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THE IMPACT OF DRINKING WATER NETWORK MODEL SPATIAL AND TEMPORAL SCALE ON HYDRAULIC METRICS INDICATING DISCOLOURATION RISK

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Abstract

Matching model complexity to application and ensuring sufficient complexity to capture the emergent behaviour of interest is a perennial challenge. In this paper, we define a model as the variables, parameters and factors that represent a particular place, time and situation, not the software or algorithms. Specifically, we explore the cross products of spatial and temporal scaling of water demands within extended period 1D network hydraulic model simulations to predict the hydraulic conditions within individual drinking water pipes. High spatial scale hydraulic models investigated include mapping each customer with a unique demand node instead of the current practice of aggregated demand to nodes at the ends of pipe lengths. For demand profiling, we compare top-down DMA inlet patterns at 15-minute resolution with bottom-up stochastic demand patterns down to 1 second timesteps. The value of the resulting increases in resolution of hydraulic model outputs are captured in a range of pipe specific metrics that are likely to be indicative of water quality risk. Results explore different hydraulic metrics some of which may indicate discolouration risk by correlating with consumer reported discolouration events, showing how these change as a function of spatial and temporal resolution. For example, increasing the temporal scale from 15 minutes to 1-second results in more than a 100-fold increase in identifying flow reversal locations that can facilitate settling of network discolouration material and therefore pose a discolouration risk. High temporal scale is shown to capture the on/off nature of customer demands but a significant impact on daily peak velocities can only be observed using a temporal scale of 36s or higher. This work provides an indication of the quantity of added information which can indicate model spatial and temporal resolution required to differentiate pipes according to discolouration risk and hence improve targeting of pro-active maintenance and discolouration management efficiency.

Keywords
Hydraulic modelling, Spatial scale, Temporal resolution, Discolouration metrics, SIMDEUM.

1 INTRODUCTION

1.1 Model spatial scale and temporal resolution

Discolouration of drinking water is a dominant issue, for example in the UK (United Kingdom) the Drinking Water Inspectorate (DWI, independent auditors of UK water companies operating practices) reported that in 2019 1,811,121 customers were affected by significant discolouration events [1]. Several studies have been conducted that estimate discolouration risk via different hydraulic metrics, such as velocity or shear stress [2-4]. The metrics have then been used by drinking water network modellers to design new systems or simulate discolouration risk.

Matching model complexity to application, and ensuring just sufficient complexity to capture the emergent behaviour of interest remains a perennial challenge.

Hydraulic models of drinking water distribution systems (DWDS) have historically been used to model the overall continuity of supply and check water pressures as the principal equations are well-known and conservative. Most of the standard principal equations of the DWDS solvers are based on the Global-Gradient-Algorithm (GGA), which combines energy loss and mass balance equations giving simultaneous solutions for pipe flows and nodal heads [5]. However, to save computing power and increase simulation speed, hydraulic models are often constructed using top-down approach and run at low temporal resolution (industry-standard temporal resolution is 15 minutes). Top-down hydraulic models (standard lumped models) include determining water demand of the whole district metered area (DMA) and then applying it to aggregated demand nodes with a reducing multiplier. This process assumes that all nodes follow identical demand profile thus failing to consider flow variability and stochastic effect [6]. Top down models have been viewed as an efficient way of saving computing power and dealing with highly random-stochastic demands of individual households [7]. However, since the creation of the GGA solver in 1988 computing power has increased millions of times [8] and stochastic demand generators such as SIMDEUM and WUDESIM offer a way of dealing with individual household demands. Both named toolkits can generate domestic water demands on a 1 second basis on a household level which allows averaging and studying the patterns at different temporal resolutions [9, 10]. SIMDEUM has been validated via field measurements and has been shown to result in a realistic representation of the likely network flows. This has the potential to highlight low flow and potential material settling zones as well as the parts of the network that may be considered self-cleaning [11].

It has been shown that the use of high-resolution SIMDEUM patterns has a direct impact on the demand variability, however, the effect of spatial and temporal scale has not been investigated on metrics determining discolouration risk [12]. Most referenced work has used hydraulic models in some form to confirm flow conditions in a network or to evaluate water quality. In this paper, we are taking the definition of a model as the variables, parameters and factors that provide an adequate representation of a particular place, time and situation, not the software or algorithms. Specifically, we explore the cross products of spatial and temporal scale of water demand within extended period 1D network hydraulic model simulations to predict the hydraulic conditions within individual drinking water pipes and the association of this with discolouration risk.

1.2 Discolouration metrics

Discolouration typically occurs when particles that have accumulated inside drinking water pipes become mobilised through hydraulic changes [3]. It is now understood that two primary processes allow material to accumulate generating a discolouration risk: cohesive material layers on all pipe surfaces or sedimentation due to self-weight forces [13, 14]. Research has shown that material accumulation is governed by daily conditioning shear stress [15]. Therefore, as velocity has the most direct impact on the hydraulic conditions (shear stress) in a pipe, for pro-active management it is important to understand the velocity thresholds that affect discolouration. One well-established velocity threshold is the Dutch self-cleaning velocity developed in systems without residual disinfectant. Earlier work on this defined a daily maximum of 0.4 m/s as self-cleaning velocity [16, 17], but more recently a daily peak of 0.2 - 0.25 m/s has been deemed sufficient to achieve self-cleaning conditions [2, 18]. It is important to note that this threshold has been identified as sufficient to keep material accumulation via pipe wall mechanism (cohesive material layers) and sedimentation minimal. Whereas another threshold of 0.05 - 0.06 m/s has been described as a threshold above which suspended particles should not be able to form sediments within the distribution pipes [2, 3, 19]. As described, discolouration is a mobilisation mechanism and thus it is essential to examine the effect of both spatial scale and temporal resolution on the threshold velocities which can be expected to affect discolouration risk.

Fieldwork has shown that certain locations in drinking water networks can still pose a discolouration risk despite experiencing velocities above the self-cleaning threshold [20]. Therefore, in addition to fluid velocity, it is also necessary to consider other criteria to map discolouration risk across a network. Other metrics affecting discolouration risk do not have as strong and proven correlation with discolouration risk as velocity but can still give an insight into areas of concern. Flow reversals have been theorised to contribute to discolouration risk by effectively creating a zone where incoming suspended material cannot escape, thus allowing sediments to accumulate [14, 20]. Flow reversals alone however might not give a full picture as it does not indicate whether material is truly stuck in any specific area of the network. Instead, flow reversals combined with water age could give a better indication of discolouration risk as water age together with flow routes has been shown to influence water quality [21].

2 METHODOLOGY

To investigate the effect of model spatial scale and temporal resolution a residential study DMA site was selected in the UK. Figure 1 presents the DMA layout in two different formats: standard lumped (top down) and all connections. The standard lumped hydraulic model for the area considers 1358 customers spread over 235 nodes and 257 pipes (average pipe length 28m). To modify the standard lumped model to an all connections model, GIS data was extracted and imported into DNVGL Synergi hydraulic software. Tools within Synergi were then adapted to split existing pipes into smaller pipe lengths (average new pipe length 4m) depending on the location of individual customers from the GIS data (Figure 1). The geospatial accuracy of the new nodes largely depends on the imported GIS data. This process created an all connections model adding 1178 new nodes and splitting the 257 pipes to 1367 pipes. All connection refers to including every customer connection as a node along the pipe lengths.

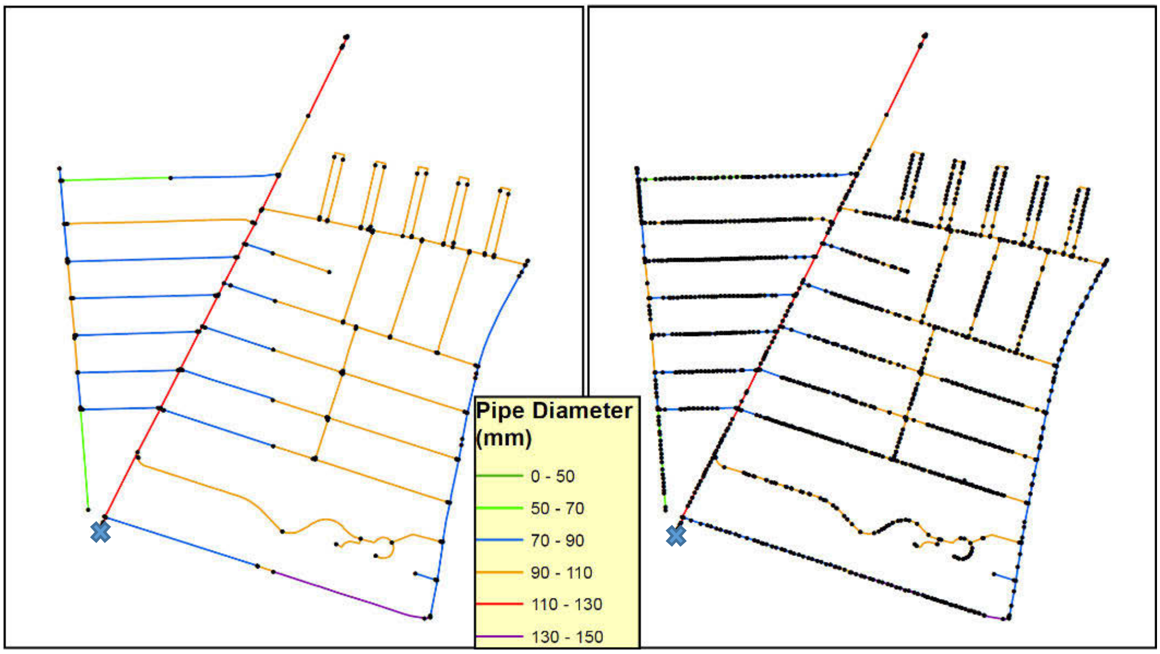

Figure 1. DMA layout in a standard lumped model (left) and all connections model (right). The blue icon represents the location of the DMA inlet.

The next step of the modification process included generating individual stochastic household demands for which SIMDEUM was selected. SIMDEUM patterns were calibrated to measured daily inlet demand by modifying daily consumption to 115.8 Lpppd (litres per person per day) and an average household size set to 2.3. For accurate calibration, social behaviour patterns that inform SIMDEUM were revised based on a recent study conducted in a comparable neighbourhood in The

Hague (NL) [22]. Social behaviour included setting unemployment rates, commuting habits and night use based on measured data. The night use was exaggerated to capture the effects of leakage by considering leakage as part of individual SIMDEUM demand profiles. Good calibration was confirmed by comparing DMA inlet patterns between different configurations, which included averaging SIMDEUM demands over multiple temporal resolutions. The selected time steps were 15 minutes, 9 minutes, 3 minutes, 36 seconds and 1 second (precise fractions of an hour) (Table 1). These individual demands were then allocated to nodes in Synergi so each node has the same profile where only the temporal resolution of the demand changes. Nodes where multiple customers share a single model node (apartments) were identified by checking GIS data. Additional SIMDEUM profiles were generated and assigned to apartment nodes based on the number of people that share a node.

The modifications retain the original lumped demand allocation in nodes and thus this converted all connections model is the base model for the standard lumped model analysis (Configuration 1, Table 2). Configurations 2-6 use the same all connection model with original demand allocation removed and SIMDEUM demands allocated to individual customer nodes. This allows comparable pipe lengths between the standard lumped model and the all connections models. As leakage is considered part of the SIMDEUM profiles, the standard lumped model leakage allocation was removed further highlighting only the effects of spatial scale and temporal resolution.

Table 1. Selected temporal resolutions with the demand profile and spatial allocation. All configurations use the all connections model (Figure 1, right) allowing comparable pipe lengths.

Configuration	**1**	**2**	**3**	**4**	**5**	**6**
Time step	15 minutes	15 minutes	9 minutes	3 minutes	36 seconds	1 second
Profile	Standard	SIMDEUM	SIMDEUM	SIMDEUM	SIMDEUM	SIMDEUM
Allocation	Lumped	Individual	Individual	Individual	Individual	Individual

The metrics investigated include pipe-specific parameters: velocity profiles, peak velocity, flow reversals and more complex metrics combining multiple thresholds. In addition, metrics such as duration at stagnation, above a threshold and below a threshold were aggregated across the model to showcase the effect of spatial and temporal scale. The effect of spatial-temporal scale on water age was investigated as a node property.

3 RESULTS

Figure 2 shows the match of inlet flow between different configurations over 24 hours showing a good calibration between automatically generated SIMDEUM profiles and the standard DMA inlet. There is a slight underestimation of SIMDEUM daytime and night-time demands compared to the standard DMA inlet pattern. The stochastic nature becomes more apparent as the temporal scale increases, which can be seen by sudden increases and decreases in the flow. To highlight the effect of temporal-spatial scale on the hydraulic model, this match between the automatically generated stochastic SIMDEUM demands, and the DMA inlet pattern is considered sufficient for this study.

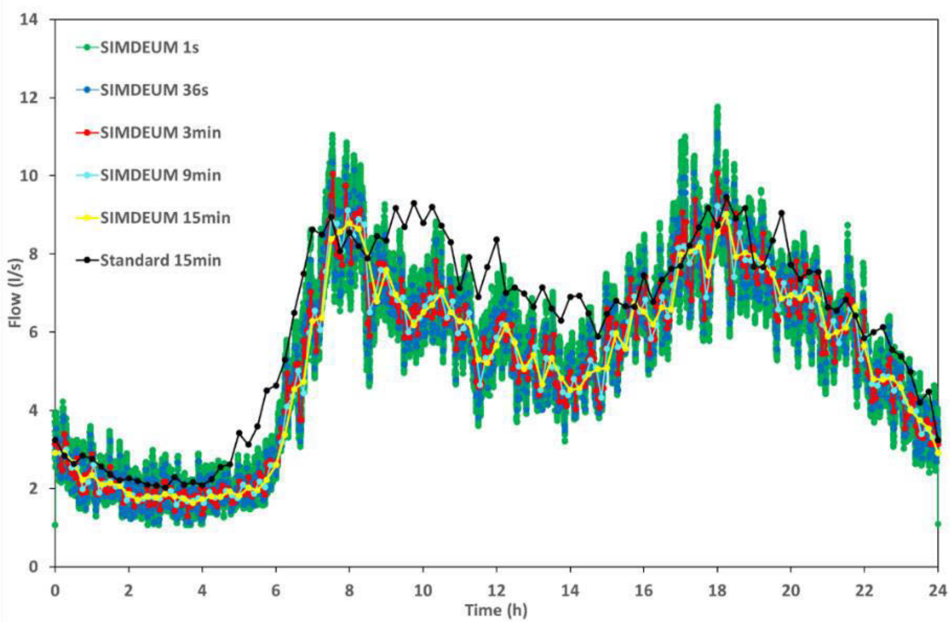

Figure 2. DMA inlet pattern for different configurations.

The effect of spatial-temporal scale on velocities can be viewed as a realistic representation of velocities in pipe sections. Figure 3 presents the velocity profile in a single pipe in the middle of a dead-end and in a pipe in the middle of a looped section. Both pipe sections are not on the main flow path. Regardless of the location of the pipe section, 1s temporal resolution always results in the highest observed velocity. Figure 3 reveals that an increase in temporal resolution has the most significant impact on the observed velocity profile. The change from low spatial scale to high spatial scale and stochastic demands seems to be more significant for pipes in loops compared to pipes at dead-end sections of the network, however, the standard demand fails to capture any stochastic behaviour. It is apparent that the velocity in the looped pipe section is much more stochastic as shown by the multiple sudden velocity changes crossing the x-axis entirely (flow reversal). In addition, configurations using SIMDEUM demands result in a strikingly different velocity profile compared to the configuration using lumped standard demand.

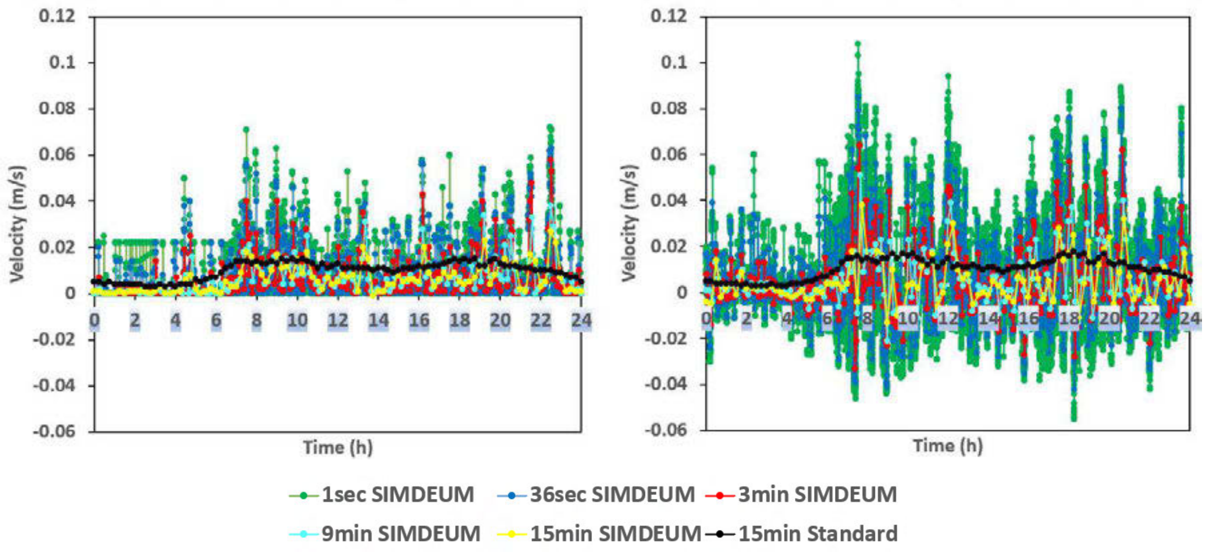

Figure 3. The effect of spatial scale and temporal resolution on velocity in a dead-end pipe (left) and on a pipe in the middle of a looped section (right).

With the potential for material to settle, for example due to low velocities, stagnation may be considered a key factor in estimating discolouration risk. For this, hours of stagnation were calculated and tabulated across different spatial-temporal resolutions, Table 2. Here the increase in spatial and temporal resolution is significant as evidenced by the steeper increase in the total number of hours of stagnation across the whole network. In addition, the total hours spent above or below two different key velocity thresholds (0.06 m/s and 0.25 m/s)[3, 18] were determined. The standard model overestimates the time spent above 0.25 m/s and underestimates time spent below 0.06 m/s compared to the higher spatial and temporal simulations. In addition, the temporal resolution of 1 second results in the highest peak velocity across all pipes. Going from a 15 minute standard lumped model to a 15 minute SIMDEUM all connections model (spatial change) has only a limited impact on peak velocities. Temporal resolution however has an increasing impact as time steps reduce in size.

Table 2. The effect of spatial scale and temporal resolution on metrics aggregated across the model. For reference, the total maximum possible hours across all DMA pipes is 32832 (hours).

	Maximum velocity across the whole model (m/s)	Total hours of stagnation across all pipes (hours)	Total hours all pipes experienced velocity above 0.25 m/s (hours)	Total hours all pipes experienced velocity below 0.06 m/s (hours)
Effect of Spatial Scale and Stochastic Demands				
15min Standard	1.20	1730	1063	24328
15min SIMDEUM	1.16	1900	610	26604
Effect of Temporal Resolution				
15min SIMDEUM	1.16	1900	610	26604
9min SIMDEUM	1.17	2059	752	26644
3min SIMDEUM	1.29	2196	894	26634
36sec SIMDEUM	1.44	2554	954	26643
1sec SIMDEUM	1.53	2754	987	26523

Figure 4 shows the total number of flow reversals in 24 hours. The most notable difference is the standard lumped model shows the total number of flow reversals across the whole network as 0. The move from the lumped to the all connections model with SIMDEUM profiles reveals the location of flow reversals plus further locations occur as the temporal resolution increases. As the temporal scale increases, however, there are more opportunities for flow reversals with 43200 chances for 1 second simulations compared to 48 for 15 minutes, hence contributing to the increase in total flow reversals observed. Configurations using SIMDEUM reveal that only the pipes near the inlet and across the bottom right of the network are mostly unidirectional. Moving away from the main flow paths results in the total number of flow reversals increasing with increasing temporal resolution of the demand patterns.

Figure 5 presents results for maximum average water age for different configurations. Water age analysis was run for 48 hours (sufficient to reach stable repeating daily patterns of water age with the maximum water age being 24hours) at 0.005 hours temporal scale for configurations 1-5, for configuration 6 the water age analysis time step was set to 0.0002778 hours (1 second). Higher propagation timestep and longer total simulation times for water propagation analysis (water age) did not have an impact on water age results. The results in Figure 5 show the maximum average water age between 24 to 48 hours. A significant difference comes when moving from the lumped model to an all connections model. The lumped model appears to have two redundant loops with high water age. Closer inspection revealed that due to the original lumped allocation of demands or top down modelling approach the loops where water age exceeds 18 hours (in 15 min lumped config) have no flow through them. Added spatial scale fixed that error by considering a more realistic spatial representation of water movement down all pipe sections. Temporal resolution, however, seems to have only a limited effect on water age.

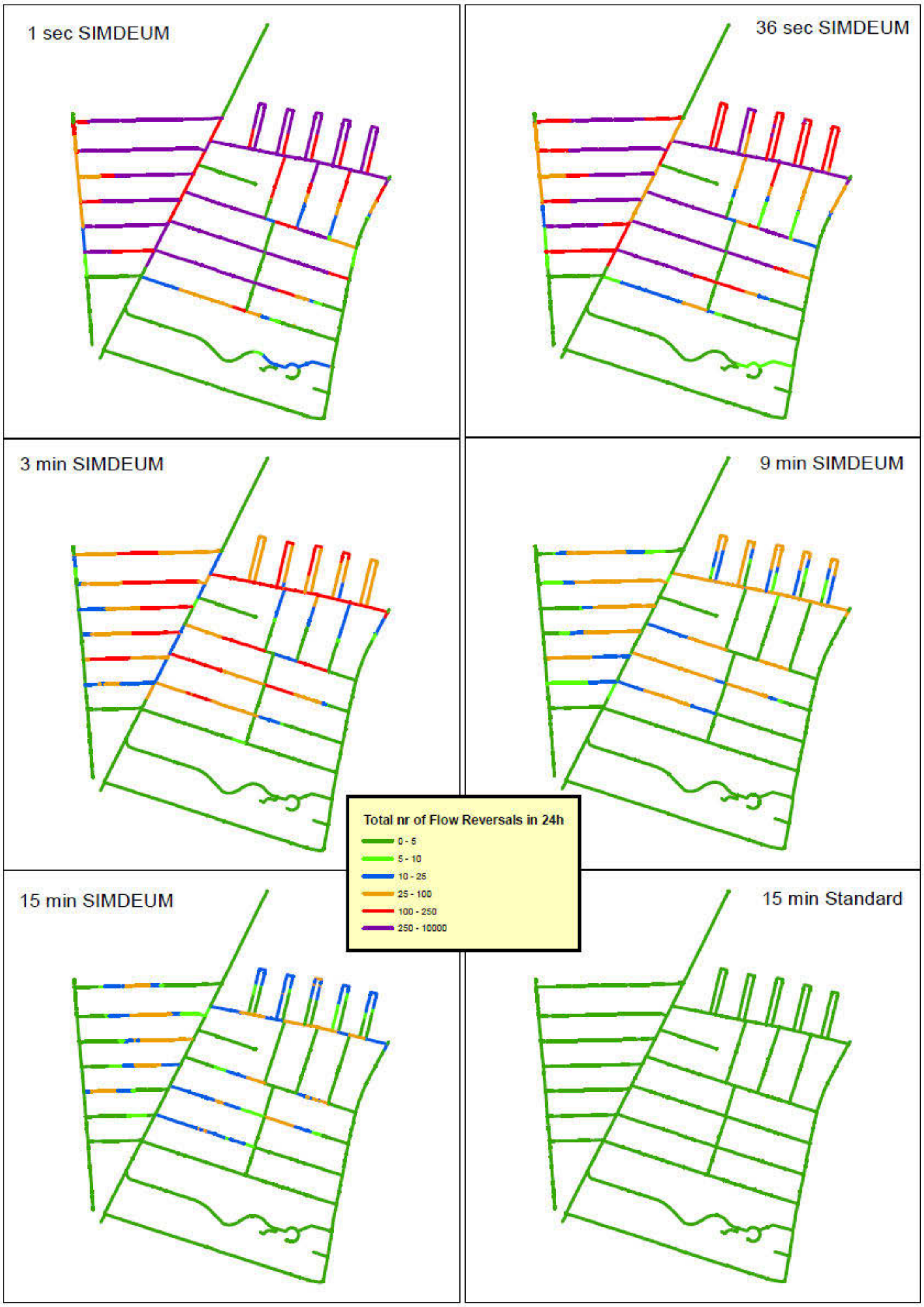

Figure 4. The total number of flow reversals in each pipe section mapped across the whole network.

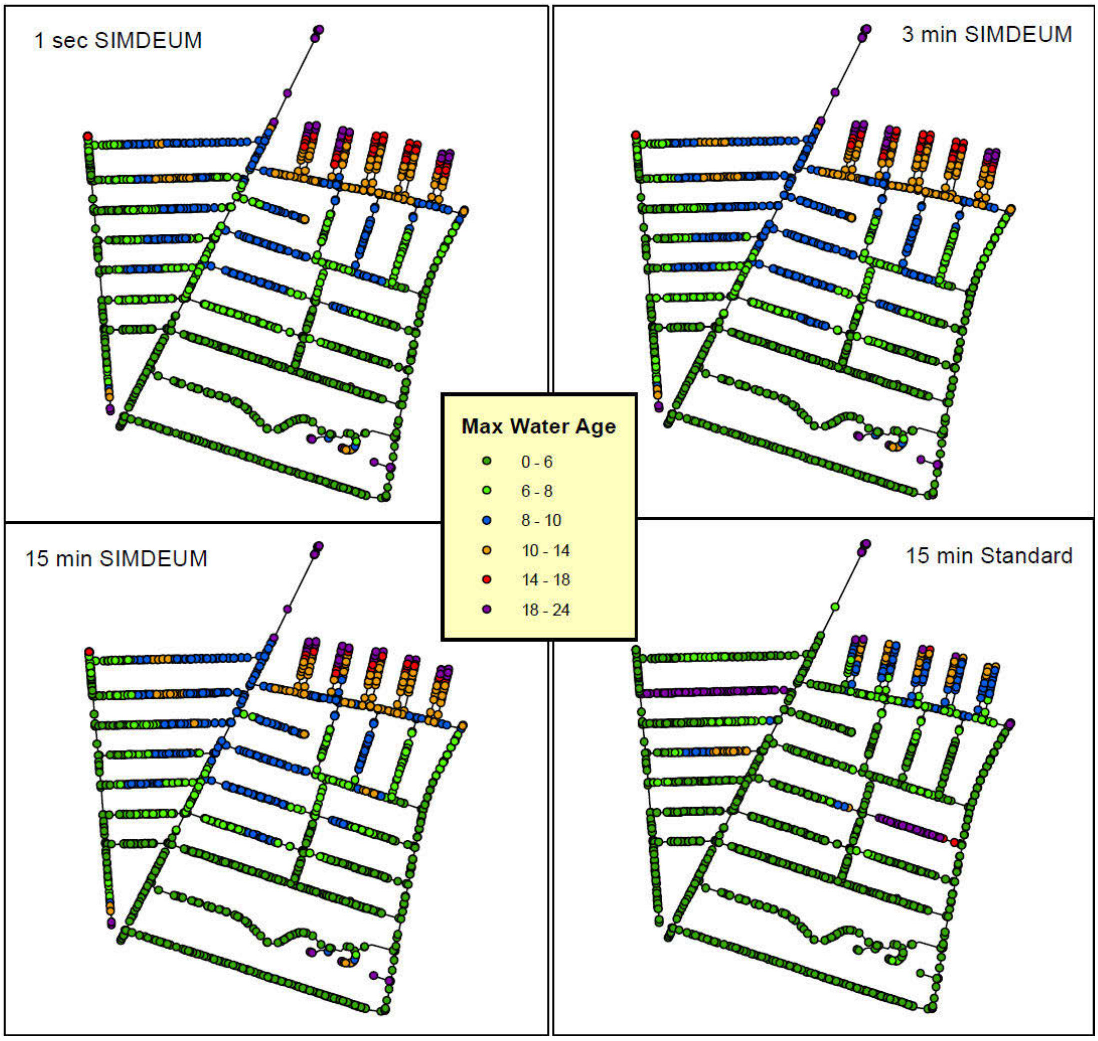

Figure 5. Maximum average water age (hours) in each customer node mapped across the whole network.

Figure 6 investigates which pipes experience the proposed self-cleaning velocities by looking at the maximum velocity in each pipe at different configurations. The figure also shows the apparent random customer discolouration contacts from the past 7 years as black dots. The spatial scale has a limited effect on maximum velocities, agreeing with the overall maximum velocity data in Table 2. However, the increasing temporal resolution does show some differences. For example, comparing 15min SIMDEUM to 1s SIMDEUM reveals that the bottom left dead-end pipe section could experience self-cleaning conditions. Customer contacts are notoriously inconsistent (many factors influence why a customer does or does not make a contact) and the potential correlation between customer contacts and any metrics including self-cleaning velocities can only be considered crude. Results however support a possible correlation with most contacts located towards the top of the DMA where there are no self-cleaning pipes whilst around the inlet with higher, potentially self-cleaning, velocities there are fewer reported discolouration events.

Figure 7 presents an example of a more complex combined metric where pipes are coloured by the number of times experiencing velocity less than 0.06 m/s for more than an hour continuously. This metric considers pipes where the velocity is below a potential sedimentation threshold for long enough to allow the possibility of suspended material to settle. As was seen in Figure 3, the increases in velocity may only be short-lived resulting in a stop-start motion of the flow, rather than quiescent conditions for long enough for the suspended particles to settle out. Pipes with a greater number of occurrences of consistently low velocity for an hour or more, perhaps correlate even more with the discolouration contacts from the past 7 years. This stop-start stochastic motion in pipes is only picked up by high-end (1s) temporal resolution considering all connections.

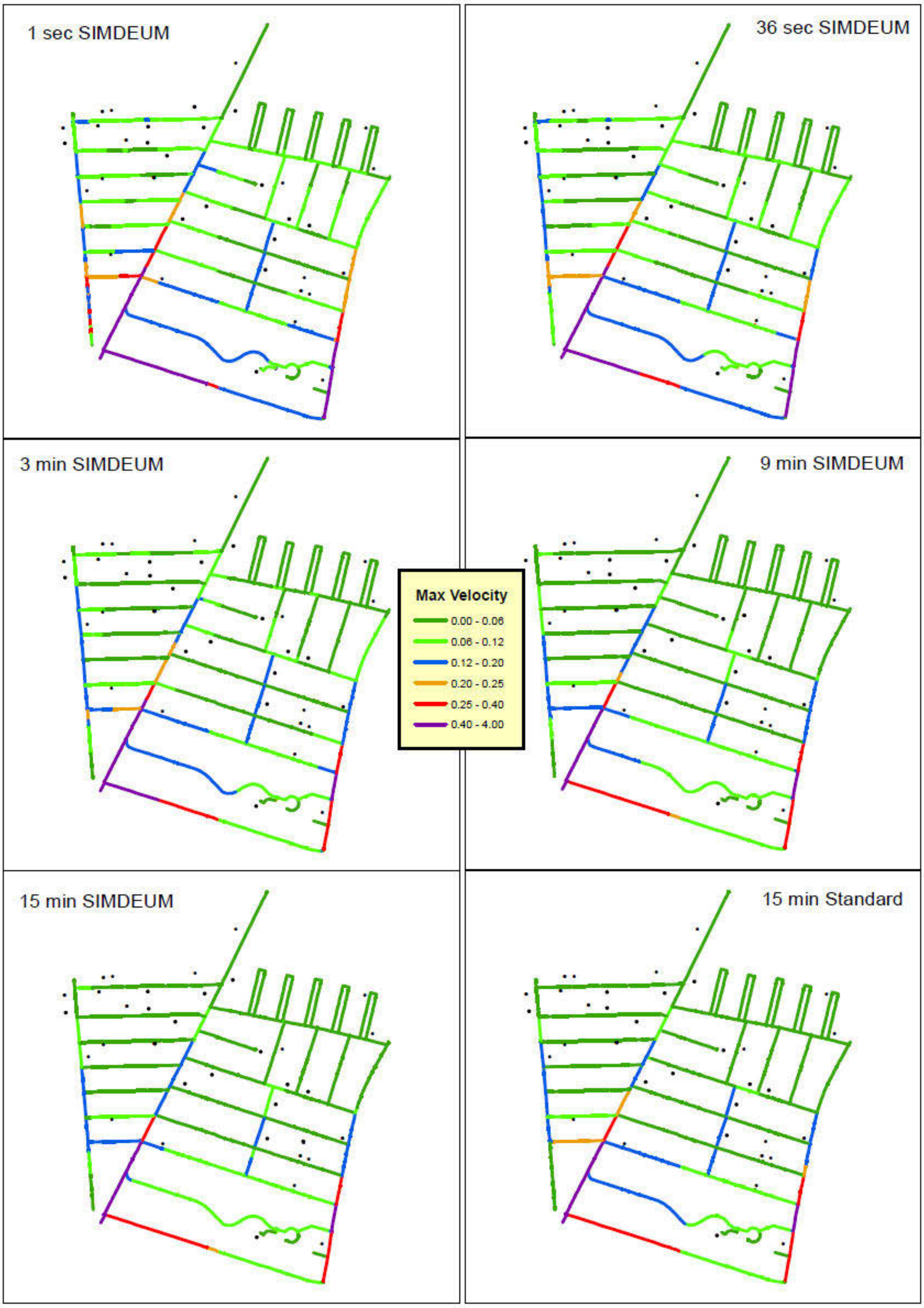

Figure 6. The maximum velocity in pipes across the DMA. Black dots mark the customer reported discolouration events from the past 7 years.

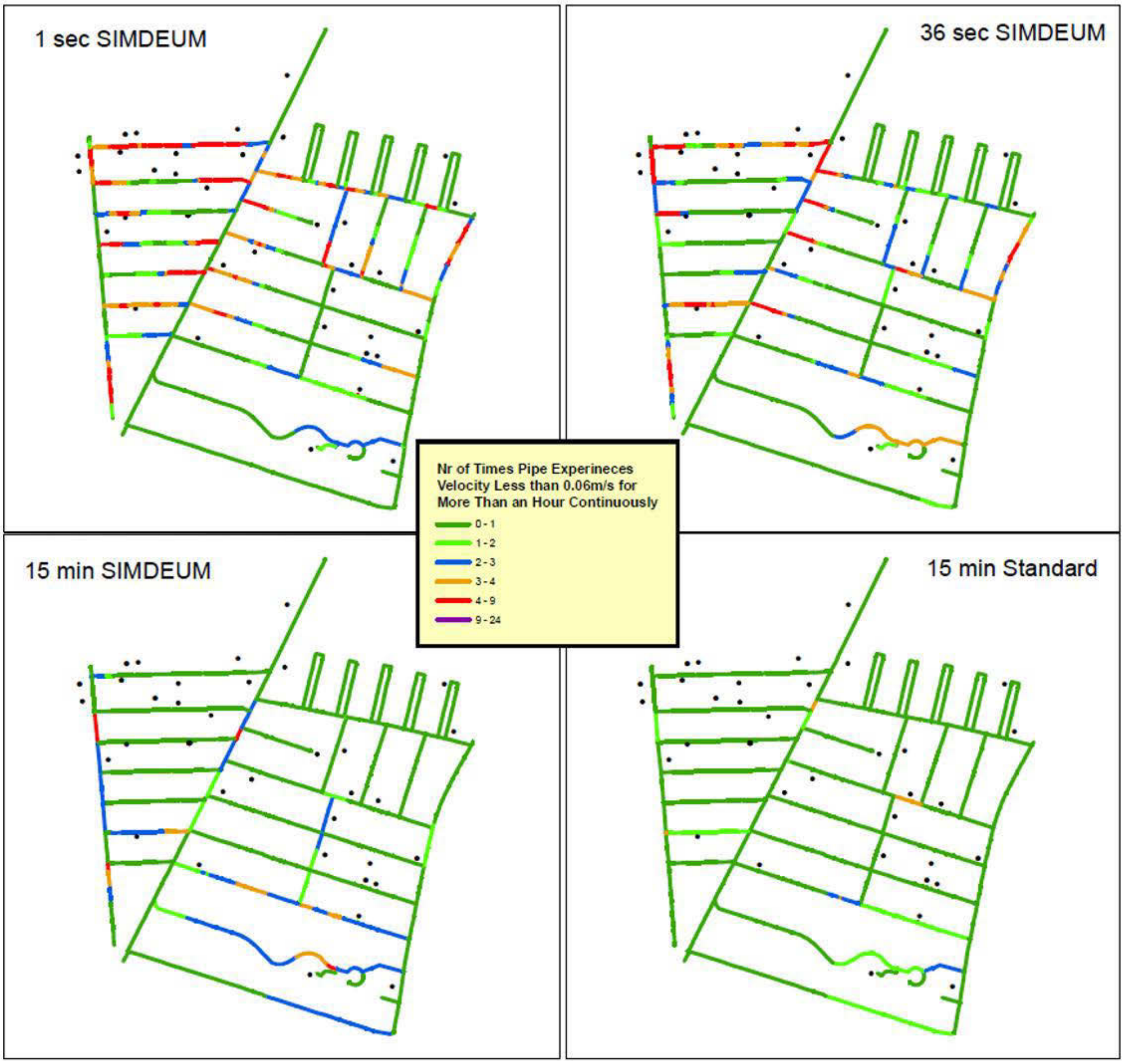

Figure 7. Network-wide look at the number of times pipe experiences velocity less than 0.06 m/s for more than an hour continuously. Black dots mark the customer reported discolouration events from the past 7 years.

4 DISCUSSION

Overall, the modification process was mostly automated and did not take much computing power or time. However, simulating results on 1-second temporal resolution was computationally demanding and could take several hours. In total 6 different scenarios were studied (Table 1) each representing a different combination of spatial-temporal scale. The comparison between configurations 1 and 2 highlighted the effect of increasing the model spatial scale and the addition of stochastic demands. Configurations 2-6 showed the effect of the model temporal scale on results.

The results reveal that the biggest effect of spatial resolution can be observed in downstream pipes away from main flow paths. Hydraulic conditions affecting discolouration risk in residential pipes off the main flow paths are not realistically represented by lumping demands to end of pipe nodes. All connection models can, therefore, be viewed as a more realistic representation of hydraulic conditions in residential area pipes, where flows are dominated by individual customer water consumption behaviours. The results are consistent with literature where it has also been shown that low spatial scale and temporal resolution models only suffice modelling trunk mains [23]. Moving from standard lumped models to the all connections model with 15 minute SIMDEUM stochastic demands affected all studied metrics apart from peak velocity. However, there was a limited impact for increasing temporal resolution on metrics that capture cumulative effects of the water moving through a network. Similarly, only spatial scale with stochastic demands seems to matter in determining total time spent under sedimentation threshold (0.06 m/s) [3, 14, 19]. Water quality surrogates such as water age (shown in figure 5) and chlorine [24] aggregate time and pipe effects from source to point of interest thus only capturing cumulative effects of the entire network.

Discolouration has been shown to be mainly a function of the network velocities (shear stress), whilst metrics such as flow reversals may serve as additional criterion to help determine risk zones [4, 13, 20]. In both cases the move to all connections model with stochastic demands seems to have only limited benefit. Instead to capture discolouration risks in detail, increase of temporal scale is needed. The results of this study show that high spatial scale models with stochastic demands at temporal scale of 36s are sufficient to capture more than 90% of peak velocity values, total time at stagnation, map location of most flow reversals and capture total hours above or below a threshold. This is consistent with previous research where it has been shown that temporal resolution of higher than 30s results in only 10% missed variance in instantaneous water demands [12]. Standard lumped models underestimating time at stagnation correlate with Blokker et al. (2008) where 1 minute temporal resolution was shown to be sufficient to determine realistic peak Reynolds number and probability of stagnation [23]. Temporal scale of 36s revealed that there are possibly hundreds of flow reversals in most residential area pipe sections even on or close to main flow paths. Based on these results, the conditions in residential water network pipes have much more start-stop motions and are more multidirectional than previously thought [25]. This could significantly contribute to discolouration risk by trapping material and allowing it to suspend or disturb already accumulated material. Customers either have their water tap on or off for a mostly short amount of time meaning, this high temporal stochastic effect plays a significant role in determining pipe specific hydraulic metrics. Based on the results of this study and literature, metrics affecting discolouration risk have been shown to be primarily a function of the hydraulic conditions in a specific length of pipe, which are influenced by both spatial scale and temporal resolution (Figures 3, 4, 7) [2, 9, 10]. The all connections hydraulic models using stochastic demands with temporal scale of 36s or higher can improve indication of discolouration risk by revealing more pipe specific information.

Identification of discolouration risk may involve a combination of several different metrics and their thresholds. Figures 6 and 7 attempted to correlate customer reported discolouration contacts with self-cleaning pipes and an example of a combined threshold metric. In looped sections of the network, an increase of the temporal scale only resulted in a small increase in number of pipes observed to exhibit proposed self-cleaning velocities which might be due to the extremely looped nature of the selected DMA. This indicates that to achieve self-cleaning velocities and reduce discolouration risk, branched network layouts may offer an improved design [17, 26, 27]. The more complex metric of Figure 7 investigated the stochastic stop-start motion of the velocity in individual pipe sections followed by a period that might facilitate both particle aggregation (increased mass due to flocculation) and settling. This has been reported to take place at velocities below 0.06 m/s [3]. It may then be considered that once settled, factors including particle shielding and potential additional cohesive forces may result in higher shear forces being required to re-mobilise allowing larger deposits to form creating a localised discolouration risk.

It is important to note that investigating potential correlations between discolouration risk and modelled metrics based on customer contacts will remain inconclusive and field evidence is required. This could then evidence both material accumulation zones and self-cleaning pipes facilitating modelling metrics to be developed to help improve targeting of pro-active network maintenance and discolouration management.

5 CONCLUSIONS

This study investigated the effect of spatial and temporal scale on the drinking water distribution system hydraulic model at a DMA level. Key findings from this study are:

- All connections models using stochastic demands capture more detailed hydraulic information in residential area pipes that are considered important in determining discolouration risk.
- Moving from industry-standard 15 minute lumped models to all connections models using 15 minute stochastic profiles (added spatial and stochastic effect) has minimal effect on observed peak velocities, but impacts other possible discolouration metrics including velocity profiles, flow reversals and water age.
- Increasing the temporal scale adds more information on pipe specific properties such as velocity profiles, peak velocity and flow reversals but little additional information on water age (as it is a water quality surrogate aggregating time and pipe effects from source to point of interest) or identifying more potential self-cleaning pipes (daily maximum velocity greater than 0.25 m/s).
- The combined threshold metric of times a pipe experiences velocity less than 0.06 m/s for more than an hour continuously could be of use in identifying discolouration risk areas.

6 ACKNOWLEDGEMENTS

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