Discolouration loose deposits: balancing views and practices

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Abstract: Tap water discolouration incidents may occur due to resuspension of loose deposits (LD) that accumulate in drinking water distribution systems (DWDS), due to velocity increases or rapid changes. While lowering the consumers' confidence in tap water's safety, they are often a cause of customer complaints, especially when recurrent. Owing to the lack of knowledge on LD dynamics and build-up processes in DWDS, however, LD control and prevention strategies are still ineffective to counteract LD accumulation and prevent tap water discolouration incidents. In this paper, supported by relevant literature and results from a four year study on LD sampling and characterisation, a conceptual model for LD dynamics and build-up processes in DWDS is proposed. The model description together with the expected LD build-up rates were used to interpret discolouration phenomena. The model's practical implications and recommendations were also discussed, including the potential strategies for LD control and prevention in DWDS. Overall, it was concluded that LD accumulation is most critical at mid-range velocities and that, under this range, it may occur exponentially in DWDS. The possible changes in the relative composition of LDs occurring over accumulation were studied and related with LD resuspension potentials, along with LD ageing and residence times.

Keywords: drinking water distribution systems, loose deposits, tap water discolouration.

Introduction

Loose deposits (LD) may develop and accumulate in drinking water distribution systems (DWDS) and often lead to tap water discolouration upon resuspension, which can be driven by velocity increases or changes (Vreeburg & Boxall 2007; Husband & Boxall 2011). Alike flow supply interruptions, discolouration is a common reason of consumers' complaints (Seth et al. 2004; van Dijk & van der Kooij 2005) while lowering the confidence on tap water's quality and safety, particularly wherever recurrent. As consequence of their typical yellow to brownish colour, LD are generally associated with cast iron corrosion particles (McNeill & Edwards 2001; Benson et al. 2012) and mostly seen as an aesthetic problem solely. However, LD accumulation may be associated with bacterial attachment and regrowth in DWDS (USEPA 2001; Batté et al. 2003), as discolouration incidents may also lead to degradation of drinking water quality upon LD resuspension (Zacheus et al. 2001; Lehtola et al. 2006).

Discolouration events may occur in every DWDS, including those devoid of cast iron pipes (Vreeburg et al. 2008), and irrespectively of the water characteristics or the presence of residual disinfectants (Gauthier et al. 1999; Zacheus et al. 2001). Particles in DWDS (Vreeburg & Boxall 2007; Husband & Boxall 2011) may come with source water (Gauthier et al. 1999; Lehtola et al. 2006) and pass through, or be originated, at the water treatment plant (WTP) (Smith et al. 1997; Gauthier et al. 2001); be produced in the distribution network, being released through pipe scaling, or corrosion (McNeill & Edwards 2001; Benson et al. 2012) and biofilm sloughing (LeChevallier et al. 1987; Batté et al. 2003; Liu et al. 2013), or occuring due to chemical precipitation/flocculation of dissolved/colloidal materials (Sly et al. 1990). Alternatively, particles may enter into DWDS during pipe rehabilitation or repair operations. Aiming at controlling LD levels and prevent discolouration incidents, routine pipe cleaning (Carriere et al. 2005; Vreeburg et al. 2009) and on site interventions (e.g., changing connections, pipe replacement) are usually performed. LD monitoring may be approached by using the resuspension potential method – RPM (Vreeburg & Boxall 2007), particle counting or turbidity measurements. These diagnostic approaches, although useful to identify critical zones for LD accumulation, to analyse effectiveness of pipe cleaning strategies and to assess the pipe's potential for discolouration, are short in providing information for the understanding of LD origin and behaviour in DWDS. As so, knowledge on LD's physical chemical characteristics and behaviour at more detailed levels is required, in order to better interpret LD occurrence in DWDS (Poças et al. 2013c). In addition, more adapted strategies for LD management and control are necessary.

Recent publications on discolouration incidents in DWDS (van Lieverloo et al. 2012, Poças et al. 2013a, Poças et al. 2013b) have focused more on the relevance of light/soft deposits (Zacheus et al. 2001), rather than on heavier particulates (e.g., sand grains). Unlike these, light LD flocs, that have densities close to water (Poças et al. 2013a) and sizes varying between 1 and 25 µm (Boxall et al. 2001, Verberk et al. 2006), accumulate in DWDS through build up processes other than gravitational forces only (Vreeburg and Boxall 2007). However, little is still known about the mechanisms underlying discolouration and LD build up processes in DWDS, or the practical implications of having such light floc materials travelling in the networks. On the other hand, the importance of LD main components, i.e., iron and volatile solids (VS), for the development of cohesive discolouration layers in distribution pipes (Vreeburg and Boxall 2007), has not yet been clearly understood.

In this paper, supported by the relevant literature on the subject, as well as by the main results obtained during a four year study on LD sampling and characterisation in the Lisbon's DWDS, a conceptual model for LD dynamics and build up processes in DWDS is proposed. In addition, the practical implications and recommendations driven by such model are discussed, with the aim of devising potential strategies for LD control and prevention in DWDS.

Material and Methods

LD were collected in DWDS from hydrants during pipe cleaning discharges. For discolouration LD representative sampling, Poças et al., (2013b) describe a low velocity methodology that is based on the collection of large sample volumes ($\geqslant$ 30 L) at the velocities achievable by the opening of the hydrants' valves. The low-velocity sampling methodology was used to characterise over 70 samples, collected from the Lisbon DWDS. LD physical-chemical characterisation followed the methods described in Poças et al., (2013a,b). The results were compared to relevant literature and translated into a model.

Results and Discussion

Results from the sampling in Lisbon DWDS showed that LD composition was similar to that reported elsewhere (Gauthier *et al.* 1999; Zacheus *et al.* 2001; Vreeburg & Boxall 2007), not only with respect to the typical main components (Poças *et al.* 2013a), but also in their relative contents (ca. 500 mg of total iron and ca. 160 mg of volatile solids per g of LD). In addition, LD's composition was not influenced by the onsite characteristics, such as pipe material or the type of connection (main or dead-end), and showed no relationship with the distance to the WTP. With respect to Fe contents, high levels (> 400 mg/g) were found in pipes of all kinds of materials. Thus, no tendency for more iron-rich LD was observed in cast-iron pipes. This is further supported by the fact that, in the Lisbon's DWDS, only ca. 19% of the pipes are made of cast-iron, as well as by the reported literature, where it is shown that discolouration incidents may occur in DWDS, irrespectively of pipe material (Vreeburg & Boxall 2007).

A number of studies have investigated the interpretation of the behaviour, composition and transport of LD in DWDS (Husband et al. 2008, Vreeburg et al. 2009, Blokker 2010). While some have focused more on LD modelling behaviour and transport (Vreeburg and Boxall 2007, Husband et al. 2008, Husband and Boxall 2011), or on the mechanisms underlying particle accumulation in DWDS, e.g., turbophoresis (Vreeburg 2007, van Thienen et al. 2011); others have focused on the physical chemical characteristics and behaviour of LD (Gauthier et al. 1999, Boxall et al. 2001, Poças et al. 2013a, Poças et al. 2014) to interpret LD build up in DWDS. Either way, it is stated that LD accumulation in DWDS does not occur due to gravitational forces alone, but mostly because of the cohesive and adhesive properties of LD (Vreeburg and Boxall 2007, Poças et al. 2014), which, in turn, may be driven by the presence of iron and VS constituents. As suggested by Poças et al., (2013a), LD may be expected to form upon the association of Fe3+ with organic components, i.e., extracellular polymeric substances (EPS), thus providing a "hydrogel floc" nature and behaviour to LD. These hydrogel floc properties, apart from the high water holding capacity (up to 99%), may confer the cohesive adhesive characteristics which are required for light flocs, such as LD, to assemble, be accumulated and stay accumulated in the turbulent regimes of DWDS. Unlike turbophoresis (van Thienen et al. 2011), which may be limited to deposition of large particles (> 50 µm) in transport mains, LD accumulation through cohesive adhesive mechanisms is not size dependent or exclusive of the turbulent regimes. In addition, it suggests that LD accumulation patterns in DWDS may be influenced by LD composition, apart from the flow characteristics.

The lack of consistent relations between LD composition and the network characteristics (e.g., pipe material, location) highlights the importance of the total particle load coming from the WTP for LD accumulation in DWDS, comparatively to the network (e.g., cast iron corrosion). To further illustrate the importance of the

WTP, van Dijk and van der Kooij (2005), showed that with a capacity of 5 million m3 per year and a residual iron concentration of 0.05 mg/L, the treated water coming from the WTP had the potential load of 500 kg Fe(OH)3 per year to the network. The particle load entering the distribution network pipes may thus be minimised by improving the efficiency levels at the WTPs. Likewise, estimations over the inputs of iron and VS compounds in treated water, e.g., EPS and assimilable organic carbon (AOC), may be useful to evaluate the drinking water's potential for LD accumulation and pipe wall biofilm development. This applies not only for WTPs under high levels of treatment, where LD build¬ up may occur (Vreeburg et al. 2009), but also for those with lower treatment levels. Similarly, it may be applied to assess LD build up potential over treatment upgrades or changes, in order to better interpret the discolouration phenomena, including LD planning and monitoring procedures.

Based on the results obtained with LD characterisation and behaviour studies (Poças *et al.* 2013a; Poças *et al.* 2013b), with pilot-scale studies (Poças *et al.* 2014), and in other literature (Zacheus *et al.* 2001; Vreeburg 2007; Vreeburg & Boxall 2007; Husband *et al.* 2008; Vreeburg *et al.* 2009; Blokker 2010), a conceptual model for LD dynamics in DWDS was developed (**Error! Reference source not found.**). In this framework, flow velocity was considered to be the main factor influencing LD build-up in DWDS. The indicated thresholds for flow-velocities are the maximum values that may occur for a few minutes (e.g., 10 – 20 minutes) every day.

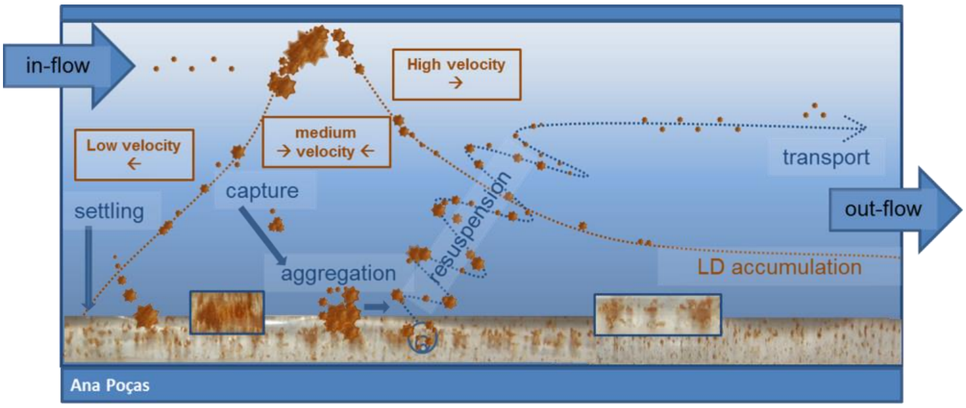

Figure 1 Conceptual model for LD dynamics in DWDS. The brown line depicts LD accumulation variation with velocity ranges (low, medium and high). The blue text boxes show the main process occurring at the different velocity ranges. The dotted blue line indicates LD resuspension.

At a low flow velocity range, which may be below 0.1 m/s (Vreeburg 2007; Blokker 2010), the main LD build-up process expected to occur is LD settling through gravitational forces (Poças *et al.* 2014). In this case, LD build-up rates are low and accumulation depends on the bulk water incoming particle loads, mostly. This may occur in the quiescent zones of the networks or in pipes with large residence times, including connections with no-flow, or whenever the specific-weight of particles (e.g., sand grains) is sufficient for gravitational settling to occur solely. Due to the turbulence that occurs in other parts of the DWDS, however, it is not to be expected that settling through gravitational forces, alone, is the main process for LD accumulation in DWDS (Boxall *et al.* 2003; Vreeburg & Boxall 2007). This is consistent with the fact that dead-end pips, where steady-low-flows may predominate, are not preferential sites for LD accumulation (Poças *et al.* 2013b).

At a mid-velocity range, which absolute values may span from 0.1 m/s to 0.3 m/s (Vreeburg & Boxall 2007), LD build-up is unlikely to be linear in time, as it depends on flow patterns, LD properties and occurrence, as well as pipe characteristics. At this velocity range, the main LD build-up process expected to occur is LD capture and further LD aggregation (Poças *et al.* 2014). This can happen during normal flow operation, due to turbulence and to the cohesive-adhesive properties of LD (Boxall & Saul 2005; Husband & Boxall 2010; Poças *et al.* 2013a), when the accumulated LD take hold on those still travelling in the bulk water. Thus, provided that there is already material accumulated, LD capture does not depend only on the bulk water loads, but also on the accumulated LD levels, and, as long as these are not at steady-state, LD capture increases with LD accumulation. Because of more inertia at the boundary layers than in the bulk water (van Thienen *et al.* 2011), LD may then be retained and surpass the flow shear stresses, which extents may be influenced by LD proprieties.

At a high velocity range, where absolute velocities may be above 0.3 m/s (Vreeburg & Boxall 2007), LD build-up may no longer be expected; instead, LD resuspension prevails. The tipping point for LD resuspension, i.e., the critical flow velocity levels at which resuspension may start, depends on: hydraulics, LD physical-chemical characteristics, as well as the levels of LD that have already accumulated. With respect to flow hydraulics, rapid and relative changes in shear stresses (Husband *et al.* 2008; Poças *et al.* 2014) may be more effective for LD resuspension than the absolute values, irrespectively of the accumulated LD levels. Relatively to composition, particularly the relative amounts of LD main constituents (i.e., water, iron and VS), interferences may be expected in resuspension potentials, as LD may become denser and more resistant to shear stresses over accumulation (Kjellberg *et al.* 2009). However, even if resuspension potentials change with LD composition and accumulation levels, and rapid increases in flow velocity are more important than the absolute values, flow velocities at this high range are at self-cleaning values (> 0.3 m/s) (Vreeburg *et al.* 2009; Blokker 2010).

The continuous sources for LD build-up in DWDS suggest LD accumulation cannot be described by constant accumulation rates and have a linear development in time, at least at mid-range velocities, where settling is not the only process contributing to LD accumulation. With enhanced LD potentials for aggregation, LD build-up should be closer to an exponential type of development, than to linearity (**Error! Reference source not found.**, on the left). This has been observed in RPM measurements done in two different areas: a research area supplied with ultra-filtered water and a reference area supplied with conventionally treated groundwater (Vreeburg 2007). Although there were only few measurements (**Error! Reference source not found.**, on the right), LD built-up differently at the research area (the more constant profile) and at the reference area (the steeper profile), which was explained by the different particle loads in the supplied waters. Thus, as long as particles with aggregation abilities reach the distribution pipes or stay accumulated, LD build-up rates may no longer approach a linear type of development, but may increase more rapidly over time due to LD aggregation. This suggests that, whenever LD have already accumulated, LD build-up may be critical at places with few cleaning frequencies and lower treatment levels.

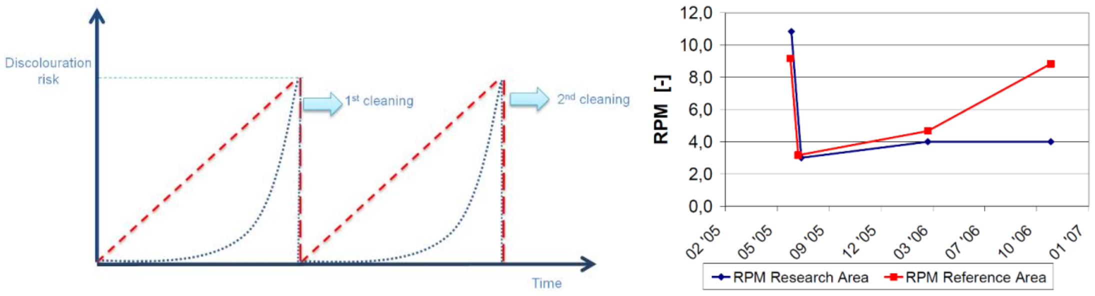

Figure 2 Discolouration potential build-up: linear and exponential (on the left; adapted from Vreeburg and Boxall, 2007). Average RPM in a research area supplied with ultra-filtered water - the more constant blue line, and in a reference area with drinking water – the red line with the steep increase (on the right; adapted from Jan Vreeburg, 2007).

Overall, LD build-up may be promoted through smooth flow increments at low velocities/shear stresses, due to LD settling and capture/aggregation, while rapid increases in velocities/shear stresses may lead to LD disaggregation and resuspension and, ultimately, to water discolouration. This is consistent, not only with the cohesive flocculent characteristics that contribute to increased LD aggregation potentials (Poças et al. 2013a), but also with the fact that relatively low velocities (≥ 0.02 m/s) are effective for LD sampling and may, likewise, trigger discolouration (Poças et al. 2013b), as long as shear stress variations are above those occurring on a daily basis. As a result, cleaning frequencies should not be outlined on the basis of the absolute outcome of the sampling results, but on the relative sharp increases that may occur over LD monitoring. Likewise, instead of waiting for e.g., discolouration complaints or lab monitoring results to trigger pipe cleaning exercises, routine LD monitoring may be used to track LD accumulation patterns and identify the time at which the exponential development really starts. As so, whenever steep increases are observed from one collection to another or the turbidity’s threshold value for consumers to detect discolouration (around 10 NTU) is reached, the pipe in study should be marked for priority cleaning. The management of LD build-up development patterns in distribution pipes, e.g., through online turbidity monitoring, may, thus, be used to prevent discolouration incidents, particularly if combined with low velocity sampling methodologies, as these do not require too much of planning or any special equipment (Poças et al. 2013b).

Due to the aggregation disaggregation features of LD, standard values of LD settling velocities in DWDS may be difficult to find. Since the diameter and density of LD flocs may change over turbulence and depend on the number of available unites for aggregation (Poças et al. 2013b), settling velocities may also change over time throughout the DWDS. In addition, because flow velocity is considered to be the main factor influencing LD build-up in DWDS, LD accumulation and resuspension potentials may change with the relative composition of LD. Likewise, the presence of iron may be related to higher stickiness/cohesive levels and densities in the accumulated LD, while VS components, namely EPS, may be related to higher aggregation potentials, along with three dimensional fractal structures (Poças et al.

2013a, Poças et al. 2014a, Poças et al. 2014b). Therefore, with extended accumulation, and due to increased iron contents, LD may get denser and resist more to shear stresses (Kjellberg et al. 2009), thus allowing for resuspension velocities to shift to the upper mid-range values (≈ 0.3 m/s). Increased EPS levels, in turn, may be related with higher flocculation and water holding capacities, thus resulting in bigger and lighter LD flocs (Poças et al. 2014a) that are, probably, more easily resuspended at the lower mid-range velocities (≈ 0.1 m/s). In addition, the relative composition of iron Fe and EPS in LD may be indicative of their age and residence times. While LD with lower EPS/Fe ratios may have accumulated in DWDS for long periods (i.e., months), those with higher EPS/Fe ratios may have accumulated for shorter ones (i.e., weeks).

As resulting from the balance between settling, capture/aggregation and resuspension, LD may then form and accumulate at different rates at different parts of the networks. Therefore, there can be pipes more prone for LD build-up (e.g., pipes with steady flow patterns and operating at mid-range velocities) while others are more for LD resuspension (e.g., pipes with flow fluctuations, velocity changes, daily peaks leading to LD erosion). Either way, wherever LD build-up, LD potentials for further LD accumulation are increased, due to LD capture/aggregation (Poças et al. 2014b). In addition, due to the predominance of velocities taking place at the mid-range velocities (0.1 – 0.3 m/s), LD capture may be the main process contributing for LD build-up processes in DWDS. In order to outline possible strategies for LD control and prevention, the critical flow velocities at which LD capture and aggregation occur in DWDS needs, therefore, to be investigated.

Conclusions

In this research, experiments and observations led to the conclusion that LD accumulation and resuspension in DWDS are driven by continuous (e.g., the particle load from the WTP, pipe-wall biofilm sloughing) and dynamic (e.g., LD capture/aggregation, exponential LD build-up, LD relative composition) processes. More specifically, results evidenced that:

- LD accumulation may follow exponential development in DWDS. Hence, sampling velocities should not be outlined with basis on absolute values, but on the tracking of relative sharp increases over LD monitoring;
- LD accumulation is most critical at mid-range velocities (0.1 – 0.3 m/s), i.e., at the common velocities occurring in DWDS. This supports observations that dead-ends are not preferential sites for LD accumulation;
- the combination of minimisation of the particle load coming from the WTP and the application of self-cleaning principles to DWDS may reduce more effectively the overall particle budget and, thus, LD occurrence in DWDS;
- the relative composition of iron and EPS in LD may be indicative of their age and residence times, as well as their potentials to stay accumulated or resuspend in DWDS.

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