Impact of network sectorisation on water quality management

Hooman Armand, Ivan Stoianov and Nigel Graham

ABSTRACT

The sectorisation of water supply networks (WSNs) includes the permanent closure of valves in order to achieve a cost-effective leakage management and simplify pressure control. The impact of networks sectorisation, also known as district metered areas (DMAs), on water quality and discolouration has not been extensively studied and it remains unknown. In addition, hydraulic variables used in the literature for assessing the likelihood of potential discolouration are limited and inconclusive. This paper investigates a methodology to evaluate the impact of networks sectorisation (DMAs) on water quality and the likelihood of discolouration incidents. The methodology utilises a set of surrogate hydraulic variables and an analysis of the hydraulic condition in pipes with historic discolouration complaints. The proposed methodology has been applied to a large-scale WSN, with and without sectors, in order to assess the potential impact of DMAs on water quality. The results demonstrate that the sectorisation of WSN (DMAs) could compromise the overall water quality and increase the likelihood of discolouration incidents. The results of this study and the proposed surrogate hydraulic variables facilitate the formulation of optimisation problems for the re-design and control of WSNs with sectorised topologies.

Key words | discolouration, district metered areas (DMAs), networks sectorisation, water age, water quality, water supply networks (WSNs)

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INTRODUCTION

Water supply networks (WSNs) are designed to satisfy customer demands and comply with water quality regulations at a minimum cost (Alperovits & Shamir 1977; Savic & Walters 1997; Parsad & Park 2004; Farmani *et al.* 2006). These interrelated factors lead to a variety of network topologies and operational characteristics. The 3Rs (reliability, redundancy and resilience) in the supply of potable water are achieved by designing looped networks with multiple sources and increasing the diameter of pipes in order to maintain the quality of service under extreme demand and failure conditions. In comparison, lower capital investment costs lead to dendritic network structures with smaller diameter pipes.

Continuous regulatory and financial pressures for water utilities to reduce leakage and the cost of supply has led to the sectorisation of WSNs and the introduction of district metered areas (DMAs) (Diao *et al.* 2013; Alvisi & Franchini 2014; Laucelli *et al.* 2017). This includes the installation of permanently closed valves (kept-shut valves, Figure 1) to partition networks into smaller areas (sectors). The networks sectorisation facilitates the monitoring of flow into sectors and the detection of leakage, and it also simplifies

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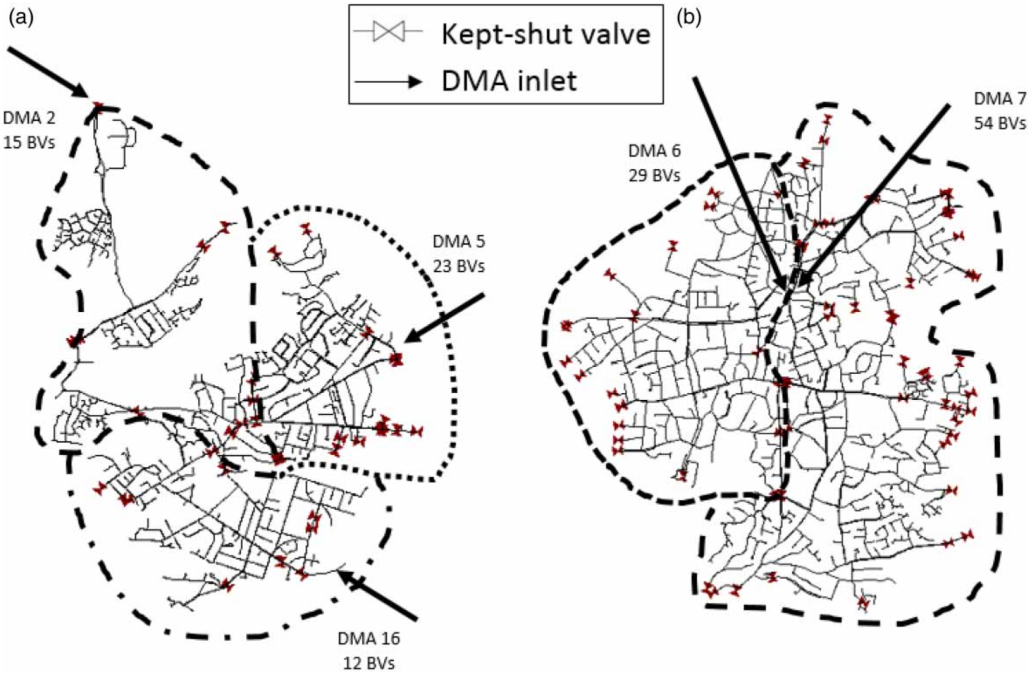

Figure 1 | Examples of DMA topology showing the spatial distribution of boundary valves (BVs) in the selected case study: (a) DMAs 2, 5 and 16, (b) DMAs 6 and 7.

the pressure control (and leakage reduction) for individual sectors.

There are many factors that affect the water quality within WSNs (Armand *et al.* 2017), such as: i) water treatment processes, and the chemical, physical and biological characteristics of potable water (Van der Kooij 1998; Vreeburg *et al.* 2008); ii) pipe material and age (McNeill & Edwards 2001; Hallam *et al.* 2002; Yu *et al.* 2010; Al-Jasser 2011); iii) steady-state hydraulic conditions (Boxall *et al.* 2001; Blokker *et al.* 2011) and unsteady-state hydraulic conditions (Aisopou *et al.* 2012, 2014); iv) residence time of potable water (Smith *et al.* 1999; Sarin *et al.* 2004); and v) environmental conditions (e.g., temperature) (Hallam *et al.* 2002; Blokker & Schaap 2015). Changes in network connectivity, resulted from DMAs, would significantly impact the residence time and hydraulic conditions (both the maximum flow velocity and the diurnal range) and that may compromise the water quality and increase the likelihood of discolouration incidents.

In the UK, the design and implementation of DMAs have evolved over a period of 10–15 years by superimposing sectors on existing WSNs using hydraulic models, extensive engineering knowledge of local networks and a continuous 'trial-and-error' manual optimisation. Design criteria include compliance with pressure requirements, minimisation of capital and operational costs, consideration of physical restrictions (elevation variation and availability and accessibility of candidate boundary valves), and the incorporation of flow measurements for leakage management and pressure reducing valves for pressure reduction. Methods for the automatic creation of DMA boundaries have been explored that consider DMA size and pressure constraints (Awad *et al.* 2009; Di Nardo & Di Natale 2011), or DMA size and various connectivity requirements such as the DMAs are supplied independently from transmission mains (Izquierdo *et al.* 2011; Di Nardo *et al.* 2014). Ferrari *et al.* (2014) proposed an approach that accounts for multiple criteria. Based on the theory of complex networks, Giustolisi & Ridolfi (2014) and Giustolisi *et al.* (2015) suggested a general methodology that allows for the division of WSNs into segments with similar pipe characteristics (e.g., pipe length) or hydraulic performance (e.g., average pipe pressures). Wright *et al.* (2014) and Pecci *et al.* (2017) proposed the design and control of dynamically adaptive sectors for the minimisation of average pressure and pressure variability indices within WSNs.

Published methods for the sectorisation of networks have not considered water quality in the formulation of the optimisation problems. This exclusion could be partly explained by the little-known impact of networks sectorisation on water quality and the ambiguity of the variables (and constraints) that need to be incorporated in the problem formulations.

Water quality complaints, which are exacerbated by the hydraulically driven design of WSNs and the sectors (DMAs), are currently managed by implementing flushing programmes to clean pipelines and restore the chlorine residuals. Pipe replacement and rehabilitation (relining), and the installation of booster chlorination, are additional measures used to reduce the risk of discolouration and microbiological failures. Although these measures have been effective in reducing the number of water quality incidents, discolouration complaints persist (Boxall & Prince 2006; Husband & Boxall 2011; Vreeburg & Beverloo 2011).

UK water utilities are facing unprecedented operational challenges with the increasingly stringent level of water quality regulations, the introduction of ODIs (outcome delivery incentives) by the Water Regulator, Ofwat, which can result in substantial financial penalties or rewards, and also far-reaching reforms to their retail and wholesale operations that drive increased levels of competition. Therefore, further analytical and experimental research is required to investigate the impact of networks sectorisation on water quality and discolouration. The operation of sectorised networks can no longer be justified only on the basis of leakage management and reporting, and pressure and leakage reduction.

This paper has two objectives: first, present a methodology and a set of surrogate hydraulic variables that can be used in assessing the overall water quality and likelihood of discolouration in sectorised WSNs; and second, apply the proposed methodology to an operational UK network in order to investigate the potential impact of networks sectorisation on the proposed surrogate hydraulic variables, and as a result, on the likelihood of discolouration and water quality deterioration.

METHODOLOGY

Surrogate hydraulic variables for the assessment of the likelihood of discolouration and water quality deterioration

Various surrogate hydraulic variables, which impact the changes in water quality within WSNs and the accumulation of sediments and biofilms, have been defined from published literature and interviews with water network operators. In addition, a particular hydraulic condition was formulated and described as dead-end-like behaviour for a specific set of surrogate hydraulic variables. The dead-end-like behaviour is based on the analysis of hydraulic conditions in pipes with historic discolouration customer complaints in an operational WSN.

Case study network

The case study network for this investigation is a UK-based WSN that has been sectorised into DMAs (Figure 2). The case study serves approximately 35,540 customer connections and comprises 22 DMAs with a total length of approximately 345 km and a daily demand (including leakage) of approximately 23 Ml/day. The network includes pipes of various materials (72.5% metal, 16.4% plastic and 11.1% AC pipes). The topology of the DMAs has been designed by trial and error and engineering judgement. The network model includes 12,136 nodes, 12,721 links and 191 permanently closed boundary valves. All DMAs are single-fed DMAs with no outlets except one which is a water transmission main supplying water from the treatment works to the DMAs.

Simulation of the hydraulic behaviour of pipes with historic discolouration complaints

The WSN had 792 customers' discolouration complaints between 2005 and 2013. Each discolouration complaint was associated with a neighbouring pipe based on a geospatial analysis, the hydraulic model and information from the discolouration complaint records (e.g., the customer address). The hydraulic conditions were simulated for a DMA-based network topology, which is the current setup.

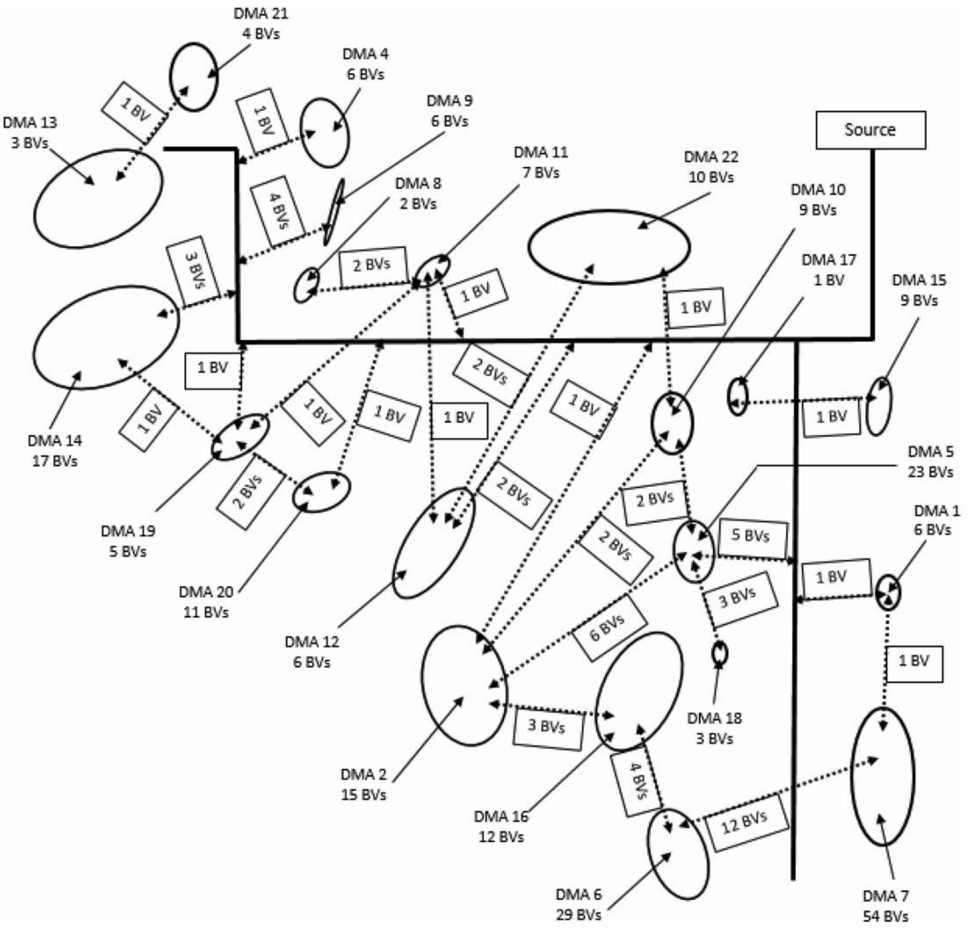

Figure 2 | Layout of the case study area (1 source, 22 DMAs). DMA 3 is the trunk main that transfers water from the source to the DMAs. Solid arrows show the DMA IDs and number of boundary valves (BVs) and dashed arrows show the closed connections between DMAs or DMAs and the trunk main. All DMAs are fed directly from the trunk main and there are no cascading DMAs.

The hydraulic model was validated based on 15-minute flow and pressure measurements for a period of 1 week as recommended by UK industry guidelines (Edwards *et al.* 2006). The water age simulation was carried out for a period of 3 days to observe steady-state nodal water age. Historic changes in the network topology and operational controls were also reviewed to ensure that the hydraulic model represents reasonably well the system behaviour within the period of investigation, 2005–2013.

Hydraulic modelling of the case study for different network connectivity configurations

The hydraulic conditions for the case study were simulated for two network connectivity configurations, namely the sectorised (current DMAs) and aggregated (aggregated DMAs) network topologies. The validated hydraulic model was then used to investigate the likelihood for discolouration and overall water quality deterioration as a result of the network sectorisation. This was carried out by quantifying the variations in specifically defined surrogate hydraulic variables for the different network topologies.

The network sectorisation was carried out in the early 1990s and it has gone through various changes. As no information was available about the network topology prior to the initial sectorisation, an alternative WSN with aggregated DMAs was created by opening closed boundary valves associated with the network sectorisation. Minor changes were made to control rules to preserve the same boundary conditions for both network configurations.

Surrogate hydraulic variables for evaluating the potential for discolouration

The discolouration potential in WSNs depends on the presence and accumulation of sediments and biofilms (the 'discolouration material') within pipes during typical diurnal hydraulic conditions, and the occurrence of random perturbations in the hydraulic conditions that impact the cohesive strength of the discolouration material. In this investigation, we assume that accumulation processes that depend on factors external to the sectors (DMAs), such as the supplied water quality, are equal for both network connectivity configurations, and the analysis focuses on the impact of the hydraulic conditions on accumulation processes. We have investigated physical, chemical and microbiological processes that contribute to the accumulation of discolouration material and classified the associated mechanisms into gravitational sedimentation, non-gravitational accumulation and biofilm and corrosion related (Armand *et al.* 2017). We presume that the potential for the occurrence of discolouration in a pipe depends on the age of water entering the pipe, pipe residence time, pipe physical characteristics (material, age and diameter), and its diurnal flow profile (min, max and mean flow velocities). These factors depend on the networks connectivity layout and resulting pipe hydraulics.

Water age

The quality of water at a specific location can be represented by physical variables (e.g., temperature, colour/turbidity, taste and odour), chemical variables (e.g., pH, alkalinity, concentration of organic and inorganic substances) and microbiological variables (e.g., number of different types of microorganisms). Grab samples guarantee regulatory water quality compliance but these samples cannot be used to assess the discolouration potential and do not provide continuous assessment of the water quality under various hydraulic conditions. A simplified and commonly used approach is to model water age (residence time) as a surrogate indicator for water quality. Machell & Boxall (2014) showed a correlation between the water age and the overall water quality performance for two networks by acquiring long-term measurements of 15 water quality variables. This study showed an increase in pH, temperature, conductivity, colour, HPC (heterotrophic plate count) and a decrease in chlorine concentration (free and combined) with water age.

While water age is a representative surrogate variable for the physical, chemical and microbiological quality of water, a universal water age threshold does not exist. Consequently, we have carried out an assessment of the distribution of nodal water age based on the mean water age from a 24-hour extended period simulation.

Residence time of flow-in-pipe and physical characteristics of pipes

The residence time of water-in-pipe represents the time that a finite volume of water spends within a pipe and this influences water age. A high residence time indicates low flow conditions that may increase the precipitation and uptake of iron in metal pipes due to corrosion and scale dissolution. In an investigation to quantify the iron uptake, Mutoti *et al.* (2007) observed that the largest iron uptake occurs under laminar conditions. The iron uptake then decreases to a minimum for the laminar-turbulent transition, and it subsequently increases with flow velocity. Therefore, laminar conditions should be minimised. The physical properties of the pipes (material, age and diameter) can further worsen the impact of residence time on the discolouration potential and water quality. Small diameter, old and unlined metal pipes represent worst conditions due to a greater ratio of pipe surface area to water volume and a greater potential for chlorine decay (Al-Jasser 2011). The reduced chlorine residual accelerates iron release (Mutoti *et al.* 2007) and biofilm formation. While maintaining flow velocities in the laminar-turbulent transitional region can be considered an effective approach for reducing iron uptake, this is difficult to achieve operationally due to its narrow range, the stochastic demand and the selection of pipe diameters based on other design criteria. In addition, flow velocities may be lower than the sedimentation threshold. Sedimentation, and steady and unsteady state flow conditions, which exceed their typical diurnal profile (Vreeburg & Boxall 2007; Ryan *et al.* 2008; Aisopou *et al.* 2014), increase the likelihood of discolouration. Therefore, the flow velocity associated with the threshold of sedimentation is used as a surrogate hydraulic variable in this study.

Diurnal flow profile in a pipe

Diurnal flow velocity profiles control the cohesive strength and the amount of material build-up within a pipe. The build-up can be caused by sedimentation in the pipe invert or the attachment of materials (cohesive layers) to the pipe circumference (Vreeburg & Boxall 2007; Armand *et al.* 2017). Suspended materials in the bulk water start to settle when the flow velocity drops below a threshold that is assumed to be around 0.06 m/s (Vreeburg & Boxall 2007; van Thienen *et al.* 2011), and the re-suspension of sediments occurs when the flow velocity reaches around 0.2 m/s (Ryan *et al.* 2008). For plastic pipes, Blokker *et al.* (2011) suggested that generating a minimum flow velocity between 0.2 and 0.25 m/s on a regular basis (e.g., every 2 days), is sufficient to re-suspend the sediments and achieve 'self-cleaning' hydraulic conditions.

Another form of accumulation is the transport and attachment of suspended materials to the pipe walls when the flow velocity increases and turbulent forces overcome the gravitational force. The rate of attachment is currently unknown but it was suggested to be related to the iron concentration in the bulk water (Cook 2007). In addition, the maximum diurnal velocity, which represents the largest magnitude of shear force exerted on the pipe wall, has been suggested to be the governing factor, which determines the amount and strength of particles accumulation (Boxall *et al.* 2001). Thus, an increase in the maximum diurnal flow rate decreases the likelihood of discolouration incidents. An ultimate strength was observed for the particles accumulation in plastic pipes (1.2 N/m^2) (Boxall & Prince 2006) and in asbestos cement pipes (1.12 N/m^2) (Husband & Boxall 2010). Increasing the shear force (i.e., flow velocity) above these thresholds would remove the accumulated materials. The existence of such self-cleaning hydraulic conditions in ageing iron pipes is not guaranteed due to the role of corrosion scales as a source of particles and support for biofilm growth. Furthermore, flow reversals, such as flushing in the reverse direction, was observed to enhance pipe cleaning (Ahn *et al.* 2011). This can be attributed to the characterisation of biofilms (i.e., cohesive layers) as streamlined wavy structures when grown under turbulent flow (Kwok *et al.* 1998; Stoodley *et al.* 1999). Horn *et al.* (2003) demonstrated the effectiveness of flow reversals in exerting additional shear stress on biofilms. Current knowledge of the effect of flow reversals on the detachment of accumulations and biofilms in WSNs is limited.

We have compared the characteristics of the cohesive layers formed on pipe walls in WSNs with the general properties (structure and mechanical behaviour) of biofilms and suggested that biofilms are an important factor for the rate and strength of sediment accumulations (Armand *et al.* 2017). Consequently, we have proposed two additional surrogate hydraulic variables that represent the cleaning hydraulic conditions.

There is a general agreement that the cohesive strength of biofilms at a specific time is a function of the shear stress during their growth (Vrouwenvelder *et al.* 2010; Radu *et al.* 2012; Douterelo *et al.* 2013). Two approaches were identified in the literature for defining the critical stress required for detachment ($\tau_{detachment}$) based on historic growth shear stress (τ_{growth}): either the relationship, $\tau_{detachment} = 2.3\ \tau_{growth}$ ($R^2 = 0.81$) (Stoodley *et al.* 2002), or as a constant shear stress value (2 N/m^2) when biofilms are grown under shear conditions in the range of 0.01–0.3 N/m^2 (Derlon *et al.* 2008; Paul *et al.* 2012).

Quantitative studies concerned with determining the strength of biofilms as a function of historic shear stress have been limited and related to steady-state flow behaviour. Choi & Morgenroth (2003) suggested that the immediately preceding 12 hour steady-state shear stress profile can determine the cleaning of biofilms during a subsequent flow increase. In the context of WSNs, and assuming that cleaning occurs during the peak demand, biofilms can be expected to be conditioned for 12 hours before cleaning. Although this duration has not been validated for WSNs, the concept and use of a shear stress 'ratio' may be indicative, as previous studies of WSNs have shown, that a quasi-unsteady diurnal flow profile with a smaller peak flow was more successful in cleaning pipelines than a steady-state flow with a greater magnitude (Husband *et al.* 2008; Husband & Boxall 2010; Aisopou *et al.* 2014). Due to the quasi-unsteady nature of the flow velocity range in WSNs, we define two additional surrogate hydraulic indicators in order to take into account the impact of time dependency on cleaning (e.g., the historic hydraulic conditions). These indicators are the ratio of maximum diurnal velocity ('cleaning shear force', which is defined as the shear force required for cleaning of biofilms) to the average diurnal velocity ('conditioning shear force', which is defined as the shear force under which the cohesive strength of biofilms forms) and the ratio of the maximum diurnal flow velocity (cleaning shear force) to the minimum diurnal flow velocity (conditioning shear force).

Hydraulic characterisation of pipes with historic discolouration complaints

The analysis of the hydraulic conditions for historic discolouration complaints showed that these complaints were mainly from customers who receive water with relatively high water age (80% of the discolouration complaints). Around 63% of the pipes associated with discolouration complaints have maximum diurnal flow velocities, which do not exceed 0.06 m/s. This low flow velocity facilitates the process of sedimentation, the formation of weakly adhered cohesive layers and the increase in iron uptake by the bulk water. In addition, nearly 18% of the pipes with historic discolouration complaints have a maximum diurnal flow velocity below the resuspension threshold of 0.2 m/s and minimum flow velocities below 0.06 m/s. These pipes could also experience sedimentation depending on the duration of minimum flow velocities. In this study, we define 'dead-end-like' pipes as pipes with hydraulic conditions characterised by high water age, a minimum diurnal velocity below the sedimentation threshold and a maximum diurnal velocity below the re-suspension threshold. The nodes associated with these pipes are defined as 'dead-end-like' nodes. These are pipes and nodes with a high likelihood of discolouration.

A summary of surrogate hydraulic variables and associated thresholds is presented in Table 1.

RESULTS

Sectorised networks (DMA-based) versus non-sectorised networks (non-DMA-based)

Water age

The results of the extensive hydraulic analysis for the selected case study show that the non-sectorised network topology decreases the number of nodes representing

Table 1 | Proposed surrogate hydraulic variables for the assessment of the potential for discolouration incidents

Components of discolouration management	Surrogate hydraulic variable	Threshold
Nodal water age (demand and non-demand nodes)	–	No absolute threshold exists. Distribution of nodal water age should be characterised
Pipe residence time (metal pipes)	Diurnal flow velocity range	Flow velocity should be above 0.06 m/s
Self-cleaning condition (sedimentation)	Maximum diurnal flow velocity	≥0.2 m/s
Self-cleaning condition (strongly adhered materials) (plastic and AC pipes)	Maximum diurnal shear stress	≥1.2 N/m^2
Cleaning (strongly adhered materials) (metal pipes)	Maximum diurnal flow velocity	No established threshold exists. A higher velocity reduces the risk of discolouration
Biofilm cleaning	Ratio of maximum diurnal velocity to average diurnal velocity (or shear stress)	1.5 (2.3), the higher ratio is more likely to facilitate the cleaning process
	Ratio of maximum diurnal velocity to minimum diurnal velocity (or shear stress)	1.5 (2.3), the higher ratio is more likely to facilitate the cleaning process
	Maximum diurnal shear stress	≥2 N/m^2 (when growth occurs between 0.01 and 0.3 N/m^2)
	Flow direction	No established absolute thresholds exist for the magnitude and duration of flow reversal (and velocity)

dead-end-like hydraulic behaviour from 7,930 to 6,065. It also reduces the average water age throughout the system (all nodes) from 55 hours to 46 hours when compared with a sectorised (DMA-based) network. However, non-sectorised network topology increased the standard deviation of the water age from 24 to 27 hours. A comparison of the nodal water age under the current DMA sectorisation and after opening the boundary valves reveals that the dead-end-like hydraulic conditions were eradicated in 17% of nodes (2,062 nodes, 6,329 customer connections). The majority of these dead-end nodes resulted from the sectorisation of the network. The non-sectorised (non-DMA) network resulted in dead-end-like hydraulic conditions in only 1.6% of the nodes (189 nodes, 805 customer connections). These were mainly attributed to low flow conditions close to the hydraulic boundaries. Approximately half of the nodes (48%, 5,863 nodes, 16,805 customer connections) remained unchanged in the dead-end-like hydraulic zone, which is attributed to the natural dead-ends in the peripheral areas of the dendritic WSN. Around 33% (4,022 nodes, 11,601 customer connections) of the nodes remained in non-dead-end-like zones.

A comparison of the number of dead-end-like nodes for the sectorised (DMA-based) and non-sectorised (non-DMA-based) networks is shown in Figure 3. Nearly all DMAs exhibited a reduction in the number of dead-end-like nodes when opening kept-shut boundary valves and aggregating the DMAs. This reduction ranged from 2 in DMA 21 to 588 in DMA 7. The only exceptions were DMA 8, in which the number of dead-end-like nodes increased by 4, and DMA 17 (39 domestic properties), in which the number remained unchanged.

Figure 4 shows the distribution of water age in each of the current DMAs for nodes with non-dead-end-like behaviour for the two network configurations. By defining changes in water age equal or greater than 2 hours as significant for a hydraulic simulation of 96 hours, the median water age was reduced for 12 DMAs after opening the boundary valves. DMA 17 is not included in the plot because it comprises dead-end nodes which preserve their water age for both network configurations. The water age increased slightly for three DMAs and it stayed the same for seven DMAs. In addition to the box plots presented in Figure 4, cumulative histograms were also analysed in order to compare the number of DMAs that operate within different water age bands (e.g., 0–5 hrs, 0–10 hrs, and so on) for the two network configurations and for the minimum, first quartile, median, third quartile and maximum water age. The results are summarised in Table S1. For all water age bands, with the exception of two water

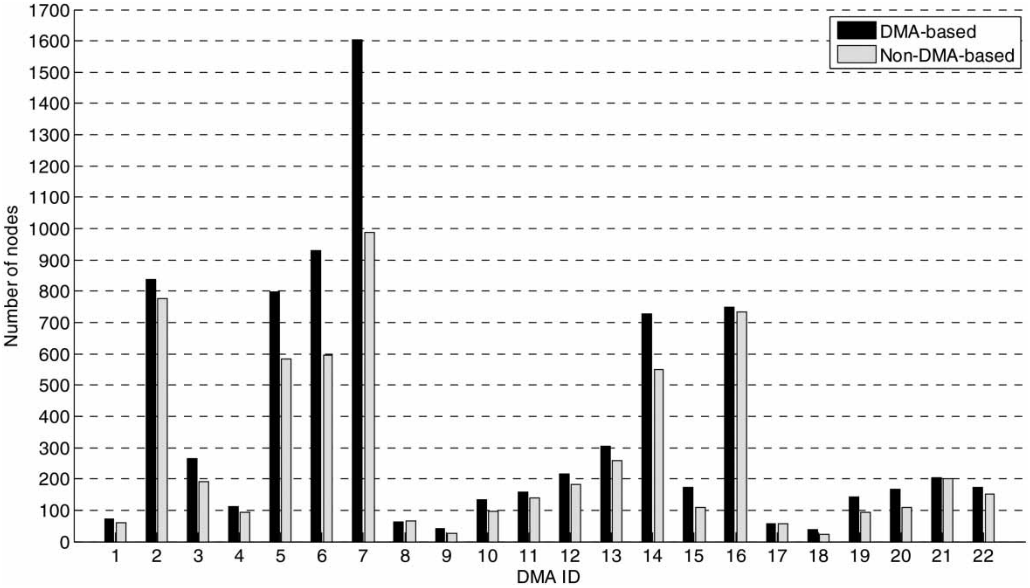

Figure 3 | Comparison of the number of 'dead-end' nodes in each DMA for the case study WSN for the closed (DMAs) and open (non-DMA-based) topologies.

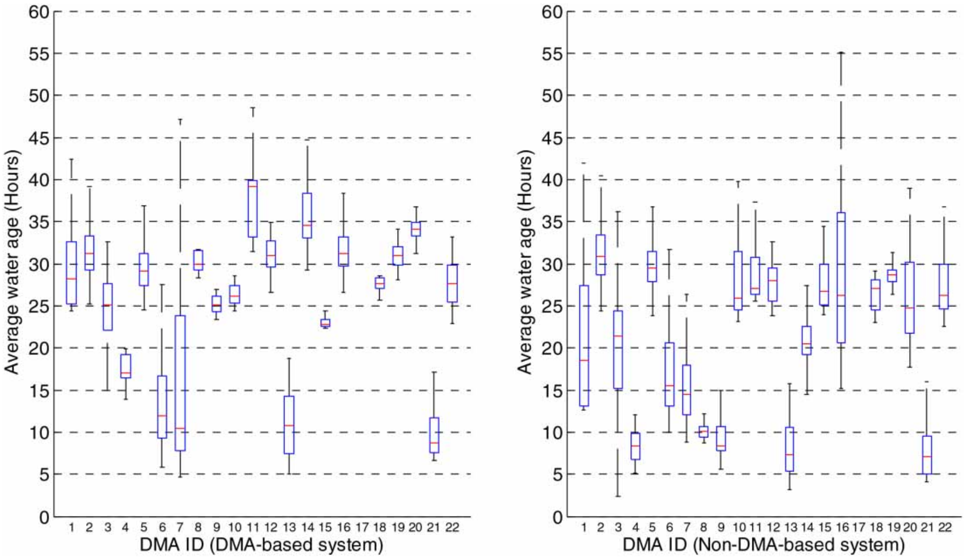

Figure 4 | Distribution of average water age within each DMA after 96 hours (3 days) for DMA-based and non-DMA-based topologies (box plot shows max/min values (dotted lines) and upper quartile, median, lower quartile values (boxes)).

age bands in the maximum water age category (0–35 and 0–50 hours), the number of DMAs operating within each water age band was greater in the non-sectorised network configuration.

Furthermore, the analysis of the water age distribution in each DMA shows that the standard deviation increased in nine DMAs, remained the same in eleven DMAs and decreased in two DMAs after opening the boundary valves. The increases are attributed to nodes (customers) being supplied through a single DMA inlet in the DMA-based network, whereas in a non-DMA-based network the supply routes to the nodes can differ during the day as a consequence of its redundancy in connectivity. These results demonstrate that the sectorised (DMA-based) network topology introduces changes in the hydraulic conditions which are detrimental for water quality and discolouration.

Flow velocity

The distribution of maximum diurnal velocities in each DMA for the sectorised and non-sectorised networks is shown in Figure 5(a) and 5(b), respectively. The results indicate that the introduction of DMAs generally reduces the median and maximum flow velocities and their interquartile ranges. Opening the boundary valves resulted in an increase in the median of the flow velocity for nineteen DMAs, reduction in two DMAs and it remained the same for one DMA. Similarly, the distribution of minimum diurnal velocities for the two network topologies is plotted in Figure 5(c) and 5(d), respectively. The non-DMA-based network topology showed an increase in the median flow velocities for sixteen DMAs, a decrease for three DMAs and it remained the same for three DMAs. Similarly, the distributions of average diurnal velocities for individual pipes within each DMA for the two network topologies are plotted in Figure 5(e) and 5(f). The median flow velocities increased for eighteen DMAs in the non-sectorised (non-DMA) network, while it decreased only for one DMA and it remained the same for three DMAs. In addition, there was an increase in the upper quartile and maximum flow velocity values. This shows an increase in the average flow velocity for at least 25% of the pipes within each DMA.

Figure 5 demonstrates the distribution of maximum, minimum and average flow velocities within each DMA. To assess the potential for biofilm cleaning, the ratios of max/min flow velocities and max/average flow velocities were analysed for each pipe. The resulting histograms are plotted in Figure 6. Each bar represents the length of pipes associated with the specific ratio bin; for example, the second bar in Figure 6(a) represents the length of pipes

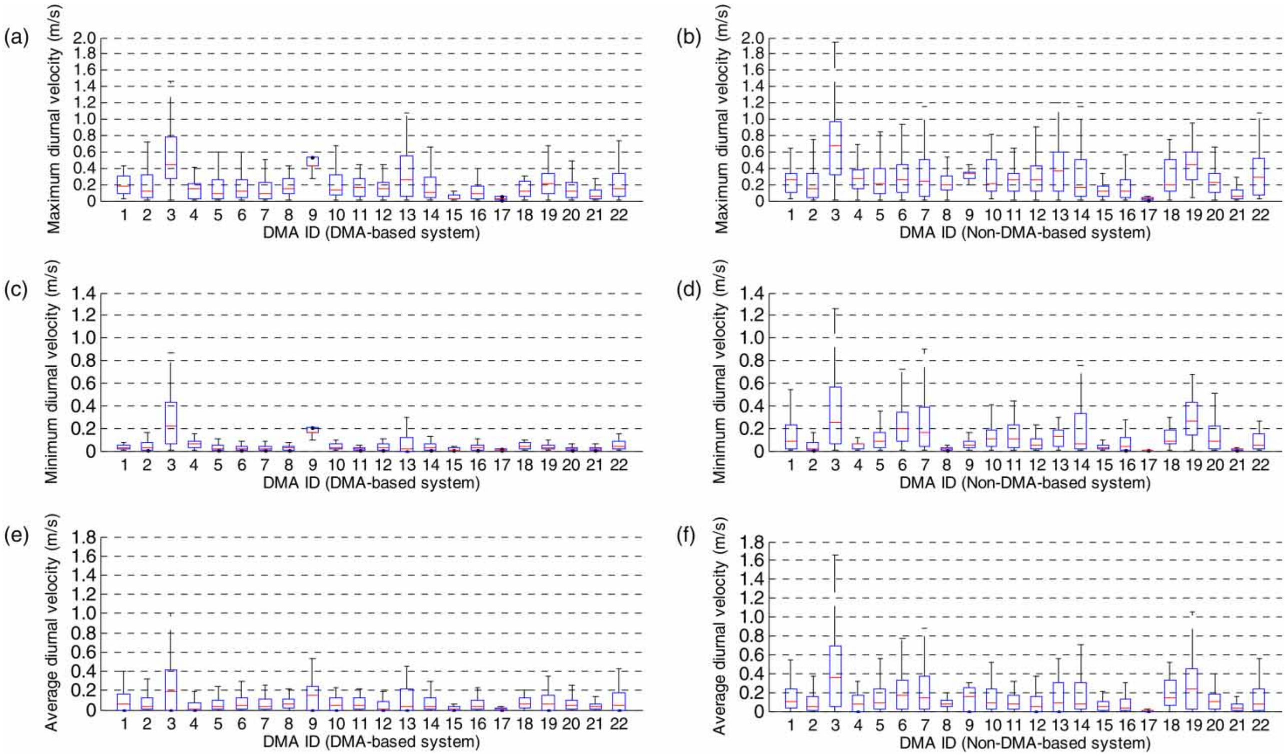

Figure 5 | Distribution of maximum (a, b), minimum (c, d) and average (e, f) diurnal velocities within each DMA for the sectorised (DMA) and non-sectorised (non-DMA) network topologies.

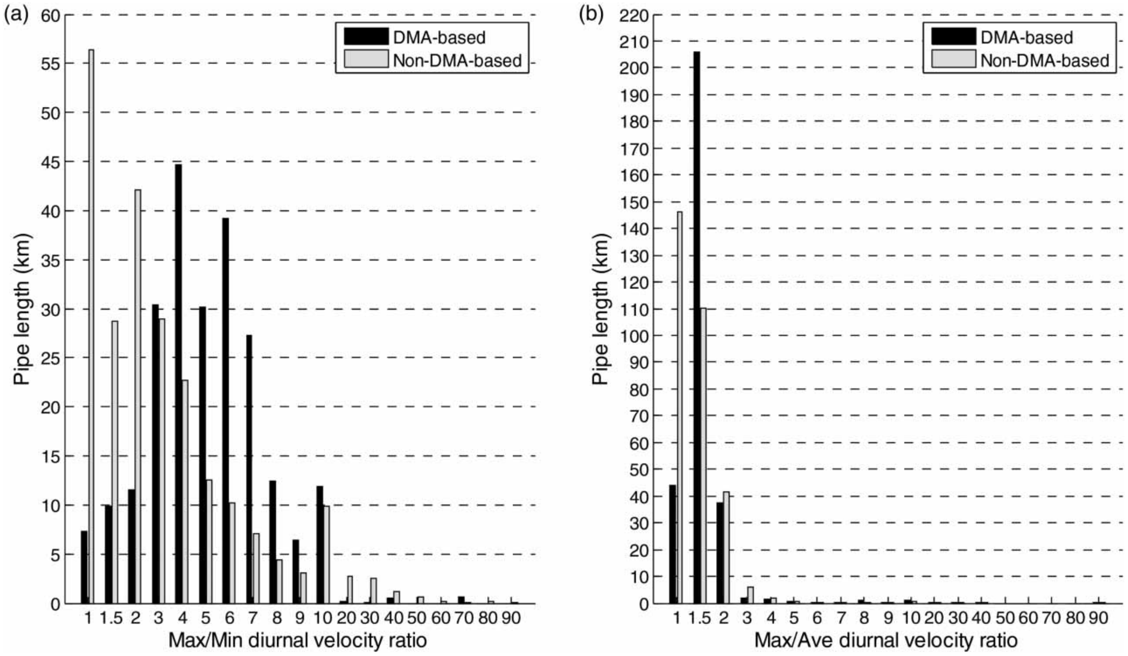

Figure 6 | Relationship between the max/min diurnal velocity ratio (a) and the max/average diurnal velocity ratio (b) with pipe length for the DMA and non-DMA topologies.

associated with velocity ratios equal or greater than 1 and smaller than 1.5. Figure 6(a) demonstrates that the non-sectorised network has increased the number of pipes, which is represented as a total length, with max/min velocity ratios equal or greater than 1 and smaller than 3. However, it has reduced the number of pipes with ratios equal or greater than 3 and smaller than 20. The number of pipes for ratios greater than 20 has increased in the non-sectorised network; these pipes, however, constitute a small proportion of all pipes. There are some pipes with negligible minimum diurnal velocities, and as a result, the max/min ratio becomes mathematically indefinable. The length of these pipes has increased from 62 km in the sectorised network to 75 km in the non-sectorised network.

Figure 6(b) presents the number (length) of pipes associated with different max/average flow velocities ratios. It is observed that while opening the boundary valves has increased the number of pipes associated with the max/average flow velocity ratios between 1 and 1.5, it has decreased the number of pipes with ratios between 1.5 and 2. The non-sectorised network has also increased the number of pipes operating at higher flow velocity thresholds but this number represents a negligible proportion of all pipes. Overall, a larger number of pipes with a total length of 250 km has experienced a max/average flow velocity ratio of 1.5 or more in the sectorised network compared to the non-sectorised network (162 km).

With regards to the number of pipes undergoing flow reversals, the results showed that 11% of pipe length (approximately 37 km) has experienced flow reversals in the non-sectorised (non-DMA) network, while the corresponding value for the sectorised (DMA) network was only 1% (approximately 3 km). This can be attributed to the increased redundancy in hydraulic connectivity. A summary of results to compare the water quality behaviour of both network configurations is given in Table 2.

DISCUSSION

Water age

This investigation has demonstrated that the creation of sectors (DMAs) could result in a substantial increase in the average water age for a set of nodes (and customer connections) and the number of nodes with dead-end-like hydraulic behaviour. The increase in water age is consistent with the results of previous studies by UKWIR (2000) and WRc (2000) that simulated the impact of network sectorisation by creating four DMAs in an urban network. These studies,

Table 2 | Comparison of surrogate hydraulic variables for the case study area under sectorised and open network topologies

Evaluating parameters	Sectorised (DMA) network	Non-sectorised (non-DMA) network
Average water age (all nodes) (hours)	55	46
Average water age (non-dead-end nodes) (hours)	23	20
Standard deviation of water age (all nodes) (hours)	24	27
Standard deviation of water age (non-dead-end nodes) (hours)	12	10
No. of nodes with stagnation (dead-end nodes)	7,930 (65%)	6,065 (50%)
Length of pipe with max diurnal velocity below 0.06 m/s (continuous sedimentation) (m)	190,902 (55%)	149,190 (43%)
Length of pipes with max diurnal velocity between 0.06 m/s and 0.2 m/s (m)	43,795 (13%)	22,600 (7%)
Length of pipes with max diurnal velocity above 0.2 m/s (self-cleaning) (m)	109,001 (32%)	171,908 (50%)
Length of pipes with min diurnal velocity below 0.06 m/s (intermittent sedimentation) (m)	299,324 (87%)	105,605 (31%)
Length of pipe experiencing flow reversal (m)	2,933 (1%)	36,933 (11%)
Length of pipes with max/min velocity ratio of equal or greater than 1.5	286,789 (84%)	252,197 (73%)
Length of pipes with max/average velocity ratio of equal or greater than 1.5	250,174 (73%)	162,435 (47%)

however, reported a beneficial impact of DMAs in a rural network, which had excess capacity. Grayman *et al.* (2009) and Murry *et al.* (2010) also investigated the impact of DMA topology in two WSNs and reported no systematic change in water age with the exception of cascading DMAs (DMAs connected in series). Cascading sectors (DMAs) were not considered in this investigation as single-fed DMAs from water transmission mains are the predominant network connectivity model in the UK.

The location of nodes with the largest increase in water age was observed to be not only in proximity to closed boundary valves, as suggested by UKWIR (2000), but also further upstream throughout the network. This is illustrated in Figure 7 in the form of long dead-end stems (Figure 7(a) and 7(d)) and dead-end loops (Figure 7(b) and 7(c)). This result highlights the importance of optimal valve placements with the careful consideration of water quality criteria in the design and optimisation methodology for network sectorisation. In addition, the random (non-systematic) distribution of dead-end-like conditions at locations further upstream of boundary valves, and within DMAs, highlights the importance of optimally simplifying hydraulic models when formulating optimisation problems for sectorising networks and including water quality related indicators as constraints.

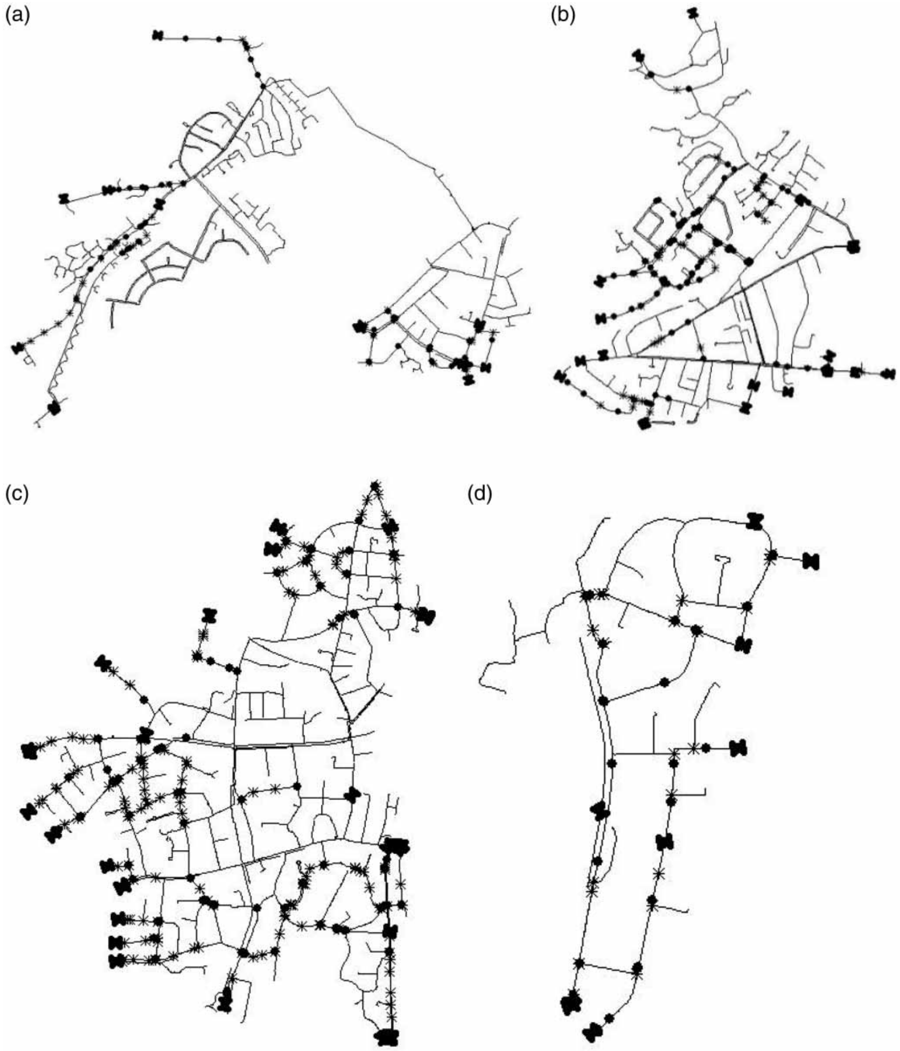

Figure 7 | Dead-end-like behaviour (black dots) caused by DMAs: (a) DMA 14, (b) DMA 5, (c) DMA 6, (d) DMA 15.

Flow velocity

The results from the case study network show that a sectorised (DMA) network topology increases the likelihood of sedimentation. This observation contradicts conclusions from previous UK studies (UKWIR 2000; WRc 2000) that fewer pipes would undergo sedimentation in a DMA-based system. However, no flow threshold values for this assessment had been provided. These studies also observed that the closure of valves caused sedimentation in proximity to the boundary valves, which is consistent with the observations of our study. Similar to water age, our study has shown that sedimentation is not only limited to boundary valves, but spread within DMAs. In fact, the pipes connected to the nodes with dead-end-like behaviour, illustrated in Figure 7, experience sedimentation either continuously or intermittently. The scattered and extensive distribution of these pipes show the potential limitations of flushing routines, which are mostly focused on pipes in close proximity to DMA boundary valves.

Furthermore, the sectorisation of WSNs tends to reduce the maximum diurnal velocity in a large set of pipes. A reduced maximum diurnal velocity would indicate a lower potential for self-cleaning of pipes and a greater likelihood of discolouration in the DMA-based system (Boxall *et al.* 2001). Only 2% of pipes in non-DMA-based system and 0.8% of pipes in DMA-based system experience a shear stress greater than 1 Pa under normal operating conditions, which is near the self-cleaning threshold for plastic and AC pipes (1.2 Pa) (see Figure S1). This result implies that the proposed self-cleaning threshold is rarely achieved under normal operating conditions in either of these network configurations.

Considering the impact of the hydraulic conditions between maximum flow velocities for 2 consecutive days (i.e., minimum and average velocities) and their impact on the strength of the accumulated materials, the potential for discolouration in each DMA is greater for the sectorised (DMA-based) network. The accumulated material is likely to have lower strength due to the lower diurnal minimum and diurnal average velocities throughout each DMA. However, an assessment of the likelihood of discolouration also depends on the max/min and max/average diurnal flow velocities ratios for each pipe.

The suggested shear stress ratio of 2.3 for effective biofilm cleaning is equal to a velocity ratio above 1.5 based on the Darcy–Weisbach equation. As shown in Figure 6, the sectorised network is expected to have a higher cleaning capacity as more pipes experience max/min and max/average velocity ratios equal or greater than 1.5. To assess the potential for biofilm cleaning based on a threshold of shear stress of 2 N/m^2, a distribution of the maximum diurnal shear stress within the system is shown in Figure S1. There are no pipes for both network configurations that experience such a high magnitude of shear stress. This demonstrates that carefully designed control strategies are required to optimally vary the hydraulic conditions in WSNs in order to increase the shear stress to a desired level. Further investigations about the impact of the hydraulic conditions between consecutive peak flows on the self-cleaning conditions and effective biofilm removal are needed.

It is acknowledged that the hydraulics of the system is a function of customer demands, and therefore the use of a diurnal demand profile with a temporal resolution of 15 min may not accurately represent the diurnal flow velocities and hydraulic conditions in pipes. The impact of network sectorisation on discolouration management under a finer temporal resolution of customer demand and capturing the dynamic hydraulic conditions will be the subject of a further study. In addition, the impact of DMA design parameters (e.g., location and number of boundary valves) and design objectives (e.g., leakage and/or pressure management) on water quality deterioration and the likelihood of discolouration remains a subject for further research.

CONCLUSIONS

WSNs must continuously and reliably deliver safe to drink potable water at a minimum cost. In recent years, the topology (connectivity) of WSNs has been actively modified in order to improve leakage and pressure management; however, no detailed design considerations have been given to the impact on water quality. We have investigated how the sectorisation of networks could affect water quality and discolouration. This study is done with reference to water age, particle accumulation mechanisms (gravitational and non-gravitational) and biofilm behaviour, and their dependence on the hydraulic conditions, which strongly depend on the network connectivity. Surrogate hydraulic variables and associated thresholds have been derived both from the literature and analysing the hydraulic conditions for locations with historic discolouration complaints.

Based on a large-scale case study of an operational network with 22 DMAs, the observed adverse impact of network sectorisation included: i) an increase in average water age (approximately 9 hours); ii) an increase in the number of nodes (and associated customers) which experience dead-end-like hydraulic behaviour (15%); iii) a decrease in the maximum diurnal velocity; iv) an increase in the length of pipes experiencing velocities associated with continuous sedimentation (12%) and intermittent sedimentation (6%); v) a decrease in the length of pipes experiencing self-cleaning/re-suspension velocity (18%); and vi) a decrease in the length of pipes undergoing flow reversal (10%).

This study has proposed a set of surrogate hydraulically based variables that can be used in the formulation of optimisation problems for redesigning current boundaries of sectors (DMAs). Furthermore, these variables could be used to inform novel DMA design and control methodologies, and to assess the overall water quality of a water supply system and the likelihood of discolouration.

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