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Rehabilitation Actions in Water Supply Systems: Effects on Biofilm Susceptibility

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Abstract

Biofilm development in water supply systems (WSSs) depends on infrastructure and operational factors, apart from water quality. We have developed a methodology that considers WSSs hydraulic (operation) and physical (design) characteristics to identify areas with different biofilm development trends within a WSS. To achieve this aim we have used meta-analysis and multi-agent system label propagation via discriminant analysis. As a result, we recognise areas with different susceptibility to biofilm development in a given WSS, and observe how modifications in the infrastructure affect the distribution and extent of these areas.

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Keywords: biofilm; drinking water distribution system; data mining; multi-agent systems, rehabilitation

1. Introduction

In the last years, various aspects have led to focus the interest in improving the protection and control of drinking water quality on distribution, after treatment. It is known that the design of the distribution systems inevitably causes water quality decay. However, most of the times, the system design, by itself, does not explain the extent of this decay. The reasons for high deterioration of water quality in distribution systems are not entirely clear, but it is known that one of the main actors involved in this decline is biofilm development in the inner pipe walls. Biofilm is a complex structure of microorganisms' communities that develops in the presence of water, adhered to surfaces and coated by a protective layer segregated by them. Thus, biofilm's bacteria are capable of withstanding biocides and antibiotics more

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effectively than free-living bacteria, supporting significantly higher doses of antimicrobial. In addition to the fact that the presence of biofilm poses a constant threat to health [1], biofilm brings in additional costs. It has an impact on energy requirements of a system, cause corrosion, and increase frictional drag.

The developed countries are facing formidable challenges in meeting the rising demands of potable water quality while avoiding costs increasing. People's health and welfare are closely connected to the availability of adequate, safe and affordable water supplies. As a result, water service managers try to increasingly produce and provide their consumers with water of higher quality while using cost-effective methods. Currently, the efforts to mitigate biofilm development in water supply systems (WSSs) are almost exclusively focused on aspects related to water quality. In order to minimize the subsequent bacterial growth, many resources, both human and material, are devoted in the water treatment stage. However, although these measures are necessary, we think that if attention is also paid to the other aspects such as the hydraulic (operation) and physical (design) aspects of the WSSs, which are also known to affect biofilm development in WSSs, the efficiency of the invested effort will increase.

Distribution systems are the major components of water utilities. Numerous processes and physical, chemical and biological reactions take place along time inside [2]. The complex and diverse environments inside the pipes create heterogeneous habitats in WSSs making biofilm exist at different levels within a distribution system. Survival and regrowth of microorganisms in these systems is affected not only by biological factors but also by the interaction of other various factors [3]. The aspects that influence biofilm development in WSSs are manifold. Numerous researches have studied the influence that the different characteristics of WSSs has on biofilm development [4, 5]. Yet, due to the complexity of the environment and the community under study, most studies about biofilm ecology in WSSs are focused on just one or two aspects. This paper tries to fill this gap by studying the joint effect that all the relevant physical and hydraulic characteristics of WSSs have on biofilm development to detect the more susceptible areas to biofilm development in WSSs. We aim to detect the most influential pipes of these hot spots to study how just the replacement of these specific pipes could reduce the susceptibility of the whole area. In this work we resort to data mining techniques and multi-agent systems to achieve our aims. We claim that this kind of approaches are the next step that have to be made in WSS management in order to mitigate the decline of water quality in distribution systems while trying to save resources and reduce costs.

The present work is divided into the following sections. In section 2 we explain the methodology carried out in this paper. In section 3 we apply this methodology to a case study, and the obtained results after the obtained replacement actions are discussed. Finally, we close the paper with some conclusions and recommendations.

2. Assessing biofilm susceptibility areas

Most researches that study biofilm development in WSSs focus just on one aspect related to biofilm development due to the complex environment and community under study. So, the influence of the whole environment is not taken into account. In order to prepare a case-study database of biofilm development in WSSs with different hydraulic and physical characteristics, data were compiled from experts and pre-processed to generate a complete and extensive database. Among other difficulties, we had to manage heterogeneity in data measurements, multi-scalarity, important degree of missing data, and differing encodings. Thus, the data was pre-processed to generate a complete database. Finally, the continuous variables were discretized to normalize the database. This resulted in a database of 210 complete cases. The variables of the database (Table 1) were all found relevant to biofilm development in WSSs when individually studied by various researchers.

Table 1. Variables and categories of the database

Biofilm (HPC/cm2)	High [$\geq 10^7$]	Medium [10^4-10^6]	Low [0-10^3]
Pipe material	Metallic	Cement	Plastic
Pipe age (years)	High [≥31]	Medium [11-30]	Low [0-10]
Velocity (m/s)	High [1.8-3.5]	Medium [0.8-1.7]	Low [0-0.7]
Hydraulic regime	Laminar	Turbulent	-

2.1. Label propagation via discriminant analysis

In order to delimit the areas of biofilm susceptibility in a WSS we carried out a clustering analysis applying the farthest-first traversal algorithm [6,7] to the obtained database. The desired number of clusters was specified before the analysis. We chose three clusters, because it is a suitable number for the network size, and also because the variable of interest (biofilm) is also divided into three categories: low, medium, and high. We observe that the medoid of each cluster corresponds coincidentally with each of the states defined for biofilm development (Table 2).

Table 2. Medoids of the clusters obtained after the application of the farthest-first traversal algorithm to the created biofilm development database

Medoids	H. regime	F. velocity	P. material	P. age	Biofilm
Cluster 0	Turbulent	Low	Plastic	Young	Low
Cluster 1	Turbulent	Medium	Cement	Medium	Medium
Cluster 2	Turbulent	High	Metal	Old	High

Then, a label negotiation was carried out in a practical case-study, assigning a cluster to each pipe. Thus, the pipes of a given WSS are classified depending on the similarities of the constructed database. Once the WSS pipes have been classified by the aforementioned discriminant analysis, an agent-based method is launched. It complements the discriminant analysis dividing the WSS into, as much as possible, homogenous areas with the aim of making a future sectorization, which could help WSS management. In this way, pipe classification is improved by negotiation. Pipe properties are inherited by the nodes, and node membership to the clusters are renegotiated [8,9]. In this case, the agent based propagation was carried using the NetLogo 4.1.3 software [10], following the algorithm described in Table 3.

Table 3. Agent-based propagation algorithm

Algorithm: agent-based propagation
1. Discriminant analysis based on theoretical database clustering
2. Membership negotiation
2.1. Facilitate sharing the same label by neighbouring pipes such that:
- have more similar velocity than the average of their current cluster
- have more similar water age than the average of their cluster
- have more similar pipe age than the average of their cluster
2.2. Facilitate sharing the same label by neighbouring pipes such that:
- have more similar pipe material than their neighbouring pipes
3. If there are not changes in last iteration then stop. Otherwise 2

Considering the discrete nature of the data the similarity was calculated using a weighted Manhattan distance, and dummy coding encryption was used in the case of nominal variables. Thus, this process can be understood as a label propagation method. The agent-based model performs a mixture of individual and collective actions. It can explore good network sectorisation layouts by trying to meet the equation

$$\sum_{i=1}^{n}\sum_{c=1}^{C}\left[a_v\left(v_i-\overline{v}_c\right)+a_w\left(w_i-\overline{w}_c\right)+a_p\left(p_i-\overline{p}_c\right)+a_m\left(m_i-\overline{m}_c\right)\right] \quad (1)$$

where n is the number of pipes of the WSS, C the total number of clusters and the a's are the associated weights to velocity (v), wage –water age– (w), page –pipe age– (p), and material (m); finally, $\bar{v}_c$, $\bar{w}_c$, $\bar{p}_c$ are the respectively averages by cluster and $\bar{m}_c$ the median for the discrete variable material. The model is validated by the corresponding stabilization of this value that we attempt to minimize.

When we extend our point of view from a pipe to a network, the spatial distribution of the pipes can be influential. In WSSs the older the water, the greater the residual disinfectant decay [11]. That is why the variable water age has been introduced as a correction factor in the calculation of membership in the negotiation, resorting to the shortest paths (km) between each node and each water inlet.

2.2. Replacement criteria

To find the key pipes to replace in order to minimize the area of the WSS susceptible to high biofilm development we identified the pipes that were found to exhibit high biofilm development in both, the discriminant analysis and label propagation. After that, according to the results of the clustering and the bibliography, we selected the metal pipes which are known to tend to support more biofilm development [12]. Among them, the older pipes were selected, obtaining the pipes susceptible to be replaced. The accumulation of corrosion and dissolved substances in older pipes can increase their roughness and a rough surface has greater potential for biofilm growth [13]. The replaced pipes would be substituted by new plastic pipes that, as found in the clustering process and in the bibliography, are the ones less susceptible to present biofilm development.

3. Case study

The Example 3 of Epanet 2.0 [14] has been chosen as a given WSS where apply the methodology explained above. The material and age of the pipes were randomly assigned. The model was run in steady-state conditions to know the hydraulic regime and flow velocity. Once the network and the medoids were ready, discriminant analysis and label propagation were applied (Fig. 1).

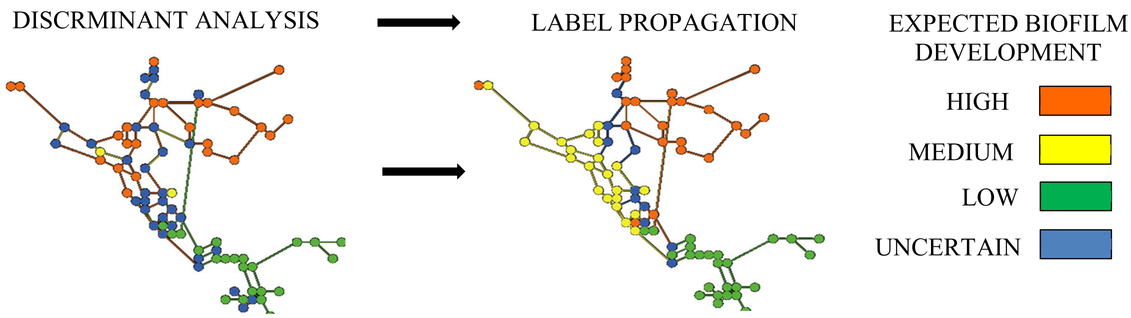

Fig. 1. Results of the discriminant analysis via label propagation

After the label propagation, an area with high susceptibility to biofilm development is observed in the North-West zone of the network. We focus on this area and look for the pipes that were found to present high biofilm development in the discriminant analysis. Then we select the metallic ones that meet this requirement. Finally, we obtain 9 pipes susceptible to be replaced (Fig. 2).

With the aim to try to save resources, we have decided to start studying the variations in the area susceptible to high biofilm development replacing first the shortest pipe (Fig. 2) and adding pipes, one by one, since arriving to the longest one (Fig. 3).

The results (Fig. 3 and Fig. 4) show that as the pipes are replaced the number of pipes susceptible to support high biofilm development decreases. However, it is observed that after the fourth replacement a stabilization in the number of pipes susceptible to high biofilm development occurs. In the last replacements (8^{th} and 9^{th}) a reduction in the number of pipes is observed again. This suggests that the replacement of some pipes is more influential than the replacement of others. Certainly, the spatial position in the network of pipes has an important role.

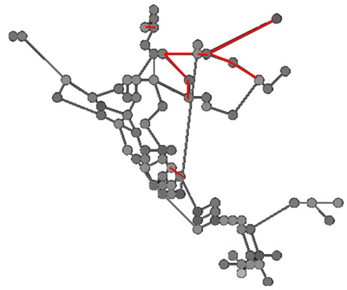

Fig. 2. Pipes susceptible to be replaced.

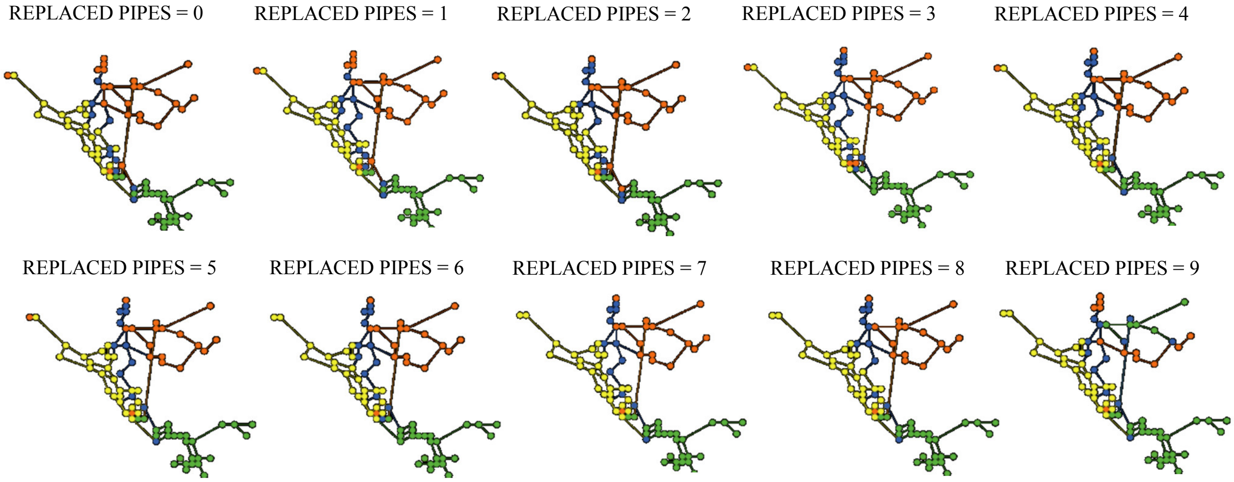

Fig. 3. Biofilm susceptibility after progressive pipe replacement

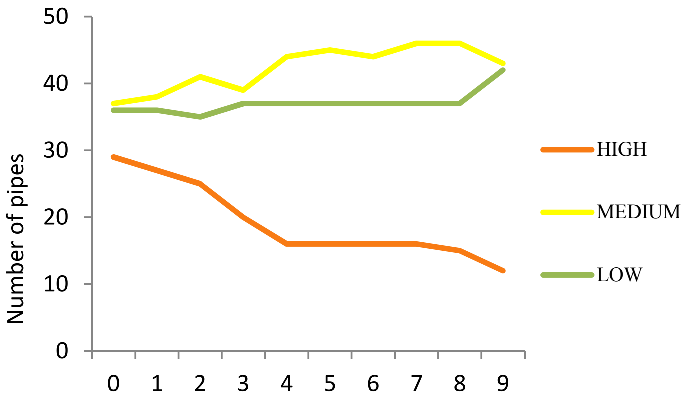

Fig. 4. Evolution of biofilm susceptibility when replacing pipes

Although the replacement criteria implemented in this paper are just an approach, in the studied network the incidence of pipes susceptible to support high biofilm development has been reduced from 25% to 10% (Fig. 5). As a result, the risk of developing high biofilm development has decreased.

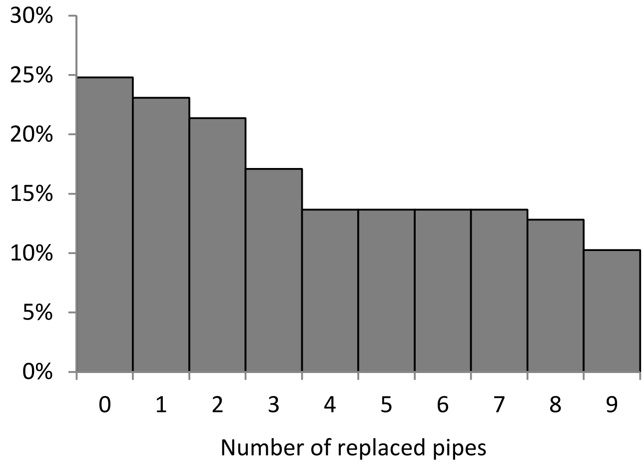

Fig. 5. High biofilm incidence proportion after progressive pipe replacement

4. Conclusions and recommendations

This paper provides an overview of an innovative work, offering a new perspective on the study of biofilm development in WSSs. An approach to use in a practical and efficient way the level of knowledge gained on the development of biofilm in WSSs is carried out.

On one hand, the combined effect of a number of physical and hydraulic characteristics of WSSs on biofilm is studied in order to identify the varying development of biofilm inside the pipes within a WSS. On the other, a new methodology is developed where data mining techniques and multi-agent systems are integrated in order to assess the susceptibility to biofilm development of homogeneous groups of pipes where various characteristics in relation to biofilm development can be described.

Finally, the effect of pipe replacement is studied in order to observe the influence on the susceptibility of WSSs to biofilm development. An example of replacement criteria is applied and a reduction from the 25% to the 10% in the incidence of high biofilm development has been observed. However, this is just an approach and much more work must be done in this area, in order to optimize as much as possible the invested resources and the obtained benefits. The results obtained in this work suggest that the replacement of some pipes is more influential than the replacement of others, probably due to their spatial position in the network. The importance of this characteristic must be more deeply studied.

In summary, this paper analyses the effect that rehabilitation actions in a WSS would have on biofilm development trends and how helpful they could be to reduce the susceptibility of a WSS to biofilm development. Although more work has to be done in this direction, we claim that this kind of new approaches could represent a clear improvement in the future of WSSs' management.

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