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EFFECT OF REGULATIONS AND TREATMENT TECHNOLOGIES ON WATER DISTRIBUTION INFRASTRUCTURE

Syed A. Imran¹, Rehan Sadiq² and Yehuda Kleiner³

Abstract - Changes in regulations on source-water withdrawals, new treatment techniques and maximum contaminant levels require drinking water utilities to constantly change, upgrade or altogether replace their historic water sources and treatment practices. Change in treatment techniques to reduce or eliminate any contaminant of concern invariably leads to changes in the water quality. These changes may trigger a cycle of changes; some of which can negatively impact the distribution system. Therefore, it is necessary that while evaluating different treatment strategies, the anticipated impacts on the existing distribution infrastructure are given due consideration. This paper summarizes the results of a recently concluded project co-funded by the American Water Works Association Research Foundation (AwwaRF) and the National Research Council Canada (NRC). The main objective of this research was to identify ‘research needs’ for evaluating water potential quality impacts on distribution infrastructure integrity.

Keywords: Drinking water, water distribution systems, water treatment, water quality, infrastructure, research needs

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BACKGROUND

Water utilities must provide safe drinking water to consumers in acceptable quantity and quality. Changes in regulatory restrictions on source-water withdrawals, treatment techniques and maximum contaminant levels (MCLs) require utilities to constantly change, upgrade or altogether replace their historic water sources and treatment practices. Strategies to comply with state/province and national regulations on the drinking water quality and quantity ultimately lead to changes in the chemistry (quality) of the water that comes in contact with the distribution networks (Imran *et al.* 2005). Though there is a general awareness that these changes might adversely impact the distribution infrastructure, utilities have historically taken a myopic outlook on protection of distribution infrastructure due to impacts of water quality.

In this paper, ‘integrity’ of distribution infrastructure is defined as its ability to transport water in acceptable quantity and quality without causing any ‘structural’ or ‘functional’ failure of its components. Most water quality failures observed in distribution system are often coupled with the long-term deterioration of the distribution infrastructure. For instance, finished water introduced into the distribution system may cause metallic corrosion and lead to red water problems at the consumers tap. From a public water system (PWS) point of view, a water quality change (e.g., increase in color) is often the first indication that the integrity of the distribution system is being compromised in some way. A PWS may conduct further investigations to ascertain the cause of water quality deterioration.

Though the ‘structural’ integrity of the system may be intact, the ‘functional’ integrity could be compromised because of the failure of the distribution system to avoid deterioration of the transmitted water. In actual PWS experience, this functional failure may persist for years before

leading to actual structural failure. For instance, water quality problems related to distribution system such as red water, loss of residual and subsequent microbiological proliferation may persist for years before actual failure of the pipe. Thus the water quality at the consumers tap can be used as an indicator of the ‘health’ of the distribution infrastructure. Since distribution infrastructure is essentially a buried structure, this indirect evidence is often used to measure the impact of finished water quality on its integrity.

PWSs have traditionally taken a long-term approach to maintaining and rehabilitating the distribution infrastructure when compared with the short-term urgency of water quality deterioration. Measures such as distribution system flushing and shock (or booster) chlorination may provide short-term relief without solving the underlying long-term problems related to deterioration of distribution components.

Compromise on the integrity of water distribution infrastructure can be caused by a number of water quality deterioration mechanisms including internal corrosion, leaching, contaminant intrusion, microbial regrowth and permeation of organic compounds through system components. Failure at the distribution level can be critical because it is closest to the point of use and there are virtually no safety barriers before consumption. PWSs must manage the source-waters, treatment processes and distribution infrastructure holistically in order to maintain the quality at the consumers tap.

This paper summarizes the results of a recently concluded project, co-funded by the American Water Works Association Research Foundation (AwwaRF) and the National Research Council Canada (NRC). The main objective of this research was to identify research needs for evaluating water quality impacts on distribution infrastructure integrity (Sadiq *et al.* 2007). This

was achieved by identifying missing links in the complex interrelation among water quality regulations, which drive new treatment technologies, which result in primary and secondary impacts on water quality in distribution system, and which ultimately affect the distribution infrastructure integrity.

USEPA Drinking Water Regulations

PWSs are under tremendous pressure to meet national and state regulations/ guidelines for maintaining maximum contaminant levels (MCLs) in the distribution system, in order to provide consumers with safe drinking water. The United States Environmental Protection Agency (USEPA) established national drinking water regulations in the US, under the Safe Drinking Water Act (SDWA) of 1974. Currently 91 contaminants are regulated by establishing MCLs in the treated water before introduction into the distribution system (Pontius 2004).

Traditionally, utilities have managed the mandated compliance levels by upgrading and optimizing their treatment processes or by changing source-waters (Daniel 1998, Taylor *et al.* 2005). As knowledge and understanding of the impacts of water quality on human health are advancing, USEPA's regulations are becoming increasingly complex and stringent.

Promulgations of the Disinfectant/Disinfection Byproduct Rules (D/DBPRs), Surface Water Treatment Rules (SWTRs), Groundwater Rule (GWR), Total Coliform Rule (TCR), and Lead and Copper Rule (LCR) indicate that the USEPA increasingly favors a 'managed approach' to drinking water safety over an MCL at the distribution 'point of entry approach'. However, despite evidence that distribution system deficiencies are among the major causes leading to waterborne outbreaks, a comprehensive regulatory approach to distribution integrity has not been attempted.

Any ‘managed approach’ that attempts at controlling contaminants (including pathogens) is as good as the state of the distribution system. Even complete compliance with all the regulations does not guarantee safe drinking water unless the distribution infrastructure is in acceptable condition. It is expected that continuing revisions to the TCR and the proposed Distribution System Rule will address some of the issues arising due to deterioration of distribution systems.

It is noted that depending on their size and water source, PWS may not have to comply with all the drinking water regulations. Most regulations are limited to PWSs of particular size and source. Therefore, where an effort has been made to include all the relevant drinking water regulations, water purveyors should determine the regulations applicable to them based on their size and water source (Sadiq *et al.* 2007).

Water Treatment Technologies

Regulatory compliance with drinking water standards can be achieved by using alternate water sources, treatment chemicals and/or treatment technologies. A survey of 200 PWSs in the US indicated that 50% of the systems anticipated changes in their treatment practices to meet future regulations (AWWA 2000). These changes in treatment practices could be as simple as controlling pH or could comprise a complete overhaul of existing water treatment facilities.

The selection of a particular technology for drinking water treatment is governed largely by the PWSs consideration of a number of constraints in addition to the requirement to provide safe drinking water. Sometimes the best technology for a particular source-water or regulated contaminant may not be feasible due to other considerations. These considerations may include state and national or environmental restrictions on the plant-siting, limitations on withdrawals

from a desirable source, restrictions on disposal of process wastes, logistic requirements of monitoring, operation and maintenance, future capacity development and cost of construction (Pontius 2003b).

The USEPA provides some of this information to small systems under the 1996 SDWA Amendments authorization through Small Systems Compliance Technology Lists. Under this authorization, the USEPA is required to provide technical and economic guidance to PWSs for compliance with the MCL for each regulated contaminant. To achieve this, the USEPA identifies certain treatment technologies that have demonstrated efficient and economic removal of regulated contaminants. These economically achievable technologies for regulated contaminants are known as ‘best available technologies’ (BATs).

The BATs are known to work for particular contaminants in some source waters if designed and operated properly. However, due to diverse source-waters and their treatment requirements, system operators often have to use their own judgment in the use of the BATs. Though the BATs identified by the USEPA may not always be the best solution to specific conditions, they provide useful baselines for the acceptability of available and future treatment technologies. Use of BATs provides (in some cases) a body of evidence that adequate contaminant mitigation measures are being carried out by the PWS. However, the ultimate criterion for the acceptance of any treatment process is a demonstrated removal of a specific contaminant below the MCL. For water treatment technologies that are not identified by the USEPA as BAT for a specific contaminant, utilities must demonstrate the efficacy of their chosen process through pilot studies (Pontius 2003a).

An AwwaRF study on balancing multiple water quality objectives identified the various constraints governing feasible treatment alternatives including water quality, regulatory, economic and operational (Daniel 1998). A similar framework can be constructed for the regulatory restrictions on the use of treatment technologies and water quality requirements, as shown in Figure 1. It should be noted that water quality requirements are sometimes conflicting and therefore require a finely tuned balanced approach (Imran *et al.* 2006).

Distribution Infrastructure Impacts

The deterioration of drinking water distribution infrastructure is among the main causes of the loss of quality and quantity of water at the consumers tap. However, since a major portion of the distribution infrastructure is underground, its deterioration does not present the same visual urgency as other visible infrastructure. Since deterioration of the distribution infrastructure adversely impacts the water quality, PWSs must not invest costs and efforts to treat water to potable levels and then transmit it through deteriorating distribution system. Some of the most critical water quality issues related to water distribution infrastructure deterioration were highlighted in a series of white papers produced by the USEPA, AWWA (American Water Works Association) and AWWSC (American Water Works Service Company). These white papers underline the importance of pro-active management of distribution systems to maintain water quality at an acceptable level (Scharfenaker 2002).

Distribution components could be of different materials including cast iron, ductile iron, steel, copper, lead, galvanized steel, reinforced concrete, asbestos cement, thermoplastics including polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), high density polyethylene (HDPE), polybutadiene and composites such as glass fibre-reinforced plastic

(GFRP). In addition to the pipes and mains, there are a number of ancillary materials like coatings, gaskets, o-rings, fittings, valves and solders. Additional variability is introduced by the presence of man-made (cement, epoxy, polymeric, or calcite lining) as well as naturally occurring films (corrosion byproducts and biofilms) on the interior of the pipe (Broo *et al.* 2001; Kirmeyer *et al.* 1994; Tombouliau *et al.* 2004).

The problem of identifying the impacts of water quality on a complex system can be simplified by evaluating the most common repeating sub-system or system component. For the purpose of evaluating the impact of water quality on the integrity of distribution infrastructure, the most common denominator is the material of construction. Though the distribution infrastructure is composed of different components fulfilling different functions, they are constructed using an exhaustive list of materials. The choice of materials in drinking water applications is determined by the health and aesthetic concerns as well as economic considerations of procurement, installation, operation and maintenance (Broo *et al.* 2001).

Depending on the material make-up of infrastructure components, they can be divided into three broad groups - metallic, polymeric or cement-based, each with its dominant deterioration processes; (physico-chemical based) internal corrosion, microbiologically induced corrosion (MIC) and leaching of material. Though a specific material may have a predominant mechanism of deterioration, all three processes play a significant role towards its overall deterioration (Table 1).

Physico-chemical based internal corrosion (from this point onwards referred to as ‘corrosion’) is defined as ‘metallurgy in reverse’, where a purified metal or its alloy interacts with the environment to return to its original more thermodynamic stable state. Three conditions

are required in order for corrosion to proceed; a metallic surface that will corrode, an oxidant that will oxidize (corrode) the metal to a more stable state and lastly, a medium that will transport the oxidant to the metal and facilitate further corrosion by moving the corrosion byproducts away from the corrosion site. All these components are present in a typical water distribution system. A water distribution system may corrode both internally and externally. However, external corrosion is only indirectly related to the water quality issues (for instance, by promoting corrosion holes that are susceptible to contaminant intrusion) and therefore is not discussed here.

Microbiologically induced corrosion (MIC) is different from other deterioration processes because it is caused by the biological activities of microorganisms. While some researchers suspect that biofilms (colonies of native microorganisms on the water/ metal interface) inhibit deterioration by providing a protective coating, others have reported biofilm as exacerbating deterioration. The presence and structure of these biofilms is related to hydraulic conditions, nutrient availability, type and concentration of residual disinfectant and the roughness of the pipe surface. Many researchers have reported that pipe material seems to have a significant effect on microbial inactivation by different disinfectants (Gagnon *et al.* 2005).

Leaching is typically defined as the release of material to water without involving corrosion processes. It can take the form of dissolution of the metal-bearing corrosion scales, monomers from plastics, or calcium from the cement-matrix.

HIERARCHICAL RELATIONAL MODEL (HRM)

This section introduces a conceptual framework, called, hierarchical relational model (HRM) that can pro-actively identify problems related to loss of integrity of distribution system that is associated with changing water quality for regulatory compliance (Sadiq *et al.* 2007). The HRM

provides a method to map various factors in a matrix form and use relational matrix in succession, while eliminating the common link at each step (Figure 2). The resultant matrix will be an ‘effect matrix’ that directly relates drinking water regulations to their impact on distribution system materials. In this section only basic formulation is provided and interested readers should refer to Sadiq *et al.* (2007) for details.

In Figure 2, “ $\otimes$ ” sign represents any composition operation, details can be found in Sadiq *et al.* (2003). The advantage of opting for this procedure is that experts in different domains/fields can provide their inputs to different relational matrices depending on their expertise. Also research needs can be identified easily by studying gaps in the ‘effect matrix’.

The relational matrix $[\alpha_{ij}]$ relates the effectiveness of common unit treatment processes towards compliance with drinking water regulations. The element α_{ij} is a measure of the effectiveness of unit treatment ‘ j ’ (UT_j) for the compliance with drinking water regulation ‘ i ’ (Reg_i). Based on a comprehensive literature review, Table 2 provides the effectiveness of selected treatment processes on the removal of regulated contaminants (it is emphasized that the relational matrices proposed in this research are ‘suggestive’ and require more research). The effectiveness estimate is a number between +1 and –1. A value of +1 indicates the most suitable technology to remove the selected contaminant, while –1 indicates the technology that might have an adverse effect on removing the selected contaminant. A value of 0 is given for the technology that has no known effect on the removal of the selected contaminant.

$$[\alpha_{ij}] = \begin{pmatrix} & UT_1 & UT_2 & \cdots & UT_J \\ \hline Reg_1 & \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1J} \\ Reg_2 & \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2J} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ Reg_I & \alpha_{I1} & \alpha_{I2} & \cdots & \alpha_{IJ} \end{pmatrix}; \text{ where } i = 1, 2, \dots, I \quad j = 1, 2, \dots, J \quad (1)$$

The matrix $[\beta_{jk}]$ relates the effect of unit technology (UT_j) on increase or decrease in selected water quality parameter (WQP_k). Primary water quality changes as well as secondary water quality impacts were evaluated for each specific treatment technology identified in Table 3. For instance, the primary impact of ion exchange is the removal of targeted ions from water and the secondary impact is the removal of non-targeted ions and the addition of counter-ions to the water. Secondary changes induced by the treatment technologies are dose-specific. For instance, depending on the source water quality, different concentration of treatment chemicals need to be added and thereby result in different concentrations of secondary ions in the finished water.

$$[\beta_{jk}] = \left(\begin{array}{c|cccc} & WQP_1 & WQP_2 & \cdots & WQP_K \\ \hline UT_1 & \beta_{11} & \beta_{12} & \cdots & \beta_{1K} \\ UT_2 & \beta_{21} & \beta_{22} & \cdots & \beta_{2K} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ UT_J & \beta_{J1} & \beta_{J2} & \cdots & \beta_{JK} \end{array} \right); \text{ where } j=1, 2, \dots, J \quad k=1, 2, \dots, K \quad (2)$$

A relational matrix $[\gamma_{kl}]$ relates the effect of change in selected water-quality parameters (WQP_k) on the deterioration of selected distribution system material (DSM_l). The water-quality parameters selected are those known or suspected in the deterioration of distribution infrastructure. The element γ_{kl} is a measure of the adverse effect that an increase in WQP_k will cause on DSM_l . Table 4 relates the effects of water quality on common distribution system material. The primary and secondary water quality impacts of the technologies shown in Table 3 are related to their effect on the deterioration of distribution system material. Table 4 gives an estimate of the magnitude of the impacts that water quality changes will have on common

distribution system material. The impacts identified here are aggregate impacts and should only be used for qualitative evaluation, rather than a quantitative one.

$$[\gamma_{kl}] = \left(\begin{array}{c|cccc} & \text{DSM}_1 & \text{DSM}_2 & \cdots & \text{DSM}_L \\ \hline \text{WQP}_1 & \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1L} \\ \text{WQP}_2 & \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2L} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ \text{WQP}_K & \gamma_{K1} & \gamma_{K2} & \cdots & \gamma_{KL} \end{array} \right); \text{ where } k = 1, 2, \dots, K \quad l = 1, 2, \dots, L \quad (3)$$

The relationships between regulation (i) and possible impact on the distribution system materials (l) can be established as following:

$$[z_{il}] = [\alpha_{ij}] \otimes [\beta_{jk}] \otimes [\gamma_{kl}] \quad (4)$$

where, $\otimes$ represents a composition operator (Sadiq *et al.* 2003). For simplicity, in this research, a simple matrix multiplication was proposed as a composition operator.

$$[z_{il}] = \left(\begin{array}{c|cccc} & \text{DSM}_1 & \text{DSM}_2 & \cdots & \text{DSM}_L \\ \hline \text{Reg}_1 & z_{11} & z_{12} & \cdots & z_{1L} \\ \text{Reg}_2 & z_{21} & z_{22} & \cdots & z_{2L} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ \text{Reg}_I & z_{I1} & z_{I2} & \cdots & z_{IL} \end{array} \right) \quad (5)$$

The element z_{il} , indicates the impact of changing treatment technique for regulatory compliance (Reg_i) on the distribution system material (DSM_l). Taking an arithmetic average (based on the number of regulations that were selected), would give the overall impact on DSM_k ($\overline{\text{DSM}_l}$).

$$\overline{\text{DSM}_l} = \frac{\sum_{i=1}^I z_{il}}{|I|}; \text{ where } |I| = \text{Number of regulations} \quad (6)$$

The advantage of this procedure is that experts in different domains/fields can provide their input to develop more comprehensive and accurate relational matrices. Also research needs can

be identified easily by studying gaps in the effects-matrices. Evaluation of the relational matrices by a wide range of experts will lead to a better understanding of the importance and priority of research gaps identified in this synthesis document (Sadiq *et al.* 2007).

EXPERT SURVEY AND WORKSHOP

The identification of research needs for the impacts of water quality on distribution infrastructure is a daunting task due to complex interrelationships between many influencing factors. In order to delineate the impact of water quality, distribution infrastructure is classified based on construction materials of components in contact with drinking water. In addition to extensive literature search, the study involved following two avenues for identifying research needs and gaps:

1. Soliciting opinions from a panel of experts through a questionnaire and subsequently discussing the survey results with this panel in a workshop and arriving at a consensus on the survey results and conclusions.
2. Consolidation of expert opinion and literature to identify the research needs at three levels of priorities – *low* (L), *medium* (M) and *high* (H).

Expert opinion was solicited in the form of responses to a survey intended to address five issues that were perceived to be important in evaluating water quality impacts on the integrity of distribution infrastructure. The survey was designed as a thinking exercise, which was sent in advance to a panel of experts invited to attend a ‘Research Needs Workshop’. In addition to the workshop participants, the survey was disseminated to other experts as well and the combined results were presented at the workshop. The participants in the workshop were asked to discuss

the survey results and build a consensus on the various issues. Initial responses to the survey were widely variable (primarily as a result of different terminology used by different experts to define infrastructure failure and components). After discussion and several clarifications of terminology that had been ambiguously stated in the survey questions, the panel obtained a convergence of opinions and final results were arrived at by consensus.

State of Knowledge

Respondents were asked to identify the current state of knowledge associated with different materials in the distribution infrastructure. Each material had three different categories of associated problems, including: external deterioration, internal deterioration, and related water quality failures. The effect of water quality on the distribution infrastructure is mainly an internal deterioration phenomenon, i.e. only surfaces in contact with the drinking water are impacted. However, the actual infrastructure may fail due to a number of other external factors like improper design, external loading, external corrosion or due to breaks caused by a third party interference. The survey participants were asked to rate from 0 (lowest possible value) to 10 (highest possible value) the contribution of the internal deterioration processes, if any, on the overall failure of the infrastructure. The participants identified unlined cast iron, copper, lead, PVC/PE and AC components as equally likely to fail as a result of external or internal deterioration. Concrete was perceived as more likely to fail due to external deterioration processes than from internal deterioration (Figure 3).

It should be noted that some aspects of the research deficits identified in this report are being undertaken as part of different AwwaRF sponsored research projects. A list of relevant

AwwaRF projects with the respective research contractors and the expected dates of completion are given in Table 5.

Deterioration Processes Dominant in Different Pipe Materials

In Table 1, three internal deterioration processes were identified as major causes of distribution infrastructure failure. The participants were asked to identify the most important deterioration process for the different types of material. Each distribution material is susceptible to a different set of environmental stresses that could lead to its failure. The participants identified PVC and other polymeric components as being the least susceptible to physico-chemical or microbially induced corrosion (MIC) (Figure 4).

Conversely, unlined iron pipes were identified to be the most susceptible to all three mechanisms of deterioration. However, the results also reflect bias, where the respondents identified problematic material on the basis of water quality deterioration rather than infrastructure deterioration. This is reflected in the respondents' high rating to materials prone to water quality deterioration (unlined iron, copper and lead) (Figure 5).

Since the intended focus of this report was on the deterioration of materials (rather than components), respondents were asked to rank the components that were the most likely to fail as a result of the impact of water quality. The respondents indicated that the most vulnerable component was the household plumbing and fixtures as well as small diameter mains and connections, followed by pump and pump appurtenances (Figure 6).

Identification of Distribution Pipes Condition

One of the main challenges facing the drinking water purveyors is the identification of the state of internal deterioration of their existing distribution infrastructure. The direct inspection of the

condition of the inner surfaces of distribution mains is a rather costly prospect. Practitioners therefore often have to resort to indirect indicators that might provide evidence on the condition of these pipes. The participating experts were asked for their opinion on the different methods of determining the internal condition of a pipe and the state of knowledge associated with these methods. Electrochemical techniques such as the use of corrator probes for corrosion monitoring, received the lowest rating in both applicability and state of knowledge. High ratings were given to water quality monitoring, water leakage and inspection of exhumed pipes. It should be noted that the experts tended to rate demonstrated technologies higher than newer ones. This could be used to indicate that electrochemical techniques remain an area for further research and development in drinking water infrastructure (Figure 7).

RESEARCH PRIORITIES IDENTIFIED IN THIS STUDY

Participating experts were given a list of research foci for each pipe material and asked to identify the most important ones. The participants were free to add their own ideas to the list, and an item was added to the list based on a suggestion from a participant. The research issues (and needs) were classified by consensus as high, medium or low priority. The resulting prioritized list of issues is suggested as a basis upon which new research projects could be defined, based on both water quality as well as mitigation of deterioration of distribution infrastructure.

Unlined Iron Components

A major portion of a typical water distribution network in North America comprises of unlined cast iron pipes that are at least a few decades old. Table 6 identifies research priorities for unlined cast iron components. This category includes old galvanized pipes and iron pipes with insufficient lining. Areas of current concern in unlined iron pipes include the accumulation and

release of heavy metals like arsenic, lead, cadmium etc., from the internal surfaces. There is also a need for tools for inspecting the internal condition of old pipes. This would help in planning rehabilitation activities.

Lead and Copper Components

The promulgation of the LCR has provided an impetus towards the mitigation of lead and copper release. However, the conflicting impacts of water quality and treatment changes on distribution infrastructure are not fully understood. Lead release due to chloramination is an example of how changes intended to comply with one regulation (Stage 2 D/DBPR) can conflict with the compliance of another (LCR) (Vasquez *et al.* 2006; Edwards and Dudi 2004). Table 6 provides research needs for lead and copper in the distribution system, as identified in the workshop.

It should be noted that health impact is the primary concern with lead pipes and connections. Therefore, the most feasible alternative for lead abatement is replacement of lead-based components in the distribution infrastructure by components made with more acceptable materials. Protection of lead pipes from deterioration is advised only in cases where the deterioration causes lead release to the drinking water.

For lead and copper pipes a major area of concern is the galvanic corrosion of these materials at the interface where they are in contact with a newer pipe material. For copper pipes, there is an additional need to evaluate whether passivated old copper pipes and newly installed copper pipes exhibit any significant galvanic corrosion.

Polymeric Components

The polymeric pipes and components (PVC, CPVC, HDPE, PE, elastomers) group is the most diverse and understudied in the distribution infrastructure. The excellent corrosion and

microbiological resistance offered by these pipes makes them the fastest growing replacement choice for water utilities. However, given that the average life of a pipe in the distribution system is measured in decades, more research is needed on the long-term performance of polymeric pipes. Table 6 provides some of the research needs identified for this pipe group.

PVC, PE and other plastic components represent newer and continuously evolving materials used in the distribution systems. These materials have a limited history and therefore need further research. Specifically, as shown in Table 7, the areas of concern are the leaching of different organic components into the drinking water and the degradation of these materials through oxidants (mainly disinfectants) in the drinking water.

Concerns about polymeric pipes mostly arise in hot water piping systems, where the combination of high temperatures, residual disinfectants and other oxidants could cause a deterioration of the pipes. On the other hand, many polymers are also capable of withstanding high temperatures and high disinfectant concentrations. Therefore when selecting polymeric pipes a careful evaluation of its compatibility with the operating and environmental conditions should be conducted.

In the survey, the ‘state of knowledge’ concerning the deterioration of polymeric components was ranked the lowest by the participating experts (Figure 3). This implies more research is needed to study the long-term behavior of polymeric pipes.

Cementitious Components

Two major categories of cementitious material exist in the distribution infrastructure, Asbestos cement and concrete. Since the cement matrix in both materials is pozzolanic in nature, a similar reaction to water quality can be expected in both. However, the mode of deterioration in each

could be completely different. In concrete or more specifically pre-stressed concrete, structural deterioration is due mainly to the corrosion of pre-stressing steel wires and subsequent loss of tensile strength. Other deterioration due to cracking and spalling could occur due to reaction of the salts within the cement matrix. Research priorities for cement-based material are identified in Table 6.

Internal Linings

Table 6 gives some of the research priorities identified for lining material in the distribution systems. These liners are typically used either as a component of new pipes or for rehabilitation of old pipes. In both cases, the long-term performance of the liners needs to be evaluated.

Linings are often the rehabilitation measure of choice for unlined iron (and other) pipes. The liner material becomes the surface in contact with the drinking water. The water quality impact in this case could occur in two stages, slow degradation of the liner material and exposure of the base host metal followed by intense localized corrosion of the base metal (Table 7). Therefore it is necessary to study the long-term performance of different lining materials.

Other Research Priorities for Distribution Infrastructure

Other research priorities were identified and are presented in Table 8. The topics addressed include water sources, water treatment and operation, maintenance and renewal activities, and are intended to minimize disruption to the existing distribution infrastructure. There is also an urgent need for addressing scale-up issues in laboratory and bench-scale experiments as they apply to the distribution system.

Different utilities have different research needs based on the applicability of specific regulations, and use of different treatment processes and materials of constructions. The proposed innovative but simple conceptual framework (HRM) presented earlier, can help utilities evaluate the impact of changes in treatment processes to the existing infrastructure. Different materials have different, often opposing water quality requirements to mitigate deterioration. Conflicting water quality impacts on different distribution materials can also be identified using this model. The model proposed in this project is intended as a proof of concept and can be further refined to incorporate more complex real systems. Further development of similar assessment models is needed to aid decision-making in evaluating treatment changes as well as evaluating material for the replacement of existing infrastructure.

SUMMARY OF RECOMMENDATIONS

The main objective of this research was to identify research needs for evaluating the impact of water quality on the integrity of distribution infrastructure. This was accomplished by an extensive review of current literature, development of a conceptual framework for hierarchical relational model (HRM), and expert opinion through a survey and workshop.

Each water utility has its own set of challenges that are determined by the source waters used, demand dynamics, applicable regulations, condition of distribution infrastructure, operation, maintenance and renewal strategies as well as economic and management issues. The HRM proposed in this research may allow each utility to predict the relative impact of changing treatment process and practices for its unique conditions. A further refinement and evaluation of the HRM in respect to local and specific conditions is recommended.

Experts from various disciplines in drinking water were polled for their opinion through a survey. The results of this survey were discussed during a research needs workshop and a consensus was built around the most and the least pressing research needs for different materials of construction of the distribution infrastructure. The detailed description of the research areas and their priorities identified in this project are given in Tables 6, 7 and 8.

The following gives a general idea of the knowledge gaps and arising research needs identified in this research project:

1. The evaluation of how changes in water sources (and qualities) can affect different components of the distribution network; for instance, some surface waters can corrode unlined iron pipes faster than groundwater;
2. The reconciliation of conflicting impacts of water quality (chemistry) on different pipe materials; for instance, water composition compatible with iron pipes may not be compatible with copper pipes. Therefore, a change in water composition, by the addition of chemicals to protect iron pipes, may cause failure of copper pipes;
3. The evaluation of unintended effects of change to water treatment processes; for instance, increasing the amount of chlorine to kill pathogenic microorganisms can cause deterioration in some pipe materials;
4. The evaluation of the effect of changes in water composition on the host pipes in terms of both the duration and frequency of these changes. For instance, the effect on distribution pipes when the utility regularly switches between surface water and groundwater sources to meet seasonal demand; and

5. The development of a decision-support model (e.g. HRM) to help water utilities evaluate the effect of changing water treatment practices on the deterioration of different pipe materials.

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Table 1. Impact of water quality deterioration mechanisms on distribution materials

Water distribution infrastructure material	Water quality deterioration mechanisms		
	Internal corrosion	Microbiologically induced corrosion	Leaching
Metallic Components (Iron, copper and lead)	Major	Unknown	Minor
Polymeric Components (PVC, PE and PAH)	None	Unknown	Major
Cement-based Components (AC and CC)	Major	Unknown	Major

AC – Asbestos cement, CC – Concrete, PE – Polyethylene, PAH – Polyaromatic hydrocarbons (bituminous or coal-tar),
PVC – Polyvinylchloride

Table 2. Effectiveness of selected ‘treatments techniques’ in removing drinking water contaminants $[\alpha_{ij}]$

Contaminant Categories	Air Stripping	Activated Carbon	Chlorination	Chloramine	Ozonation	Coagulation	Ion Exchange	Precipitation /Softening	Filtration	Membranes
Inorganics										
Arsenic						0.8	0.8	0.8		0.9
Disinfection Byproduct Formation Potential										
Bromate		0.4			-1.0					
TTHMs		1.0	-1.0	-0.2						0.8
HAA ₅		1.0	-1.0	-0.2						0.8
Microorganisms										
HPC bacteria			1.0	0.8	1.0	0.6			0.5	0.8
Viruses			1.0	0.5	0.8	0.6				0.8
Cryptosporidium			1.0	0.5	1.0	0.6				0.8
Organic Contaminants										
Volatile organics	1.0	0.8			0.5					0.5
Dissolved organics	0.5	1.0			0.5	0.8				0.8

“Effectiveness” is defined as follows:

Table 3. Secondary water quality impact of ‘treatment techniques’ $[\beta_{jk}]$

Treatment techniques	pH	Calcium	Alkalinity	Sulfate	Chloride	Dissolved oxygen (DO)	TDS	Chlorine	Chloramine	Natural organic matter (NOM)
Air Stripping	0.5					0.8				
Activated Carbon										-1.0
Chlorination										
Cl ₂ gas	-0.2				0.5		0.1	1.0	-1.0	
NaOCl	0				0.5		0.1	1.0	-1.0	
Chloramination	0				0.5		0.1	-1.0	1.0	
Ozonation						0.8				-0.5
Coagulation										
FeSO ₄ or Alum	0.8		-0.5	0.8						-0.8
FeCl ₃	0.8		-0.5		0.8					-0.8
Ion Exchange		-0.8					-0.5			
Precipitation/Softening	0.8	-0.5	-0.5							-0.4
Filtration										-0.6
Membranes		-0.8	-0.8				-0.8			-0.9

“Effectiveness” is defined as follows:

Table 5. Recent (and ongoing) AwwaRF projects addressing some of the research priorities identified in this study

Project Number	Title	Research Contractor	Expected Completion
2970	Proof-of-concept model to predict water quality changes in distribution pipe networks (Q-WARP)	National Research Council of Canada	2009
2991	Effects of microbes on the leaching of vinyl chloride and organotin from PVC piping used in drinking water delivery	Cornell U.	2008
3018	Contribution of service line and plumbing fixtures to lead and copper rule compliance issues	HDR/EES, Inc.	2008
3100	Secondary impacts of arsenic removal treatment in distribution systems	Malcolm Pirni, Inc.	2007
3107	Effect of changing disinfectants on distribution system lead and copper release	HDR Engineering, Inc.	2006
3109	Non-uniform internal corrosion in copper piping – Monitoring techniques	Virginia Polytechnic Institute & State U.	2009
3112	Performance and metal release of non-lead brass meters, components and fittings	HDR Engineering, Inc.	2007
3115	Decision tools to help utilities develop simultaneous compliance strategies	Malcolm Pirnie, Inc.	2009
3118	Assessment of inorganics accumulation in drinking water system scales and sediments	HDR Engineering, Inc.	2009
3172	The role of free chlorine, chloramines and natural organic matter in the release of Lead into drinking water	U. of Iowa	2009
3174	Investigation of the mode of action of Stannous Oxide as an inhibitor of Lead corrosion	U. of Minnesota	2009
4015	Effect of nitrification on corrosion in the distribution systems	Virginia Polytechnic Institute & State U.	2009
4029	Secondary impacts of corrosion control on distribution system and treatment plant equipment	Colorado State U.	2010
4031	Changes in water use patterns	U. of Louisville	2009
4033	Impact of phosphate corrosion inhibitors on cement-based pipes and linings	Camp Dresser and McKee Inc.	2010
4036	Impacts of lining material on water quality	Weston Solutions, Inc.	2010
4064	Influence of water chemistry on the dissolution and transformation rates of Lead corrosion products	Washington State U. in St. Louis	2010

Table 6. Research priorities identified for impacts on distribution infrastructure

Themes identified for research priorities	UI	L & C	PVC & PE	AC & Concrete	Liners (PAH & epoxy)
Develop and test methods of evaluating the impacts of different disinfectants on deterioration and integrity of the material	H ^{*†}	H ^{*†}	H ^{‡‡}	M [§]	L [‡]
Control of corrosive action of common disinfectants	H [§]	H [§]	N	N	N
Identify interactions between corrosion rate, microbiological activity and disinfectant type and residual	H ^{*†}	H [‡]	N	N	N
Document and model the genesis and evolution of corrosion scale and release controlling solid phases under different water qualities	M [‡]	M [‡]	N	N	N
Develop guidance for mitigation of internal deterioration in old pipes	M [*]	N	N	N	N
Document and compare performance of newly lined pipes on remaining life	M [§]	M [‡]	N	N	N
Develop a forensic model to identify internal deterioration problems based on the type and concentration of the particulate released	L [‡]	L [§]	N	N	N
Evaluate accumulation and release of heavy metals from corrosion scales	L [‡]	N	N	N	N
Identify and control permeation of organic contaminants through pipe walls of plastic pipes	N	N	H [‡]	N	N
Examine and quantify the leaching of monomers and other organic components from the pipe or liners	N	N	M [‡]	N	M [‡]
Evaluate softening of pipe materials under different water quality scenarios	N	N	N	M [‡]	N
Corrosion of reinforcing steel or prestressing wires and impact on integrity of concrete structures and pipes	N	N	N	L ^{*†}	N
Evaluate the long-term performance of lined pipes and liners	N	N	N	N	H [‡]

* Some research needed; ‡ Considerable research done; § No research done yet; † continuing research in active AwwaRF projects

N: Not applicable or not important; H: High on priority; M: Medium on priority; L: Low on priority

UI: Unlined iron pipes; L & C: Lead and Copper; PVC and PE: Polyvinyl chloride; PE: Polyethylene; PAH: Polyaromatic hydrocarbon

Table 7. Research priorities identified for impacts on water quality in distribution system

Themes identified for research priorities	UI	L & C	PVC & PE	AC & Concrete	Liners (PAH & epoxy)
Develop and test methods for comparison of disinfection efficacy for different pathogen groups using different disinfectants	H [‡]	N	N	N	N
Develop models for residual disinfectant depletion due to interaction with corrosion byproducts and pipe walls	H ^{*†}	H [‡]	N	N	N
Model and evaluate accumulation, growth and release of physical, chemical and microbiological contaminants	H [‡]	N	N	N	H [‡]
Develop practical solutions for water quality deterioration	M ^{*†}	M [*]	M [‡]	N	N
Evaluate control measures to increase the formation of passivating solid phases	L [§]	L [§]	N	N	N
Evaluate impacts of chloramines on lead and copper release and LCR compliance	N	H [‡]	N	N	N
Evaluate impact of new copper plumbing installations on LCR compliance	N	H [‡]	N	N	N
Evaluate impact of partial replacement of lead pipes on LCR compliance	N	H [‡]	N	N	N
Evaluate impacts of chloramines on leaching from pipe/ liner matrix	N	N	H [§]	N	M [‡]
Characterization of contaminants leaching from pipes and their impact on health and aesthetic water quality	N	N	H [‡]	N	N
Evaluate impacts of new installations on health and aesthetic water quality deterioration	N	N	L [‡]	M [‡]	M [‡]

* Some research needed; ‡ Considerable research done; § No research done yet; † continuing research in active AwwaRF projects

N: Not applicable or not important; H: High on priority; M: Medium on priority; L: Low on priority

UI: Unlined iron pipes; L & C: Lead and Copper; PVC and PE: Polyvinyl chloride; PE: Polyethylene; PAH: Polyaromatic hydrocarbon; LCR: Lead and Copper Rule

Table 8. Other research priorities for distribution infrastructures

Priority	Impacts on Distribution Infrastructure	Impacts on Water Quality
HIGH (H)	‡ Develop and evaluate methods to identify water quality impacts on different materials simultaneously. ‡ Develop a standard assessment procedure to identify the extent of internal deterioration in pipes and other inaccessible infrastructure. ‡ Develop methods to evaluate scale-up issues arising from bench and laboratory studies.	‡ Develop methods to evaluate and optimize water sources and treatment processes to protect the existing distribution infrastructure.
MEDIUM (M)	‡ Determining optimum monitoring strategies to evaluate internal deterioration in distribution systems. ‡ Mechanisms of inhibition by corrosion inhibitors.	‡ Develop methods to evaluate scale-up issues arising from bench and laboratory studies.
LOW (L)	‡ Impact of disinfectants on performance of liners.	

* Some research needed

‡ Considerable research done

§ No research done yet

† Continuing research in active AwwaRF projects

Figure 1. Selection of contaminant specific treatment technologies (Sadiq *et al.* 2007)

Figure 2. Proposed hierarchical relationship model (HRM) (Sadiq *et al.* 2007)

Figure 3. Current state of knowledge on different materials based on consensus of participating experts

Figure 4. Significant deterioration processes in different materials - survey results

Figure 5. Water quality failures associated with different materials

Figure 6. Relative importance of components based on water quality impacts

Figure 7. Rating of assessment measures for ‘integrity’ of distribution infrastructure