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Managing discolouration in drinking water distribution systems by integrating understanding of material behaviour

Joby Boxall [a,*], Mirjam Blokker [b], Peter Schaap [c], Vanessa Speight [a], Stewart Husband [a]

[a] Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK
[b] KWR Water Research Institute, the Netherlands Delft University of Technology, the Netherlands
[c] Evides, the Netherlands

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ABSTRACT

Discoloured drinking water, caused by elevated concentrations of organic and inorganic particles, is unacceptable. It occurs due to accumulation and subsequent mobilisation of material from within drinking water distribution infrastructure. Discolouration is currently partially explained by either the theories of cohesive layers or gravitational sedimentation. It is proposed and shown here how the processes behind these two theories both occur and how to integrate them to better explain observed behaviour and inform operational interventions to reduce discolouration. Deficiencies in understanding regarding the process and factors that influence material accumulation are highlighted. Future research addressing these deficiencies will enable determination of long term sustainable management strategies balancing capital investment and operational maintenance to safeguard distribution of high quality drinking water.

1. Introduction

Discoloured water is the leading drinking water quality issue experienced by customers worldwide, impacting quality perception, service satisfaction and ultimately willingness to pay (De França Doria, 2010). Although considered aesthetic, discolouration is a result of elevated levels of organic and inorganic particulate matter entrained into the fluid phase. Inorganic material is often dominated by iron and manganese and depending on the water treatment potentially aluminium, with regulatory exceedances likely before turbidity standards are breached (Seth et al., 2004; Cook et al., 2015; Sunny et al., 2019). Organic material is associated with the ubiquitous presence of biofilms that colonise all Drinking Water Distribution System (DWDS) and particle surfaces, irrespective of treatment or disinfection strategies (Gauthier et al., 2001; Husband et al., 2016a; Chan et al., 2019).

Discolouration is caused by material accumulation and subsequent release within DWDS. Material sources are from the water treatment works (particulate and dissolved) and processes occurring in the network (corrosion, flocculation, precipitation and biological). Material accumulation is typically a long term process from the low background flux of material. During mobilisation events, which are typically hydraulically mediated, particles re-join the fluid phase and exit pipes in high concentrations. This leads to significant light scattering from the suspended particles that is observed as discolouration. Discolouration as experienced by customers is therefore measured as turbidity, not total solids or concentration of specific chemicals or number of bacterial cells. Discolouration events are often short in duration relative to the 24/7 operation of DWDS, but the impacted water may be experienced by customers, potentially leading them to contact their water provider. Due to their short duration and sporadic nature, discolouration events are very rarely captured by the discrete sampling of regulatory compliance practices.

Although often local to specific pipes or parts of DWDS, discolouration can also occur at city or system scale. Examples of this that generated significant media coverage include Tucson USA 1992, Winnipeg Canada 2013 and Incheon South Korea 2019. Such large-scale incidents are usually associated with significant changes in treated water quality that destabilise material accumulated in the DWDS such that it is then more easily mobilised by changes in hydraulic conditions. As a result, widespread discolouration can occur months after the change and be ongoing for many more months.

Understanding the processes governing the behaviour of material responsible for discolouration is critical to develop effective and proactive tools and strategies for managing these complex systems to

* Corresponding author.
E-mail address: j.b.boxall@sheffield.ac.uk (J. Boxall).

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mitigate discolouration. However, it is difficult to distinguish the causes in operational DWDS because of all the interacting processes, including changing particle characteristics and processes occurring on the vast, and difficult to observe, internal surfaces of the buried DWDS infrastructure. In addition, the processes of interest can rarely be measured directly, and instead interpretation from emergent data such as time series turbidity measurements is required. Laboratory experiments can provide insight into the processes, yet these cannot account for site-specific variations.

This paper synthesises the two state of the art theories considered to describe discolouration within DWDS, viz. the cohesive layer theory and gravitational sedimentation, highlighting that neither fully describes all observed behaviour. It is stated that both are occurring and need to be considered together for effective discolouration management. Based on the two discolouration theories, a novel conceptual framework that integrates them is proposed. It is then shown how this can be used to enable situation specific understanding and inform selection of interventions to manage discolouration. Due to the infinite range of network configurations, the work intentionally does not set out to provide specific targets or prescribed practices but aims to enable informed decision-making. Wider critique draws out gaps in understanding regarding material accumulation processes, and the factors effecting these that currently limit our ability to determine optimal long term management strategies.

2. Discolouration theories

Two theories dominate discolouration literature. One is based on consideration of particle self-weight driven gravitational sedimentation, forming invert deposits, bed load transport and resuspension (WRC, 1989; Carriere et al., 2005; Vreeburg, 2007; Ryan et al., 2008). The underpinning physical understanding and expressions are based on those applied to describe river and sewer sediment transport, such as Shield's criterion or number (critical velocity for the initiation of particle motion) (Akers and White, 1973). The other theory is of particles forming cohesive layers of different strengths on the entire pipe surface (Boxall et al., 2001; Boxall and Saul 2005; Husband et al., 2008). This is based on a theory previously developed to describe observed behaviour of estuarine muds (Parchure and Mehta, 1985). The nature and source of cohesive strength is not explicit in the theory, but there is growing evidence that biofilms are central (Husband et al., 2016a). The cohesive layer theory was proposed based on the observation that discolouration particles are often too small and low density for their self-weight to dominate their behaviour. Hence there is a fundamental disconnect and difference in the two theories. Despite the disparity, the understanding gained from both these theoretical approaches have effectively informed international best practice for the selection, design and implementation of discolouration management strategies (Vreeburg et al., 2009; Husband and Boxall, 2009; Blokker et al., 2009; Blokker et al., 2012; Husband and Boxall, 2015; Husband and Boxall, 2016b). In both theories, mobilisation of material responsible for discolouration is commonly initiated by atypical hydraulic conditions overcoming resistance forces that sustain in-pipe accumulations.

2.1. An integrated framework

Both sedimentation and cohesive layer theories were derived from observed discolouration behaviour across many different DWDS. However, neither is capable of describing all situations or observations. Both theories are useful; what is needed is a framework to integrate the two and enable differentiation of where, when, and why one is dominant. The dominant process can be understood by considering the interaction of the local (temporal and spatial) hydraulic conditions and particle characteristics. This integration is captured conceptually in Fig. 1, showing how particle size and self-weight factors alongside daily hydraulics are needed to identify the dominant process.

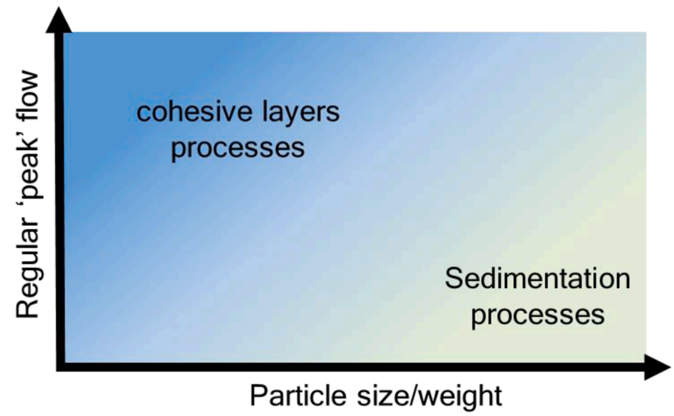

Fig. 1. Conceptual framework for drinking water distribution system material accumulation processes.

At the top left of Fig. 1, hydraulic forces are so great and particles self-weight so small that settling to the pipe invert is not feasible, turbulent motion will bring particles into contact with the pipe wall creating the opportunity for them to become trapped in cohesive layers. For particles with very low settling velocities, even the lowest daily peak flow conditions within distribution networks will prevent them accumulating as an invert deposit. Hence cohesive layer theories dominate over the entire left side of Fig. 1. At the bottom right of Fig. 1, particles are so heavy that they remain as an invert load, with behaviour entirely dictated by sedimentation processes, including bed load transport. It is uncommon that discolouration particles' self-weight is so large they are not suspended by strong daily DWDS hydraulics; hence self-weight does not dominate the entire right side of Fig. 1.

The boundary conditions of Fig. 1 rarely occur exclusively in any given operational DWDS pipe. Observed discolouration behaviour is more commonly an interaction of the processes behind the two theories. At low daily peak flows, self-weight driven gravitational sedimentation processes govern. When heavier particles are present this extends to pipes that experience higher daily peak flows. As flows increase, turbulence more readily overcomes gravitational forces preventing sedimentation and transports material present in the bulk flow to the pipe walls, facilitating cohesive layer formation. Thus it is likely both processes take place to varying degrees in any given pipe within a DWDS throughout a day.

Van Summeren and Blokker (2017), considering sedimentation processes only, presented a variation of the Shield diagram with a contour plot of bulk flow velocities and particle diameter with Shields number plotted as diagonal lines providing thresholds for when sedimentation might be expected or not. This is analogous to the bottom right region suggested in Fig. 1. It also has hydraulic conditions and particle size as the factors determining discolouration behaviour in DWDS.

2.2. Particle characteristics

Analysis of material entrained during flushing operations has repeatedly demonstrated a particulate nature, with sizes predominately around 10 μm with a primary range from international samples covering 3 - 30 μm and a specific gravity of 1 - 1.3 (van Summeren and Blokker, 2017).

Particle characteristics define the x-axis of Fig. 1 reflecting that different size and density particles will behave differently under different hydraulic conditions. Given that DWDS particles are not a uniform or fixed size distribution, this indicates that there will always be multiple processes occurring. Results from investigating particle size and settling behaviour of samples collected during flushing from a UK and a Dutch site are shown in Fig. 2. This shows, as expected, the larger

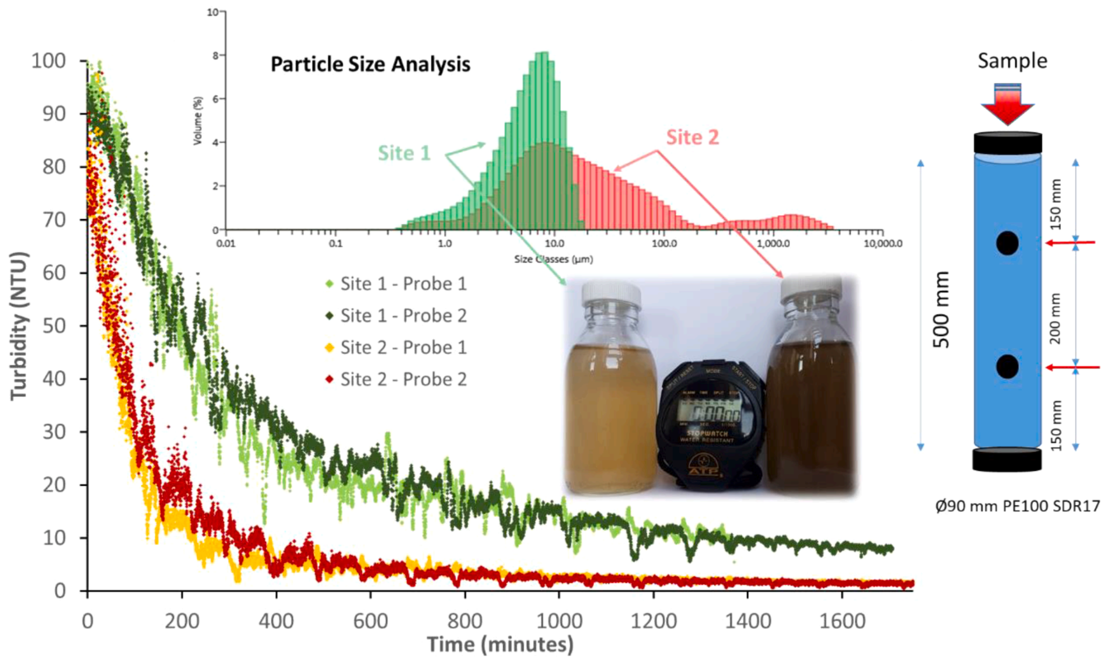

Fig. 2. Particle size analysis (inset plot, peak particle volume around 10 μm) and settling behaviour (main plot, measured in a 500 mm long 90 mm diameter settling column, shown on the right) of samples collected during flushing from the UK (Site 1) and The Netherlands (Site 2).

particles (in this case from the Dutch system, Site 2), exhibit greater self-weight and settle quicker, in the range of hours to settle 100 s of millimetres. This suggests a tendency towards dominance of sedimentation processes for large particles and limited or no accumulation due to cohesive layers. The smaller particles of site 1 take considerably longer to settle, with turbidity greater than the UK regulatory limit of 4 NTU at the customer's tap persisting beyond 24 h. There is reduced likelihood of sedimentation effects for this sample, suggesting processes described by the cohesive layer theory are more likely to be significant. The distribution of both these samples, as with all others presented in the literature for discolouration samples, span across the 20 μm threshold between cohesive and cohesion-less behaviour reported by Mehta and Lee (1994) for estuarine muds. This perhaps explains why neither theoretical process alone is able to explain all observed discolouration behaviour, and why no one behaviour will always dominate within a given DWDS.'

The particles size distributions in Fig. 2 are presented as volume due to the instrumentation used, however light scattering effects observed as discolouration and measured as turbidity are a function of particle numbers which is heavily biased to the smaller particles, with a peak effect for particles at 5 μm (Russell, 1993). Numbers of particles in this size range should therefore be of greatest concern. It should be noted that even at high numbers and hence high turbidity, the mass of such small particles will be low, often near the limits of detection of solids measurement techniques.

Investigations have found a relatively higher concentration of smaller particles in the water at the end of pipes than at the beginning, supporting the idea of differential sedimentation based on particle characteristics (Vogelaar and Blokker, 2010). Other studies however have shown particle size distribution to be consistent across and between networks (Boxall et al., 2001). Although not directly investigated, it has been suggested these differences may be associated to disinfectant regimes with the former networks not using a residual during distribution. Whatever the cause, it highlights the complex behaviour arising from particle characteristics.

2.3. Hydraulic conditions

While daily flow patterns drive daily cycles of accumulation and mobilisation, the regular maximum flow (typically the daily peak) experienced in a pipe governs longer term effects and the state of material accumulation and hence discolouration events as potentially experienced by customers (this can be considered as a 'buffer zone'). Therefore, it is the regular peak flow that has been used to define the y-axis of Fig. 1. It is worth noting that an upper threshold will exist, defined by the hydraulics possible within a specific pipe and its location within a DWDS.

There is a constant low-level background concentration of material in the bulk water that can be transported to the pipe wall by turbulent flows processes (van Thienen et al., 2011). The cohesive layer theory then explains trapping and accumulation of this material, although ambiguous as to the actual processes and the source of the cohesive strength. These conditions can and do occur in any pipe anywhere in any DWDS. This supports the observation cohesive layers are ubiquitous, irrespective of pipe material and final water quality (Husband and Boxall, 2009) and observed around the world (Boxall and Prince, 2006). While accumulation is ubiquitous, it can be slow and at low levels, in which case discolouration potential can be small, but increasing over time.

For self-weight driven sedimentation to occur for typical particle sizes of discolouration material, velocities of less than ~0.07 m/s have been reported to be required, such as experimentally shown by Ryan et al. (2008). Blokker (2010) estimated that in a Dutch network 70% of pipes by length had (instantaneous, at 36 s timestep) maximum flow velocity at 50% of the days above this threshold. However, during the night time most pipes will have operating demands well below this level. In the same Dutch network, Blokker (2010) reported that most pipes experience laminar flow for at least 50% of the day. The requirement for prolonged periods of low flow readily associates sedimentation with dead-end pipes where low water demands exist. Sedimentation is also associated with over-sized pipes leading to reduced hydraulic forces, and tidal points where the looped nature of DWDS (designed to provide hydraulic resilience) leads to balance points that experience no or low oscillating flows.

2.4. Observed turbidity behaviour explained by theoretical understanding

Across the world an association between hydraulics and turbidity is observed in DWDS. Considering a typical diurnal residential flow pattern with morning and afternoon peaks and minimal overnight flows, there is typically elevated turbidity (albeit well below customer perception) in response to the morning peak flows and sometimes a lesser response in the afternoon depending on the hydraulic conditions. During the reduced night time flows there remains low level turbidity, the continual flux of background material (coming from the water treatment works and/or upstream pipes). This behaviour is readily observed for pipes that have been transporting water for sufficient time to develop a stable operating environment. Such flow and turbidity responses, extracted from operational data, is shown in the first 48 h of the central timeline in Fig. 3. Also shown in Fig. 3 are representative pipe cross sections to visualise how the commonly observed turbidity behaviour can be described by cohesive layer or sedimentation theories.

1 At point 1 on Fig. 3 when the morning peak occurs, the imposed hydraulic forces exceed resistance forces of prior accumulations. Under the sedimentation theory, drag and turbulent forces exceed self-weight resistance of invert deposits and particles are mobilised. Particles with lower self-weight are fully mobilised, while larger and/or heavier particles may move as a bed load. Particles with greater self-weight remain. Under the cohesive layer theory, the resistive cohesive forces of weakly adhered material layers around the pipe perimeter are overcome by the increase in boundary shear stress and particles from these layers are mobilised.
2 During night time low flow (likely laminar) conditions, point 2 on Fig. 3, hydraulic forces are low permitting material to accumulate. Under cohesive layer theory, layers with cohesive strengths greater that the shear stress imposed by the current hydraulic conditions develop around the full pipe circumference. With sedimentation processes, the settling velocity of particles drives them towards the pipe invert and provided low or no turbulence conditions persist for long enough, these particles settle to the pipe invert.
3 At an intermediary stage, point 3 of Fig. 3, under sediment transport theory small light particles remain as a suspension due to turbulence in the flow, while medium particles will be moved as a bed load or saltation and the largest particles may settle to the invert. In the cohesive approach, particulate layers with cohesive strength greater than the imposed hydraulic shear stresses continue to develop. Layers with a cohesive strength less than the imposed hydraulic shear stresses do not develop.
4 Point 4 on Fig. 3 depicts a hydraulic event greater than the normal peak daily flow, for which either process explains a large amount of material mobilisation. With cohesive theory, any layers with strength less than the imposed hydraulic shear stress force are mobilised, thus layers with strengths between the normal daily peak hydraulic forces and those of the event are mobilised. Under sedimentation processes, only particles previously settled to the pipe invert with self-weight sufficient to resist the daily peak but less than the new imposed force are mobilised. Under both theories mobilised material is transported downstream and may be observed as discolouration by consumers. As the flow rate drops following the event, sedimentation theory dictates that entrained material with higher settling velocities will immediately start to settle towards the pipe invert. Under the cohesive theory, material remains entrained with loss from the bulk water occurring only as re-attachment on the pipe wall as cohesive layers.

Both theories can help explain the observed turbidity response,

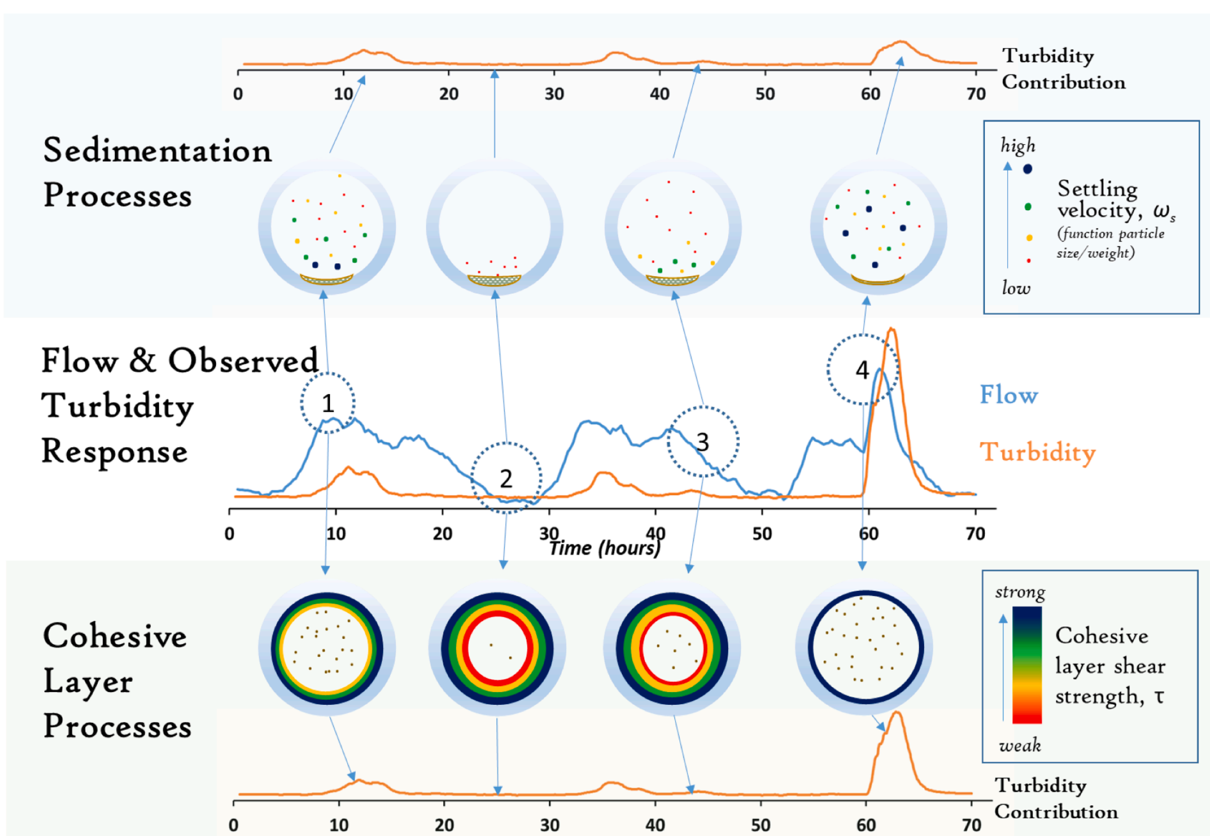

Fig. 3. Ubiquitously observed turbidity behaviour in response to a repeating diurnal hydraulic pattern (data extracted from operational distribution pipe). Three days are represented, two typical diurnal cycles followed on day 3 by a hydraulic event that induces a discoloration response, e.g. flushing. Representative pipe cross sections show how the observed turbidity behaviour can be effectively described by either sedimentation (top) or cohesive layer theories (bottom).

either independently or in combination, this is explored in the following sections. With standard measurement of turbidity it is not possible to distinguish which process is dominant, yet this understanding is important for delivery of best management. As the conceptual framework (Fig. 1) highlights, a unified single approach is unlikely to be practical as it would require location specific knowledge of hydraulic conditions and particle sizing to understand the processes that are dominant and hence the most appropriate and effective interventions.

3. Managing discolouration

The management of discolouration by utilities is typically undertaken in response to a perceived risk and can use different strategies depending on location and operational control philosophies. However, with a deeper understanding of the fundamental theories underpinning discolouration behaviour, it is possible to select the pipes and intervention strategy for best return on investment, both financially and with respect to water quality benefits. This section, incorporating both cohesive and sedimentation theories, outlines how different types of data can be used to understand the factors driving discolouration and subsequent management techniques including reduction in material loading, prevention of material accumulation, and controlled hydraulic mobilisation.

3.1. Data analysis to better understand discolouration

Data from distribution systems can provide insights into discolouration behaviour to help utilities understand the dominant processes and ultimately, the best mitigation measures. Data sources vary from reactive and potentially uncertain, such as customer contacts, to proactive, such as online turbidity monitoring.

3.1.1. Customer contacts

Interventions to address discolouration have historically been reactive to consumer contacts and localised to where issues are reported. The aim of discolouration management should be proactive to mitigate events occurring, protecting water quality and reducing the need for customers to contact their supplier. Contacts are a source of potentially useful data but, with many factors contributing to an individual's behaviour, lead to high uncertainty if analysed on an individual or small scale. Clustering analysis of contacts, at sufficient (temporal and spatial) scale can yield valuable information. Van Summeren et al. (2015) showed that higher temperatures led to increased discolouration. Husband et al. (2010) report an analysis of clusters of contacts (defined as 5 or more contacts in a rolling 24-hour period and affecting multiple distribution management areas within a water supply zone) across 7 years indicating that 41% of a UK water company's contacts were due to material mobilising from the upstream (transport main) system. Clustered contacts can account for large number of contacts and can be due to a low number of events resulting from the high number of potential downstream customers affected, as explored by Cook et al. (2015). Management to improvement the upstream transport mains can be very effective in these situations.

Conversely, in another study (van Rooij, 2016) in a Dutch city, it was shown that most discolouration incidents only led to one to three local customer contacts, hence likely dominated by local processes. Flushing the local affected areas would therefore be an effective intervention for this type of discolouration occurrence.

These two cases resulting in customer contacts highlight different sources of discolouration events (local versus upstream), demonstrating how an understanding of the dominant process would aid selection of the most appropriate maintenance intervention.

3.1.2. Regulatory sampling data

The transitory nature of discolouration events mean that they are rarely captured by regulatory discrete sample collection. Discrete regulatory sample data, in particular iron, manganese and turbidity, can still provide insight into discolouration by characterising the background water chemistry and microbiology of a DWDS. For example, using machine learning techniques such as self-organizing maps, Speight et al. (2019) identified underlying factors associated with discolouration, or the potential for material accumulation, including low disinfectant residual, nitrification, and corrosion of unlined cast iron mains at scales ranging from city to country.

3.1.3. Turbidity data

Evidence of DWDS water quality is increasingly being collected by monitoring turbidity as time series data. In most cases, turbidity monitoring uses nephelometric sensors that detect 90° reflected light from entrained particles, providing a real-time effective measure. Advances in technology, including LED light sources, battery life, data capacity, and telemetry have allowed significant gains in performance, stability, and size. Kitchener et al. (2017) reviews the challenges and complexities of turbidity measurement. Regular ongoing review of data and maintenance of such optical based measurement is essential to yield useful reliable data. Mobile temporary (relevant when DWDS changes are expected) and longer term (at key strategic locations) deployments both yield useful data.

15-minute data capture and reporting has been a common standard and this has been shown to enable event identification, through either manual or machine learning techniques (Mounce et al., 2015). While this measurement frequency removes the impact of customer variability, it results in reactive reporting of events. The ability to capture and transmit 1-minute (or greater frequency) data provides more confidence in the results and the ability to track events for real-time decision making, with potential for proactive information as data resolution and analytics improve further. Data driven approaches to analyse resulting turbidity time series data can provide valuable information, indicating not only sensor performance but also asset performance such as when pipes may change behaviour from accumulating to releasing material (Mounce et al., 2015). Notable from Mounce et al. (2015) is that the insight gained was multiplicative not additional through combination of data from multiple instruments and with other data, such as hydraulic information.

The application of data mining techniques demonstrates that historic turbidity measurements are an excellent predictor of future turbidity performance (Mounce et al., 2016), highlighting the repetitive behaviour that can be associated with consistent accumulation processes and the value of time series turbidity monitoring over other discretely measured parameters such as iron concentration.

Interpretation of turbidity data from (controlled) discolouration events can yield useful insight into the underlying processes occurring and hence selection of interventions, as shown in Fig. 4. These following descriptions are both for the ideal scenario assuming mobilisation occurs effecting only a single pipe length (no loops, junctions etc.).

The cohesive layer theory describes mobilisation as taking place from layers over the complete pipe surface, with material mobilisation progressing sequentially from weaker to stronger layers (Boxall and Saul, 2005; Husband and Boxall, 2009). The process may take up to a few hours to remove the higher strength material. This tends to describe a smooth overall response, increasing to a peak in turbidity at one turnover and then a gradual recession limb lasting for up to several more pipe turnovers (Fig. 4a). Spikes in turbidity are expected for regions with lower daily hydraulic forces such as dead-ends and tidal points where weaker layers can accumulate. Very short-term spikes may also be observed because of localised turbulence causing material accumulation around fittings or other physical features such as changes in pipe diameter. Such spikes are generally of less concern than the overall pipe response as with the short duration they are less likely to result in customer contacts.

Under the self-weight driven sedimentation theory, all particles with self-weight resistive forces less than the imposed hydraulic force are

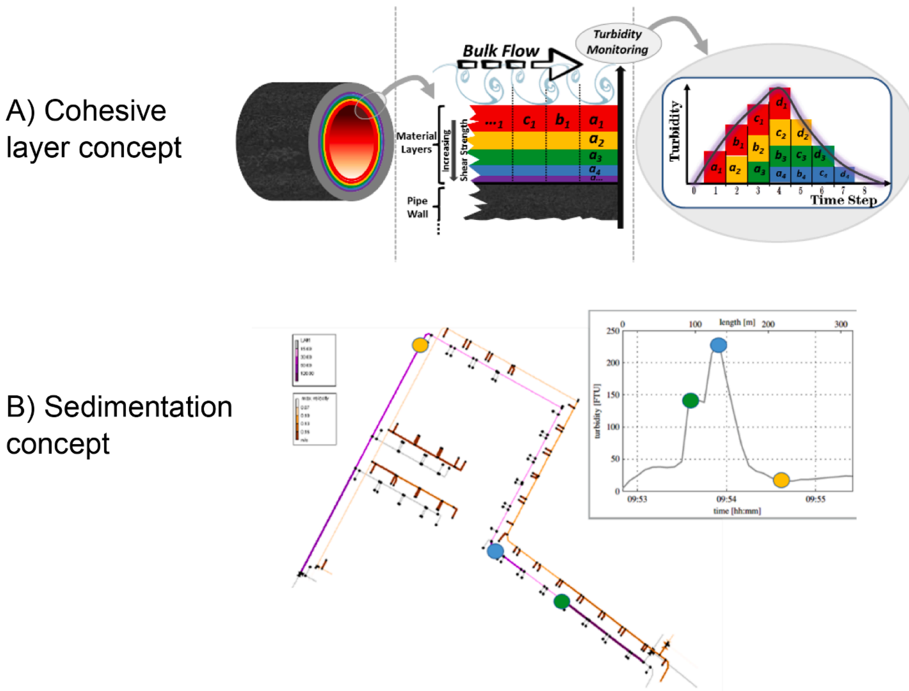

Fig. 4. Theoretical turbidity behaviour in response to a high flow event with dominant process being A) cohesive layers where sequential mobilisation from strong to weak layers leads to a smooth response peaking at one turnover and an exponential recession limb potentially lasting several turn overs of the pipe volume or B) sedimentation, where material is instantaneously mobilised with turbidity response occurring in one pipe volume turnover and with peaks and spikes associated with local features where enhanced accumulation occurs. (Source: 4A after Husband and Boxall, 2016b, 4B after Blokker, 2010).

mobilised nearly instantaneously and are transported to the end of the pipe in one turnover of the pipe volume. Sediment accumulations are biased to points of lower hydraulic forces, such as around valves, bends, and tidal points (Fig. 4b) – tidal points being the part of pipe loops where changing demands cause alternating flow directions over a day, like the tide in an estuary. Material should also tend to collect at longitudinal low points, due to topology and gravitational forces acting down longitudinal pipe gradients. Thus, spikier turbidity responses that are complete within a single turnover are expected when sedimentation processes dominate.

The sedimentation and cohesive layer theories differ in how they describe turbidity response to further increases in imposed hydraulic forces. An increase above the self-weight derived critical velocity causes sediments to be mobilised with further increases having limited or no further impact (unless particles with greater self-weight are present). For cohesive layers, the greater the excess shear stress, the greater the rate, and with more layers exposed the greater the amount, of material that can be mobilised. Further increases in shear stress also cause further releases of material. This suggests that cohesive layer material is never fully removed in response to hydraulic loading. This has been found to be the case for cast iron pipes, although there is some evidence that an ultimate strength may be reached in plastic pipes (Husband and Boxall, 2009; Cook and Boxall, 2011). This should not be confused with suggesting less material is accumulated and less discolouration potential is posed by sedimentation processes.

Husband et al. (2009) explored the practical implications of converting between shear stress and velocity thresholds, showing how velocity accounts for diameter effects, and that shear stress then adds consideration of the effects of boundary roughness. They show that the conversion between velocity and shear stress is non-linear, increasingly so for rougher walled pipes, hence a single unifying (velocity) value cannot emerge.

3.1.4. Simulation software

Software is available to simulate observed turbidity behaviour and has generally focused on describing mobilisation responses. These are often as water quality extensions to one dimensional network modelling software, building on solution of the hydraulic conditions and utilising transport and tracking functions. Single pipe length software as a free service application is also available, such as the PODDS App (www.PODDS.co.uk) for simulating cohesive layer behaviour. Different implementations of gravity driven sedimentation expressions are available as are formulations to capture the ideas of cohesive layers. All these models are empirical, requiring calibration of parameters to obtain useful simulation results. Once suitable parameters have been obtained, and if there is confidence in their transferability, they can be used in a more predictive manner. Some software also tries to capture longer term accumulation behaviour, such as the open access Variable Condition Discolouration Model (VCDM) (Furnass et al., 2014 and 2019, www.PODDS.co.uk).

Software that can accurately describe the settling process can help to determine when and where to flush, or how to redesign the network in order to need less cleaning. The WQDMTB software has incorporated particle settling and resuspension. Vogelaar and Blokker (2010) tested the software on a single pipe and a network and found that not all material accumulation was predicted well. Van Summeren and Blokker (2017) argued that bed load transport needed to be added, which was then realised in Aquarellus (van Summeren et al., 2022).

3.2. Reducing hydraulic mobilisation events

Reducing the occurrence and magnitude of hydraulic events that cause discolouration is a conceptually obvious mitigation option. However, there are many reasons and causes of hydraulic changes in DWDS that are beyond control, such as seasonal changes in demand or pipe bursts. One category of mobilisation events that can be managed are deliberate operational activities, including network re-zoning, system improvements requiring operational modifications, and similar interventions. Analysis of turbidity and customer contact data and work management records found that operational flow increases led to higher customer reported discolouration than burst incidents (Cook et al., 2015). Similarly, through an application of hydraulic backtracking Furnass et al. (2013) found 17.6% of discolouration issues over a six-year period to be associated with maintenance jobs.

As a mitigation for these events, it is important that any planned network operation considers how it will change the hydraulic conditions in the network. Pipes that are expected to experience an increase in flow should be cleaned to an appropriate level prior to the operation. In this case, the appropriate cleaning level would instil resilience to the anticipated hydraulic force through removal of more weakly adhered material (cohesive layers or sediments). While it is not possible to predict individual burst event time, location or size, it is possible to estimate the likelihood and magnitude of different burst scenarios and from this the impact on different pipes and hence the resulting discolouration potential can be estimated (Boxall and Dewis, 2005). This type of mitigation aligns with the risk-based management approaches advocated in the Bonn Charter for Safe Water (IWA, 2016).

3.3. Removing and preventing accumulation of discolouration material

3.3.1. Flushing

One of the simplest methods of controlled removal of discolouration material is flushing; opening a hydrant to generate additional flow to mobilise and expel material. Flushing can have various levels of complexity and efficacy. Perhaps the most complex but effective is the combined use of Resuspension Potential Method (Vreeburg et al., 2004) and unidirectional flushing. Resuspension Potential Method involves accurate flow control to measure the amount of material and calculate a pipe-specific discolouration potential; when repeated, this method will yield an estimate of how discolouration potential evolves over time. This is included in a Dutch best practice manual (Mesman and Meerkerk, 2015). Unidirectional flushing involves a planned sequence of valve operations and hydrant openings that progress systematically through a network to maintain a clean water front. Due to the complex arrangement of many networks, it is common that a whole zone unidirectional flushing programme is required (AWWA, 2017) to mitigate potential upstream impact. Ideally hydraulic forces required and imposed should be estimated for each pipe in a network (Friedman et al., 2003). However, the effort involved, consequence (customers potentially exposed per pipe) and onsite practicalities often mean that rigorously planned (commercial software tools to help plan and optimise this are available) full zonal unidirectional flushing is simplified. Effective flushing of smaller diameter pipes (<150 mm) can be achieved with simple universally applied target velocities, such as 1.0 to 1.5 m/s, but still with care and attention to flow routes and mobilisation of upstream material (Vreeburg and Boxall, 2007). The basis of these target velocities are often from pragmatic observations and experience (Friedman et al., 2003). Such large flows will impose forces significantly above the self-weight of discolouration particles and/or the usual daily flow that defines the lowest strength of cohesive layers.

Resource limitations restrict the wholesale application of complex cleaning operations across entire networks, hence combinations of unidirectional flushing and simpler universal velocity thresholds are often employed. Dead-end pipes, where there are often very low daily flows and hence there is potential for significant sedimentation to occur can also be effectively managed by (passive) flushing at very low flow rates, flow rates as low as 0.5 l/s can be effective (Cook et al., 2022; Blokker and Schaap, 2007). Indeed, low flow rates are recommended if only dead-end flushing is conducted to limit the often complex and unpredictable mobilisation of material from upstream pipes. This approach however only reduces the discolouration potential in the dead ends.

Flushing can be simple and effective at dealing with discolouration symptoms, which many water companies have and do effectively exploit. There are some challenges, but they can be overcome. Flushing requires the discharge of significant volumes of water. This means that flushing is typically constrained to smaller diameter pipes. Flushing discharges have varying levels of acceptability in different places and at different times of year. An optimal flushing plan can limit the length of pipes that needs to be flushed, and operations can be planned in the preferred season. If customers are warned beforehand and operations are conducted at appropriate times customer impacts can be minimised. Flushing is rarely considered a viable option for cleaning larger transport mains due to the volumes of water concerned and where discolouration events can affect tens of thousands and even millions of customers. Through careful consideration and application of the cohesive layer theory, many water companies have been effectively applying the idea of 'flow conditioning' (Husband and Boxall, 2015 and 2016b). This approach relies on carefully managed increases in flow that together with real-time monitoring allows controlled mobilisation with discolouration responses managed to below regulatory limits. The flow increases can be timed to coincide with peak demands to minimise additional use of water (Sunny et al., 2023). In cases where elevated flows cannot be sustained to mobilise all material in one intervention, repeat exercises can be planned until the desired layer strengths are achieved. Higher resilience targets also can be attained using sequential repeats over a number of days that slowly increase the imposed force. Whatever hydraulic strategy is adopted, by increasing the applied hydraulic forces the cohesive layers more easily mobilised are removed. Careful planning and modelling with real-time monitoring is considered essential for flow conditioning due to the operation taking place during normal operation and the number of downstream customers potentially affected. Monitoring during these exercises also provide valuable evidence demonstrating material removal and resilience achieved.

3.3.2. Invasive cleaning, relining or pipe renewal

Invasive cleaning can be used to remove accumulated discoloration material, or pipes can be lined or even renewed/replaced. These options generally require pipes to be taken out of service causing disruption, require pipe shut-downs (and subsequent re-commissioning), and temporary re-routing of flows that can induce additional network-wide risks.

Considering sedimentation, elevated flushing velocities can remove all material of particle diameters and densities found in discolouration samples (Vreeburg and Boxall, 2007). With this understanding, the benefits of more invasive cleaning strategies are questionable. Under the cohesive layer theory, invasive cleaning would remove all layers, including those with significant strength. However, these strong layers are not readily mobilised under normal or event hydraulic operating conditions so benefit of invasive cleaning may not justify the cost and effort. The lack of additional benefit from invasive cleaning was confirmed operationally by Sunny et al. (2016).

Invasive cleaning may be justified and beneficial if there is particular concern with the composition of accumulated material from a legacy of poor water quality such as arsenic, such that it should be entirely removed. Invasive cleaning could also be beneficial in situations where significant changes in water chemistry or biology such as changes in source, treatment, or disinfection residual are planned. Such environmental changes can result in pipe wall material becoming destabilised creating a significant and pro-longed discolouration.

Relining and replacement are costly and can rarely be justified for discolouration management alone. The discolouration benefits are particularly suspect when considering the longer term. As discolouration material has been shown to be continually present within transported water and hence able to continuously accumulate, it follows that any single intervention can only provide a temporary reprieve (Husband and Boxall, 2011). Replacing or lining iron pipes, fittings and fixtures conceptually removes a source of material and is beneficial both for the pipe in question and downstream. However, particulate material, and in many cases iron and the other components of discolouration, are still present (even if only in the treated water) and hence discolouration will still regenerate in iron free networks (Vreeburg, 2007). It follows that for long-term effective discolouration management, sustainable and critically repeatable or ongoing, maintenance strategies are required.

3.3.3. Self-cleaning networks and hydraulic conditions

Based on the sedimentation theory, accumulation of discolouration material can be minimised by a self-cleaning network (Vreeburg et al., 2009). This involves designing the network such that velocities in excess of those which particles are held are experienced on a daily basis. Blokker et al. (2010) found small temporal resolution flow velocities of 0.2 to 0.25 m/s to be sufficient in the Netherlands. Self-cleaning network design is achieved by decreasing pipe diameters and utilising a branched layout at the end of the system. This required consultation with the firefighting services in the Netherlands that included appreciation of significantly improved building standards and materials and in firefighting equipment that resulted in an updated agreement of the required provisions. This has yet to be repeated elsewhere. The self-cleaning concept has now successfully been applied by Dutch water companies since 2000 (Blokker et al., 2009; Vreeburg et al., 2009). This approach can be applied through network (re)design when systems are installed or renewed. Alternatively, self-cleaning effects can be achieved in existing DWDS by valve manipulations to control flow routes (Blokker et al., 2012; Abraham et al., 2017), although this is best supported with associated reduction of pipe diameters.

The self-cleaning network concept is founded on the theory of sedimentation, inducing a daily hydraulic force that exceeds the threshold of motion for the particles of interest. Its benefits are also consistent with the cohesive layer theory, where the minimum strength of layers is defined by the normal (daily) hydraulics. By increasing the normal (daily) flow, the discoloration potential of cohesive layers is reduced. Given that sedimentation and / or cohesive layer accumulation is a gradual process, the possibility also exists for periodic valve manipulations to temporally change network hydraulic routes to manage developing layers (Armand et al., 2017). Importantly, under the sediment theory alone, self-cleaning pipes would be effectively clean with no discolouration potential as accumulation of material is prevented. Under the cohesive layer theory, material remains in layers of greater strength and a hydraulic event of higher force would still result in discolouration.

3.3.4. Particle dispersion device

Another concept to minimise accumulation within a specific pipe is the particle dispersion device (PDD, Carter et al. 2017). It is a nylon static mixer placed into a pipe through a hydrant, so no excavation is required. By changing the flow patterns, turbulence and shear stresses, material accumulation is minimised as shown in a laboratory setup (Blokker and Beverloo, 2009). A CFD model showed that the PDD gives only a small extra head loss and can affect the turbulent viscosity up to 30 times the pipe diameter downstream of the PDD. The PDD was developed and mechanically tested in Australia (Yarra Valley Water) and used in dead ends leading to a reduction of discoloured water complaints.

3.3.5. Sediment catcher

The concept of a sediment catcher, similar to sediment traps in sewers (Ashley et al., 2000), was studied in the transport network of the Dutch utility Evides. The idea is to promote gravitational sediment settling at a controlled location by substantially decreasing the flow velocity locally in a large diameter pipe, thus limiting particles reaching the downstream DWDS. In 1997 Evides installed several devices, two of which were still present in 2009. Dimensions of the test site pipes were 323.9 mm with several meters of 812.8 mm, and 160 mm with several meters of 406.4 mm. Measurements around the sediment catchers showed that the length / duration was too short to capture the sediments (Blokker and Beverloo, 2009).

3.4. Reducing discolouration material load

There is always a flux of material moving through DWDS that can and does accumulate under favourable conditions, meaning that any cleaning intervention is only temporary. Controlling the flux or load of material presents an important management option but is an area where evidence and understanding is limited.

There are two sources of discolouration material in a DWDS, that entering the system in the water from the treatment works and that generated from the pipes and fittings within the network, the latter often considered to be dominated by corrosion of (cast) iron. From the treatment works, particles can be carried over into the DWDS from incomplete filtration/removal, or as dissolved substances that precipitate into particulate form in the DWDS. Within DWDS a correlation between turbidity and particle size, mass, iron and manganese concentrations has been observed as a function of source water, treatment processes (in particular flocculants used), supply area (extent of corroding assets) and residence time of the particles in the DWDS (Seth et al., 2004; Carriere et al., 2005; Blokker et al., 2009; Husband and Boxall, 2015). There are also processes of ingress during hydraulic transients and long-term depressurisation, cross connections and back siphoning that will contribute discolouration material to DWDS. However, the durations, volumes, and local nature of these processes mean that they are rarely major factors in discolouration (Fox et al., 2015 and Ebacher et al., 2012).

Consistent accumulation rates of discolouration material have been observed by undertaking monitored flushing trials between sites fed from the same treated water (Husband and Boxall, 2009; Mounce et al., 2014), whilst studies of material accumulation in two similar networks over many years found rates variable with changing water quality, i.e. the same source but a different transport route to the DWDS that were measured (Blokker and Schaap, 2015a). These findings confirm that the treated water quality is important, defining the base flux of material for accumulation. This is supported by trials with ultra-filtered water where particles were still found to exist in the network, yet the reduction in particle numbers caused a significant decrease in accumulation rates (Vreeburg et al., 2008).

Microbial activity and chemical reactions contribute to the ongoing processes that result in a continual and changing particulate load and flux of material. Hence the rate of material accumulation in a specific pipe is a function of the water quality at that point (Husband et al., 2010; Blokker and Schaap, 2015a). While details of the factors and processes that influence rates of material accumulation are unknown, it has been observed in operational systems to be a repeatable process (Husband and Boxall, 2011 and Blokker et al., 2011) and to be a linear function with time (Cook and Boxall 2011).

Accumulation rates have been found to be higher when associated with corroding pipes (Sarin et al., 2004; Husband and Boxall, 2011). The discolouration impact of corrosion is not only on the pipe itself, but also on those downstream: the corrosion process provides an additional material source increasing the downstream material flux. The ratio between iron and manganese in a bulk water sample may hint at the origin of the particulate material, as manganese is considered to originate in the source water only. If iron increases significantly between the treatment works and discolouration location, active corrosion may be at work (Schaap and Blokker, 2012), or heavier manganese particles may have settled (Sly et al., 1990; Arsénio, 2012).

The proven association between treated water quality and corrosion within DWDS may seem like strong drivers for improvements to treated water quality and / or asset renewal. However, the benefit in terms or reducing material flux and hence the interval between ongoing cleaning interventions remains largely unquantified.

3.5. Summary of discolouration management and reduction strategies

Risk is typically defined as the product of probability of occurrence and consequence. In the case of discolouration, the probability of occurrence depends on the amount of accumulated material and the likelihood of mobilisation. The consequence is determined by the magnitude of discolouration response and the number of customers exposed. Table 1 outlines these elements of discolouration risk and broadly how these elements change based upon location in the DWDS. In essence a network is considered to have a small number of trunk mains compared to downstream distribution pipes and these are considered

Table 1
Discolouration Risk by DWDS location and basis of management options.

			Discolouration Risk *DWDS Location*				
Risk assessment	Risk Element	**Controlling Factors**	**Trunk mains**	**Dead-ends**	**Over-sized pipes**	**Tidal points**	**Small diameter high flow pipes**
	Dominance of behaviour by cohesive layers	Shear stress	High	Low	Low	Low	High
	Dominance of behaviour by sedimentation	Velocity	Low	High	High	High	Low
	Amount of accumulated material	Duration of loading, local water quality, corrosion	Pipe specific	Pipe specific	Pipe specific	Pipe specific	Pipe specific
	Probability of mobilisation	Resistive strength of layers and/or sediment resuspension velocity	Med	Low	High	High	Low
	Number of customers affected	Duration of the event, number of connections downstream	High	Low	Medium	Medium	Low
Management	Reduction of mobilisation events		Control of planned operations, management of large (industrial) users, reduce likelihood of bursts				
	Removal of accumulated material		Flow conditioning	Flushing / network operation			Network design / build
	Reduction of material loading through networks		Improve water quality. Enhanced water treatment. Reduce length of corroding cast iron pipe				

less subject to unmanaged changes in demand or bursts that can impact the risk. The table shows that understanding discolouration, and hence selecting appropriate management strategies, requires network and location specificity as well as an understanding of the incoming water quality, network corrosion, and system configuration. These risk categorisations are broadly in line for well-managed DWDS, there will however be exceptions to each case when risk factors have been allowed to increase.

At all locations in the DWDS, reduction of mobilisation events can be achieved by managing hydraulic conditions carefully, including planning for operations that will affect flows and preventing pipe bursts. Similarly, mitigations that reduce the material loading through the network such as improving water treatment and reducing corrosion will benefit all locations across the DWDS. Removal of the accumulated material requires different techniques depending on the DWDS location. For large diameter trunk (transmission) mains, the volume of water required for flushing may be impractical to waste and the extent of sedimentation may be low, therefore indicating that hydraulic conditioning mitigations are most appropriate. For other DWDS locations, flushing is more appropriate as a discolouration mitigation approach, especially where sedimentation is highest. Dead-ends and tidal points may also be addressed through network (re)design approaches.

4. Discussion

The theories of cohesive layers and sedimentation, and considering where and when each might dominate, provide a useful framework for understanding and modelling the behaviour of particulate material within DWDS that can inform management to reduce discolouration. Neither theory provides a complete understanding and associated modelling tools require coefficients and approximations derived from field data, such as velocity thresholds and layer strength coefficients. It is not possible to have a complete understanding of the processes due to the infinite range of possible interactions occurring for formation, trapping, and retaining material within DWDS. As a result, a comprehensive analysis of the different factors and the degree of contribution is not yet attainable. While field and laboratory derived evidence show that material accumulation is repeatable (Husband and Boxall, 2011) and a linear function of time (Cook and Boxall, 2011), and various factors such as turbidity of the incoming water (Blokker and Schaap, 2015a), hydraulic conditions (Blokker et al., 2009; Sharpe et al., 2017), temperature (Blokker and Schaap, 2015b; Cook et al., 2015; Preciado et al., 2021), chlorine residual (Fish et al., 2020), AOC concentrations (Pick et al., 2021a) microbiological processes (Prest et al., 2023) and other water quality parameters (Mounce et al., 2014 & 2016; Speight et al., 2019) impact accumulation, there remains a lack of understanding of the key processes in a given DWDS and location and hence how to select the best combination for long term management.

A too common issue with research that should help elucidate the processes of material accumulation is the lack of specificity in describing and considering the mechanisms and forces. This is epitomised by the phrase 'loose deposits'. Loose is too vague to accurately describe the force regime that is being considered, either imposed or resistive. Deposits are commonly defined as 'put or set down in a specific place' hence infers sedimentation processes. Mussared et al. (2019) in 'The origins and risks associated with loose deposits…' start from the assumption of sedimentation dominated processes, but the findings point to the importance of corrosion and biological processes that occur over the complete pipe surface not just the pipe invert, which are cohesive layer processes. Torvinen et al. (2004), which also uses the phrase in the paper title, analysed material collected by mechanical cleaning, concluding on the central role of mycobacterium and biofilms. Mechanical cleaning indicates that the material analysed was not 'loose' and biofilms form on the complete surface so are more likely cohesive layers than sedimentation. While these two works have been arbitrarily selected as examples, "loose deposits" and the lack of care in terminology used is common. It is important that research is exact in the terms used and hence that processes, mechanisms, and behaviour are correctly associated and integrated. This paper aims to address this deficiency and lay out a framework to move forward in discolouration research from a unified theoretical basis.

4.1. Physical factors influencing discolouration

4.1.1. Hydraulic conditions

Velocity thresholds are key to sedimentation theories. Velocity greater than ~0.07 m/s is quoted as preventing sedimentation (Ryan et al., 2008). Blokker et al. (2010) showed that pipe lengths with maximum daily velocities around 0.07 m/s experienced the highest material accumulation. The application of mathematical expressions to derive this value are inconclusive (Boxall et al., 2001; Blokker et al., 2010; Pothof and Blokker, 2012; van Thienen et al., 2011). It should be noted that the threshold for mobilisation is generally greater than the velocity to prevent sedimentation, with Vreeburg and Boxall (2007) quoting a self-cleaning velocity threshold of 0.4 m/s and Blokker et al. (2010) refining this to a value between 0.2 and 0.25 m/s. These different threshold velocities were based on the same data from operational DWDS, with the revised velocities based on improved accuracy in the hydraulic modelling. This highlights the importance of accuracy of hydraulic models for understanding discolouration, in this case accuracy of peak velocities.

The difference between velocity thresholds for settling and mobilisation or self-cleaning are consistent with physical concepts such as exposure angle, armouring and sheltering of mix grain sediment beds from river and sewer domains. The research of Braga and Filion (2022a&b) that isolated only physical processes confirms such processes for iron particles. They did not report thresholds for settling or mobilisation. Their coupon analysis showed invert deposits only, confirming physical sedimentation occurred. In operational systems it is likely that once accumulated, chemical and biological processes could also occur imparting further resistive strengths.

The cohesive layer theories are based on a force balance between imposed hydraulic shear stress forces and layer cohesive shear strengths. While shear stress can be readily calculated from head-loss as intrinsically estimated in every network modelling software, accuracy requires a high quality of hydraulic model calibration. The cohesive layer models also require empirical coefficients to convert the force balance to turbidity and these can only be obtained by model calibration to measured turbidity data.

Understanding of material mobilisation under dynamic conditions and the impacts on non-linear pipe sections or fittings remains unclear (Pothof and Blokker 2012; Braga et al., 2020). Some researchers have attempted to investigate the association of transients with water quality. Computational studies suggest that while small magnitude and duration additional dynamic forces are generated by hydraulic transients, simulated turbidity response was not improved over steady state assumptions (Naser et al., 2006). The ability for transients to cause mobilisation when equivalent steady state hydraulic conditions could not was demonstrated under controlled but representative conditions by Weston et al. (2019). Exploration of mechanisms to explain the mobilisation response by Weston et al. (2021) indicated via a slight time lag that it is the rapidly changing velocity profiles and not the pressure fronts that are responsible. This understanding supports practices such as slow valve movements during network operations to minimise transients as a possible self-inflicted cause of mobilisation.

Hydraulic conditions in a given pipe have been shown to influence the rate of accumulation. Blokker et al. (2009) measured turbidity during flushing in three parts of a supply area finding that the pipes that experience the highest daily flow velocities returned the lowest discolouration. The effect of hydraulic conditions has also been observed under controlled but fully representative laboratory experiments by Sharpe et al. (2017). It was found that a pattern of varying hydraulics reduced the accumulation rate of cohesive discolouration material, even when the peak of the pattern was less than a steady hydraulic condition. By incorporating lower flow (overnight) conditions within the varying hydraulic profile, this work highlighted that these periods are relatively unimportant provided that there is a strong morning peak in hydraulic forces. Sharpe et al. (2017) used pipe coupons at the crown, invert and side of the pipe finding no difference in material accumulation between these locations, including no gravity dominated invert deposit even with steady state flows of ≈ 0.1 m/s. However, it should be noted that the lowest hydraulic conditions studied were transitional, not laminar. Both Blokker et al. (2009) and Sharpe et al. (2017) findings of lower accumulation and hence discolouration potential with increasing flow suggest that the accumulation processes occurring were not limited by the rate of supply of material despite the low concentrations in the bulk water. But what these processes are and how hydraulic conditions are influencing remain uncertain.

The idea of regular increases in hydraulic conditions is at the heart of the ‘flow conditioning’ concept (Husband and Boxall, 2015 and 2016b). A concern with this approach is that while accumulated material is mobilised and removed from the pipe of interest, it is not removed from the system, unlike with flushing. Perhaps counter intuitively Sunny et al. (2019) report the efficacy and benefits of such hydraulic conditioning on downstream networks, as well as the trunk main. This was explained by the observation of reduction in the chronic material loading in bulk water quality. This suggests that there is a clear balance to be found between managing water quality and regular cleaning activities. The bulk water quality clearly influences the rate of fouling or accumulation, so improvements such as via treatment works upgrades will reduce this. But this will only extend the period between cleaning interventions and not eliminate them. So, the outstanding question is how much the accumulation rate is reduced by improvements to bulk water quality and hence will extend the required period between periodic maintenance interventions. To answer this, the challenge remains to determine if it is possible and how to estimate the rate of accumulation in a given pipe as a function of the bulk water quality.

4.1.2. Particle size and behaviour

Particle size is not constant in DWDS. Treated water contains low concentrations of iron and manganese and organics, hence when turbulence is low enough flocculation could be occurring in DWDS, encouraging the formation of particle flocs with greater self-weight than individual particles. Blokker and Schaap (2011) showed that the ratio between turbidity and suspended solids differs between long and short accumulation times in the DWDS. Interestingly the turbulence limits of Bridgeman et al. (2008) equate to velocities of the order of the 0.07 m/s as have been found to limit sedimentation driven discolouration. The generation of floc and the role of this in accumulation has not been proven. Other physical, chemical and biological processes also occur within DWDS, forming particles and changing their size. This includes dissolution to aggregation to sequestering. Further research is required to understand the effects on accumulation and mobilisation mechanisms and the potential key hydraulic thresholds that could influence these processes.

4.2. Chemical factors influencing discolouration

Once at the pipe wall, the exact mechanisms of material attachment and retention are unknown. With key components being iron and manganese that can exist in multiple states, it is likely to involve a range of chemical interactions. While metals are present in discolouration samples, there is no obvious inorganic chemical bonding that explains the ubiquitously observed cohesive layer discolouration behaviour or the differences in settling and remobilisation forces for sedimentation. The ubiquitous presence of metals at site and network specific relative concentrations suggests a localised site specificity depending on water chemistry and therefore differing behaviours and responses across and within networks. The presence of these metals also supports the perception that discolouration is an inorganic issue (Sly et al., 1990; Sarin et al., 2004). These inorganics are certainly an important factor in the light scattering effect that is experienced by customers. Iron and manganese are typically the dominant inorganics in discolouration samples, although a cocktail of other metals is often present in lower concentrations (Seth et al., 2004). The behaviour of both iron and manganese is important (Sly et al., 1990). Pragmatic studies suggest that manganese removal as a measure of improving treated water quality can be an effective to help manage discolouration (van der Wielen and van der Wettering (2021) and https://www.waterindustryjournal.co.uk/reducing-customer-discolouration-complaints-by-controlling-manganese-at-water-treatment-works [accessed February 2022]).

4.3. Biological factors influencing discolouration

Discolouration material includes significant organic content (Gauthier et al., 2001). With 95% of the biomass found in DWDS existing as biofilms (Flemming, 2002), it is logical to connect biofilms and discolouration (Husband et al., 2016a). Biofilms form at the pipe water interface and are a complex matrix including bacteria, archaea, viruses, protists and fungi bound together with extra-cellular polymeric substances (EPS) (Fish et al., 2017; Mathieu et al., 2019). EPS forms the greatest part of the biofilm and is accredited with many functions, including structure and stability (Fish et al., 2017). The presence of biofilms can provide processes to explain the accumulation of inorganics at the pipe wall through the complex array of structures and integrity derived by EPS, which has been shown to have associated inorganics (Laspidou and Rittmann, 2004) including iron and manganese (Ginige et al., 2011). Biofilms have also been observed to have cohesive strength, with erosion associated with increasing shear stress (Ramasay and Zhang, 2005; Neu and Lawrence, 2010; Abe et al., 2012). It is consequently believed that biofilms, and in particular the EPS component, is able to accumulate particles subjected to radial transport processes (van Thienen et al., 2011) and provide the cohesive behaviour observed from material accumulated on all pipe surfaces (Husband et al., 2016a).

While the role of biofilms seems important in discolouration, significant unknowns remain about the actual processes of accumulation and what governs and influences the strength characteristics. Studies are exploring the microbial composition of biofilms within DWDS biofilms and the factors that affect this (for example Fish et al., 2020; Preciado et al., 2021). However, more important for discolouration is a deeper understanding of function, including response to environmental pressures and in particular how this manifests as EPS and the physical properties this imparts.

Biofilm mobilisation suffers from ambiguity in language with the terms erosion and sloughing often used confusingly and interchangeably. Telgmann et al. (2004) differentiated these in terms of the particles mobilised. More common is a differentiation between ongoing exchange and one off larger events. Ongoing processes are more often termed erosion, at odds with physical sedimentation processes as this is often a metabolically driven process in the evolution of the biofilms. One off release is often termed sloughing; this can be both due to an imposed hydraulic force or bulk release due to biological evolution (instability) of the biofilm. Sloughing is thus often a particularly ambiguous confusing term. More precision in language is needed to further advance understanding.

The concept of biologically stable water has been advocated for some time (Prest et al., 2016). It is commonly assessed with respect to bulk water properties, such as change in water quality from point of entry to tap, with management often focused on the limiting nutrients, primarily AOC. Biostability concepts do not typically consider interaction with biofilms, largely due to the complexity of accessing and hence studying them. Pick et al., (2021a & b) used novel biofilm sampling and monitoring and flow cytometry to show that biofilm formation rates in distribution systems does depend on the incoming water quality (AOC). The association of discolouration with material from biological origin as biofilms (more specifically material accumulated in the biofilm, as discussed above) has been shown in a non-chlorinated supply area (Prest et al., 2023).

4.4. Management strategies for discolouration

Fig. 1 is conceptually useful, but its axes are not quantified or the parameters entirely clear. We could populate the horizontal axis as a function of measuring and analysing particles. But even the parameter for the vertical axis is inconsistent. Sedimentation theory is based on velocity while cohesive layer theory is based on shear stress, with a nonlinear relationship between the two. So different parameters are required. Based on the earlier analogy to Shield's diagram and variations thereof such as van Summeren and Blokker (2017), it is tempting to think that Fig. 1 should be populated with self-weight velocity thresholds. This however is too simplified. Even considering physical effects only, there remains no understanding of the different settling and mobilisation thresholds, or different long and short term effects (Braga and Fillion, 2022a&b). This is further complicated when considering flocculation and similar effects that may cause self-weight velocities to change. Further, sedimentation theory for balancing turbulence forces are generally based on individual particles while the light scattering effects of turbidity are due to large numbers of particles that will and do interact and influence each other's behaviours. These reasons and the further explanations and ideas explored here explain why Fig. 1 remains conceptual. It is still useful to help interpret behaviour and hence inform management. It may be sufficient to assume that cohesive layers form in all pipes, and where this dominates discolouration is a linear function of increase in excess shear stress. Or, where hydraulics are low enough and particles heavy enough for sedimentation to occur it will dominate, and discolouration will be governed by exceedance of thresholds. Further research is required to help us better define and understand the zone where the processes interact.

Practically one of the biggest unknowns that is vital for planning long term sustainable management is how often to repeat maintenance interventions to maintain a desired level of service or resilience to discolouration. Conceptually this could be a third axis to Fig. 1. More understanding is needed to know how different capital investment options that could improve bulk water quality would change the rate of material accumulation, and hence how this would impact the period between operational cleaning interventions. This is key to optimising total investment, enabling answers to questions such as is it better to improve a treatment works or replace cast iron pipes to improve water quality, or manually flush or implement automated valves, pumps etc. to regularly flow condition or self-clean networks. It is important to note that capital investment options will typically be associated with benefits beyond discolouration, such as treatment work upgrades to improve overall water quality compliance or pipe replacement to reduce leakage and bursts.

5. Conclusions & outlook

- Discolouration within drinking water distribution systems occurs due to complex and interacting physical, chemical and biological processes within the vast, pipe surface dominated infrastructure.
- Effective discolouration management requires understanding of the dominant behaviour:
  - gravitational settling can dominate when particle size is relatively large and daily peak hydraulic forces relatively low
  - formation of cohesive layers on boundary surfaces of all pipes, irrespective of hydraulic conditions.
- Cleaning strategies must target the dominant processes, e.g. flow conditioning of trunk mains where cohesive behaviour usually dominates and the strategic importance and risks can justify the detailed design, monitoring and automation necessary; or flushing to remove sediment deposits from distribution networks, including dead-ends or 'tidal' points on pipe loops. A uni-directional flushing scheme ensures good results.
- Cleaning strategies must be ongoing as there is a continual low level flux of material that will continually re-accumulate. Best practice will be a balance between controlling material source and periodic maintenance.
- The rate of material accumulation or pipe fouling (deterioration) is a function of the bulk water quality in that pipe. More understanding is required to estimate this rate as a function of the water quality, and how it will change if water quality is improved.
- Understanding and quantification of the processes behind material accumulation is required to predict and control the rates of accumulation and hence inform the optimal balance between capital investments to improve bulk water quality and ongoing maintenance interventions. This is essential to identify long term optimal sustainable management strategies.

The authors declare no conflict of interest.

Declaration of Competing Interest

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References

Abe, Y., Skali-Lami, S., Block, J.C., Francius, G., 2012. Cohesiveness and hydrodynamic properties of young drinking water biofilms. Water Res. 46 (4), 1155–1166. https://doi.org/10.1016/j.watres.2011.12.013.

Akers, P., White, W.R., 1973. Sediment transport: new appraoch and analysis. Proc. ACSE. 99 (11), 2041–2060. HY.

Abraham, E., Blokker, E.J.M., Stoianov, I., 2017. Network analysis, control valve placement and optimal control of flow velocity for self-cleaning water distribution systems. Procedia Eng. 576–583.

Armand, H., Stoianov, I., Graham, N., 2017. A holistic assessment of discolouration processes in water distribution networks. Urban Water J. 14 (3), 263–277.

Arsénio, A., 2012. Particle Characterisation in the Transport and Distribution Network of Treatment Plants Harderbroek and Fledite. KWR, Nieuwegein. BTO 2012.023(s).

Ashley, R.M., Fraser, A., Burrows, R., Blanksby, J., 2000. The management of sediment in combined sewers. Urban water 2 (4), 263–275.

AWWA, 2017. Manual of Water Supply Practices—M68 Water Quality in Distribution Systems. In: AWWA, Denver.

Blokker, E.J.M., Schaap, P.G., 2007. Sedimentverwijdering Bij Verschillende Snelheden. Kiwa Water Research, Nieuwegein. BTO 2006.070.

Blokker, E.J.M., Beverloo, H., 2009. Methoden Om Vermaasde Nettenschoon Te Houden. KWR, Nieuwegein. BTO 2009.053 (s).

Blokker, E.J.M., Schaap, P.G., Vreeburg, J.H.G., 2009. Self-cleaning networks put to the test. In: Alegre, H., Almeida, M.D.C. (Eds.), Chapter, Strategic Asset Management of Water Supply and Wastewater Infrastructures; Invited papers from the IWA Leading edge conference on strategic asset management (LESAM). Lisbon, pp. 407–417. October 2007.

Blokker, E.J.M., 2010. Stochastic Water Demand Modelling For a Better Understanding of Hydraulics in Water Distribution Networks. Delft University of Technology.

Blokker, E.J.M., Vreeburg, J.H.G., Schaap, P.G., van Dijk, J.C., 2010. The Self-Cleaning Velocity in Practice. WDSA 2010, ASCE, Tuscon, AZ.

Blokker, E.J.M., Schaap, P.G., 2011. Het Modelleren Van Deeltjes in Het Leidingnet. KWR, Nieuwegein. *BTO 2011.047*.

Blokker, M., Vogelaar, H., Goos, K., Vreeburg, J., 2012. Using valve manipulation to manage discolouration risk in drinking water distribution networks. Water Asset Manag. Int. 8, 07–10.

Blokker, E.J.M., Schaap, P.G., 2015a. Particle accumulation rate of drinking water distribution systems determined by incoming turbidity. In: Procedia Engineering 13th Computing and Control for the Water Industry Conference, 2015. CCWI, pp. 290–298.

Blokker, E.J.M., Schaap, P.G., 2015b. Temperature influences discolouration risk. In: Procedia Engineering 13th Computing and Control for the Water Industry Conference, 2015. CCWI, pp. 280–289.

Boxall, J.B., Skipworth, P.J., Saul, A.J., 2001. A novel approach to modelling sediment movement in distribution mains based on particle characteristics. In: the Computing and Control in the Water Industry Conference. A.A. Balkema Publishers, De Montfort University, UK.

Boxall, J.B., Saul, A.J., 2005. Modelling discolouration in potable water distribution systems. J. Environ. Eng. ASCE 131 (5), 716–725. https://doi.org/10.1061/(ASCE)0733-9372(2005)131:5(716).

Boxall, J.B., Dewis, N.D, 2005. Identification of discolouration risk through simplified modelling. In: ASCE ERWI World Water and Environmental Water Resources. Anchorage, USA, 15-19 May.

Boxall, J., Prince, R., 2006. Modelling discolouration in a Melbourne (Australia) potable water distribution system. J. Water Supply 55 (3), 207–219.

Braga, A., Saulnier, R., Filion, Y., Cushing, A., 2020. Dynamics of material detachment from drinking water pipes under flushing conditions in a full-scale drinking water laboratory system. Urban Water J. 17, 745–753.

Braga, A., Filion, Y., 2022a. Initial stages of particulate iron oxide attachment on drinking water PVC pipes characterized by turbidity data and brightfield microscopy from a full-scale laboratory. Environ. Sci. https://doi.org/10.1039/D2EW00010E.

Braga, A., Filion, Y., 2022b. The interplay of suspended sediment concentration, particle size and fluid velocity on the rapid deposition of suspended iron oxide particles in PVC drinking water pipes. Water Res. X 15. https://doi.org/10.1016/j.wroa.2022.100143.

Bridgeman, J., Jefferson, B., Parsons, S., 2008. Assessing Floc strength using CFD to improve organics removal. Chem. Eng. Res. Des. 86, 941–950.

Carriere, A., Gauthier, V., Desjardins, R., Barbeau, B., 2005. Evaluation of loose deposits in distribution systems through unidirectional flushing. Am. Water Works Assoc. 97 (9), 82–92.

Carter, Means, Owen and Jones, 2017. Fostering innovation within water utilities: case studies. Water Res. Foundation. Project #4642.

Chan, S., Pullerits, K., Keucken, A., Persson, K.M., Paul, C.J., Rådström, P., 2019. Bacterial re-lease from pipe biofilm in a full-scale drinking water distribution system. Npj Biofilmsand Microbiomes 5 (1), 1–8. https://doi.org/10.1038/s41522-019-0082-9.

Cook, D.M., Boxall, J.B., 2011. Discolouration material accumulation in water distribution systems. J. Pipeline Syst. Eng. Pract. ASCE 2 (4), 113–123. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000083.

Cook, D.M., Husband, P.S., Boxall, J.B., 2015. Operational management of trunk main discolouration risk. Urban Water J. 13 (4), 382–395. https://doi.org/10.1080/1573062X.2014.993994.

Cook, D.M., McLeud, D., Boxall, J., Husband, S., 2022. Analysis of discolouration customer contacts to assess performance and intervention efficacy. In: 2nd International Joint Conference on Water Distribution Systems Analysis & Computing and Control in the Water Industry (WDSA/CCWI). Valencia (Spain), 18-22 July 2022.

De França Doria, M., 2010. Factors influencing public perception of drinking water quality. Water Policy 12, 1–19. https://doi.org/10.2166/wp.2009.051.

Ebacher, G., Besner, M.C., Clément, B., Prévost, M., 2012. Sensitivity analysis of some critical factors affecting simulated intrusion volumes during a low pressure transient event in a full-scale water distribution system. Water Res. 46 (13), 4017–4030.

Fish, K., Osborn, A.M., Boxall, J.B., 2017. Biofilm structures (EPS and bacterial communities) in drinking water distribution systems are conditioned by hydraulics and influence discolouration. Sci. Total Environ. 593-594, 571–580. https://doi.org/10.1016/j.scitotenv.2017.03.176.

Fish, K.E., Reeves, N., Husband, S., Boxall, J.B., 2020. Uncharted waters: the unintended impacts of residual chlorine on water quality and bio films. Nat. Partner J. 6, 34. https://doi.org/10.1038/s41522-020-00144-w.

Flemming, H.-C., 2002. Biofouling in water systems–cases, causes and countermeasures. Appl. Microbiol. Biotechnol. 59 (6), 629–640, 2002.

Friedman, M.J., Martel, K., Hill, A., Holt, D., Simth, S., Ta, T., Sherwin, C., Hiltebrand, D., Pommerenk, P., Hinedi, Z., Camper, A., 2003. Establishing Site-Specific Flushing Velocities. Awwa Research Foundation, Denver, CO.

Fox, S., Shepherd, W.J., Collins, R.P., Boxall, J.B., 2015. Experimental quantification of contaminant ingress into a buried leaking pipe during transient events. ASCE J. Hydraul. Eng. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001040.

Furnass, W.R., Mounce, S.R., Boxall, J.B., 2013. Linking distribution system water quality issues to possible causes via hydraulic pathways. Environ. Model. Softw. 40, 78–87. https://doi.org/10.1016/j.envsoft.2012.07.012.

Furnass, W.R., Collins, R.P., Husband, P.S., Sharpe, R.L., Mounce, S.R., Boxall, J.B., 2014. Modelling both the continual erosion and regeneration of discolouration material in drinking water distribution systems. IWA Water Sci. Technol. 14 (1), 81–90. https://doi.org/10.2166/ws.2013.176.

Furnass, W.R., Mounce, S.R., Husband, P.S., Collins, R.P., Boxall, J.B., 2019. Calibrating and validating a combined accumulation and mobilisation model for water distribution system discolouration using particle swarm optimisation. J. Smart Water 4 (3), 1–24. https://doi.org/10.1186/s40713-019-0015-z.

Gauthier, V., Barbeau, B., Millette, R., Block, J.-C., Prevost, M., 2001. Suspended particles in the drinking water of two distribution systems. Water Sci. Technol. 1 (4), 237–245.

Ginige, M.P., Wylie, J., Plumb, J., 2011. Influence of biofilms on iron and manganese deposition in drinking water distribution systems. Biofouling 27, 151–163. https://doi.org/10.1080/08927014.2010.547576.

Husband, P.S., Boxall, J.B., Saul, A.J., 2008. Laboratory studies investigating the processes leading to discolouration in water distribution networks. Water Res. 42 (16), 4309–4318.

Husband, P.S., Boxall, J., 2009. Field studies of discoloration in water distribution systems: model verification and practical implications. J. Environ. Eng. 136 (1), 86–94.

Husband, P.S., Whitehead, J., Boxall, J.B., 2010. The role of trunk mains in discolouration. Proc. Inst. Civ. Eng. 163 (8), 397.

Husband, P.S., Boxall, J., 2011. Asset deterioration and discolouration in water distribution systems. Water Res. 45 (1), 113–124.

Husband, P.S., Boxall, J., 2015. Predictive water quality modelling and resilience flow conditioning to manage discolouration risk in operational trunk mains. J. Water Supply 64, 529–542.

Husband, P.S., Fish, K., Douterelo, I., Boxall, J., 2016a. Linking discolouration modelling and biofilm behaviour within drinking water distribution systems. Water Sci. Technol. 16.4, 942–950. https://doi.org/10.2166/ws.2016.045.

Husband, P.S., Boxall, J., 2016b. Understanding and managing discolouration risk in trunk mains. Water Res. 107, 127–140. doi.org/10.1016/j.watres.2016.10.049.

IWA (2016) 'The Bonn Charter for safe drinking water' https://iwa-network.org/publications/the-bonn-charter-for-safe-drinking-water/ [accessed 14th January 2022].

Kitchener, B.G.B., Wainwright, J., Parsons, A.J., 2017. A review of the principles of turbidity measurement. Progr. Phys. Geogr. 41 (5) https://doi.org/10.1177/0309133317726540.

Laspidou, C.S., Rittmann, B.E., 2004. Modelling the development of biofilm density including active bacteria, inert biomass, and extracellular polymeric substances. Water Res. 38 (14–15), 3349–3361.

Mathieu, L., Paris, T., Block, J.C. (2019). Microbiome of drinking water distribution systems. In: Hurst, C. (eds) The Structure and Function of Aquatic Microbial Communities. Advances in Environmental Microbiology, vol 7. Springer, Cham. doi:10.1007/978-3-030-16775-2_9.

Mehta, A.J., Lee, S.C., 1994. Problems in linking the threshold conditions for the transport of cohesionless and cohesive sediment grain. J. Coast. Res. 10 (1), 170–177. Part.

Mesman, G.A.M., Meerkerk, M.A., 2015. PCD 2 Sediment in drinkwaterleidingen. Beoordelen en Beheersen 2015, PCD 2. KWR, Nieuwegein. https://library.kwrwater.nl/publication/54136959/.

Mounce, S., Husband, S., Furnass, W., Boxall, J., 2014. Multivariate data mining for estimating the rate of discoloration material accumulation in drinking water systems. Procedia Eng. 89, 173–180.

Mounce, S.R., Gaffney, J.W., Boult, S., Boxall, J.B., 2015. Automated data-driven approaches to evaluating and interpreting water quality time series data from water distribution systems. ASCE J. Water Resour. Plan. Manag. 141 (11), 1–11. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000533.

Mounce, S.R., Blokker, E.J.M., Husband, S.P., Furnass, W.R., Schaap, P.G., Boxall, J.B., 2016. Multivariate data mining for estimating the rate of discolouration material accumulation in drinking water distribution systems. IWA J. Hydroinformatics 18 (1), 96–114.

Mussared, A., Fabris, R., Vreeburg, J., Jelbart, J., Drikas, M., 2019. The origin and risks associated with loose deposits in a drinking water distribution system. Water Supply (2019) 19 (1), 291–302. https://doi.org/10.2166/ws.2018.073.

Naser, G., Karney, B.W., Boxall, J.B., 2006. Red water and discolouration in a WDS: anumerical simulation. In: 8th Annual Water Distribution Systems Analysis Symposium. Cincinnati, Ohio, USA. August 27-30 2006.

Neu, T.R., Lawrence, J.R., 2010. Extracellular polymeric substances in microbial biofilms. Chapter, Microbial glycobiology. Elsevier, pp. 733–758.

Parchure, T.M., Mehta, A.J., 1985. Erosion of soft cohesive sediment deposits. J. Hydraul. Eng. 111, 1308–1326.

Pick, F.C., Fish, K.E., Boxall, J.B., 2021a. Assimilable Organic Carbon Cycling within Drinking Water Distribution Systems. Water Res. 198 https://doi.org/10.1016/j.watres.2021.117147.

Pick, F.C., Fish, K.E., Husband, P.S., Boxall, J.B., 2021b. Non-invasive Biofouling Monitoring to Assess Drinking Water Distribution System Performance'. Front. Microbiol., Sect. Microbiotechnol. 12 https://doi.org/10.3389/fmicb.2021.730344. Vol.

Pothof and Blokker, 2012. Dynamic hydraulic models to study sedimentation in drinking water networks in detail. Drinking Water Eng. Sci. Discuss. 5 (11), 87–92. https://doi.org/10.5194/dwes-5-87-2012.

Preciado, C.C., Boxall, J.B., Soria-Carrasco, V., Martínez, S., Douterelo, I., 2021. Implications of climate change: how does increased water temperature influence biofilm and water quality of chlorinated drinking water distribution systems?'. Front. Microbiol., Sect. Microbiotechnol. https://doi.org/10.3389/fmicb.2021.658927.

Prest, E.I., Hammes, F., Kötzsch, S., van Loosdrecht, M.C.M., Vrouwenvelder, J.S., 2016. A systematic approach for the assessment of bacterial growth-controlling factors linked to biological stability of drinking water in distribution systems. Water Supply (2016) 16 (4), 865–880. https://doi.org/10.2166/ws.2016.001.

Prest, E.I., Martijn, B.J., Rietveld, M., Lin, Y., Schaap, P.G., 2023. Micro) biological sediment formation in a non-chlorinated drinking water distribution system. Water (Basel) 15 (2), 214.

Ramasamy, P., Zhang, X., 2005. Effects of shear stress on the secretion of extracellular polymeric substances in biofilms. Water Sci. Technol. 52 (7), 217–223. https://doi.org/10.2166/wst.2005.0204.

Russell, S., 1993. Water Industry Instrument Handbook—Book 4 Turbidity. WRc plc, Wiltshire, U.K.

Ryan, G., Mathes, P., Haylock, G., Jayaratne, A., Wu, J., Noui-Mehidi, N., Grainger, C., Nguyen, B.V., 2008. Particles in Water Distribution Systems. Cooperative Research Centre for Water Quality and Treatment, Salisbury, Australia. Research report 33.

Sarin, P., Snoeyink, V., Bebee, J., Jim, K., Beckett, M., Kriven, W., Clement, J., 2004. Iron release from corroded iron pipes in drinking water distribution systems: effect of dissolved oxygen. Water Res. 38 (5), 1259–1269.

Schaap, P., Blokker, M., 2012. Understanding Differences in Sediment Characteristics in Drinking Water Distribution Networks, 2012. WDSA, Adelaide, Australia, pp. 435–441.

Seth, A., Bachmann, R., Boxall, J., Saul, A., Edyvean, R., 2004. Characterisation of materials causing discolouration in potable water systems. Water Sci. Technol. 49 (2), 27–32.

Sharpe, R.L., Biggs, C.A., Boxall, J.B., 2017. Hydraulic conditioning to manage potable water discolouration' ICE Proceedings. Water Manag. https://doi.org/10.1680/jwama.16.00038. VOL.

Sly, L., Hodgkinson, M., Arunpairojana, V., 1990. Deposition of manganese in a drinking water distribution system. Appl. Environ. Microbiol. 56 (3), 628–639.

Speight, V.L., Mounce, S.R., Boxall, J.B., 2019. Identification of the causes of drinking water discolouration from machine learning analysis of historical datasets. Environ. Sci. 5 (4), 747–755.

Sunny, I., Husband, P.S., Drake, N., Mckenzie, K., Boxall, J.B., 2016. Quantity and quality benefits of in-service invasive cleaning of trunk mains. In: 14th International Conference on Computing and Control for the Water Industry, 7-9th November. Amsterdam, Netherlands.

Sunny, I., Husband, S., Boxall, J., 2019. Impact of hydraulic interventions on chronic and acute material loading and discolouration risk in drinking water distribution systems. Water Res. https://doi.org/10.1016/j.watres.2019.115224.

Sunny, I., Husband, S., Boxall, J., 2023. Simulating long term discolouration behaviour in large diameter trunk mains. Environ. Sci. 9, 756–771, 2023.

Telgmann, U., Horn, H., Morgenroth, E., 2004. Influence of growth history on sloughing and erosion from biofilms. Water Res. 38 (17), 3671–3684.

Torvinen, E., Suomalainen, S., Lehtola, M.J., Miettinen, I.T., Zacheus, O., Paulin, L., Katila, M.L., Martikainen, PJ., 2004. Mycobacteria in water and loose deposits of drinking water distribution systems in Finland. Appl. Environ. Microbiol. 70 (4), 1973–1981. https://doi.org/10.1128/AEM.70.4.1973-1981.2004, 2004 AprPMID: 15066787; PMCID: PMC383162.

van der Wielen, P.W.J.J., van de Wetering, S.T.S.C.M., 2021. De Invloed Van Mangaan Op Biofilm En Sediment in Het Distributiesysteem. KWR, Nieuwegein. BTO 2021.039.

van Rooij, D.J.M., 2016. Bachelor thesis. Fontys Hogescholen.

van Summeren, J., Raterman, B., Vonk, E., Blokker, M., Van Erp, J., Vries, D., 2015. Influence of temperature, network diagnostics, and demographic factors on discoloration-related customer reports. In: Procedia Engineering 13th Computing and Control for the Water Industry Conference, CCWI 2015, pp. 416–425.

van Summeren, J., Blokker, M., 2017. Modeling particle transport and discoloration risk in drinking water distribution networks. Drink. Water Eng. Sci. 10 (2), 99–107. https://doi.org/10.5194/dwes-10-99-2017.

van Summeren, J.R.G., Dash, A., Morley, M.S., de Waal, L., van Steen, J.E., 2022. Aquarellus: a numerical tool to calculate accumulation of particulate matter in drinking water distribution systems. In: 2nd Int. Joint Conference on WDSA & CCWI. Valencia, Spain.

van Thienen, P., Vreeburg, J.H.G., Blokker, E.J.M., 2011. Radial transport processes as a precursor to particle deposition in drinking water distribution systems. Water Res. 45 (4), 1807–1817. https://doi.org/10.1016/j.watres.2010.11.034.

Vogelaar, A.J., Blokker, E.J.M., 2010. Particle Sediment Modelling. Test and Analysis of Programme WQDMTB v4.3. KWR, Nieuwegein. BTO 2010.011.

Vreeburg, J.H.G., Schaap, P.G., van Dijk, J.C., 2004. Measuring discoloration risk: resuspention potential method. In: Leading edge Technology conference. IWA, Prague.

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

Vreeburg, J.H.G., Boxall, J.B., 2007. Discolouration in potable water distribution systems: a review. Water Res. 41 (3), 519–529.

Vreeburg, J.H.G., Schippers, D., Verberk, J.Q.J.C., van Dijk, J.C., 2008. Impact of particles on sediment accumulation in a drinking water distribution system. Water Res. 42 (16), 4233–4242.

Vreeburg, J.H.G., Blokker, E.J.M., Horst, P., van Dijk, J.C., 2009. Velocity based self cleaning residential drinking water distribution systems. Water Sci. Technol. 9 (6), 635–641. https://doi.org/10.2166/ws.2009.689.

Weston, S.L., Collins, R.P., Boxall, J.B., 2019. A novel demonstration of adhered material mobilisation by hydraulic transients'. Environ. Sci. https://doi.org/10.1039/c9ew00686a.

Weston, S.L., Collins, R.P., Boxall, J.B., 2021. An experimental study of how hydraulic transients cause mobilisation of material within drinking water distribution systems. Water Res. 194 https://doi.org/10.1016/j.watres.2021.116890.

WRC, 1989. Removing Loose Deposits from Water mains: Operational Guidelines. WRc Wiltshire.