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Hydraulic conditioning to manage potable water discolouration

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Abstract

Results are reported from studies conducted using a unique laboratory based, full scale, temperature controlled pipe facility to examine the impact of conditioning shear stress on discolouration risk, as characterised by bulk water samples (turbidity, iron and manganese) and biofilm pipe wall measurements. The facility uniquely allowed for replication of the dynamics of an operational network but with rigorous control, thus yielding fully representative results overcoming limitations of bench scale or operational studies. The effect of the daily variation in flow (and boundary shear stress) was observed to be greater than the effect of the average daily flow rate at reducing discolouration risk. This is useful for informing operation and maintenance strategies, specifically that regularly imposing cycles of flow variation are more effective than increasing total average flow rates at limiting discolouration risk. The application of such knowledge aids the development of cost effective, proactive, operational interventions to manage discolouration.

Keywords chosen from ICE Publishing list

Water Supply

1. Introduction

1.1 Background

Discoloured water is the dominant water quality related customer complaint within the UK water industry and is a significant issue internationally. Although termed discolouration, the regulated parameter is turbidity as the aesthetic impact is due to suspension of fine particulate material (Boxall et al., 2001). The Drinking Water Inspectorate (DWI) regulates the UK water industry for drinking water quality and has set the customer's tap turbidity standard at 4 NTU (DWI, 2000). Water leaving the treatment works is regulated at 1 NTU, however by the time it reaches the customer it can fail to reach the distribution standard (Bristol Water, 2008). Even if one considers external particle sources, such as source water and ingress due to negative pressures (Fox et al., 2015), it is clear that processes within the network contribute considerably to increased turbidity by the time the water reaches the tap. The main cause is thought to be mobilisation of material layers from pipe walls due to changes in hydraulic conditions, such as increases in flow, which increases shear stress, and thus forces acting to mobilise accumulated material (Boxall et al., 2001). Hydraulic conditions within operational systems are complex, commonly exhibiting a diurnal pattern in flow driven by consumption, but also due to events and incidents like bursts. Processes leading to particle accumulation include physical, chemical and biological factors (Vreeburg and Boxall, 2007). Previous knowledge and understanding of the processes that influence accumulation and mobilisation of material have been developed via experimental investigations for example laboratory, pilot and field flushing studies (controlled increase of the pipe flowrate intended to mobilise material, Husband et al., 2008) and via model theories (Boxall et al., 2001). Due to the limitations of such approaches significant uncertainty remains, including the exact nature of the influence of normal (daily) hydraulic conditions within operational networks.

1.2 Discolouration Experimental Research

Conditions in operational distribution networks are complex, uncertain and inadequately understood or quantified. Network conditions vary considerably and are sensitive to physicochemical and biological conditions (Block, 1992). Discolouration events, resulting in customer contacts, are unpredictable and happen over a short time period, making them difficult to study in operational networks (Vreeburg and Boxall, 2007). Controlled discolouration events (flushing) are possible, and have shown strong correlations between increased turbidity and iron (Fe) and manganese (Mn) levels (Seth et al., 2004). In particular the long term network conditions prior to flushing are also often unknown, varied and uncontrolled. It is therefore very difficult to conduct detailed investigations into the build-up of accumulates and discolouration risk in operational networks.

Bench scale testing devices such as PropellaTM and annular reactors like the Robbins device (Kharazmi et al., 1999) and RototorqueTM provide alternatives to field studies, providing potential for control of influential factors such as nutrient supply. Many of these devices include plugs inserted into the surface so that accumulates can be analysed (Flemming, 2002). Donlan et al. (2002) developed a reactor that incorporated removable 'biofilm growth surfaces' allowing formation under different shear stress conditions. Although these have been very useful in providing a continuous non-destructive set of information, the conditions do not effectively replicate some important aspects of a DWDS. Bench scale tests do not recreate the DWDS boundary layer hydraulics and turbulence, or the correct ratio of bulk water to surface area and transfer between these. Hydraulic conditions in bench scale tests are often simply defined by reference to and control of the speed of rotation. The hydraulic conditions generated are complex and poorly represent pipeline hydraulic conditions. Most bench scale investigations assess material accumulation and detachment under steady state hydraulic conditions, which never occur in operational distribution systems. Furthermore most bench top research only investigates accumulation (e.g. Schwartz et al., 1998; Murga et al., 2001; Batte et al., 2003). Few bench scale studies have attempted simulating mobilisation due to hydraulic changes; those that have, crudely increase the speed of rotation (Abe et al., 2011, 2012). Such studies can only observe the loss from the wall, not the bulk water response. A recent investigation by Luo et al. (2015) confirmed such limitations, finding that bioreactors provide an unrealistic representation of biofilms growth in operational systems.

Investigations reported by Husband et al. (2008) provide a compromise between bench scale and operational networks by using a 90m long re-circulating HDPE pipe facility within a controlled laboratory environment. Week long investigations were completed at a constant conditioning flow rate of 0.3 l/s, before being flushed by small flow increments (15 minutes each). Data generated demonstrated a positive relationship between shear stress and turbidity, validating the basis of the

PODDS model (Boxall et al., 2001). A second experiment conducted four, one month, studies measuring the impact of constant and varied flow on turbidity. During the first flushing step more material was mobilised during the constant flow trials than during variable flow. It was therefore concluded that during steady state flow, weaker particle layers develop than during varied flow. The variability in flow was hence deemed as a significant factor determining the risk of discolouration. However, there were limitations to the experiment including no temperature control and variable elevated temperatures likely to influence chemical and biological processes. The experiment only recorded turbidity and so provided no further insight into the material mobilised or the processes involved. While the length of the facility was significant, it was not sufficient to be certain that pipe surface effects dominated entirely over tank and ancillary fitting and fixture effects. Finally the facility was a single loop offering no simultaneous replication and there may have been variation in source water between repeats with different hydraulic conditions.

Other pilot scale research has been conducted; however they too have significant limitations. Martiny et al. (2003) sampled biofilm and bulk water from a model water distribution system supplied with untreated ground water. Their experiment solely investigated steady state hydraulic condition. Steel plugs were inserted in a 12.2m loop for biofilm sampling, but were not designed flush to the pipe wall, so would have produced locally significant distortion of the boundary layer and turbulence regime. Further pilot scale research was reported by Lehtola et al. (2004), investigating the differences in water quality and formation of biofilms in a pilot scale distribution system comparing copper and plastic (polyethylene, PE) pipes. Research design limitations included the size of the network, which did not effectively recreate the boundary layer hydraulics and the turbulence regime of operational systems, hence the exchange with bulk water for the correct ratio of bulk water to pipe surface area.

1.3 Hydraulic Conditioning and Discolouration Risk

Hydraulic conditioning has been suggested as a management strategy to reduce discolouration risk. The ‘self-cleaning’ method employed in the Netherlands, constitutes of keeping velocity higher than 0.4 m/s to reduce build up (Van den Boomen et al., 2004). The authors proposed that due to low velocity, particles can accumulate in areas such as redundant loops and oversized pipes. This has been shown to be a pragmatically effective value in the Netherlands. Alternatively, research by Boxall et al. (2001) assume the existence of cohesive material layers accumulated within the DWDS, and that layers formed during conditions of high average flow are stronger than layers formed during lower average flow. This approach has been supported by UK (Husband and Boxall, 2010) and international (Boxall and Prince, 2006) DWDS field trials. In further support, Cook et al. (2010) found a correlation between decreased conditioning shear stress and increased discolouration customer contact frequencies. Such investigations were based on field studies therefore the previous conditioning hydraulic demand profiles, water chemistry and biology were uncertain. For example work by Blokker et al. (2010) that considered stochastic demand prediction suggested that the Dutch threshold should increase by 0.2 to 0.25m/s. While such works clearly show the influence of hydraulic conditions, there is uncertainty if it is peak or average hydraulic conditions that are important, or some combination. This ambiguity is attributable to the uncertainty of flow in individual pipes of operation networks, only available from one dimensional hydraulic models that attempt to simulate an idealised 24 hour period. Further work, such as Smith et al. (1999) which made use of a pipe test facility, has suggested that interactions occurring during low flow, night time stagnation conditions are important in processes leading to aesthetic water quality issues. However, this was for cast iron pipes and was likely dominated by ion release and accumulation in the bulk water during the low flow period.

In summary while modelling and bench top experiments can help predict system response to events, studies in operation systems have too many uncontrolled factors and uncertainties and do not allow for deeper understandings of controlling environmental factors. Research in a controlled laboratory is required to determine the impact of different shear stress profiles and whether it is the peak, average or variability of the flow pattern which is the most important factor in discolouration risk.

2. Research Aims

The aim of this research was to investigate the impact of hydraulic conditions on material accumulation on the pipe wall within DWDS, and the subsequent mobilisation (discolouration) response of this material due to flushing. Specifically the impact of different net flow rates and diurnal patterns was studied. A key advance of the research was ensuring that hydraulic and temperature conditions were fully representative of operational systems, but with the control and replication of a laboratory environment. The value of this research is to help to inform intervention strategies to best manipulate hydraulic conditions to manage discolouration risk.

3. Materials and Methods

3.1 Experimental Pipe Facility

An internationally unique, large scale, experimental pipe loop facility housed in a temperature controlled room was used for the experiments reported (Figure 1). The use of a pipe line fundamentally addresses the issues with bench top systems, set out in section 1.2, while providing the control and repetition not possible in operational systems, section 1.3. The facility comprised of three loops, controllable to represent different hydraulic regimes. The loops were exact replicates providing confidence in results. The laboratory temperature was controlled by cooling units (±1°C), with water temperature monitored to confirm. The length of the pipe loop ensured that the pipe surface effects were dominant over others such as ancillary fittings and fixtures. HDPE pipes were chosen to correspond to the design of a modern DWDS. Each coil had a final straight section for hydraulic control and flow measurement. The pipe diameter was selected to be representative of the dominant pipe diameter by length of UK DWDS (based on the data contained in UKWIR (2003) 'National database of mains failures 2003' Report No. Z3/3G/05/7). Unlike bench scale experiments the realistic volume to area ratio and turbulence regime of the test loop facility fully replicated the exchange processes and interactions between the bulk fluid and the pipe wall of operational systems, such as nutrient and particle exchange. The full scale nature of the facility, including hydraulic and turbulence regime also meant that the boundary layer conditions and hence surface forces were fully representative.

The system was supplied with water from the local distribution system characterised by a peat upland source, iron coagulation based treatment system, high standard final filters and free chlorine disinfection and residual. There was ~10km of predominantly cast iron trunk main and one service reservoir before the water reached the laboratory, with no local distribution systems and minimal pipe connectivity prior to the laboratory. Once filled from this source the system was operated with a trickle turn over to achieve the desired water age, providing a renewal of bulk water material including chlorine residual. Bulk and incoming water quality were sampled throughout.

The facility was operated in a recirculating manner with a single enclosed tank. Water was transferred to the loops by a single variable speed pump and then a three way manifold. Overall system pressure was computer controlled by the pump speed, with flow rates through each of the loops independently computer controlled by valves at the end of each loop, before being returned to the tank. Each loop thus had a residence time as a function of the hydraulic conditions created within it, and this was independent of the system residence time controlled by the overall trickle feed and drain. A single tank was selected such that the loops shared the same bulk water, allowing for seeding and mixing between the loops. This is representative of a complex, looped operational networks where interacting pipe conditions occur upstream of any given pipe length, and ensured that any difference between the loops was purely a function of the hydraulic conditions created within that loop.

To achieve the study aims, coupons were required to investigate the amount of material accumulation on the pipe wall. Pennine Water Group Coupons (Deines et al., 2010) were used, allowing for direct observation of material on the pipe wall. The coupons consist of an HDPE disc, which follows the pipe curvature, with a removable flat section for microscopy (Figure 1). The flat microscope section is only 4.5mm wide, such that the deviation from pipe curvature approaches that of roughness heights used to represent plastic pipes in hydraulic modelling, thus minimising distortion of the boundary layer flow (Douterelo et al., 2014).

3.2 Experimentation Design

3.2.1 Experimental Design Overview

Using the unique facility two experiments were conducted consisting of a 28 day accumulation phase, followed by short duration flushing (substantially increased flow) phases for material mobilisation. The experiments were conducted to determine the impact of hydraulic conditions on discolouration risk, defined here as the quantity of material accumulated on the pipe wall and the amount mobilised into the bulk water after imposed flushing. The environmental variable controlled and studied was the hydraulic conditions during the accumulation phase. One experiment investigated the impact of steady state conditioning shear stress on material behaviour, the other compared this with and explored the effect of diurnal flow patterns.

Figure 2 shows the 24 hour hydraulic patterns used during the accumulation phases. These patterns, the range of system pressures, flow rates and hydraulic retention times used in this research were determined by reviewing and averaging the outputs from UK pressure calibrated hydraulic models, with demand patterns extrapolated from flow meters of several networks, as in Husband et al. (2008). Average values of pressure, flow and hydraulic retention times used were based around 40 m, 0.3 l/s (0.06 m/s, Re ¼ 4200) and 1 day, respectively. Flow patterns were offset within the day, such that night time minimum conditions occurred in early afternoon to enable sampling or checks to be made during low flow conditions and hence minimising any impacts. All experiments were performed in winter. In order to mitigate for any temperature change effects (i.e. chemical or microbial processes and interactions), laboratory temperature was matched to the incoming winter water temperature, 8°C. The test loop facility was cleaned before each set of experiments to achieve consistent starting conditions by disinfection with a 20 mgl-1 sodium hypochlorite solution (< 16% free chlorine), re-circulated within the facility for 24 hours, at the maximum attainable flow rate (4.5 ls-1). Afterwards, the test loops were flushed recurrently with fresh water, until chlorine and turbidity levels stabilised to those of the inlet water.

3.2.2 Accumulation

The first set of experiments investigated the impact of three different steady state flow rates, or conditioning shear stresses, on material behaviour. Steady state experiments were conducted to determine the controlled effect of 0.1, 0.2 and 0.5N/m² conditioning shear stress on discolouration risk, thus improving on bench scale tests by providing controlled definitive knowledge and understanding of the amount of material accumulation and mobilisation. The chosen conditioning shear stresses relate to typical low, medium and high values experienced within the UK DWDS (Husband et al., 2008). Although research into steady state shear stresses usefully demonstrate the different impacts of net flow effects and conditioning shear stress, it is not realistic of demand induced diurnal flow patterns experienced in operational distribution networks. Hence the second set of experiments explored the effects of diurnal flow patterns. Profiles were chosen based on typical flow profiles from a UK network (Husband and Boxall, 2010). An average double peak residential pattern, taken from flow in a 75mm pipe, was used as the basic flow pattern to define two varied flow patterns (Figure 2). The second set of experiments also repeated the medium flow rate of the steady state trials as a control and to allow for direct comparison and repeatability checks. Each of these (two varied flow pattern, and medium steady state) had the same total flow in 24 hours, removing net flow effects from comparison between these. The two varied, daily, flow patterns were design to achieve different peak conditions such that the effect of this could be studied. The patterns were also designed to have the same night time minimum conditions. Thus if different results were obtained for varied patterns, the peak effect is important. Whereas if similar results occur for the two varied flow patterns, and these tended to be the results from the lowest steady state conditioning experiment, then the night time minimum is important.

3.2.3 Mobilisation

Following the 28 day accumulation phase, a simulated flushing mobilisation phase was performed in each loop sequentially. The selected loop was flushed by increasing the shear stress in small increments, designed to generate detailed data about the strength profiles of the developed layers. In order to avoid acceleration or transient dynamic force effects, flushing increments were controlled by smooth transition rather than step change. Hence all mobilisation was by pseudo steady state shear stress, not dynamic force or shock loading. Each flushing increase lasted for three turnovers to allow enough time for turbidity to stabilise and for the water quality to become well mixed. Flushing rates are provided in Table 2 for flow, velocity and shear stress.

Discolouration was quantified as a measure of continuous bulk water turbidity, discrete samples of iron and manganese and coupons for the direct quantification of material on the pipe wall surface. Three replicate discrete water quality samples were taken at each sampling point. Samples were taken straight after each other in different containers. Samples were stored in 100ml vials containing 5M of nitric acid and sent for ICP-MS analysis at an accredited laboratory using water industry standard methods[1].

3.3 Pipe Wall Investigations

Coupons were used to determine the amount of material accumulated, in the form of cells. To test the impact of different conditioning flow profiles on material accumulation and mobilisation, coupons were removed on day zero, day 28 and the start and end of flushing. Three replicate coupons were removed at each sampling point, from random points along the coupon pipe length. The flat insert section was then separated from the coupon and fixed in 5% formaldehyde before storage at 4°C. After fixing, the inserts were stained with 20μM Syto 63 for 30 minutes. Syto 63 is a cell-permeative

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[1] ALcontrol Laboratories, Rotherham, UK

nucleic acid stain, which was used to visualise the cells (McSwain et al., 2005). The samples were then washed three times in sterile water, air dried for 10 minutes then stored in darkness at 4^0C (<1 month)[2]. Images were taken using an x20 EC Plan Neoflaur Objective (0.5 NA) a 31.54ųper pixel speed, pin hole set to an optical slice of 4.7ųm, resolution 832 x 832 pixels and a frame size of 420 x 420ųm. LSM510 image examiner software was used to visualise the images. Each insert was imaged for seven random fields of view to provide an accurate representation of cell coverage.

4. Data Processing

4.1 Turbidity Data

Although continuous turbidity data was collected, the recirculating nature of the facility leads to complex time series results. The net change in the bulk water due to flushing is of interest hence, and in order to simplify the time series it was averaged to yield a single value with the change in this average value then interpreted. As these baseline values varied between experiments and because the effect of interest is the change due to flushing, all values were normalised by subtracting the loop specific base line value after the tank and loop water had been mixed.

4.2 Discrete Metal Water Quality Data

Discrete metal water quality data refers to measurements of iron and manganese sampled at three turnovers of the system for each flushing step. Three turnovers were selected as all material should have been mobilised and well mixed with the bulk water. Metal water quality data are presented as an average based on the three readings with one standard deviation error bars. As with the turbidity data the metal water quality data was normalised for concentrations at the end of mixing phase.

4.3 Pipe Wall Investigations

After preparation, coupon samples were studied under the microscope for seven random fields of view to account for any spatial variability of cells. A z-stack for each field of view was produced allowing a cross sectional picture from top to bottom of the layer. To analyse and quantify the data, separation of the different fluorescence signature was required (un-mixing). So the cell stain could be isolated disregarding any background noise, data was separated between different fluorescence

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[2] A Zeiss LSM 510 Meta Confocal Florescent Microscope was used for the florescent microscopy and imaging.

signatures against a spectral database. Digital image analysis was applied to the images to calculate the pixels associated with the Syto 63 stain. Volume of material was calculated based on the area covered in each slice of the z-stack images and then multiplication with respect to the spacing of the slices.

5. Results

5.1 Bulk Water Results

Water quality sample data (Table 1) collected during the accumulation phase indicated that there was no significant change over or between each 28 day long accumulation phase. All measurements recorded were below WHO standards (Frisbie et al., 2012).

Figures 4 and 5 a, b and c present the results after data processing comparing the impact of conditioning shear stress on bulk water turbidity, iron and manganese. ± one standard deviation error bar are presented as a combined error based on the error from the initial value used to normalise the data and the actual recording.

Mobilisation data for steady state shear stress trials at 8ºC (Figure 3) depicted a general trend for less material mobilised into the bulk water in terms of turbidity, iron and manganese with increasing steady state shear stress. The exception to this was observed for the turbidity value at 2.5N/m² for the highest steady state shear stress (Figure 3a).

Despite the same 24 hours total flow of each hydraulic regime there was generally more material mobilised from the material accumulated under the steady state conditioning shear stress of 0.2N/m² compared to the varied conditioning shear stress experiments (Figure 4). This was especially pronounced for iron (Figure 4b) and manganese (Figure 4c) and after 2N/m² for turbidity (Figure 4a). Little difference in iron and manganese results were observed between the low and high varied hydraulic condition experiments.

Comparing the 0.2N/m² steady state results from the two sets of experiments (Figure 3 and 4), show slight variability between the two repeats but in general the same trends and magnitudes of response are evident across the turbidity, iron and manganese parameters.

5.2 Pipe Wall Material Results

Only just measurable material was detected on the day zero coupons, and no difference found between the day 28 and start of flushing samples. Figure 5 depicts amounts of material on the coupons at the start and end of the flush programme for each of the conditioning daily shear stress values. The volume fraction is the amount of three dimensional space occupied by material for the entire image and is a useful measurement of the overall amount of material per field of view.

The error bars on Figure 5 are considerable, with errors increasing as a function of average volume, suggesting that the volume of material is highly spatially heterogeneous. Despite this, general trends are visible. Initially considering the steady state experiments a trend can be seen with the lowest conditioning shear stress generating the highest levels of material accumulation and subsequent mobilisation and with the highest shear stress of 0.5N/m² seeing the least build up and the smallest error bars. Although, the spatial heterogeneity was such that the start and end flushing of 0.5N/m² suggests an increase in material. Comparing the two sets of experiments reveals significant differences between the steady state and varied flow experiments, with more material being accumulated and mobilised under steady state conditions, even when the high steady state flow rate was slightly greater than the peak in the high varied flow pattern (Figure 2). This corresponds with bulk water data (Figure 3 and 4) where more material was mobilised during steady state conditions. For the higher steady state shear stress and the varied shear stress experiments the difference between the start and the end data was small. More material was seen to accumulate and be mobilised in the high varied flow (HVF) experiment compared to low varied flow (LVF).

6. Discussion

The results of these highly controlled, yet physically fully representative experiments support the PODDS assumptions (Boxall et al. 2001) and previous less controlled experimental results (Husband and Boxall 2008) that the accumulation and mobilisation of cohesive layers with variable strength profiles within drinking water distribution systems are responsible for discolouration. This is evident in the sequential release of material with each increase in imposed boundary shear stress (Figures 4 and 5), rather than threshold release of material when particle self-weight is overcome.

This paper contends that the normal daily hydraulic conditions within a pipe have a direct influence on the amount of material that accumulates on pipe walls within potable water distribution systems and ultimately leads to discolouration risk. Under steady state flow conditions it was observed that the amount of material accumulated at the pipe wall (cells) and mobilised (turbidity, iron and manganese) by subsequent flushing is directly related to the steady state shear stress, with decreasing amounts with increasing shear stress.

It was found that varied shear stress profiles were more effective at reducing discolouration risk than steady state shear stress. Varied (daily profile) flow conditions were observed to reduce the amount of material accumulated at the pipe wall (cells, Figure 5) and mobilised (bulk water turbidity, iron and manganese, Figure 3 and 4) compared to steady state conditions with the same total daily flow. Indeed, the daily profile conditions were observed to supress material accumulation to levels below the highest steady state profile, despite the peak in high varied daily flow being slightly less than the steady state value, and the low varied shear stress being significantly less. Thus despite experiencing a low night time flow and the same average of $0.2N/m^2$ as all the medium steady state experiments, the peak has a substantial influence in reducing discolouration material accumulation and is therefore an effective management strategy over average or net flow conditions.

The mobilisation results of the two varied flow profiles suggests that slightly more material was mobilised (turbidity, iron and manganese) from the high daily shear stress compared to the low shear stress (Figure 5). However, material accumulation data (cells, Figure 5) suggest that less material was accumulated and mobilised under low varied conditions. These results are contradictory, preventing clear differentiation of the effects of daily peak versus night time stagnation. This suggests the additional $0.1N/m^2$ (0.2l/s) increase associated with the peak in high varied flow compared to the low varied flow does not make much difference to the results. Further experiments are required to check these findings to test whether this was because the increase was too small, because after a threshold there is no longer a further reduction, or because the overnight stagnation period was the same. The dominance of daily flow profiles over total average flow rates is an important for the interpretation of past data, in particular from bench top reactors usually operated at steady state hydraulic conditions.

Even after flushing at a shear stress of 3N/m² material remained attached to the pipe wall (Figure 5) for all test conditions. Similarly the rising trend of the majority of turbidity, iron, and manganese (Figure 3 and 4) results show more material could potentially be mobilised by greater imposed shear stress. Conversely previous field research has suggested that above a certain threshold only small amounts of additional material are mobilised for plastic pipes; Cook (2011) recommended a value of 0.7N/m² while Husband and Boxall (2010) recommended 1.2N/m². If the results of the experiments reported here are correct for operational systems, cost effective flushing or other cleaning operations need to be designed with respect to maximum expected flow increase for any pipe length (risk based approach) rather than by achieving universal target value of flow, velocity or shear stress. While cleaning above such a target might remove more material, that material was strongly bound and did not necessarily pose a discolouration risk, unless the material layers were weakened for example by major changes in the bulk water quality. However, it should be noted that the material layers reported here were only generated for 28 days at 8ºC, while those occurring within operation systems have developed over the life time of the pipes. There may also be seasonal effects driven by changes in the water temperature, affecting the nature and rate of the chemical and biological processes. Further research may therefore be desirable to better understand the impact of a wider range of temperatures, although the central range experience in the UK has been covered here. The results reported here are the product of one-month growth period, while it may be desirable to run longer periods to provide further definitive evidence such experiments are probably unnecessary due to the evidence based from operation systems that the processes of interest are a linear function of time, such as Cook et al (2011). While the facility used provided conditions fully representative of operational networks, it provides only one combination of the factors, specifically only one source water quality (as set out in 3.1 and table 1) and only plastic pipe materials of 78mm diameter. Previous work has suggested that the primary effect of different source water quality and pipe material is to change the rate of material accumulation at the pipe wall, not the ultimate risk level. Specifically, Husband et al (2011) present evidence that surface water sourced CI pipes present a fully regenerated discolouration risk after 1½ years, groundwater sourced CI pipes present a fully regenerated discolouration risk after 3 years and that on average plastic pipes present a fully regenerated discolouration risk after 4 years. Hence, the effect of these factors will be to change the frequency of ‘regularly imposing cycles of flow variation’ recommended from this research. If this variation is achieved through daily flow variations, then from data such as that of Husband et al (2011) the timescale of source water and pipe material effects makes them irrelevant. Alternatively, if the flow variation requires some valve operations or other intervention, these could either be automated and done at a high frequency relative to the above values or optimised based on the above and site specific experience. The operation data set of Husband et al (2016) suggest that the approach of regularly increasing flows scales to trunk main diameter pipes giving confidence in extrapolating results here to other pipe diameters.

Overall the most substantive finding is that following any cleaning strategy, the subsequent material accumulation can be effectively minimised by the implementation of regular variations in the conditioning hydraulics, rather than implementing net flow increases, and thus the time to next cleaning intervention extended or even avoided.

7. Conclusions

This paper shows the importance of hydraulic conditions in controlling the accumulation and mobilisation of discolouration material within potable water distribution systems. Findings include: There is an inverse relationship between steady state hydraulic conditions during layer development and both the amount of material that is accumulated and mobilised. A daily cycle of hydraulics has a dominant effect in limiting discolouration material accumulation and subsequent release. The effect of the daily variation in flow (hence boundary shear stress) is far greater than the effect of the average daily flow rate. The results are inconclusive regarding the dominance of night time stagnation versus magnitude of morning peak on material accumulation and release.

Flushing up to 3N/m² was not sufficient to completely remove all material accumulated at the pipe wall. The research evidences the importance of hydraulic conditions on in-pipe processes, and the need to accurately recreate these for findings to have practical value, specifically that future studies should include demand driven flow patterns as a key variable. These results usefully inform the operation and management of potable water distribution systems to reduce discolouration risk. Firstly this suggests that control strategies regularly imposing cycles of flow variation more effectively limit discolouration risk (in particular limiting accumulation) than increasing total average flow rates. Secondly flushing only removes material up to the force imposed, if increases above the flush rate occur, further discolouration will result (even in plastic pipes), hence flushing or other cleaning operations should be designed for the greatest flow rate expected for the pipe length, rather than an unrealistic expectation of entirely clean pipes.

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Figures

Figure 1. Drinking Water Distribution System (DWDS) simulation pipe facility and Pennine Water Group (PWG) Coupon.

A) Test facility, total volume (tank and loops) 4.5 m3, tank volume 1.53 m3, Each loop consisted of nine-and-a-half 21.4m long coils of 79.3mm internal diameter High-Density Polyethylene (HDPE), with a total length of ~200m. MV = Manual valves used to separate the three loops, 1a, 2a and 3a indicate the 5th coil of each loop into which PWG coupons were inserted, 1b, 2b and 3b indicate the 50 mm internal diameter pipes containing flow meters (FM) and control valves;

B). Detail of loop arrangement, T = turbidity meter (measured using a Chemtrac TM2200 (Chemtrac Inc., USA) turbidity instrument), CV = control valve, other annotations as for A);

C) Coupons secured in the apertures;

D) HDPE PWG coupon and rubber gasket, to ensure a watertight fit; E) PWG coupon components (insert for microscopy and outer coupon for molecular analyses) and dimensions (Reproduced from Fish et al., 2015).

Figure 2. Accumulation phase daily experimental flow profile (HVF refers to High Varied Flow and LVF refers to Low Varied Flow). Reynolds number for these flow rates ranged from 3500 to 10500 (Husband et al. 2008). Thus flow was either just transitional or fully turbulent.

Figure 3. Comparison of normalised mean (a) turbidity, (b) iron and (c) manganese concentrations during the flushing phase for loops conditioned by steady state hydraulic conditions of 0.1, 0.2 and 0.5N/m².

Figure 4. Comparison of normalised mean (a) turbidity, (b) iron and (c) manganese concentration during the flushing phase for loops conditioned by low varied, steady state $0.2 N/m^2$ and high varied hydraulic conditions.

Figure 5. Average pipe wall material at the start and end of mobilisation flushing. $0.2 N/m^2$ is based on the average of the two sets of experiments.

Table 1. Water quality sample data collected during the accumulation phases (averages based on three replicates per weekly sample (n=12)).

Table 2. Mobilisation phase flow rate conversion table.

Figure 1

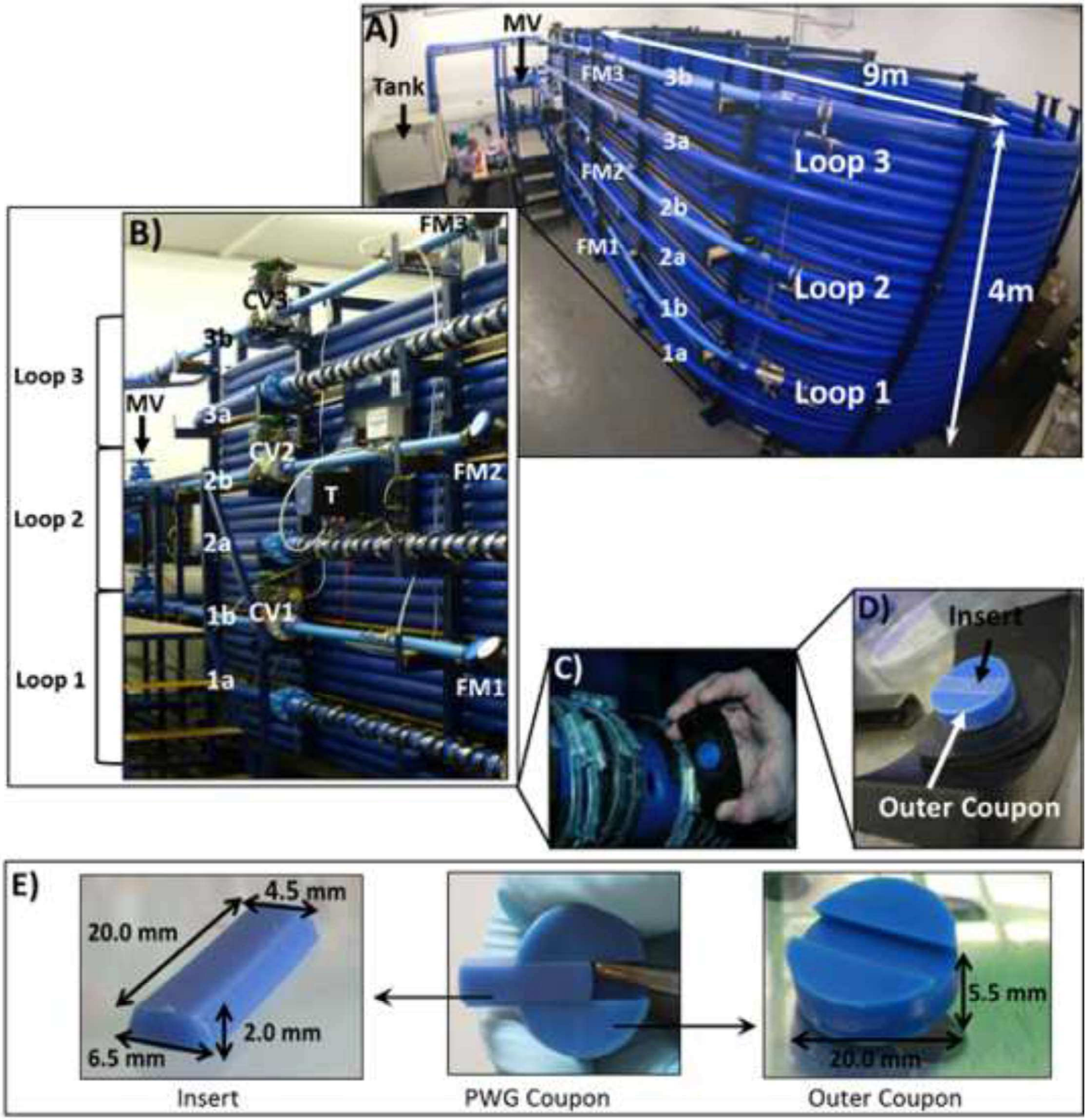
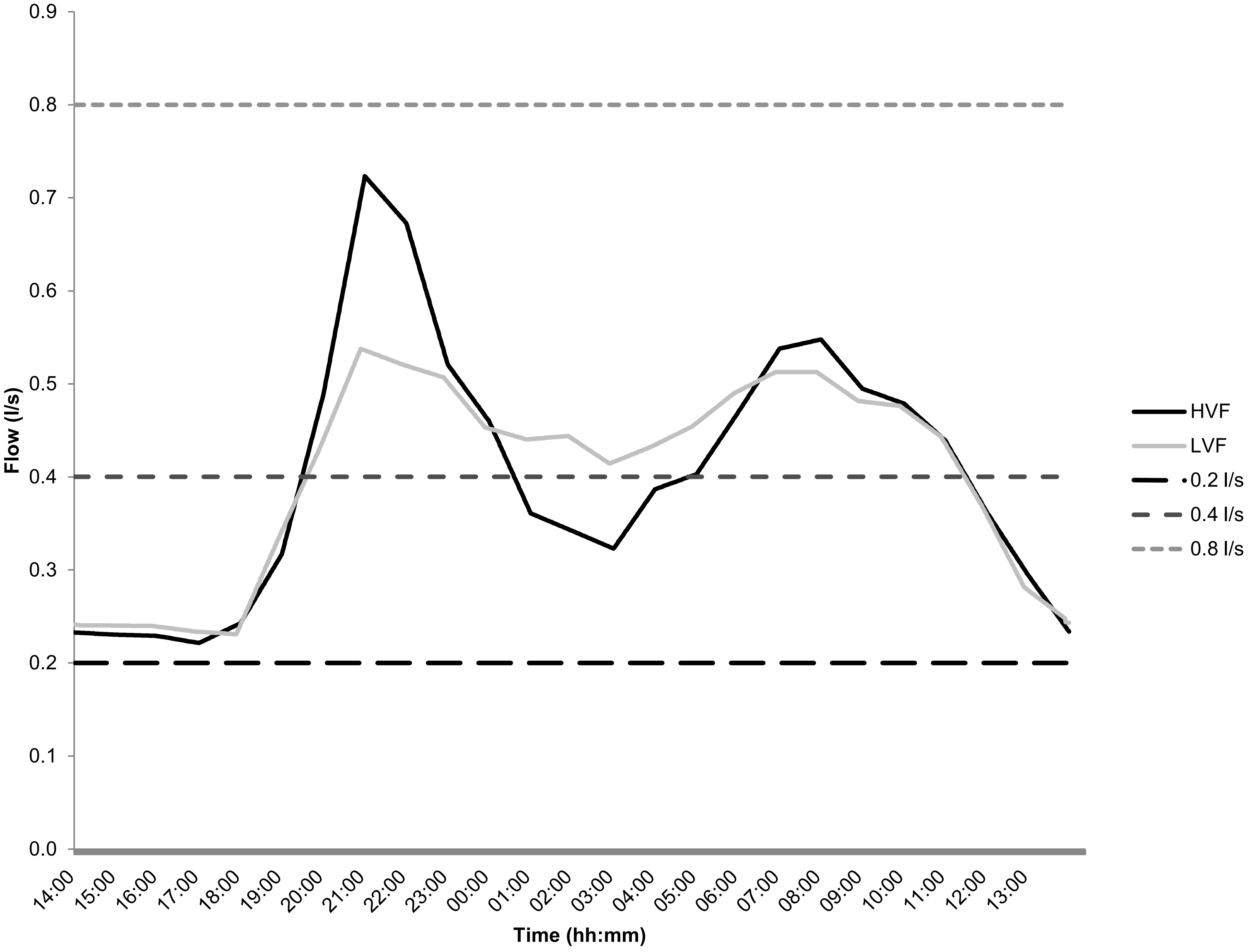
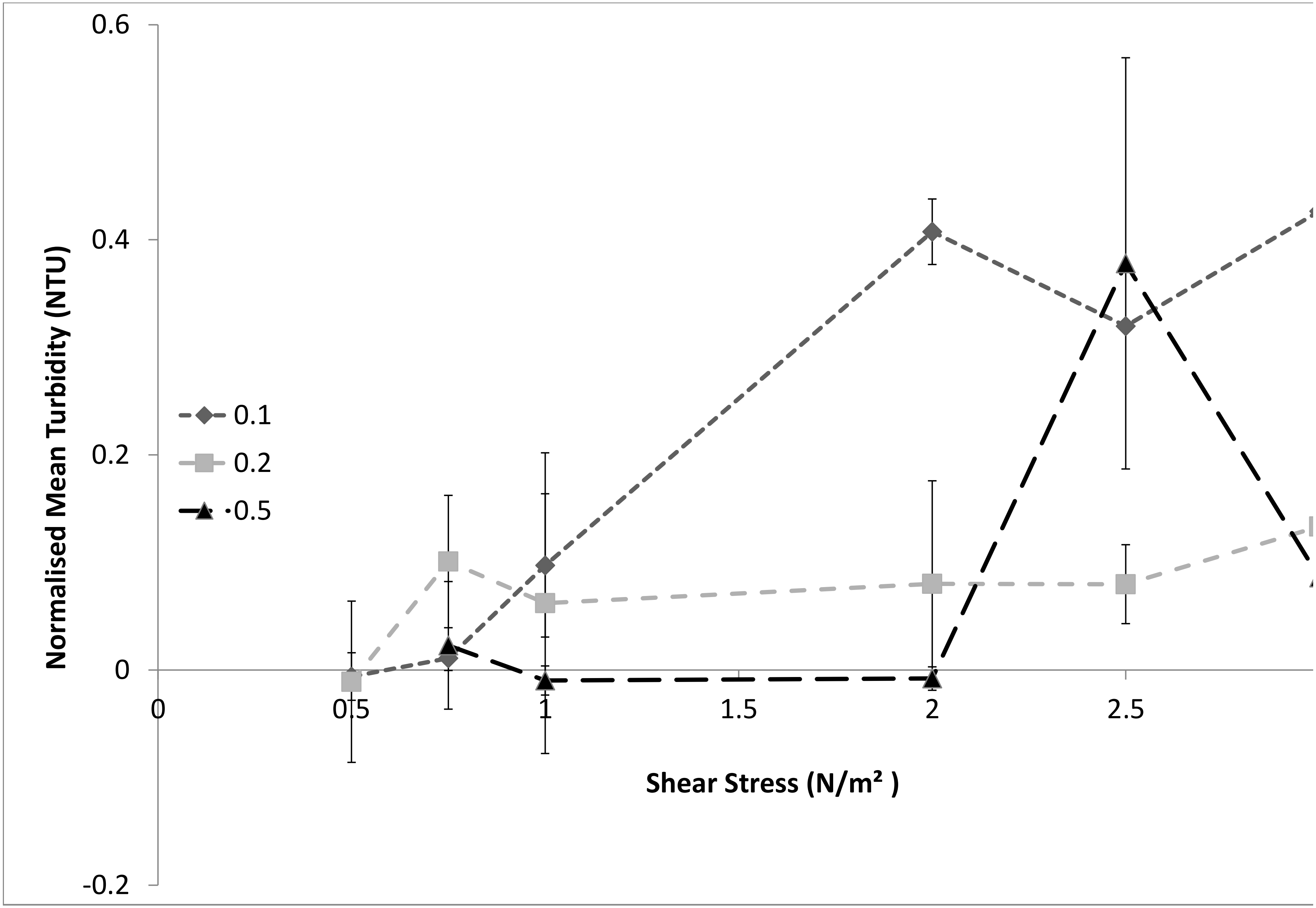
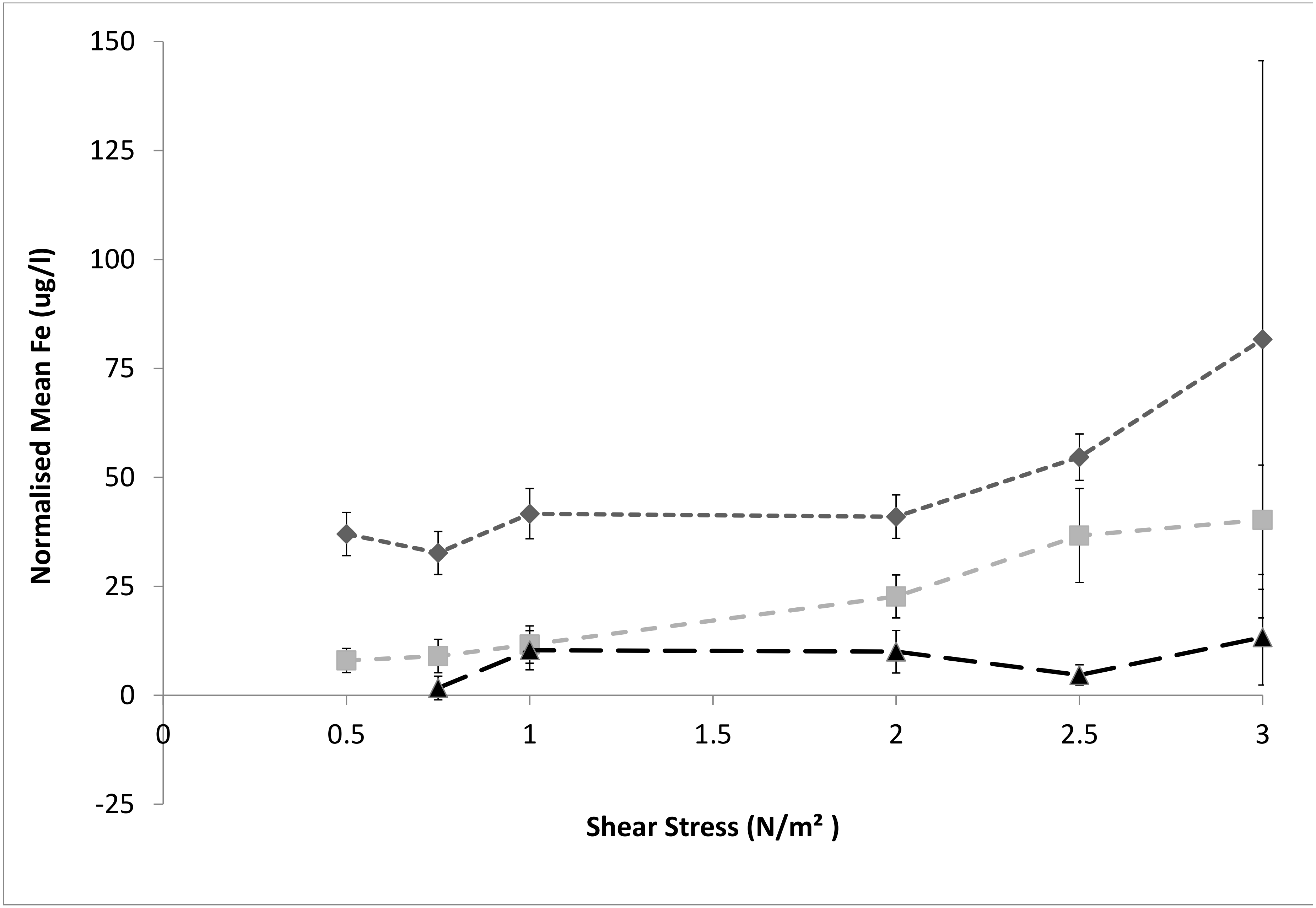

A)
MV
Tank
FM3
3b
9m
3a
Loop 3
FM2
2b
FM1
2a
Loop 2
4m
1b
1a
Loop 1
B)
FM3
CV3
3b
Loop 3
MV
3a
CV2
2b
FM2
T
Loop 2
2a
1b
CV1
Loop 1
1a
FM1
C)
D)
Insert
Outer Coupon
E)
4.5 mm
20.0 mm
2.0 mm
6.5 mm
Insert
PWG Coupon
5.5 mm
20.0 mm
Outer Coupon

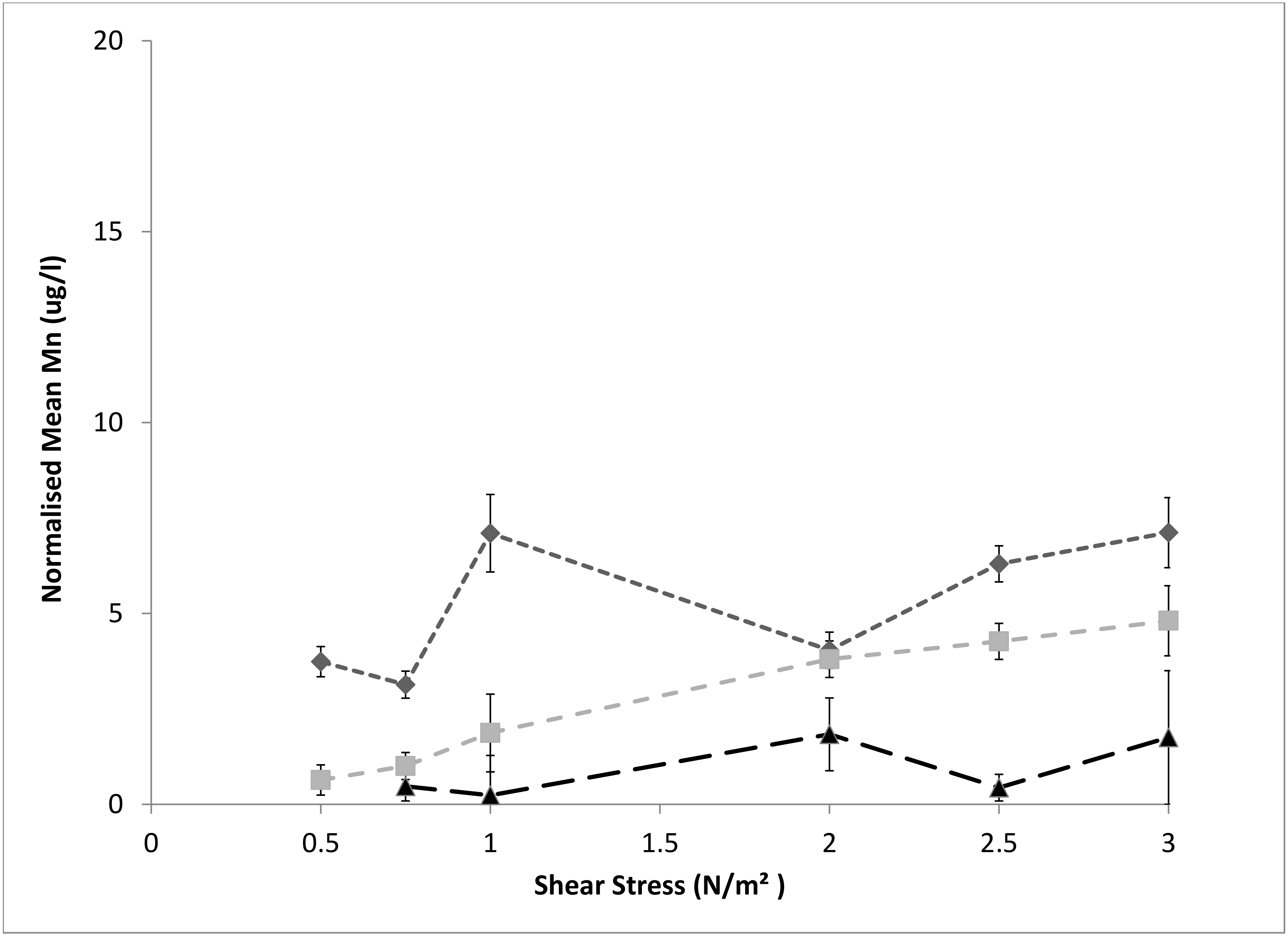
Figure 2


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Flow (l/s)
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
Time (hh:mm)
HVF
LVF
0.2 l/s
0.4 l/s
0.8 l/s

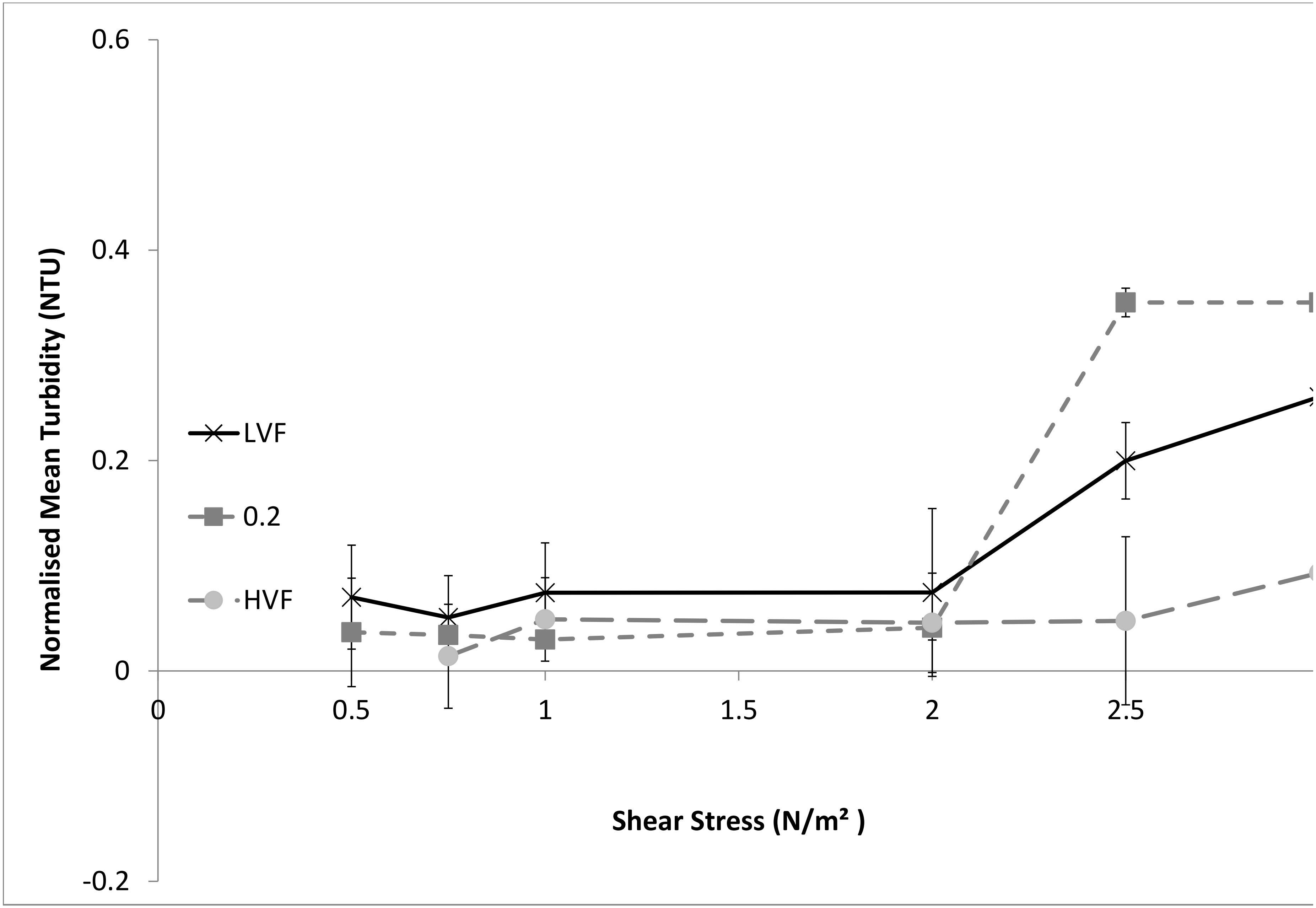
Comparison of normalised mean (a) turbidity, (b) iron and (c) manganese concentrations during the flushing phase for loops conditioned by steady state

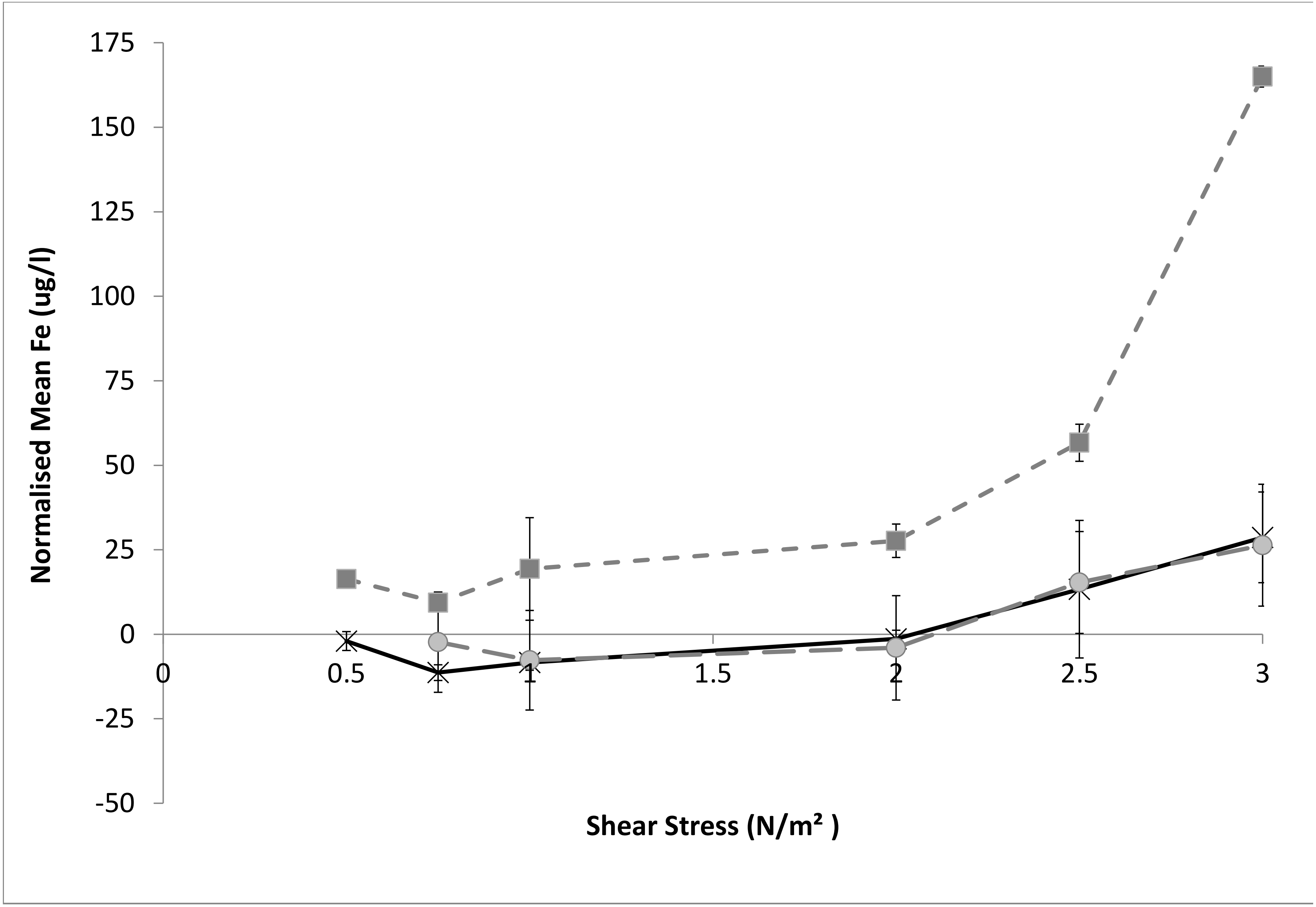



150
125
100
75
50
25
0
-25
Normalised Mean Fe (ug/l)
0
0.5
1
1.5
2
2.5
3
Shear Stress (N/m²)

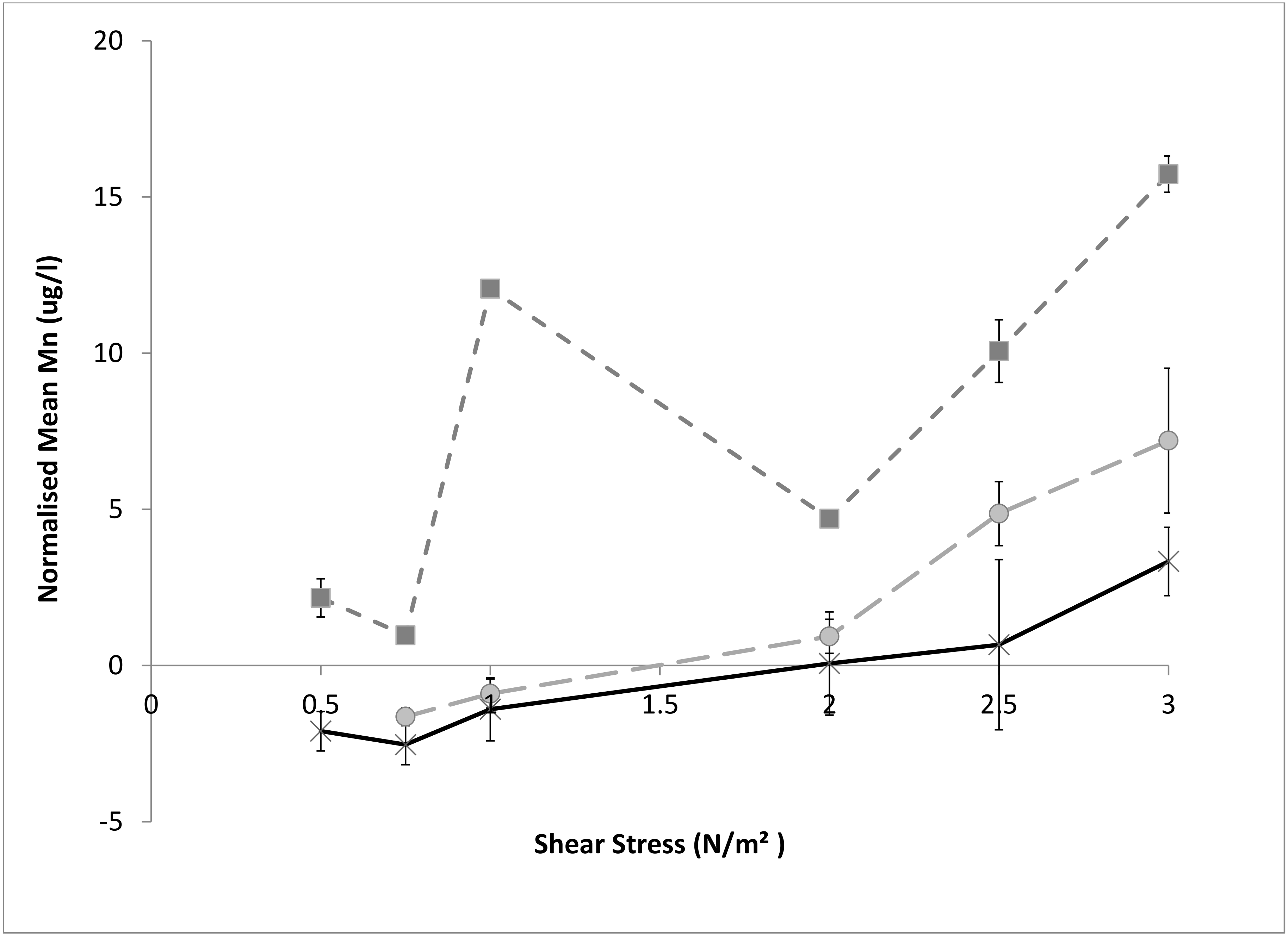

Normalised Mean Mn (ug/l)
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
Shear Stress (N/m²)

Comparison of normalised mean (a) turbidity, (b) iron and (c) manganese concentration during the flushing phase for loops conditioned by low varied, steady





175
150
125
100
75
50
25
0
-25
-50
Normalised Mean Fe (ug/l)
0
0.5
1
1.5
2
2.5
3
Shear Stress (N/m²)


Normalised Mean Mn (ug/l)
20
15
10
5
0
-5
0
0.5
1
1.5
2
2.5
3
Shear Stress (N/m²)

Average pipe wall material at the start and end of mobilisation flushing. 0.2N/m² is based on the average of the two sets of experiments.

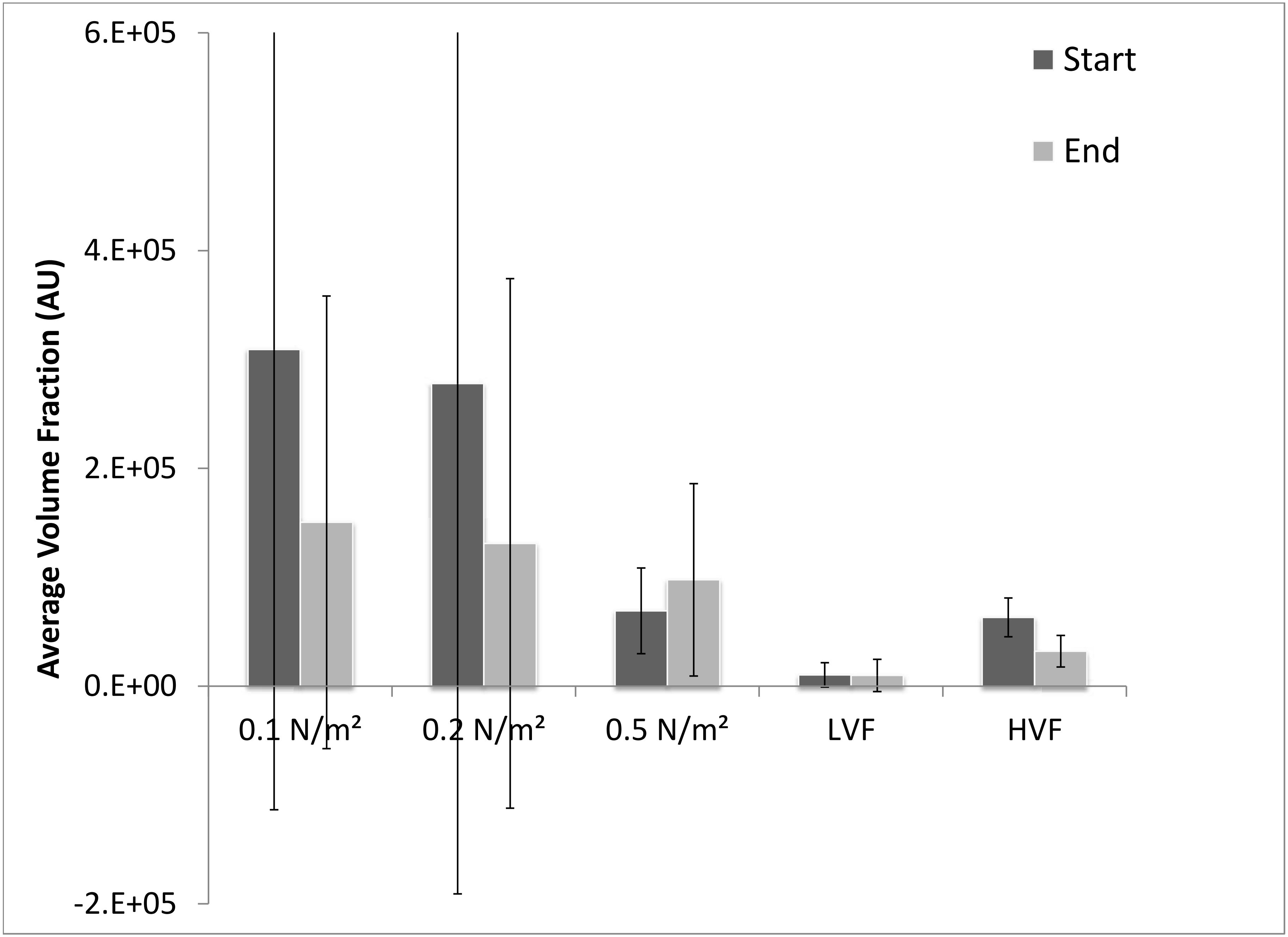


Table 1 Water quality sample data collected during the accumulation phases (averages based on three replicates per weekly sample (n=12)) (WHO standard (Frisbie et al., 2012))

Water Quality Parameter	Steady State tests (mean)	Varied state test (mean)	WHO Standard
Cl2 (mg/L)	0.2	0.1	5
Fe (mg/L)	0.02	0.03	0.02
Mn (mg/L)	0.002	0.005	0.005
Turbidity (NTU)	0.011	0.019	4 NTU at customer taps 1 NTU at water treatment works
Conductivity (µS/cm)	542	580	2500 µS/cm at 20°C
pH	7.4	7.3	6.5 - 9.5

Table 2 Mobilisation phase flow rate conversion table.

Conditioning flow (l/s)	Velocity (m/s)	Conditioning Shear Stress (N/m^2)
0.8	0.16	0.5
1.2	0.24	0.73
1.75	0.35	1.07
3.2	0.65	2
4	0.81	2.5
4.5	0.91	3