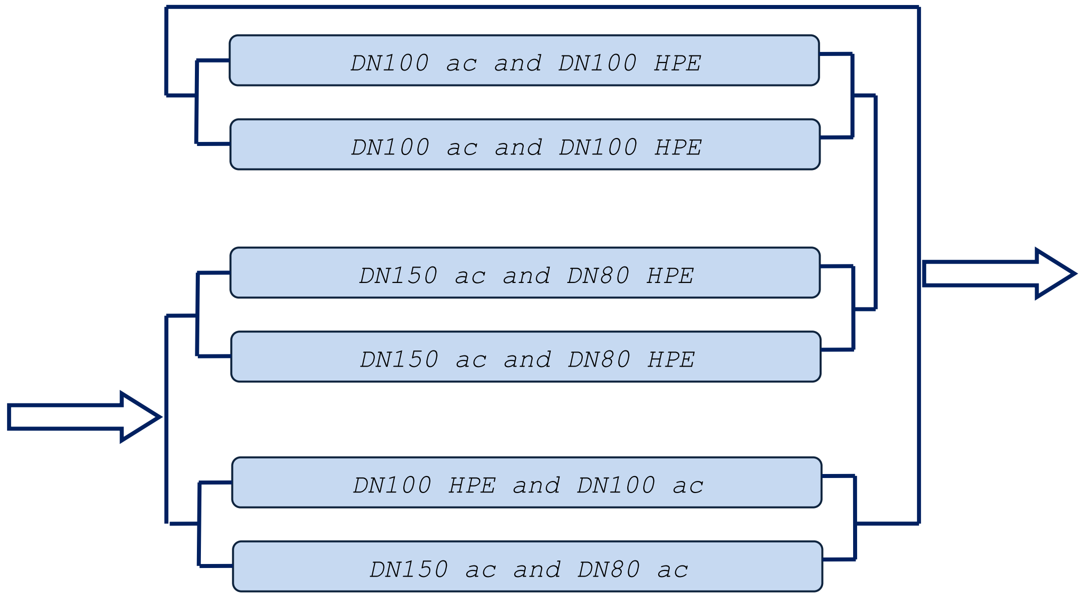

Figure 1. Distribution Network Model Device (DNMB) flow chart and material and diameter setup.

We had regular sampling (approximately 90 days) at the sampling points of the distribution network model device (DNMB), with the removed the artificial substrates replaced by a clean one. The substrates obtained at each sampling time were examined with light absorbance method to determine whether there is a relation between the amount of biofilm developed and the amount of inorganic matter sedimented on the substrate surface, and the absorbance of the microscopic glass slides. The slides from the DNMD were comparatively examined with a clean slide with regard to an array of predetermined wavelength absorbance. Prior to the actual absorbance experiments we conducted a series of 1 nm resolution sweep absorbance measurements of samples, and as a result we were able to determine the optimal wavelength for this measurement type was at 320 – 400 nm. This wavelength offered the most sensitivity as it resulted in the highest absorbance values with the lowest disturbance. The primary consideration while choosing the wavelength utilized was that the measurement should be conducted with the minimal disturbance rather than aiming for known maximal absorbance wavelength of a (supposed) component present in the biofilm and sediment. The actual measurement consisted of absorbance measurements in at least 10 sampling points distributed evenly over the surface of the substrate. Initially the absorbance of every sampling point was measured using 10 different wavelengths, but the number of wavelengths used was later reduced to 3, as the initial measurements proved that the deviation of the results is lowest between 380 and 400 nm, and thus the results obtained with these wavelength should be the most reliable.

The high disturbance present over the 320 – 370 nm wavelength range makes the evaluation of absorbance results obtained for these wavelengths very difficult.

In some cases we measured the ferric and manganese content of the coating developed over the substrate.

A visual evaluation of the pipe interior was conducted using industrial endoscopy. The results obtained with the fiber optics technology provided valuable data regarding the most promising area of focus for the future research. We documented the interior of the network with photos and videos for future evaluation (see Figures 2 – 4.).

Figure 2 – 4. Sediment accumulated inside the DNMD (first and second picture) and the artificial substrate inserted in the special framework.

Flushing experiments over the distribution network

Our goal with the flushing experiments was to determine not only the amount and the composition of the suspended matter flushed from the network, but also to establish the quantitative changes of the flushed matter over the course of flushing. We have conducted nine different flushing experiment and sampling over the Budapest network. The experiment sites chosen were situated at the dead-end pipe that was not flushed for more than one year.

In accordance with the practice used for flushing the fire hydrants were flushed until a „clear water" state was achieved. A variable time interval sampling program was executed after the opening of the fire hydrant with up to 17 samples taken. The hydrant was fully open (complying with the standard operation of flushing), and the amount of water flushed was determined by scaling at the end of the experiment.

Following each sampling the suspended solids, dry matter and total inorganics of the samples was measured in laboratory.

The total amount of flushed suspended solids and its respective organic and inorganic portion was calculated using the concentration values measured for each sample interval and the measured water flow.

To calculate the specific values regarding the pipe area affected by the flushing we need to determine the network section affected during the experiment as well as the various hydraulic parameters (e.g., velocity, water flow) in effect over this area during the course of flushing. Using the water velocity values for each pipe section affected the distance covered by the flushed water in each pipe can be calculated, and thus the specific amount of flushed matter with regard to pipe surface can also be assessed.

RESULTS

Pairing the concentration and quantitative data of the suspended, organic and inorganic matter with the respective sampling times reveals that the suspended matter time series off all but three flushings are very similar to a saturation type curve. Some of the measurements produced a linear increase in the flushed matter during the whole measurement, while one measurement resulted in an ever increasing mass of flushed matter (Figures 5 – 6.). Parallel to this, the concentration of suspended material was slowly declining during flushing – as it is to be expected. In some cases though we observed a second peak in the suspended solids concentration diagram, which is probably the result of the flushing effect reaching a new pipe section.

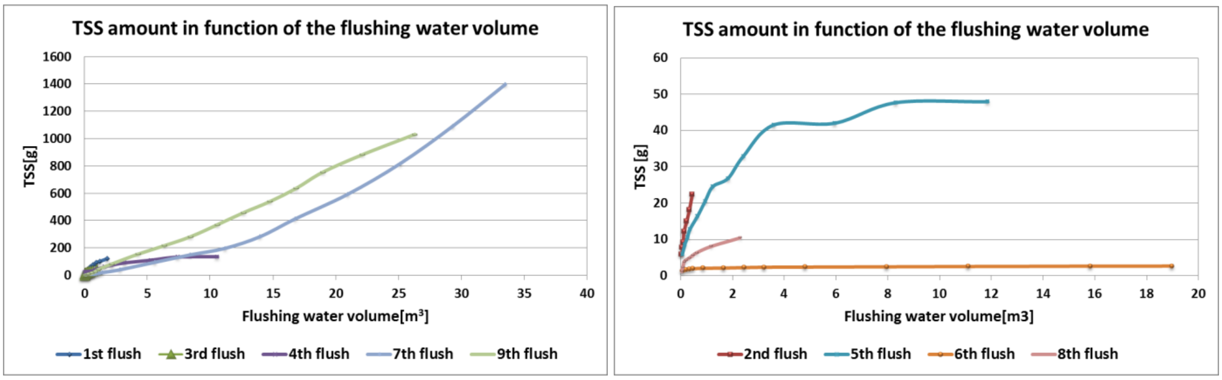

Figure 5 - 6. Total flushed matter as a function of the flushed water volume.

The characteristic distribution of the ratio of organic-inorganic components in the flushed suspended matter is similar during the flushing. In the initial stages of flushing the inorganic components are the dominant fraction – coming mainly from the corrosion saturated stagnant water enclosed in the fire hydrant.

To make the comparison of the results easier we present the result for the different sampling points in a single diagram. *Figure 7/A.* presenting the organic-inorganic component distribution of the flushed matter shows the ratio being nearly identical for all samples – mostly falling in the range of 55 – 60%. There are only two notable exceptions. The results of the first flushing are being dominated be the stagnant water flushed from the fire hydrant (with a very high ferric oxide concentration), while the 8^{th} flushing shows the signs of the recent and undocumented opening of the hydrant. This theory is further supported by the sudden drop in the inorganic matter concentration in the initial stages of the flushing.

While the organic-inorganic matter ratio of the flushed matter is nearly constant the absolute mass of the flushed matter is highly variable over the different samples (see Figure 7/B.).

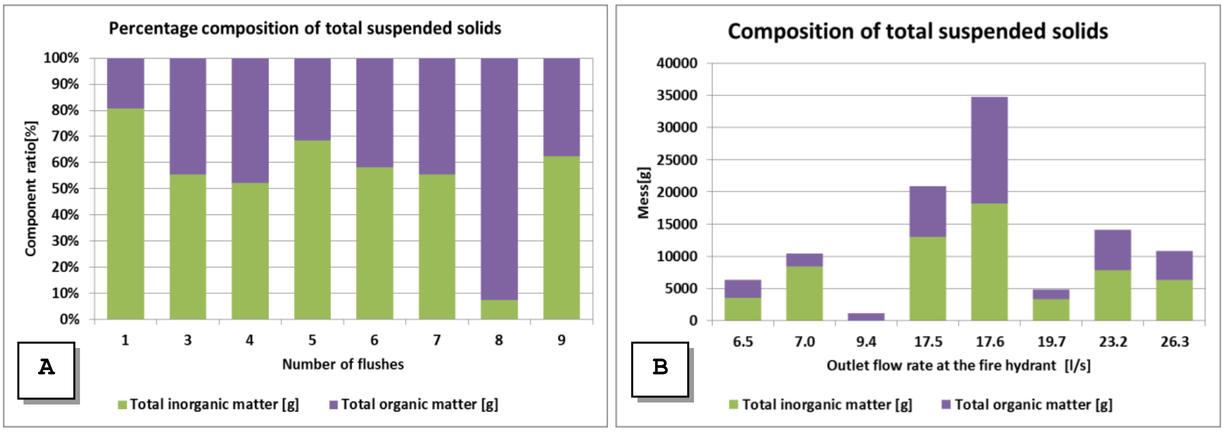

Figure 7/A.-7/B. Percentile composition of the flushed matter (7/A), and flushed mass and composition (7/B).

In order to eliminate the possible confusion resulting from the different flushed water quantities we present the specific mass of flushed matter. The results are presented on Figure 8.

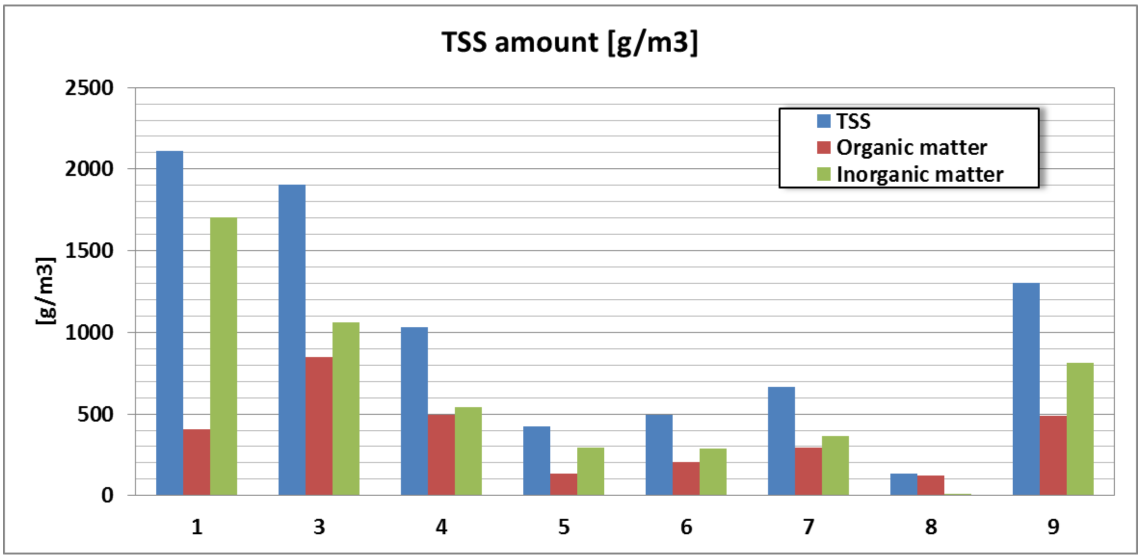

Figure 8. Specific values of the organic and inorganic mass flushed during the experiments.

We plan on continuing during 2012 with a more intensive flushing campaign, as the results obtained are very promising.

Light absorbance experiments using the artificial substrate from the Distribution Network Model Device

As a result of the light absorbance experiments conducted over samples of different age obtained from three different sampling points located on the DNMD we have established that the absorbance of the microscopic slides increases over time. Presenting the change in absorbance values of three different wavelengths for each sample over time will show us a trend similar to a saturation curve (see Figure 9.). A possible explanation of this phenomenon would be the biofilm reaching its final growth potential over a 270 day time frame, but it is more likely that the samples with 370 days age simply surpass the measurement capacity of this method. This theory is further supported by the fact that the initial deviation of absorbance values for different wavelength disappeared for the samples with an age of 370 days. As a result we are currently inspecting and developing other methods for the further evaluation of biofilm growth on the artificial substrate surface.

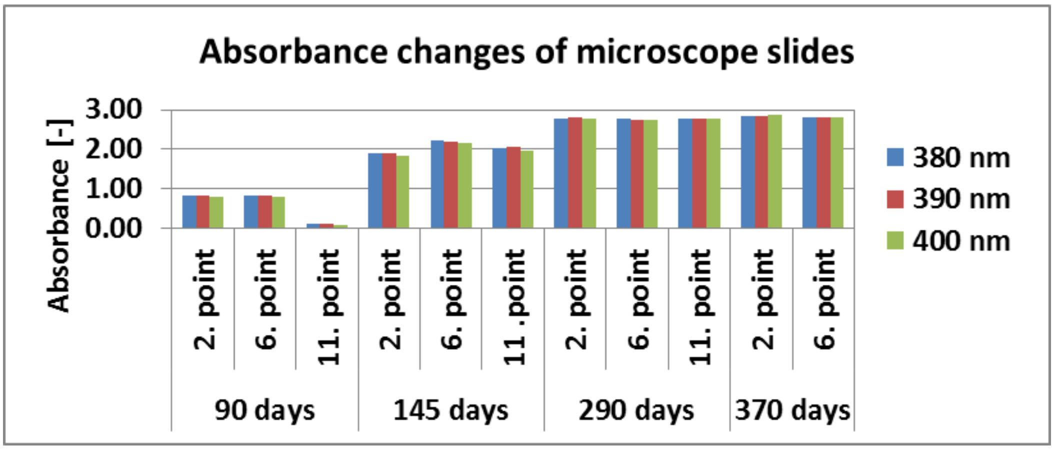

Figure 9. Development of absorbance values of the artificial substrates.

CONCLUSIONS

Aside from small local variations the composition of the suspended solids with regard to the ratio of organic-inorganic matter is fairly constant. Further observations are needed to confirm this statement.

The samples were obtained from different areas (districts) distributed all over Budapest, yet the organic-inorganic ratio of the suspended matter flushed with potable water was nearly identical (see Figure 7/A.). It is likely that the main factors influencing the processes of sediment accumulation and biofilm development are the water velocity and the material of the pipe.

The results obtained from inspection of the artificial substrate coatings developed in the distribution network model device are also seems to confirm the statement above. The water quality parameters measured at different sampling points over the device show almost identical values yet the thickness of the biofilm developed over the surface of the artificial substrates varies even for the substrates with the same exposition time. As in the DNMD there is no difference in the water flowing inside each pipe, and the pipes are operated under the same circumstances, the resulting difference in the coating thickness should be the result of varying water velocities and pipe materials.

Budapest Water Works is capable of providing outstanding potable water from both quantitative and qualitative point of view, but the increase in costs and the change of costumer habits resulted in an unprecedented decrease of the water demand over the last 20-25 years. The distribution network has to comply not only to the hydraulic demands of water distribution, but also to diverse operational and safety regulations (consumer comfort, fire department demands, etc.). Over the years this duality inevitably resulted in a network with hydraulic capacities vastly outmatching the actual water demands. In order to comply with health regulations the water transported over the network always contains a disinfecting agent (chlorine characteristically). This agent however is a strong oxidant, and thus is capable of oxidizing the soluble ferrous and manganese present in the water. We presume this residue to be the main source of the sediment accumulation inside the network. Although this sediment in itself present no health hazard, it also offers a living space for the bacteria, thus it is undesirable over the network as a possible source of secondary contamination. Furthermore, should a reductive zone be developed over the network, these oxides participate in undesirable electrochemical processes resulting ultimately in pipe corrosion.

Determining the origins of the suspended solids flushed from the network requires further investigations. Based on the results of our experiments and measurements we suppose that the considerable portion of the matter flushed from the network is accumulated as a result of sedimentation processes. The considerable amount of sediment accumulated in the pipes revealed by the fiber optical inspection of the DNMD also supports this theory. However, the shear stress experiments conducted with pipes obtained from network reconstructions alludes to the fact that under standard conditions present in the network during regular flushing there is no considerable amount of biofilm peeling from the pipe walls. The bottom of the pipe obtained from network reconstruction shows wearing on the bottom of the pipe interior, which hints at erosion resulting from the sediment movement over the network.

As a summary of our experiment and measurements we can state that the biofilm development inside the distribution network pipes is influenced by the pipe material and water velocity. The pipes examined showed a high amount of sediment accumulation, and it is practical to extract as much of this sediment as possible in order to prevent spontaneous mobilization resulting in water quality problems. However, the accumulated mass of the sediment is substantially higher than the mass of biofilm peeled off during the shear stress peeling experiments, so we presume that contrary to the previous assumptions of biofilm peeling, the accumulation and spontaneous mobilization of sediment is the primary cause of water quality deterioration over the distribution network.