Abstract

Cost-effective management of leakage has driven the sectorization of water supply networks into discrete areas that are referred to as District Metered Areas (DMAs). The resulting change in network topology has a major impact on the hydrodynamic conditions and consequently changes in water quality. This paper investigates the impact of DMAs on the potential for discoloration by analysing the spatio-temporal distribution of historic discoloration-related customer contacts for a UK water company. The results demonstrate that the sectorization of networks could have a negative effect on discoloration. A management strategy to reduce the risk of discoloration in DMA-based systems is discussed.

Keywords: Water distribution systems; District metered areas; Water quality; Discoloration risk management; Discoloration customer contact

1. Introduction

Deterioration of water quality in distribution networks is of growing concern to utilities due to ageing infrastructure, increasingly stringent regulations and the introduction of performance-based incentives. Reducing the risk of discoloration is a key performance indicator due to being directly evident to customers and linked to public health risks caused by associated microbial and chemical contaminants. Consequently, investigations into the factors contributing to discoloration are required to provide better understanding of the underlying mechanisms. Discoloration pathways can be generally classified as follows: gravitational sedimentation, non-gravitational accumulation, corrosion-related and biofilm-related. The occurrence and severity of each pathway and interaction between pathways are governed by the diurnal hydrodynamic profile and associated velocity within individual pipes.
throughout the system. The diurnal hydraulic profile is in turn a function of system design, operation and management. Changes to the topology of distribution networks imposed by the sectorization into DMAs for leakage management are likely to have a major effect on the risk of discoloration.

DMAs tend to be designed and commissioned by trial and error. The process relies upon engineering judgement which takes into account hydraulic criteria, capital and operational costs, physical restrictions and leakage policies. Water quality metrics are generally neglected due to the lack of theoretical knowledge and reliable water quality models. Empirical knowledge is then used to increase the flushing frequency in affected areas and/or to change topological connectivity. Water quality criteria are still not included in recently published methodologies for the automatic design of DMA boundaries [1, 2].

It is inevitable that such design approach would lead to a suboptimal water quality performance of DMAs. However, this potential problem has received little attention most likely because of (i) the empirically derived mitigation strategies (e.g. an increased flushing frequency); (ii) the trial and error evolution in DMA configuration to mitigate water quality issues; (iii) the availability of water quality data with sufficient temporal and spatial resolution. Consequently, the risk of water quality failures/incidents remains unknown. To our best knowledge, there have been only four studies investigating the impact of DMA sectorization on the water quality performance of distribution networks, and these are summarized as follows. Susceptibility for sedimentation and variations in water age and chlorine residual were analytically evaluated [3, 4] and it was concluded that the negative effects of DMAs are concentrated in areas that are hydraulically stagnant, namely, between kept-shut boundary valve and last customer. It was also reported that creation of DMAs causes both negative and positive impacts within the network and that the positive impacts compensate or slightly outweighs the negative impacts. More recently, the variations in water age of two networks were modelled under different designs (DMA-based and non-DMA-based) and no systematic difference was found, except for a cascading structure when the water age increased [5, 6].

This paper investigates the impact of DMA sectorization on increasing the risk of discoloration. We analyse the spatio-temporal distribution of historic discoloration events in a DMA-sectorized supply network to assess the importance of the hydraulic conditions, network topology, and DMA-induced topological changes on the risk of discoloration. The results can assist utilities in the optimal design of DMAs and the development of control strategies to reduce the risk of discoloration and water quality deterioration.

Fig. 1. Layout of the case study area
2. Methodology

The case study area (see Figure 1) is a section of an operating DMA-structured network in the UK that serves circa 42,000 people and consists of 22 DMAs. The network comprises of 12121 nodes, 9806 links (total length of approximately 345 km) and 191 permanently closed boundary valves. All the DMAs are discrete (no outflow) except one which is a long main feeding water into DMAs from the treatment works.

Discoloration-related customer contacts received from the case study area over a period of six years (2008-2013) were obtained and spatio-temporally analysed to identify the number, cause and origin of the discoloration events. To group the discoloration contacts associated with different events, three mechanisms, which are believed to generate the greater proportion of discoloration events [7], were selected. These include pipe bursts, planned works, and water treatment works issues. In this study, flushing data were the only available data of the case study area which could be used as representing planned works. In addition, the roles of water treatment works and trunk mains are combined and considered as “upstream issues” which refers to incidents that are generated upstream of the DMA inlets.

To determine the number of discoloration events associated with upstream issues, discoloration customer contacts were grouped based on their spatio-temporal specifications and the time lag between the inlet water age (diurnal average) of DMAs from which discoloration customer contacts were received. An additional condition was that the date and time of the customer contacts for the DMAs with greater inlet water age needed to be greater than the date and time of customer contacts for the DMAs with a smaller inlet water age. This removes the events where the lag between the reported discoloration contacts was less than the difference between the average inlet water age of associated DMAs. To determine the average water age at DMA inlets, a hydraulic simulation was run for a period of one month to establish the steady-state behaviour. Based on these criteria three groups of upstream events were defined:

- Customer contacts were received from different DMAs with 0-24 hours lag while the difference in inlet water age of associated DMAs was also between 0 and 24 hours (group 1)
- Customer contacts were received from different DMAs with 24-48 hours lag while the difference in inlet water age of associated DMAs was also between 24 and 48 hours (group 2)
- Customer contacts were received from different DMAs with greater than 48-hour lag while the difference in inlet water age of associated DMAs was also greater than 48 hours (group 3)

To group the discoloration customer contacts caused by systematic flushing, the following condition was imposed:

- Discoloration contacts need to be in the same DMA as that in which flushing is performed and reported within 24 hours after the time of flushing

Similar spatial correlation as for flushing was used to identify the discoloration contacts caused by the events generated by a pipe burst. However, for temporal correlation, discoloration contacts received between 24 hours before, and 24 hours after a pipe burst was assumed to be due to the pipe burst. This differs because it is assumed that it may take 0-24 hours for a pipe burst to become visible and reported to the water utility.

The remaining discoloration contacts which were not correlated with events caused by upstream issues, flushing or pipe bursts, were further grouped to identify the events originating inside DMAs irrespective of the cause of the events. Discoloration contacts received from the same DMA on the same day are considered to be due to the same
event. Individual inspection of the spatial distribution of the discoloration contacts corresponding to each event showed that discoloration events can be categorised into the following four groups:

- Single customer contact on a single pipe (type 1)
- Multiple customer contacts on a single pipe (type 2)
- Multiple customer contacts on adjacent consecutive pipes (type 3)
- Multiple customer contacts on scattered pipes within the system (type 4)

Determining the “exact” origin of discoloration events (i.e. location of material detachment/re-suspension) solely based on the customer contact data (location of detection) was infeasible given the level of perception and availability of customers to detect an event and their willingness to report it. In this study, the immediate upstream pipe which is in common between the routes supplying water to discoloration contact locations was selected as the origin of discoloration events. Thus, for discoloration event “type 1” and “type 2”, the pipe in which discoloration contacts were detected is considered as the origin of the event. For “type 3”, the most upstream pipe with a discoloration contact was considered as the origin of the event. For “type 4”, hydraulic tracing was first performed to identify the first upstream junction which is in common between supply routes of discoloration contact locations and the upstream pipe associated with this junction was considered as the origin of the discoloration event. The hydraulic conditions of the selected pipes were evaluated and from water quality modelling the extent to which these pipes were the origin of discoloration events was discussed.

To evaluate the role of DMAs in generating the observed discoloration customer contacts, the hydrodynamic conditions of the allocated pipes were modelled and compared for two different network arrangements: the original DMA-based system and a non-DMA-based system, where all boundary valves were open.

3. Results

The number of discoloration events caused by trunk mains (upstream issues) was 18, 11 and 0 for groups 1, 2 and 3, respectively. These 29 events constitute 9% of the total events in the case study area. The spatial distribution of the discoloration contacts associated with the events shows that 2 DMAs were affected by each event. Of these 29 events, 22 events caused 2 discoloration contacts each, 3 events caused 3 discoloration contacts each, 2 events caused 4 discoloration contacts each, 1 event caused 7 discoloration contacts and 1 event caused 9 discoloration contacts. In total, discoloration events due to upstream issues generated 77 customer contacts which constitute 15.2% of total customer contacts received between 2008 and 2013 (in another study [8], clustering the customer contacts showed 9% of discoloration contacts to be due to trunk mains). There were no records of any water treatment failures for the days when discoloration events occurred. Therefore, these events were all attributed to trunk main issues. Modelling the hydraulic behaviour of the trunk mains shows that these pipes operate with a maximum diurnal velocity in the range of 0.3-2.5m/s, a minimum diurnal velocity in the range of 0.07-1.1m/s, and an average water age in the range of 0-30 hours. Assessment of the hydraulic condition of the pipes where discoloration events were detected indicates that 73.1% of the customer contacts were received from the pipes that operate continuously in the sedimentation zone; i.e. maximum diurnal flow velocity is less than sedimentation threshold (0.06m/s). Of these, 43.9% was caused by the closure of DMA boundary valves. Water age analysis of these pipes shows that 82.1% of the pipes experience significantly high water age (linear increase), of which 31.9% was associated with DMA boundaries; linear increase in water age refers to the condition where water age at a node increases linearly with simulation clock.

A similar analysis was carried out to identify the discoloration events caused by valve operations of systematic flushing. Results show that implementation of flushing caused 14 events which constitute 4.3% of total events during the six years. From these 14 events, 10 events caused 1 discoloration contact each, 3 events caused 2
discoloration contacts each, and 1 event caused 6 discoloration contacts. Overall, discoloration events due to flushing generated 22 customer contacts which constitute 4.3% of total customer contacts received between 2008 and 2013. Hydraulic analysis of the pipes that were flushed (selected as the pipe on the main connected to the hydrant branch) showed that while all flushing that caused the discoloration events were performed on the pipes with maximum diurnal velocity greater than 0.25 m/s (except 2 pipes with 0.04 m/s and 0.02 m/s), 68.2% of discoloration contacts were received from pipes that undergo continuous sedimentation. Of these, 28.6% was due to DMA boundary valves. Water age analysis of the pipes where discoloration events were detected showed that 90.5% of pipes operate under significantly high water age (linear increase), of which 25% was associated with the closure of DMA boundary valves.

Occurrence of pipe bursts was the cause of 39 discoloration events which constituted 12.1% of total discoloration events observed in the case study area. Of these, 25 events caused 1 discoloration contact each, 6 events caused 2 discoloration contacts each, 1 event caused 3 discoloration contacts, 2 events caused 4 discoloration contacts each, 3 events caused 5 discoloration contacts each, 1 event caused 7 discoloration contacts, and 1 event caused 11 discoloration contacts. Overall, discoloration events due to pipe bursts generated 81 customer contacts which constituted 16% of total customer contacts received between 2008 and 2013. The spatial distribution of the pipe bursts that generated the discoloration events shows that while 25.7% of bursts occurred in pipes that undergo continuous sedimentation, 48.1% of the generated discoloration contacts were received from pipes that operate in the sedimentation zone at all times. Of these, 40.7% was attributed to DMA topology. Water age analysis shows that 70.9% of the pipes where discoloration contacts were received operate with significantly high water age (linear increase), and of these, 41% was due to the DMA structure.

Overall, trunk main issues, flushing and pipe burst caused 35.5% of the discoloration contacts received during the six year period. Spatio-temporal analysis of the remaining discoloration contacts resulted in identifying 228 discoloration events. Of these, 179 discoloration events were attributed to the “type 1”, and 49 discoloration events were attributed to the cases where each discoloration event caused multiple contacts ranging from 2 to 9. The spatial distribution of the events with multiple discoloration contacts shows that 12 events were associated with “type 2” discoloration events, 22 events associated with “type 3” discoloration events, and 15 events associated with “type 4” discoloration events.

A hydraulic analysis of the pipes associated with “type 1” discoloration events showed that 59.8% of the pipes continuously operate in the sedimentation zone and the flow velocity never exceeds the sedimentation threshold. 35.8% of the pipes experience sedimentation only during low flow conditions and 3.9% are always in the non-sedimentation region. Water age analysis also shows that 82.1% of the pipes operate under significantly low flow conditions where water age increases linearly with the simulation clock. Similarly, velocity profiles of the pipes associated with “type 2” discoloration events indicate that while all the pipes experience sedimentation at least during the low flow condition, 66.7% of the pipes undergo continuous sedimentation, and 75% of the pipes operate under linearly increasing water age. A similar hydraulic analysis was performed for pipes representing the “type 3” discoloration events and it was observed that continuous and intermittent sedimentation constitutes 40.9% and 92.3% of the pipes, respectively. 63.6% of the pipes were observed to experience a linear increase in water age. Finally, inspecting the specifications of the diurnal velocity profile of the “type 4” discoloration events reveals that only 6.7% of pipes operate with a velocity continuously lower than the re-suspension threshold, 78.3% experience sedimentation during low flow conditions and a linear increase in water age was observed in 26.7% of the pipes. Overall, in 54.8% of the pipes, the maximum diurnal velocity never exceeds the sedimentation threshold. In addition, these pipes all represent a significantly high water age (linear increase). In evaluating the role of DMAs in creating the low flow conditions and significantly high water age (linear increase) in the pipes associated with the remaining discoloration contacts, it was observed that 37.3% of low flow conditions (pipes with continuous sedimentation behaviour) and 32.5% of nodes with linear increase in water age are attributable to the DMA development. A summary of the hydraulic results is shown in Table 1. Columns 2 and 3 are associated with pipes that were identified
as representative of the origin of discoloration events and columns 4 and 5 are associated with the pipes that were identified as representative of the location of detecting the discoloration events.

Table 1. Hydraulic analysis of discoloration events

<table>
<thead>
<tr>
<th>Discoloration event type</th>
<th>Origin of event (% of pipes)</th>
<th>Detection of event (% of pipes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max diurnal velocity (&lt;= 0.06 m/s)</td>
<td>Water age (linear increase)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk main issues</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flushing</td>
<td>14.3</td>
<td>21.4</td>
</tr>
<tr>
<td>Pipe burst</td>
<td>25.7</td>
<td>50</td>
</tr>
<tr>
<td>Type 1</td>
<td>59.8</td>
<td>82.1</td>
</tr>
<tr>
<td>Type 2</td>
<td>66.7</td>
<td>75</td>
</tr>
<tr>
<td>Type 3</td>
<td>40.9</td>
<td>63.6</td>
</tr>
<tr>
<td>Type 4</td>
<td>6.7</td>
<td>26.7</td>
</tr>
</tbody>
</table>

4. Discussion

The majority of the pipes associated with events generated by trunk mains, flushing, pipe bursts and type 4, experience the diurnal re-suspension velocity threshold (maximum diurnal velocity ≥ 0.2 m/s): 100% of trunk mains operate under maximum diurnal velocity ranging from 0.3 to 2.5 m/s; 85.7% of pipes that were flushed operate under maximum diurnal velocity ranging between 0.25-1.65 m/s; 51.3% of bursts occurred on pipes that operate under maximum diurnal velocity ranging between 0.2 to 0.77 m/s; 80% of pipes associated with “type 4” discoloration events operate under maximum diurnal velocity ranging between 0.23-0.75 m/s. The majority of pipes associated with flushing and pipe bursts experience sedimentation during low flow periods (diurnal minimum velocity ≤ 0.06 m/s) but this is not problematic as experiencing the re-suspension threshold every day prevents gradual and continuous accumulation. This shows that detachment of cohesive layers is most likely the dominant mechanism in generating the discoloration events. The maximum diurnal velocity is the determining factor in the conditioning (strength) of accumulated materials [9]. Thus, these pipes are expected to accumulate strongly-adhered layers which resist detachment. However, the occurrence of discoloration is also a function of the magnitude of the disturbing force (the difference between conditioning and disturbing shear forces) [10] and the cumulative amount of detachments in all the pipes affected by the force. Thus, for proactive management of discoloration risk control rules should be formulated such that the length of pipes experiencing the cleaning condition is maximised, including those with high maximum diurnal velocity (distribution mains and trunk mains).

Irrespective of the cause and origin of the events, a significant proportion of the discoloration contacts are related to the pipes that operate under low flow conditions (V_{max} ≤ 0.06 m/s). This can be explained as follows. Firstly, such hydraulic conditions increase the likelihood of detection of an event irrespective of where the event has started and accumulated materials are re-suspended. Given the availability of customers as an essential factor in discoloration detection, low flow condition increases the residence time through pipes, and consequently the risk of detection by customers before materials settle in the bottom of the pipes. The strategic location of these pipes is also an important factor in increasing the probability of detection. A great proportion of the pipes with low flow condition are associated with the naturally-created or DMA-induced dead ends. Thus, sediments that are re-suspended upstream and carried with the bulk water into these pipes will remain in the pipes until it is discharged through customer taps (where discoloration is detected if the concentration reaches a certain limit) or through hydrants by timely flushing. In this study, 73.1% of the events that originated outside of DMAs (owing to trunk main issues) were detected in the downstream pipes with low flow conditions within the DMAs. Flushing data shows that 70% of the discoloration contacts associated with flushing the pipes with high maximum diurnal velocity (distribution mains) were received from low flow pipes (dead ends). The percentages for pipe burst and “type 4” discoloration events were 39.6% and 50%, respectively. Given the short lag between the disturbing hydraulic event and associated discoloration contacts, and the travel time between the locations of disturbance and detection, it is unlikely that re-suspended materials due to upstream event are able to settle in the low flow pipes and re-suspend again due to local disturbing condition. Instead, re-suspended materials are directly detected by the customers on low flow pipes before settlement occurs.
Secondly, in addition to continuously storing the sediment load, low flow pipes can increase the concentration of particles through different mechanisms. These pipes were observed to operate under significantly high water age and consequently very low or absence of disinfectant residuals. This increases the release of iron from tubercles [11] which can be an important mechanism affecting the risk of incidents given the high residence time and possible flow stagnation during night times. It also induces biofilm development which is known to be a source of turbidity when biofilms detach [12]. In addition, biofilms grown under low flows are known to be less cohesive [13, 14] and consequently readily detach under hydrodynamic forces. Another important factor is the impact of the pipe properties and condition. Both iron release and biofilm development can be exacerbated in old metallic pipes due to corrosion and tubercle formation. In this study, low flow pipes associated with the locations of detection were observed to be mostly made of metal pipes (92.7%) with a length-weighted average age of 77 years. These pipes are expected to have undergone significant tuberculaton. Thus, for “type 1”, “type 2” and “type 3” discoloration events it is reasonable to assume that a significant proportion of the events are generated locally (re-suspension of sediments). In addition, given the dilution and propagation impact of the junctions, as we move upstream from the point of detection the chances of an upstream pipe being the origin of the discoloration event decreases. Given the number of properties on the dead end pipes, and level of customer demand in the calibrated model of the area, it is unlikely that the aggregation of local customer demands is sufficient to generate the disturbing re-suspension velocity (greater than, or equal to, 0.2m/s). This could imply the importance of high flow events caused by pressure transients that originate upstream, where their effect propagates through the system reaching the dead end pipes. This can generate the required disturbance for re-suspension. Unsteady flow events occur frequently in WDSs [15].

Hydraulic tracing of discoloration contacts associated with two of the “type 4” discoloration events (each caused 3 discoloration contacts) converged approximately at DMA inlet. This can be an indication of the events were due to upstream issues (trunk main) and were not detected in other DMAs or due to PRV oscillation or pump start-up/shut down in response to increase/decrease in demand. The impact of pressure transient on the rate of material detachment requires further investigation.

The spatial distribution of the low flow pipes associated with discoloration contacts shows that these pipes are mostly located in the dead-ends which are created due to the natural topology of the system or due to the closure of DMA boundary valves. Overall, throughout the case study area, 57.3% of pipes, where discoloration events were detected, are associated with those that continuously operate in a low-flow, sedimentation zone. Of these, 38.5% were due to DMA boundary valves. Analysis of water age shows that 77.4% of pipes, where detection occurred, operate with significantly high water age (linearly increase), where 33.1% was due to closure of DMA boundary valves. More than a third of problematic areas can be attributed to the DMA structure. This indicates the important impacts that DMA design and location of permanently closed boundary valves can have on water quality incident management. It is noted that this study was only focused on the impact of DMAs on areas with historic water quality issues. Variation in the risk of water quality failure imposed by DMAs at the system level needs further investigation.

Currently, water utilities deal with discoloration risk by minimising the sediment load into WDSs, replacement and relining of metal pipes, and implementation of flushing. Although these approaches have been successful in reducing the risk, occurrence of discoloration events still persists. An alternative approach can be to develop a control framework to enhance the in-situ/self- cleaning of pipelines. This can be achieved by formulating the rules to regulate: the attachment and detachment of cohesive layers, the settlement and re-suspension of sediments, and iron uptake from pipe wall and tubercles. Based on the results of this study such controls should also involve:

- Minimising the number of dead ends
- Minimising the number of pipes with low flow conditions and significantly high water age (linearly increasing)
Maximising the number of pipes experiencing in-situ/self-cleaning

In DMA-based systems, regular flushing and installation of washouts are two measures used to manage the deteriorating impact of low flow conditions in the dead ends created by DMA boundary valves. As recommended previously for the design of DMAs [3, 16, 17], mains larger than 300mm (so called trunk mains) should be excluded from the list of candidates for closure to avoid low flow conditions. However, it was observed in this study that creating dead-ends on smaller diameter pipes is also problematic and timely cleaning of dead-ends is emphasised. Determining an optimum cleaning frequency is a difficult task. The occurrence and severity of a discoloration event at a particular time and location is a complex function of: the magnitude of the force applied during prior cleaning, the steady-state diurnal flow profile between cleaning and disturbing conditions, the magnitude of the disturbing force, the pipe material and age, and the length of pipes affected by the disturbing force. This is further complicated when taking the uncertainties associated with unsteady flows (e.g. pressure transients), customer behaviour (e.g. demand), asset failure (e.g. pipe burst, pump/valve malfunctioning), asset condition (actual pipe diameter) and operational activities of the utilities (valve movement) into account. Increasing the frequency of proactive flushing can minimise the aforementioned uncertainties and the risk of discoloration. However, this is unappealing to water utilities as it wastes water, is labour intensive and environmentally unfriendly. In addition, the disadvantage of dead ends as the locations with an increased likelihood of customer detection (due to low flow conditions) still exists.

Alternatively, DMA boundary valves can be exploited to regulate the cleaning of pipelines and eliminate the dead ends. Maintaining the integrity of DMAs for leakage management is only essential for a few hours a day. For the rest of the day these valves can be open to integrate the DMAs and eliminate the DMA-induced dead ends. Furthermore, by developing a valve-scheduling optimisation scheme, these valves can be further exploited to minimise the deteriorating hydraulic conditions within the system and enhance the conditioning and cleaning of pipelines as discussed earlier. Such a management strategy was proposed by [18] to enhance leakage management. It can be extended to include water quality criteria to reduce the risk of discoloration.

5. Conclusion

The development of a control framework to minimize the risk of discoloration and achieve proactive and timely cleaning of pipelines is of interest to water utilities. Formulating the control rules requires identifying the impact of network topology and hydrodynamic conditions on the generation of discoloration events. This paper has investigated the cause and origin of discoloration events and the impact of a DMA structure (closure of boundary valves) on the risk of discoloration. Using a particular case study area, the hydrodynamic conditions and vulnerable sections of the network topology that increase the likelihood of creating, and/or detecting, discoloration events were identified. In addition, the role of operational activities and asset failures in generating discoloration events were clearly evident. Specific conclusions from this study are as follows:

• Clustering discoloration customer contacts indicated that trunk mains, flushing and pipe bursts were the cause of approximately 35% of discoloration events.

• Trunk mains and distribution mains operating with maximum diurnal velocity greater than 0.2m/s caused a proportion of discoloration events. This highlights the role of non-gravitational accumulation on the pipe wall in generating discoloration events. Conditioning/cleaning of these pipes needs to be included in the control rules for minimizing the risk of discoloration.

• Low-flow pipes significantly increase the risk of discoloration events and the likelihood of discoloration event detection. Elimination of such hydraulic condition needs to be included in the control rules.

• Irrespective of the origin and cause of discoloration events, discoloration contacts are mostly attributed to the pipes that operate continuously in the sedimentation zone with significantly high water age. This is the hydraulic
condition which is predominant at dead-end pipes. Thus, minimizing the number of dead-ends or the occurrence of dead-end-like hydraulic behavior within the system needs to be taken into account in formulating the controls.

- More than a third of locations where discoloration events were detected are associated with a DMA network structure (closure of boundary valves). The significant increase in the number of dead-ends due to DMAs needs to be taken into account in designing DMAs and developing controls for discoloration management.

References