Particles in the drinking water system: from source to discolouration

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Abstract Water discolouration in networks results from increased turbidity due to high levels of suspended particles. Hydraulic incidents such as pipe burst or hydrant use impose extra shear stresses on sediment layers in the network, leading to particle resuspension. The mass balance over a network or parts of the network may be used to analyse the different sources and accumulation processes; this article focuses on the contribution of the “mass in” from the pumping station as particles. Three analysis methods have been developed within the joint research program of the Dutch water companies (BTO-program): the continuous monitoring of turbidity, the Mass Settling Potential Method and the Resuspension Potential Method. The continuous monitoring of turbidity and particle counting enable an analysis of the relative contribution of sources for particles, e.g. corrosion of cast iron. The Mass Settling Potential and Resuspension Potential methods add insight into actual sediment load and actual discolouration risk. Further development of these methods will enhance knowledge of the origin and fate of particles in a network, enabling the formulation of effective measures against discolouration and associated water quality problems.

Keywords Drinking water quality; particles; discolouration

Introduction

Particles in finished drinking water are an important factor in the generation of discoloured water. Discolouration is one of the main causes for customers to complain to the water company. Not only the aesthetics of discolouration are a concern, but serious indications show that sediment has an impact on the biological water quality.

Resuspension of sediment is probably the most important cause for discolouration incidents leading to customer complaints. Resuspension occurs as velocities in the network change drastically inducing higher shear stresses on sediment layers. Typical “hydraulic incidents” are pipe burst, hydrant use and valve exercise that result in velocity changes and excess shear stresses.

The sediment in the network originates from several sources accumulating in the network in a complicated process. Understanding and hence controlling this process requires a good insight in the main sources for the sediment. As model to analyse the origin and fate of the particles a mass balance over the network is used.

Mass balance in the network

The cause of discolouration in the network is increased turbidity as result of (too) high level of particles in the water. Sudden increase of the velocity of the water resuspends particles that are accumulated in the pipes. Hydraulic incidents as pipe burst, hydrant use or any other increased demand result in these sudden velocity increases adding extra shear stresses on the sediment layers in the network. The extra forces resuspend the particles, leading to increased turbidity and discolouration of the water. The mass balance over a network or parts of the
network is used as a model to analyse the different sources and accumulation processes. The goal of the analysis is to identify the relative contribution of the different sources of particles to the mass accumulation in sediment layers and its mobility in the network.

The elements of a mass balance are basically the incoming or produced mass, the outgoing or consumed mass and the net storage of mass in the system. Schematically the elements of the mass balance can be represented as shown in Figure 1.

In a formula the basic elements of a mass balance can be presented as:

\[ \text{Mass in} = \text{mass out} + \text{storage} \]

Closer analysis of these basic elements:

**Mass in**

\( C_{\text{in}} \). The concentration of mass coming into the network. This mass load originates from the treatment plant. If the mass balance is made for a part of the network, the incoming mass load originates from the upstream network.

*Material or biofilm.* Corrosion of ferrous material or leaching of cementitious material will form particles that can either settle on the pipe bottom or stay in suspension and discolor the water directly. In the biofilm AOC will materialise in biological activity. The sloughing of biofilm will contribute to the formation of mass also.

*Formation of material.* Two different processes. The first is mixing of water from different sources that can lead to extra particles as a result of destabilisation of suspended matter. The second process is smaller parts coagulating to larger parts that can settle.

**Storage**

Regular deposition and resuspension of material in the storage assumes dynamic storage volume. The flow and consequently the velocities in a network vary over time influencing the sheer stresses that govern the resuspension and settling of particles. This may result in a net accumulation of material and eventually equilibrium. Incidental resuspension of particles induced by high velocities e.g. high sheer stresses ultimately cause the discoloration. When looking at discoloration aspects the mobile part of the sediment is relevant.

**Mass out**

\( C_{\text{out}} \). The mass load that is supplied to the customer or removed by cleaning the pipes. If the mass balance is made for a part of the network, the outgoing mass is transported to the downstream side of the network.

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**Figure 1** Mass balance in a network
This article focuses on the contribution of the “mass in” from the pumping station as particles. Corrosion products that contribute to the net storage of particles can have a major contribution in networks containing unlined cast iron or steel pipes. The contribution of biofilm to the storage of particles is difficult to quantify. This is, however, mass that is trapped within the biofilm itself. Unknown is what the contribution is to the available mass that can be resuspended, and this is a matter of research (van Dijk, 2004).

The share of cast iron in the network in The Netherlands is relatively low (10%, VEWIN) and consequently the contribution of corrosion products to the mass balance is small. This makes the contribution of the mass in the treated water and the produced mass through biological processes significant.

Materials and methods
To quantify the elements of the mass balance three analysis methods are developed within the joint research program of the Dutch water companies (BTO-program): the continuous monitoring of turbidity, the Mass Settling Potential Method and the Resuspension Potential Method. The three methods are discussed in this paper.

Continuous monitoring of turbidity patterns
In The Netherlands over the past decade many measurements have been performed at pumping stations and the drinking water network to evaluate the degree of fouling of the network. The focus was to determine what actions should be undertaken to control the problem of discolouration. The main parameter used is turbidity as a surrogate parameter for the mass of particles that is suspended in the water. There is no universal relation between the particle counting and sizing and the turbidity. For specific circumstances however, the turbidity is a good indication of the amount of particles in the water (Gregory, 1997).

Figure 2 shows some typical results of continuous measurement of the turbidity at pumping stations and in the network.

In the figures the turbidity at the pumping station and several locations in the network is represented. The propagation of a natural variation of the turbidity level can be followed. Typical elements for the analysis are the base-level of turbidity and the pattern during longer time. In the left picture the base line is not completely constant and the pattern shows multiple variations at the pumping station (the red line; base line 0.4 FTU and maximum 0.68 FTU). The area between the assumed base line and the peak is representative for the extra sediment load of the finished water. These variations indicate some irregularities at the pumping station, for instance as a result of backwashing of filters or pump switches. The two network locations show the same pattern, but with deviating maximum values. If a base line

![Figure 2](https://iwaponline.com/ws/article-pdf/4/5-6/431/477472/431.pdf)
is considered, the surface area and the relative peaks in relation to the specific base level are practically equivalent. This indicates that the incoming mass is equal to the outgoing mass and that there is no net accumulation of sediment.

In the right picture the level at the pumping station is smoother and lower. Base line level is 0.06 FTU and the peak is 0.27 FTU. The spike in turbidity however dies of in the network, indicating an accumulation of sediment. “Mass out” is less than “mass in”, so “storage” is increasing.

The conclusion is that both water types have a different effect on the mass balance in the network. Considering the mass balance of Figure 1 in the first case either the particles do not settle and stay in suspension, or the accumulated sediment is in dynamic equilibrium with the water. In the second case it could be that the pipes are completely clean so the regular resuspension doesn’t occur and only the settlement of the particles is observed. The sediment layers in this situation are regenerated until equilibrium is reached again.

To quantify the influence of the mass load of the finished water, without the effect of the “old” sediment in the network, a new analysis method is designed: the Mass Settling Potential Method (MSM).

**Corrosion of cast iron as source for particles**

Corrosion of cast iron is considered a major source for particles. Mostly this is analysed using samples taken at the pumping station or feeding reservoirs and compared the iron content with samples taken after passage through cast iron pipes. A net pickup of iron indicates the contribution of the cast iron. Continuous monitoring of water quality shows, however, that it is difficult to relate samples taken at the supply point and samples taken in the network. Diurnal variations in the iron content of the supply point influence the conclusions based on grab samples. Turbidity and iron content can be related to each other to a certain extent, especially when applied to a single water type. Increase in turbidity indicates an increase in iron content.

In Figure 3 the effect of continuous monitoring of turbidity in a cast iron pipe is represented at three different stages. The first stage (left upper Figure 3) is the situation prior to cleaning of the pipe. The turbidity shows a constant level that is not related to the diurnal flow pattern. This indicates a stable sediment layer.

The second stage (right upper Figure 3) is a few weeks after cleaning the pipe using pigs. The initiation of the cleaning is a rehabilitation program in which some of the cast iron pipes

![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](image-url)
are actually replaced and some are only cleaned. The turbidity pattern in this case shows a diurnal pattern with a rise of the turbidity during the hours after midnight till the early morning. This indicates an active production of particles caused by the corrosion of the cast iron. During the nighttime hours the residence time is longer allowing the water to take up the corrosion products. During daytime hours the residence time is shorter allowing less particles to be taken up. In this stage particles will settle and contribute to the net storage in the pipe.

The third stage (lower, Figure 3) is the same pipe a year later. The active corrosion still occurs, but to a much lower level. The layer of corrosion product has almost stabilised again and the production of particles nearly stopped.

Using the continuous monitoring of turbidity allows us to analyse whether a pipe actively contributes to the sediment accumulation.

The mass settling potential method

Turbidity measurements or more accurately particle counting of the finished water does not give sufficient information on the accumulation of particles in the network. As the example of Figure 1 shows, it is possible to have a relative high turbidity that does not change during transport through the network, whilst water with a lower turbidity probably add particles to the storage volume in a network. To assess the amount of mass that can actually settle in a network, the Mass Settling Potential Method is under development. The principle is that an amount of water is kept in a stirred vessel and after time on the bottom accumulated sediment is analysed. A picture and a schematic drawing of the test vessel is given in Figure 4.

The protocol starts with filling the vessel with 200 litres of water. During the filling a sample of the water is drawn and analysed on total dry mass by filtering an amount of water over a 45 μm mesh filter. The vessel is left for 24 hours while being stirred with the mixer. The energy input is set at 50 s⁻¹, the optimum used in coagulation experiments with jar tests. After the 24 hours the weir is stopped and a sample is taken of the supernatant water and analysed on dry solids in the same way as the pre-test. The accumulated sediment is washed out and the amount is determined. With these three figures the mass balance over the vessel can be made, giving an indication of the total amount of settle able matter in the finished water. The method is developed recently and still in a very experimental stage. The first results of the analysis of several water types is given in Table 1.

Although highly experimental the results of this method are promising. A good indication can be given of the potential of the mass that can settle in the network. Absolute values are difficult to give, but the methods allow for a quick analysis of possible improvements obtained in pilot plants. Both samples are taken at the same location in a network. It shows the different characteristics of the samples although being from the same origin. The first sample shows that 17% of the available dry solids can settle and the second sample shows

![Figure 4](image_url)
almost 15% of the material being settleable under these conditions. Improving the overall performance of the treatment towards the load of particles (for instance measured as turbidity) will decrease the sediment load to the network dramatically.

Resuspension potential method

The Resuspension Potential Method (Vreeburg, 2004) gives information on the mobility of the accumulated sediment in a network. This is additional information to the mass balance of the system and quantifies the actual risk for discolouration events in the network. The protocol of the method is based on the principle of a discolouration event: a disturbance in the velocity and the sheer stress on sediment. The velocity in the pipe is increased with 0.35 m/s on top of the normal velocity during 15 minutes while the reaction of the turbidity is measured. Scoring the rise of the turbidity during the first five minutes and the last ten minutes (absolute and average value) and the resettling time on a relative scale gives a discolouration risk on a scale from 0 to 15. Until now the RPM has mostly been used to decide on cleaning programs for the network (Slaats, 2003).

Discussion of measuring methods

The three measuring methods presented, continuous monitoring of turbidity and particle count, Mass Settling Potential (MSP) and Resuspension Potential allow for analysis of the dynamic mass balance in a network. Because especially the MSP is in an early experimental phase, the analysis can only be made theoretically.

The Mass Settling Potential gives an indication of the mass that can settle in a network. As the first experiments show, this can be up to 15–17% of the dry solids that are available in the finished water. Further development will enhance the accuracy of the method and make it possible to assess the theoretically available mass to settle in a piped system.

The continuous monitoring gives information on the performance of the treatment plant especially with regard to the continuity of process. As an example the turbidity of the finished water of a ground water pumping station is given in Figure 5.

Theoretically the MSP has a relation with the turbidity. The average turbidity is low (± 0.1 FTU) while the peaks amount to 0.7 FTU. The period between two cleaning actions in the network supplied by this pumping station is shorter than would be expected based on the average turbidity. Based on this analysis the conclusion is that the particle load for the network can be considerably decreased if the peaks in turbidity could be lowered. Further analysis showed that improving the backwashing process and allowing more time to reinstall the washed filter would decrease the sediment load.

This experience showed that one of the further developments of the MSP would be to have a continuous flown through test vessel allowing the peaks in turbidity add to the total amount of material settled within the vessel.

The combination of the continuous monitored turbidity and the MSP would give theoretically the amount of available sediment originating from the treatment plant. Assessment of the actual available amount of sediment would give an indication of the relative contribution of the treatment plant and the other sources for sediment, the corrosion and the sloughing of biofilm.

<table>
<thead>
<tr>
<th>Sample 1 (200 l)</th>
<th>Sample 2 (200 l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass in</td>
<td>274.4 mg</td>
</tr>
<tr>
<td>Mass out</td>
<td>226.7 mg</td>
</tr>
<tr>
<td>Residue</td>
<td>46.7 mg</td>
</tr>
<tr>
<td>% residue</td>
<td>17.0 %</td>
</tr>
</tbody>
</table>
Eventually the Resuspension Potential Method shows the real discolouration risk in the network and the need for remedial action such as cleaning the network. Also the RPM gives insight in the actual time it takes to accumulate enough sediment to cause a discolouration risk. Figure 6 shows the pre- and post-assessment of the RPM in a certain location. The RPM determined after three years following the cleaning action shows that the regeneration time is about three years.

**Conclusion**

Particle load from the pumping/treatment station is an important factor in the generation of discoloured water and associated bacteriological problems. The measuring principles of continuous monitoring of turbidity and particle counting allow for an analysis of the relative contribution of the sources for particles as the finished water and the corrosion of cast iron.

Novel methods as the Mass Settling Potential and the Resupension Potential add to the insight of the actual sediment load and the actual discolouration risk. Further development of these methods will enhance the knowledge about origin and fate of particles in a network.
enabling to formulate effective measure to prevent discolouration and associated other water quality problems.

References