UNIVERSITÉ DE MONTRÉAL

RISK EVALUATION OF DRINKING WATER DISTRIBUTION SYSTEM CONTAMINATION DUE TO OPERATION AND MAINTENANCE ACTIVITIES

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Cette thèse intitulée:

RISK EVALUATION OF DRINKING WATER DISTRIBUTION SYSTEM CONTAMINATION DUE TO OPERATION AND MAINTENANCE ACTIVITIES

présentée par : BESNER Marie-Claude
en vue de l'obtention du diplôme de: Philosophiae Doctor
a été dûment acceptée par le jury d'examen constitué de:

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RÉSUMÉ

L'intégrité des infrastructures utilisées pour la distribution de l'eau potable est d'une importance capitale afin de minimiser le risque de contamination de l'eau entre l'usine de traitement et les consommateurs. Les problèmes reliés au réseau de distribution les plus préoccupants en terme d'impact potentiel sur la santé publique ont récemment été soulevés (NRC, 2006). Les installations et réparations de conduites (priorité élevée) ainsi que les faibles pressions transitoires et intrusions (priorité moyenne) ont été mentionnées. Des pressions faibles ou négatives en réseau de distribution peuvent résulter de pratiques opérationnelles et d'activités d'entretien telles que le départ/arrêt des pompes, la manipulation rapide de vannes ou de bornes-fontaines, le rinçage de conduites, les bris de conduite ou encore des pannes de courant. Le lien entre une contamination de l'eau distribuée et la réalisation de travaux d'entretien en réseau est souvent basé sur des cas spécifiques de contamination lorsque des épidémies de maladies d'origine hydrique sont rapportées. Peu de données sont disponibles pour évaluer l'impact de l'opération d'un réseau et des travaux d'entretien en conditions normales d'opération.

L'objectif principal de ce projet de recherche est d'évaluer les conditions pouvant mener à l'intrusion de contaminants microbiologiques en réseau associées à l'opération du réseau et à diverses activités d'entretien. De façon plus détaillée, ce projet cherche à:

1. Démontrer, à partir d'une étude de bases de données, qu'une fraction significative d'événements de non-conformité (présence de coliformes à l'eau distribuée) est liée à l'opération du réseau et à la réalisation de travaux d'entretien.
2. Investiguer, en réseau réel, le lien entre (i) la réalisation de travaux, (ii) les variations hydrauliques en réseau, et (iii) les changements potentiels de qualité d'eau (avec une emphase sur les pressions négatives et les intrusions de microorganismes).

3. Effectuer la modélisation en régime transitoire et la modélisation des intrusions pour évaluer les volumes potentiels d'intrusion associés aux événements de pressions négatives en réseau de distribution.

La première phase du projet a consisté à développer et appliquer une approche d'intégration de données basée sur la combinaison et la considération (simultanée) de données relatives à la qualité de l'eau, à la structure du réseau, à l'opération et aux activités d'entretien, de l'information provenant d'un modèle hydraulique et d'un système d'information géographique. Un outil de requêtes et de visualisation a été utilisé pour l'analyse. Au total, 140 cas de présence de bactéries coliformes détectées dans cinq réseaux de distribution ont été analysés et les résultats ont montré que le rôle de l'opération du réseau et des travaux d'entretien sur l'apparition des coliformes était variable d'un réseau à l'autre. Selon le réseau, un minimum de 9% jusqu'à 45% du nombre de cas de coliformes a pu être associé à l'opération ou à l'entretien.

Afin d'obtenir des informations supplémentaires à l'étude de bases de données, des travaux sur le terrain ont été réalisés. Ces derniers ont consisté en un suivi de certaines activités pouvant affecter l'intégrité physique ou hydraulique du réseau. Les changements potentiels de qualité d'eau associés à ces activités ont été mesurés en réseaux réels. Les activités pour lequel un suivi a été effectué sont les suivantes : réparations de bris ou fuites de conduites, rinçages (ou vidanges) de conduites, tests de débit aux bornes-fontaines, arrêts et départs de pompes ainsi que l'opération normale du réseau. Deux routes potentielles d'intrusion de microorganismes ont aussi été caractérisées: le sol et l'eau des tranchées entourant les conduites enfouies ainsi que l'eau provenant des chambres de vannes air-vacuum inondées. Le suivi a été effectué sur les réseaux des villes de Laval et de Montréal. Toutefois, la majorité des travaux ont été effectués sur le réseau de Laval, dans la même zone où Payment et collègues (1991, 1997) ont réalisé leurs études épidémiologiques et dont les résultats ont montré un taux plus élevé de maladies gastro-entériques associé à la consommation de l'eau du robinet.

L'impact des réparations de conduites (planifiées) sur la qualité de l'eau est estimé faible suite aux résultats obtenus. Des évidences d'intrusion ont été observées à sept des seize sites investigués. Toutefois, les résultats suggèrent que l'étape de rinçage lorsque la réparation est terminée est efficace pour minimiser la contamination (pour le type de réparation évalué). Des coliformes totaux ont été détectés dans 17 échantillons d'eau sur 424 (4.0%) et ces échantillons ont presque tous été prélevés lors de l'étape de rinçage. La fréquence de détection de microorganismes indicateurs de contamination fécale dans le sol et l'eau des tranchées était faible dans les deux réseaux où les travaux étaient effectués. Le suivi a également permis d'observer des variations du résiduel de désinfectant et de la turbidité à l'extérieur de la zone de travaux lorsque des changements hydrauliques étaient engendrés.

Un suivi à long-terme de la pression a été effectué en conditions d'opération normale du réseau de Laval de juin 2006 à novembre 2007 et des suivis ponctuels ont été réalisés lors de certaines activités d'entretien. Des pressions transitoires ont été observées lors de réparations de conduites, rinçage de conduites, test de débit aux bornes-fontaines et associées à l'opération de pompes. Toutefois, la principale cause de pression négative sur le réseau de Ville de Laval a été identifiée comme étant les pannes de courant affectant l'opération des pompes à l'usine de traitement.

L'établissement d'un lien entre un événement de pression négative dans un réseau de taille réelle et les changements de qualité d'eau engendré par cet événement représente un défi considérable. Une occasion "unique" d'échantillonner la qualité de l'eau suite à un événement de pression négative soutenue sur le réseau de Laval s'est présentée. Toutefois, l'établissement d'un tel lien s'est avéré difficile, même si des échantillons de plus grand volume ont été prélevés. Les concentrations de chlore résiduel dans ce réseau ont considérablement augmenté ces dernières années, principalement dû à des dosages plus élevés en sortie de l'usine de traitement.

À cause des difficultés associées avec la mesure de volumes d'intrusion en réseau réel, la vulnérabilité d'un système à la contamination par intrusion peut-être évaluée par l'utilisation de la modélisation transitoire. Un événement de faible pression à l'usine de traitement pour lequel des pressions négatives ont été mesurées en réseau a été simulé. Même si la version actuelle du modèle prédit des pressions négatives plus faibles (pires) que celles mesurées, les profils de pression obtenus en différents points du réseau ont montré une bonne correspondance entre les données mesurées et simulées. Les volumes d'intrusion potentiels durant cet événement ont été simulés selon différents scénarios. Les résultats ont montré que l'intrusion via les vannes air-vacuum submergées était plus importante que l'intrusion via les fuites dans les conduites. De plus, la caractérisation microbiologique de ces deux routes potentielles a montré que des indicateurs de contamination fécale étaient détectés plus fréquemment et à des concentrations plus élevées dans l'eau des chambres de vannes inondées que dans le sol ou l'eau des tranchées. Les volumes d'intrusion simulés sont probablement plus élevés qu'en réalité. Toutefois, ces résultats indiquent un risque potentiel associé avec les chambres où des vannes air-vacuum sont installées et dont le niveau d'eau se situe au-dessus de l'orifice de la vanne.

Suite aux résultats obtenus durant ce projet, des travaux additionnels sont requis pour évaluer avec confiance le risque d'intrusion associé aux pressions négatives en réseau. La modélisation réalisée durant ce projet était plutôt de nature exploratoire et a permis la prédiction des endroits et des volumes d'intrusion dans le réseau étudié. La prochaine étape devrait inclure la modélisation permettant d'évaluer l'effet du résiduel de désinfectant sur les microorganismes introduits. Si on se réfère au concept de "quantitative microbial risk assessment (QMRA)", les travaux présentés dans cette thèse pourraient être considérés comme des travaux de fond fournissant de l'information nouvelle sur la caractérisation de l'exposition aux microorganismes introduits suite à des événements de pression négative et aux réparations de conduites. Les travaux futurs considérant l'impact du résiduel de désinfectant contribueront à raffiner cette entrée dans un éventuel modèle évaluant l'impact sur la santé publique.

ABSTRACT

The integrity of the infrastructure used to deliver drinking water from the treatment plant to the customers is of paramount importance to minimize the risk of water contamination. Recent work by a committee of experts (NRC, 2006) highlighted distribution system issues of greatest concern in terms of their potential health risk. The issues listed included new and repaired water mains (high priority) and low pressure transients and intrusion (medium priority). Low pressure may result from a wide variety of distribution system operational practices and maintenance activities such as pump starting or stopping, rapid opening or closing of valves, hydrant flushing, main breaks, and loss of power. The link between contamination of distributed water and occurrence of operation and maintenance activities in a distribution system is often based on specific cases when waterborne disease outbreaks are reported. Few data are available to evaluate the impact of operation and maintenance activities under normal operating conditions.

The main objective of this research project was to assess the conditions leading to intrusion of contaminants in a system during a set of standard operations and maintenance activities in order to identify solutions to minimize such events and protect public health. On a more detailed level, this project seeked to:

1. Demonstrate through data mining that a significant portion of non-compliance events may be linked to distribution system operation and maintenance activities;
2. Investigate, in full-scale distribution systems, the link between O&M activities, distribution system hydraulics and potential water quality changes (with an emphasis on the occurrence of negative transient pressures and microbial intrusion);
3. Achieve transient and intrusion modeling to assess the potential level of intrusion associated with negative pressure events in a full-scale distribution system.

The first part of the study consisted in the development and application of a data integration approach based on the combination and simultaneous consideration of water quality data, network structural data, system O&M data, information from a hydraulic model and a geographical information system (GIS) for data visualization. The Interactive Data Analyzer tool was used for the analysis. A total of 140 total coliform samples in five distribution systems were investigated. The results showed that the role of O&M activities on the occurrence of coliforms was variable from one system to another, explaining a minimum of 9% and up to 45% of the number of coliform cases investigated in each system.

In order to complement the information obtained from the data-based study, field work was conducted and consisted in monitoring some activities that could affect the physical/hydraulic integrity of a system and verify how these activities could lead to changes in water quality in full-scale distribution systems. The activities monitored included: repairs of water main breaks/leaks, water main flushings, hydrant flow tests, pump start-up and shutdowns, and normal distribution system operation. Two potential pathways of microbial intrusion were also investigated: soil and shallow groundwater surrounding buried water mains and water from flooded air-vacuum valve vaults. Monitoring took place in the Laval and Montreal distribution systems with most of the work conducted in the Laval system, in the same area where Payment and colleagues (1991, 1997) conducted their epidemiological studies and measured an increased rate of gastrointestinal illnesses associated with the consumption of tap water.

The impact of (planned) water main repairs on water quality was found to be low. Evidence of intrusion was observed at seven sites out of 16 but the results suggest that adequate pipe flushing after a repair is completed is effective to minimize contamination for the type of repair investigated. A total of 17 water samples out of 424 (4.0%) were positive for total coliforms and the positive samples were almost all collected during the flushing operation. The frequency of faecal microbial indicators detection in the soil and trench water surrounding the mains was low in the two systems investigated. Hydraulic

changes were also shown to induce variations in chlorine residuals and turbidity outside of repair areas.

Long-term pressure monitoring was conducted in the Laval distribution system from June 2006 to November 2007 as well as targeted pressure monitoring during some O&M activities. Although transient pressures were observed during standard system operation (repairs of water main leaks, flushing, hydrant flow tests, pump operation), the main cause of negative pressures in the Laval distribution system was identified as power failures affecting the operation of pumps at the water treatment plant.

Establishing a link between the occurrence of negative pressure in a full-scale system and resulting changes in water quality is a big challenge. A "unique occasion" to sample water following the occurrence of a sustained negative pressure event in the Laval distribution system took place. However, such a link was found to be difficult to establish, even using larger sample volumes. The free chlorine residual concentrations in this distribution system were found to increase over the years, mostly because of increased dosages at the water treatment plant.

Because of the difficulties associated with the actual measurements of intrusion volumes in full-scale distribution systems, the vulnerability of a system to contamination may be evaluated using transient modeling. One low pressure event at the WTP that was found to result in negative pressure in the distribution system was simulated. Although the model predicted lower negative pressures than measured, the pressure profiles at various locations showed a good correspondence between field and model data. Potential intrusion volumes during this event could be simulated under different scenarios. Intrusion through submerged air-vacuum valves was found to be more important than intrusion through pipe leaks. Moreover, the microbial characterization of these two pathways of intrusion indicated that faecal contamination was recovered more frequently and at higher levels in the water from the flooded air-vacuum valve vaults than in the soil or trench water. Intrusion volumes obtained from the model are likely to be higher than in reality, however, such results indicated the potential risk associated with flooded air-valve vaults in this distribution system.

From the results obtained during this project, additional research is therefore needed to assess with confidence the risk of intrusion associated with the occurrence of transient negative pressures. The modeling work performed during this study was rather exploratory and allowed the prediction of locations and volumes of intrusion in the distribution system. The next step should include modeling to assess the effect of the residual disinfectant on the intruded microorganisms. Based on the quantitative microbial risk assessment concept, the work presented in this thesis may therefore be considered as background work bringing new information for the characterization of the exposure to intruded microorganisms due to transient negative pressures and pipe repairs. The future consideration of the impact of the residual disinfectant will help refining this input.

CONDENSÉ EN FRANÇAIS

L'intégrité des infrastructures utilisées pour la distribution de l'eau potable est d'une importance capitale afin de minimiser le risque de contamination de l'eau entre l'usine de traitement et les consommateurs. Les problèmes reliés au réseau de distribution les plus préoccupants en terme d'impact potentiel sur la santé publique ont récemment été soulevés (NRC, 2006). Les installations et réparations de conduites (priorité élevée) ainsi que les faibles pressions transitoires et intrusions (priorité moyenne) ont été mentionnées. Les faibles pressions (même négatives) en réseau de distribution peuvent résulter de pratiques opérationnelles et de multiples activités d'entretien telles que le départ ou l'arrêt des pompes, la manipulation rapide de vannes ou de bornes-fontaines, le rinçage de conduites, les bris de conduite ou encore des pannes de courant. Toutefois, le lien entre une contamination de l'eau distribuée et la réalisation de travaux d'entretien en réseau est souvent basé sur des cas spécifiques de contamination lorsque des épidémies de maladies d'origine hydrique sont rapportées. Peu de données sont disponibles pour évaluer l'impact de l'opération d'un réseau et des travaux d'entretien en conditions normales d'opération. Dans les années 1990, les études épidémiologiques réalisés par Payment et al. (1991, 1997) ont montré qu'entre 14 à 40% des cas de gastro-entérites étaient reliés à la consommation d'eau du robinet qui rencontrait les standards de qualité en place et que le réseau apparaissait comme potentiellement responsable de ce niveau endémique de maladies. De tels résultats ont donc soulevé des questions relatives à l'intégrité des réseaux, et ce même en conditions normales d'opération.

L'objectif principal de ce projet de recherche est d'évaluer les conditions pouvant mener à l'intrusion de contaminants microbiologiques en réseau associées à l'opération du réseau et à diverses activités d'entretien. De façon plus détaillée, ce projet cherche à:

1. Démontrer, à partir d'une étude de bases de données, qu'une fraction significative d'événements de non-conformité (présence de coliformes à l'eau

distribuée) est liée à l'opération du réseau et à la réalisation de travaux d'entretien.

2. Investiguer, en réseau réel, le lien entre (i) la réalisation de travaux, (ii) les variations hydrauliques en réseau, et (iii) les changements potentiels de qualité d'eau (avec une emphase sur les pressions négatives et les intrusions de microorganismes).
3. Effectuer la modélisation en régime transitoire et la modélisation des intrusions pour évaluer les volumes potentiels d'intrusion associés aux événements de pressions négatives en réseau de distribution.

La première phase du projet a consisté à développer et appliquer une approche d'intégration de données basée sur la combinaison et la considération (simultanée) de données relatives à la qualité de l'eau, à la structure du réseau, à l'opération et aux activités d'entretien, de l'information provenant d'un modèle hydraulique et d'un système d'information géographique. Un outil de requêtes et de visualisation a été utilisé pour l'analyse. Cette approche a été utilisée pour déterminer les causes potentielles de problèmes de qualité (historiques) dans plusieurs réseaux de distribution. Au total, les données relatives à 140 cas de présence de bactéries coliformes détectées dans cinq réseaux de distribution ont été analysées. À partir des données fournies par les municipalités, les résultats ont montré que le rôle de l'opération du réseau et des travaux d'entretien sur l'apparition des coliformes était variable d'un réseau à l'autre. Selon le réseau, un minimum de 9% jusqu'à 45% du nombre de cas de coliformes a pu être associé à l'opération ou à l'entretien. Cette étude a donc fourni des évidences spatio-temporelles (ainsi qu'hydrauliques) d'un lien entre la détection de coliformes et l'opération et les activités d'entretien. Toutefois, les échantillons prélevés par les municipalités provenaient principalement de leur suivi de routine, à des points spécifiques du réseau. Par conséquent, les résultats obtenus ne donnent qu'un aperçu de l'impact des activités d'entretien pour les travaux réalisés à proximité des points de suivi de la qualité.

Afin d'obtenir des informations supplémentaires à l'étude de bases de données, des travaux sur le terrain ont été réalisés. Ces derniers ont consisté en un suivi de certaines activités pouvant affecter l'intégrité physique ou hydraulique du réseau. Les changements potentiels de qualité d'eau associés à ces activités ont été mesurés en réseaux réels. L'intrusion de microorganismes était spécifiquement ciblée ici. Les activités pour lequel un suivi a été effectué sont les suivantes : réparations de bris ou fuites de conduites, rinçages (ou vidanges) de conduites, tests de débit aux bornes-fontaines, arrêts et départs de pompes ainsi que l'opération normale du réseau. L'impact potentiel des réparations de conduites sur la qualité de l'eau a été directement évalué lors des réparations. Pour les autres activités, leur impact sur l'intégrité hydraulique a d'abord été évalué par le suivi des pressions afin de détecter si des pressions faibles ou négatives pouvaient être engendrées lors de ces activités. Deux routes potentielles d'intrusion de microorganismes ont aussi été caractérisées : le sol et l'eau des tranchées entourant les conduites enfouies ainsi que l'eau provenant des chambres de vannes air-vacuum inondées. Le suivi a été effectué sur les réseaux des villes de Laval et de Montréal. Toutefois, la majorité des travaux ont été effectués sur le réseau de Laval, dans la même zone où Payment et collègues (1991, 1997) ont réalisé leurs études épidémiologiques et dont les résultats ont montré un taux plus élevé de maladies gastro-entériques associé à la consommation de l'eau du robinet.

L'impact des réparations de conduites (planifiées) sur la qualité de l'eau est estimé faible suite aux résultats obtenus. Le protocole d'échantillonnage développé consistait en la prise d'échantillons d'eau et de sol dans la tranchée afin d'en vérifier le contenu microbiologique et ainsi déterminer le potentiel d'intrusion. Des échantillons d'eau ont été prélevés chez les consommateurs situés dans la zone de réparation ainsi qu'à l'extérieur de cette zone et à la borne-fontaine utilisée lors de l'étape de rinçage. Des échantillons étaient prélevés avant, pendant et après les travaux. Le suivi a été réalisé en 2004-2005. L'évidence d'intrusion (basé sur la détection de coliformes totaux, *E. coli* ou des endospores aérobies) a été observée à sept sites sur un total de seize sites investigués. Toutefois, les résultats suggèrent que l'étape de rinçage lorsque la réparation est terminée est efficace pour minimiser la contamination (du moins pour le type de réparation évalué). La fréquence de détection de microorganismes indicateurs de contamination fécale dans le sol et l'eau des tranchées était faible dans les deux réseaux où les travaux étaient effectués. Considérant l'ensemble des points d'échantillonnage et les étapes de prélèvement, des coliformes totaux ont été détectés dans 17 échantillons sur 424 (4.0%). Ces échantillons ont presque tous été prélevés lors de l'étape de rinçage (16 échantillons sur 17). Le suivi a également permis d'observer des variations du résiduel de désinfectant et de la turbidité à l'extérieur de la zone de travaux lorsque des changements hydrauliques étaient engendrés par la fermeture de vanne pour isoler le secteur à réparer (création de cul-de-sac et changements de direction de l'écoulement).

Des capteurs de pression (permettant jusqu'à 20 lectures de pression par seconde) ont été utilisés pour déterminer la fréquence et l'amplitude des événements de pressions transitoires faibles ou négatives en réseau de distribution. Un suivi à long-terme a été effectué en conditions d'opération normale du réseau de Laval de juin 2006 à novembre 2007 et des suivis ponctuels ont été réalisés lors de certaines activités d'entretien. Le suivi à long-terme s'est déroulé en 4 périodes avec un maximum de 12 capteurs installés à des bornes-fontaines selon la période.

Des pressions transitoires ont été observées lors de réparations de conduites, rinçage de conduites, test de débit aux bornes-fontaines et associées à l'opération de pompes sans toutefois résulter en pressions négatives. Sans considérer les pressions associées au pompage, la plupart des activités pour lequel un suivi a été effectué ont été réalisées dans des zones de réseau où la pression initiale était relativement élevée (en moyenne entre 290 et 558 kPa (42 et 81 psi)). Des chutes de pressions variant de 14 à 379 kPa (2 à 55 psi) ont été enregistrées de telle sorte que si ces activités sont réalisées dans des secteurs de réseau où la pression est initialement plus faible, des pressions négatives pourraient potentiellement résulter. Toutefois, la principale cause de pression négative sur le réseau de Ville de Laval a été identifiée comme étant les pannes de courant affectant l'opération des pompes à l'usine de traitement. La zone d'étude sur le réseau de

Laval s'est avérée vulnérable aux pressions faibles et négatives avec neuf événements de faible pression à l'usine de traitement durant la première année du suivi (Juin 2006-Juillet 2007).

Lorsque des pressions négatives surviennent, l'intrusion de microorganismes dans le réseau peut survenir via les fuites dans les conduites (ou autres orifices). Pour le réseau de Laval, le pourcentage d'eau estimé perdu via les fuites est d'environ 20%. Pour ce réseau, une autre source potentielle d'intrusion a été identifiée comme étant les vannes air-vacuum dont l'orifice est submergé d'eau dû à une inondation de la chambre souterraine abritant la vanne. Durant l'été 2007, 45 chambres de vannes dans lesquelles se trouvait soit (i) des purgeurs d'air, (ii) des vannes air-vacuum, ou (iii) des vannes à air combiné ont été visitées. Dans 30 de ces chambres, des échantillons d'eau ont pu être récoltés et pour 10 de ces chambres, le niveau de l'eau se trouvait au-dessus de l'orifice de la vanne permettant à l'air d'entrer dans la conduite. Le sol, l'eau de tranchée ainsi que l'eau provenant des chambres de vannes ont été caractérisés pour déterminer leur contenu microbiologique. La fréquence de détection d'organismes indicateurs de contamination fécale était plus élevée pour l'eau des chambres de vannes et les concentrations détectées également. Seulement un échantillon de sol sur 16 s'est avéré positif pour *E. coli* tandis que ce microorganisme a été détecté dans 68% des échantillons de chambres de vannes.

L'établissement d'un lien entre un événement de pression négative dans un réseau de taille réelle et les changements de qualité d'eau engendré par cet événement représente un défi considérable. Pour qu'une intrusion survienne, trois conditions sont nécessaires: (i) pression négative, (ii) route d'entrée, et (iii) source de contamination. Ces trois conditions doivent survenir simultanément en un même endroit. Une occasion "unique" d'échantillonner la qualité de l'eau suite à un événement de pression négative soutenue sur le réseau de Laval s'est présentée lors de la fermeture planifiée d'une conduite de large diamètre (400 mm). Comme de faibles pressions et des changements de direction de l'écoulement étaient anticipés lors de ces travaux, une campagne d'échantillonnage de la qualité de l'eau a été réalisée. Le rinçage de la conduite avant sa réouverture a résulté en deux épisodes de pressions négatives de plus de cinq minutes chacun à un des trois points où des échantillons d'eau étaient prélevés. L'établissement d'un lien entre l'événement de pression négative et la qualité de l'eau s'est avéré difficile, même si des échantillons de plus grand volume (1 L au lieu de 100 mL) ont été prélevés. Des concentrations de chlore résiduel libre d'environ 0.2 mg/L ont été mesurées à ce point tout au long de la fermeture. D'ailleurs, les concentrations de chlore résiduel dans ce réseau ont considérablement augmenté ces dernières années, principalement dû à des dosages plus élevés en sortie de l'usine de traitement.

À cause des difficultés associées avec la mesure de volumes d'intrusion en réseau réel, la vulnérabilité d'un système à la contamination par intrusion peut-être évaluée par l'utilisation de la modélisation transitoire. Un événement de faible pression à l'usine de traitement pour lequel des pressions négatives ont été mesurées en réseau a été simulé à l'aide du logiciel commercial InfoSurge. La version actuelle du modèle prédit des pressions négatives plus faibles (pires) que celles mesurées, ce qui peut-être expliqué par des incertitudes telles que la demande aux nœuds et la vitesse de l'onde de pression. Également, les vannes air-vacuum n'ont pas été incluses dans le modèle comme équipement de protection. Malgré ces différences, les profils de pression obtenus en différents points du réseau ont montré une bonne correspondance entre les données mesurées et simulées. Les volumes d'intrusion potentiels durant cet événement ont été simulés selon différents scénarios. Les résultats ont montré que l'intrusion via les vannes air-vacuum submergées était plus importante que l'intrusion via les fuites dans les conduites. De plus, la caractérisation microbiologique de ces deux routes potentielles a montré que des indicateurs de contamination fécale étaient détectés plus fréquemment et à des concentrations plus élevées dans l'eau des chambres de vannes inondées que dans le sol ou l'eau des tranchées. Les volumes d'intrusion simulés sont probablement plus élevés qu'en réalité puisque (i) le modèle prédit des pressions négatives pires que celles mesurées, (ii) l'équation d'orifice utilisée pour simuler les intrusions prédit que chaque nœud ou la pression extérieure est supérieure à la pression dans la conduite subira l'intrusion (il est faux de penser que toutes les conduites sont submergées – sous la nappe d'eau – dans un réseau) et (iii) des incertitudes existent quant à la modélisation via les vannes air-vacuum. Toutefois, ces résultats indiquent un risque potentiel associé avec les chambres où des vannes air-vacuum sont installées et dont le niveau d'eau se situe au-dessus de l'orifice de la vanne.

La question à l'origine de ce projet de recherche était: quel est le risque de contamination microbiologique associé aux pratiques opérationnelles en réseau et aux activités d'entretien? L'étude de bases de données a montré qu'un lien pouvait être établi entre l'opération, l'entretien et l'apparition de coliformes. Les résultats des travaux terrain ont montré une contamination limitée associée aux réparations de conduites planifiées et (un) événement de pression négative soutenue. Sur cette base, le risque de contamination associé aux réparations (réparations planifiées dans des excavations relativement "propres") peut être estimé comme étant faible. Toutefois, les évidences sont moins claires pour l'événement de pression négative. Il peut être supposé que des microorganismes indicateurs auraient été détectés dans plus d'un échantillon si la situation avait été critique. Les concentrations de chlore mesurées dans ce secteur du réseau offrent probablement une certaine protection. Toutefois, la modélisation des intrusions soulève le risque d'intrusion associé aux vannes air-vacuum submergées durant les événements de pressions négatives. Cette route d'entrée des microorganismes dans le réseau devrait, et peut facilement être éliminée par l'inspection systématique des chambres de vannes.

Suite aux résultats obtenus durant ce projet, des travaux additionnels sont requis pour évaluer avec confiance le risque d'intrusion associé aux pressions négatives en réseau. La modélisation réalisée durant ce projet était plutôt de nature exploratoire et a permis la prédiction des endroits et des volumes d'intrusion dans le réseau étudié. La prochaine étape devrait inclure la modélisation permettant d'évaluer l'effet du résiduel de désinfectant sur les microorganismes introduits. Si on se réfère au concept de "quantitative microbial risk assessment (QMRA)", les travaux présentés dans cette thèse pourraient être considérés comme des travaux de fond fournissant de l'information nouvelle sur la caractérisation de l'exposition aux microorganismes introduits suite à des événements de pression négative et aux réparations de conduites. Les travaux futurs considérant l'impact du résiduel de désinfectant contribueront à raffiner cette entrée dans un éventuel modèle évaluant l'impact sur la santé publique.

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LIST OF ABBREVIATIONS

AGI	Acute gastrointestinal illness
AIDS	Acquired immune deficiency syndrome
AOC	Assimilable organic carbon
Atm	atmosphere
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
AR	Annular reactor
BDL	Below detection limit
BOM	Biodegradable organic matter
^{o}C	Degree Celcius
c	wave speed
CCL2	Final contaminant candidate list
C_d	Orifice discharge coefficient
CFU	Colony-forming unit
CI	Cast-iron
Cl_2	Chlorine
ClO_2	Chlorine dioxide
Cult	Culturing methods
D	Diameter
DI	Ductile iron
DAPI	Diamidino-4',6-Phenylindol-2 Dichlorhydrate
DBF	Database format
DS	Distribution system
DVC	Direct viable count
DW	Dirty water
DWD	Denver Water Department
E. coli	*Escherichia coli*

E_c	Elastic modulus of conduit
E_f	Elastic modulus of fluid
EPS	Extended period simulation
FISH	Fluorescent in situ hybridization
FA	Fluorescent antibody
FH	Fire hydrant
ft	feet
ft/sec	feet per second
g	gram
g	gravitational acceleration
GAC	Granular activated carbon
GCWW	Greater Cincinnati Water Works
GI	Gastrointestinal
GIS	Geographical information system
h	hour
HACCP	Hazard Analysis and Critical Control Point
HCl	Hydrogen chloride
H_{ext}	External head
HIV	Human immunodeficiency virus
$H_{L,I}$	Line (interior) head
HPC	Heterotrophic plate count
ID	Identification
in	inch
INRS	Institut National de Recherche Scientifique
IPIU	Immunoperoxidase infectious unit
Km	Kilometer
kPa	KiloPascal
K_R	Coefficient of restraint for longitudinal pipe movement
L	Liter

L	Length
L/min	Liter per minute
Log	logarithm
m	Meter
$MgCl_2$	Magnesium chloride
Mgd	Million gallon per day
mg/L	Milligram per liter
mL	Milliliter
ML/d	Million liters per day
mm	millimeter
MPN	Most probable number
MPNCU	Most probable number of cytopathic units
m/sec	meter per second
MSX	Multi-Species eXtension
µg	Microgram
µS	Micro siemens
N	Normal
N_{50}	Median infection dose
NA	Not available
NH_2Cl	Monochloramine
NSERC	National Sciences and Engineering Research Council
NTU	Nephelometric turbidity unit
NW	North West
O&M	Operation and maintenance
p	Level of statistical significance (p-value)
PC	Polycarbonate
PCR	Polymerase chain reaction
PDF	Probability density function
PFU	Plaque forming unit

Ph.D.	Philosophiae Doctor
Psi	Pounds per square inch
PVC	Polyvinyl chloride
Q_i	Intrusion flowrate
QMRA	Quantitative microbial risk assessment
RT	Residence time
RT-PCR	Reverse transcription-polymerase chain reaction
SCADA	Supervisory control and data aquisition
Scan RDI	A laser scanning cytometer
SS	Stainless steel
t	pipe tickness
T_0	Initial system condition
T_{end}	Final system condition
TC	Total coliforms
UDF	Unidirectional flushing
UK	United Kingdom
uPVC	Unplasticized polyvinyl chloride
U.S.	United-States
US EPA	United-States Environmental Protection Agency
V	Velocity
VBNC	Viable but non-culturable
WBDOs	Waterborne disease outbreaks
WQ	Water quality
WTP	Water treatment plant
w/v	weight per volume

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

The integrity of the infrastructure used to deliver drinking water from the treatment plant to the customers is of paramount importance to minimize the risk of water contamination. A significant portion of waterborne disease outbreaks (WBDOs) has been shown to be caused by distribution system deficiencies (Craun and Calderon, 2001). These authors showed that, for the period 1971 to 1998, 18.3% of the outbreaks reported in public water systems in the U.S. were caused by chemical and microbial contaminants entering the distribution system. The main distribution system deficiencies responsible for the outbreaks during this 27-year period are listed in Table 1-1. Recent data show that for the year 2001-2002, 20% of the WBDOs associated with drinking water in the U.S. (total n=25) were caused by distribution system deficiencies (Blackburn et al., 2004). For the 2003-2004 report, a new classification for deficiencies was established by the Center for Disease Control which provides a clear distinction on where the contamination takes place (in the system under the jurisdiction of a water utility or at a point outside the jurisdiction of the water utility or point of use). For these last two years, 11 WBDOs were related to drinking water with deficiencies originating from source water, treatment or distribution (in system before water meter or property line). Overall, 14 deficiencies were reported and distribution system deficiencies (including storage) accounted for 43% of these (Liang et al., 2006). Although the actual number of WBDOs reported since 1980 has decreased, the proportion of WBDOs due to distribution system contamination is increasing (NRC, 2006). Equivalent figures in Canada are not systematically reported, but similar numbers are to be expected.

Table 1-1: Distribution system deficiencies causing outbreaks for the 1971-1998 period in the U.S. (modified from Craun and Calderon, 2001)

Deficiency	**Public water systems***	
	# outbreaks caused by deficiency	**%**
Cross-connection / backsiphonage	60	53.1
Contamination during storage	15	13.3
Corrosion / leaching of metals	13	11.5
Broken or leaking water mains	10	8.8
Contamination of household plumbing	8	7.1
Contamination of mains during construction / repair	6	5.3
Inadequate separation of water main and sewer	1	0.9
Total	**113**	**100**

* Public water systems = data for community water systems and noncommunity water systems

Cases of water contamination due to distribution system deficiencies, leading to illnesses and even deaths in the supplied population, have been witnessed over the last few years. In 1997, the failure of a 600 mm (24 in.) diameter pipe supplying the city of Le Havre in France, and the subsequent depressurization of the network was identified as being the cause of about 300 cases of diarrhea out of a population of 50,000 (Mansotte and Beaudeau, 1999). In the small town of Cabool (Missouri), an outbreak of hemorragic *E. coli* serotype O157:H7 caused 243 known cases of diarrhea and four deaths out of a population of 2090 inhabitants, between December 15, 1989 and January 20, 1990. Two major distribution line breaks were the suspected sources of contamination (Geldreich et al., 1992). Inadequate maintenance of a municipal water storage tank was identified as the cause of a *Salmonella* serovar *typhimurium* outbreak reported in Gideon (Missouri) in 1993 (Clark et al., 1996; Angulo et al., 1997). The tank had an improper roof vent and an uncovered hatch that allowed free access to wild birds resulting in water contamination from bird droppings. Out of a population of 1104, almost 600 people were affected with diarrhea and seven people died. These two U.S. distribution systems did not use residual disinfection at the time of the outbreaks.

Distribution system deficiencies that result in waterborne disease outbreaks constitute obvious breaches to the integrity of the distribution networks, however, the integrity of distribution systems under normal operating conditions has also been questioned. In the 1990's, the studies by Payment et al. (1991; 1997) indicated that between 14 and 40% of the gastrointestinal illnesses were related to tap water meeting the current water quality standards and that the distribution system appeared to be partly responsible for this endemic level of illnesses. These studies are almost systematically referred to in numerous research papers dealing with distribution system water quality and greatly contributed to the increased attention devoted to the distribution system as being the last and vulnerable barrier between the treatment plant and the customers.

In order to reflect the need to protect this last barrier, work has been undertaken, particularly in the U.S., to evaluate the distribution system aspects that could lead to potential risks to consumers. It started in 2000, with a recommendation issued to the U.S. Environmental Protection Agency (US EPA) by the Federal Advisory Committee for the Microbial/Disinfection By-products Rule. In 2003, the US EPA, in its commitment to revise the Total Coliform Rule (which relates to microbial water quality in the distribution system), agreed to explore the possibility of providing a comprehensive approach for addressing water quality in the distribution system environment, therefore encompassing the concept of distribution system integrity as part of the rule (NRC, 2005). For this process, the US EPA, along with other external experts, has produced a series of nine distribution system white papers on aspects that could lead to potential health risks in distribution systems. The topics are listed below:

- Intrusion of contaminants from pressure transients (LeChevallier et al., 2002)
- Cross-connections and backflow (USEPA, 2002a)
- Deteriorating buried infrastructure (American Water Works Service Co., Inc., 2002)
- Permeation and leaching (AWWA and Economic and Engineering Services, Inc., 2002a)
- Nitrification (AWWA and Economic and Engineering Services, Inc., 2002b)
- Microbial growth and biofilms (USEPA, 2002b)

- Finished water storage facilities (AWWA and Economic and Engineering Services, Inc., 2002c)
- Water age (AWWA and Economic and Engineering Services, Inc., 2002d)
- New or repaired water mains (AWWA and Economic and Engineering Services, Inc., 2002e)

To further refine the process, the US EPA has mandated a committee of the National Academies' Water Science and Technology Board to identify and prioritize the issues of greatest concern (in terms of their associated potential health risks) for distribution systems. In its first report (NRC, 2005), the committee achieved the following classification, based on their review of the available literature (Table 1-2):

Table 1-2: Prioritization of distribution system issues by the National Academies' Water Science and Technology Board Committee (NRC, 2005)

Priority	Issue
Highest	Cross-connections and backflow New and repaired water mains Finished water storage Premise plumbing Distribution system operator training
Medium	Biofilm growth Loss of residual via water age and nitrification Low pressure transients and intrusion
Lower	Other effects of water age Other effects of nitrification Permeation Leaching Control of post precipitation

Among the issues listed in Table 1-2, cross-connections, new and repaired water mains and low pressure transients are probably the most susceptible to result in the intrusion of microbial contaminants in the distribution system. These have been ranked as high priority issues, except for the low pressure transients, classified as medium, only because there are insufficient data to indicate whether it is a substantial health risk or not (NRC, 2005). In their study of pathogen intrusion in distribution system, Kirmeyer et al.

(2001), out of an expert panel workshop, have identified these three issues as pathogen routes of entry presenting a high risk potential (in terms of severity of disease, probability of waterborne disease outbreak, volume contaminated, and frequency of intrusion). Water treatment breakthrough was the other high risk route also listed.

The general aging and deteriorating state of the infrastructure used to distribute water is a threat to the integrity of distribution systems and increases the vulnerability of distribution systems to water contamination to a level that is not known today. The American Society for Civil Engineers allocated a D- for the poor state of drinking water infrastructures in the U.S. (ASCE, 2005). For the city of Montreal (Quebec), it is estimated that 33% of the mains reached their useful life in 2002 and that an additional 34% will reach this state before 2020 (Proulx et al., 2002). Maintenance activities such as repairs of pipe breaks, rehabilitation of existing pipes and installation of new mains are therefore likely to increase in number and frequency. Furthermore, the presence of pipe leaks, that may lead to the loss of about 30% of the produced water in Canadian distribution systems (Environment Canada, 2005), provides multiple potential entry points for intrusion of microbes into treated drinking water during negative or low pressure events. These low/negative transient pressures may originate from various routine activities (pump starting or stopping, rapid opening or closing of valves, hydrant flushing) and other events such as main breaks or loss of power (Kirmeyer et al., 2001). The integrity of the distribution system is therefore at risk every time these routinely occurring actions take place.

The role of distribution system operation and maintenance (O&M) activities on the occurrence of system contamination (usually measured in terms of coliforms) resulting in non-compliance with the regulations in place is not clear. Microbial contamination in the distribution system may be caused by a wide variety of conditions, i.e. treatment breakthrough (Morris et al., 1996), intrusion (Blackburn et al., 2004) and microbial regrowth (LeChevallier et al., 1987). However, the relative importance of these contamination pathways is unknown. Although the occurrence of positive coliform samples in distribution systems has traditionally been associated with coliform regrowth (LeChevallier, 1990), it is hypothesized, as the basis of this Ph.D. work, that system operation and occurrence of maintenance activities may play a role in distribution system contamination.

Up to this day, it has been shown that low or negative pressure transients occur in full-scale distribution systems (Kirmeyer et al., 2001; LeChevallier et al., 2004; Gullick et al., 2004; Gullick et al., 2005; Hooper et al., 2006), that the soil and water surrounding water mains may be contaminated with faecal pollution (Karim et al., 2003), and that intrusion of contaminated water takes place under negative pressure transients, as verified under pilot system simulation conditions (Boyd et al., 2004a; Boyd et al., 2004b). However, evidence of water contamination under such conditions in full-scale distribution systems has not been assessed yet. No studies have been conducted in full-scale distribution system to actually monitor changes in distributed water quality when routine activities take place. Therefore, this Ph.D. work intends to fill this gap by assessing the risk of water contamination induced by system operation and routine maintenance activities.

1.2 STRUCTURE OF DISSERTATION

The next chapter (Chapter 2) will provide an overview of the current knowledge related to water contamination in distribution systems. The goals of the proposed project and the methodology are then presented in Chapter 3. In Chapter 4 through Chapter 6, the reader will find papers that have been either published or are currently under revision in peer-reviewed journals. Chapter 4 completes the literature review by providing an in-depth review of the studies where microbial intrusion was simulated and the impact of a residual disinfectant investigated. Chapter 5 presents the results of our data-based study where the proportion of coliform occurrences potentially associated with O&M activities in distribution systems is assessed. In Chapter 6, the outcomes of our field study on the impact of water main repairs on water quality are presented. In Chapter 7, a draft of a paper completes the discussion of the field work performed during this PhD work. The occurrence of negative pressure events in a full-scale distribution system is presented along with the modeling work performed to assess the risk of intrusion during such events. Finally, a general discussion is provided in Chapter 8. The conclusions and recommendations are provided in Chapter 9.

CHAPTER 2

LITERATURE REVIEW

This literature review seeks to answer the three following questions:

(i) what are the microorganisms that have been identified in distribution system water samples?

(ii) how can they enter the distribution system? and

(iii) what happens once they are introduced into the system?

The first part of this literature review will therefore consist in identifying the major pathogens that have been involved in waterborne disease outbreaks associated with drinking water. The second section will review the various pathogen routes of entry that have been reported in the literature. Thirdly, a review of the various experiments related to the intrusion of microorganisms into simulated distribution systems will be provided and finally, the concept of risk, linked to the intrusion of microorganisms into distribution systems will be discussed.

2.1 PATHOGENIC MICROORGANISMS RESPONSIBLE FOR WATERBORNE DISEASE OUTBREAKS

In developed countries, even if water treatment technologies are available and usually in place, waterborne disease outbreaks still take place, affecting various numbers of people. In order to identify the pathogenic agents usually involved in these outbreaks, the following table (Table 2-1) offers an overview of the disease and microorganisms that were reported in various countries over different time periods (12 to 29 years). The causes of the outbreaks listed in Table 2-1 are not differentiated and include outbreaks from untreated contaminated surface water, untreated contaminated groundwater, treatment deficiency, distribution system deficiency and unknown or miscellaneous deficiency.

Table 2-1: Pathogenic microorganisms involved in waterborne disease outbreaks

Type of agent	Disease	Pathogenic microorganism	Outbreaks				
			United-States[1]	England/Wales[2]	Canada[3-4-5]	Finland[6]	Sweden[2]
			No. illnesses 1971-1996	No. illnesses (public supplies) 1971-2000	1974-1996 2000 2001	1980-1992	1980-1999
UNIDENTIFIED	AGI	Unidentified	82 797			*	*
NOT MENTIONED BY AUTHORS	Gastroenteritis			3 653			
	Chronic gastroenteritis		94				
BACTERIAL	AGI	*E. coli* O157:H7	305		*		
	AGI	*E. coli* O6:H16	1 000				
	AGI	*Plesiomonas shigelloides*	60				
	AGI	Toxin producing *E. coli*					*
	Campylobacteriosis	*Campylobacter*	5 487	910	*	*	*
	Cholera	*Vibrio Cholerae*	28				
	Salmonellosis	*Salmonella*	2 995		*	*	*
	Shigellosis	*Shigella*	9 055		*		*
	Typhoid fever	*Salmonella Typhi*	282				
	Yersiniosis	*Yersinia*	102				
PARASITIC	AGI	*Cyclospora*	21				
	Amebiasis	*Entamoeba histolytica*	4				*
	Cryptosporidiosis	*Cryptosporidium*	420 016	3 994	*		*
	Giardiasis	*Giardia*	28 129	60	*		*
	Toxoplasmosis	*Toxoplasma gondii*			*		
VIRAL	AGI	Calicivirus					*
	AGI	Norwalk agent	10 700		*		
	AGI	Rotavirus	1 761				
	AGI	Viruses				*	
	Hepatitis A	Hepatitis A	827		*		

AGI: Acute gastrointestinal illness; *: No number available on cases of illness; [1]AWWA, 1999; [2]Stanwell-Smith et al., 2003; [3]Environment Canada, 2001; [4]Hrudey et al., 2003; [5]Stirling et al., 2001; [6]Lahti et Hiisvirta, 1995;

Among these outbreaks, the most "spectacular" is probably the waterborne *Cryptosporidium* infection that took place in Milwaukee (WI), in 1993. This outbreak affected more than 400 000 people and an estimated 104 deaths (Morris et al., 1996). Treatment breakthrough, associated with a dramatic increase in turbidity level was associated with the outbreak. In Canada, the waterborne disease epidemic in Walkerton (ON), where more than 2300 individuals experienced gastroenteritis and seven people died in 2000 certainly raised some concerns in the population about the risks of drinking water contamination (Hrudey et al., 2003). *E. coli* O157:H7 and *Campylobacter jejuni* were the pathogens identified as responsible of the illnesses. This was followed by the North Battleford (SK) waterborne cryptosporidiosis outbreak in 2001 where inadequate filtration was found as being the cause of the breakthrough of the pathogenic parasite into treated water (Stirling et al., 2001). From Table 2-1, it can be seen that the most common pathogenic agents (in terms of occurrence in different countries) determined as causes of waterborne disease outbreaks are *Campylobacter* (5 countries out of 5), *Salmonella*, *Cryptosporidium* and *Giardia* (in 4 countries out of 5). Between 1991 and 1998, *G. lamblia* and *C. parvum* have caused 32% of all reported outbreaks in the U.S. (Craun et al., 1998).

In the U.S., a synthesis has been completed by Craun and Calderon (2001) on the main pathogenic agents involved in outbreaks due to distribution system deficiencies during the 1971-1998 period, as listed in Table 2-2 (care must be taken in considering the variety of pathogenic organisms listed in Table 2-1 and 2-2 as the etiology of outbreaks is often unidentified, so it is likely that such a list is incomplete; moreover, it is known that the number of waterborne outbreaks is likely to be underreported as reliable estimates on the number of outbreaks that can go unrecognized are not available (Blackburn et al., 2004)).

Table 2-2: Etiology of outbreaks caused by distribution system deficiencies, Period 1971-1998 (Craun et Calderon, 2001)

Etiology	**Microorganism**
Bacteria	*Salmonella, Shigella, Campylobacter, E. coli* O157:H7, *Vibrio cholerae*
Parasites	*Giardia, Cyclospora*
Virus	Norwalk-like virus, Hepatitis A

In Table 2-2, *Cryptosporidium* is not listed as being involved in outbreaks caused by distribution system deficiencies. However, this pathogen should not be left out as a potential contaminant of distributed water as it has been associated with two cryptosporidiosis outbreaks in the UK where the suspected source was distribution system contamination (Craun et al., 1998). However, for both outbreaks, the most likely sources of *Cryptosporidium* could not be identified. A recent investigation by Aboytes et al., (2004) showed that infectious *Cryptosporidium* (mostly *C. parvum*) could be detected in filtered drinking water from conventional treatment plants (using cell culture – polymerase chain reaction) and that it could be responsible for about 52 infections/10 000 people/year. Consequently, this parasite could be responsible for an endemic level of illnesses in distribution systems.

2.1.1 Opportunistic pathogens

In addition to pathogenic microorganisms, opportunistic pathogens can also be found in distribution systems. Opportunistic pathogens are bacteria that may invade and cause disease in individuals with weakened immune systems (elderly people), those with compromised immune systems (AIDS patients, cancer survivors, organ transplant patients), and infants with underdeveloped immune barriers (AWWA, 1999). As birth rate generally declines, a growing proportion of the population is over 65 years of age. In Canada, it is estimated that by the year 2031, about 20% of the total population will be seniors (Centre of Canadian Studies at Mount Allison University, 2005). Furthermore, the number of immunocompromised persons is also increasing (NRC, 2005). In 1996, this segment of the population represented almost 20% of the population in the United-States (Gerba et al., 1996). Consequently, the risk of contamination of distributed water with opportunistic pathogens should not be minimized as the severity of the diseases is likely to be much higher in this population category. Opportunistic pathogens include: (i) *Legionella* spp., *Aeromonas* spp., and *Pseudomonas aeruginosa*, which are known to colonize distribution system biofilms (Szewzyk et al., 2000; Flemming et al., 2002); (ii) *Helicobacter pylori* that can cause gastritis and an increased risk of gastric cancer (WHO, 2006), has been identified in municipal tap water samples (Hulten et al., 1998) and *Helicobacter* sp. has been detected for the first time in distribution system pipe biofilm by Park et al. (2001); (iii) *Mycobacteria* that have been detected in water and biofilms of distribution systems (Falkinham III et al., 2001; Le Dantec et al., 2002) with *Mycobacterium avium* known to be a major cause of deaths in AIDS patients; (iv) *Microsporidia*, a parasite, for which a possible water route of contamination was suspected in a microsporidiosis outbreak affecting HIV infected persons (Cotte et al., 1999). Four species of bacteria – *Legionella*, the *Mycobacterium avium* complex, *Aeromonas hydrophila*, and *Helicobacter pylori*– have been recognized as emerging pathogens of concern by Health Canada (2006). However, according to the reference used, the list of microorganisms defined as emerging pathogens may vary and also includes other pathogenic agents such as viruses and protozoa (Szewzyk et al., 2000).

Some of these microorganisms have been included in the US EPA final drinking water contaminant candidate list (CCL2) which includes nine microbiological contaminants, as listed in table 2-3 (USEPA, 2005). This list includes unregulated contaminants that are known or expected to occur in public water systems, that may pose a risk in drinking water, for which historical databases of occurrence are not available, and that could eventually be regulated. Gerba et al. (2003) tested the disinfection resistance of these microorganisms and found that *Mycobacterium* spp. is the most resistant to chlorine, indicating that it will be difficult to control in distribution systems even when a disinfectant residual is present. That could cause concerns in area supplying immunocompromised population.

Table 2-3: US EPA Final drinking water microbiological contaminant candidate list (USEPA, 2005)

Microbial agent	Microorganism
Bacteria	*Aeromonas hydrophila* *Cyanobacteria* (blue-green algae), other freshwater algae, and their toxins *Helicobacter pylori* *Mycobacterium avium intracellulare* (MAC)
Viruses	Adenoviruses Caliciviruses Coxsackieviruses Echoviruses
Protozoa	*Microsporidia* (Enterocytozoon & Septata)

2.1.2 Possible sources of microbial contamination in distribution systems

In the context of an accidental contamination of a distribution system, due to a main break located in the vicinity of a leaking sewer main, or caused by other types of system deficiency, raw sewage becomes a likely source of contamination. Intrusion of raw sewage in distribution system pipes could lead to the introduction of many pathogenic organisms. The types and numbers of microorganisms typically found in untreated wastewater and their corresponding infectious dose (when available) are presented in Table 2-4. Rao et al. (1986) report that more than 120 different virus types are known to be excreted in human faeces by infected persons. These viruses belong to the groups of enteroviruses (polioviruses, coxsackieviruses, echoviruses, hepatitis A), reoviruses, adenoviruses and parvo-viruses. Meschke et al. (2002) indicate that human enteric viruses are shed in human feces at levels exceeding 10^6 units/g. Consequently, the intrusion of faecally contaminated water or soil particles into water mains would certainly represent a health risk that would be more or less influenced by site-specific conditions such as the volume of intruded sewage, the residual disinfectant present, and the type of microorganism introduced.

Table 2-4: Typical microorganisms found in untreated wastewater and corresponding infectious dose (from Metcalf and Eddy, Inc., 2003)

Organism	Concentration (MPN/100 mL)	Infectious dose (number of organisms)
Bacteria:		
Bacteroides	10^{7}-10^{10}	
Total coliform	10^{7}-10^{9}	
Faecal coliform (enteropathogenic *E. coli*)	10^{6}-10^{8}	10^{6}-10^{10}
Clostridium perfringens	10^{3}-10^{5}	1-10^{10}
Enterococci	10^{4}-10^{5}	
Faecal streptococci	10^{4}-10^{7}	
Pseudomonas aeruginosa	10^{3}-10^{6}	
Shigella	10^{0}-10^{3}	10-20
Salmonella	10^{2}-10^{4}	10^{1}-10^{8}
Protozoa:		
Cryptosporidium parvum oocysts	10^{1}-10^{3}	1-10
Entamoeba histolytica cysts	10^{-1}-10^{1}	10-20
Giardia lamblia cysts	10^{3}-10^{4}	<20
Helminth:		
Ova	10^{1}-10^{3}	
Ascaris lumbricoides	10^{-2}-10^{0}	1-10
Virus:		
Enteric virus	10^{3}-10^{4}	1-10
Coliphage	10^{3}-10^{4}	

The infectious dose necessary to infect individuals is quite variable and depends on the type of pathogenic agent. In general, the infectious doses for viruses and parasites are very low in comparison to the number of bacterial pathogenic organisms necessary for infection. Furthermore, viruses and parasites are more resistant to chlorine disinfection than bacteria (USEPA, 2001a). In the case of water contamination due to distribution system deficiency where the only protection consists in the presence of a disinfectant residual, it can therefore be anticipated that the inactivation of virus and protozoa will be much less than for bacteria. This subject will be discussed more in detail in Section 2.3 dealing with the intrusion of microorganisms in experimental settings.

Another likely source of pathogenic microorganisms in distribution system is the soil and shallow groundwater surrounding the buried water mains. A field study by Karim et al. (2003), consisting in the collection of soil and water samples at sites immediately exterior to drinking water pipelines during pipe repairs, was conducted in order to assess the occurrence of indicator microorganisms and the potential for pathogen intrusion due to pressure transients (which is a route of entry that will be discussed in Section 2.2.2.3). As listed in Table 2-5, these authors detected indicator microorganisms and enteric viruses (detected by cell culture and reverse transcription-polymerase chain reaction (RT-PCR)) in more than 50% of the samples examined (from a total of 65 samples). Out of 32 sites investigated, 18 (56.2%) were positive by either cell culture or RT-PCR for one of the three viruses tested (Enterovirus, Norwalk virus, and Hepatitis A virus). Such results therefore suggest that opportunities do indeed exist for pathogens to intrude into the distribution system, either during pressure transients or during pipe repairs.

Table 2-5: Indicator microorganisms detected in soil and water samples collected from repair sites (Karim et al., 2003)

Indicator microorganism	**% of water samples with indicator detected**	**Max concentration in water sample (CFU/100mL)**	**% of soil sample with indicator detected**	**Max concentration in soil sample (CFU/100g)**
Total coliforms	58%	$1.6*10^3$	69.7%	$1.6*10^4$
Faecal coliforms	42.8%	$1.6*10^3$	50%	$1.6*10^4$
C. perfringens spores	30%	$2.5*10^3$	25%	$1*10^5$
Bacillus spores	80%	$4.6*10^6$	96.9%	$1.3*10^8$
Coliphages	6.7%	$1*10^4$	0%	--

2.1.3 Coliform bacteria as the indicator of bacteriological water quality

Routine monitoring of treated and distributed water quality does not involve the measurement of any specific pathogenic or opportunistic pathogenic microorganisms in water samples. This is considered as being of little value on a day to day basis (detection methods development and availability, necessary resources and expertise, etc.) (Allen et al., 2000). Rather, it relies on the presence/absence or enumeration of total coliforms and faecal coliforms/*E. coli* in water samples to assess the microbiological quality of the water. Theoretically, the absence of such indicator bacteria should guarantee the consumer a good quality water, free of any pathogenic organisms. However, the validity of using coliforms as indicators of the microbiological quality of drinking water may be questioned, since:

- **they are sometimes detected when there is no evidence of contamination.** Many water utilities have experienced coliform occurrences in distribution system water samples that could not be directly linked to contamination from treatment barrier breakthrough or intrusion (Martin et al., 1982; Ludwig et al., 1985; LeChevallier et al., 1987; Colbourne et al., 1991; Emde et al., 1992; Oliver et Harbour, 1995; Lu et al., 1997). In such cases, coliforms have been shown to survive under favorable conditions in the biofilm on pipe surfaces or in corrosion or loose deposits.
- **they are sometimes not detected when pathogenic organisms are found in the water.** Waterborne disease outbreaks have occurred in U.S. water systems that have not violated the coliform regulations (Moore et al., 1994; Kramer et al., 1996; Craun et al., 1997). Craun et al. (1997) reported coliforms detection during most (64%) of the waterborne illness outbreaks caused by bacteria, viruses and unidentified agents in the 1983-1992 period in the U.S., but during relatively few (35%) of the outbreaks caused by protozoa. Similar results have also been reported in the UK (Furtado et al., 1998). In their review of the WBDOs reported in the U.S. between 1991-1998, Nwachuku et al. (2002) concluded that coliform bacteria were inadequate to assess an increased risk of waterborne outbreaks caused by *Giardia* and *Cryptosporidium* as well as for some viruses. The more rapid chlorine inactivation of the coliform organisms in comparison to protozoa or other types of enteric viruses (Snead et al., 1980; Payment, 1999) and the fact that enteric pathogens are generally less susceptible to chlorine injury than coliforms (McFeters and Singh, 1991; McFeters, 1997) are factors playing against the validity of coliforms as indicators.

As coliform bacteria comprise a large part of the population of organisms in warm-blooded animal and humans feces, they are often correlated with faecal contamination and may indicate the presence of potentially disease-causing pathogenic organisms in the water. However, many strains of coliforms are also naturally occurring in the aquatic environment, originating from soil and vegetation (Krieg and Holt, 1984). Consequently, the presence of these non-faecal coliforms in distributed water does not necessarily represent faecal contamination but is more indicative of a breach in the water system. Accordingly, the magnitude of the health risk associated with their presence has been somewhat mitigated - a tolerance of 5% for water samples testing positive for non-faecal coliforms on a monthly basis is allowed in the US (USEPA, 1989)). In the province of Quebec, up to 10% of positive total (non-faecal) coliform samples can be collected over a 30-day period (MDDEP, 2005).

To improve the link between faecal contamination and regulations, *Escherichia coli*, (the only coliform that is solely derived from faecal material) has been proposed as a better indicator than total coliforms since simple analytical techniques are now available (Edberg et al., 2000). Moreover, many regulating agencies are suggesting the abandonment of a rule on total coliforms to concentrate only on *E. coli* as the main indicator of faecal pollution (Australian Government, 2003). Table 2-6 gives an overview of the microbiological parameters that must be monitored in order to comply with microbial drinking water regulations in the province of Quebec and in some other countries.

Table 2-6: Microbiological parameters included in various regulations

Province / country	**Microorganism**	**Limit / details**
Quebec (MDDEP, 2005)	Total coliforms	- Max of 10 cfu/100 mL if enumeration method is used - No more than 10% of positive samples on a 30-day period
	Faecal coliforms or *E. coli*	Absent
Canada (Health Canada, 2007)	Total coliforms	0/100 mL - If number of samples collected <10: no sample should be positive - If number of samples collected >10: no consecutive sample should be positive; not more than 10% of samples should be positive
	E. coli	0/100 mL
United-States (USEPA, 2001b)	Total coliforms	- If number of samples collected <40/month: not more than 1 positive sample - If number of samples collected >40/month: not more than 5% are coliform positive samples (Monthly MCL violation) - Acute MCL violation: 1 repeat sample is *E. coli* or faecal coliform positive; 1 routine sample is *E. coli* or faecal coliform positive followed by total coliform positive repeat sample
France (Ministère de la Santé et des Solidarités, 2007)	*E. coli*	0/100 mL
	Enterococci	0/100 mL
United Kingdom (DWI, 2005)	Directive requirements: *E. coli* *Enterococci*	 0/100 mL 0/100 mL
	National requirements: Coliform bacteria *E. coli*	 0/100 mL 0/100 mL

Table 2.6: Microbiological parameters included in various regulations (continued)

Australia (Australian Government. National Health and Medical Research Council, 2004)	*E. coli* or thermotolerant coliforms	0/100 mL

The detection of total coliforms therefore do not pose nor necessarily indicate a health risk (Allen and Edberg, 1997). However, it is often one of the few tools (with HPC measurements) that water utilities use to monitor the bacteriological quality of their water. Consequently, when detected, utility personnel should determine the reasons of the coliform occurrences and take the appropriate actions to resolve such a problem.

2.2 MECHANISMS OF MICROORGANISMS INTRODUCTION INTO DISTRIBUTION SYSTEMS

Two primary mechanisms are responsible for the introduction of coliform bacteria and other microorganisms into distribution systems. They may breakthrough into treated water as a result of inadequate or breach of treatment or be introduced as a result of intrusion into the distribution system downstream of the treatment plant. The first route of entry will only be briefly discussed as the scope of this Ph.D. work is centered on the risk of pathogen intrusion directly in distribution systems. In this latter section, a detailed review of the potential causes of distributed water contamination will be provided.

2.2.1 Inadequate treatment

Coliform presence in treated water is seldom reported, which is logical since the treatment is usually designed to inactivate or remove, at least, bacterial contamination and its efficiency is evaluated using coliform-indicator bacteria. Nevertheless, this absence of coliforms in treated water may only be apparent as:

- only a very small fraction of treated effluents are monitored, making the detection of a time-limited breakthrough illusory (the fraction of the volume sampled for coliform analysis usually ranges from $1/10^6$ to $1/10^9$).
- the microorganisms may remain undetected due to the culture-based techniques used for their detection: coliform injured bacteria following disinfection may not be able to grow on traditional agar media but can be recovered using modified cultivation techniques (McFeters, 1990; McFeters et al., 1986; LeChevallier et McFeters, 1985). Craddock and Castle (1997) detected injured coliforms in 10.4% of 173 treated water samples from four treatment plants in the UK, while routine bacteriological tests indicated that only 0.6% of the samples were coliform-positive.
- Viable but non-culturable (VBNC) cells may be present and consequently not detected at all by culture-based detection methods. Baudart et al. (2002) and Baudart et al. (2005) showed that a significant proportion of *enterobacteriaceae* could be present in treated drinking water under the form of VBNC cells using the DVC-FISH-ScanRDI detection method.

Lack of, or inadequate treatment has led to the detection of pathogenic organisms in treated water such as *Giardia*, *Cryptosporidium* and enteric viruses (Gofti-Laroche et al., 2003; Ali et al., 2004), without the occurrence of waterborne disease outbreak in the supplied population. However, in some cases, waterborne disease outbreaks have resulted in systems fed with treated surface water (as in Milwaukee and North Battleford, see Section 2.1; Rab et al., 1997), treated groundwater (Fogarty et al., 1995; Hrudey et al., 2002), and untreated groundwater (Kukkula et al., 1997; Maurer and Stürchler, 2000; Häfliger et al., 2000). The use of new and improved detection methods is suggesting that pathogenic microorganisms could even be released in treated water following adequate treatment. Monitoring studies for the detection of specific microorganisms in treated drinking water meeting the required water quality regulations (absence of indicators) have shown that:

- viable enteroviruses could be detected in treated water (Grabow et al., 2001; Vivier et al., 2004). Using integrated cell culture/nested PCR approach followed by restriction enzyme analysis, Vivier et al. (2004) detected *Coxsackie B* viruses in 11% and 16% of water samples from two surface water treatment plants (out of a total of 172 samples).
- infectious *Cryptosporidium* could be detected in 1.4% of 1690 100L finished water samples collected from 22 out of 82 surface water treatment plants, using cell culture–polymerase chain reaction (Aboytes et al., 2004). Water quality and treatment plant characteristics were no different for the positive sites than for the sites that had no oocyst detections.

Consequently, the use of molecular techniques for the detection of pathogenic organisms is gradually confirming that the acceptable water quality indicators may not necessarily reflect the virus and parasitical content of treated water.

One mechanism playing an important role in treatment breakthrough is the release of particulate matter in treated water, which may facilitate the introduction of coliforms and other microorganisms into the distribution system. Particles released from granular activated carbon (GAC) filter beds were shown to be colonized with coliform bacteria (Camper et al., 1986). The particulate matter that embeds bacteria offers the microorganisms protection against disinfection (Gauthier et al., 1999; Morin et al., 1999; Stringfellow et al., 1993; Berman et al., 1988; Herson et al., 1987; Ridgway and Olson, 1982). Coliforms may also be associated with other types of particles such as invertebrates. These organisms (nematodes, rotifers and protozoa) have been observed in treatment plant effluent by many authors, e.g. van Lieverloo (1997), Schreiber et al. (1997), Gauthier et al. (1997) and Brazos and O'Connor (1996). Protection of bacteria against disinfection may be provided through ingestion by the protozoa (amoebae and ciliates), nematodes and amphipods (Locas et al., 2007; Ding et al., 1995; King et al., 1988; Levy et al., 1986). Particulate matter and invertebrates might thus protect some microorganisms from treatment plant disinfection and allow them to be transported into the distribution system.

2.2.2 Distribution system intrusion

Intrusion of pathogenic microorganisms into the distribution system can be expected if deteriorated and badly maintained infrastructure is in place. Waterborne disease outbreaks have been linked with the contamination of poorly maintained storage tank (with an inappropriate roof vent and an uncovered hatch allowing free access to wild birds) (Clark et al., 1996; Angulo et al., 1997), and to the combination of lack of chlorination, equipment failure, and back-siphonage in a distribution system (Mermin et al., 1999). In another case, without being in a situation of disease outbreak, the lack of water pressure and cross-contamination between the municipal water supply and sewer system was associated to an increased number of gastrointestinal illnesses in a study where self-reported incidence of diarrhea was compared between two groups (with and without access to piped water) (Semenza et al., 1998).

However, intrusion of pathogenic microorganisms may take place even in well-maintained systems. Four direct pathogen routes of entry have been identified by Kirmeyer et al. (2001). These are: (i) covered and uncovered storage facilities, (ii) water main installation and repair sites, (iii) cross-connections, and (iv) transitory contamination events through water main leakage points. Figure 2-1 illustrates the different components that may lead to intrusion along with the links between each main route. Backflow of non-potable water through cross-connection and transitory contamination are linked as the latter may be considered as a subset of backflow events. Water main installation and repair is in itself a possible pathway for pathogen intrusion, which also involves the operation of valves and hydrants which can lead to transient pressures. Main repair sites therefore appear as particularly vulnerable locations for intrusion. The four main routes of pathogen intrusion are described below.

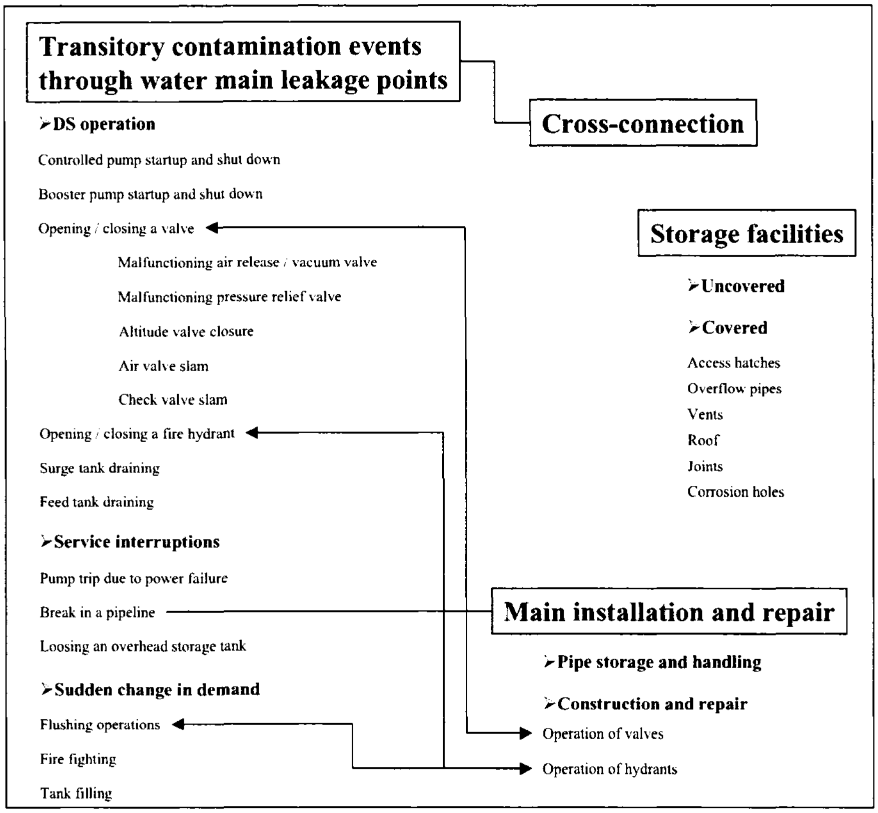

Figure 2-1: Direct pathogen routes of entry into DS (modified from Kirmeyer et al. (2001) and Friedman et al. (2004))

2.2.2.1 Uncovered and covered storage facilities

Uncovered storage facilities located in distribution systems are subject to microbial contamination through the dejection of birds and small mammals that comes in contact with the water. LeChevallier et al. (1997) has measured increased protozoa concentrations following open reservoir storage, however, the organisms appeared to be non-viable. In their study of the factors influencing the occurrence of coliform bacteria in distribution systems, LeChevallier et al. (1996) have confirmed that the presence of open finished water reservoirs is one of the factors responsible for increasing the number of coliform occurrences. To the knowledge of the author, the use of open water reservoir to store treated drinking water is not or rarely used in the province of Quebec.

For covered storage facilities, appurtenances such as access hatches, overflow pipes, vents, roofs, and poorly constructed sidewall joints are potential portal of entry for microorganisms (that would be airborne) (Kirmeyer et al., 2001). Inadequate maintenance of a municipal water storage tank was identified as the cause of a *Salmonella* outbreak reported in Gideon (Missouri) in 1993 (Clark et al., 1996; Angulo et al., 1997). Tears or rips in floating covers could lead to loss of chlorine residual (Harvey et Kopansky, 2007) or contamination of treated water with accumulated rain water, potentially contaminated by bird droppings (Kirmeyer et al., 1999). Contamination of untreated well water in a storage facility, cleaned the previous month, has led to a *Campylobacter jejuni* outbreak in Minnesota in 1993 (Kramer et al., 1996).

2.2.2.2 Cross-connections

Cross-connections, defined as connections between a potable drinking water supply and a non-potable, undesirable or contaminated source, may pose a threat to distribution system integrity (Herrick, 1997) if they are not protected or if the device used for protection fails. Contaminated water may be introduced into distribution pipes from the backflow of water through the cross-connections due to a differential in pressure between the connected systems, especially during low pressure events in the distribution system (backsiphonage) or increased pressure from a non-potable source (backpressure). Lahti and Hiisvirta (1995) reported two outbreaks in Finland caused by cross-connections involving sewage and seawater, both showing evidence of the presence of *E. coli.* In the United-States, US EPA has compiled data from 459 backflow incidents and estimated 12 093 illnesses due to those incidents between 1970 and 2001 (USEPA, 2002a). In the Netherlands, dual water supply was installed in some new housing estates but cross-connection incidents between the drinking water supply system and water supply for non-potable use was one of the reasons leading to the termination of the dual water projects owned by water companies in this country (Oesterholt et al., 2007).

In the white-paper discussing the issue of cross-connection, USEPA (2002a) describes the common types of cross-connections (that can lead to either chemical or biological contamination) that include: irrigation, fire systems, garden/washdown hoses, and boilers. One study by Duranceau et al. (1998) showed that fire systems may be less of a risk in terms of microbial contamination. A detailed investigation of the water quality in 84 wet-pipe fire sprinkler systems showed that total coliforms were mostly absent from those systems. USEPA (2002a) reports that biological contaminants introduced through cross-connections are most often reported as sewage or non-specific microbes. Pathogens such as *E. coli* and *Giardia* have been associated with cross-connection contamination events. Because of the pressure drop induced (and some other site-specific favorable conditions), some maintenance activities (meter repair, main shutdown for valve replacement, and main break) have resulted in backflow of contaminated water into distribution systems.

Most cross-connections generally take place inside the private plumbing system of the customer. In a survey answered by 719 water utilities, Lee et al. (2003) report that 16% of documented cross-connections were in areas under the direct control of the water utility while 83% were in private buildings. The authors also report that 55.5% of the identified cross-connections by utilities were connected to non-health hazards, 39% to health hazards, and 5.5% to sewage. Along with this survey, the authors also performed computer modeling to assess transient flow conditions created by sudden changes in demand (modeled through hydrant opening). The results showed that drastic transient flow conditions could be generated and result in significant pressure loss and flow reversal in distribution systems of any sizes. However, such results were obtained with hydrant opening times of two seconds. The representativeness of such a short opening time with respect to field conditions may be questioned.

In the U.S., although the program requirements may vary widely between states, 50 states have a requirement for the control of cross-connections and/or backflow prevention (USEPA, 2002a). In the province of Quebec, municipalities are not compelled to apply such cross-connection control programs.

2.2.2.3 Transitory contamination events through water main leakage points

Transitory contamination events are related to the occurrence of negative or low pressures in water mains that would result in the introduction (backflow) of untreated water into the main (conditional to an available pathway such as pipe fracture or orifice, cross connection, leaking joints, etc.). A high potential risk of introduction of pathogenic microorganisms into the distribution system exists when transient negative pressure events occur in pipelines (LeChevallier et al., 2003). Pressure transients are caused by abrupt changes in the velocity of water and, as shown in Figure 2-1, multiple factors may lead to their occurrence (distribution system operation, service interruptions and sudden changes in demand), some of which can be controlled whereas some others don't.

The scientific evidence available today shows that:

- **low and negative pressure transients have been measured in full-scale distribution systems.** One of the first occurrences of low pressure transients to be reported in the literature was by Walski and Lutes (1994). More recently, monitoring of distribution systems with high speed pressure transient data loggers has been conducted. Low distribution system transitory pressures have been measured by Kirmeyer et al. (2001) in network areas with history of low-pressure problems and in association with fire flow from hydrants. During their 18-month monitoring of the Davenport (Iowa) distribution system, LeChevallier et al. (2004) reported only five occasions (out of a combined 3 190 days of pressure monitoring) where the pressure dropped below 138 kPa (20 psi), while no negative pressures were recorded. For this same study, considering additional data, Gullick et al. (2005) reported nine low pressure events ($P < 138$ kPa (20 psi)) but still no negative pressure events for a combined 3 286 days of pressure monitoring. In a multiple distribution system study, fifteen negative transient pressures events were measured by Gullick et al. (2004) in four out of the eight systems monitored. The main cause of negative pressure was a sudden shutdown of pumps at a treatment plant or pump station. Null or negative pressures lasted from 0.55 to 165 seconds. Based on a total of 499 days of logger data in a distribution system with about 60 000 connections, Hooper et al. (2006) recorded 11 low pressure events where the pressure was below 138 kPa. The minimum pressure that could be recorded by the loggers used in this study was 0 kPa.

- **indicator microorganisms and enteric viruses have been detected in soil and water surrounding water mains.** The work of Karim et al. (2003) previously discussed in Section 2.1.2 showed that recovery of these organisms was common in the systems investigated. Early work conducted by Harris (1959) showed that elevated bacterial densities were found in trench bottoms next to existing pipes and that moisture content increased the counts substantially. The potential for bacterial contamination from damp soil near a leaking main is therefore elevated. Sewerage from leaking sewer mains can certainly contaminate the soil surrounding drinking water pipes as microorganisms are transported through soil. A review by Abu-Ashour et al. (1994) showed that microorganisms can migrate significant distance in soil through macropores, worm holes, cracks and fractures. The transport mechanisms involve advection and dispersion, that are influenced by the effects of filtration, adsorption, desorption, growth, decay, and sedimentation. Common engineering standards typically call for an horizontal separation of three meters (10 ft) and vertical separation of 0.45 meters (18 in) between drinking water and sewer lines (Kirmeyer et al., 2001). In the province of Quebec, the Directive 001 (Ministère de l'Environnement du Québec, 2002) calls for a 0.3 meters (12 in) horizontal separation between the closest drinking water and sewer pipe walls and a 0.3 meters (12 in) vertical separation between the bottom of the drinking water main and the top of the sewer main, the drinking water main being located above the sewer main. If there is any increased risk of potential contamination, a minimal three meters (10 ft) horizontal distance between the drinking water and sewer main is required. In older sections of distribution systems, it can be wondered if such standards are always observed.

- **Intrusion volumes have been measured in a pilot-scale test rig** that has been used to simulate intrusion associated with transient pressures (Boyd et al., 2004a; Boyd et al., 2004b). Intrusion volumes were assessed using three methods: a chemical tracer (cesium) method, a volumetric method and using theoretical estimates. The chemical tracer method showed average intrusion volumes of 11.4 and 71.2 mL for a 0.91 m (3 ft) external head and orifice diameters of 3.2 mm (1/8 in) and 6.4 mm (1/4 in.) respectively. Although higher values were obtained by the other two methods, the chemical tracer method clearly showed that the water that intruded was not merely re-extruded during the transient event. Although differences exist between a test rig and a full-scale distribution system, this study provides strong laboratory evidence that intrusion can occur during transient pressure events and that part of the intruded material remains in the pipe. Prior to this study, intrusion volumes had been modeled for three full-scale distribution system sections using surge analysis with the SURGE 5.2 model from the University of Kentucky (Kirmeyer et al., 2001). This model includes a so-called leakage/intrusion element that can be placed at nodes susceptible to low pressure conditions. The volume of intrusion/leakage is then calculated at each specified node depending on pressure conditions. Different conditions were used for simulation: (i) transient duration (from 20 to 120 seconds), (ii) external head (between 0.3 and 3 m (1-10 ft), (iii) orifice diameter (between 0.8 to 51 mm (1/32 to 2 inches)), and (iv) assumed leakage flow (assumed or derived from utility records). However, the calculated intrusion volumes under different scenarios (power loss, main break, and fire flow) were not field verified and served as a comparison purpose only. LeChevallier et al. (2004) also performed intrusion simulations for 14 cases modeled using surge analysis as part of the Davenport (Iowa) study using the Surge2000 model (University of Kentucky). Intrusion volumes in the distribution system varied from

0 to 20 L (5.27 gallons) for a simulation of power outage resulting in seven pump trip. A wave speed of 914 m/sec (3000 ft/sec) and an external head of 0 m were used.

Distribution system characteristics and conditions that contribute to the occurrence of low and negative pressure have been investigated by Fleming et al. (2006). Using the results of transient (or surge) modeling for 16 distribution systems, the authors observed that systems delivering less than 38 ML/d (10 mgd), using groundwater as the source water and with few floating storage facilities were more susceptible to low or negative pressures. Other characteristics found to increase susceptibility within a system included: located near a pump station with downstream velocity greater than 0.9 m/sec (3 ft/sec), located greater than 1.6 km (one mile) away from elevated storage, elevation greater than 12-15 m (40-50 ft) above surroundings, located near a dead-end or near a hydrant on a major main.

However, the missing link between the evidences mentioned above (occurrence of transient negative pressures, microbial contamination of soil and water surrounding water mains, and intrusion volumes obtained through laboratory settings or modeling) is the actual measurement of intruded material in a full-scale distribution system due to the occurrence of a low/negative pressure transient. Recently, a *Giardia* outbreak in a trailer park was related to a power outage that created a negative pressure transient in a distribution system. Contamination entered the system either through a cross-connection or a leaking pipe close to a sewer crossing (Blackburn et al., 2004). In England, a case-control study of sporadic cryptosporidiosis showed a strong association between self-reported diarrhea and reported low water pressure at the faucet (Hunter et al., 2005). The methodology used was based on the completion of a postal questionnaire where the respondents were asked if they had had a case of diarrhea within the two weeks preceding the reception of the questionnaire. Among other things, they were asked if they had a loss of water pressure at home during the same period.

Possible pathways for pathogen intrusion include the ones related to pipeline structural integrity: pipe fracture, deflections at flexible couplings, leaking joints, and deteriorating seals (Kirmeyer et al., 2001). Consequently, leak detection programs are usually recommended in order to minimize the risk from transitory events as well as for other economical and operational considerations. However, leak detection programs could sometimes result in a decline in water quality due to increased stagnation time of water in the system due to the reduction of leaks (Deb et al., 2000). As reported by these authors, the Boston Water and Sewer Commission experienced such a situation throughout the course of their leak reduction program. However, the problem was resolved by practicing pipe flushing and replacing larger mains with smaller ones where warranted. Colombo and Karney (2003) argue that the presence of leaks offers a protection against pipe bursting as leakage is an important mechanism for mitigating transient pressures in distribution system. However, a quantitative analysis of this effect is not straightforward.

Cross-connections (as described in Section 2.2.2.2) and (submerged) air-vacuum valves are also possible pathways for the introduction of microorganisms. Illustrating this last path, McMath and Casey (2000) measured sub-atmospheric pressures at one distribution system point downstream of the pumping station of a UK system during surges. The authors observed that this point (an air valve vault) was flooded with dirty water during wet weather, thus explaining the high coliform failure rate in the corresponding distribution system area. In a survey of 26 water utilities conducted by Kirmeyer et al. (2001), 12 utilities indicated that the number of flooded valve vaults in their system could vary between 0 to 80% of total vaults. Location of water mains below the water table may be more at risk if the external head is higher than the internal system pressure.

2.2.2.4 Main installation and repair

Water main repair has been associated with waterborne disease outbreaks as in the case of Cabool, MI (Section 1.1). Record low temperatures in December 1989 resulted in 43 outdoor service meters to freeze and two major distribution lines to break (Geldreich et al., 1992). The meters had to be replaced (some were found to be submerged under water) and the pipes repaired. This was combined to an undersized and deteriorating sewer collection system that was found to overflow through manholes, contaminating surface soil and runoff. Consequently, this contaminated runoff could have entered the system while the repairs were conducted. In Sweden, a waterborne disease outbreak affecting 10,000 people was due to a change in pipeline (Andersson et Bohan, 2001). The pipeline, containing stagnant raw water was brought into use without being flushed first. In France, the servicing of a large transmission main (24 in. or 60 cm diameter) after several weeks of construction work corresponded with an increase of diarrhea among the population, although the number of affected people could not be evaluated (Deshayes et al., 2001). About 60,000 people were without drinking water for a 15-day period as faecal coliforms and sulfite-reducing spores were detected in the water.

A list of the potential sources or pathways of microbiological contamination during pipe repair has been compiled by Pierson et al. (2001) from the input of the utilities participating to the project. The authors determined three phases where contamination could occur: (1) prior to construction/repair, (2) during construction/repair, and (3) after construction/repair, as detailed in Table 2-7.

Table 2-7: Potential sources of contamination during water main repairs (Pierson et al., 2001)

Phase	Potential contamination source	Relative level of risk	
		Common	Higher risk
Pre-installation exposure	Soil/sediment entry	X	
	Animal/human wastes		X
	Dead animals		X
	Unsanitary human contact	X	
	Incidental dirty water (runoff, sprays)	X	
	Trash/garbage	X	
Repair activities	Soil/sediment entry	X	
	Animal wastes		X
	Unsanitary human contact	X	
	Water from broken water pipe enters trench	X	
	Groundwater enters trench	X	
	Sewage water enters trench		X
	Agricultural runoff enters trench		X
	Rainfall fills trench	X	
Post-repair conditions	Transitory pressure variations	X	
	Backflow/cross-connection to service line	X	
	Cross-connection to system (hydrant)	X	
	Contaminated potable water supply		X

A case of contamination prior to installation has been reported by Haas et al. (1998). Although swabs of an internal surface of a 12 in. (305 mm) pipe stored on the curbed side of the street and exposed to the local environment was negative for the presence of total coliforms, 75% of the swabs were positive for noncoliform bacterial growth on membrane filters and 100% were positive for HPCs. The presence of noncoliform growth is used by the Philadelphia Water Department as an indicator for contamination such that the authors concluded that contamination may be influenced by the conditions of pipe storage prior to installation.

During the repair activities, points of concern of 250 water utilities surveyed by Haas et al. (1998) were mainly unsanitary construction practices (for nearly 40% of the utilities surveyed) and contamination from soil and trenchwater exposure (for 20% of the utilities). As discussed previously (Section 2.2.2.3), soil and water samples from trenches can be potentially contaminated with microorganisms (Harris, 1959; Karim et al., 2003). Several factors are likely to influence the potential for contamination during repair: shutdown time, nature of the excavation, method of repair, storage or cleanliness of materials, and size of the job (Haas et al., 1998). As such, in order to minimize the potential contamination, main repairs should be conducted "under pressure", i.e. the water main is not isolated or completely shut down by closing valves (Kirmeyer et al., 2001). In the survey conducted by these authors, 6 of 26 water utilities reported that no water mains were repaired under pressure. Pierson et al. (2001) reports that potential cross-connections that may be associated with main repairs include backflow from a contaminated service connection, connection of a contaminated flushing point to the repaired section of main, and flow of contaminated water across a leaking or improperly seated isolation valve.

LeChevallier et al. (2006) monitored male-specific coliphages (viruses that infect *E. coli*) in water samples from the Davenport (Iowa) chloraminated distribution system for about a year and a half and detected these microorganisms in 5.6% of the samples (average concentration of 0.1 pfu/100 mL – range of 0-5 pfu/100 mL). They had more than 77% of the positive coliphage samples that occurred within 72 hours of a main break. The authors speculated that the presence of coliphage could be associated with the unusually large number of main breaks during the winter months, although the two events were not closely related (Figure 2-2). They hypothesized that the poor effectiveness of the chloramine residual against viruses could have contributed to their survival in the distribution system or in biofilms. However, the association was not particularly strong and the authors determined that additional research was necessary to establish a link between these parameters. The use of GIS-linked mapping has been suggested.

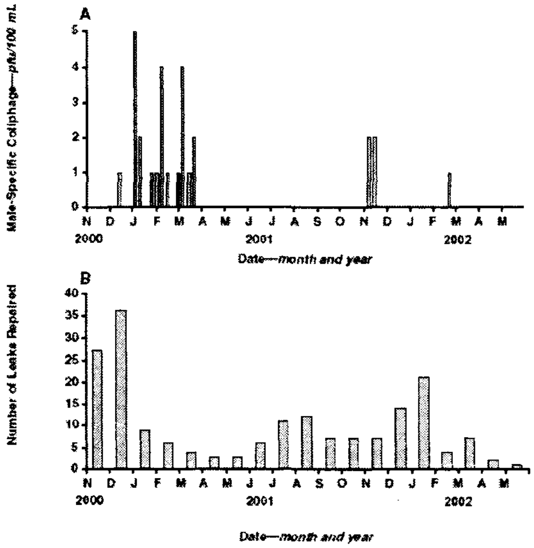

Figure 2-2: Occurrence of male-specific coliphage detected from water samples and pipeline repairs in the Davenport distribution system (LeChevallier et al., 2006)

After the repair is completed, flushing, disinfection (according to AWWA Standard C651), and water quality testing are the recommended actions for contamination control (Pierson et al., 2001). Haas et al. (1998) reports that another potential source of contamination may come from stagnant water created by closed valves adjacent to the area of the construction or repair. In the Netherlands, results of water quality testing after invasive distribution system operations provided by three water companies showed that 0.57% of 16,047 water samples collected after operations contained *E. coli* or thermotolerant coliforms (van Lieverloo et al., 2006). A recent study in Norway showed that pipe breaks and maintenance work (with presumed loss of water pressure) in distribution systems caused an increased risk of gastrointestinal illness among water recipients (Nygard et al., 2007). Following 88 low pressure episodes taking place in seven distribution systems, exposed and unexposed households were selected and interviewed within 8-14 days after the episodes. They were asked, among other things, if they had noticed any discolouration or strange taste of tap water or if they thought any work was done on water pipes recently. They were also asked about episodes of acute gastrointestinal (GI) illness in household. During a 1-week period after the episode, 12.7% of the exposed households reported GI illness compared with 8% in the unexposed households. Unfortunately, few water quality data were available to correlate with the results obtained. Water samples were available for only 18 episodes and one sample was found positive for *E. coli*. No information regarding the level of residual disinfectant used in the distribution systems was given.

Using U.S. statistics on the occurrence of water main breaks compiled in 1992 and the total miles of mains (as of 1994), Kirmeyer et al. (2001) estimated that about 237,600 water main repairs are performed annually in the U.S. The same type of estimation was not found for Canada, but the frequency of repairs is likely to be high. Mirza and Haider (2003) reported the results of a Canadian municipal infrastructure survey conducted in 1995/96 by McGill University and the Federation of Canadian Municipalities that showed that 59% of the water distribution networks were in unsatisfactory condition at that time.

2.3 IMPACT OF DISINFECTANT RESIDUAL ON MICROBIAL INTRUSION

2.3.1 Experimental studies

As discussed in the previous sections, potential routes of microbial intrusion into a distribution system include cross-connections, intruded material remaining after repair work, ill-maintained storage tanks and pipe leaks or other orifices when transient negative pressures occur. If no residual disinfectant is used in the system, it can be hypothesized that microorganisms will be able to survive and colonize pipe biofilm for some time. However, if a residual disinfectant is in place, will such microorganisms be inactivated? Will they be able to colonize the biofilm? In order to provide some insight into these questions, this section of the literature review was reorganized into an in-depth review paper submitted to a peer-reviewed journal (the *Journal of the American Water Works Association*) and can be found in Chapter 4. The paper discusses the data of published studies that simulate intrusion and examine the fate of microorganisms introduced into experimental systems. Various testing scales are evaluated in order to determine what can be learned from these experiments.

2.3.2 Modeling studies

Another way to assess the effectiveness of a disinfectant residual against the intrusion of pathogens in distribution systems is through the use of theoretical approaches and modeling. While many papers are available on the simulation of chlorine (and other water quality parameters) in distribution systems (Munavalli and Mohan Kumar, 2004; Tryby et al., 2002; Rodriguez and Sérodes, 1999; Gagnon, 1998; Rossman et al., 1994), to the knowledge of the author, two groups have published research work illustrating the action of a disinfectant residual on microbial intrusion in a distribution system. These studies are based on the use of hydraulic modeling. Upgrades to the EPANET model, which in its original format is limited to track the dynamics of a single component as it is transported through the network, now allow the modeling of the fate and transport of multiple dissolved constituents in distribution system (Uber et al., 2004). This new EPANET extension is now available as EPANET-MSX (Multi-Species eXtension) (USEPA, 2007).

Propato and Uber (2004) developed a simulation framework based on water quality modeling coupled with a statistical approach to quantify the risk of delivering infected water to consumers. The framework includes the following elements:

- a network hydraulic model, performing an extended period simulation;
- a microbial intrusion model, where intrusions are equally likely to occur at any point of water consumption and modeled as constant mass flow rate of an infinite duration. As noted by the authors, such assumptions are more consistent with the worst-case scenario of intentional intrusion. The only mechanism that is considered for microbial inactivation is the effect of the residual disinfectant;
- a residual maintenance strategy, that may consider booster chlorination, conventional dosing at the treatment plant, use of free chlorine or chloramines;

- a network water quality model, that uses the Chick Watson kinetics for the rate of inactivation of microorganisms coupled with a 1st order kinetic model for the decay rate of disinfectant;
- a vulnerability assessment, that provides "vulnerability curves" showing the probability that the fraction of the population exposed to contaminated water is less than or equal to a specified value.

Case studies performed on two water distribution systems, using *Giardia* as the intruded microorganism, showed that the risk of consumer exposure was affected by the residual maintenance strategy employed. A chloramine residual was found to be less effective than free chlorine and offered only a very modest improvement when compared to when no residual was used. The addition of booster chlorination at storage tanks was found to improve consumer protection. The level of improvement of such a practice was found to be a function of the size of the population served by the storage tanks.

Baribeau et al. (2005) also used the EPANET-MSX model (with first-order (Chick Watson) inactivation kinetics), to model the disinfectant residual effectiveness on the intrusion of *Giardia* (worst-case scenario) and *Escherichia coli* O157:H7 (an average organism) at a specific distribution system location. The authors concluded that a free chlorine residual of 0.5 mg/L was insufficient to provide adequate control of *Giardia* (concentration of 5000 cysts/L) but could provide ample protection against *E. coli* (5000 cfu/L). Chloramines were predicted to have a negligible effect even on a relatively susceptible organism such as *E. coli.*

2.4 RISKS RELATED TO ACCIDENTAL INTRUSION OF MICROORGANISMS IN DISTRIBUTION SYSTEMS

The concept of risk, linked to intrusion of microorganisms in distribution systems, may be divided into two types. First, there is the risk of microbial intrusion associated with system operational practices and maintenance activities. Secondly, there is the subsequent risk of infection associated with the consumption of contaminated drinking water due to accidental microbial intrusion. These two types of risks are described below.

2.4.1 Risk of microbial intrusion due to system O&M activities

Research work has been conducted to identify distribution system locations most susceptible to intrusion by Lindley and Buchberger (2002). These authors have developed a framework based on hydraulic modeling and geographic information system (GIS) to integrate multiple risk factors including historical break data, locations susceptible to adverse pressure, susceptibility because of intrusion pathways, and susceptibility from existence of a contaminant source. Implementation of this framework involves obtaining the appropriate data sets, performing hydraulic simulations, estimating structural integrity, locating high-risk connections or sensitive populations and performing spatial data queries.

A different type of approach, called the Hazard Analysis and Critical Control Point (HACCP) approach has also been used to identify potential hazards in distribution systems. The HACCP approach has been identified as an interesting framework for managing risks related to drinking water (Deere et al., 2001). The intent of HACCP is to focus on system control at critical points throughout a process, thereby preventing hazards from occurring, or reducing hazards to an acceptable level (Martel et al., 2006). Besides, this proactive approach is the basis of the drinking water guidelines issued in countries such as Australia (Australian Government, 2004) and of the water safety plans making up the drinking water quality guidelines issued by the World Health Organization (WHO, 2004).

The first application of HAACP to drinking water supply has been performed by Havelaar (1994). The author identified the major hazard in distribution system as being the recontamination of treated water during storage and distribution. The critical control points have been defined as: adequate construction, maintenance of positive hydrostatic pressure at all times, and application of hygienic precautions when laying new mains or working on existing facilities. Within the framework of an AwwaRF project, Martel et al. (2006) report on the prioritization of the potential hazards in the distribution system of the city of Austin (TX) following the application of HACCP: backflow through unprotected cross-connections, contamination at new construction sites, backflow from failing septic systems into distribution main, contamination due to water main break or repair and pathogen intrusion to distribution main due to leaky sewage main were the top five hazards out of ten listed.

2.4.2 Risk of infection associated with consumption of contaminated drinking water due to accidental intrusion

In order to estimate the potential level of infection that a pathogenic microorganism may induce in a population, quantitative microbial risk assessment (QMRA) is used and is generally based on the following four conceptual steps, as described by Haas and Eisenberg (2001):

- hazard identification: identification of a pathogen as an agent of potential significance.
- exposure assessment: determination of the microbial doses typically consumed by the direct user of a water and routes, amount and duration of the exposure.
- dose-response assessment: analysis of dose-response curve for which it is generally necessary to extrapolate a fitted curve into the low-dose region.
- risk characterization: combination of the information on exposure and dose-response into an overall estimation of likelihood of an adverse consequence. This can either be presented as a point estimate of risk or as a distribution of risk.

Haas and Eisenberg (2001) have noted some limitations of the QMRA framework for the assessment of microbiological risks. QMRA was initially developed for chemical risk assessment, and it does not consider properties that are unique to infectious disease transmission (secondary (person-to-person) disease transmission, long- and short term immunity, and the environmental population dynamics of pathogens).

QMRA has been used by Westrell et al. (2003) to evaluate the anticipated annual number of infections in a study population caused by *Cryptosporidium parvum*, rotavirus, and *Campylobacter jejuni* for different treatment failures (precipitation, filtration, disinfection malfunctions) and distribution failures (cross-connection, reservoir and pipe contamination). In the system studied (Gothenburg, Sweden), sub-optimal particle removal and disinfection malfunction were the main risk incidents whereas distribution system incidents were less frequent and only affected a small proportion of the population. However, it is interesting to note that a major part of the potential yearly infections originated from the normal operation of the system and not from failures.

A calculation method to assess the risk of contamination during distribution has been developed by van Lieverloo et al. (2006) within the framework of the "Microrisk" research project supported by the European Commission. The authors based their assessment on the pathogen to *E. coli* ratio for possible contamination sources such as untreated sewage, surface water and soil/shallow groundwater (surrounding water mains) as an index for pathogen concentrations in water samples. The representative pathogens selected were *Cryptosporidium* and *Giardia* for protozoan parasites, *Campylobacter* for bacteria and enterovirus for viruses. Retrospective pathogen exposures were calculated for different conditions such as during a waterborne outbreak taking place in the Netherlands in 2001, during 50 non-outbreak faecal contamination events recorded by seven water companies in the Netherlands from 1994 through 2003, and during incidental occurrence of *E. coli* using positive *E. coli* sample data supplied by 22 water companies from five countries. The authors used bootstrapping to multiply the probability density functions (PDF) of positive *E. coli* concentrations and pathogen to *E. coli* ratios to obtain a PDF of pathogen concentrations. Because the source of contamination events in distribution systems is often unknown, the authors concluded that the developed method was flawed mainly because of the uncertainties and variation of the actual pathogen to *E. coli* ratios between and within possible contamination sources. Enterovirus to *E. coli* ratios in soil and shallow groundwater were calculated using the Karim et al. (2003) data and were found to be much higher than in surface water or untreated sewage calculated using data from the Netherlands and Germany. Mean exposure to enterovirus was almost a million times higher when assuming pathogen to *E. coli* ratios from soil/shallow groundwater than from untreated domestic sewage. Because of such large variations, the proposed method was found barely applicable to estimate pathogen concentrations and resulting infection risks to consumers during faecal contamination events. However, in the current absence of a better index of pathogen exposure it is still considered by the authors as the only method available to estimate the possible health effects for consumers.

A framework for estimating the spatial and temporal distribution of health impacts resulting from ingestion of contaminated drinking water has been proposed by Murray et al. (2006). This framework considers the use of a dynamic disease model (which predict temporal spread of disease through susceptible, infected and recovered subpopulations), a dose-response curve with the potential dose calculated from flow and transport simulations using a hydraulic model. One potential application of this model is to help in designing a spatial network of sensors to detect contamination events.

In terms of assessing the risk for public health from intrusion specifically resulting from low/negative pressure transients in distribution system, LeChevallier et al. (2003) have identified the following factors as influencing the magnitude of this risk:

1. number and effective size of orifices (leaks)
2. type and amount of contaminant external to the distribution system
3. frequency of the pressure transient event
4. duration of the pressure transient event
5. magnitude of the pressure transient event
6. population exposed

The authors note that to this day, there is insufficient data to indicate whether pressure transients are a substantial source of risk to water quality in the distribution system. McInnis (2004) has developed a relative-risk framework (based on the QMRA concept) for the evaluation of transient pathogen intrusion in distribution systems. The author used a reference groundwater contamination, intrusion volumes are obtained through transient modeling, and transport of contaminant is simulated using a water quality model (taking into account the free chlorine residual inactivation on coliform bacteria). The concentration data are then input into a Monte Carlo simulation which provides a probability distribution of the number of microorganisms ingested by a given receptor (which depends on the frequency distribution of the time to draw and consume water, time at which water is consumed during intrusion event and volume of water consumed). The model was not specifically used for the estimation of the actual risks to human health (because of the difficulty to obtain all required data) but rather for the estimation of the risk reduction achieved from various mitigation strategies.

CHAPTER 3

RESEARCH OBJECTIVES AND METHODOLOGY

3.1 CRITICAL REVIEW OF THE LITERATURE ON DISTRIBUTION SYSTEM INTRUSION

In general, the link between the contamination of distributed water and occurrence of operation and maintenance activities in distribution system is mostly based on specific cases resulting in waterborne disease outbreaks (Geldreich et al., 1992; Mansotte et Beaudeau, 1999; Deshayes et al., 2001; Andersson et Bohan, 2001). It is also possible to know the fraction of reported outbreaks (particularly in the U.S.) which can be attributed to distribution system deficiencies (Craun et Calderon, 2001; Blackburn et al., 2004; Liang et al., 2006). However, without being in a situation of disease outbreak, water utilities can be faced with non-compliance events (with respect to regulations) due to the occurrence of positive coliform samples in their distribution system. No specific study of the fraction of these non-compliance events that can originate from distribution system activities has ever been compiled.

Four direct pathogen routes of entry into a distribution system have been identified by Kirmeyer et al. (2001). These are covered and uncovered storage facilities, water main installation and repair sites, cross-connections, and transitory contamination events through water main leakage points. The concern of pathogen intrusion into distribution system due to negative or low pressure transients is relatively recent, with the first papers on this topic published in the late 1990's. It has been shown that negative pressure transients occur in full-scale distribution systems (Gullick et al., 2004), that the soil and water surrounding water mains may be contaminated with faecal pollution (Karim et al., 2003), and that intrusion of contaminated water takes place under negative pressure transients, as verified under pilot system simulation conditions (Boyd et al., 2004a; Boyd et al., 2004b). These studies lend support to the current concern that intrusion phenomena may be more common in full-scale distribution systems than previously believed, but evidence of water contamination under such conditions in full-scale systems has not been assessed yet. Recent studies have suggested a link between the occurrence of low pressure events (associated with pipe burst and occurrence of other maintenance work) and increased gastrointestinal illness rate in the population (Hunter et al., 2005; Nygard et al., 2007). However, no measurements have been conducted in real networks to actually monitor changes in distributed water quality under the different distribution system operational characteristics that may lead to the occurrence of low and negative pressures either transient or sustained (standard operation, service interruptions and sudden changes in demand).

For the other intrusion pathways, most of the data available to assess their importance in terms of pathogen intrusion rely on the occurrence of waterborne disease outbreaks, surveys among water utilities, and intuitive thinking. Although field studies assessing the impact of cross-connections can be relatively difficult to accomplish, such studies can certainly be conducted to investigate main installation and repairs, and provide a basis on which to evaluate risks.

By looking at the links existing between each main route of intrusion (Figure 2-1), main repair sites appear as a particularly vulnerable location for intrusion because of the operational characteristics involved as part of this maintenance activity (repair procedure itself, operation of valves and hydrants). Moreover, the conclusions of our literature review of experiments simulating intrusion of microorganisms suggest that conditions experienced when pipe break repairs are conducted in full-scale systems are likely the most favorable to pathogen persistence in a water system. To this day, no descriptive studies have been conducted on the impact of repair procedures on water quality. Although it is generally assumed that water utilities apply the AWWA Standard C651 for disinfection after repairs, this is far from always being the case and disinfection is likely to be applied only after major repairs are conducted. Limiting the time that water service is interrupted is one reason for this (Burlingame and Neukrug, 1993). Moreover, the impacts of repair procedures outside of the isolated distribution system area are hardly addressed in the existing literature. Only Haas et al. (1998) mentioned that stagnant water created by closed valves adjacent to the area of the construction or repair may become problematic, but no data were provided.

Some authors have argued that monitoring for microbial intrusion, particularly from pressure transients, is impractical (LeChevallier et al., 2003). This is certainly true if no specific activities are targeted. However, it is felt that by intensively monitoring some specific O&M activities, it will increase the chance of measuring transient pressures and resulting water quality variations.

Our in-depth review of the experimental studies investigating the fate of microorganisms injected in simulated distribution systems clearly showed that the conclusions about the efficacy of a disinfectant residual to protect against pathogen intrusion are not converging. The laboratory-scale (or bench-scale) systems, the pilot-scale systems and the full-scale system all lead to different observations. To the knowledge of the author, a comprehensive review such as the one presented in Chapter 4, has never been published before.

Finally, although the HACCP concept may be used to target critical control points in terms of intrusion, scientific data are necessary in order to assess the importance of operational practices and maintenance activities on potential intrusion in distribution system. This first step is necessary to eventually assess the subsequent risk from intrusion on public health.

3.2 OBJECTIVES

The main question that this research seeks to answer is the following one:

What is the risk of microbial contamination in a drinking water distribution system when routinely conducted operation and maintenance activities take place?

The main objective of this research project is to assess the conditions leading to intrusion of contaminants in a system during a set of standard operations and maintenance activities in order to identify solutions to minimize such events and protect public health. On a more detailed level, this project will seek to:

1. Demonstrate through data mining that a significant portion of non-compliance events may be linked to distribution system operation and maintenance activities;
2. Investigate, in full-scale distribution systems, the link between O&M activities, distribution system hydraulics and potential water quality changes (with an emphasis on the occurrence of negative transient pressures and microbial intrusion);
3. Achieve transient and intrusion modeling to assess the potential level of intrusion associated with negative pressure events in a full-scale distribution system.

The fulfillment of these objectives will allow us to bring the following innovative contributions:

- The development of an approach allowing to identify the causes of water quality variations in distribution systems (such as the occurrence of coliform positive samples);
- The characterization of potential microbial intrusion pathways in a full-scale distribution system;
- A detailed field investigation of a selection of operational and maintenance activities and their impact on system hydraulics and water quality;
- An assessment of potential intrusion volumes in a full-scale distribution system during negative pressure events obtained through modeling;

The completion of this project is based on the following research hypotheses:

1. Although O&M activities (such as pipe flushing for example) are beneficial on the long run for improving water quality in a distribution system, they can lead to short-term negative impacts such as the occurrence of coliforms at routine sampling points.

This hypothesis may be demonstrated by comparing the spatio-temporal occurrence of positive coliform samples with the spatio-temporal occurrence of maintenance work in a system using historical databases.

2. Main repair procedures influence the level of potential contamination inside and outside the isolated distribution system area.

   This hypothesis may be verified by conducting water quality samplings during repairs of water mains using a protocol allowing for simultaneous sample collection both outside and inside the distribution system area isolated for repair.

3. Standard distribution system operation and some maintenance activities may lead to measurable pressure transients that may in turn cause significant contamination by ingress in full-scale distribution systems.

   This hypothesis may be verified by monitoring pressure, characterizing potential pathways of intrusion and conducting water quality samplings during some selected O&M activities in full-scale systems. Intrusion levels related to negative pressure events associated with standard system operation may be assessed by using transient modeling based on field monitoring data.

3.3 METHODOLOGY

The research plan included three main steps as described below.

3.3.1 Demonstration, through data mining, that non-compliance events may be linked with distribution system O&M activities

Testing for the presence of coliform bacteria is usually conducted by water utilities in order to assess the microbiological quality of their distributed water and conform to the regulations in place. This first task therefore consists in identifying the causes of the positive colifom samples collected in distribution systems to determine the fraction that can be attributed to O&M activities. This is done in order to identify the most critical activities with respect to distribution system water quality and fulfill our research objective #1 (Section 3.2). In 2002, a review paper has been produced by the author of this thesis (Besner et al., 2002) with the main intent of explaining the occurrence of coliforms in distribution systems and showed that O&M activities were a likely source of contamination (the contribution of this paper was recognized by the American Water Works Association (AWWA) as it was awarded the 2004 AWWA Distribution & Plant Operations Division Best Paper Award). Such evidence was the starting point of this first research objective.

This first research task was conducted using a data integration approach based on the consideration of historical databases. The concept of data visualization and database query was used to facilitate the identification of the spatio-temporal relationship between the coliform data and the other types of data available. Within the framework of the author's master thesis (Besner et al., 2001), a version of a simple visualization tool was developed in collaboration with the MADITUC group from Ecole Polytechnique (Professor M. Trépanier and R. Chapleau). This collaborative work with the MADITUC group was continued during this Ph.D. work resulting in an improved version of a prototype of an interactive database analyzer. Although it has been used for a research purpose, this innovative tool was also transferred to the participating water utilities, allowing them to manage their own databases.

Databases were collected from five water utilities with different water types and operating characteristics. These utilities, located in North-America and Europe are the City of Laval (Quebec, Canada), the City of Montreal (Quebec, Canada), the City of Moncton (New-Brunswick, Canada), the City of Egham (United-Kingdom), and the City of Caen (France). The main steps of the work conducted for this task are decribed below.

3.3.1.1 Database collection

In order to identify the causes of the occurrence of coliforms in a distribution system, many parameters, and not just water quality data, must be taken into account. The typical parameters are listed in Table 3-1:

Table 3-1: Typical database parameters needed for distribution system water quality investigation

Data type	Parameters
Quality data (source water, treated water, distributed water)	Coliform bacteria, heterotrophic plate count, disinfectant residual, conductivity, temperature, pH, turbidity, etc.
DS structural characteristics	Node elevation, pipe diameter, pipe length and roughness coefficient, pipe material and year of installation, presence of storage tanks, pumps and valves characteristics, hydrants and valves location, etc.
DS hydraulics	*Epanet* simulated parameters (flow, velocity, pressure, residence time, etc.), Field measurements
DS operation & maintenance data	Valve/hydrant maintenance program, flushing program, pipe relining and cleaning, new pipe installation, pipe leaks and breaks, firefighter interventions, SCADA results, etc.
Geographical data (GIS)	Street names and lay-out, municipality limits, land use, etc.

DS: Distribution system; GIS: Geographical information system

For each water utility, a database, as complete as the local availability of the information allowed, was built to include water quality parameters, system hydraulics and distribution system operation and maintenance work (including accidental events, as far as feasible). If possible, the data for a period of at least four years was requested.

The goal was to integrate all these different types of data under the same platform, designed to include a geographical component allowing data visualization. This may seem straightforward at first, but database management may be quite variable between and within water utilities. Data are often dispersed among different departments (laboratory, public works, planning, etc) and can also be available under different formats (from paper to electronic files to ready-to-use GIS files).

3.3.1.2 Data formatting and geocoding

Data formatting consisted in correctly classifying data, along with their associated attributes (complementary information used to describe an event such as a date, an address, a description, etc.), in fields in Microsoft Excel spreadsheets. This software is used to store data as it presents the advantages of being universal and very flexible to import/export data with the different types of information management systems available in utilities.

A data geocoding step (i.e. allocation of geographical (x-y) coordinates) was then performed to achieve data visualization using a GIS-type software. In databases, the data referenced using (a) a street address, (b) a street intersection, or (c) an item ID (such as a valve or hydrant) do not implicitly contain the (x-y) coordinates necessary to locate the information on a map. Geocoding was achieved using a correspondence file where (x-y) coordinates are available for each civic address, intersection or item. However, this type of file was not always directly available, and its availability depended on the extent of GIS development at a utility.

3.3.1.3 Database queries

Using the prototype tool that was developed, a systematic study of all the positive total coliform samples collected in each distribution system was conducted. The tool was used to perform multi-table (simultaneous queries in different databases) and multi-criterion (according to hydraulic, spatial, temporal and specific parameter values) database queries for each positive coliform occurrence available in the utility databases. A total of 140 positive coliform samples in five distribution systems were investigated. Results of the queries were directly viewed with the GIS software, allowing the identification of all the events that could have affected the water quality at the studied location. For each water utility, matrices were constructed with the potential causes of each positive coliform sample identified from the database study. From this, the main O&M activities associated with the occurrence of coliform samples could be identified as well as the fraction of coliform occurrences attributable to O&M activities.

The causes of coliform occurrences identified are naturally linked with the types of data available. Also, the fact that coliform samples are generally collected at fixed distribution system sampling locations and at specific frequencies, only gives a picture of what is taking place in the close area of these points at the time of sample collection.

This supports further investigations and is the main reason a field study was conducted to complement the information obtained from this task.

3.3.2 Investigation of the link between O&M activities, distribution system hydraulics and water quality variations in full-scale distribution systems

Maintenance of a distribution system physical and hydraulic integrity is an essential condition to minimize potential water contamination (NRC, 2006). When O&M activities are conducted, a possibility exists that the physical and/or hydraulic integrity of the system may be lost. Examples include repairs of water mains, where the physical integrity of the system is obviously affected as the system is opened to the atmosphere. Even under normal system operating conditions, loss of hydraulic integrity is possible, such as when power failures occur and affect pump operation at a WTP resulting in the decreased ability of the system to supply water at the required flow and pressure.

The field work conducted as part of this task therefore consisted in monitoring some activities that could affect the physical/hydraulic integrity of a system and verify how these activities could lead to changes in water quality in full-scale distribution systems. Microbial intrusion was specifically targeted here. As illustrated in Figure 3-1, the activities monitored included: repairs of water main breaks/leaks, water main flushings, hydrant flow tests, pump start-up and shutdowns, and normal distribution system operation. The potential impact of water main repairs on water quality was directly assessed during the monitored repairs. For the other selected activities, their impact on hydraulic integrity was first assessed by monitoring pressures to detect low and negative transient pressures that could be induced. Two potential pathways of microbial intrusion were investigated: soil and shallow groundwater surrounding buried water mains and water from flooded air-vacuum valve vaults.

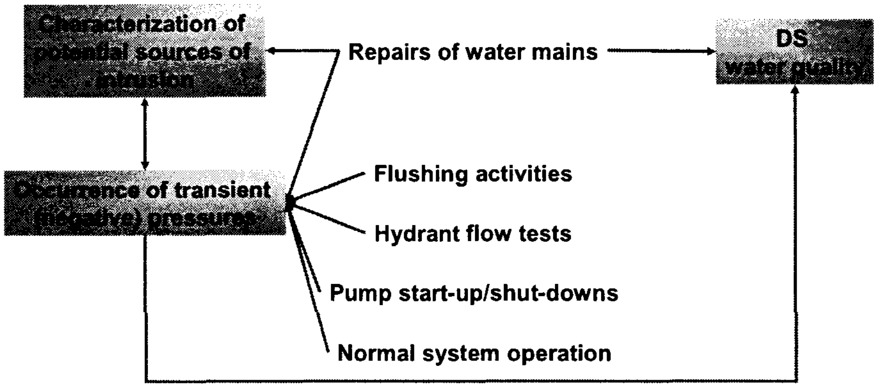

Figure 3-1: Study of link between O&M activities, distribution system hydraulics and water quality

Because of the climatic conditions experienced in the Montreal area, the field work was conducted mostly during summertime (usually between May and October) from 2004 to 2007. During wintertime, cold weather and freezing conditions make the access to distribution systems more difficult and monitoring equipment such as pressure sensors cannot be installed outside (such as on fire hydrants).

3.3.2.1 Characterization of potential pathways of intrusion

3.3.2.1.1 Soil / Shallow groundwater surrounding buried water mains

Soil and shallow groundwater samples were collected during repairs of water mains that took place in the Laval and Montreal distribution systems during the summer of 2004 and 2005. Soil samples were collected in the vicinity of the exposed main using a sterile trowel. The samples were put into large plastic (Ziploc® type) bags. Water samples were collected using four autoclaved one-liter plastic bottles.

3.3.2.1.2 Water from flooded air-vacuum valve vaults

A list of the location of valve vaults where either (i) an air-release valve; (ii) an air-vacuum valve; or (iii) a combination air-valve was positioned was provided by the city of Laval. These sites were visited from July to October 2007 and water samples were collected if some standing water was found in the vault. When completely flooded, a pump was used to pump the excess water and verify that the valve was in fact an air-valve. Water samples were collected using seven autoclaved one-liter plastic bottles (with 0.01% (w/v) sodium thiosulfate to neutralize residual chlorine if necessary). When possible, water samples were collected directly by dropping the bottle into the standing water. When not possible, a manual pump (Attwood, Lowell, MI) and 6 mm (0.25 in.) PVC tubing were used to fill the sampling bottles.

3.3.2.1.3 Bacteriological and coliphages analyses conducted on soil/water from pipe trenches and water from flooded air valve vaults

For soil samples, 20 grams of soil were mixed with 200 mL of saline and stirred on a magnetic stirrer for 1 minute. The sample was left to stand for 30 minutes and the supernatant was then recuperated for bacteriological and coliphages analysis. For water, the 1-liter samples were pooled and stirred on a magnetic stirrer for 1 minute, left to stand for 30 minutes and 250 mL of supernatant were recuperated for bacteriological and coliphages analysis. These analyses were conducted by the INRS-Institut Armand-Frappier laboratory, an external laboratory, through a collaboration with Dr. Pierre Payment.

Samples were assayed for the presence of aerobic endospores, *Clostridium perfringens*, *E. coli*, total coliforms (not assayed in 2004) and *Enterococci* (only in water from flooded valve vaults) within 24 hours of sampling using membrane filtration methods. Two 10 mL and two 1 mL portions (or appropriate dilutions) of the sample were assayed on each culture media. Tryptic soy broth (Difco Laboratories) with 0.01% triphenyl tetrazolium chloride was used to enumerate aerobic endospores. Samples were filtered on a membrane, placed in a 50 mm Petri dish containing a pad saturated with the medium, pasteurized during 15 minutes at 75°C in a water bath and incubated at 35°C for 24 hours. Red colonies were counted as aerobic endospores (Barbeau et al., 1997), and the vast majority of these organisms are species of *Bacillus*. The method described by Armon and Payment (1988) was used to enumerate *C. perfringens* by membrane filtration using mCP agar and incubation at 45°C for 18-24 hours. In 2005 and 2007, MI (Difco Laboratories) agar was used for the simultaneous detection of *E. coli* and total coliforms after 24 hours at 35°C (USEPA, 2002c). Blue colonies were reported as *E. coli* and fluorescent colonies under longwave ultraviolet light (366nm) (including the blue colonies under ambient light) as total coliforms. In 2004, *E.coli* were detected with mTEC agar by membrane filtration (USEPA, 2002d). The dishes were incubated at 35 ± 0.5°C for 2 h. After a 2h incubation at 35 ± 0.5°C, the plates were transferred at 44.5 ± 0.2°C for 22-24 h. An absorbent pad was placed in the lid of the same petri dish, and saturated with Urea Substrate Medium. The membranes from mTEC Agar were transferred to the saturated absorbent pad and kept at room temperature for 15-20 min. Yellow, yellow-green, or yellow-brown colonies were counted as *E. coli*. Method 1600 of the U.S. EPA was used for the detection of *Enterococci* (mEI agar, 41°C for 24 hours) (USEPA, 2002e). Blue colonies or colonies with a blue halo were counted as *Enterococci*.

For the coliphages assay, method 1602 of the U.S. Environmental Protection Agency (USEPA, 2001c) was used with *E. coli* CN-13 as host strain for somatic coliphages and *E. coli* F-amp as host strain for male-specific coliphages. Volumes of 1 and 10 mL were assayed for each coliphages in duplicate.

3.3.2.1.4 Virus detection in soil/water from pipe trenches and in water from flooded air valve vaults

As for the previous microbiological analyses, virus detection was conducted by the INRS-Institut Armand-Frappier laboratory. Soil (100g) was weighed, mixed for 30 minutes with 400 mL of 3% beef extract and then centrifuged for 15 minutes at 3000 x g. The supernatant was transferred into a sterile bottle for organic flocculation (pH 3.5 and $FeCl_3$ 0.1%) followed by centrifugation for 15 minutes at 4°C at 3000 x g. The supernatant was discarded, the pellet resuspended in glycine buffered medium (pH 9) and the volume completed to 15 mL with Minimum Essential Medium (MEM) with antibiotics (1% penicillin-streptomycin and 0.1% gentamicin). The pH was adjusted to 7.2 and the concentrate stored at -80°C until the viral assay was performed. For water, a sample of 4 liters was centrifuged for 15 minutes at 3000 x g. The supernatant and the pellet were conserved for virus analysis.

A volume of 50 mL of $MgCl_2$ (final concentration of 0.05M) was added to the supernatant. The supernatant was then adjusted to pH 6 with HCl 1.2N and filtered on a series of 142 mm filters: a prefilter AP25 (Millipore), a 0.45 μm and a 0.5 μm. The filters were eluted using 150 mL of beef extract (1.5%, pH 9.75) and reconcentration was done by organic flocculation (pH 3.5 and $FeCl_3$ 0.1%) followed by centrifugation for 15 minutes at 4°C at 3000 x g. The supernatant was discarded, the pellet resuspended in glycine buffered medium (pH 9) and the volume completed to 15 mL with Minimum Essential Medium (MEM) with antibiotics (1% penicillin-streptomycin and 0.1% gentamicin). The pH was adjusted to 7.2 and the concentrate stored at -80°C until the viral assay was performed. The pellet was weighed and beef extract (3%) was added in a 1:4 ratio. After 30 minutes of mixing, it was centrifuged at 3000 x g for 15 minutes. The supernatant was kept and reconcentration of viruses was done by organic flocculation (pH 3.5 and $FeCl_3$ 0.1%) followed by centrifugation for 15 minutes at 4°C at 3000 x g. The supernatant was discarded, the pellet resuspended in glycine buffered medium (pH 9) and the volume completed to 15 mL with Minimum Essential Medium (MEM) with antibiotics (1% penicillin-streptomycin and 0.1% gentamicin). The pH was adjusted to 7.2 and the concentrate stored at -80°C until the viral assay was performed.

Before the virus assay, every concentrate was treated with 1,1,2 trichlorotrifluoroethane and 5% penicillin-streptomycin 100X to remove toxic compounds, contaminants and debris. MA-104 (African green monkey kidney cells) cells were grown until they produced a confluent monolayer in 25 cm^2 plastic flasks. One milliliter of the concentrate (or an appropriate dilution) was placed on the cells and the flasks were incubated at 37°C for 60 minutes on a rocker platform. Ten mL of culture media containing antibiotics (1% penicillin-streptomycin and 0.1% gentamicin) were then added to each flask. Flasks were incubated at 37°C for 11 days, freeze-thawed at -20°C and a second passage was performed for 7 days on fresh cell cultures in 24 well plates (using one well for each first passage flask). The cells were fixed with absolute methanol containing 1% hydrogen peroxide (to destroy indigenous peroxidase). The fixed monolayers were submitted to an immunoassay developed in our laboratory using commercial hyper-immune human serum globulins to detect viruses in infected cells (Payment and Trudel, 1987). Infected cells appear dark brown under an inverted microscope making it easy to detect the viral infection even in the absence of a cytopathic effect. The number of viruses in the original samples was calculated using the number of positive (cytopathic effect or immunoperoxidase positive) and negative wells after the second passage and estimating the most probable number of infectious unit per liter as described previously (Payment and Trudel, 1987).

3.3.2.2 Impact of water main repairs on water quality

The monitoring of pipe repairs took place in the Laval and Montreal distribution systems during the summer of 2004 and 2005. These were mostly planned repairs of pipe leaks, not visible at the ground surface. These are the same repairs during which samples of soil and trench water were collected. Ideally, distribution system areas with low chlorine residual or where pipes would likely be located under the water table were wanted. However, we had no control over the choice of the location where repairs were performed.

In order to monitor the impact of pipe repair on water quality, water samples were collected at different times and locations within the distribution system. As the closure of valves usually takes place in order to isolate a section of the leaking main (Figure 3-2), customer houses located both inside (House In) as well as outside (House Out) of the isolated area were used for sample collection. A flexible PVC hose (disinfected with chlorine) connected to the external hose bib was used for water sampling at customer houses (flow was set to approximately 5 L/min). Other sampling locations included the hydrant used for flushing when the repair is completed. In 2005, a second house outside of the isolated area (House Out^2) was added as well as one customer house on the isolated section of main to study possible service line contamination (House SL). These are all illustrated in Figure 3-2. To simplify the analysis, results of the two sampling locations outside of the repair area were considered together and referred to as House Out only.

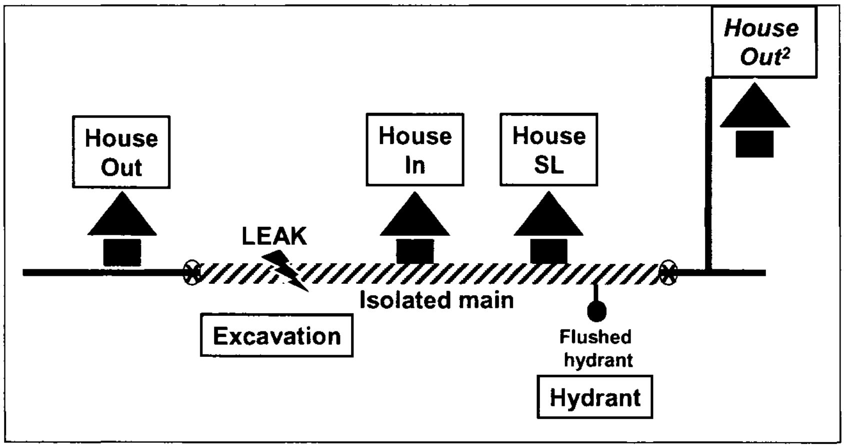

Figure 3-2: Sampling locations during repairs

During the repair, the water sampling sequence was as follows:

(i) sampling at House In, House Out and House SL before valve closure, ie. initial system condition (T_0);

(ii) sampling at House Out when valves were closed to isolate the section of main to be repaired;

(iii) sampling at House Out prior to the opening of the first valve to start flushing;

(iv) sampling at House In, House Out and at the Hydrant during flushing;

(v) sampling at House In, House Out and Hydrant prior to the closure of the hydrant;

(vi) sampling at House SL (first flush) immediately after the hydrant closure and sampling at House In and House Out 15 minutes after the hydrant was closed.

The field crews did not perform any chlorination of the repaired mains, only pipe flushing was conducted to remove any possible contamination. Water samples were collected in 1L autoclaved plastic bottles (with 0.01% (w/v) sodium thiosulfate). For steps (ii) and (iv), six samples were collected at 1, 2, 4, 7, 10 and 15 minutes after valve closure or start of flushing. One water sample was collected at each location for the other steps.

3.3.2.2.1 Parameters analyzed in distribution system water

The microbiological parameters that were analyzed in distribution system water (collected from House In, Out, SL and Hydrant) included the presence/absence of total coliforms and *E. coli* using the Colilert® (IDEXX Laboratories, Westbrook, Maine) detection method. Aerobic endospores were enumerated using the membrane filtration method developed by Barbeau et al. (1997) (Trypticase soy broth culture medium, pasteurization at 75°C for 15 minutes followed by incubation at 35°C for 24 hours). Heterotrophic plate counts (HPC) were enumerated using the membrane filtration method using R2A agar incubated at 35°C for 48 hours (method 9215D, (APHA and AWWA, 1998)). HPC were only monitored in 2004 as they were not found useful for detection of intrusion.

The physico-chemical parameters were analyzed using the standard methods described in APHA and AWWA (1998): free chlorine residuals using the DPD-FAS method (method 4500-Cl G), pH (method 4500-H+ B), temperature, conductivity (method 2510), turbidity by the nephelometric method (method 2130B) and total iron analyzed using the phenantroline colorimetric method (method 3500-Fe B).

3.3.2.3 Pressure monitoring in full-scale distribution systems

High-speed pressure transient data loggers were used for pressure monitoring in order to detect rapid changes in pressure, typical of transient events (where pressure variations may take place over a few seconds). Two types of high-speed pressure transient data loggers were used. The RDL 1071L/3 model from Radcom Technologies (Woburn, MA) that can read up to 20 pressure values per second within a range of -103 to 1551 kPa (-15 psi to 225 psi) was installed either directly on transmission mains (via corporation stops), on sink's taps inside buildings, or on fire hydrants. The HPR31 model from Telog Instruments (Victor, NY) can read up to four pressure values per second within a -103 to 1379 kPa (-15 psi to 200 psi) range was used to monitor pressure on fire hydrants. The Radcom loggers were zeroed to atmospheric pressure according to the manufacturer's instructions before installation. Pressure values were read every seconds and a tolerance of ±1.4 m (2 psi) was set for recording of pressure readings. The Telog loggers were set at four pressure readings per seconds, with the maximum and minimum pressure values recorded over intervals of 15 seconds.

3.3.2.3.1 Pressure monitoring during selected O&M activities

Targeted pressure monitoring was performed during the following maintenance activities:

- planned repairs of pipe leaks to determine the impact of valve/hydrant operation on the occurrence of transient pressures (in the Laval and Montreal distribution system as described previously)
- water main flushing (in the Laval system)
- hydrant flow tests (in the Montreal distribution system)
- pump operation associated with modified distribution system hydraulics due to transmission main rehabilitation (in the Montreal system)

For water main repairs, pressure in the distribution system was monitored at one or two locations (hydrants) nearby the repair site on 10 occasions. For main flushing, pressure monitoring was performed for three routes of a unidirectional flushing program in the Laval distribution system. One or two high-speed pressure transient data loggers were installed on hydrants either on or in the vicinity of the route being flushed. Pressures were also monitored during two hydrant flow tests in the Montreal system. These flow tests involved the consecutive opening of four orifices from two hydrants and did not involve any closure of valves. Three high-speed pressure transient data loggers were used during each flow test and were located on the nearest hydrants. Finally, the rehabilitation of a transmission main in the vicinity of a storage reservoir completely changed the supply scheme inside an area of the Montreal distribution system. Another reservoir had to be used to supply the area which completely modified the hydraulics of the system. Pressure monitoring was conducted at three locations (inside of university buildings) affected by these changes. These locations were very close to the alternative reservoir used for supply during the rehab work, which lasted a couple of weeks. Pressure monitoring was conducted during 36 days.

3.3.2.3.2 Continuous pressure monitoring in the Laval distribution system

Continuous pressure monitoring was performed in one area of the Laval distribution system corresponding to the same area where Payment et al. (1991; 1997) conducted their epidemiological studies and measured an increased rate of gastrointestinal illnesses associated with the consumption of tap water. The distribution system area studied is mostly supplied by a single WTP (Pont-Viau WTP). Apart from the clearwells at the WTPs, no storage tank nor pump station is located on the distribution system because of the ground topography.

Pressure monitoring of this distribution system area, using the high-speed pressure transient data loggers, was started in June 2006. Four distinct monitoring periods were conducted:

- Phase 1 (June 2006 to September 2006): Exploratory phase with 12 pressure sensors installed all over the distribution system area studied.

- Phase 2 (September 2006 to October 2006): Targeted phase with 9 pressure sensors installed in distribution system area prone to negative pressures.
- Phase 3 (October 2006 to June 2007): Reduced monitoring due to wintertime (pressure sensors cannot be installed on fire hydrants due to cold weather and freezing conditions). Only two pressure sensors could be installed inside buildings in area prone to negative pressures.
- Phase 4 (June 2007-November 2007): Repeat targeted sampling with 12 pressure sensors installed in area prone to negative pressures. This phase lasted until November 2007.

From June 2006 to November 2007, pressure was continuously monitored at the outlet of the supplying water treatment plant. Figure 3-3 illustrates the locations of the pressure sensors during the different monitoring periods.

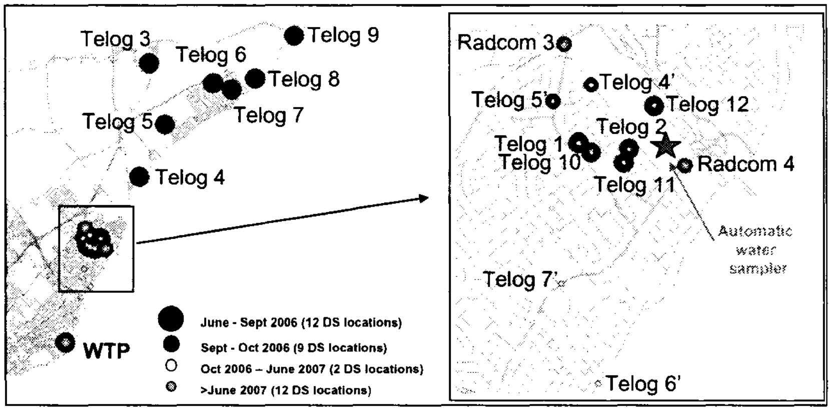

Figure 3-3: Locations of high-speed pressure transient data loggers in distribution system

During phase 1, in August 2006, a major planned repair (closure of a 400 mm (16 in.) transmission main) was conducted in the distribution system, affecting about 15 000 customers in a sub-area of the monitored network (Figure 3-4B). This pipe closure was expected to cause major hydraulic disturbances (flow reversals, low pressures) in this distribution system sub-area as water supply would be provided by another treatment plant under the repair conditions (WTP B instead of WTP A).

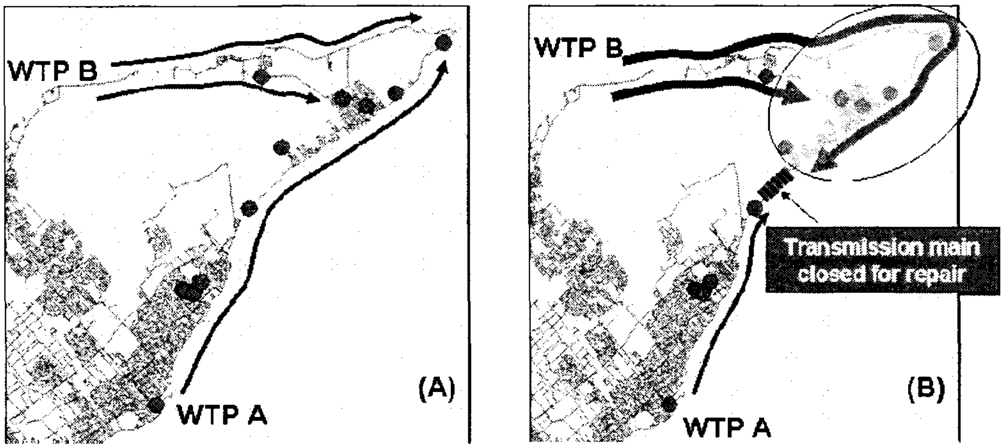

Figure 3-4: Distribution system area where continuous pressure monitoring was conducted during phase 1 (pressure loggers are the red dots); (A) Flow conditions under normal distribution system operation; (B) Flow conditions under repair conditions (shaded area represents affected sub-area)

As low pressures were predicted by hydraulic modeling, six additional high-speed pressure data loggers were installed, for a total of 12 pressure sensors in the affected distribution system sub-area.

3.3.3 Transient pressure and intrusion modeling

Transient (or surge) pressure modeling was performed to simulate (replicate) transient low pressure events measured at the Pont-Viau WTP during the continuous pressure monitoring, which resulted in confirmed or suspected negative pressures in the Laval distribution system. Transient modeling was necessary to simulate these low pressure events since they lasted typically less than five minutes.

Transient modeling was performed using the InfoSurge software (MWH Soft, Arcadia, CA). This software also includes an intrusion module allowing the simulation of potential intrusion volumes under various assumptions. The work performed as part of this task intends to present the first steps of what could later be used to develop a risk assessment methodology on microbial intrusion due to transient negative pressures in distribution systems. The modeling work presented may certainly be refined and should be considered as exploratory work.

The specific steps performed to achieve transient and intrusion modeling of the Laval distribution system are described below.

3.3.3.1 Construction of transient hydraulic model

The hydraulic model used in this study is the model obtained from the city of Laval in August 2007. This updated version of the model was used to try to get simulated information that would be representative of the field measurements conducted in 2006-2007. The previous version of the model that was available to our research group dated from 2001 and needed to be updated. In order to obtain a model that would be usable for transient modeling, the following steps were achieved:

- The hydraulic model from the city of Laval consisted in an extended-period simulation (EPS) with consumption data corresponding to average day demands. The model included nine consumption patterns (four patterns for leakage depending on pipe material and expected condition, residential, industrial, institutional, commercial and municipal usages). Because the city of Laval uses a different hydraulic software (Piccolo from Safège (France)), data were first transferred into the Epanet software (Rossman, 2000) and then into the InfoWater software (MWH Soft, Arcadia, CA). Results obtained using the Epanet and InfoWater models were validated against the results obtained from the Piccolo model both for steady-state and EPS modeling. This EPS model included 29,213 nodes and 32,266 pipes or links. Such a model size is too large to perform transient modeling, the InfoSurge software being limited to 20,000 links.
- Skeletonization of the EPS model was achieved using the InfoWater Skeletonizer module in order to reduce the number of links below 20,000. The following operations were conducted: (i) elimination of the interior nodes of all series pipes

with same diameter, (ii) trimming of the dead-end pipes shorter than 50 m. After the skeletonization, the model size was reduced to 8,132 nodes and 11,185 pipes.

- Because the distribution system is composed of various pipe materials, specific pressure wave velocities had to be assigned. The equation for wave speed c (or sonic speed) is usually expressed as:

$$c = (E_f / \rho(1+K_R E_f D / E_c t))^{0.5}$$

where E_f and E_c are the elastic modulus of the fluid and conduit respectively, D is the pipe diameter, t is the pipe thickness and K_R is the coefficient of restraint for longitudinal pipe movement. Because the pipe thickness and coefficient of restraint are unknown, the following figure has been used to assign the wave speed to the various pipe materials. The ratio pipe inside diameter/pipe wall thickness was considered at a value of about 35.

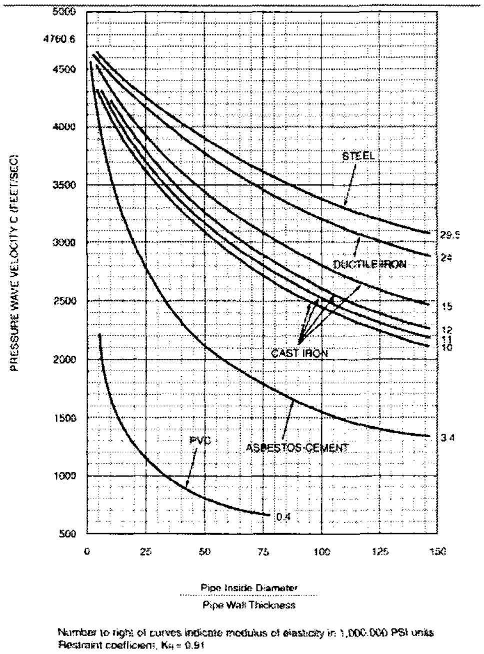

Figure 3-5: Pressure wave velocity for water in round pipes (Boulos et al., 2006)

The following typical wave velocities have been assigned: cast-iron: 1060 m/sec, ductile iron: 1200 m/sec, concrete: 600 m/sec, PVC: 300 m/sec, steel: 1200 m/sec. This approximation was considered better than using a single wave speed value for all the pipes included in the model.

3.3.3.2 Simulation of transient low pressure events

The transient model was used to simulate some low pressure events that were recorded at the outlet of the supplying WTP during the field pressure monitoring. For each event, the following data were available:

- time of the low pressure event
- pressure profile out of the Pont-Viau WTP (one pressure value per second)
- flow out of the Pont-Viau WTP (one value per 10 minutes)
- Pressure and flow out of the other two WTPs supplying the distribution system (one value per 10 minutes).

These data were used to set the boundary conditions in the model. Furthermore, pressure data at the monitoring locations in the distribution system were also available for comparison with simulation results.

At the Pont-Viau WTP, up to nine high-pressure pumps are available to deliver water into the distribution system. However, no records are available to know which pumps were operating at a specific time in the past. Because of that, one pump providing the flow and pressure conditions at the time of the low pressure event was modeled. The low pressure event was created by simulating a pump closure using pump speed change. Simulation time was set to 300 seconds.

The surge modeling was performed assuming that no surge protection devices were installed in the distribution system. This is not true since air-vacuum and combination air valves are in fact installed in some locations (as visited during the field work). However, because the size of these devices is not known they were not included in the model. Because of this, the model will likely give negative pressures that are more extreme than actually measured in the distribution system.

3.3.3.3 Simulation of intrusion volumes

For each low pressure event modeled, the intrusion module of the InfoSurge software was used to simulate the potential intrusion volumes in the distribution system. Intrusion volumes based on a leakage factor was used. Under this model option, intrusion at all demand nodes is computed when the exit head value (head of water above pipe - fixed by the user) is above the internal pipe pressure value according to the following equation (derived from the work of Funk et al. (1999)):

$$Q_i = ((\pi\ C_D D_i^2)/4) * [2g(H_{ext}-H_{L,i})]^{0.5}$$

where Q_i = intrusion flowrate, C_D = orifice discharge coefficient, D_i = orifice diameter, g = gravitational acceleration, H_{ext} = external head and $H_{L,i}$ = line (interior) head at the node. The leakage factor is used to set the size of the orifice. Leakage values between 5 and 25% were simulated along with exit heads of 0 (atmospheric pressure) and 1.4 m (2 psi).

Intrusion through flooded air-valve vaults was also simulated. In such a case, the intrusion module described above was not used and intrusion was considered only through submerged air-vacuum valves. The locations of these vaults in the distribution system area studied are known and were assigned to model nodes. The flooded vaults were modeled as one-way feed tanks, where the water is only allowed to flow from the tank into the system. All the vaults visited were assumed to contain air-vacuum valves, which is a worst-case scenario. In reality, some vaults only contained air-release valves that are not specifically designed to let air into the pipe in case of negative pressures (but they can let some air in). For the simulation, different numbers of flooded vaults were assumed according to the results from the field study. The height of water above the air-vacuum valve was assumed to be 0.5 m. Different air-vacuum valve outlet diameters were also tested (12, 100 and 150 mm).

3.3.3.4 Simulation of contamination transport into the distribution system

Once the intrusion volumes were obtained for different scenarios, the next logical step was to simulate the contamination transport into the distribution system in order to assess the proportion of customers that could be affected. Because of the exploratory nature of this work, the intruded contaminant was assumed conservative. Such an assumption is certainly not representative of the conditions in the Laval distribution system but greatly simplified the simulation.

Transport of contaminant for one case of intrusion through flooded air-valves and one case of intrusion through leakage points were compared. For each case, the EPS-large size model (about 30,000 nodes and pipes) was used and a number of microorganisms was introduced at each node where intrusion was determined. Geometric mean of microorganism concentrations in soil/trench water and water from flooded vaults was used as the typical pathway concentration. This was multiplied by the simulated volume of intrusion at each node, as determined in section 3.3.4.3. The number of microorganism was set as the initial water quality in the EPS simulation. The simulation was started at the pattern time corresponding to the time of the low pressure event and was run for 120 hours. The InfoWater software (MWH Soft, Arcadia, CA) was used for this task.

CHAPTER 4

PUBLICATION #1: EFFICACY OF DISINFECTANT RESIDUAL AGAINST MICROBIAL INTRUSION IN DISTRIBUTION SYSTEMS: A REVIEW OF EXISTING STUDIES

This chapter includes an in-depth review and analysis of the studies available in the literature investigating the fate of microorganisms introduced into experimental systems. More specifically, the efficacy of disinfectant residual on microbial intrusion was reviewed at various scales of experimentation. This chapter is a paper that has been submitted to the *Journal of the American Water Works Association* for publication.

EFFICACY OF DISINFECTANT RESIDUAL AGAINST MICROBIAL INTRUSION IN DISTRIBUTION SYSTEMS: A REVIEW OF EXISTING STUDIES

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Abstract: In order to determine the effectiveness of a disinfectant residual in the event of accidental microbial intrusion, we conducted a literature review of numerous studies

specifically investigating the fate of microorganisms introduced into experimental systems (laboratory-, pilot- and isolated full-scale). In these experiments, various types of microorganisms were monitored, including pathogens, in the presence or absence of a disinfectant residual. The monitoring of the organisms was performed in the bulk water and/or the biofilm. This review shows that the conclusions about the efficacy of a disinfectant residual in protecting against pathogen intrusion are not in agreement with conflicting observations regarding the persistence of microorganisms in biofilms in laboratory- and pilot-scale testing. The most critical conditions with respect to microorganism persistence in a water system can, however, be identified: (i) intrusion taking place under zero- or low-flow conditions; and/or (ii) delay between the time of intrusion and the onset of chlorination.

4.1 INTRODUCTION

The integrity of the infrastructure used to deliver drinking water from the treatment plant to the consumer's tap is of paramount importance to minimize the risk of water contamination. A significant portion of waterborne disease outbreaks (WBDOs) has been shown to be caused by distribution system deficiencies (Craun and Calderon, 2001). These authors showed that, for the period 1971 to 1998, 18.3% of the outbreaks reported in public water systems in the USA were caused by chemical and microbial contaminants entering the distribution system. Although the actual number of WBDOs reported since 1980 has decreased, the proportion of WBDOs due to distribution system contamination is increasing (NRC, 2005). Data from some other countries, suggest that 36% of 42 reported waterborne outbreaks in the UK and 20-37% of the outbreaks reported in Scandinavia were associated with distribution system contamination (Hunter, 1997; Stenström, 1994). Even under normal operating conditions, significant increases in gastrointestinal (GI) illnesses have been associated with water distribution, and the integrity of the distribution system has been questioned (Payment et al, 1997; Payment et al, 1991).

Unfortunately, some cases of water contamination due to distribution system deficiencies have been associated with illnesses and even fatalities in the supplied population. In the small town of Cabool (Missouri, USA), an outbreak of hemorrhagic *E. coli* serotype O157:H7 caused 243 known cases of diarrhea and four deaths in a population of 2,090 inhabitants. The suspected sources of contamination were two major distribution line breaks and 43 service meter failures that occurred during unusually cold weather (Geldreich et al, 1992). The number of new cases declined rapidly after residents were ordered to boil their water and the water supply was chlorinated (no disinfectant was added to the water supply prior to the outbreak) (Swerdlow et al, 1992a). In another case, inadequate maintenance of a municipal water storage tank was identified as the cause of a *Salmonella* serovar *typhimurium* outbreak reported in Gideon (Missouri, USA) in 1993 (Angulo et al, 1997; Clark et al, 1996). An improper roof vent and an uncovered hatch on the tank had provided access to wild birds, resulting in contamination of the water from bird droppings. In a population of 1,104, close to 600 people were affected with diarrhea and 7 people died. The water supplied by this distribution system was not disinfected at the time of the outbreak. In Peru, pathogens such as *Vibrio cholerae* have been shown to enter the distribution network through cross-contamination by sewage, and to survive and cause disease in the absence of adequate pressure and chlorine residual (Geldreich, 1996; Swerdlow et al, 1992b). These examples show that some conditions or maintenance activities in distribution systems can actually lead to pathogen intrusion and cause outbreaks under specific conditions of operation. They also show the risk associated with the intrusion of pathogens in distribution systems in the absence of a disinfectant residual. Kirmeyer et al (2001) have identified four high-risk routes of entry of pathogens into distribution systems: (1) water treatment breakthrough; (2) transitory contamination; (3) cross-connection; and (4) water main repairs/breaks. Three of these routes are directly related to the distribution network itself, making it a vulnerable barrier.

In view of the many potential pathways of microbial contamination in a distribution system and of the positive role of chlorination in limiting water distribution-borne outbreaks, the maintenance of a disinfectant residual could be considered an absolute necessity. It is, in fact, usually recommended as a barrier against any contamination resulting from the loss of integrity of the system and to control microbial regrowth. Under this management approach, the main justifications for using a disinfectant residual in a distribution system include: overcoming system contamination, preventing the regrowth of coliform bacteria, inhibiting or controlling biofilm formation, stabilizing water quality, preventing the occurrence of opportunistic pathogens, and signaling contamination by its absence (sudden disappearance of the residual at places where it is usually present) (Trussell, 1999). This management approach is widely accepted in North America and the United Kingdom, and is endorsed by the WHO (Ainsworth, 2004; World Health Organization (WHO), 2003). However, not all scientific experts and regulatory agencies favor it. In several European countries, the use of a secondary disinfectant such as chlorine is limited or non-existent, mostly because of concerns about the formation of disinfection by-products and low tolerance of chlorine taste and odor (van der Kooij et al, 1999). Some European utilities, located mainly in The Netherlands and Germany, are successfully producing and distributing hygienically safe and biologically stable drinking water without a disinfectant residual (van der Kooij et al, 1999; Fokken et al, 1998). This is possible through the application of multiple treatment barriers, the production of biostable water and the use of biostable materials for building distribution infrastructures, as well as the application of protective measures to prevent recontamination in the distribution system (te Welscher et al, 1998; van der Kooij et al, 1995). Van Lieverloo et al (2006) report that outbreaks are rare in The Netherlands and estimate that faecal contamination incidents occur 4-5 times a year in this country.

In North America, the age and vulnerability of some distribution infrastructures make it difficult to adopt a low, or no, secondary disinfectant residual strategy (Haas, 1999). LeChevallier (1999) has suggested that, unless water suppliers can guarantee limitation of microbial regrowth and control of distribution system contamination, the elimination of secondary disinfection is not possible without increasing the risks for consumers. For surface-water systems (or groundwater under the influence of surface water), regulations in the United States (USEPA Surface Water Treatment Rule (USEPA, 1989), the Stage 1 Disinfectant/Disinfection By-Products Rule (USEPA, 2001a)) require a minimum of 0.2 mg/L chlorine at the entrance to the distribution system. This residual must not exceed 4.0 mg/L for chlorine and chloramines. Similar minimum and maximum values are used in Canada, while the European Drinking Water Directive (Council of the European Union, 1998) does not explicitly prescribe a disinfection residual, either at the system entrance or throughout the distribution system.

4.2 THE FATE OF MICROORGANISMS EXPERIMENTALLY INTRODUCED INTO DRINKING WATER SYSTEMS

Accidental intrusion of microbial contaminants into a distribution system may occur from a cross-connection, from intruded material remaining after repair work, from ill-maintained storage tanks or through pipe leaks or other orifices when transient negative pressures occur. If no residual disinfectant is used in the system, it can be hypothesized that microorganisms will be able to survive and colonize pipe biofilm for some time. However, if a residual disinfectant is in place, will such microorganisms be inactivated? Will they be able to colonize the biofilm? In order to provide some insight into these questions, this paper reviews and discusses the data of published studies that simulate intrusion and examine the fate of microorganisms introduced into experimental systems. Various testing scales are evaluated in order to determine what can be learned from these experiments. Because the focus is on experimental systems, the assessment of the effectiveness of disinfectant residuals against microbial intrusion obtained from modeling studies will not be discussed here. If interested, the reader can refer to Baribeau et al (2005) and Propato and Uber (2004) for more information.

Because of the limitations of tracking introduced organisms in full scale systems, results have typically come from laboratory- (or bench-) and pilot scale systems. In the experiments reviewed here, various types of microorganisms were used (bacteria, protozoa, viruses) including frank and opportunistic pathogens and indicator bacteria, in the presence or absence of a disinfectant residual. The organisms were usually monitored for a fairly extended period of time after the introduction of the microorganisms into the system, both in the water and in the biofilm if the experimental setting allowed it. Because the interest here is on studies involving the impact of a disinfectant residual on microbial intrusion, an overview of the main characteristics of such studies (with residual disinfectant concentration >0.1 mg/L) is given in Table 4-1. This table summarizes the type of experimental systems used, the type and concentration of disinfectant residual tested, the type of intrusion simulated and the monitoring parameters for each study. The type of intrusion is further defined in Table 4-2 which lists the concentrations of microorganisms injected in the reviewed studies along with the detection methods used by the authors.

Table 4-1: Overview of studies where impact of a disinfectant residual (>0.1 mg/L) on microbial intrusion was investigated

Scale of study	Reference	Type of system	Disinfectant residual tested (concentration in mg/L)				Type of intrusion	Monitoring			
			None	Free Cl_2	Chloramines	Chlorine dioxide		Bulk water	Biofilm	Type of coupons	Time
LAB/BENCH SCALE	Snead et al, 1980	4L beakers		0.2 and 1.0	0.2 and 1.0		Autoclaved raw sewage seeded with test microorganisms (0.01 to 10% by volume)	✓			2 hours
	Payment, 1999	2L beakers		0.4 and 0.6			Untreated raw sewage (0.1-1-10% by volume)	✓			24 hours
	McMath et al, 1999	Jar tests			0.2-0.3		Sewage effluent (1-5-10% by volume)	✓			48 hours
	Momba et al, 1999	Lab scale unit run as chemostat	✓	0.7	0.8		*E. coli* (ATCC 11775)		✓	SS	3 days
	Storey and Ashbolt, 2001	Annular reactors		0.5			Two model enteric viruses		✓	uPVC	30 days
	Camper et al, 1998	Annular reactors		0.05 and 0.2			Two enteric pathogens and two opportunistic pathogens	✓	✓	Polycarbonate	20-60 days
	Baribeau et al, 2005	Annular reactors		1.0	1.0		Continuous dose of *E. coli* (K-12) for a period of 24 hours	✓	✓	Polycarbonate and CI	≅ 160 days
PILOT SCALE	Parent et al, 1996	1 pipe loop (Pipe length=31 m, Pipe diameter=100mm, RT=24h, V=1 m/s)		0.5			Slug injection of *E. coli*	✓	✓	PVC	9 days
	Sibille et al, 1997	Same as Parent et al (1996), 3 pipe loops, RT=12h/loop		0.25			10L settled raw wastewater (4% of first loop volume)	✓	✓	PVC	12 days
	McMath et al, 1999	Piperig of 1.3 km, pipe diameter=110mm, RT=13-31-46h, V=0.008 m/s			0.24-0.31		Slug injection of 25L treated domestic wastewater effluent (0.2% of pipe rig volume)	✓			3 to 11 months
	Gibbs et al, 2003	1 pipe loop (Pipe length=25 m, Pipe diameter=152mm, RT=24h, V=0.3 m/s)		0.2-0.3			Continuous wastewater cross-connection (0.3% of system volume per day for 90 days ((0.1%-835 ml) every 8 hours))	✓	✓	DI	Bulk water (pre-during and post-x-connection), biofilm during 3 days after removal of x-connection
FULL SCALE	Olivieri et al, 1986	Test DS with several hundred feet of 100mm CI main and internal plumbing of 2 army barracks	✓	1.0-1.04	1.0-1.08	0.95-1.0	slug injection of 1800 mL of raw sewage seeded with f2 bacterial virus (≈0.1% of DS volume)	✓			4 hours and 3 days

CI: Cast-iron ; DI: Ductile iron ; DS: Distribution system ; PVC: Polyvinyl chloride; RT: Residence time; SS: Stainless steel; uPVC: unplasticized polyvinyl chloride; V: Velocity

Table 4-2: Concentrations of microorganisms injected in reviewed studies on microbial intrusion

Scale of study	Reference	Type of intrusion	Target microorganisms	Range of concentration of microorganisms at time of injection	Detection method
Lab/bench	Snead et al, 1980	Autoclaved raw sewage seeded with test microorganisms (0.01 to 10% by volume)	Coliforms, *Salmonella typhimurium*, *Shigella sonnei*, Poliovirus-1 f2 bacterial virus	Not given (results are presented as log N/N_0)	Bacteria: Spread plate technique on Xylose Lysine (XL) agar f2 bacterial virus: soft agar overlay method poliovirus-1: plaque assays using BGM cells
	Payment, 1999	Untreated raw sewage (0.1-1-10% by volume)	Thermotolerant coliforms	Not given (results are presented as % remaining)	m-FC agar
			Somatic coliphages		Double agar method on *E. coli* 13706
			Clostridium perfringens		Membrane filtration on m-CP medium
	McMath et al, 1999	Sewage effluent (1-5-10% by volume)	Total coliforms	NA	Colilert
			E. coli	$\approx 10^4$-10^5 CFU/100 mL	
	Momba et al, 1999	*E. coli* (ATCC 11775)	*E. coli*	$\approx 10^3$ CFU/100 mL	Membrane filtration method using m-FC agar
	Storey and Ashbolt, 2001	Two model enteric viruses	Phage B40-8	$\approx 10^8$ pfu/mL	Double-agar layer pour plate method
			Coliphage *MS-2*	$\approx 10^8$ pfu/mL	
	(1) Camper et al, 1998	Two enteric pathogens and two opportunistic pathogens	*Salmonella typhimurium*	$\approx 10^3$ to 10^6 CFU/100 mL	Plated on xylose lysine deoxycholate (XLD) agar
			E. coli O157:H7	BDL	Plated on m-T7 agar
			Aeromonas hydrophila	$\approx 10^1$ to 10^3 CFU/100 mL	Plated on m-Aeromonas (mAA) agar and on ampicillin dextrin agar (ADA)
			Klebsiella pneumoniae	$\approx 10^3$ to 10^5 CFU/100 mL	Plated on m-Klebsiella (mKa) agar and on m-T7 agar
					+ for all microorganisms: staining with fluorescent antibodies (DNA stain: propidium iodide, activity stain: rhodamine 123)
	Baribeau et al, 2005	Continuous dose of *E. coli* (K-12) for a period of 24 hours (injected into AR #3)	*E. coli*	$\approx 10^2$ to 10^3 CFU/100 mL	Membrane filtration technique using m-ENDO agar LES

Table 4.2: Concentrations of microorganisms injected in reviewed studies on microbial intrusion (continued)

Pilot	[2] Parent et al, 1996	Slug injection of *E. coli*	*E. coli*	≈10^7 CFU/100 mL	Agar culture method using a selective medium with lactose and tergitol 7
	Sibille et al, 1997	10L settled raw wastewater (4% of first loop volume)	Total coliforms	≈10^7 CFU/100 mL	Membrane filtration technique using TTC-Tergitol 7 agar medium
			Faecal coliforms	≈10^6 CFU/100 mL	
			Streptococci	≈10^6 CFU/100 mL	Membrane filtration technique using m-agar for enterobacteria
	McMath et al, 1999	Slug injection of 25L treated domestic wastewater effluent (0.2% of pipe rig volume)	Total coliforms	≈10^6 CFU/100 mL	Colilert + membrane filtration method using membrane lauryl sulphate (MLS) broth
	Gibbs et al, 2003	Continuous wastewater* cross-connection (0.3% of system volume per day for 90 days; 0.1% (835ml) every 8 hours) *Wastewater was obtained following grit removal and ahead of primary clarification	Total coliforms	≈10^7 MPN/100 mL	Quanti-Tray 2000
			E. coli	≈10^6 MPN/100 mL	Quanti-Tray 2000
			Enterococci	≈10^5 CFU/100 mL	Membrane filter technique
			Salmonella	≈10^5 MPN/100 mL	Xylose lysine tergitol 4 (XLT4) agar plates
			Aeromonas	≈10^8 CFU/100 mL	Membrane filtration
			Endospores	≈10^5 CFU/100 mL	Membrane filtration
			HPC	≈10^8 CFU/mL	R2A agar spread plates
Full scale	Olivieri et al, 1986	Slug injection of 1800 ml of raw sewage seeded with f2 bacterial virus (≈0.1% of DS volume)	Total coliforms	NA	Multiple tube dilution procedure
			f2 bacterial virus	≈10^6 pfu/mL	Agar overlay technique using *E. coli* K-13 as host bacterium

BDL: Below detection limit; CFU: Colony forming unit; DS: Distribution system; HPC: Heterotrophic plate count; MPN: Most probable number; NA: Not available; PFU: Plaque forming unit;

(1) Concentration of injected microorganism not given. Values in Table correspond to approximate range of concentrations measured in bulk water at T_0 (3 days after introduction of dilution water) using selective media

(2) Parent et al (1996) specify that a single dose of 10^{11} CFU of *E. coli* was injected. Value in Table is obtained by dividing 10^{11} CFU by loop volume.

4.3 LABORATORY- OR BENCH-SCALE SYSTEMS

4.3.1 Survival of microorganisms in bulk water in the presence of a disinfectant residual

One of the first studies to simulate the contamination resulting from a cross-connection was conducted by Snead et al (1980). These authors performed batch tests using small volumes (4 L) of tap water with free and combined chlorine (chloramines) concentrations of approximately 0.2 and 1.0 mg/L. Varying volumes (from 0.01 to 10%) of autoclaved raw sewage seeded with various microorganisms (coliform bacteria, *Salmonella typhimurium*, *Shigella sonnei*, poliovirus 1, f2 bacterial virus) were injected into the 4-L samples. Monitoring of the bulk water during the first 2 hours following the sewage injection showed that the free chlorine residual was more effective than the combined chlorine residual in inactivating the microorganisms in the water. The inactivation observed depended on the amount of sewage injected (better inactivation at a lower sewage concentration), and poliovirus 1 and the f2 virus were always more difficult to inactivate than the bacteria (with, in general, at least a 1 log difference two hours after microorganisms injection). In terms of resistance to chlorine inactivation, it is generally recognized that viruses are more resistant than bacterial cells (USEPA, 2001b) and that free chlorine is a better disinfectant than chloramines (USEPA, 1999). High pH and low temperatures are also usually the least favorable conditions for microbial inactivation (White, 1999). Snead et al (1980) therefore concluded that free chlorine residual conferred protection against bacterial contamination and that its disappearance or decay could also be used to detect a contamination event. The lower efficacy of chloramines was also demonstrated by McMath et al (1999) using laboratory jar tests. These authors showed low levels of total coliform bacteria survival (200-300/100 mL) after mixing chloraminated drinking water (0.2-0.3 mg Cl_2/L) with increasing volumes (1%, 5% and 10%) of sewage effluent containing 10^4-10^5 *E. coli*/100 mL. Although *E. coli* bacteria were undetectable after 30 minutes of mixing, the low total coliform concentrations were still present in the water 48 hours after the initial mixing. Residual total chlorine concentrations were still detectable at 0.17 to 0.29 mg/L.

Payment (1999) reported similar trends using a comparable experimental approach: increasing volumes of untreated raw sewage (0.1%, 1.0% and 10%) were injected into 2-L water samples obtained directly from a drinking water treatment plant outlet (free chlorine residuals were 0.4 and 0.6 mg/L). A rapid inactivation of the faecal coliforms in the water was observed, whereas more resistant microorganisms (*C. perfingens*) were almost completely unaffected by the residual chlorine levels for several hours. The author concluded that the use of chlorine in distribution systems provides a false sense of security by providing negative total coliform and *E. coli* readings while potential pathogenic microorganisms may still be present. Unfortunately, the organisms that are more resistant to chlorine are the ones with low median infection doses (N_{50}). Between 1 and 100 organisms of viruses or protozoa are needed to cause infection in 50 percent of the individuals exposed, whereas approximately 10^8 pathogenic *Escherichia coli* are needed to result in the same level of infection (Montgomery Watson Harza (MWH), 2005).

4.3.2 Survival of microorganisms in biofilms in the absence of residual disinfectant

Researchers have used various types of laboratory reactors to study the fate of injected microorganisms in biofilms. Experiments conducted without a disinfectant residual showed that:

(i) After the inoculation of pure strains of *Klebsiella pneumoniae, Salmonella enteritidis* and *E. coli* in a reactor previously fed with a dilute nutrient solution, the injected *Enterobacteriaceae* were able to form substantial biofilm populations within 24 hours (Jones and Bradshaw, 1996);

(ii) *Klebsiella oxytoca* were able to survive on surfaces after being seeded in a chemostat model containing a heterotrophic bacterial population; however, the authors could not clearly determine whether or not the microorganism was slowly growing in the biofilm (Packer et al, 1997);

(iii) *E. coli* and *Aeromonas hydrophila* can colonize a mixed-population biofilm after their inoculation in laboratory chemostats (Colbourne et al, 1991). In that case, 0.6 mg/L of monochloramine was needed to inactivate *E. coli* in the biofilm, whereas *A. hydrophila* continued to survive at a concentration of 1.2 mg/L Cl_2;

(iv) *Legionella pneumophila* and *Salmonella typhimurium* could survive in biofilms for prolonged periods of time (20 to >40 days) under warm-water conditions (24°C) (Armon et al, 1997);

(v) *Helicobacter pylori* were detected using reverse transcription PCR analysis in a mixed species heterotrophic biofilm present on the stainless steel coupons of a modified Robbins device (Manz et al, 1993) for 192 hours after injection into the experimental system (Mackay et al, 1998);

(vi) *Cryptosporidium* oocysts continue to adhere to a multi-species biofilm grown on glass slides for a 1-month period (trial duration using a chemostat) with a significant proportion still viable at the end of the trial (Rogers and Keevil, 1995). This last experiment shows that oocysts entering distribution systems may be present for several weeks within biofilms even in the presence of a disinfectant residual because such a residual has barely any effect on this organism. Subsequent sloughing could possibly lead to the release of the attached pathogens and infection even if the water is considered safe based on bacterial indicators.

These studies therefore suggest that the absence of a disinfectant residual allows colonization of distribution system biofilms by intruded microorganisms.

4.3.3 Survival of microorganisms in biofilms in the presence of a disinfectant residual

The effect of a disinfectant residual (free chlorine, chloramines) on the persistence of intruded microorganisms in biofilms has been investigated by four groups of researchers, as detailed below. For two of these studies, simultaneous investigation of microorganism survival in bulk water was also conducted. The main characteristics of these four studies are presented in Table 4-3.

Table 4-3: Laboratory studies investigating the impact of a disinfectant residual on the fate of microorganisms in biofilm

Reference	**Injected microorganisms**	**Concentration (CFU/100 mL or MPN/100 mL or pfu/mL for phages)**	**Chlorine concentration at time of microorganism injection**	**Chlorine concentration and injection delay after intrusion event**	**Persistence of microorganisms in biofilm (T_0=$T_{intrusion}$)**	**Monitoring period**
Momba et al, 1999	• *E. coli*	10^3	• 0.7 mg/L free Cl_2	---	• 3 days	3 days
			• 0.8 mg/L NH_2Cl	---	• BDL	
Storey and Ashbolt, 2001	• Phage B40-8	10^8	---	Average of 0.56 mg/L free Cl_2 started 1 day after microorganism injection	• 30 days	30 days
	• Coliphage *MS-2*	10^8			• 22 days	
[1] [2]Camper et al, 1998	• *Salmonella typhimurium*	10^3-10^6	---	• No chlorine added	• 8-14 days (cult.)	Between 20-60 days
				• 0.05 mg/L free Cl_2 added on day 38 and 0.2 mg/L free Cl_2 added on day 44	• 30-60 days (FA)	
	• *E. coli* O157:H7	BDL		• No chlorine added	• BDL (cult.)	
				• No chlorine added	• 20-30 days (FA)	
	• *Aeromonas hydrophila*	10^1-10^3		• 0.05 mg/L free Cl_2 added on day 7, and 0.2 mg/L free Cl_2 added on day 14	• 5-15 days (cult.)	
				• 0.05 mg/L free Cl_2 added on days 7 to 13 and 0.2 mg/L free Cl_2 added on days 15 and 16	• 20 days (FA)	

Table 4-3: Laboratory studies investigating the impact of a disinfectant residual on the fate of microorganisms in biofilm (continued)

	• *Klebsiellae pneumonia*	10^3-10^5		• 0.05 mg/L free Cl_2 added on day 12 and 0.2 mg/L free Cl_2 added on days 16 and 17	• 13-30 days (cult.)	
				• 0.05 mg/L free Cl_2 added on day 14 and 0.2 mg/L free Cl_2 added on days 14 and 17	• 19-30 days (FA)	
(2)Baribeau et al, 2005	• *E. coli*	10^2-10^3	• 1.0 mg/L free Cl_2 (outlet of AR1)	11 weeks after microorganism injection, free Cl_2 raised to [1.0 mg/L (outlet of AR1) + 0.5 mg/L (outlet of AR3)]	• Duration of monitoring period (PC) • ≈ 135 days (CI)	≈160 days
			• 1.0 mg/L total Cl_2 (outlet of AR1)	11 weeks after microorganism injection, total Cl_2 raised to [1.0 mg/L (outlet of AR1) + 1.0 mg/L (outlet of AR3)]	• BDL (PC) • Duration of monitoring period (CI)	

AR1: Annular reactor #1; AR3: Annular reactor #3; BDL: below detection limit; CFU: Colony forming unit; CI: Cast iron; Cult: Culturing methods; FA: Fluorescent antibodies; MPN: Most probable number; NA: Not available; PC: Polycarbonate; PFU: Plaque forming unit;

(1) Concentration of injected microorganisms not given. Values in Table correspond to approximate range of concentrations measured in bulk water at T_0 (3 days after introduction of dilution water) using selective media

(2) These authors also conducted bulk water monitoring (as described in text)

Using a laboratory-scale unit run as a chemostat equipped with stainless steel coupons and fed with groundwater (either without a disinfectant, with free chlorine or with monochloramine), Momba et al (1999) monitored the attachment and persistence of *E. coli* in a young biofilm. An inoculum concentration of ±2.6 x 10^3 *E. coli* per 100 mL was injected 24 hours after the system was started. Monitoring the attached *E. coli* during the first 96 hours after the start-up of the system (or 72 hours after the injection of the *E. coli*) showed, not surprisingly, that the attachment of *E. coli* to the young biofilm was greatest for the chemostat fed with non-disinfected groundwater. The presence of a monochloramine residual (0.8 mg/L) at the time of *E. coli* injection was more effective in preventing the attachment of *E. coli* to the biofilm (*E. coli* being non-detectable at all times) than the presence of a free chlorine residual (0.7 mg/L) at the time of injection. The monochloramine residual was still detectable (0.3 mg/L) 24 hours after the injection of *E. coli*, whereas free chlorine was not.

Storey and Ashbolt (2001) investigated the persistence of two model enteric viruses (*Bacteroides fragilis* phage B40-8 and coliphage *MS-2*) in chlorinated experimental settings, slug-dosed at approximately 10^8 pfu/mL into an annular reactor. This reactor contained unplasticized PVC (uPVC) coupons of a 70-day-old naturally grown pipe biofilm collected from a modified Robbin's device installed in a full-scale distribution system. The phages were allowed to accumulate in the annular reactor biofilm for 24 hours under no-flow conditions before the continuous supply of the reactor was restarted with water containing an average free chlorine residual of 0.56 ± 0.12 mg/L. The persistence of the phages in the biofilm was monitored for a 30-day period. Results showed that, even when a free chlorine residual is present, viruses may persist in the biofilm on uPVC pipes. Phages B40-8 were detected for the duration of the experiment (30 days). The virus loss/inactivation followed an initial rapid phase followed by a very slow phase representing a more persistent subpopulation (~0.01% of the original virus population). MS-2 was not detected after 22 days.

Laboratory polycarbonate annular reactors were also used by Camper et al (1998) to study the fate of pathogens in model distribution system water and biofilms. Four target organisms, including two enteric pathogens (*Salmonella typhimurium* and *E. coli* O157:H7) and two opportunistic pathogens (*Aeromonas hydrophila and Klebsiellae pneumonia*), were injected into reactors operated under warm-water conditions (20°C) and with enhanced nutrients (assimilable organic carbon (AOC) solution at 500 μg C/L). The reactors were run as chemostats for 60 hours after inoculation, (with only AOC and buffer feed solutions). After this period, the continuous feed of non-sterile reverse-osmosis water (with a mixed heterotrophic bacterial population of ~10^4 CFU/mL) was started. Free chlorine was added to the influent approximately 2 weeks after the establishment of the biofilm (containing the target organisms) at an initial concentration of 0.05 mg/L, which was then raised to 0.2 mg/L. In this study, the target bacteria were enumerated by culture-based methods, but also by microscopy after the cells had been stained using specific fluorescent antibodies. Results using the culture-based techniques show that chlorination resulted in a rapid elimination of *A. hydrophila* from both the biofilm and the bulk water, reduced the number of *K. pneumonia* cells from the bulk water (but not always from the biofilm) and resulted in *S. typhimurium* cell numbers below the detection limit in bulk water, but still present in the biofilm. *S. typhimurium* cells from the biofilm were not recovered by culturing methods after 20 days, but were detectable for long periods of time using the fluorescent antibody method. To test cells viability, slides were removed from the reactor 60 days after the beginning of the experiment and incubated for 2 days in dilute nonselective broth. After this enrichment period, *S. typhimurium* formed colonies on selective media, indicating that cells were capable to recover their culturability. *E. coli* O157:H7 was not detectable either in the bulk water or in the chlorinated biofilm at any time, by either culturing or fluorescent antibody techniques.

Baribeau et al (2005) also tested annular reactors (polycarbonate and cast iron (CI) operating in series of three) under similar operating conditions (tap water treated by granular and biological activated carbon filtration, with added nutrients such as biodegradable organic matter (BOM) at a concentration of 100 µg/L at 20°C). For a 3-week period, the reactors were fed without disinfectant to allow biofilm colonization. The authors then spiked the third reactor with a continuous dose of *E. coli* (K-12) for a period of 24 hours, about a week after a low disinfectant level had been achieved at the outlet of the first reactor (either 1.0 mg/L free chlorine for chlorinated trains or 1.0 mg/L total chlorine for chloraminated trains). A high disinfectant level phase where chlorine was added at the influent of both reactors 1 and 3 (in order to achieve the concentration values specified previously at the outlet of reactor 1 and 0.5 mg/L free chlorine or 1.0 mg/L total chlorine at the outlet of reactor 3) was then started 11 weeks after the spike. The results show that, after the *E. coli* spike, these bacteria were detected in all trains (chlorinated polycarbonate, chlorinated CI, chloraminated CI) for the remainder of the experiment (total duration of ≈160 days), except for the chloraminated polycarbonate train. A total mortality or a complete inactivation of *E. coli* took place in this reactor, both for the bulk liquid and the biofilm organisms. The authors also showed that *E. coli* in the bulk water were easier to inactivate than in the biofilm. In the CI reactors, chloramines were more efficient than free chlorine against *E. coli* in the biofilm, but this was not the case for the suspended *E. coli*.

4.3.4 Findings from laboratory-, bench-scale experiments

Results from the annular reactors experiments (Baribeau et al, 2005; Storey and Ashbolt, 2001; Camper et al, 1998) indicate that pipe biofilms can act as a reservoir for bacteria that are of significance for public health if faecal pathogenic bacteria are introduced into the system. However, although faecal bacteria were detected in the biofilm, low free chlorine levels (Table 4-3) under the tested conditions did appear to provide some degree of protection from bacterial pathogenic contamination of the bulk water (Baribeau et al, 2005; Camper et al, 1998), supporting the conclusions of Snead et al (1980) and Payment (1999). Although this interpretation is adequate for results obtained with culture-based methods, these techniques greatly underestimate the numbers of faecal bacteria and how long they persist when compared to the results with immunofluorescence assays (Camper et al, 1998). This observation questions the real significance of the controls based only on the enumeration of faecal indicator bacteria by culture-based methods.

The laboratory-scale experiments (considering the various settings used: beakers, jar tests, chemostat, annular reactors) therefore suggest that the free chlorine levels generally found in distribution systems (Table 4-1): (i) are able to eliminate or to inactivate (loss of culturability) the indicator and some pathogenic bacteria in the bulk water; (ii) are not efficient in rapidly inactivating more chlorine-resistant organisms (virus, protozoa); and (iii) have various levels of effectiveness in inactivating microorganisms in the biofilm, with some pathogens persisting there. This would indicate that, even when pathogenic microorganisms are not detected in the water following an intrusion, there remains a risk of contamination if subsequent biofilm colonization and detachment takes place due to erosion or sloughing caused by changes in flow conditions. When chloramine is used as the residual disinfectant, laboratory-scale experiments (Baribeau et al, 2005; McMath et al, 1999) showed conflicting results regarding the inactivation of pathogens from the bulk water, but generally agreed (Baribeau et al, 2005; Momba et al, 1999) on the ability of chloramines to limit the persistence of detectable pathogens in the biofilm.

4.4 PILOT-SCALE SYSTEMS

Pipe loop systems varying in length from 25 m (82 ft) to 1300 m (4265 ft) have been used to simulate the intrusion of microorganisms in free chlorinated or chloraminated distribution systems (Table 4-1). Three studies were also found where intrusion in non-chlorinated pilot-scale systems was conducted. These are discussed below for comparison purposes with disinfected systems.

4.4.1 Microbial persistence in the absence of a chlorine residual

Using a pipe loop fed with the city of Nancy (France) treated drinking water (total chlorine ≤ 0.1 mg/L, nutrient level not mentioned), Fass et al (1996) and Parent et al

(1996) have shown that strains of *E. coli* are able to grow at 20°C in distribution pipes largely colonized by autochthonous bacteria. However, even in the absence of a chlorine residual, colonization by *E. coli* was shown to be only partial and transient. With a single and rapid injection of 1.12×10^{12} cells of an environmental strain of *E. coli* in a pipe-loop system (approximately 10^8 cells/100 mL), Fass et al (1996) showed a rapid adsorption of *E. coli* onto the biofilm within the first few hours. During the 18-day monitoring period, *E. coli* was measured in the bulk water (>4 log CFU/mL) as no chlorine was present. Growth of *E. coli* in the pilot was observed by the 12th day of the experiment (the number of *E. coli* in the system (bulk water and biofilm) was greater than the number of cells predicted by the theoretical washout curve). However, the *E. coli* growth was insufficient to allow the long-term persistence of these bacteria in the pilot network. Fass et al (1996) were unable to show a plateau indicating stabilization of the *E. coli* counts. The growth rate of the bacteria was slightly lower than the dilution rate.

Predation through the ingestion of bacteria by protozoa is another mechanism that has been identified as being responsible for the disappearance of injected microorganisms in non-chlorinated distribution systems (Sibille et al, 1998). These authors observed that a single injection of 10^{11} cells of *E. coli* into the first loop of a pilot-scale network (approximately 10^7 CFU/100 mL) supplied with water filtered by granular activated carbon (GAC) decayed much more rapidly (in water plus biofilm) than a single injection of 4×10^{10} cells of *E. coli* into the first loop of a parallel network ($\approx 10^7$ CFU/100 mL) supplied with nanofiltered water. This was attributed to the higher level of protozoa present in the first system.

Persistence of enteric viruses in a non-disinfected pilot-scale system has been investigated by Quignon et al (1997). The authors injected poliovirus-1 (at about 3 to 9×10^3 MPNCU (most probable number of cytopathic units)/mL) in drinking water with no, or a very low, free chlorine residual (0 to 0.04 mg/L). In some cases, the viruses were pre-adsorbed onto clay particles before injection. The authors found that, when viruses were not inactivated, they were distributed both in the water and in the biofilm. More viruses were recovered from the biofilm than from the bulk water (between 2- and 10-fold). The results also demonstrated that virus adsorption onto clay favored its transfer to the biofilm.

4.4.2 Microbial persistence in the presence of a chlorine residual

The main characteristics of the pilot-scale studies investigating the fate of microorganisms in chlorinated water and biofilms are listed in Table 4-4. Parent et al (1996) used the same pipe-loop pilot system and methodology as Fass et al (1996), but added a continuous chlorine concentration from the 6th day following the injection of 10^{11} *E. coli* ($\approx 10^7$ CFU/100 mL). Chlorine was continuously added to the system to obtain 0.5 mg/L. A chlorine concentration of 0.1 mg/L was sufficient to inactivate the *E. coli* from the bulk water, and 0.5 mg/L (reached 3 days after the onset of chlorination) was needed to inactivate the attached *E. coli*.

Table 4-4: Pilot-scale studies investigating the fate of microorganisms in chlorinated water and biofilms

Reference	Injected microorganisms	Concentration (CFU/100 mL or MPN/100 mL)	Chlorine concentration at time of microorganism injection	Chlorine concentration and injection delay after intrusion event	Persistence of micro-organisms in bulk water (T_0=$T_{intrusion}$)	Persistence of micro-organisms in biofilm (T_0=$T_{intrusion}$)	Monitoring period
Parent et al, 1996	• *E. coli*	10^7	---	6 days after microorganism injection, addition of free Cl_2 to reach residual ≈ 0.5 mg/L	≈ 6.5 days (as soon as chlorine was detected)	9 days	18 days
Sibille et al, 1997	Settled raw wastewater: • Total coliforms • Faecal coliforms • *Streptococci*	10^7 10^6 10^6	≈ 0.25 mg/L free Cl_2	---	< 1 day	< 1 day	12 days
McMath et al, 1999	Treated domestic wastewater: • Total coliforms	10^6	≈ 0.24-0.31 mg/L chloramines	---	BDL	NA	3 to 11 months
Gibbs et al, 2003	Wastewater: • total coliforms	10^7	Before x-connection: 0.2-0.3 mg/L free Cl_2 During x-connection: 0-0.1 mg/L free Cl_2	---	• < 1 day	• 1 day	3 days after removal of x-connection
	• *E. coli*	10^6			• < 1 day	• < 1 day	
	• *Enterococci*	10^5			• < 1 day	• BDL	
	• *Salmonella*	10^5			• BDL	• BDL	
	• *Aeromonas*	10^8			• NA	• 1 day	

Table 4-4: Pilot-scale studies investigating the fate of microorganisms in chlorinated water and biofilms (continued)

• Aerobic endospores	10^5			• 1 day	• 2 days
• HPC	10^{10}			• 3 days	• 3 days

BDL: below detection limit; CFU: Colony forming unit; MPN: Most probable number; NA: Not available

In two parallel experimental chlorinated networks (supplied with nanofiltered water and GAC-filtered water), Sibille et al (1997) were not able to recover faecal contamination indicators from the water or from biofilm samples following the injection of a slug dose of 10 liters of settled raw wastewater. The contamination led to an increase in the total number of cells (enumerated by epifluorescence microscopy after DAPI staining) in the bulk water and the loss of the chlorine residual. Free chlorine returned to its initial concentration (of about 0.25 mg/L) after 9 days in the system fed with nanofiltered water and 6 days in the system fed with GAC water. In both experimental distribution systems, total and faecal coliforms were detectable in the bulk water and biofilm only on the day of the injection, and faecal *Streptococci* were only detected in the bulk water. However, these three indicators disappeared from both systems within one day in the bulk water and in the biofilm. The authors concluded that faecal indicators did not, therefore, easily adapt to distribution systems fed with chlorinated nanofiltered and GAC-filtered water.

McMath et al (1999) made the same observation when they injected a 25-liter slug dose of a treated domestic wastewater effluent ($\approx 10^6$ total coliforms/100 mL) into a chloraminated, 1.3-km experimental pipe rig. At water temperatures of 9°C (chloramine concentration = 0.31 mg/L) and 15°C (chloramine = 0.24 mg/L), no positive coliform samples were collected in the water downstream of the injection point during the entire monitoring period (3 times weekly – for 11 months at 9°C and for 3 months at 15°C). This is in contrast to the results obtained by the same authors with laboratory jar tests, where low levels of coliforms could be detected in the water 48 hours after injection. Under no-flow conditions, simulating a dead-end pipe, the authors found that coliforms could survive in the water for a period varying from 35 days (17-22°C) to 65 days (6-9°C). However, when the dead-end standing water was reintroduced into the main pipe rig, no coliform could be measured downstream. Accordingly, an increase in the flow to dislodge any deposits or biofilm was not conclusive, as again, no coliform could be detected. From these results, the authors concluded that a low chloramine residual of 0.2-0.3 mg/L appeared to be effective in preventing the survival of the coliform within the system. However, dead-end pipes are critical sites with favorable conditions for the survival of microorganisms.

The effect of a long-term wastewater cross-connection on the biofilm of a pilot-scale distribution system (the USEPA – distribution system simulator) was investigated by Gibbs et al (2003). Wastewater obtained following grit removal and ahead of primary clarification was injected (at a ratio of wastewater to system volume of 0.3% – with 0.1% injected every 8 hours) over a 90-day period into the pilot system supplied with the City of Cincinnati's tap water. The initial free chlorine concentration before the establishment of the cross-connection was 0.2-0.3 mg/L. Discharge water and biofilm were analyzed for the presence of seven types of microorganisms: total coliforms, *E. coli*, *Enterococci*, *Salmonella*, *Aeromonas*, aerobic endospores and heterotrophic bacteria (HPC). During the cross-connection, the discharge water had detectable amounts of all the study organisms. When the cross-connection was terminated, all the study organisms could be detected in the discharge water at 0h while only HPCs were detected after 24h. In the biofilm, study organisms were detected at low levels (no *Enterococci* or *Salmonella*) at 0h while only HPCs and endospores were detected at 24h. In agreement with the other pilot-scale distribution system studies conducted with a disinfectant residual (McMath et al, 1999; Sibille et al, 1997; Parent et al, 1996), Gibbs et al (2003) could only conclude that there was no evidence of long-term retention of the study organisms within an established biofilm following the termination of a long-term (90-day) wastewater cross-connection. HPCs in the discharge water decreased rapidly following the termination of the cross-connection (due to the washout of organisms from the system and the inactivation of organisms due to increased Cl_2). Removal of the organisms from the biofilm probably resulted from the sloughing of loosely attached organisms, increased chlorine and the lack of organism replacement. The only impact from the cross-connection was an increase in HPCs in the biofilm, which could have inhibited the growth of the study organisms introduced via the cross-connection.

In a subsequent study, under the same conditions but with a cross-connection lasting 70 days, Gibbs et al (2004) evaluated the ability of various free chlorine concentrations (0, 1, 2 and 5 mg/L) to inactivate the seven study microorganisms in the biofilm after the termination of the cross-connection. Ductile iron and PVC coupons were extracted from the pipe rig and placed into small (50 ml tubes) airtight static containers for the chlorine testing. The experimental setting minimized the flow (in order to eliminate the removal of organisms due to turbulent-flow conditions) to focus only on microbial inactivation due to disinfection (over a 72-hour period). The simulated conditions were therefore similar to those found in storage tanks. In unchlorinated samples, the authors measured a reduction in the number of organisms after 12 hours for both types of coupons, which indicates that the study bacteria were able to attach to the biofilm, but were not able to remain in it. They also found that a free chlorine concentration of 1 mg/L was sufficient to inactivate the study microorganisms in both the biofilm and the water column within a 24-hour period. For all the free chlorine concentrations tested, aerobic spores were detected in the biofilm and in the water for 72 hours after the termination of the cross-connection. This indicates that the biofilm can act as a reservoir for the release of chlorine-resistant microorganisms that could potentially be pathogenic. Biofilm sloughing in response to various free chlorine concentrations (0.6 to 5.0 mg/L) has been studied by Daly et al (1998). The authors used a biofilm (formed of 4 bacterial strains among which *E. coli*) generating system allowing the measurement of cells directly derived from the established biofilm (through the elution of the system with fresh medium prior to sampling – the reader is referred to the paper for a complete description of the experimental setting). Daly et al (1998) showed that a complete inhibition of biofilm sloughing (inhibition of bacterial loss into the planktonic phase) was only observed at free chlorine concentrations greater than 3 mg/L (which is higher than the usual distribution system residuals). Moreover, upon removal of the chlorine residual, biofilm detachment rapidly resumed with the detection, in the planktonic phase, of *E. coli* cells sloughed from the biofilm. Langmark et al (2005) identified desorption (detachment) as one of the primary mechanisms that could affect the fate of microorganisms in a pilot-system biofilm.

4.4.3 Findings from pilot-scale systems

The pilot-scale experiments (using continuously flowing pipe loops) suggest that chlorine concentrations in the range of 0.2-0.5 mg/L (Table 4-4) do not allow detection of intruded bacteria in bulk water for more than 24 hours after the intrusion. Similarly, under the tested conditions, indicator microorganisms do not seem able to extensively colonize the biofilm and be detected in the system for more than 24 hours after an intrusion (or termination of a lasting cross-connection) takes place in chlorinated distributed water. The concentrations of injected microorganisms in these studies ranged from 10^5 to 10^8 CFU or MPN/100 mL (HPCs were at 10^{10} CFU/100 mL) (Table 4-4) and intrusion volumes of up to 4% of the system volume were simulated (Table 4-1). Even in the absence of a chlorine residual, Fass et al (1996) were not able to show a sustained detection of *E. coli* (injected at $\approx 10^8$ cells/100 mL) in the biofilm for an extended period of time. However, more resistant microorganisms (such as aerobic endospores) were detected for a slightly longer time in the biofilm (one additional day) (Gibbs et al, 2003). No or low flow conditions simulated at the pilot scale showed that dead-end conditions still remain critical for the persistence of microorganisms in bulk water (McMath et al, 1999) and for allowing biofilm colonization by microorganisms that have intruded into the system.

4.5 FULL-SCALE TEST DISTRIBUTION SYSTEM

One study was found in the literature where a full-scale distribution system was used to evaluate the stability and effectiveness of various disinfectant residuals (free chlorine, chloramines and chlorine dioxide) when challenged by a sewage contaminant. Olivieri et al (1986) used a test distribution system consisting of several hundred feet of 4 in. (100 mm) diameter pipe (CI) and the internal plumbing of two army barracks (galvanized, copper and plastic pipes – from 0.5 in. (12 mm) to 2 in. (50 mm)). The test system was isolated from the Fort George G. Meade (Maryland) distribution system by a back-flow preventer and an air-gap at the reservoir used to supply the test system. This 1.5 m^3 (400 gal.) reservoir was filled with water from the city distribution system, and the disinfectant residual was adjusted for the experiment series. Raw sewage, seeded with f2 bacterial virus (10^6 pfu/mL) and a tracer dye in order to monitor the progress of the contamination, was injected into the test system (at a level of about 0.1%). Total coliforms and the f2 virus were only monitored in water samples.

In a multi-tap, short-term test (T° 13-17°C, pH 7.3-7.7) designed to evaluate the effectiveness of the residuals after challenging with sewage for a contact time of less than 4 hours (at a system flow rate of 3.8 L/min), it was found that free chlorine (C_0=1.04 mg/L) was the most effective residual for short contact times and consistently yielded the lowest level and frequency of coliform recovery. The next most efficient residuals were chlorine dioxide (C_0=0.95 mg/L) and chloramines (C_0=1.08 mg/L). For the f2 virus, chlorine dioxide was the most efficient and consistently yielded f2-free water at the tap.

Long-term multi-tap tests (3-day monitoring, system flow of 0.38 L/min, T° 19-22°C, pH 7.3-8.2), showed that chloramines (C_0=1.0 mg/L) performed most effectively against coliforms and the f2 virus. The loss of the free chlorine (C_0=1.0 mg/L) and chlorine dioxide (C_0=1.0 mg/L) residuals explained their reduced efficacy (see Table 4-5 for a synthesis of the results). However, when conditions favored the stability of free chlorine (lower T°: 10°C), this residual was more efficient than the other disinfectants in inactivating the coliform bacteria and f2 viruses. For both the short- and long-term investigations, coliforms and the f2 virus could be detected at high levels for the entire duration of the experiment (240 minutes and 72 hours), when no disinfectant residual was present. This suggests that the expected time that the slug of contaminant stands in the system is too short to provide pathogen reduction by natural die-away and that the only protection lies in the presence of a disinfectant residual.

Table 4-5: Efficacy of the disinfectant residuals in the multi-tap tests by Olivieri et al (1986)

Injected microorganisms	**Concentration (pfu/mL)**	**Chlorine concentration at time of microorganism injection**	**Efficacy of the residual against a) total coliforms and b) f2 virus**	**Monitoring period**
Raw sewage (total coliforms monitored)	NA	Free Cl_2: 1.04 mg/L ClO_2: 0.95 mg/L NH_2Cl: 1.08 mg/L	a) Free chlorine > chlorine dioxide > chloramines	4 hours
f2 bacterial virus	10^6		b) Chlorine dioxide > free chlorine > chloramines	4 hours
Raw sewage (total coliforms monitored)	NA	Free Cl_2: 1.0 mg/L ClO_2: 1.0 mg/L NH_2Cl: 1.0 mg/L	a) Chloramines > free chlorine and chlorine dioxide	3 days
f2 bacterial virus	10^6		b) Chloramines > free chlorine and chlorine dioxide	3 days

PFU: plaque forming unit; NA: Not available

4.5.1 Findings from this full-scale study

According to Olivieri et al (1986), the inactivation of microorganisms in sewage slugs in full-scale distribution system water seems to be heavily dependent on: (i) the type of disinfectant residual; (ii) the contact time; and (iii) the temperature. This view is not shared by Wierenga (1985) who stated that a free chlorine residual and bacterial sampling should not be relied on to ensure a safe potable water, based on coliform episodes (due to the entry of a slug of contamination into the water supply) which took place in the Grand Rapids (Michigan) distribution system in the presence of a substantial free chlorine residual (0.6 to 1.0 mg/L). The author maintained that proper design, operation and maintenance of water treatment and distribution facilities constitute the first line of defense against intrusion.

In the case of an intrusion caused by a pressure transient, LeChevallier et al (2003) discussed the opportunity for effective disinfection as the volume of intruded water is a fraction of the water contained within the pipe network (much less than 1%). However, as noted by the authors, turbidity, compounds causing a chlorine demand and limited mixing (in a relatively plug-flow condition) are factors that may affect the disinfection efficacy of the disinfectant residual in full-scale systems. The volume of sewage in the Olivieri et al (1986) full-scale testing represented 0.1% of the distribution system volume and they still detected some coliforms and f2 virus at the taps. However, as noted by Olivieri and colleagues, the injected concentration of the f2 virus (10^6 pfu/mL) was much higher than the density of human enteric viruses usually present in sewage (10^1-10^2 mpn/mL) (Metcalf and Eddy Inc., 2003).

4.6 DISCUSSION: WHAT CAN BE LEARNED FROM THESE EXPERIMENTS?

4.6.1 Laboratory- and pilot-scale results are not converging

In general, the results obtained from studies using laboratory settings to investigate the fate of microorganisms injected into water systems containing a disinfectant residual show that the residual (preferably free chlorine) is usually able to inactivate the bacteria in the bulk water, but that this is not always the case for the attached microorganisms of the biofilm. This result is not surprising, as chlorine disinfection is typically less effective against biofilm bacteria than against bulk water microorganisms (Parent et al, 1996; Servais et al, 1995; Mathieu et al, 1992; Paquin et al, 1992; van der Wende and Characklis, 1990). However, the results from pilot-scale distribution system studies do not show the same trends in the ability of indicators and pathogens to colonize biofilm. Indicator microorganisms injected in continuously flowing chlorinated systems do not seem able to extensively colonize the biofilm and be detected in the system for more than 24 hours (Table 4-4). Consequently, a longer persistence of the microorganisms is observed in the biofilms of the annular reactors (Table 4-3). This observation is mostly based on the use of detection methods based on culturing techniques for the lab-and pilot-scale studies reviewed (Table 4-2) as will be discussed later.

Operational characteristics of the pipe loops were not that different from those of the annular reactors (Table 4-6). Although Parent et al (1996) and Sibille et al (1997) used a higher water velocity of 1 m/sec, Gibbs et al (2003) used a velocity of 0.3 m/sec, which is identical to the velocity in the annular reactors of Camper et al (1998) and Baribeau et al (2005). Except for Camper et al (1998) who used a short water residence time in annular reactors (2 hours), the other experiments (when such a value was available) had hydraulic residence times varying between 12-24 hours (up to 46 hours in one case).

Table 4-6: Operational characteristics of experimental systems (annular reactors and pipe loops)

Scale of study	Reference	Type of system	Type of coupons (for biofilm)	Simulation	Residence time	Temperature
Lab/bench	Storey and Ashbolt, 2001	Annular reactor	uPVC	Linear velocity of 1 m/sec*	NA	NA
	Camper et al, 1998	Annular reactor	polycarbonate	Shear stress in a 4" pipe with flow of 0.3 m/s	2 hours	20±1°C
	Baribeau et al, 2005	Train of 3 annular reactors	polycarbonate and CI	Shear stress in a 4" pipe with flow of 0.3 m/s	2 hours in AR1, 4 hours in AR2, 6 hours in AR3: 12 hours through entire AR train (Sampling at RT=12h)	20±1°C
Pilot	Parent et al, 1996	1 pipe loop (L=31 m, D=100 mm)	PVC	V = 1 m/sec	24 hours	19-22°C
	Sibille et al, 1997	3 pipe loops (L=31 m/loop, D=100 mm)	PVC	V = 1 m/sec	12 hours/loop: 36 hours for pilot DS (Sampling at RT=12h)	NA
	McMath et al, 1999	Pipcrig (L=1300 m, D=110 mm)	Not applicable	V = 0.008 m/sec	13-31-46 hours**	9°C and 15°C
	Gibbs et al, 2003	1 pipe loop (L=25 m, D=152 mm)	DI	V = 0.3 m/sec	24 hours	12.7-21.1°C

AR: Annular reactor; CI: Cast-iron; D: Diameter; DI: Ductile iron; DS: Distribution system; L: Length; NA: Not available; PVC: Polyvinyl chloride; RT: Residence time; uPVC: unplasticized polyvinyl chloride; V: Velocity; *Calculated from mean hydraulic demand of 19 L/min and assumed diameter of 150 mm (uPVC main in system); **Sampling locations at these residence times

A methodological difference in the experimental procedures used for the inoculation of microorganisms into bench- or pilot-scale systems could explain the difference in persistence of microorganisms in biofilm. Microorganisms injected into annular reactors are usually allowed to colonize the biofilm under no-flow conditions for a certain period of time (from 24 to 60 hours in the studies reported here), which is not the case for the testing protocols used at pilot scale. Consequently, no-flow conditions seem to have an effect on the survival of microorganisms in biofilms. Annular reactors are also characterized by a very high surface to volume ratio, as compared to real pipe sections, and Camper (1996) observed higher concentrations of HPCs in biofilm in these reactors (about ten times higher) than in a 100 mm (4 in.) pipe rig fed with the same water. This constitutes a limitation of the annular reactor, in terms of its representation of a real pipe system, and could explain the increased persistence of the biofilm microorganisms in the laboratory studies reviewed here. Although annular reactors are very useful for the modeling of microbial processes in distribution systems (they are hydraulically simple to use, allow greater control in operational and environmental parameters), it is generally considered that pipe rigs are more representative of distribution system conditions than annular reactors (Eisnor and Gagnon, 2003). However, each scale of experimentation has its limitations. Pilot-scale and full-scale studies can lack experimental control conditions along with the ability to obtain representative samples (particularly for biofilm), etc.

4.6.2 Delay in chlorination affect microorganisms survival in biofilm

From Tables 4-3 and 4-4, it can be observed that, in general, when there is a time delay between the injection of microorganisms and the start of chlorination (varying from 1 to 38 days), greater persistence of the microorganisms in the biofilm seems to be favored. This would indicate that the period of contact without chlorine allows a stronger attachment of the microorganisms to the biofilm, which, in turn, allows the microorganisms to survive longer, even in the presence of chlorine. This is observed for both types of settings (laboratory and pilot) when there is a delay in chlorination, whereas such persistence is not observed in the biofilms of pilot systems when the microorganisms are injected directly into chlorinated water. However, other factors may play a role and two of the laboratory studies (Baribeau et al, 2005; Momba et al, 1999) show that, even if *E. coli* are injected into chlorinated waters, they could persist in the biofilm.

4.6.3 Results regarding persistence of microorganisms are mostly based on culturing techniques

As described in Table 4-2, investigators studying the persistence of microorganisms in distribution systems following an intrusion event mostly used culture-based techniques for bacterial enumeration; however, these are known to underestimate the number and diversity of microorganisms (Rompré et al, 2002; Szewzyk et al, 2000) as they do not take into account the viable but non-culturable bacteria (Byrd et al, 1991). Detection of microorganisms using culture-based methods may also be more difficult when clumps of organisms originating from biofilms or several organisms associated with particles are present, necessitating a disaggregation step to improve the plate counts. While enzymatic methods (Colilert and Quanti-Tray/2000 by IDEXX, Westbrook, Maine) have been used for the detection of coliform bacteria by some authors (Gibbs et al, 2003; McMath et al, 1999), only Camper et al (1998) used a detection method that was not culture-based – a fluorescent antibody method – and which was significantly more sensitive. With this method, the level of detection reached up to five orders of magnitude higher than that obtained with the conventional culture methods on selective media for *Salmonella typhimurium*. However, the authors have noted some limitations of this method when used with field water samples: interference from particulate material, the tedium of direct microscopy, the potential for false positives/negatives and nonspecific staining. In addition, there is the inability to determine whether the fluorescent cell is viable or if it has simply retained enough of the antigen to cause a positive response. With whole-cell in-situ hybridizations using fluorescently tagged 16S rRNA-targeted oligonucleotide probes, Williams and Braun-

Howland (2003) showed the presence of viable *E. coli* in biofilms exposed to 1 mg/L of hypochlorous acid (for 67 minutes after 2 weeks of incubation). The authors seeded flow chambers (their experimental settings) with bacterial concentrates obtained from distribution water that was determined to be free of *E. coli* using membrane filtration onto m-FC agar. Consequently, it was assumed that *E. coli* cells were most probably injured and not detected on standard selective media. The lack of culturability of the biofilm microorganisms in the pilot-scale studies reviewed here should not, therefore, lead to the assumption that the organisms were absent from the system. The use of detection techniques such as DVC-FISH-ScanRDI has even showed increased concentrations of viable but nonculturable *Enterobacteriaceae* cells in the bulk water of a distribution system at temperatures above 18°C; however, the free chlorine residual was below 0.1 mg/L (Baudart et al, 2005).

4.7 CONCLUSIONS

Whereas the laboratory-scale experiments reviewed in this paper showed that indicator and pathogenic microorganisms can survive for some time in the biofilm of water mains under the typical disinfectant residual concentrations used in distribution system, the pilot-scale studies indicate no evidence of long-term retention of injected microorganisms. Such an observation comes from results mostly based on culture-based methods for the enumeration of microorganisms. In general, the target microorganisms could not be detected in the biofilm for more than 24 hours in the pilot-scale experiments. However, results from both experimental scales tend to agree on the higher risk from the intrusion of chlorine-resistant organisms such as viruses or protozoa.

From this review, we can identify the most critical conditions in terms of the persistence of microorganisms in a water system as the following: (i) the intrusion takes place under no- or low-flow conditions (such that the microorganisms can accumulate in the biofilm), and (ii) there is a delay between the time of intrusion and the time of application of the disinfectant. Such conditions are very similar to the field conditions experienced during pipe breaks and failures in full-scale distribution systems. In the case of major repairs, it may sometimes take days before normal pipe flow is restored and chlorination is fully reinstated. Under these conditions, such results would therefore emphasize the need to perform extensive chlorination and flushing procedures before a water main is returned to service. This should be done in order to minimize the establishment of potentially pathogenic microorganisms in the biofilm which could subsequently be released in the bulk water if changes in flow conditions occur.

As previously highlighted, nearly all the studies reviewed here are based on the enumeration of microorganisms by culture-based methods. The few studies tracking the viability of bacteria rather than their culturability seem to indicate greater abundance and persistence of indicator and pathogenic bacteria, although significant methodological hurdles remain. Research is now needed to confirm this observation and to investigate the sanitary risks associated with the presence of viable but nonculturable pathogenic microorganisms in the distribution system biofilm.

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CHAPTER 5

PUBLICATION #2: ASSESSING THE EFFECT OF DISTRIBUTION SYSTEM O&M ON WATER QUALITY

This chapter presents the results of the application of the data integration approach for seven distribution systems. It summarizes the research work on the establishment of the causes of (historical) coliform occurrence in several distribution systems. Other water quality variations such as HPC events and consumer complaints are also included because this paper was intended as a complete summary of the data integration approach application. This chapter was published in the *Journal of the American Water Works Association*.

ASSESSING THE EFFECT OF DISTRIBUTION SYSTEM O&M ON WATER QUALITY

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Abstract: The investigation of historical water quality variations was performed in several distribution systems using a data integration approach. Participating water utilities included three Canadian cities, two European cities and two American utilities. The proposed approach combines the use of water quality, system operation and maintenance data, a hydraulic model and geographical information system. Temporal, spatial and hydraulic proximities between events are achieved through database queries. The investigation included: 140 positive coliform samples in five distribution systems; 48 HPC events in four systems; and 217 customer complaints in three systems. The objective of the research was to identify the main causes of water quality variations to eventually determine the proportion attributable to operation and maintenance activities. The results showed that the role of O&M activities on the occurrence of coliforms in distribution systems varies from one system to another, explaining a minimum of 9% and up to 45% of the number of coliform cases investigated in each system. About a third of the customer complaints investigated in each of the networks studied could be associated with O&M work, while its association with HPC events was negligible in three systems out of four. These results are of course based on the available data supplied from the participating water utilities. Although O&M activities are beneficial for water quality on a long-term basis, their short-term negative impacts should be understood for better prevention and control of potential water quality degradation.

5.1 INTRODUCTION

Maintaining treated water quality throughout the distribution system up to the consumer's tap is the goal of every water purveyor, but it still remains a real challenge today. Microbial contamination in the distribution system may be caused by a wide variety of conditions, i.e. treatment breakthrough (Morris et al, 1996), intrusion (Blackburn et al, 2004) and microbial regrowth (LeChevallier et al, 1987). However, the relative importance of these contamination pathways is unknown. Although the occurrence of positive coliform samples in distribution systems has traditionally been associated with coliform regrowth (LeChevallier, 1990), it is hypothesized that system operation and maintenance (O&M) activities may play a role in system contamination. Although maintenance activities (such as pipe flushing, pipe repairs/rehabilitation, etc.) are beneficial in the long run for improving water quality in distribution systems (Antoun et al, 1999; Oliver and Pimentel, 1998), they can potentially lead to short-term negative water quality impacts. Transitory contamination events through water main leakage points (caused by the opening/closing of valves and fire hydrants, service interruptions, sudden changes in demand) and water main installation and repair have been classified as direct routes of entry of pathogens into distribution systems (Friedman et al, 2004; Kirmeyer et al, 2001). New/repaired water mains are also an issue, and one which has been classified as high-priority in terms of its associated potential health risk by the Committee on Public Water Supply Distribution Systems of the National Research Council (NRC, 2005). Because of the general aging and state of deterioration of the infrastructure used to distribute water (ASCE, 2005), distribution system maintenance activities are therefore likely to increase in number and frequency in the future.

In order to evaluate the proportion of positive coliform samples collected in a distribution system that can be attributed to O&M activities (or to other causes), a data integration approach was developed to study historical coliform data from numerous water utilities. This data integration approach is based on the combination and simultaneous consideration of water quality data, network structural data, system O&M data, information from a hydraulic model and a geographical information system (GIS) for data visualization. It is essential to consider all this information if we are to answer such questions as: (i) where and when was the water sample collected? (ii) what was the likely route of the water supply for the sampling location? (iii) were there any global factors (water temperature, organic matter concentration, disinfectant concentration, deficient operation of treatment plant) that could explain the presence of coliforms? and (iv) did any event occur in the system (planned or emergency maintenance, fire flows, etc.) that could have affected the system hydraulics or provided a potential route of intrusion? Some of this information may be difficult for water quality managers to access, since they may not necessarily be aware of distribution system operation, maintenance and hydraulics, possibly due to the dispersion of data, to communication issues or to the level of training of water quality staff (if they are not familiar with hydraulic modeling, for example). Moreover, water quality variations may result from events that took place some time before the actual effect was observed.

The data integration approach used for this study therefore allows for the consideration of various types of data and tools (a hydraulic model, GIS) using a single interface called the Interactive Data Analyzer tool as described later. The concept is illustrated in Figure 5-1.

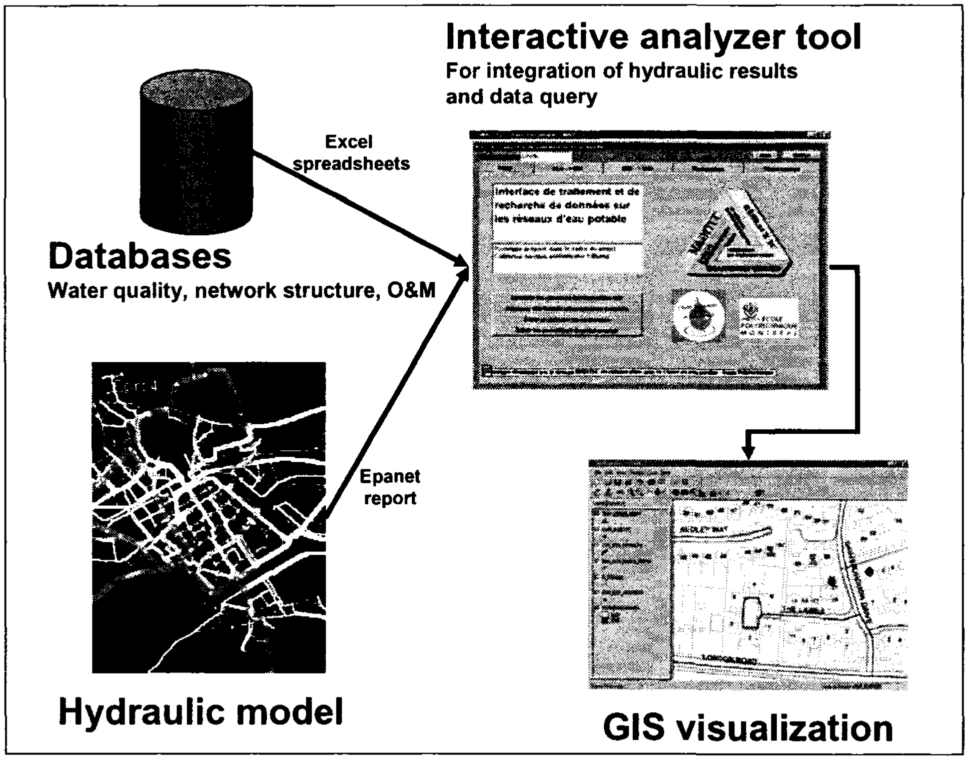

Figure 5-1: Concept of data integration approach

The approach was initially developed to investigate the causes of historical positive coliform samples (Besner et al, 2001), but was also used to investigate other types of water quality variations such as heterotrophic plate count bacteria (HPC) events and customer complaints (Besner et al, 2005), in several distribution systems. Investigation of the causes of complaints was part of the AwwaRF research project #2764, "Data Integration for Water Quality Management" (Martel et al, 2005), as the approach was selected as a demonstration tool. This paper therefore presents the main results of all investigations into the causes of coliform occurrences, HPC events and customer complaints in several systems through the use of a data integration approach based on data querying and visualization. With the USEPA's upcoming revision to the Total Coliform Rule (Rotert and Warn, 2005), the identification of the factors that can lead to coliform occurrences can certainly provide some insights into the most appropriate strategies for prevention, control and monitoring in distribution systems.

5.2 OBJECTIVES

The data integration approach was used to investigate water quality events in seven distribution systems, with the following objectives: (i) validation of the feasibility of the approach (depending on the data management practices in place) and of its applicability (depending on occurrence and type of water quality problems) in each water utility; (ii) assessment of the efficacy of the data integration approach in explaining water quality variations as a function of the available information; and (iii) identification of the main causes of water quality variations, mainly positive coliform samples, HPC events, and customer complaints in several systems, in order to eventually determine the proportion attributable to O&M activities.

5.3 METHODOLOGY

5.3.1 Details of the water quality events investigated

The data integration approach was tested in seven water utilities in Canada, the United States and Europe with their different types of water, operating characteristics and water quality problems. These utilities are described in Table 5-1. The main criteria for utility participation were: (i) distribution systems with water quality issues typically represented by events with monitored parameter values outside normal ranges; (ii) the availability of databases on network structure, water quality, O&M, and hydraulic modeling; and (iii) the willingness to collaborate in a research-oriented project.

Three types of water quality variations were investigated using the data integration approach in the participating distribution systems over time periods varying from 21 months to 4 years: 140 positive coliform samples in five systems, 48 HPC events in four systems and 217 customer complaints in three systems (Table 5-2).

Table 5-1: Characteristics of participating water utilities

System characteristics	**Participating water utilities**						
	LAVAL (Quebec, Canada)	**MONTREAL** (Quebec, Canada)	**MONCTON** (New-Brunswick, Canada)	**EGHAM** (United-Kingdom)	**CAEN** (France)	**GCWW** (Cincinnati, OH)	**DWD** (Denver, CO)
Study area	1 pressure zone (entire DS)	3 pressure zones (3-4-5)	DS city of Moncton	1 pressure zone (E23)	1 pressure zone (Zone Basse)	3 service areas	8 pressure zones (geographically limited area within NW zone)
Pipe length	1465 km (910 miles)	141 km (88 miles)	435 km (270 miles)	79 km (49 miles)	80 km (50 miles)	460 km (286 miles)	~ 400 km (249 miles)
Average demand	210 000 m^3/d (55 MGD)	90 000 m^3/d (24 MGD)	50 000 m^3/d (13 MGD)	~ 3300 m^3/d (0.9 MGD)	7640 m^3/d (2 MGD)	3140 m^3/d (0.8 MGD)	~ 75 700 m^3/d (20 MGD)
# of WTPs supplying area	3 (surface water)	2 (surface water)	1 (surface water)	1 (surface water)	2 (surface water and groundwater)	1 (surface water)	1 to 3 (surface water)
# storage reservoirs inside study area	0	4	1	0	1	3	4
# sampling points for routine WQ monitoring	12	16	18	Random sampling points	8 (+5 specifically for this project)	5	5

DS: Distribution system; DWD: Denver Water Department; GCWW: Greater Cincinnati Water Works; NW: North West; WQ: water quality; WTPs: Water treatment plants

Table 5-2: Water quality variations investigated using the data integration approach

	Participating water utilities						
	LAVAL (Quebec, Canada)	**MONTREAL** (Quebec, Canada)	**MONCTON** (New-Brunswick, Canada)	**EGHAM** (United-Kingdom)	**CAEN** (France)	**GCWW** (Cincinnati, OH)	**DWD** (Denver, CO)
Period of study	1997-2000	1997-2000	2000-Sept. 2001	1997-1999	1997-April 2001	1997-2000	1999-2000
# of positive coliform samples in DS	88	14	11	16 (11 from routine sampling, 5 from special study, 1L samples)	11		
% of coliform positive samples in DS	*0.9*	*0.5*	*0.6*	*7.9 (routine samples only)*	*1.1*		
# of positive coliform samples with free chlorine ≤ 0.1 mg/L	*33 (out of 39 samples with free Cl_2 conc. available)*	*11*	*0*	*14*	*10 (out of 10 samples with free Cl_2 conc. available)*		
# of positive coliform samples with T° ≥ 15°C	*58*	*13*	*Not available*	*5 (out of 5 samples with T° available)*	*4 (out of 10 samples with T° available)*		
# of samples with total coliforms > 10 cfu/100 ml	*2*	*3*	*3 *Including 2 samples with E. coli (21 & 29 cfu/100ml)*	*2*	*0 *3 samples with faecal coliforms = 1 cfu/100ml*		
# of HPC events		12	13	7	16		

Table 5-2: Water quality variations investigated using the data integration approach (continued)

# of customer complaints			39 (April 1st-June 30th 2000) - water complaint - dirty water - water inquiry - water low pressure			138 - rusty water	40 - dirty water - taste and odor

DS: Distribution system; DWD: Denver Water Department; GCWW: Greater Cincinnati Water Works

While positive coliform samples are easy to identify (with their coliform count > 0 CFU/100 ml), the definition of HPC events is more complicated. As illustrated in Figure 5-2, for each distribution system sampling location, HPC concentrations can vary over time, depending on: (i) the baseline HPC concentration, which often varies with seasonal patterns and sampling point characteristics such as residence time, disinfectant concentration, temperature, etc.; (ii) the background noise around the seasonal pattern; and (iii) the peak variations reflecting sudden changes in water quality (due to contamination, hydraulic disturbances, etc.). The peak variations are defined here as the HPC events to be investigated. The temporal variation of the HPCs was studied at each sampling point in order to define site-specific thresholds. For the customer complaints, specific categories were selected for investigation (rusty water, dirty water, and taste and odor).

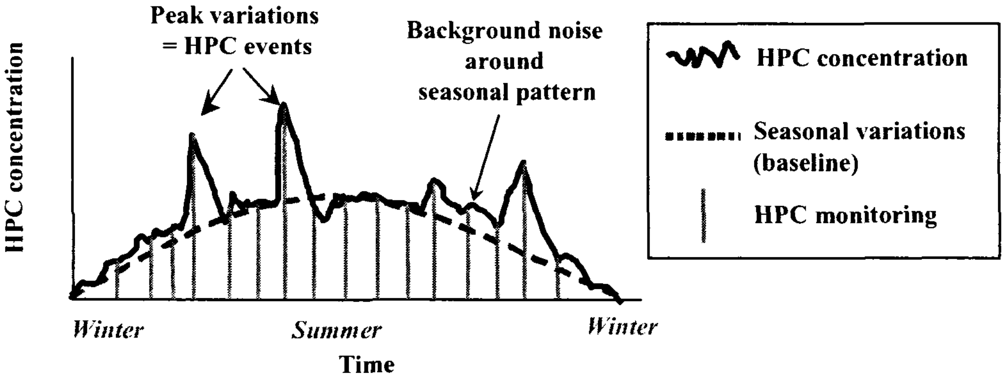

Figure 5-2: Schematic of typical temporal variation of HPC concentration at a distribution system sampling point

5.3.2 Main steps of the data integration approach

The approach used to study the different water quality events includes a number of steps which have previously been explained in detail by Gauthier et al (2001) and Besner et al (2005):

- Collection of the available databases in the utility. As mentioned previously, in addition to water quality data, other types of data must be considered in order to be able to explain water quality variations in distribution systems (Table 5-3). For each type of data, the information related to the temporal (date) and spatial localization (street address) should, ideally, be available;

Table 5-3: Types of data needed for distribution system water quality investigation

Type of data	Typical parameters
Water quality (source, treatment plant, distribution system)	• Coliform bacteria • Heterotrophic plate counts • Disinfectant residual • Conductivity • Temperature • pH • Turbidity • Consumer complaints
Treatment plant operation and other data	• Treatment plant events o Ozone failures o Power shutdowns • Rainfall/weather events
Distribution system structure and hydraulics	• Simulated parameters from calibrated hydraulic model o Flow o Velocity o Pressure o Residence time • Pipe material, year of installation • Pumping controls • Location and operation of storage tanks • Hydrant and valve locations
Distribution system O&M activities	• Valve/hydrant maintenance program • Flushing program • Pipe relining and cleaning • New pipe installation • Pipe leaks and breaks • Firefighters interventions • Computerized maintenance management system data • Inspection data

- Formatting (validation of format and content) and geocoding (allocation of geographical (x-y) coordinates) of the databases for their visualization (using a GIS);

- Use of a hydraulic model to obtain specific hydraulic paths, ie. all the possible water paths supplying a selected point in the distribution system (upstream route). This is achieved using a search algorithm which verifies for a selected node if at any moment of the simulation, water flowed from the upstream pipes to the node. The algorithm is stopped when the upstream route reaches the source of supply, i.e. the treatment plant.

- Mining of data using a unique visualization/exploration tool in order to identify the relationship between database parameters and water quality events. This is performed through database queries and data visualization.

The visualization/exploration tool that was developed as part of the data integration approach is a software prototype referred to as either the IMADSIG tool (Trépanier et al, 2006) or the Interactive Data Analyzer tool (Besner et al, 2005). This GIS-based tool uses software elements such as Microsoft Excel[1] for data storage, EPANET version 2.00.10 (Rossman, 2000) for hydraulic modeling and ESRI Arc Explorer[2] for GIS visualization. Visual FoxPro[1] was used for programming and the Structured Query Language (SQL) is the code used for database queries. The in-house user interface is available in both French and English. A relatively simple tool had to be developed because of the participating utilities' specific needs, data availability and data formats, established procedures and software for data collection, and hydraulic modeling. This is the main reason for the selection of Microsoft Excel, EPANET and ESRI Arc Explorer, which are widely available, the last two being free and available for download through the Internet. The use of proprietary and other advanced commercial software was possible but not considered, since the approach was designed to be transferred back to the water utility staff for their own use after the study had been completed.

The Interactive Data Analyzer tool's main functions include: (1) examination and management of Excel and database format (DBF) databases (which already included geo-locations – x and y coordinates); (2) generation of DBF files and GIS shapefiles from Excel files; (3) synthesis of EPANET extended period simulation results (minimum, maximum and average values for each node/link) and generation of corresponding DBF files and GIS shapefiles; (4) determination of the upstream hydraulic path for a specified node (all the possible water paths upstream of a node) based on statistics obtained from the hydraulic simulation; and (5) definition of database queries as multi-table (simultaneous queries in different databases) and multi-criterion (according to hydraulic, spatial, temporal and specific parameter values), with direct visualization of the results through the GIS freeware, Arc Explorer. The main functions are illustrated in Figure 5-3.

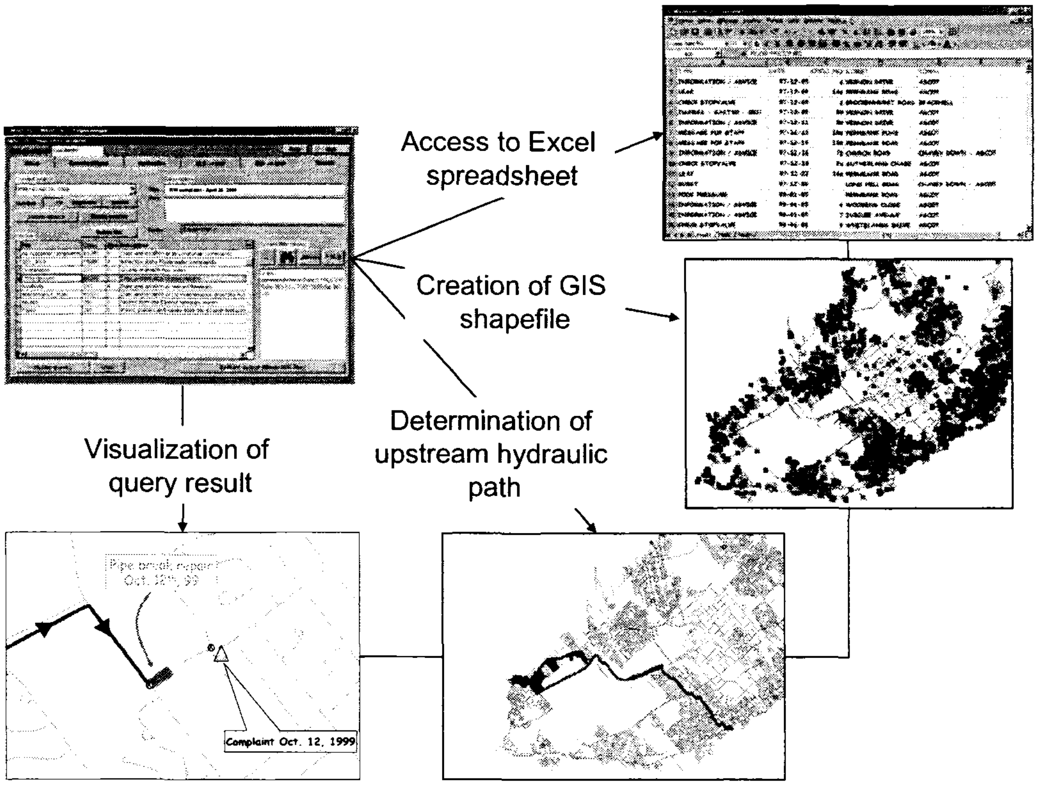

Figure 5-3: Main functions of the Interactive Data Analyzer tool

5.3.3 Systematic study of each type of water quality variation was conducted

Using the Interactive Data Analyzer tool, a systematic study of all the positive coliform samples, HPC events and customer complaints in each distribution system (as detailed in Table 5-2) was conducted. As an example, for each positive coliform sample investigated, trends in water quality data were verified in order to determine whether or not the coliform could originate from changes in source, finished or distributed water. Available SCADA data were reviewed to assess whether or not the operation of the system (changes in water demand) could have caused system disturbances, and database queries were performed to determine whether or not any specific system event(s) (such as O&M) took place in the same area as the sampling location. Furthermore, the upstream hydraulic path was also determined, allowing the theoretical water path from the treatment plant to the sampling location to be identified. Because all this information can be directly visualized using the GIS, the Interactive Data Analyzer tool makes it possible for the user to select the events that are related in both time and space to the occurrence of a water quality variation. However, the impact of each event on water quality may be more or less important, depending upon its type, the system hydraulics and temporal/spatial/hydraulic proximity. The user of the tool is the one assessing the potential impact of each event, using his knowledge and experience. It is clear that the result of such an analysis does not provide the origin of the water quality variation with certainty, however a "qualitative probability" or a "level of confidence" may be associated with each event. Using this approach, three levels of probability that an event was the cause of the water quality variation investigated were defined: (i) a low probability; (ii) a medium probability; or (iii) a high probability. Human judgment is therefore involved here, as the tool was not designed to be an expert system. It was primarily intended to support water utility personnel in accessing different types of databases, performing queries in them and visualizing the data. The qualitative probabilities assigned by the research team were validated by the utility personnel before compilation of the results. For each type of water quality variation investigated and for each distribution system, the results were compiled and presented in a matrix format with the potential causes identified from the data integration study. From this, the main O&M activities associated with the occurrence of water quality variations in each system could be identified, as well as the proportion of the variations attributable to O&M activities.

5.4 RESULTS

The seven water utilities in which the data integration approach was tested had very different characteristics in terms of the number and type of customers, the type of water supplied and the network layout. As a result, the data management practices and the types of data available were found to vary from one utility to another. The types of data that were available to the research team to perform the data integration approach in the various utilities are listed in Table 5-4. Occasionally, some of the data listed were not available for the whole study period. Also, the fact that some data could not be transferred to the research team does not necessarily mean that they were not collected by the utility.

Table 5-4: Types of data available to conduct the data integration analysis

Types of data available to conduct analysis	Laval	Montreal	Moncton	Egham	Caen	GCWW	DWD
WATER QUALITY							
Source water			Yes			Yes	Yes
Treated water (outlet of WTP)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Distributed water	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Customer complaints	Yes	Yes	Yes	Yes	Yes	Yes	Yes
OPERATION & MAINTENANCE							
PIPES							
Break and leak repairs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Leak detection	Yes						Yes
Pipe rehabilitation	Yes	Yes	Yes (cleaning)	Yes	Yes		Yes
New main installation	Yes	Yes	Yes	Yes	Yes		Yes
HYDRANTS							
Hydrant maintenance	Yes	Yes	Yes	Yes	Yes		Yes
Hydrant operation	Yes	Yes					Yes
Hydrant flow test			Yes		Yes	Yes	Yes
Dead-end flushing							Yes
Pipe unidirectional flushing	Yes		Yes				
VALVES							
Valve maintenance	Yes	Yes	Yes				Yes
Valve operation	Yes	Yes				Yes	Yes
STORAGE TANKS							
Reservoir cleaning	Not applicable			Not applicable	Yes		Yes
OTHER EVENTS							
Specific events in DS	Yes		Yes		Yes		
Specific events at WTPs	Yes						
Action after reception of complaint						Yes	
Water interruption notices					Yes		
Change in type of supplying source					Yes		
SCADA							
Flows	Yes					Yes	Yes
Tank level	Not applicable			Not applicable			Yes
Weather							Yes
Valve status							Yes
HYDRAULIC MODEL							
Extended period simulation	Yes	Yes	Yes	Yes	Yes	Yes[*]	Yes[**]
FIELD MEASUREMENTS							
Pressures in DS	Yes						
Flows in DS	Yes						

DS: Distribution system; DWD: Denver Water Department; GCWW: Greater Cincinnati Water Works; WTP: Water treatment plant
[*]Version provided was not representative of actual system operation, [**]Skeletonized hydraulic model

5.4.1 General performance of the approach in identifying causes of water quality variations

The results of the systematic investigation of the positive coliform samples in five distribution systems are illustrated in Figure 5-4. The percentage of coliform samples for which a potential cause was identified (with a low, medium or high probability of causing the coliform occurrence) is illustrated for each utility. An important fraction of the positive coliform samples could be explained with a high probability cause in three systems (38% in Egham, 43% in Laval and 55% in Caen). The explanation was less successful for the Montreal and Moncton systems, as only 14% and 9% of the positive samples were linked to documented events identified as high-probability causes. These two utilities had the highest level of unexplained cases, with no cause being identified for 36% of their positive coliform samples. The number of samples investigated was quite similar for four of the systems, varying between 11 and 15, while 88 positive samples were studied for Laval. This was mainly due to the fact that the entire distribution system in this city was included in the study and that the 12 sampling points in the network are monitored from 4 to 7 times a week. Because of the large number of samples collected over the 4-year period (n=9946), these 88 positive coliform samples still corresponded to only 0.9% of the samples collected. Specific results for this large database study are presented and discussed here later. HPC events were investigated in four distribution systems, and their numbers were found to vary between 7 and 16 events per system. The approach was able to identify high-probability causes for 8% to 31% of the events investigated (Figure 5-5). However, the percentage of unexplained HPC events (no cause identified) was higher than for the coliform samples, varying from 8% to 83% of the events investigated in each system. The study of customer complaints (including rusty water, dirty water, taste and odor, and low pressure) was conducted in three distribution systems. A high-probability cause was identified for 26% to 36% of the customer calls (Figure 5-6). However, from 36% to 53% of the complaints investigated in each system were unexplained. Three cases (coliforms, HPC and complaint events) for which high-probability causes were identified are discussed later in the paper.

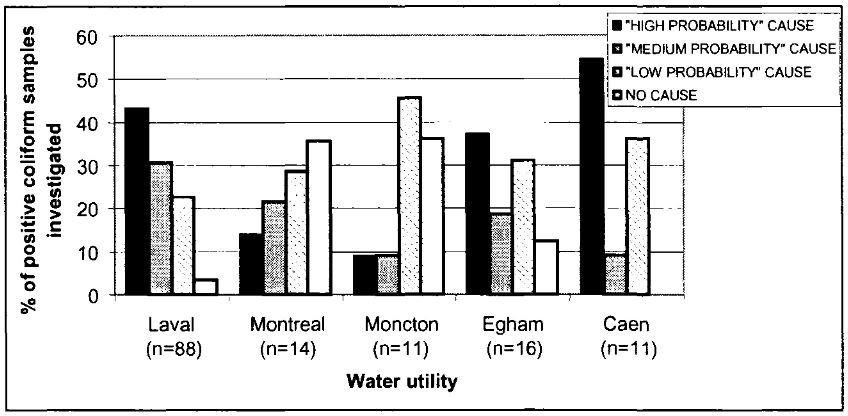

Figure 5-4: Capacity of the data integration approach to identify causes of positive coliform samples

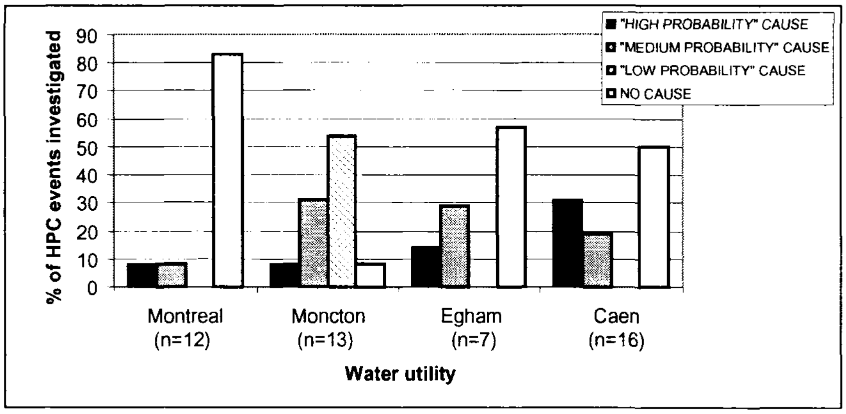

Figure 5-5: Capacity of the data integration approach to identify causes of HPC events

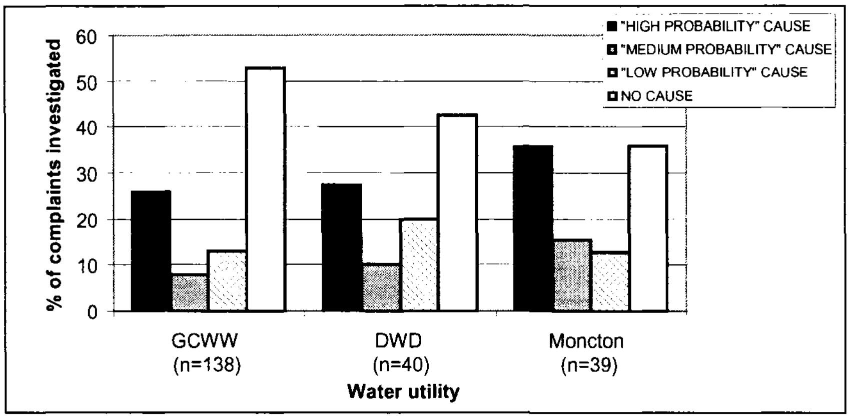

Figure 5-6: Capacity of the data integration approach to identify causes of customer complaints (GCWW: Greater Cincinnati Water Works, DWD: Denver Water Department)

5.4.2 High-probability causes identified

The occurrence of coliforms could be associated with pipe replacement (Egham) and with spot flushing and valve operation (Montreal). In the Laval distribution system, multiple types of high-probability causes were identified: unidirectional flushing, valve and hydrant operation, lower pressures in localized area of the system, change in quality of the water supply (due to coliforms measured at the water treatment plant (WTP) outlet and spring turnover) and peaks in water consumption. In the Caen distribution system, coliforms were found to be related to high flow hydrant testing, pipe break repair and change in quality of water supply, and in the Moncton system to the installation of new pipes and mains cleaning and relining. The high-probability causes identified for HPC events were pipe replacement (Egham), pipe break repair (Montreal), high flow hydrant testing and change in type of water supply (Caen) and unidirectional flushing (Moncton). Unidirectional flushing was also related to most of the explained customer complaints in the Moncton distribution system. Mains repair and hydrant maintenance were the other high-probability causes identified in this system. Valve operation, mains repair and fire flow tests were associated with complaints in the Greater Cincinnati distribution system, and work related to fire hydrants (replacement, routine maintenance, flushing) was the type of cause that explained most of the complaints in the Denver system. A summary of the high-probability causes identified for the three types of water quality variations investigated is provided in Table 5-5.

Table 5-5: High-probability causes identified through the application of the data integration approach

	# of coliform samples with cause identified	**# of HPC events with cause identified**	**# of complaints with cause identified**
LAVAL (TC samples = 88)	**38** See Table 6		
MONTREAL (TC samples = 14) (HPC events = 12)	**2** Valve operation & spot flushing (2)	**1** Pipe repair	
MONCTON (TC samples = 11) (HPC events = 13) (complaints = 39)	**1** New main installation & cleaning/relining	**1** Unidirectional flushing	**14** Unidirectional flushing (12) Pipe repair (1) Hydrant maintenance (1)
CAEN (TC samples = 11) (HPC events = 16)	**6** Change in quality of water supply (1) Pipe repair (1) High flow hydrant testing (4)	**5** Disturbances in DS hydraulics and water turbidity (1) Change in type of water supply (2) High flow hydrant testing (2)	
EGHAM (TC samples = 16) (HPC events = 7)	**6** Pipe replacement (6)	**1** Pipe replacement	
GCWW (complaints = 138)			**36** Valve operation (16) Pipe repair (14) Pipe repair & valve operation (5) Fire flow test & valve operation (1)
DWD (complaints = 40)			**11** Hydrant replacement/maintenance (4) Valve operation for hydrant testing (3) Pipe repair (2) Hydrant replacement & spot flushing (2)

DS: Distribution system; DWD: Denver Water Department; GCWW: Greater Cincinnati Water Works; TC: Total coliforms

5.4.3 Approach permitting the establishment of links between water quality data and O&M activities

In the Laval distribution system, a strong link was established between low pressure events in a section of the system and five positive coliform samples during the summer 1999 at three sampling locations (R8, R10, R12) in the disrupted area (Figure 5-7a). At that time, construction work was going on in the eastern part of the Laval system. The work was actually conducted on the sewer system, but it resulted in the intermittent closure of a drinking water main (400 mm-(16 in.)) supplying the area, limiting the supply of this part of the system to a single pipe from WTP A. Field pressure measurements at two of the sampling stations (R10, R12) indicated pressures sometimes lower than 20 psi (138 kPa) during that period (data not shown). In combination with lower system pressures, four out of the five positive coliform samples in this area were found to have been collected during periods of increased water consumption (summer). Moreover, for two of these samples, the operation of system valves was also identified as being a key factor in the explanation of the occurrence of coliforms. Database queries helped to reveal that, a few days before the occurrence of coliforms at sampling station R10, three valves had been operated on the other 350/400 mm (14/16 in.) pipe supplying the area, which resulted in changes in flow direction in this part of the distribution system (Figure 5-7b). According to the pressure field measurements available, very low pressures (close to 0 psi) were briefly recorded at sampling stations R10 (at around 3 a.m.) and R12 (between 1 a.m. and 4 a.m.), which suggests that the two mains supplying the area were possibly closed at the same time for a very short period. This combination of events (low system pressures, increased water consumption and valve operation) was therefore strongly associated with the coliform occurrences taking place in this distribution system area, which was characterized by low or non-detectable free chlorine residuals at that time. The lower pressures could have led to the intrusion of contaminated material into the pipes (Kirmeyer et al, 2001) and major flow reversals may have led to sediment resuspension in this area.

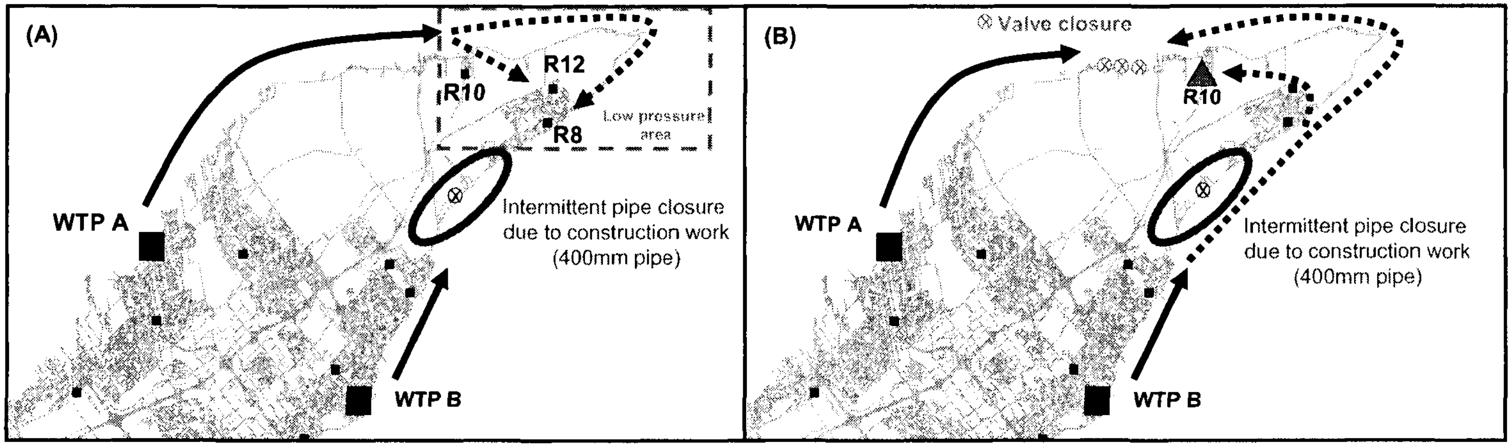

Figure 5-7: (A) Distribution system area of lower pressure due to intermittent pipe closure; (B) Valve closures on the other water main, creating flow reversals in the already disturbed area (Laval distribution system)

In the Montreal distribution system, an HPC event (340 CFU/ml) was investigated and the high-probability cause of this event was identified as the repair of a water main break. HPC concentrations at this sampling location are usually very low, with 95% of the samples having HPC concentrations of less than 14 CFU/ml for a 4-year period (n=201). For this same period, all but two of the samples had HPC concentrations of less than 70 CFU/ml. Using the Interactive Data Analyzer tool, the hydraulic path upstream of the sampling point was first identified, along with any maintenance events that had taken place in the previous months. The visualization of the database query results obtained led to the identification of a 200 mm (8 in.) pipe repair that took place the day prior to the HPC event, a few blocks upstream of the sampling point (Figure 5-8). It was therefore concluded that, because of the very good temporal and hydraulic proximity, this repair was a high-probability cause for this localized microbial degradation. Unfortunately, the repair procedures used by the field crew (whether or not the repair was done under pressure, what were the flushing and disinfection practices in place) are not known from the available data.

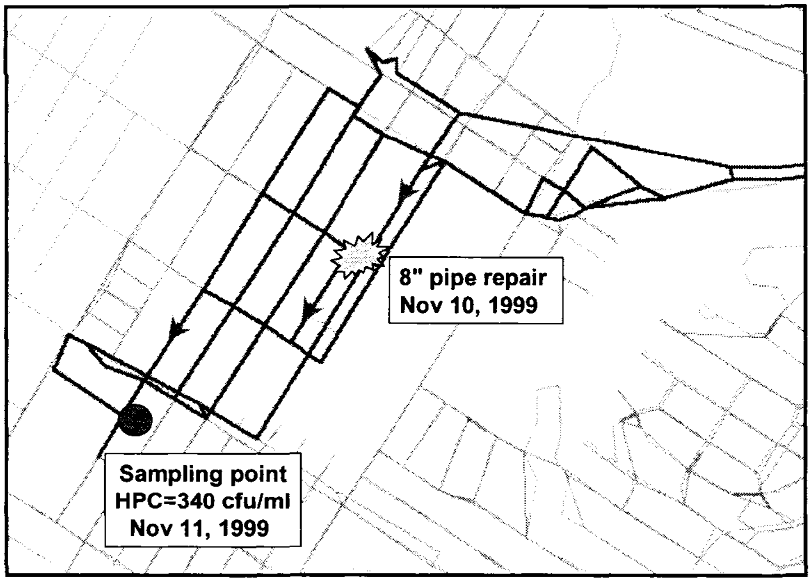

Figure 5-8: HPC event having the repair of a water main as a high probability cause (Montreal distribution system)

In the Denver distribution system, a dirty water complaint (brown water and particulates) was received on August 21, 2000 (Figure 5-9). According to the investigation by Denver Water staff (available through the complaint report), red particles, which appeared to be iron flakes, were found in the customer's water and in a nearby fire hydrant. The staff associated this situation with deterioration of the water main supplying the area, which, it was found, was installed circa 1904. The investigation using the data integration approach showed that, on the same day the call was received, two major excavations for hydrant replacement took place nearby, which could very well explain the occurrence of colored water following the induced disturbance. Unfortunately, the skeletonized hydraulic model did not permit determination of whether or not these excavations were upstream of the complaint location. However, the comments of the field crew performing hydrant flushing the day after the complaint was received (Figure 5-9), would tend to corroborate this hypothesis.

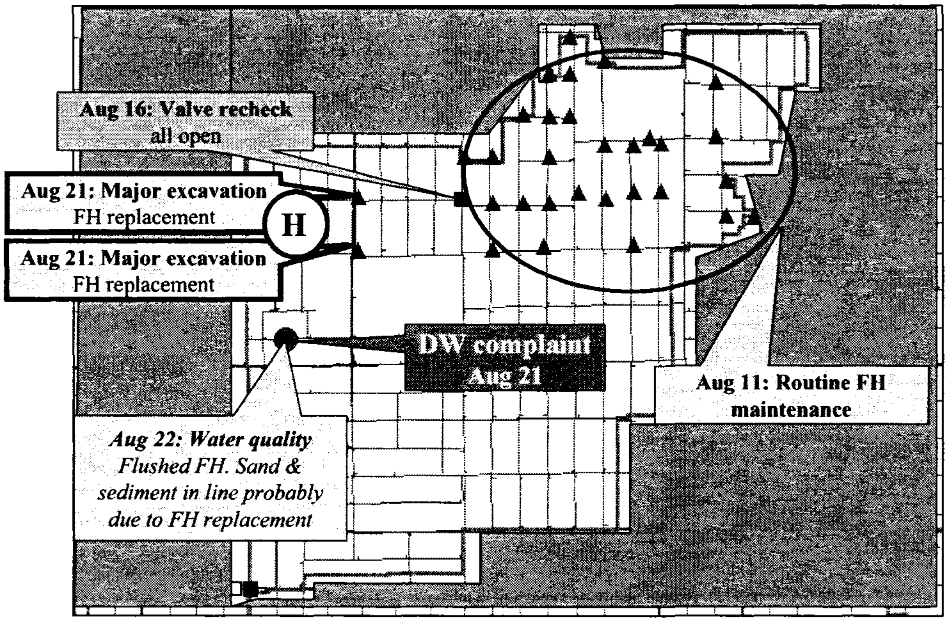

Figure 5-9: Events related to the occurrence of a dirty water complaint in Denver Water distribution system (DW: dirty water; FH: Fire hydrant; H: High probability cause)

5.4.4 Investigation of a large set of coliform data

As mentioned previously, 88 positive coliform samples were investigated in the Laval distribution system for the 1997-2000 period. A high-probability cause was identified for 38 samples, corresponding to 43% of the samples investigated. The causes identified could include a single event or a combination of events, as listed in Table 5-6. Coliforms measured in the treated water (at the WTP outlet) and higher turbidity in the source water are considered as WTP events, and were associated with the occurrence of 8 positive coliform samples, which represents 9% of the total number of cases investigated. Seventeen coliform samples were associated with an increase in water consumption in the system, corresponding to 19% of the investigated cases. However, it is rather difficult to classify higher water consumption events as strictly WTP- or distribution system-originating events, as the change in water quality could equally well originate from the WTP or the network. Moreover, the data available for this study did not permit differentiation among the possible origins, and, as a result, higher demands are here considered as a combination of WTP and distribution system events. Five coliform samples were associated with a combination of higher consumption and distribution system events, such as valve operation, lower system pressures and pipe flushing, and 8 samples were directly related to distribution system events (unidirectional flushing, hydrant operation and lower system pressures). Consequently, 15% of the 88 positive coliform samples investigated were directly related to the occurrence of distribution system events in the Laval network over the 1997-2000 period.

Table 5-6: Type of events identified as having a high probability of causing coliform occurrence in the Laval distribution system

Type of event	Description of event	Number of positive coliform samples explained by event	% of investigated cases (total n=88)
WTP	Total coliforms in treated water	7	8%
	High turbidity in source water (spring turnover)	1	1%
WTP and/or DS	Increased water consumption	17	19%
WTP and/or DS (with aggravating DS event)	Increased water consumption + few valve operation + lower DS pressures	2	2%
	Increased water consumption + lower DS pressures	2	2%
	Increased water consumption + pipe flushing	1	1%
DS	Lower DS pressures	1	1%
	Pipe flushing	6	7%
	Few hydrant operation	1	1%
	TOTAL	**38**	**43%**

DS: Distribution system; WTP: Water treatment plant

5.5 DISCUSSION

With the type of approach used for this study, there is obviously some expertise involved in the process of assigning a "qualitative" probability or confidence level to an event in causing a water quality variation. For this reason primarily, trends rather than specific numbers should be used to interpret the results presented. For the investigation of historical positive coliform samples, satisfactory results (more than about 40% of the cases explained by a high-probability cause) were obtained for three distribution systems out of five. In all the systems where customer complaints were investigated, about a third of the complaints in each system could be assigned a high-probability cause. Finally, HPC events seemed to be the most difficult type of events to explain using such an approach. The rate at which they were explained reached 31% in one system, while reaching only 8% and 14% in the other distribution systems. While it is known that an increase in shear stress due to modifications to the network hydraulic conditions is certainly a factor leading to the detachment of cells from pipe biofilm (Servais et al, 2004), it was not often possible to link distribution system events with an increase in HPC concentrations, at least for the data that were available. Moreover, HPCs are often more representative of disinfection efficacy, regrowth and biofilm formation in a system than total coliforms (Laurent et al, 2005), making it more difficult to relate HPC events to specific distribution system events.

It was expected that the data integration approach developed here would not be able to explain 100% of the investigated cases (for all types of water quality variations). The limitations associated with a study based on data analysis are numerous, as only available data can be considered. Limiting factors are the following:

- Some information can either be known, but not archived (emergency hydrant uses for fire fighting, etc.), or simply unknown (undetected leaks, illegal cross-connection, etc.).
- WTP data, especially those related to operational events at the plant (power failure, shutdown of a treatment component, cleaning of the installation, etc.) are rarely archived in a systematic way. Only one participating water utility had this information, but the details were often only partial.
- Some available data may be improperly dated (erroneous temporal location) or geocoded (erroneous spatial location) because of incorrect data validation.
- Depending on system management, the number of water quality samples and their frequency of collection may be too small to effectively determine the onset of a water quality variation, and hence the events associated with it.
- The hydraulic model, which is an essential part of this approach, may only give an approximate view of system hydraulics, due to: the updating process for describing long-term (system development) and short-term (main closure during rehabilitation) changes in hydraulic configuration, the detailing of water consumption, the use of extended-period simulations, the use of a skeletonized vs. an all-mains model and the intensity of the model calibration effort.

- The cause of the water quality variation investigated may not be identifiable through the use of standard collected data (e.g. internal plumbing problem for complaints or regrowth of HPCs in water mains).

It is not possible to compare the results obtained in the various distribution systems, as they are totally dependent on the data that were available for each participating water utility. The heterogeneity observed in the types of data available for each system reflects: (i) different plant and system management practices (e.g. unidirectional flushing is not performed in all systems); (ii) different regulations in place (e.g. yearly storage tank cleaning is compulsory in some countries such as France (Ministère de l'Emploi et de la Solidarité, 2001)); and (iii) different data management systems (centralization and computerization of data, use of SCADA systems). The application of the approach on several systems therefore highlighted different types of causes resulting in water quality degradation.

Because of the nature of the data available (mostly related to distribution system events), a large part of the explained cases are related to O&M activities conducted in the network, as illustrated in Table 5-5. The results obtained therefore show a minimal fraction of positive cases for which O&M activities likely played a role in water quality variation in the different systems. For the occurrence of positive coliform samples, events related to O&M can explain at least 9% of the cases in Moncton, 14% in Montreal and 38% in Egham. For two systems, some causes were related to events at the WTP or changes in the quality of the water supplied. Consequently, at least 45% of the positive coliform samples were related to distribution system events in Caen, and, in Laval, a minimum of 15% of the 88 coliform samples investigated were directly related to distribution system activities (considering only the 13 samples identified as being associated with distribution system events (Table 5-6), and not the other 17 samples associated with increased water consumption that could also be linked to the system in some way). Lehtola et al (2004) have shown that increased water consumption in a Finnish distribution system was the cause of lower water quality (increased iron and bacteria concentration, increased turbidity) due to the disturbance of old soft pipe deposits. For Laval, considering these 17 supplementary samples would link distribution system events to up to 34% of the 88 positive coliform samples investigated.

The role of O&M activities on the occurrence of coliforms in distribution system therefore seems to vary from one system to another. However, the development of improved strategies for conducting system work identified as a highly probable cause of coliform occurrences (pipe replacement, pipe flushing and cleaning, etc.) would certainly help reduce water quality disturbances. In Moncton, water mains were initially cleaned mechanically with high-speed water flows, causing disturbances in the upstream distribution system area (pipe scouring, increased water turbidity and possibly total coliforms). When the utility performed similar work subsequently, the contractor used an alternative cleaning method, thus avoiding major hydraulic disturbances to adjacent water mains.

For the other types of water quality variations, a constant fraction (about a third) of the customer complaints investigated in each of the three systems studied could be associated with O&M work, while the association with HPC events was negligible in most systems. However, the results obtained here most likely represent the minimal fraction of cases explained by distribution system events, and are based on available data sets. As an example, for the Denver distribution system, four complaints that could not be explained using the data integration approach were associated with the installation of new mains by the utility staff (as described in the available complaint reports). The data set related to the installation of new mains was unfortunately incomplete for the study period, and, as a result, this cause could not genuinely be related to complaints. Moreover, the role of O&M activities on the occurrence of coliforms and HPC events may also be underestimated, as monitoring of water quality only takes place at fixed sampling points (except for the Egham system). O&M work is very often conducted in distribution system areas where no monitoring takes place on a routine basis, making it more difficult to assess the real impact of these activities unless specific sampling campaigns are conducted.

Although these research findings may highlight temporary and local negative impacts that maintenance work (such as pipe replacement or unidirectional flushing) may have on water quality, this should not be interpreted as having a major detrimental effect leading to the value of these activities being questioned. There is no doubt that unidirectional flushing and pipe replacement are necessary and beneficial in maintaining distribution system reliability and integrity. However, the short-term detrimental impacts of the O&M activities found to be responsible for water quality degradation should be identified and understood by water utility staff in order that appropriate strategies can be developed for the prevention and control of potential future contamination (targeted water quality samplings, improved working procedures, etc.).

5.6 CONCLUSIONS

In this study, a data integration approach was applied to investigate historical data related to coliform occurrence, HPCs and customer complaints in several distribution systems. The results obtained led to the identification of some of the main causes of water quality variations in these systems. The explained cases led to the assessment of the minimal proportion of water quality events associated with O&M activities. However, the degree to which these cases can be explained using such an approach is totally dependent on the availability of high-quality data which provide a comprehensive analysis and a highly accurate diagnosis. Data on water quality, network hydraulics and distribution system operations, including all operations that may cause a significant hydraulic disturbance, must be available for the approach and the proposed tools to be applied to their full potential. Missing information, erroneous temporal and spatial localization of collected data, water quality sampling strategies and hydraulic model issues are some of the limitations associated with this type of analysis.

After this study was completed, the data integration approach and associated tools were transferred back to the staff of the participating water utilities. For some, the implementation of automatic geocoding for new data and the motivation to maintain well formatted and geocoded databases resulted from their participation in these research projects. The approach was therefore not only found useful for investigating water quality variations, but also for data management. The Veolia Water Company has implemented such a data integration approach in the city of Metz (France). Technical knowledge (better use of different types of information, better understanding of water quality in distribution systems), commercial benefits (technological showcase, development of GIS aspects, modeling) and the legal obligations of water providers under the revised regulations drove the application of the approach by the company.

The proposed approach is a first step in trying to establish links between O&M activities and changes in water quality. In order to refine the results obtained through data integration in relation to the impact of O&M activities on water quality (as the results obtained only give a picture of what is taking place close to routine sampling points for coliforms and HPCs), a subsequent field study was initiated with two Canadian water utilities, in which the impact of selected O&M activities on water quality is being monitored through extensive field samplings at the time work is conducted. To this day, the impact on water quality of sixteen water main repairs, ten pipe flushings, two hydrant pressure tests, routine pump operation and one transmission main closure has been assessed. It is anticipated that this will allow a more complete understanding of the risk of contamination associated with these distribution system activities.

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Footnotes: [1] Microsoft Corp., Redmond, WA; [2] ESRI, Redlands, CA

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CHAPTER 6

PUBLICATION #3: IMPACT OF WATER MAIN REPAIRS ON WATER QUALITY

From the results obtained through the general literature survey and the in-depth review of intrusion experiments as well as from the database study on the impact of O&M activities, repair sites were identified as one critical pathway for possible system contamination. This chapter therefore presents the results of our field study during which planned repairs of water main leaks were monitored in two full-scale distribution systems. Evaluation of water quality was performed both inside and outside the repair area in order to provide information that is not yet available in the scientific literature. This chapter is a paper that has been submitted to the *Journal of the American Water Works Association* for publication.

IMPACT OF WATER MAIN REPAIRS ON WATER QUALITY

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Abstract: The investigation of 16 planned repairs of pipe leaks in the distribution systems of two Canadian cities was performed in 2004-2005. The objective was to study the occurrence of microbial intrusion in full scale distribution systems associated with repair activities. Samples of soil and water were collected in pipe trenches while distribution system water was collected at customer houses and flushed hydrants. The frequency of faecal microbial indicators detection in the soil and water surrounding the mains was low. Evidence of intrusion (using total coliforms, *E.coli* and aerobic endospores in distribution system water) was obtained at seven sites out of 16 but the results suggest that adequate pipe flushing after a repair is completed is effective to minimize contamination for the type of repair investigated. The positive samples were almost all collected during the flushing operation. Variations in chlorine residuals and turbidity were also observed outside of repair areas.

6.1 INTRODUCTION

The last few years have seen an increasing interest in better understanding the impact of routine operations (e.g., pump, hydrant or valve actions, main repairs, etc.) on the water quality within a distribution system. The possibility of the contamination of drinking water with pathogenic organisms is a concern for any water purveyor and some conditions or activities in distribution systems may influence the potential for pathogen intrusion. Drinking water main repair sites appear as particularly vulnerable locations for intrusion because of the operational characteristics involved as part of this maintenance activity (loss of system's physical integrity, repair procedure, operation of valves and hydrants). As such, new and repaired water mains have been ranked as a high priority/risk level pathogen route of entry by Kirmeyer et al (2001) and by the National Academies' Water Science and Technology Board Committee (NRC, 2006). Conclusions from a literature review of numerous studies specifically investigating the fate of microorganisms introduced into experimental systems showed that conditions experienced when pipe break repairs are conducted in full-scale distribution systems are likely the most favorable to pathogen persistence in a water system (Besner et al, 2007a). Nygard et al (2007) observed that breaks and maintenance work with presumed loss of water pressure in distribution systems in Norway caused an increased risk of gastrointestinal illness among water recipients with a risk ratio of 1.58 in exposed households.

Data available to assess the importance of pipe repairs in terms of pathogen intrusion mostly rely on the occurrence of waterborne disease outbreaks (Deshayes et al, 2001; Geldreich et al, 1992) and surveys among water utilities (Pierson et al, 2001; Kirmeyer et al, 2001; Haas et al, 1998). Requirements and procedures to limit microbial contamination during construction, repair and replacement of water mains have also been provided (Pierson et al, 2001; Burlingame and Neukrug, 1993). However, detailed field data related to water quality parameters during repairs are usually missing. The number of sanitary release samples after new main installation is the most common type of data available (Haas et al, 1998).

A list of the potential sources or pathways of microbiological contamination during pipe repair has been compiled by Pierson et al (2001) from the input of water utility personnel. The authors determined that pre-installation exposure, installation or repair activities and post-repair conditions were susceptible to lead to water contamination. During the repair activities, points of concern of 250 water utilities surveyed by Haas et al (1998) were mainly unsanitary construction practices (for nearly 40% of the utilities surveyed) and contamination from soil and trenchwater exposure (for 20% of the utilities). Soil and water samples from trenches can be potentially contaminated with faecal microorganisms and even human enteric viruses (Karim et al, 2003; Harris, 1959). Other factors that are likely to influence the potential for contamination during repair include shutdown time, nature of the excavation, method of repair, storage or cleanliness of materials, and size of the job (Haas et al, 1998). Flushing, disinfection (according to AWWA Standard C651), and water quality testing are the recommended actions for contamination control after a repair is completed (Pierson et al, 2001). Haas et al (1998) reports that another potential source of contamination may come from stagnant water created by closed valves adjacent to the area of the construction or repair. However, no field data are provided and the impact of repair procedures outside of the isolated distribution system area is hardly addressed in the existing literature.

The general aging and deteriorating state of the infrastructure used to distribute water is a threat to the integrity of distribution systems and increases the vulnerability of distribution systems to water contamination to a level that is not known today. Kirmeyer et al (2001) estimated that about 237,600 water main repairs are performed annually in the U.S. The number of repairs is likely to stay high and may even increase: (i) the American Society for Civil Engineers allocated a D- for the poor state of drinking water infrastructures in the U.S (ASCE, 2005) and, (ii) the results of a Canadian municipal infrastructure survey conducted in 1995/96 showed that 59% of the water distribution networks were in unsatisfactory condition at that time (Mirza and Haider, 2003). Consequently, a field study to actually monitor changes in distributed water quality when pipe repairs are conducted is needed to assess the risk of contamination linked to this activity.

6.2 OBJECTIVES

In order to evaluate the potential for contamination associated with pipe repairs in drinking water distribution systems, a study was undertaken involving field investigations of hydraulic and water quality parameters during planned repair work in two full-scale distribution systems. This project was conducted over two years (summers of 2004 and 2005). The objectives of this study were to develop a sampling protocol that could be tested in full-scale distribution system in order to assess the risk of contamination associated with the repairs of water mains.

6.3 METHODOLOGY

The sampling protocol developed to assess the impact of pipe repairs on water quality has been tested in two full-scale distribution systems located in the province of Quebec (Canada). The first water utility (Utility A) provides drinking water to about 380,000 consumers. The distribution system services mostly customers inhabiting single-family dwellings and could be classified as of a "suburban type". An active pipe leak detection program has been in place at this utility for over 15 years. Most of the repairs in this system are scheduled and conducted rapidly after indications of a leak are reported by the field crews. The second water utility (Utility B) provides drinking water to about 1.8 million consumers and is divided into 27 districts. The distribution system of one district, supplying water to a population of 128,440, was selected as the study area. This district is among the five more densely populated districts in the city and the majority of housing is composed of multiple-dwelling structures. For the selected district, no specific program exists to detect pipe leaks such that repair work can be classified as generally more reactive than preventive.

For logistic reasons, only planned repairs were investigated for this study. Notification by the field crews of the time and place at which the repair would take place was therefore possible. A total of 16 repairs were monitored. During summer 2004, 11 repairs were monitored in system A and during summer 2005, three repairs were investigated in system A and two repairs in system B.

6.3.1 Collection of soil and water samples from pipe trenches

Soil samples were collected in the vicinity of the exposed main using a sterile trowel. The samples were put into large plastic (Ziploc® type) bags. Water samples were collected using four autoclaved one-liter plastic bottles. Samples were kept in a cooler and received by the laboratory within a few hours of collection (usually less than 5 hours). For soil samples, particle size analysis was conducted using the hydrometer method (ASTM D 421, 1998).

6.3.2 Bacteriological analyses conducted on soil and water from pipe trenches

For bacteriological analysis, 20 grams of soil were mixed with 200 mL of saline and stirred on a magnetic stirrer for 1 minute. The sample was left to stand for 30 minutes and the supernatant was then recuperated for bacteriological and coliphages analysis.

For water, the 1-liter samples were pooled and stirred on a magnetic stirrer for 1 minute, left to stand for 30 minutes and 250 mL of supernatant were recuperated for bacteriological and coliphages analysis.

Samples were assayed for the presence of aerobic endospores, *Clostridium perfringens*, *E. coli* and total coliforms (total coliforms were not assayed in 2004) within 24 hours of sampling using membrane filtration methods. Two 10 mL and two 1 mL portions (or appropriate dilutions) of the sample were assayed on each culture media. Tryptic soy broth (Difco Laboratories) with 0.01% triphenyl tetrazolium chloride was used to enumerate aerobic endospores. Samples were filtered on a membrane, placed in a 50 mm Petri dish containing a pad saturated with the medium, pasteurized during 15 minutes at 75°C in a water bath and incubated at 35°C for 24 hours. Red colonies were counted as aerobic endospores (Barbeau et al, 1997), and the vast majority of these organisms are species of *Bacillus*. The method described by Armon and Payment (1988) was used to enumerate *C. perfringens* by membrane filtration using mCP agar and incubation at 45°C for 18-24 hours. In 2005, MI (Difco Laboratories) agar was used for the simultaneous detection of *E. coli* and total coliforms after 24 hours at 35°C (USEPA, 2002a). Blue colonies were reported as *E. coli* and fluorescent colonies under longwave ultraviolet light (366nm) (including the blue colonies under ambient light) as total coliforms. In 2004, *E.coli* were detected with mTEC agar by membrane filtration (USEPA, 2002b). The dishes were incubated at 35 ± 0.5°C for 2 h. After a 2h incubation at 35 ± 0.5°C, the plates were transferred at 44.5 ± 0.2°C for 22-24 h. After incubation, the membranes from mTEC Agar were transferred on absorbent pads saturated with Urea Substrate Medium and kept at room temperature for 15-20 min. Yellow, yellow-green, or yellow-brown colonies were counted as *E. coli*. Results are reported as colony forming unit (cfu) per 100 mL or per 100 g.

6.3.3 Coliphages assay

Method 1602 of the U.S. Environmental Protection Agency (USEPA, 2001a) was used with *E. coli* CN-13 as host strain for somatic coliphages and *E. coli* F-amp as host strain for male-specific coliphages. Volumes of 1 and 10 mL were assayed for each coliphages in duplicate. The results were reported as plaque forming unit (pfu) per 100 mL or per 100 g of sample.

6.3.4 Virus detection in soil and water from pipe trenches

Soil (100g) was weighed, mixed for 30 minutes with 400 mL of 3% beef extract and then centrifuged for 15 minutes at 3000 x g. The supernatant was transferred into a sterile bottle for organic flocculation (pH 3.5 and $FeCl_3$ 0.1%) followed by centrifugation for 15 minutes at 4°C at 3000 x g. The supernatant was discarded, the pellet resuspended in glycine buffered medium (pH 9) and the volume completed to 15 mL with Minimum Essential Medium (MEM) with antibiotics (1% penicillin-streptomycin and 0.1% gentamicin). The pH was adjusted to 7.2 and the concentrate stored at -80°C until the viral assay was performed. For water, a sample of 4 liters was centrifuged for 15 minutes at 3000 x g. The supernatant and the pellet were treated separately.

6.3.4.1 Supernatant

A final concentration of 0.05M $MgCl_2$ was added to the supernatant that was then adjusted to pH 6 with HCl 1.2N and filtered on a series of 142 mm filters: an AP25 prefilter (Millipore), a 0.45 µm and a 0.25 µm (Duo-Fine media, Filterite Corp). The filters were eluted using 150 mL of beef extract (1.5%, pH 9.75) and reconcentration was done by organic flocculation (pH 3.5 and $FeCl_3$ 0.1%) followed by centrifugation for 15 minutes at 4°C at 3000 x g. The supernatant was discarded, the pellet resuspended in glycine buffered medium (pH 9) and the volume completed to 15 mL with Minimum Essential Medium (MEM) with antibiotics (1% penicillin-streptomycin and 0.1% gentamicin). The pH was adjusted to 7.2 and the concentrate stored at -80°C until the viral assay was performed.

6.3.4.2 Pellet

The pellet was weighed and beef extract (3%) was added in a 1:4 ratio and mixed for 30 minutes to elute the viruses, and then was centrifuged at 3000 x g for 15 minutes. Viruses were concentrated from the supernatant by organic flocculation (pH 3.5 and $FeCl_3$ 0.1%) followed by centrifugation for 15 minutes at 4°C at 3000 x g. The supernatant was discarded, the pellet resuspended in glycine buffered medium (pH 9) and the volume completed to 15 mL with Minimum Essential Medium (MEM) with antibiotics (1% penicillin-streptomycin and 0.1% gentamicin). The pH was adjusted to 7.2 and the concentrate stored at -80°C until the viral assay was performed.

6.3.4.3 Virus assay

Before the assay, every concentrate was treated with 1,1,2 trichlorotrifluoroethane and 5% penicillin-streptomycin 100X and centrifuged to remove toxic compounds, contaminants and debris. MA-104 (African green monkey kidney cells) cells were grown until they produced a confluent monolayer in 25 cm^2 plastic flasks. One milliliter of the concentrate (or an appropriate dilution) was placed on the cells and the flasks were incubated at 37°C for 60 minutes on a rocker platform. Ten mL of culture media containing antibiotics (1% penicillin-streptomycin and 0.1% gentamicin) were then added to each flask. Flasks were incubated at 37°C for 11 days, freeze-thawed at -20°C and a second passage was performed for 7 days on fresh cell cultures in 24 well plates (using one well for each first passage flask). The cells were fixed with absolute methanol containing 1% hydrogen peroxide (to destroy indigenous peroxidase). The fixed monolayers were submitted to an immunoassay developed in our laboratory using commercial hyper-immune human serum globulins to detect viruses in infected cells (Payment and Trudel, 1987). Infected cells appear dark brown under an inverted microscope making it easy to detect the viral infection even in the absence of a cytopathic effect. The number of viruses in the original samples was calculated using the number of positive (cytopathic effect or immunoperoxidase positive) and negative wells after the second passage and estimating the most probable number of infectious unit per liter as described previously (Payment and Trudel, 1987).

6.3.5 Collection of water samples from distribution system pipes

In order to monitor the impact of pipe repair, water samples were collected at different times and locations within the distribution system. As the closure of valves usually takes place in order to isolate a section of the leaking main (Figure 6-1), customer houses located both inside (House In) as well as outside (House Out) of the isolated area were used for sample collection. A flexible PVC hose (disinfected with chlorine) connected to the external hose bib was used for water sampling at customer houses (flow was set to approximately 5 L/min). Other sampling locations included the hydrant used for flushing when the repair is completed. In 2005, a second house outside of the isolated area (House Out^2) was added as well as one customer house on the isolated section of main to study possible service line contamination (House SL). These are all illustrated in Figure 6-1. To simplify the analysis, results of the 2 sampling locations outside of the repair area are considered together and referred to as House Out only.

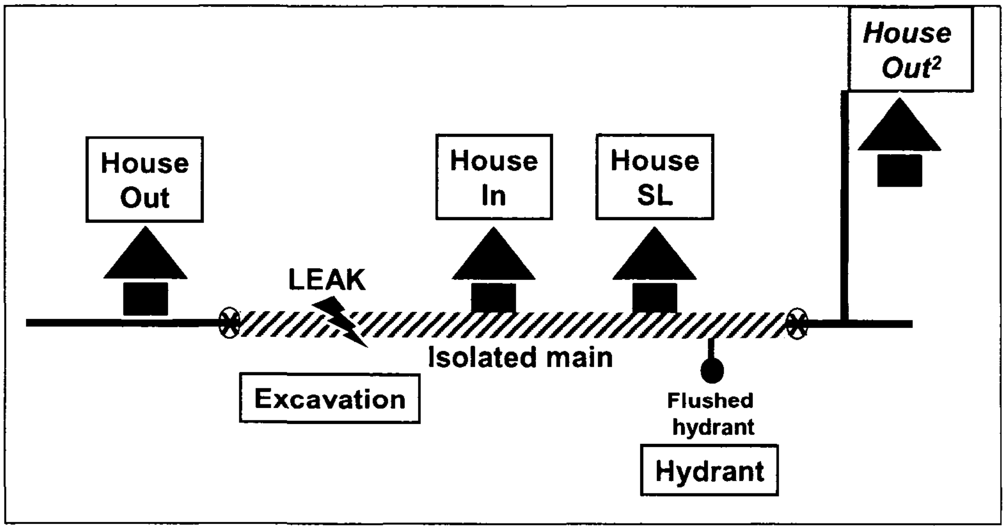

Figure 6-1: Sampling locations at site of water main repair

During the repair, the water sampling sequence was as follows:

1. sampling at House In, House Out and House SL before valve closure, ie. initial system condition (T_0);
2. sampling at House Out when valves were closed to isolate the section of main to be repaired;
3. sampling at House Out prior to the opening of the first valve to start flushing;
4. sampling at House In, House Out and at the Hydrant during flushing;
5. sampling at House In, House Out and Hydrant prior to the closure of the hydrant;
6. sampling at House SL (first flush) immediately after the hydrant closure and sampling at House In and House Out 15 minutes after the hydrant was closed.

The field crews did not perform any chlorination of the repaired mains, only pipe flushing was conducted to remove any possible contamination. Water samples were collected in 1L autoclaved plastic bottles (with 0.01% (w/v) sodium thiosulfate). For steps (2) and (4), six samples were collected at 1, 2, 4, 7, 10 and 15 minutes after valve closure or start of flushing. One water sample was collected at each location for the other steps.

6.3.6 Parameters analyzed in distribution system water

The microbiological parameters that were analyzed in distribution system water (collected from House In, Out, SL and Hydrant) included the presence/absence of total coliforms and *E. coli* using the Colilert®[1] detection method. Aerobic endospores were enumerated using the membrane filtration method developed by Barbeau et al (1997) (Trypticase soy broth culture medium, pasteurization at 75°C for 15 minutes followed by incubation at 35°C for 24 hours). Heterotrophic plate counts (HPC) were enumerated using the membrane filtration method using R2A agar incubated at 35°C for 48 hours (method 9215D, APHA and AWWA (1998)). HPC were only monitored in 2004 as they were not found useful for detection of intrusion.

The physico-chemical parameters were analyzed using the methods described in APHA and AWWA (1998): free chlorine residuals using the DPD-FAS method (method 4500-Cl G), pH (method 4500-H+ B), temperature, conductivity (method 2510), turbidity by the nephelometric method (method 2130B) and total iron analyzed using the phenantroline colorimetric method (method 3500-Fe B).

Pressure in the distribution system was also monitored at one or two locations nearby the repair site. Two types of high-speed pressure transient data loggers were connected to fire hydrants (model HPR21 from Telog Instruments[2] and model RDL 1071L/3 from Radcom Technologies[3]). These are able to measure up to 4 and up to 20 readings/sec respectively and were used in order to capture transient pressure events that could be associated with system operations during the repair.

Statistical analysis of the results (Student's t-test, Mann-Whitney test, Wilcoxon matched pairs test) was performed using the Statistica[4] version 7.1 software. The level of significance was set at $p \leq 0.05$.

6.4 RESULTS

Sixteen pipe repairs were monitored for this study. Fourteen repairs were in fact repairs of circumferential leaks, requiring the installation of repair sleeves. One repair was on a valve and one repair involved the installation of a new section of main (about 4 m (13 ft) long). Thirteen repairs were on 150 mm (6 in.) diameter mains and 3 repairs were on pipes with diameter of 200 mm (8 in.). Unlined cast-iron was the dominating pipe material. The duration of repairs, from the first valve closure to the closure of the hydrant after flushing, varied between 2 hours 45 minutes to 9 hours, with an average of 5 hours. Not all repairs were conducted under pressure.

6.4.1 Potential for contamination originating from pipe trenches

For the 16 repair sites, a total of 17 soil samples and 11 water samples could be collected from pipe trenches. For one site, two distinct simultaneous repairs were conducted on the same isolated portion of main, explaining the additional soil sample collected. The lower number of water samples is explained by the fact that some of the repairs were conducted in almost dry excavations. For each repair site, results for the concentrations of microorganisms detected in soil and water samples from the trenches are listed in Table 6-1 and Table 6-2.

Table 6-1: Concentration of microorganisms detected in soil samples from pipe trenches

Sample	**Date**	***E. coli* (cfu/100g)**	**Total coliforms (cfu/100g)**	**aerobic endospores (cfu/100g)**	***C. perfringens* (cfu/100g)**	**Somatic and male-specific coliphages (pfu/100g)**	**Enteric viruses (ipiu/100g)**
A2004-1	26-05-04	<1E+02	NA	1.9E+06	2.0E+02	<1E+02	<0.03
A2004-2	01-06-04	1.0E+03	NA	2.9E+05	<5E+02	<5E+02	<0.03
A2004-3	07-06-04	<50	NA	5.1E+05	<50	<50	<0.03
A2004-4	10-06-04	<50	NA	1.3E+05	50	<50	<0.03
A2004-5	06-07-04	<1E+03	NA	4.1E+05	NA	<50	<0.03
A2004-6	12-07-04	<50	NA	1.0E+04	<50	<50	<0.03
A2004-7	13-07-04	<5E+02	NA	1.0E+06	50	<50	<0.03
A2004-8	03-08-04	<5E+02	NA	3.2E+05	<5E+02	<50	<0.03
A2004-9	09-08-04	<5E+02	NA	4.8E+05	<5E+02	<50	<0.03
A2004-10a	15-09-04	<5E+02	NA	3.7E+04	<5E+02	NA	NA
A2004-10b	15-09-04	<5E+02	NA	4.1E+04	<5E+02	NA	NA
A2004-11	28-09-04	<5E+02	NA	6.1E+04	<5E+02	<5E+02	NA
A2005-1	20-07-05	<50	2.7E+04	2.0E+05	1.0E+03	<50	NA
A2005-2	21-09-05	NA	4.0E+02	5.5E+04	<5E+02	<50	NA
A2005-3	04-10-05	<50	<50	3.0E+04	<50	<50	NA
B2005-1	26-07-05	<50	<50	3.3E+04	<50	<50	NA
B2005-2	17-08-05	<50	1.9E+04	2.3E+04	<5E+02	<50	NA
Total number of analyses		16	5	17	16	15	9
Min concentration		<50	<50	1.0E+04	<50	<50	<0.03
Max concentration		1.0E+03	2.7E+04	1.9E+06	1.0E+03	<5E+02	<0.03

cfu: colony forming unit; ipiu: immunoperoxidase infectious unit; NA: not available; pfu: plaque forming unit

Table 6-2: Concentration of microorganisms detected in water samples from pipe trenches

Sample	Date	*E. coli* (cfu/100 mL)	Total coliforms (cfu/100mL)	aerobic endospores (cfu/100mL)	*C. perfringens* (cfu/100mL)	Somatic and male-specific coliphages (pfu/100mL)	Enteric viruses (ipiu/100mL)
A2004-1	26-05-04	<10	NA	1.9E+04	<10	<10	<0.64
A2004-2	01-06-04	NA	NA	1.7E+05	2.5E+02	<50	<1.13
A2004-3	07-06-04	<5	NA	3.3E+04	5	<5	<0.64
A2004-4	10-06-04	▨	▨	▨	▨	▨	▨
A2004-5	06-07-04	<1E+02	NA	7.1E+04	<50	<5	<0.64
A2004-6	12-07-04	<50	NA	1.4E+05	<50	<5	<0.64
A2004-7	13-07-04	<50	NA	3.9E+04	<50	<5	<0.64
A2004-8	03-08-04	▨	▨	▨	▨	▨	▨
A2004-9	09-08-04	▨	▨	▨	▨	▨	▨
A2004-10a	15-09-04	<50	NA	1.7E+04	<50	NA	NA
A2004-10b	15-09-04	<50	NA	4.4E+03	<50	NA	NA
A2004-11	28-09-04	▨	▨	▨	▨	▨	▨
A2005-1	20-07-05	<5	2.7E+03	4.0E+03	<50	<5	NA
A2005-2	21-09-05	NA	9.0E+02	4.1E+03	<50	<5	NA
A2005-3	04-10-05	▨	▨	▨	▨	▨	▨
B2005-1	26-07-05	<10	1.4E+03	6.7E+03	<10	<5	NA
B2005-2	17-08-05	▨	▨	▨	▨	▨	▨
Total number of analyses		9	3	11	11	9	6
Min conc.		<5	9.0E+02	4.0E+03	<10	<5	<0.64
Max conc.		<1E+02	2.7E+03	1.7E+05	2.5E+02	<50	<1.13

cfu: colony forming unit; conc: concentration; ipiu: immunoperoxidase infectious unit; NA: not available; pfu: plaque forming unit; Shaded cells: no water sample collected

Only one soil sample out of 16 had a concentration of *E. coli* superior to the samples detection limits with 1x10^3 cfu/100 g. All the water samples had *E. coli* concentrations below the samples detection levels. The maximum concentration of total coliforms detected was 2.7x10^4 cfu/100 g in soil samples and 2.7x10^3 cfu/100 mL in water samples. Total coliforms were detected in all three water samples analyzed and in three soil samples out of five. The number of samples analyzed for total coliforms is low as testing was initiated only in 2005. Aerobic endospores were detected in all soil and water samples (these microorganisms are part of the normal flora of soil), in concentrations ranging from 10^4-10^6 cfu per 100 g of soil and 10^3-10^5 cfu per 100 mL of water. *C. perfringens* were detected in four soil samples out of 16 in concentrations varying between 50 and 1x10^3 cfu/100 g of soil. They were detected in only two water samples out of 11 at 5 cfu/100 mL and 250 cfu/100 mL. Somatic and male-specific coliphages were not detected in any samples and human enteric viruses were not detected in the nine soil and six water samples analyzed. Figure 6-2 illustrates the percentage of soil and water samples that were found positive for microbiological indicators.

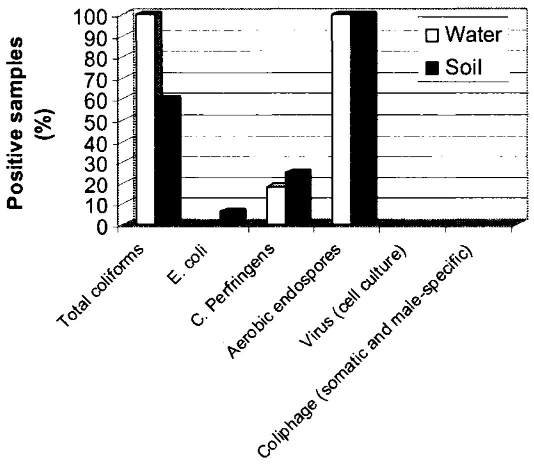

Figure 6-2: Percentage of soil and water samples from pipe trenches positive for microbiological indicators

For the soil samples, particle size analysis was performed on seven samples (A2004-1 to A2004-6 and A2004-9). Percent of clay particles in the samples varied between 6.4% and 16.3%, and percent of silt was from 11.1% to 17.2%. The percent of sand and gravel were similar with values between 27.0% to 51.4% and 28.3% to 52.8% respectively.

6.4.2 Microbial indicators detected in distribution system water

Total coliforms, *E. coli* and aerobic endospores were used as microbial indicators of contamination in piped water during main repairs. Considering all sampling locations and repair steps at which water samples were collected, a total of 17 samples out of 424 (4.0%) were positive for total coliforms (Table 6-3).

Table 6-3: Occurrence of total coliforms in distribution system water

Repair step	**Number of positive total coliform samples**				**Number of samples analyzed for total coliforms**	**% of positive total coliform samples**
	House Out	**House In**	**House SL**	**Flushed hydrant**		
Before valve closure (T_0)	0	0	0	--	38	0.0%
When valves are closed	--	0	--	--	5	0.0%
Before valve opening	0	--	--	--	20	0.0%
During flushing	1	4	--	11	279	5.7%
Prior to hydrant closure	0	0	--	0	49	0.0%
After hydrant closure	--	1	0	--	33	3.0%
Number of samples analyzed for total coliforms	71	189	9	155	424	
% of positive total coliform samples	1.4%	2.6%	0.0%	7.1%		

--: No total coliform analysis performed

The majority of positive samples were collected during the flushing step of the repair (16 out of 17 samples), predominantly at the hydrant itself (11 samples out of 16). Only one sample was found positive for total coliforms once the repair was completed (collected at House In). Among the positive total coliform samples, only one was found positive for *E. coli*. This sample was collected at the hydrant used for flushing the repaired main, one minute after flushing was started (this case is presented in detail below). Five water samples out of 424 (1.2%) had concentrations of aerobic endospores significantly higher ($p<0.1$) than the background concentration in routine flushing water (Cartier et al, 2007). Aerobic endospore concentrations varied between 240 and 3130 cfu/L in these samples. These samples were also all collected at the hydrant during flushing of the main. Overall. seven repair sites out of 16 had microbial indicators detected in distribution system water (Table 6-4). Water temperatures at all sites varied between 12.3°C and 26.0°C.

Table 6-4: Repair sites with microbial indicators detected in distribution system water

Repair site	# of positive total coliform samples	Repair step	# of positive *E. coli* samples	Repair step	# of positive aerobic endospore samples	Repair step
A2004-1	2	During flushing				
	1	After hydrant closure				
A2004-2	1	During flushing				
A2004-8					1	During flushing
A2004-10	7	During flushing				
A2005-1	5	During flushing	1	During flushing	3	During flushing
A2005-2					1	During flushing
A2005-3	1	During flushing				

6.4.3 Link between microbial content of pipe trenches and microbial indicators detected in distribution system water

The potential for contamination at repair sites can be evaluated based on the microbiological content of the pipe trenches. Overall, seven repair sites had only aerobic endospores detected in soil and in water (when present in the trench). Nine sites had total coliforms and/or faecal indicators (*E. coli* or *C. perfringens*) in addition to aerobic endospores in the soil/water from the excavation. The link between the microbiological content of the trenches and the detection of indicators (total coliforms, *E. coli*, aerobic endospores) in distribution system water during a repair, is given in Table 6-5.

Table 6-5: Microbial content of pipe trenches and microbial indicators detected in distribution system water

Pipe trench		DS water		Intensity of response in DS[§]	
Microbial content of pipe trench	**Number of repair sites**	**Microbial indicators detected in DS water**	**Number of repair sites**	**% of positive total coliform samples**	**% of positive aerobic endospore samples**
Aerobic endospores only	7	None	4		
		Aerobic endospores* only	1		4.5%
		Total coliforms (no endospores)	2	30.4% 2.4%	
Aerobic endospores and total coliforms and/or faecal indicators	9	None	5		
		Aerobic endospores* only	1		3.3%
		Total coliforms (no endospores)	2	13.6% 4.3%	
		Total coliforms and aerobic endospores*	1	13.9%	10.7%

[§] Intensity of response corresponds to the percentage of positive (total coliform or aerobic endospore) samples in distribution system water. Number of samples collected in DS during a repair could vary between 20 and 40 samples.

*Concentrations of aerobic endospores significantly higher than background concentrations in routine flushing water

DS: distribution system

For the seven sites where only aerobic endospores were detected in the pipe trench, three sites had microbial indicators detected in distribution system water, corresponding to 43% of the sites. Similarly, the same percentage of sites with indicators in piped water (44%) was obtained when the excavation was found to have aerobic endospores combined to other microbial indicators. The percentage of positive (total coliform or aerobic endospore) samples in distribution system water (intensity of the positive response) is about the same (between 2% and 14% of the samples collected during a repair, the number of which could vary between 20 and 40 samples) whether or not the pipe trench has total coliforms and /or faecal indicators in addition to the aerobic endospores. For one case, 30% of the collected water samples during the repair (n=23) were found positive for total coliforms. This site was the one for which two simultaneous repairs were conducted on the same isolated portion of main.

Unfortunately, because total coliforms were only measured in samples collected in 2005, it is possible that six sites out of seven with aerobic endospores only in pipe trench may also contain total coliforms. If this was the case, up to 15 repair sites would have pipe trenches with microbial indicators among which six sites with microbial indicators detected in distribution system water (40% of the sites). For one repair (A2005-3), only spores were detected in the pipe trench while 2.4% of the distribution system water samples were positive for total coliforms.

Contamination of distribution system water may also be influenced by the presence of muddy water in the bottom of the pipe trench when conducting the main repair. Ten repair sites had muddy water and 50% of these had microbial indicators of contamination detected in the piped water in comparison to 33% of the dry excavations sites. This difference is not statistically significant.

6.4.4 *Impact of chlorine residual and turbidity on detection of microbial indicators in distribution system water*

The seven repair sites where microbial indicators were detected in distribution system water had a lower median chlorine residual level (0.19 mg/L) prior to the start of the repair work (House In, before valve closure) than the nine repair sites where none were detected (0.38 mg/L) (Figure 6-3). However, this difference is not statistically significant (Student's t-test, p=0.131). The same comparison was made for residual chlorine measured at the flushed hydrant before closure. In this case, the chlorine residual was significantly lower (Student's t-test, p=0.018) at the sites where microbial indicators were detected in distribution system water (median free chlorine concentration = 0.11 mg/L) in comparison to the other repair sites (median free Cl_2 of 0.48 mg/L) (Figure 6-3). Prior to hydrant closure, the median turbidity value measured at the repair sites with microbial indicators in piped water was 3.5 NTU. This was higher but not statistically different (Mann-Whitney test, p=0.7) than the median turbidity at the other sites (0.81 NTU). Flushing times and repair duration were not significantly different for the sites with or without microbial indicators detected in the water (Student's t-test, p=0.74 and p=0.12 respectively).

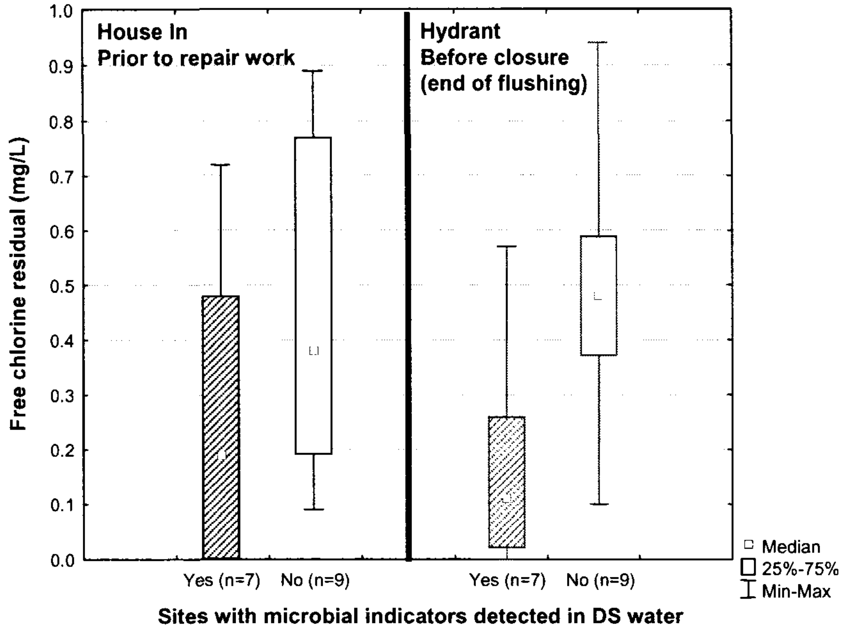

Figure 6-3: Box and whiskers plot of free chlorine residuals measured at repair sites with/without microbial indicators detected in distribution system water (prior to repair work and before closure of hydrant after flushing)

6.4.5 Detection of E. coli in flushing water for one repair

Out of the 16 repairs investigated, only one repair led to the detection of *E. coli* in flushing water. This repair (A2005-1) took place at the extremity of distribution system A, in an area with very low free chlorine concentrations (mostly below 0.05 mg/L). Total coliforms were detected in the soil and water from the pipe trench and *C. perfringens* were detected in the soil. The concentrations of these indicator microorganisms were the highest obtained from all the repair sites. In contrast to the other repairs investigated, this repair consisted in removing a leaking valve. Instead of replacing the gate valve by a new one, only the valve bonnet (along with the disk) was removed and the opening was capped with a plate as illustrated in Figure 6-4. As listed in Table 6-4, five positive total coliform samples (among which one was *E. coli* positive) and three aerobic endospores samples were collected during flushing, indicating that a contamination has taken place.

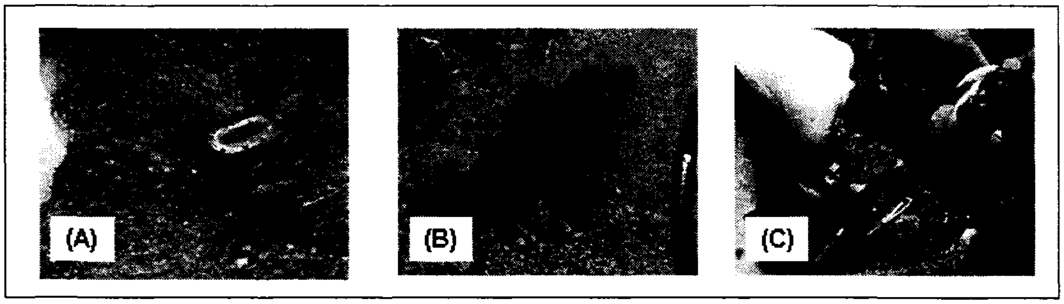

Figure 6-4: Pipe opening (A) created by removal of gate valve bonnet (with disk) (B) and installation of a plate to cap the opening (C).

6.4.6 Impact on water quality in surrounding repair area

The closure of valves to isolate the main to be repaired sometimes result in hydraulic variations outside of the repair area. According to the network configuration, changes in flow direction and dead-ends can be created while the repair is conducted. This was in fact the case for seven repair sites, where the House Out sampling location could be used to monitor the impact that such hydraulic changes had on water quality. Free chlorine residuals were found to decrease at sites where a change in flow direction and a dead-end was created at House Out (Figure 6-5). This trend was not observed at the sites where such hydraulic changes did not take place. Turbidity peaks were observed at two sites out of seven where a change in flow direction and a dead-end were created by the valve closure (Figure 6-6). Maximum turbidity values reached 39 NTU for repair site A2004-6 and 18 NTU for repair site A2004-9. While for most of the sites where no hydraulic changes took place the turbidity did not vary significantly following the valve closure, a peak in turbidity reaching 34 NTU was observed at site A2004-11. This was explained by the sequence of actions performed by the field crew: the hydrant was first opened followed by the closure of valves to isolate the main to be repaired. For the other repairs, the usual procedure involved the closure of valves and then the opening of the hydrant to let the excess pressure out.

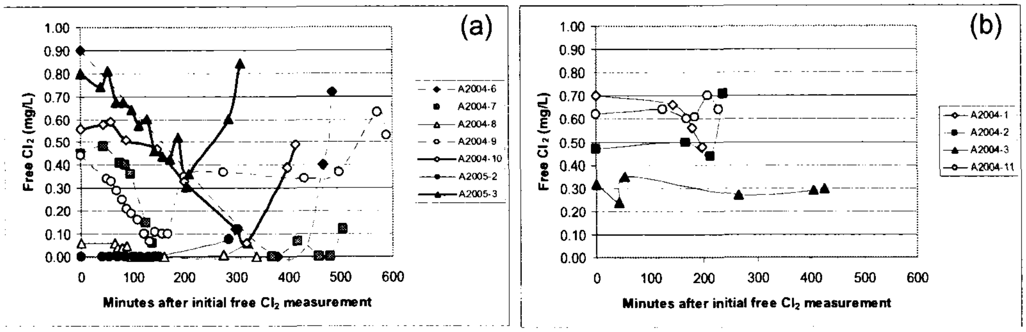

Figure 6-5: Free chlorine variation outside of the repair area (a) when a change in flow direction and creation of a dead-end takes place at House Out; (b) when no such changes take place

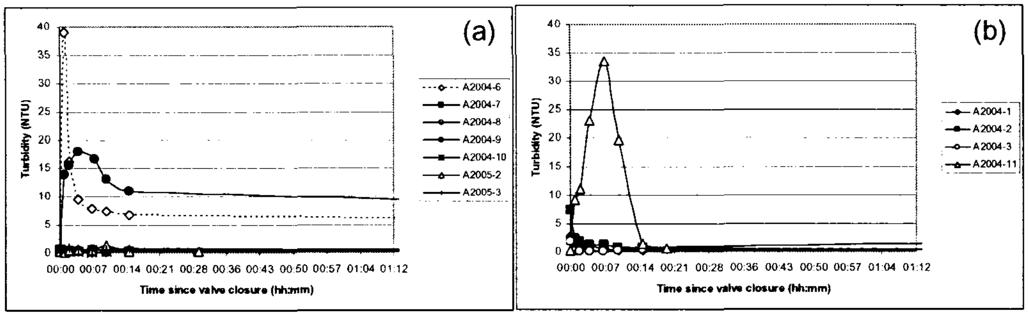

Figure 6-6: Turbidity variations outside of the repair area following valve closure (a) when a change in flow direction and creation of a dead-end takes place at House Out; (b) when no such changes take place

Flushing of the main after the repair work may also be a cause of hydraulic disturbances outside of the repair area. Figure 6-7 illustrates the turbidity values measured at House Out during flushing of the repaired main. At one site, turbidity values up to 200 NTU (upper detection limit of turbidimeter used) were measured. In general, the first 15 minutes of flushing resulted in turbidity values below or close to 20 NTU in the vicinity of the repair area.

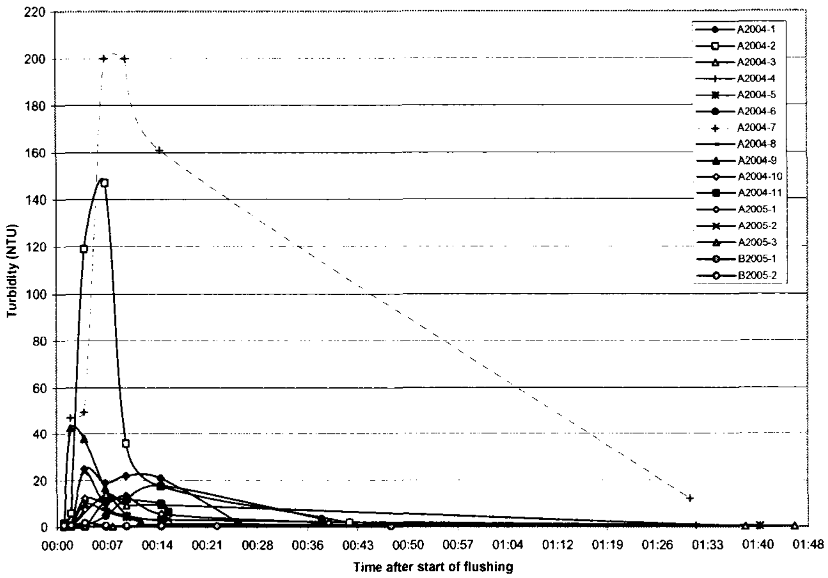

Figure 6-7: Turbidity variations outside of the repair area during flushing

The repairs conducted in the distribution systems clearly had an impact on water turbidity outside of the repair area. As illustrated in Figure 6-8, the turbidity values measured at House Out were significantly higher at the end of the repairs (Wilcoxon matched pairs test (n=12 sites with paired turbidity values), p=0.0096) than the initial values collected prior to the beginning of work. The free chlorine concentrations were not significantly different (Student's t-test, p=0.44). The same analysis was performed for the customer houses located on the isolated portion of main (House In sampling locations). There was no significant difference between the free chlorine concentrations at the beginning and end of the repair (Student's t-test, p=0.687). The turbidity values after the repairs were also not statistically different (Wilcoxon matched pairs test (n=16 sites with paired turbidity values), p=0.278) from the initial values.

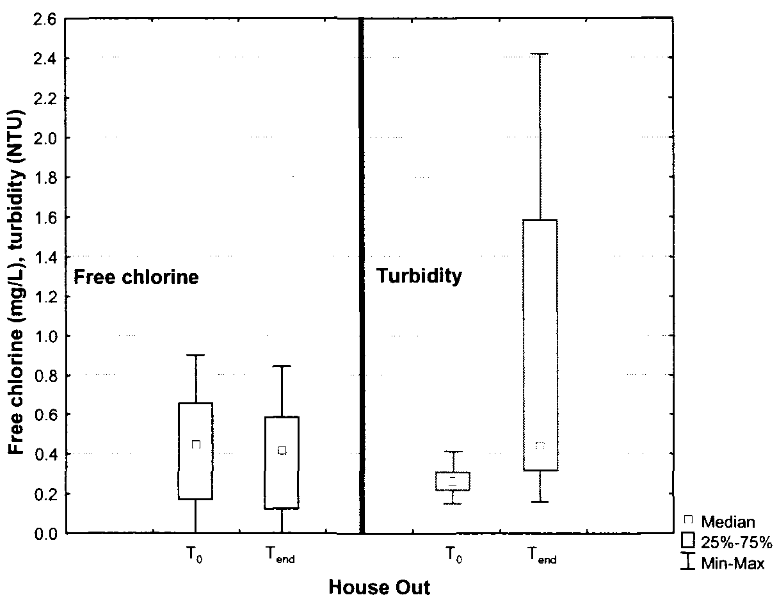

Figure 6-8: Impact of repair on free chlorine residual and turbidity outside of the repair area

6.5 DISCUSSION

6.5.1 Microbial occurrence in pipe trenches

The protocol used for sampling and analysis of soil and water samples from pipe trenches was similar to the one used in a previous investigation conducted by Karim et al (2003). These authors performed a similar study on approximately 30 soil and 30 water samples collected near excavated water mains. As in this study, total coliforms and *B. subtilis* spores were frequently detected both in soil and water samples (greater than 58% of the samples). The results for *C. perfringens* were also similar with approximately 20-30% of samples containing this microorganism. Coliphages were not detected in this study and were only detected in water samples by Karim et al (2003) but at a low rate (two samples out of 30). However, the biggest difference between the two studies concerns the faecal coliform and virus loads detected in the soil and water. These authors had a greater percentage of their soil and water samples positive for thermotolerant coliforms (50% and 42.8% respectively) while only one soil sample contained *E. coli* (corresponding to 6% of the samples) in this study. They also had

9.3% of their soil samples and 10% of water samples positive for culturable enteric viruses while no viruses could be detected in this study. They also assayed the samples for viral RNA by RT-PCR for detection of enteroviruses, hepatitis A and Norwalk viruses, which was not done here. Overall, they found that 56.2% of their investigated sites (18 out of a total of 32) were positive either by cell culture or RT-PCR for one of the three viruses tested. In this study, for public health risk assessment purposes, cell culture of enteric viruses was prioritized in order to detect infectious virus particles (Payment and Trudel, 1985). This cannot be assessed using PCR analysis (Choi and Jiang, 2005; Borchardt et al, 2003; Sobsey et al, 1998; Kopecka et al, 1993) where positive results do not necessarily indicate that the viruses are infectious.

Evidence of faecal pollution and enteric viruses was therefore low in the two distribution systems investigated. The microbial concentrations detected were also lower than in the Karim et al (2003) study. The distance between the sewer lines and the drinking water mains is not known. However, the single *E.coli* positive sample collected in soil resulted from a location where the storm sewer main was directly located over the drinking water main being repaired. At all the other sites, the sewer mains were not visible in the excavation. This is in accordance with the results of a survey by Kirmeyer et al, 2001 who reported that 20 utilities out of 26 indicated that less than 5% of the sewer and drinking water mains are usually located in the same trench. The distance between the sewer and drinking water pipes, the less-saturated soil conditions and the geological structure are factors that could possibly explain the difference obtained in the level of faecal contamination between the two studies. The percentage of clay particles in the seven soil samples analyzed was below 20% (range: 6.4% to 16.3%) which is significantly lower than the percent of clay particles in the soil samples analyzed by Karim et al (2003) who had 82% of the samples with a clay content above 20%. Because of its properties (such as large surface area and high cation exchange capacity), clay minerals usually favor increased virus sorption (Sobsey et al, 1980).

6.5.2 Repair work and detection of microbial indicators in distribution system water

Overall, 4.0% of all the water samples collected throughout the 16 investigated repairs (n=424) were positive for total coliforms. This can be considered as low as it is even less then the actual TCR requirement of 5.0% of total coliform positive samples for a monthly violation (USEPA, 2001b). The positive coliform samples were almost all collected at the hydrants during the flushing operation. This shows that planned repairs (usually involving small leaks in pipe trenches that are generally "clean") do not generally lead to distributed water contamination remaining in the system. Five positive coliform samples were collected at sampling houses during flushing. This indicates that if a demand is exerted during a flushing operation (by a customer that would be unaware of the maintenance activities on the system for example), it can potentially lead to the introduction of "contaminant" into the service lines. High turbidity values were not necessarily associated with positive coliform samples in these cases with some values in the range of 0.31-2.8 NTU. Overall, evidence of intrusion was obtained at seven sites out of 16 (44% of the sites).

Although it is generally recommended to apply the AWWA Standard C651 for disinfection after repairs, disinfection was not applied following the repairs investigated. In the participating utilities, chlorination is usually applied after the installation of new mains and not in the case of leak repairs. The results of the investigation suggest that adequate pipe flushing after a repair is completed is in fact effective to minimize contamination. Clement et al (2003) reported that utilities practicing flushing, disinfection and coliform testing of all pipe repairs and pipe replacements had lower total coliform incidence levels in their systems than utilities only practicing two out of three of these practices. For 2004 and 2005, the annual positive total coliform rate for utility A (where most of the repairs were investigated) was 0.3%.

On one occasion, *E. coli* along with total coliforms and aerobic endospores were detected in water being flushed from the hydrant. Two hypotheses are possible to explain this contamination: (i) possible unsanitary repair procedures conducted by the field crew and (ii) broken hydrant. During the repair, the parts used to cover the opening left by the removal of the old valve bonnet (Figure 6-4) were put down directly on the soil in the trench. These parts were not disinfected prior to installation and faecal contamination was observed in this trench (with the detection of an elevated concentration of *C. perfringens* and also total coliforms). Once installed (Figure 6-4C), these parts were in direct contact with the standing water in the main (Figure 6-4A). Consequently, basic actions such as the disinfection of the parts used for repair or the localized addition of chlorine (through the pipe opening) could have minimized the risk of contamination. The second hypothesis for contamination is the possible backflow of groundwater through the leaking drain valve of the flushed hydrant. This dry-barrel hydrant was operated on the morning of the repair in order to install a pressure recorder. However, this could not be done as water was coming out from the auxiliary valve, indicating a problem with the integrity of this hydrant. It is therefore possible that remaining water in the ground was forced back into the hydrant when flushing started. This emphasizes the importance of well maintained equipment in the system. A preventive boil water order was issued to this distribution system sector and the results of additional water samples were all negative for coliforms and *E. coli*. In their investigation of the impact of low pressure episodes on the occurrence of gastrointestinal illnesses, Nygard et al (2007) found an increased risk for exposed households and report that only one sample was positive for *E. coli*. However, water samples were obtained for only 18 episodes out of 88, details regarding the location and time of sample collection are not available and no chlorine concentrations are reported. It is therefore difficult to relate their results to water quality parameters.

Aerobic endospores were also used as indicator of potential intrusion during repair work because they are part of the soil normal flora and found in large concentrations while their concentrations in treated water are usually very low (below 10 cfu/L for Utility A). Five water samples collected during flushing at repair sites had aerobic endospore concentrations significantly higher than background concentrations found in routine flushing water (Cartier et al, 2007), likely indicating soil or dirty water intrusion during the repair. Total coliforms and aerobic endospores were generally not detected simultaneously in distribution system water except for one case (repair A2005-1). This suggests that both indicators should be used by water utilities if a verification of the water quality following repair work is necessary. Furthermore, the laboratory methods for these two indicators are relatively simple and inexpensive. The use of aerobic endospores as indicators of loss in system's physical integrity has also been suggested by other authors (Karim et al, 2003; APHA and AWWA, 2005). LeChevallier et al (2006) established a link between the detection of coliphages in a chloraminated system and the occurrence of main breaks. The use of such an indicator would not be applicable here because of the free chlorine disinfectant residual (coliphages are more resistant to chloramines than free chlorine (USEPA, 1999)) and its absence in the soil and water surrounding repaired water mains.

Soil and water from pipe trenches are clearly a possible source of contamination when repair work is conducted. Although there is some uncertainties regarding the microbial content (total coliforms) of six pipe trenches, the percentage of sites with microbial indicators in distribution system water is about the same: 43% when the pipe trench only contains aerobic endospores (three sites out of seven - assuming the six samples do not include total coliforms), 44% when the pipe trench includes endospores and other indicators (four sites out of nine) and 40% if the pipe trench include endospores and other indicators (six sites out of 15 - assuming the six samples do include total coliforms). Consequently, about 40% of the sites had microbial indicators detected in distribution system water, whether or not the trench was "contaminated". Results show that even if no total coliforms are detected in the soil/water surrounding the repaired water main, these indicators can be detected in distribution system water with a low intensity (2.4% of positive total coliform samples in this case). The highest percent of positive total coliform samples in distribution system water was 30.4% for repair A2004-10. This site was the one for which two simultaneous repairs were conducted on the same isolated portion of main, which would indicate that such a practice should be avoided if possible. If not, precautions should be undertaken. When muddy water was present in the bottom of the excavation during repair work, half of the sites had microbial indicators in distribution system water in comparison to a third of the sites with dry excavations. Although this difference is not significant, the use of a pump to remove the excess water is recommended.

Other sources of contamination include intrusion from transient pressures induced by valve and hydrant operation during the repair. This seems unlikely as pressure monitoring during 10 repairs showed no sign of very low or negative transient pressures associated with valve closure and flushing operation (Besner et al, 2007b). Unsanitary practices may also lead to contamination and the role of field crews is major in minimizing the occurrence of such contamination events. The strict follow-up of defined working procedures should be enforced. The province of Quebec drinking water quality regulations require (as of December 1st, 2005) that at least one field crew member involved in any distribution system related work had successfully completed a training course on system operation and maintenance.

The sites where microbial indicators were detected in distribution system water had lower free chlorine residual concentration at the beginning of the repair work in comparison to the other sites. Although the difference was not statistically significant at that time, it became significant prior to hydrant closure at the end of the flushing. This could be due to the consumption of the residual because of the presence of dirt in the repaired main or it could also be explained by the lower free chlorine in the water used for flushing. A decrease in the residual was observed in areas outside of the repairs in some cases. However, it is also possible that the detection of indicator microorganisms in water was increased by the lower free chlorine concentrations initially present at those sites.

6.5.3 Water quality outside of the repair area

The closure of valves and flushing operation conducted as part of the repairs of water mains had an impact on free chlorine residuals and turbidity outside of the isolated distribution system area. A decrease of free chlorine (up to 0.9 mg/L) was observed when changes in flow direction and dead-end mains were created by valve closures. No bottle tests were conducted on these water samples to determine the chlorine bulk reaction coefficient but the presence of unlined cast-iron or unlined ductile iron pipes increases the chlorine reaction rate (Digiano and Zhang 2005; Hallam et al, 2002; Kiéné et al, 1998). Peaks in turbidity were observed in some cases when valves were closed at the beginning of work. It is well documented that hydraulic disturbances may cause sediment resuspension in water (Slaats et al, 2003; Prince et al, 2001). After the repairs were completed, the only significant difference in water quality parameters (T_0 versus T_{end}) was for the turbidity outside of the repair area. Flushing of the repaired mains created upstream disturbances resulting in increased turbidity. Consequently, very high flushing velocities should not necessarily be targeted after the repairs of water mains since this type of flushing is not unidirectional in nature (from a cleaned section to a "dirty" section). Both distribution systems investigated do not have a systematic unidirectional flushing program. Utility A performs some routes at various frequencies while Utility B does not practice unidirectional flushing. Consequently, loose particles may accumulate in some areas and be re-entrained and resuspended due to higher flow velocities when flushing is conducted after water main repairs.

6.6 CONCLUSION

This study showed that planned repairs, usually involving small leaks in pipe trenches that are generally "clean" (with low level of faecal microorganisms), do not generally lead to distributed water contamination remaining in the system. The positive coliform samples (4% of all samples) were almost all collected during the flushing operation. Evidence of intrusion was obtained at seven sites out of 16 but the results suggest that adequate pipe flushing after a repair is completed is effective to minimize contamination. Care should be taken not to directly extend these conclusions to new main construction and emergency repairs, where the field conditions may be different and chlorination necessary.

Although these results show minimal contamination, the detection of *E. coli* on one occasion under the applied sampling program indicates that it still can happen under real-life field conditions. The sustained vigilance of field crews is necessary and strict follow-up of defined working procedures would minimize the occurrence of such contamination events.

Water quality variations are observed in distribution system area having uninterrupted water supply in the vicinity of a repair. Changes in chlorine residuals and turbidity mainly result from the operation of valves and hydrants rather than from the repair work itself. Although these short-term changes do not have direct public health impacts, they may lead to increased customer complaints.

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Footnotes: [1]IDEXX Laboratories, Westbrook, Maine; [2]Telog Instruments, Victor, New York; [3]Radcom Technologies, Woburn, Massachusetts; [4]StatSoft Inc., Tulsa, Oklahoma

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CHAPTER 7

ADDITIONAL RESULTS: NEGATIVE PRESSURE EVENTS AND WATER QUALITY

Microbial intrusion is possible due to a loss of physical system integrity (as in the case of water main repairs as studied in the previous chapter). However, compromised hydraulic integrity may also lead to potential system contamination. For this reason, the occurrence of low and negative pressures in full-scale distribution systems has been investigated. Pressure monitoring was conducted under both normal system operation and some selected O&M activities.

A draft of a paper to be submitted to a peer-reviewed journal is presented in this Chapter. The content of this paper includes the results of the research work related to the characterization of potential pathways of microbial intrusion and occurrence of negative pressures in the Laval distribution system. This distribution system was specifically targeted as it is where the two epidemiological studies by Payment et al (1991, 1997) were conducted. To complement the field work, a section on transient analysis and modeling is also included. In its actual version, this draft paper includes the modeling of only one low pressure event out of nine that took place at the Pont-Viau WTP during the study period. It is intended to model the nine events and compare the results obtained prior to the submission of the paper for publication.

During the pressure monitoring period, the closure of a transmission main took place in the area under study. This event led to sustained negative pressure in the distribution system. Increased pressure monitoring and a field campaign to assess water quality during this event were conducted. This case-study is available in Appendix A.

TRANSIENT NEGATIVE PRESSURES AND POTENTIAL INTRUSION VOLUMES AT THE SITE OF THE PAYMENT'S DRINKING WATER EPIDEMIOLOGICAL STUDIES (draft version)

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Abstract: The epidemiological studies by Payment et al. suggested that the increase in gastrointestinal illnesses observed in a system, meeting all water quality regulations, could be associated with distribution system deficiencies. The possibility of microbial intrusion in this distribution system was assessed by (i) characterizing potential pathways of intrusion, (ii) monitoring the frequency and magnitude of negative pressures, and (iii) modeling low pressure events to assess potential volumes of intrusion. Pressure monitoring showed that power failure affecting the operation of pumps was the main cause of negative pressures in this distribution system. Transient modeling of the system showed that flooded air-vacuum valve vaults were critical locations for intrusion. Larger intrusion volumes, high frequency of recovery and higher concentrations of faecal indicators characterized these locations in the distribution system studied.

7.1 INTRODUCTION

In the 1990's, two epidemiological studies were conducted by Payment et al. (1991; 1997) in a Canadian distribution system of a water utility. The first study (Payment et al., 1991) compared the rate of gastrointestinal (GI) illnesses between a group consuming tap water (307 households) and a group consuming the same water filtered through a reverse-osmosis (RO) unit (299 households). After a 15-month period, the estimated annual incidence of GI illness was 0.76 among tap water drinkers compared with 0.50 among filtered water drinkers. It was therefore estimated that at least 35% of the reported GI illnesses among the tap water drinkers were water-related. In their second study, Payment et al. (1997) used four groups of 350 households drinking either: (i) tap water, (ii) tap water from a continuously purged tap, (iii) bottled plant water, and (iv) purified bottled water (tap water treated by RO or spring water). After 16 months, the excess of GI illnesses associated with tap water was 14% in the tap group and 19% in the tap-valve group with respect to the purified water group. This rate was higher for children 2-5 years old with an excess of 17% in the tap group and 40% in the tap-valve group. Water produced from the treatment plant met or exceeded the water quality standards at the time and the distribution system was found to be in compliance for both coliforms and chlorine. Because there was no significant difference in the rate of GI illnesses between the bottled water groups, the authors suggested that the distribution system might be partly the source of the differences observed with the tap water groups.

These results raised questions about the integrity of distribution systems and the likelihood of their contamination during normal operations. Numerous conditions that can compromise water quality during distribution have been identified. Loss of physical/hydraulic integrity may be caused by a variety of factors such as: cross-connections, repairs, loss of pressure, etc (NRC, 2006). Public health concerns regarding the occurrence of transient negative pressures in full-scale distribution systems have been expressed as it was suspected that a high potential risk of introduction of pathogenic microorganisms into distribution systems exists when transient negative pressure events occur in water mains (LeChevallier et al., 2003). Several studies have monitored pressure in distribution systems and reported the occurrence of low or negative pressures (Kirmeyer et al., 2001; LeChevallier et al., 2004; Gullick et al., 2004; Gullick et al., 2005; Hooper et al., 2006). These transient events may originate from routine activities (pump starting or stopping, rapid opening or closing of valves and hydrants, hydrant flushing), main breaks or loss of power (Kirmeyer et al., 2001).

Kirmeyer et al. (2001) conducted transient pressure modeling of the distribution system studied by Payment et al. They found that the system was prone to low and negative pressures. In one case, 90% of the modeled nodes were drawing pressures below 5 psi under a modeling scenario of a power outage affecting the pumps at all treatment plants, representing extreme conditions (note: the water utility has three water treatment plants and the distribution networks are partly interconnected). Transient modeling was conducted on a portion of the system only which can be problematic as the interface nodes (with the rest of the distribution system) must be modeled in a way that properly reflects the dynamic effect of the balance of the system on the piece being analyzed. A verification of the results obtained by Kirmeyer et al. (2001) is needed by using a model of the entire distribution system.

In their review of the Payment's epidemiological studies, the National Academies' Water Science and Technology Board Committee (NRC, 2006) concluded that low disinfectant residuals and a vulnerability of the distribution system to pressure transients (suggesting intrusion as a possible mechanism of contamination) could account for the observed illnesses.

7.2 OBJECTIVES OF THE STUDY

The first Payment's study was conducted almost 20 years ago and obviously, some operating conditions for both the water treatment plants and the distribution system are likely to have changed. However, the transient modeling performed by Kirmeyer et al. in 2001 indicated that the system was vulnerable to negative pressures. In order to assess this vulnerability, the NSERC Industrial Chair on Drinking Water returned to this distribution system and designed a study with the following objectives: (1) to characterize some potential pathways of microbial intrusion; 2) to determine the frequency and magnitude of transient low and negative pressures in the same area studied by Payment et al. and 3) to evaluate the link between negative pressure and potential intrusion and changes in water quality.

7.3 METHODOLOGY

7.3.1 Description of the distribution system

The distribution system where this study was conducted provides drinking water to about 350,000 consumers. The average annual water demand is about 210,000 m^3/d (52.8 MGD) and is supplied by three water treatment plants (WTPs) using surface water as their raw water source. Each WTP supplies specific network areas that are not delimited by isolation valves, making the distribution systems partly interconnected. Apart from the clearwells at the WTPs, no storage tank nor pump station is located on the distribution system because of the ground topography. The distribution system has a total length of about 1 590 km (988 miles) and includes pipe materials such as cast-iron (41% of the total pipe length), ductile iron (35% of the total pipe length), concrete (hyprescon) and PVC (10% and 8%, respectively).

The distribution system area studied is mostly supplied by a single WTP and corresponds to the same area where Payment et al. conducted their epidemiological studies. Location of the households who participated to the second epidemiological study (drinking tap water and tap water from continuously purged taps) is illustrated in Figure 7-1.

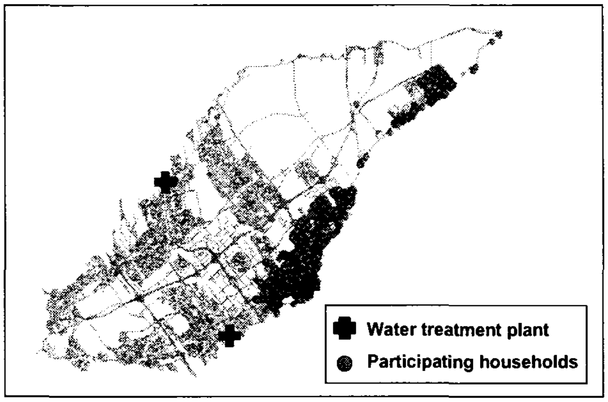

Figure 7-1: Studied distribution system area corresponding to location of households in the epidemiological study of (Payment et al., 1997)

7.3.2 Characterization of potential pathways of intrusion

7.3.2.1 Soil / Shallow groundwater surrounding buried water mains

Soil and shallow groundwater samples were collected during repairs of water mains that took place during the summer of 2004 and 2005. Soil samples were collected in the vicinity of the exposed main using a sterile trowel. The samples were put into large plastic (Ziploc® type) bags. Trench water samples were collected using four autoclaved one-liter plastic bottles.

7.3.2.2 Water from flooded air-vacuum valve vaults

A list of the location of valve vaults where either (i) an air-release valve; (ii) an air-vacuum valve; or (iii) a combination air-valve was positioned was provided by the water utility. These sites were visited during summer 2007 and water samples were collected if some standing water was found in the vaults. When completely flooded, a pump was used to pump the excess water and verify that the valve was in fact an air-valve. Water samples were collected using seven autoclaved one-liter plastic bottles (with 0.01% (w/v) sodium thiosulfate to neutralize residual chlorine if necessary). When possible, water samples were collected directly by dropping the bottle into the standing water.

When not possible, a manual pump (Attwood, Lowell, MI) and 6 mm (0.25 in.) PVC tubing were used to fill the sampling bottles.

7.3.2.3 Bacteriological and coliphages analyses conducted on soil/water from pipe trenches and water from flooded air valve vaults

For soil samples, 20 grams of soil were mixed with 200 mL of saline and stirred on a magnetic stirrer for 1 minute. The sample was left to stand for 30 minutes and the supernatant was then recuperated for bacteriological and coliphages analysis. For water, the 1-liter samples were pooled and stirred on a magnetic stirrer for 1 minute, left to stand for 30 minutes and 250 mL of supernatant were recuperated for bacteriological and coliphages analysis.

Samples were assayed for the presence of aerobic endospores, *Clostridium perfringens*, *E. coli*, total coliforms (not assayed in 2004) and *Enterococci* (only in water from flooded valve vaults) within 24 hours of sampling using membrane filtration methods. Two 10 mL and two 1 mL portions (or appropriate dilutions) of the sample were assayed on each culture media. Tryptic soy broth (Difco Laboratories) with 0.01% triphenyl tetrazolium chloride was used to enumerate aerobic endospores. Samples were filtered on a membrane, placed in a 50 mm Petri dish containing a pad saturated with the medium, pasteurized during 15 minutes at 75°C in a water bath and incubated at 35°C for 24 hours. Red colonies were counted as aerobic endospores (Barbeau et al., 1997), and the vast majority of these organisms are species of *Bacillus*. The method described by Armon and Payment (1988) was used to enumerate *C. perfringens* by membrane filtration using mCP agar and incubation at 45°C for 18-24 hours. In 2005 and 2007, MI (Difco Laboratories) agar was used for the simultaneous detection of *E. coli* and total coliforms after 24 hours at 35°C (USEPA, 2002a)). Blue colonies were reported as *E. coli* and fluorescent colonies under longwave ultraviolet light (366nm) (including the blue colonies under ambient light) as total coliforms. In 2004, *E.coli* were detected with mTEC agar by membrane filtration ((USEPA, 2002b). The dishes were incubated at 35 ± 0.5°C for 2 h. After a 2h incubation at 35 ± 0.5°C, the plates were transferred at 44.5 ±

0.2°C for 22-24 h. After incubation, the membranes from mTEC Agar were transferred on absorbent pads saturated with Urea Substrate Medium and kept at room temperature for 15-20 min. Yellow, yellow-green, or yellow-brown colonies were counted as *E. coli*. Method 1600 of the U.S. EPA was used for the detection of *Enterococci* (mEI agar, 41°C for 24 hours) (USEPA, 2002c). Blue colonies or colonies with a blue halo were counted as *Enterococci*.

For the coliphages assay, method 1602 of the U.S. Environmental Protection Agency (USEPA, 2001) was used with *E. coli* CN-13 as host strain for somatic coliphages and *E. coli* F-amp as host strain for male-specific coliphages. Volumes of 1 and 10 mL were assayed for each coliphages in duplicate. The results were reported as plaque forming unit (pfu) per 100 mL or per 100 g of sample.

7.3.3 Pressure monitoring in distribution system

Continuous pressure monitoring of the study area, using high-speed pressure transient data loggers, was started in June 2006. Four distinct monitoring periods were conducted as described below:

- Phase 1 (June 2006 to September 2006): Exploratory phase with 12 pressure sensors installed all over the distribution system area studied.
- Phase 2 (September 2006 to October 2006): Targeted phase with 9 pressure sensors installed in distribution system area prone to negative pressures.
- Phase 3 (October 2006 to June 2007): Reduced monitoring due to wintertime (pressure sensors cannot be installed on fire hydrants due to cold weather and freezing conditions). Only two pressure sensors could be installed inside buildings in area prone to negative pressures.
- Phase 4 (June 2007-November 2007): Repeat targeted sampling with 12 pressure sensors installed in area prone to negative pressures. While this phase lasted until November 2007, only the results obtained prior to July 25, 2007 are considered here.

From June 2006 to November 2007, pressure was continuously monitored at the outlet of the supplying water treatment plant. Figure 7-2 illustrates the locations of the pressure sensors during the different monitoring periods.

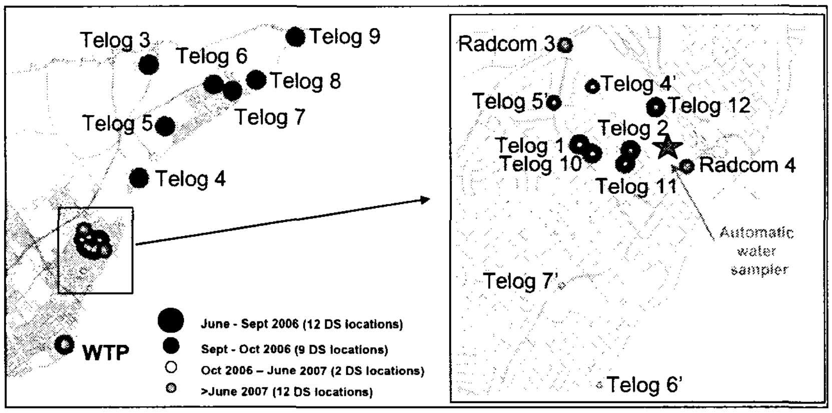

Figure 7-2: Locations of high-speed pressure transient data loggers in distribution system

Pressure monitoring was conducted using two types of high-speed pressure transient data loggers. The RDL 1071L/3 model from Radcom Technologies (Woburn, MA) that can read up to 20 pressure values per second within a range of -15 psi to 225 psi was installed either directly on transmission mains (via corporation stops), on sink's taps inside buildings, or on fire hydrants. The HPR31 model from Telog Instruments (Victor, NY) can read up to four pressure values per second within a -15 psi to 200 psi range and was used to monitor pressure on fire hydrants. The Radcom loggers were zeroed to atmospheric pressure according to the manufacturer's instructions before installation. Pressure values were read every second and a tolerance of ±2 psi (1.4 m) was set for recording of pressure readings. The Telog loggers were set at four pressure readings per second, with the maximum and minimum pressure values recorded over intervals of 15 seconds.

7.3.4 Transient pressure modeling

Transient (or surge) pressure modeling was performed using the InfoSurge software (MWH Soft, Arcadia, CA). Transient modeling was performed to simulate one low pressure event at the water treatment plant that was recorded on June 27, 2006. Preliminary steps for the transient pressure model construction included the skeletonization of the extended period simulation (EPS) model from the water utility in order to reduce the number of links below 20,000 (actual size was 29,213 nodes and 32,266 links). This was achieved by (i) eliminating the interior nodes of all series pipes with same diameter, and (ii) trimming the dead-end pipes shorter than 50 m. After the skeletonization, the model size was reduced to 8,132 nodes and 11,185 pipes. Typical wave velocity values were assigned to cast-iron mains (1060 m/sec), ductile iron mains (1200 m/sec), concrete mains (600 m/sec), PVC mains (300 m/sec) and steel mains (1200 m/sec). This approximation was considered better than using a single wave speed value for all the pipes included in the model. In order to simulate a low pressure event, transient conditions were created by simulating a pump closure using a change in the pump speed. Simulation time was set to 300 seconds.

The intrusion module of the InfoSurge software was used to simulate the potential intrusion volumes in the distribution system under various assumptions (intrusion at all demand nodes based on a specified rate of leakage rate, intrusion at location of flooded air valve vaults). For intrusion using a leakage rate, intrusion at all demand nodes is computed when the exit head value (head of water above pipe - fixed by the user) is above the internal pipe pressure value. The leakage factor is used to set the size of the orifice. Leakage values between 5 and 25% were simulated along with exit heads of 0 (atmospheric pressure) and 2 psi (1.4 m). Intrusion through flooded air-valve vaults were simulated using one-way feed tanks, where the water is only allowed to flow from the tank into the system. For the simulations, different numbers of flooded vaults were assumed according to the results from the field study. The height of water above the air-vacuum valve was assumed to be 0.5 m. Different air-vacuum valve outlet diameters were also tested (12, 100 and 150 mm).

The transport of the intruded contaminant (assumed conservative) was then simulated using an extended period simulation performed using the InfoWater software (MWH Soft, Arcadia, CA).

7.4 RESULTS

7.4.1 Detection of faecal indicators of contamination in soil/water from pipe trenches and water from flooded air-valve vaults

Soil and water samples surrounding water mains were collected at 14 repair sites. 25 water samples were collected from flooded air-valve vaults out of a total of 36 vaults visited (overall, 30 water samples were collected out of 45 vaults visited but the microbiological results for the last five samples were not available as of mid-november 2007). In nine vaults, the air-valve was completely submerged under water while 16 vaults had stagnant water levels below the air-valve outlet. The location of collected samples is illustrated in Figure 7-3.

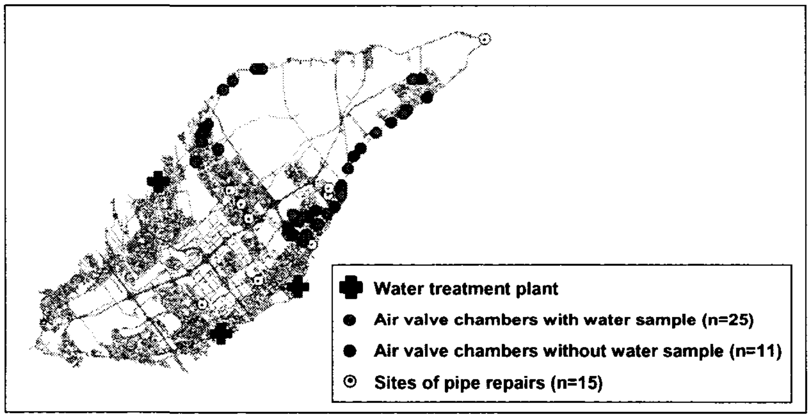

Figure 7-3: Location of samples collected from pipe repair sites and air-valve vaults

The detection of the targeted microorganisms was more frequent in the water samples collected from the air-valve vaults that in the soil/shallow groundwater surrounding water mains (Figure 7-4). While a large proportion of the soil/trench water/water from valve vaults was positive for the detection of aerobic endospores and total coliforms, the frequency of detection of *E. coli* and *Clostridium* was significantly higher in the water from the air-valve vaults than in the soil samples (p=0.0008 and 0.0677 respectively) and the trench water samples (p=0.0021 and 0.0399 respectively). *Enterococci* were not analyzed in the soil/trench water samples but were detected in 24 samples out of 25 in the water collected from the air-valve vaults. Coliphages (somatic and male-specific) were detected in 10% of the water samples from valve vaults while none were detected in soil or trench water. Human enteric viruses were not detected in any soil or trench water samples (see Chapter 6 for the detailed methodology). The results of virus analyses are not yet available for the samples from the valve vaults.

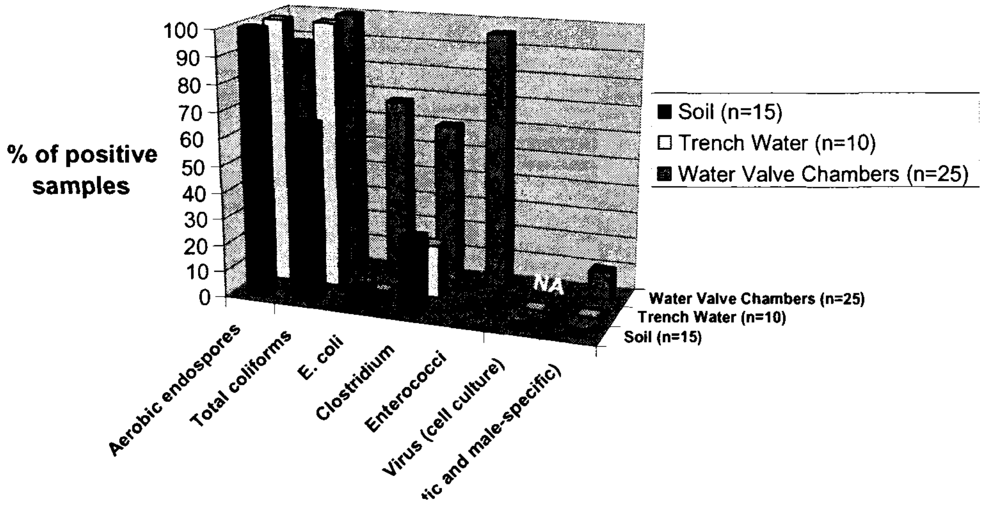

Figure 7-4: Percent of positive samples in the pathways of intrusion investigated

The mean concentrations for the microorganisms detected in the soil and water samples collected are listed in Table 7.1. The geometric mean was used for calculation and 1/10 of the detection limit was used as the concentration value when the measure was given as below the detection limit. Concentrations of microorganisms in soil were initially expressed as per 100 g of soil. They were modified and reported as per 100 mL for comparison with the water samples. Geometric means of total coliforms and *E. coli* concentrations in the water from the valve vaults were higher than in the soil or trench water samples while the geometric means of *Clostridium* and aerobic endospores were lower in the water from the valve vaults. The concentration of coliphages (geometric mean) was about the same for the different pathways investigated.

Table 7-1: Geometric mean of microorganism concentrations in soil, trench water and water from air-valve vaults

	Soil		**Trench water**		**Water from air-valve vaults**	
Microorganism	**n**	**Concentration (/100 mL)**	**n**	**Concentration (/100 mL)**	**n**	**Concentration (/100 mL)**
Total coliforms	5	34.8	3	1,504	25	7,888
E. coli	16	2.1	9	2.3	25	7.5
Enterococci	0		0		25	59.2
Clostridium perfringens	16	3.7	11	5.3	25	1.5
Coliphages	15	0.7	9	0.7	25	1.1
Aerobic endospores	17	12,582	11	20,930	25	440

7.4.2 Occurrence of negative pressures in distribution system

7.4.2.1 First phase of pressure monitoring

During the first monitoring period (June-Sept 2006), pressures lower than 20 psi were recorded at 11/12 sites and negative pressures at 7/12 sites in the distribution system. Contamination through intrusion may take place under both low and negative transient pressures if the pressure of the water surrounding the water main exceeds the internal pressure. The average, minimum and maximum pressure values recorded at each site are illustrated in Figure 7-5.

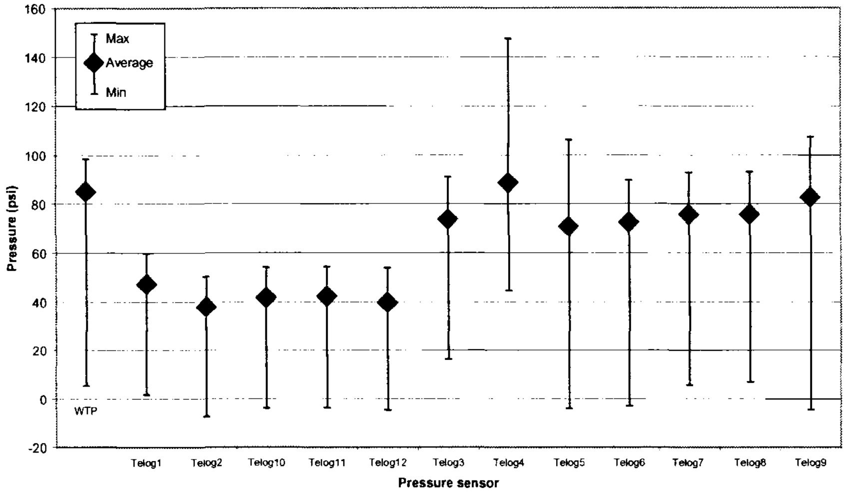

Figure 7-5: Pressures recorded in distribution system during phase 1 (June –Sept 2006)

These results are strongly influenced by a planned water main closure that took place during the observation period (Besner et al., 2007a). Overall, 11 negative pressure events (defined as when one or more loggers recorded negative pressure) took place. Four events were related to power failure at the WTP causing pumps shutdown. Negative pressures were recorded at up to four locations in the distribution system (Telog 2-10-11-12) during these events. These four sites are all located at higher ground elevation with a static pressure of about 40 psi (Figure 7-5). Operating pressures at the treatment plant before the pump shutdowns were between 76 and 89 psi. Minimum transient pressures following these events varied between 5 and 25 psi at the plant and a 2-3 minute period was necessary for full recovery of the initial pressure. The worst event occurred on August 22, 2006 around 08:20 when pressure at the WTP dropped from 89 psi to 5 psi resulting in negative pressures during one minute at four distribution system sites with the lower pressure recorded corresponding to -7.3 psi (Figure 7-6).

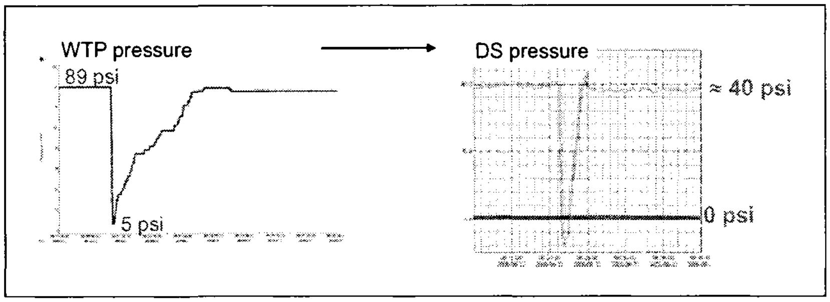

Figure 7-6: Transient pressure induced by power failure at WTP and resulting pressure at one distribution system (DS) site

Four negative pressure events were related to the closure of a transmission main. This closure caused major hydraulic disturbances affecting a smaller zone of the system. During the repair, the affected area was supplied by another water treatment plant, resulting in reversal in flow directions and low pressures. Distribution system sites where the Telog 3-6-7-8-9 were installed had low pressures recorded (<20 psi) while negative pressures were recorded at the Telog 5 site. Because this maintenance activity had a significant impact on the water pressures, about 15,000 customers were put under a preventive boil-water order during the repair work.

Finally, three negative pressure events were related to repairs of isolated water mains. Negative pressures were recorded at Telog 6-9-12 under such conditions for periods varying between 28 minutes and 4 hours. Such negative pressures cannot be classified as transient events as the monitored hydrant was located inside the isolated section for repair.

The first phase of monitoring allowed the identification of the sector of the distribution system that was more susceptible to transient negative pressures. The successive phases of pressure monitoring were therefore established in the area where the Telog 1-2-10-11-12 were installed.

7.4.2.2 Subsequent phases of pressure monitoring

From September 8, 2006 to July 25, 2007, negative pressure events in the distribution system were recorded on five occasions as listed in Table 7-2. Three of these events are not considered as transient in nature since they lasted from 3 to 32 minutes (Nov 20, 2006 and July 11, 2007). It is suspected that these events probably originate from construction work in the area of the pressure monitoring sites as no other sites were affected by low pressures.

Table 7-2: Negative pressure events in distribution system

Phase	# negative pressure events in DS	Date	Location	Cause
1 June 20 to Sept 8, 2006	11	2006-06-27	Telog 2	Power failure at WTP
		2006-08-02	Telog 2-11-12	Power failure at WTP
		2006-08-22	Telog 2-10-11-12	Power failure at WTP
		2006-08-27	Telog 2-12	Power failure at WTP
		2006-08-02	Telog 6	Repair in DS area (no pressure for 34 minutes)
		2006-09-05	Telog 9	Repair in DS area (no pressure for 4 hours 26 minutes)
		2006-08-08	Telog 12	Possible repair in DS area? (no pressure for 28 minutes)
		2006-08-24	Telog 5	Transmission main closure
		2006-08-25	Telog 5	Transmission main closure
		2006-09-06	Telog 5	Transmission main closure
		2006-09-07	Telog 5	Transmission main closure
2 Sept 8 to Oct 12, 2006	0			
3 Oct 12, 2006 to June 14, 2007	1	2006-11-20	Radcom 4	Repair in DS area? (no pressure for 32 minutes)
4 June 14 to July 25, 2007	4	2007-07-10	Telog 12	?
		2007-07-10	Telog 12	?
		2007-07-11	Telog 12	Hydrant use by construction crew doing work in adjacent building? (no pressure for 6 minutes)
		2007-07-11	Telog 12	Hydrant use by construction crew doing work in adjacent building? (no pressure for 3 minutes)

From September 8 2006, pressure values below 35 psi were recorded five times at the WTP. These were susceptible to lead to low or negative pressure in distribution system and all occurred during phase 3 where pressure monitoring was reduced in the distribution system (only the Radcom 3-4 were installed inside public buildings). These five events did not result in negative pressures at the Radcom sites but pressures below 20 psi were recorded for each event at the Radcom 4 site. Because the static pressure is higher at the Radcom 4 site in comparison to the Telog 2-10-11-12 (about 10-15 psi difference), it is therefore suspected that the network area where those Telog are usually installed experienced negative pressures.

During phase 4, that started in June 2007 (up to July 25), the lowest pressures were recorded at the Telog 2-10-11 sites with 16.6, 20.9 and 20.7 psi respectively. Localized negative pressures were recorded at the Telog 12 location (Table 7-2) on July 10 and 11. Some construction work was going on in the area close to the hydrant used for pressure monitoring. It is therefore suspected that the hydrant could have been operated by construction crews. Incidentally, the hydrant was closed on July 12 without the city knowing about it.

7.4.2.3 Pressures recorded during specific O&M activities

In this distribution system, targeted pressure monitoring was performed during repair of water mains in order to assess the amplitude of transient low pressures associated with the operation of valves and hydrants during such a maintenance activity. Pressure measurements were conducted during nine planned repairs of water main leaks that were performed on pipe diameters of 6-8 inches (150-203 mm) (Besner et al., 2007b). The initial static pressure values at the 10 sites monitored (one site with two pressure loggers) varied between 42.7 psi and 74.8 psi. The pressure drop induced by the onset of main flushing varied between 4.5 and 55.8 psi. In this last (and only) case, the pressure during flushing was below 20 psi (16.9 psi) for 17 minutes 35 seconds. Overall, the minimum pressures recoded at the various sites during the repair varied between 16.9 and 46.8 psi.

Pressure monitoring was also performed for three routes of a unidirectional flushing (UDF) program taking place in the eastern part of the studied area in July-August 2006 (Besner et al., 2007b). High-speed pressure transient data loggers were installed on hydrants either on or in the vicinity of the route being flushed. Because these UDF routes were located in a distribution system area with relatively high static pressures (between 74.1 and 84.3 psi), the impact of hydrant opening and main flushing on transient pressures were relatively low. The maximum downsurge measured was 21.6 psi and the minimum pressure recorded from all sites was 56.9 psi.

From these results, although transient pressures were observed during flushing and pipe repair activities, the main cause of negative pressure in the studied distribution system, under standard operating conditions, is when the pump operation at the WTP is affected by power failures. Sustained negative pressures were also experienced due to major work in the system when a transmission main was closed. A total of nine low pressure events were recorded at the WTP during the first year of monitoring (June 2006-June 2007) resulting in four confirmed and five suspected transient negative events in the distribution system.

7.4.3 Modeling of low pressure events at the water treatment plant

Transient (or surge) modeling was used to simulate the low pressure events recorded at the WTP during the first year of monitoring. The use of transient modeling is necessary as the low pressure events are usually of a short duration, in the order of minutes. Extended period simulation cannot be used to model such events.

To this day, one event, taking place on June 27, 2006 has been modeled out of the nine events recorded at the WTP. The transient event was simulated by modeling a pump closure using a change in the pump speed. The pump speed change curve is a model input and was fitted in order to obtain the same pressure out of the WTP as the profile measured. These two curves are illustrated in Figure 7-7.

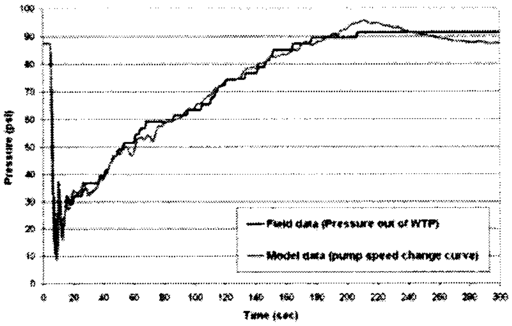

Figure 7-7: Pressure measured out of the WTP and pressure obtained from pump speed change curve entered in model

Because field pressure data were available at some locations in the distribution system, results obtained from the model could be compared with the field data. Figure 7-8 illustrates the model and field data obtained from two locations in the distribution system.

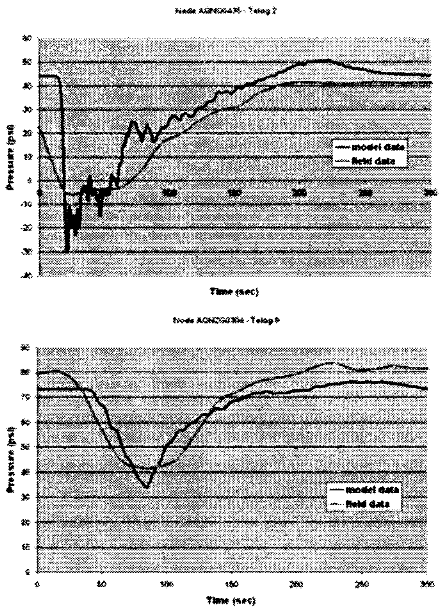

Figure 7-8: Pressure profiles obtained from field and model data at two distribution system locations

The agreement between the pressure values obtained from the model and the ones measured in the field is considered good. As shown in Figure 7-8, the negative pressure values obtained from the model are worst than the pressure values measured using the sensors. In the model, negative pressures go down to -64 psi. This is unrealistic as cavitation (when liquid flashes into vapor) usually occurs when the pressure in the pipe drops below the vapor pressure of the water (0.35 psi at 20°C-absolute pressure, corresponding to -14.35 psi gage pressure) (Streeter and Wylie, 1985). However, the pressure profiles obtained from the model when cavitation was set to occur at -14.35 psi were difficult to interpret because cavitation was found to occur at several locations (which in fact indicates that the model gives lower pressures than measured in the field since cavitation was not observed from the field data). In order to simplify and observe the transient response, the cavitation value was therefore lowered in the model.

The area of negative pressure in the distribution system predicted by the model is illustrated in Figure 7-9. The demand at the nodes experiencing negative pressure corresponded to 9% of the total demand in the system.

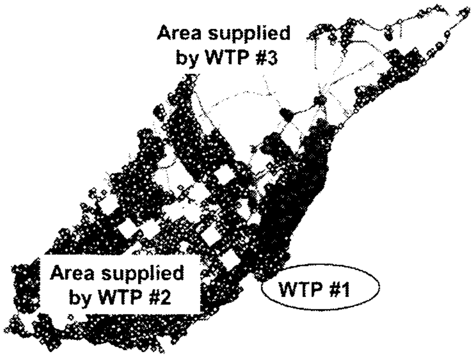

Figure 7-9: Area of negative pressure in distribution system for low pressure event at WTP #1 (red dots indicate node with negative pressure)

Potential intrusion volumes obtained through the use of a leakage factor and an exit head are illustrated in Figure 7-10. Percent of leakage in the distribution system were assumed from 5% to 25% and two exit heads ((height of water above the water main, creating an external pressure) were tested (0 and 1.4 m or 2 psi). Under such conditions, the model considers that all the nodes (with an assigned demand) where the internal pressure is below the external specified pressure will experience intrusion. Intrusion volumes varied from a minimum of 41 liters to a maximum of 218 liters in the distribution system for the simulated conditions.

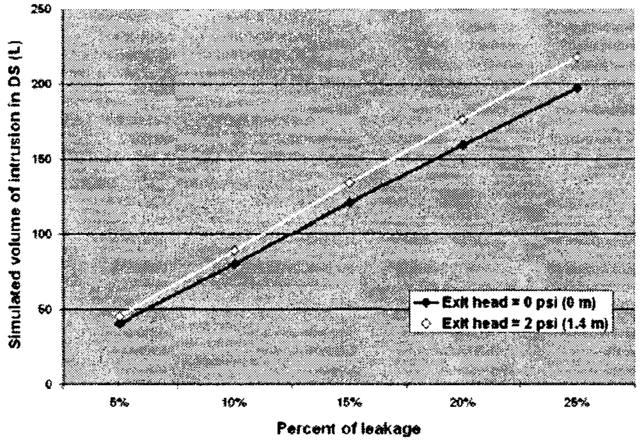

Figure 7-10: Intrusion volumes in distribution system when a leakage factor and exit head are used

Potential intrusion volumes obtained from the simulation of intrusion through submerged air-vacuum valves are illustrated in Figure 7-11. All the vaults visited were assumed to contain air-vacuum valves, which is a worst-case scenario. In reality, some vaults only contained air-valves that are not specifically designed to let air into the pipe in case of negative pressures (but they can let some air in). Different scenarios were tested (data for the complete valve vaults investigation (n=45 vaults) were included here): (i) all 45 vaults that were visited were flooded, (ii) the 30 vaults where a water sample was collected were flooded, (iii) the 10 vaults where the air-valve was actually found submerged under water were flooded. The diameter of the one-way feed tank used to simulate the flooded vault was set to a very large value in order to keep a constant level of water. For comparison, a simulation was also run with a tank diameter of 2 m (to represent more closely the field situation) and this was shown not to affect the results (Figure 7-11).

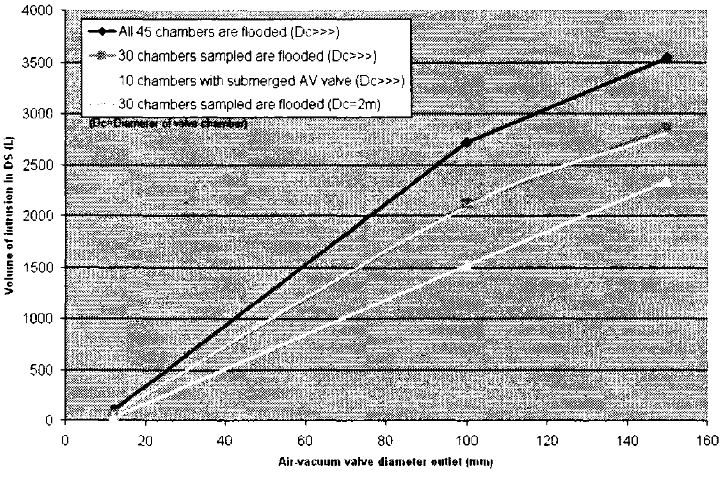

Figure 7-11: Intrusion volumes in distribution system through submerged air-vacuum valves (air-vacuum valve outlet diameter = 12, 100 and 150 mm; height of water above valve outlet = 0.5m)

For the 10-flooded valves scenario (probably the more realistic one), total intrusion volume in the distribution system varied between 37 liters to 2339 liters according to the air-vacuum valve outlet diameter.

For the two types of intrusion simulated, two worst cases were selected for comparison of the total number of microorganisms introduced into the distribution system (as the level of contamination differed in the pathways of intrusion). Case 1 is the simulated intrusion through 10 submerged air-vacuum valves with a valve outlet diameter of 150 mm. Case 2 is the intrusion through all the demand nodes with an internal pressure lower than 2 psi under a 25% leakage rate in the system. The geometric mean was used for the value of microorganism concentration in the soil/trench water and water from air-valve vaults. These results are provided in Table 7.3

Table 7-3: Total number of microorganisms intruded in distribution system for two cases of intrusion

	Case 1 - 10 submerged air-vacuum valves (log value of number of microorganisms)	**Case 2 - 25% leakage and 2 psi exit head (log value of number of microorganisms)**
# of nodes with intrusion	5	943
Total volume intruded in system (L)	2339	218
Total coliforms	$1.8\text{x}10^{8}$(8.25)	$1.7\text{x}10^{6}$(6.23)
E. coli	$1.8\text{x}10^{5}$(5.26)	$4.8\text{x}10^{3}$(3.68)
Enterococci	$1.4\text{x}10^{6}$(6.15)	
Clostridium	$3.5\text{x}10^{4}$(4.54)	$9.8\text{x}10^{3}$(3.99)
Coliphages	$2.6\text{x}10^{4}$(4.41)	$1.5\text{x}10^{3}$(3.18)
Aerobic endospores	$1.0\text{x}10^{7}$(7)	$3.6\text{x}10^{7}$(7.56)

7.5 DISCUSSION

A series of investigations were conducted in the same distribution system where Payment and colleagues conducted their epidemiological studies. This work was achieved in order to better understand the vulnerability of this system to occurrence of low and negative pressures and potential intrusion, these factors being often associated with the results obtained during the epidemio studies. From their second study, Payment et al. (1997) concluded that the distribution system could be a likely source of the increased level of GI illness observed in the population drinking tap water.

7.5.1 Pathways of intrusion

The soil and shallow groundwater in the vicinity of buried mains and the submerged air-vacuum valves are two potential pathways of intrusion that were characterized during this study. The frequency of detection of microbial indicators of faecal contamination was higher in the water collected from the air-vacuum valve vaults than in the soil and trench water samples collected during repairs of water mains. The standing water found in the air-valve vaults could originate from two potential sources: infiltrated groundwater due to the vault (and water main) being located below the water table or street runoff following wet weather events. However, the delimitation between these two sources is not clear. The studied system is located on an island, and is therefore surrounded by water. Some vaults located close to the river (with elevation of about 15 m) had no water while some other vaults located within the center of the island (at elevations up to 51 m) were found to have standing water above the orifice of the air-vacuum valve. It is possible that some of the vaults without standing water located close to the river are more watertight than the others. However, it is unlikely that the vaults located at higher elevations are below the water table. Makepeace et al. (1995) reports the detection of total coliforms, *E. coli*, *Enterococci*, other bacteria and even viruses in urban storwater as well as multiple chemicals such as mercury, total polycyclic aromatic hydrocarbons and tetrachloroethylene. The lower concentrations of aerobic endospores detected in the water from the air-valve vaults (440 cfu/100 mL versus 12,582 and 20,930 cfu/100 mL in soil and trench water on average) correlates well with a contamination originating from faecal sources.

The lowest level of faecal contamination observed in the soil and trench water samples could be explained by the distance between the sewer lines and the drinking water mains. Although this distance is not known, the sewer mains were not visible in any excavation except at one site. This site was in fact the only location where a soil sample was positive for *E.coli* and the storm sewer main was directly located over the drinking water main being repaired.

7.5.2 Frequency of negative pressure

The occurrence of power failures affecting the operation of pumps at the WTP is the main cause of negative pressure events in the distribution system studied. When the pressure at the plant drops below 35 psi, negative pressure is likely to occur in the distribution system. The most susceptible area for negative pressure is located at higher elevation since this system has no storage tank or pumping station out in the system. Adequate pressure is provided by the high-pressure pumps at the WTPs.

During the first year of monitoring (June 2006 to June 2007), nine low pressure events (<35 psi) were recorded at the WTP which resulted in four confirmed and five suspected negative pressure events in the distribution system. Apart from the (sustained) negative pressures created by the closure of a transmission main, the other negative pressure events in the distribution system were found to affect single sensor locations, very often linked with the occurrence of maintenance work in the system. Since June 2007, no low pressure event was recorded at the WTP.

Other researchers have performed pressure monitoring in full-scale distribution systems using high-speed pressure transient data loggers. Gullick et al. (2004) observed 15 surge events that resulted in negative pressure in four systems out of eight monitored over a total period of 4524 days (12.4 years). Most of these events were caused by a sudden shutdown of all the pumps at a pump station. In a subsequent study of the Davenport (Iowa) distribution system, Gullick et al. (2005) monitored the system during 1.4 years and observed nine occasions when pressures were less than 20 psi in the distribution system. No negative pressures were observed. Finally, Hooper et al. (2006) monitored pressure in a distribution system for four months (0.3 year) and found 11 low pressure events with three of these resulting in readings of 0 psi (lowest value read by sensors). For the sake of comparison, the number of zero or negative pressure events recorded in these studies can be reported for a one year period and frequencies of negative pressure events would correspond to 1.2/year (but in multiple distribution systems) (Gullick et al., 2004), 0/year (Gullick et al., 2005) and 10/year (Hooper et al., 2006). However, one must be careful here as the frequency of recording negative pressure events is totally dependent on factors such as the number and location of sensor available, the period of the year (power failures may be more frequent during summertime), and the level of maintenance activities performed in the system.

7.5.3 Transient pressure modeling

The simulation of one low pressure event occurring at the WTP on June 27, 2006 showed that the transient model was predicting lower negative pressures than observed from the field data. The following factors could explain this:

(i) the demands included in the model correspond to average-day demands at the 17 hr time-step (which corresponds to the time at which the event occurred (17:20)). These demands were multiplied by a factor in order to correspond with the total demands measured in the system prior to the low pressure event. Consequently, the repartition and values of the assigned node demands in the model are different than the ones experienced on June 26.

(ii) Typical wave speed values have been assigned to the different pipe materials in the system. However, the wave speed depends on the pipe diameter and pipe wall thickness, which has not been considered here. The magnitude of the pressure wave is affected by the wave speed into the system.

(iii) Air-vacuum valves, which are surge protection devices, have not been included in the model as such (although potential intrusion through these devices has been studied). The air-vacuum valves are not all submerged under water and some are actually working correctly. Consequently, these devices help in reducing the amplitude of the negative pressure in the system.

Despite these differences in the prediction of the level of negative pressure, the pressure profiles obtained at various sites in the distribution system fitted well with the field data. Of course, it is expected that the area and number of nodes experiencing negative pressure in the model is larger than in reality.

Potential intrusion volumes have also been assessed for two modeling scenarios. The volumes obtained are likely to be worst than in reality for the following reasons:

- the model is predicting negative pressures that are higher in amplitude than what was measured in the field

- the intrusion module included in the model (predicting intrusion through pipe leaks) predicts that all nodes subjected to a lower internal pressure than the specified exit head will experience intrusion. As an example, if the exit head is set to 0, the model will consider that all the nodes experiencing negative pressure will experience intrusion. In reality, this is highly unlikely as the area subject to negative pressure is typically located at higher elevation in this distribution system. The likelihood that these locations are below the groundwater table is very low. The modeling scenario considering the 2 psi (1.4 m) exit head was therefore selected as a worst-case scenario.
- Intrusion through submerged air-vacuum valves is a more serious threat for this system. The intrusion volumes obtained via this pathway (considering the location of the 10 flooded vaults as found in summer 2007) are higher than for the intrusion through leaks. Intrusion volumes are about 10 times higher through submerged air-vacuum valves than through pipe leaks. However, care must be taken when considering the number of liters intruded. Many assumptions make the situation worst in the model than in reality: (i) air-vacuum valves have been assumed in all the vaults while this is not the case in the distribution system. Air-release valves (with typical outlet diameters smaller than ¼ in. (6 mm) may also be located in these vaults; (ii) the actual diameter of the air-vacuum valve outlets are not known; (iii) modeling the flooded vaults with a one-way feed tank requires the assignation of a resistance factor based on a coefficient of discharge (C_d) that depends on the shape of the orifice. This value is unknown and a C_d of 0.6 was used.

In the Kirmeyer et al. (2001) study, transient modeling of a section of this distribution system was performed. These authors obtained intrusion volumes following a loss of flow (changing the speed of supplying pumps from full to zero in five seconds) of 55, 98, 140 and 247 liters during four simulations. These values were obtained using leakage percent of 5, 10, and 15 and an equivalent orifice diameter of 1/8 in. (3.2 mm) in the last case (all with an exit head of 1 m). It is difficult to compare these values to the volumes obtained in this study because of the different simulating conditions used in the two studies. The intrusion volume is totally dependent upon the negative pressure magnitude and duration obtained from the model.

Because both the level of faecal contamination and the volumes of intrusion were found to be higher for the submerged air-vacuum valve pathway, a comparison was made regarding the total number of microorganisms that would find their way into the system under two worst-case conditions of intrusion through submerged valves and pipe leaks. According to the model, intrusion through submerged air-valves located in the area of negative pressure would lead to an additional load of microorganisms into the system varying between 0.5 to 2 log (Table 7-3). However, there is no assessment here on the potential impact of the residual free chlorine present in the distribution system on the inactivation of the microorganisms. The numbers of microorganisms listed in Table 7-3 are intruded through multiple nodes. It must also be remembered that these numbers were obtained from two worst-case contamination scenarios as discussed above.

Flooding of air-valve vaults is not specific to this system. Kirmeyer et al. (2001) report that 12 utilities out of 26 surveyed had information on flooding of meter and valve vaults. For these 12 utilities, the number of flooded vaults (not only air-valve vaults) varied widely, between 0 to 80% of total vaults. These authors also report on a water utility finding standing water in 100% of the air-valve vaults inspected. Good engineering practices for the installation of air valves should include an open ended pipe that extend 0.3 m above grade, fitted with a screened, downward facing elbow (Ministère de l'Environnement du Québec, 2002). In the distribution system studied, a regular inspection program should be put in place in order to eliminate this potential source of contamination in the distribution system. The zone identified as being susceptible to negative pressure should be prioritized.

7.6 CONCLUSION

The possibility of microbial intrusion in the distribution system where Payment et al conducted their epidemiological studies was investigated. Potential pathways of intrusion were characterized, frequency and magnitude of negative pressures were monitored in the system and transient modeling of low pressure events was conducted to assess potential volumes of intrusion.

The monitoring of distribution system pressures during one year showed that a part of the system was vulnerable to negative pressures when power failures occurred at the WTP, affecting the operation of pumps. Although transient pressures were measured during the monitoring of targeted maintenance activities (operation of valves and hydrants), these were not associated with the occurrence of low or negative pressure at the monitored sites.

One low pressure event at the WTP that was found to result in negative pressure in the distribution system was simulated using transient modeling. Although the model predicted lower negative pressures than measured, the pressure profiles at various locations showed a good correspondance between field and model data. Potential intrusion volumes during this event could be simulated under different scenarios. Intrusion through submerged air-vacuum valves was found to be more important than intrusion through pipe leaks. Moreover, the microbial characterization of these two pathways of intrusion indicated that faecal contamination was recovered more frequently and at higher levels in the water from the flooded air-vacuum valve vaults than in the soil or trench water. Intrusion volumes obtained from the model are likely to be higher than in reality, however, such results indicate that air-valve vaults should be prioritized in term of inspection and maintenance, in order to minimize the risk of intrusion in this distribution system.

The transient modeling performed as part of this study intends to present the first steps of what could later be used to develop a risk assessment methodology on microbial intrusion due to transient negative pressures in distribution systems. The modeling work presented may certainly be refined and should be considered as exploratory work.

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CHAPTER 8

GENERAL DISCUSSION

This general discussion highlights the main findings obtained through this PhD research. The concept and benefits of data integration will first be discussed. Results and challenges related to the investigation, in full-scale distribution systems, of losses in physical integrity and hydraulic integrity will then be reviewed. Finally, the benefits of such study for the water industry will be presented.

The results presented in this thesis come from a total of seven different water distribution systems. Through the data-based study, data were obtained from seven water utilities (Laval, Montreal, Moncton, Caen, Egham, Cincinnati and Denver) and field investigations were also conducted in two of these distribution systems (Laval and Montreal). The Laval distribution system, and more specifically the area of the system where Payment and colleagues conducted their epidemiological studies, is where the majority of the field work took place. Therefore, part of the discussion is devoted to this specific system.

8.1 INTEGRATION OF DATA WAS FOUND USEFUL TO EXPLAIN WATER QUALITY VARIATIONS

In the past, prediction of total coliform occurrences in drinking water distribution systems (both in time and space) has been attempted. A review of four models was provided in Besner et al. (2002) and these models were mostly based on the consideration of the classical water quality parameters associated with regrowth: water temperature, total count of bacteria, residual chlorine and organic matter. However, because water quality parameters are clearly insufficient to explain the occurrence of coliforms in distribution systems (Besner et al., 2002), it was suggested that the use of dynamic visualization/data-based approach could be useful to better understand water quality variations.

The data integration approach developed during this project is based on the combination and simultaneous consideration of water quality data, network structural data, system O&M data, information from a hydraulic model and a geographical information system (GIS) for data visualization. Data analysis was performed using the Interactive Data Analyzer tool that was developed in collaboration with Professor Trépanier of the MADITUC group at Ecole Polytechnique. At the time of development, and because of the constraints related with the participation of several water utilities, all with different database management strategies, a software tool as "simple" as possible was elaborated (based on widely available components). Figure 5-3 of Chapter 5 provides a good overview of the tool capabilities.

Using such an approach, it was therefore possible to examine the potential causes of historical water quality variations in a distribution system. Occurrence of coliform samples is one type of water quality problem that was investigated. From the results obtained, the proportion of coliform samples attributable to O&M activities could then be established. Based on the available data provided by the water utilities, a total of 140 total coliform samples in five distribution systems were investigated. The results showed that the role of O&M activities on the occurrence of coliforms was variable from one system to another, explaining a minimum of 9% and up to 45% of the number of coliform cases investigated in each system. This study provided some spatio-temporal (and hydraulic) evidences of a link between O&M and coliform occurrences. However, most of the samples included in this study were collected from routine sampling locations by the water utility. Therefore, the results are providing a limited view of the real impact of O&M on water quality since O&M work can be conducted in any part of the distribution system, not only in area where routine sampling points are located. A field evaluation of some O&M activities was then required.

The Laval distribution system was included in this study and results showed a link between low pressure events and coliform occurrence in summer of 1999. The affected area was characterized by low or non detectable free chlorine residuals at that time.

Fifteen percent (15%) of the positive total coliform samples collected in this distribution system between 1997 and 2000 were associated with events taking place in the distribution system (lower pressures, pipe flushing, hydrant operation and times of increased water consumption associated with lower pressures, valve operation and pipe flushing).

8.2 LOSS IN SYSTEM'S PHYSICAL INTEGRITY: FIELD ASSESSMENT OF THE IMPACT ON WATER QUALITY

The field investigation of the impact of pipe repairs on water quality was driven by the following evidences:

- A loss in distribution system's physical integrity (through repairs or installation of water mains) has been identified as a potential source of contamination (NRC, 2006).
- Our in-depth review of simulated intrusions in various experimental settings (Chapter 4) showed that when the intrusion took place under no- or low-flow conditions or when there was a delay between the time of intrusion and the time of application of the disinfectant, these conditions were likely to result in increased persistence of microorganisms in the water system. Such conditions can in fact be related to field conditions experienced during pipe repairs in full-scale distribution systems.
- Detailed field data related to water quality parameters during repairs are usually missing in the literature. The number of sanitary release samples after new main installation is the most common type of data available (Haas et al., 1998).

8.2.1 Challenges of conducting experimentation in full-scale distribution systems

Conducting field work in full-scale distribution systems presents organizational challenges. The setting for experimentation is not a controlled environment (in comparison with a laboratory setting for example). The selection of sampling locations for the monitoring of pipe repairs was totally dependent upon the site conditions and customers' acceptance of having their water sampled during the event. The utility field crews were in general very collaborative but sometimes procedures such as valve or hydrant operations were conducted without notice, making the field measurements more difficult. The number of repairs investigated depended on the number of repairs performed by the water utility and the constraints associated with laboratory work (availability to perform microbiological analyses – within 24 hours of the repair). Monitoring of pipe repairs was quite labor-intensive as it required the participation of a group of four to six people in order to collect the required water samples at the various locations.

Despite these challenges, monitoring in full-scale systems provides measurements of actual water quality changes due to operations. The protocol developed for the investigation of pipe repairs and their impact on water quality is a first and allowed the identification of effects both inside and outside of the isolated repair area. To the knowledge of the author, no comparable study has been published on this topic.

8.2.2 Low contamination associated with planned repairs of water mains

Out of 16 repair sites investigated, evidence of microbial intrusion (total coliforms, *E. coli*, aerobic endospores) was observed at seven sites (44% of the sites). Considering all sampling locations and repair steps at which water samples were collected, a total of 17 samples out of 424 (4.0%) were positive for total coliforms. The majority of positive samples were collected during the flushing step of the repair (16 out of 17 samples), predominantly at the hydrant itself (11 samples out of 16). Only one sample was found positive for total coliforms once the repair was completed (collected at House In) and among the positive total coliform samples, only one was found positive for *E. coli* (collected at hydrant during flushing). These results show limited contamination associated with the type of repairs investigated and suggest that adequate pipe flushing after a repair is completed is in fact effective to minimize contamination.

In comparison, van Lieverloo et al. (2006) report that 28 out of 50 faecal contamination events reported for the 1994-2003 period in the Netherlands were related to operations in mains (18 replacements, 8 repairs and 2 cleaning operations). Most of these cases were detected through targeted sampling (within the first day after the mains were cleaned), performed by the water companies (however, no details regarding site conditions are available). It is noted that water supply was started immediately after the operations, but not before the mains were flushed and in some cases disinfected. Systems providing water in the Netherlands are characterized by the distribution of water without a disinfectant residual, which can probably explain the recovery of faecal indicators. In our study, if faecal contamination would have been more common, it is expected that more samples would have been positive for *E. coli* during flushing. Although chlorine residuals were not measured in the first samples collected during flushing, the likelihood that a chlorine residual was present in those samples is very low. These samples were often characterized by an elevated turbidity.

Soil and water samples from pipe trenches had a low level of faecal contamination, which could explain the results obtained. Our results differ from the ones obtained by Karim et al. (2003) who performed a similar investigation in several U.S. water systems. Frequency of recovery of faecal contamination in the soil and trench water samples collected by Karim et al. (2003) was much higher with the detection of human enteric viruses (detected using both cell-culture and PCR) in some samples. In our study, only one soil sample was found positive for *E. coli*, and this was the only occasion a sewer main could be observed in the same trench as the repaired main. Recent samplings (during summer of 2007) of soils and trench water samples during repairs of water mains were conducted in different distribution systems (St-Jean-sur-Richelieu and Repentigny, Quebec). Although few samples are available (n=3), results indicate that *E. coli* was again detected in trench water of the only site where a large diameter sanitary sewer main was found to cross over the repaired drinking water main. These results indicate that sites where the drinking water mains are located in the vicinity of sewer mains are especially vulnerable to contamination, either during repairs or through intrusion if pipe leaks are present.

The fact that the repairs investigated were planned repairs of pipe leaks is also a factor that could influence the results obtained. The field conditions experienced under emergency repairs, when water is flowing and potentially flooding the streets and buildings, may be quite different. For such cases, there is a need for the field crews to act rapidly in order to limit potential damages. Such situations were not investigated during this study, mainly because of logistical constraints (unknown time of event, sampling equipment as well as a team of four to six persons ready at all times). The number of repairs completed each year (from 1985 to 2004) in the Laval distribution system is illustrated in Figure 8-1. Using the available information for the 2000-2004 period, it was found that 52% to 60% of the repairs (performed during a year) were performed on the same day as the pipe failure was detected. Although it is strongly suspected that the repairs conducted on the same day as a failure is detected do not all represent major pipe failure events, we can therefore conclude that the situations investigated during this study (planned repairs) likely represent the conditions encountered during 40-50% of the repair work conducted in this system (corresponding to about 200 repairs per year on average).

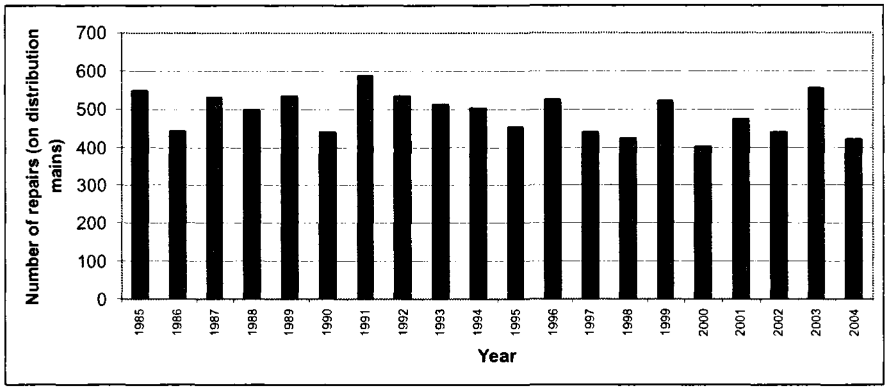

Figure 8-1: Yearly number of distribution main repairs conducted in the Laval distribution system (1985-2004)

The results obtained from the field study are in agreement with the results obtained from the data-based study conducted for the Laval distribution system. From the historical data analysis, pipe repairs were not identified as a high-probability cause of the explained coliform occurrences in this system. However, even if the field results showed limited contamination, field crews must remain cautious regarding the sanitary practices during repairs. A lack of sanitary precautions is one hypothesis suggested for the detection of *E. coli* in one water sample collected from a flowing hydrant. Consequently, even if flushing was found to be adequate to remove intruded contamination, minimal disinfection (of the tools and other equipment used during the work) could easily be performed and provides an additional barrier in preventing potential contamination of the system. This is applicable to planned repairs such as the ones investigated during this study.

8.3 LOSS IN SYSTEM'S HYDRAULIC INTEGRITY: FIELD ASSESSMENT OF THE IMPACT ON WATER QUALITY

The evaluation of the risk of intrusion associated with low or negative pressures due to standard system operation or occurrence of maintenance activities in full-scale distribution systems was an important part of this PhD work. Accordingly, the three conditions necessary for intrusion to take place were investigated: (i) occurrence of negative pressure; (ii) available pathway for intrusion; and (iii) source of contamination. Although some of the pressure measurements were conducted in the Montreal distribution system (hydrant flow tests, monitoring of pump operation), the majority of the work was performed in the Laval distribution system, in the same system area where Payment and colleagues (1991, 1997) conducted their epidemiological studies. Continuous pressure monitoring was performed from June 2006 up to November 2007 in this distribution system.

Power failures affecting the operation of pumps at the water treatment plant were identified as the main cause of transient negative pressure in the Laval distribution system. Sudden shutdown of pumps has also been reported by Gullick et al. (2004) as being the main cause of negative pressures in at least three systems out of four where negative pressure was recorded. Operational practices such as valve and hydrant operations associated with repair or flushing activities, were found to induce transient pressures but no negative pressure resulted. The pressure monitoring in the Montreal system showed similar results with larger transient pressures induced by pump operation (resulting in pressures of 83 kPa (12 psi) at the monitoring location). Apart from pumping operations, most of the O&M activities monitored took place in area of the systems where the initial pressures were relatively high (with average initial pressure between 290 and 558 kPa (42 and 81 psi) (Besner et al., 2007). Pressure drops varying from 14 kPa up to 379 kPa (2 to 55 psi) were measured such that there is a potential for these operations to create negative pressures when conducted in distribution system area where the initial pressure is low. In the literature, there is no report of measured negative pressure associated with these operations (flushing, hydrant flow tests, fire fighting flows, pipe breaks).

The Laval distribution system study area was found to be vulnerable to low and negative pressures with nine events of low pressure at the WTP during the first year of monitoring (June 2006-July 2007). Negative pressure mainly resulted at locations of higher elevations due to the absence of storage tanks and pump stations in the distribution system. It is not known if such system's characteristics (high-pressure pumps at the WTP only and absence of storage tank in distribution system) are commonly found in other systems. Such a setting increases the vulnerability to negative pressures, especially at locations of higher elevations.

When low or negative pressures occur, microbial intrusion in the Laval distribution system may take place through pipe leaks or other orifices (as in all distribution systems) but also through submerged air-vacuum valves that are located in flooded vaults. A survey of 45 vaults showed the presence of water in 30 vaults among which 10 vaults were flooded with water submerging the air-vacuum valve orifice. For the pipe leaks, it is estimated that 20% of the water is lost through these. Soil, trench water and water from the flooded vaults were characterized to determine their level of faecal contamination. The frequency of recovery and concentrations of faecal microbial indicators were higher in the water from the valve vaults, making this pathway of intrusion, a critical one in this distribution system.

8.3.1 Establishing the link between negative pressure and water quality changes

Establishing a link between the occurrence of negative pressure in a full-scale system and resulting changes in water quality is a big challenge. Even if the three conditions for intrusion are in place in the Laval system (negative pressure, pathway, source of contamination), these conditions have to occur simultaneously at a location for intrusion to take place. As previously discussed, negative pressure affects the higher elevation area of the system where it is unlikely that the pipes will be submerged under water. However, some flooded air-valve vaults are located in this area and of course, the location of potential cross-connections is unknown.

Water quality sampling during transient pressure events cannot be planned as it is impossible to predict the time of occurrence of a negative pressure event. Moreover, these events are usually transient in nature, having a duration of less than a few minutes. To offset such a constraint, an automatic water sampler, able to collect 150 liters of water following a low pressure event, was installed (in July 2007) inside a city building in the area vulnerable to negative pressures. Results regarding this part of the study were only recently obtained and are very preliminary. Hence, they are not presented nor discussed in this thesis. However, we think it is worthwile to mention that such a field initiative was attempted.

The occurrence of a sustained negative pressure event in an area of the Laval distribution system associated with the planned closure of a transmission main (Appendix A) represented a "unique occasion" to sample water following the occurrence of a negative pressure event in a full-scale system. The flushing operation of the 400 mm (16 in.) diameter main at the end of the first closure induced negative pressure for two episodes lasting more than five minutes each at a site where water quality was being sampled. As detailed in Appendix A, even if larger volumes were sampled (1 L) and analyzed for the microbial indicators of intrusion used (total coliforms/*E. coli*, aerobic endospores) no microbial contamination could be detected at this site. The free chlorine residual after the pressure loss (0.18-0.20 mg/L) was about the same as before the flow was stopped. Water quality samplings at two other sites in the affected area showed no significant evidence of microbial contamination as only one sample was positive for total coliforms and happened to be collected 30 hours after the end of the first closure but still in the middle of the second closure. However, the free chlorine residual was below the detection level for this sample. To our knowledge, this is the first attempt where water quality could be evaluated following the occurrence of a major negative pressure event in a full-scale system.

If this sustained negative pressure event resulted in an intrusion (as the theory, literature and some of our previous results would likely suggest), it could therefore not be detected. Some hypotheses for this can be offered:

- grab water samples were collected and the time of collection did not coincide with the time at which the contamination was transported to the sampling location
- the residual chlorine in the system was able to offer some protection and inactivated the intruded microorganisms (at least the indicators)
- viable but nonculturable (injured) bacteria could not be detected with the detection methods used during this study (Colilert - enzymatic method for total coliforms and membrane filtration for the aerobic endospores). However, aerobic endospores are more resistant to disinfection (Rice et al., 1996; Barbeau et al., 1999) and therefore less subject to chlorine injury. This last hypothesis reflects the same concerns expressed regarding the detection methods used in the studies reviewed in Chapter 4. The use of a detection technique such as the DVC-FISH-ScanRDI allowing the detection of nonculturable *Enterobacteriaceae* cells would have been possible as the equipment was available in our laboratory. However, it was decided not to use such a method since past experience showed that the maximum volume of distribution system water that could be filtered was 100 mL, assuming a low turbidity of the water sample. The distribution system water samples analyzed in the past (Baudart et al., 2005) also contained a very low free chlorine concentration (<0.1 mg/L).

Free chlorine concentrations in the Laval distribution system have significantly increased over the years (Figure 8-2). This figure illustrates box plots (min, 25th percentile, median, 75th percentile and max values) summarizing the daily concentrations measured at the outlet of the Pont-Viau WTP supplying the area under study.

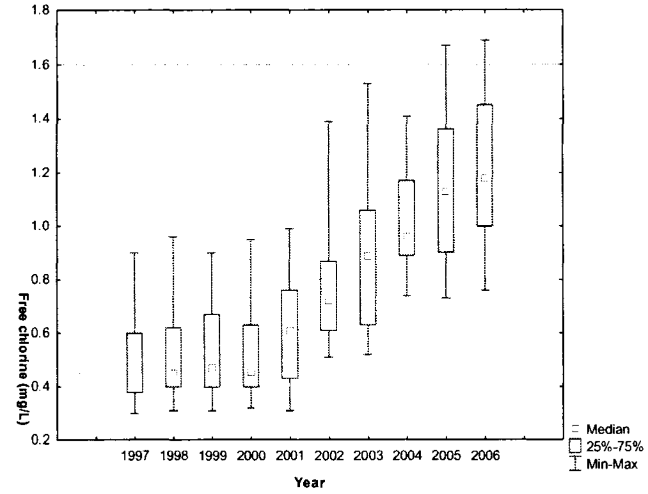

Figure 8-2: Free chlorine concentrations at the outlet of the Pont-Viau WTP

For the year 2006 (up to the end of October), the free chlorine residual at the outlet of the plant resulted in the concentrations illustrated in Figure 8-3 for the three routine monitoring sites in the distribution system supplied by the Pont-Viau WTP. Free chlorine was always detectable at the site located at the greatest distance from the plant and usually close to 0.2 mg/L for the lowest values although some values were at about 0.1 mg/L.

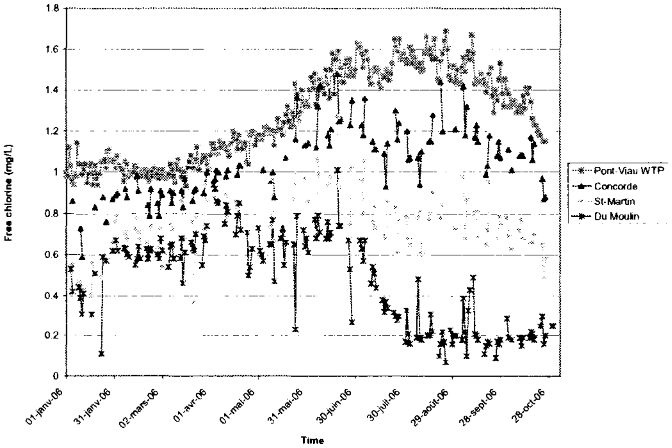

Figure 8-3: Free chlorine concentrations in distribution system (January-October 2006)

Under such conditions, the detection of microorganisms becomes more difficult because of their potential inactivation and relative scarcity in the system. As an example, the occurrence of total coliform positive samples originating from the routine collection of water samples is at its lowest level since 2004 (Figure 8-4). In 2004 and 2005, only one sample was found positive for total coliforms in the distribution system.

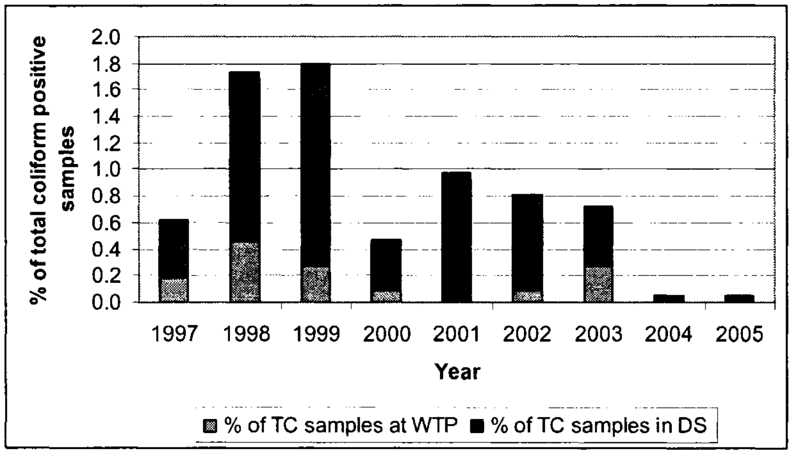

Figure 8-4: Percentage of positive total coliform samples from routine water quality monitoring in the Laval distribution system

In order to increase the chance of detecting an indicator of intrusion during the sustained negative pressure event, larger volumes of water were collected for analysis. Instead of the usual 100 mL sample used for total coliform/*E. coli* detection, volumes of 1L were used for filtration, increasing by a factor of 10 the likelihood of detecting total coliforms in the sample (900 ml were filtered through a 0.45μm filter and the filter was then placed in 100 mL of sample to which the Colilert reagent was added). The issue of large volume sampling for detection of microorganisms in distribution system is an ongoing issue. There are no defined sampling procedures in place at this time. Studies using multiple 250 mL samples (Owen et al., 2007) to trials where up to 20 L of water could be filtered using a filtration capsule or module (McCuin et al., 2007) were recently or are currently conducted. In the context of a field study with simultaneous sampling at different locations, such as the one presented here, field constraints may limit the amount and type of equipment that can be used.

The results obtained from this investigation, showing limited contamination linked to the occurrence of sustained negative pressure, would therefore suggest a low health risk. However, this is in contradiction with the studies conducted by Hunter et al. (2005) and Nygard et al. (2007) which report an association between gastrointestinal illness and low-pressure events in distribution systems in England and Norway. Both studies are based on episodes of diarrhea reported by water recipients in several distribution systems. Very few water quality data are available and there is no information regarding the level of residual disinfectant used in these distribution systems. Although this cannot be ascertained in this case, water is often distributed with a lower disinfectant residual in European countries compared to the practices in place in North-American systems (Chapter 4). If this is in fact the case, this could certainly explain some of the differences observed.

8.3.2 Transient modeling as a tool to understand the risk of intrusion

Because of the difficulties associated with the actual measurements of intrusion volumes in full-scale distribution systems, the vulnerability of a system to contamination may be evaluated using transient modeling. In the past, transient flow analysis has mostly been used to evaluate peak positive and negative pressures in pipe systems in order to select appropriate strength pipe materials and appurtenances and for the design of effective surge control devices (Ghidaoui et al., 2005). As noted by these authors, water qualtity predictions in potable water system is an emerging application in water hammer analysis. It is therefore expected that the hydraulic parameters allowing the simulation of intrusion will be refined in the future. This is an area where interesting developments are likely to take place.

As previously discussed in Chapter 7, intrusion volumes simulated for one low-pressure event at the WTP are likely to be higher than in reality because (i) the model is predicting worst negative pressures than measured in the field; (ii) the orifice equation used to model intrusion predicts that all nodes subjected to a lower internal pressure than the specified exit head will experience intrusion; and (iii) uncertainties about the simulation of air-vacuum valves exist. Despite these constraints, the use of transient modeling helped in identifying a critical pathway for intrusion in the distribution system studied (the submerged air-vacuum valves). Simulation of intrusion was mostly performed through pipe leaks in previous studies (Kirmeyer G.J. et al., 2001; LeChevallier et al., 2004; McInnis, 2004). To our knowledge, this is the first study where two potential pathways (with information on their respective level of contamination) are compared.

The next step will be to simulate the transport of the intruded contaminant into the system. This can be achieved by the use of the extended period simulation model. However, it is imperative that the residual disinfectant effect be taken into consideration in order to obtain a realistic understanding of the impact of the negative pressure events in the distribution system studied. Further work will consist in defining the risk of infection in the population, associated with consumption of contaminated drinking water due to an accidental intrusion. The model proposed by McInnis (2004) could be used as a basis. Based on the QMRA concept, the work presented in this thesis may therefore be considered as new information allowing a more accurate characterization of the exposure.

8.4 BENEFITS FOR THE WATER INDUSTRY

The nature of the research conducted during this project is very practical. The data integration approach and the interactive analyzer tool were transferred back to the staff of the participating water utilities once this part of the project was completed. For most of the utilities, the data-based study highlighted the need for a well-managed database with adequate information on the spatio-temporal location of events. A real-life application of the data integration approach is now in place in the city of Metz (France) distribution system, managed by Veolia Water (The N° 1 company worldwide for water services with an annual revenue, in 2006, of 10.1 billion euros). Technical knowledge (better use of different types of information, better understanding of water quality in distribution systems), commercial benefits (technological showcase, development of GIS aspects, modeling) and the legal obligations of water providers under the revised regulations drove the application of the approach by the company. In 2007, the city of Toulouse (France) was added as a new pilot site for the application of the approach. The approach also raised some interest from the research community as it was included in two research projects funded by the American Water Works Association Research Foundation (AwwaRF) One study is already published (Martel et al., 2005) and one is currently conducted (AWWARF 3116 – Strategy to manage and respond to total coliforms and *E. coli* in the distribution system).

The results obtained through the field studies will benefit the water utilities by allowing them to improve their daily O&M activities. The work presented provides support to identify and control vulnerable distribution system locations.

Finally, regulatory agencies now have access to scientific knowledge to elaborate guidelines or regulations on distribution system operation and better assess the importance of intrusion associated with system operational practices and maintenance activities. The work presented can be considered as background work that can be used to assess the importance of intrusion in terms of public health. In such a process, this PhD work brings new information allowing a more accurate characterization of the exposure.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

This PhD work resulted in the following conclusions regarding the link between distribution system O&M activities and potential distribution system contamination:

- The investigation of the causes of 140 historical coliform occurrences in five water distribution systems showed that some O&M activities could be associated with the subsequent detection of coliform positive samples. The likely causes identified included: pipe replacement, spot flushing and valve operation, unidirectional flushing, valve and hydrant operation, lower pressures in localized area of the system, high flow hydrant testing, pipe break repair, installation of new pipes and mains cleaning and relining.
- The results obtained from the data-based study are totally dependent on the availability of high-quality data which provide a comprehensive analysis and a highly accurate diagnosis. From the available data, it was found that the role of O&M activities on the occurrence of coliforms in distribution systems varies from one system to another, explaining a minimum of 9% and up to 45% of the number of coliform cases investigated in each system.
- Evidence of intrusion (using total coliforms, *E.coli* and aerobic endospores in distribution system water) at sites of pipe repairs was obtained at seven sites out of 16. However, the results suggest that adequate pipe flushing after a repair is completed is effective to minimize contamination for the type of repair investigated. Almost all the positive total coliform samples (17 samples out of 424 (4.0%)) were collected during the flushing operation and at the hydrant predominantly. Detection of *E. coli* in flushing water occurred on a single occasion. The low level of faecal contamination of the soil and trench water in the two distribution systems studied may explain some of these results.

- During the time period necessary for a repair to be completed (usually less than 10 hours), variations in chlorine residuals and turbidity can be observed outside of the repair area when changes in flow direction and dead-end mains are created by valve closures.
- The frequency and magnitude of negative pressures associated with both system operation and some targeted maintenance activities were evaluated, with the majority of the work taking place in the Laval distribution system. Pressure monitoring showed that transient pressures were recorded under all events monitored. However, power failure affecting the operation of pumps was the main cause of negative pressures in this distribution system. The frequency of these events was quite high during the first year of monitoring. Nine low pressure events were recorded at the water treatment plant
- A "unique occasion" to sample water following the occurrence of sustained negative pressure in the Laval distribution system showed limited microbial contamination associated with this event. Total coliforms could be detected in only one water sample even if larger sample volumes were used.
- Transient and intrusion modeling were used to assess the potential level of intrusion associated with negative pressure events in the Laval distribution system. Although adjustments should be made to the model, the results showed that flooded air-vacuum valve vaults were critical locations for intrusion in this distribution system. Combining the results from the model and the field sampling, these locations are characterized by larger intrusion volumes, high frequency of recovery and higher concentrations of faecal indicators.

The initial question that this research seeked to answer was: what is the risk of microbial contamination in a drinking water distribution system when routinely conducted operation and maintenance activities take place? The data-based study showed that a link could be established between O&M activities and total coliform occurrences. The results from our field studies showed limited contamination linked with planned repairs and (one) sustained negative pressure event. Based on this, the risk of contamination associated with repairs (planned repairs in relatively "clean" pipe trenches) can be estimated as low. However, evidences are less straightforward for the negative pressure event. It can be suspected that indicator microorganisms would have been detected in more than one sample if the situation was critical. The free chlorine residual in the area of the distribution system studied was shown to increase significantly over the years, which can probably offer a certain level of protection. However, transient modeling highlights the risk of intrusion from submerged air-vacuum valves during negative pressure events. This pathway of intrusion should and can easily be eliminated by the systematic inspection and maintenance of the valve vaults.

Additional research is therefore needed to assess with confidence the risk of intrusion associated with the occurrence of transient negative pressures and assess the effect of the residual disinfectant. Because the modeling work performed during this study was rather exploratory, this part should be expanded. In the context of the study presented here, future work should include adjustments to the actual transient model in order to obtain results that would be more representative of the field data. Sensitivity analyses should be conducted for the model parameters that cannot be directly assessed. For the simulated scenarios of intrusion, transport of the intruded microorganisms should be coupled to the inactivation provided by the residual disinfectant. A model such as the EPANET-MSX model, which considers the fate and transport of multiple constituents in distribution system could be used. Such results would give a much refined input into a QMRA model designed to evaluate the risk of infection in the population, associated with the consumption of contaminated drinking water due to an accidental intrusion. Transient modeling of the sustained low pressure event would also be very interesting in order to confirm (or not) the results that were obtained from the field.

O&M activities in a distribution system include a wide range of operations. Unfortunately, all of these could not be evaluated in the framework of this study. As more attention is now devoted to the distribution system as the last barrier against potential contamination, research should continue in order to provide a more accurate view of the impact of such operations.

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APPENDIX A

CASE STUDY:

NEGATIVE PRESSURE AND WATER QUALITY ASSESSMENT DURING THE CLOSURE OF A TRANSMISSION MAIN IN THE LAVAL DISTRIBUTION SYSTEM

Abstract: The magnitude of low and negative pressures induced by the closure and repair of a transmission main in a distribution system was investigated along with the potential for intrusion and changes in water quality associated with these low/negative pressures. Field equipment included high-speed pressure transient data loggers, on-line turbidimeters and grab samples that were analyzed for total coliform bacteria, *E. coli*, aerobic endospores, residual chlorine, temperature and conductivity. Results of the monitoring showed that the closure of the transmission main was the cause of significant and sustained negative pressures in the DS under study. However, the water quality monitoring did not reveal significant water contamination. The specific conditions of the system under study and the inability to detect contamination in chlorinated systems with the current analytical methods could explain such results.

INTRODUCTION

Negative or low pressures in water mains are problematic as they can result in the introduction (backflow) of untreated water into the main if an available pathway is present (pipe fracture or orifice, cross connection, leaking joints, etc.).

The general aging and deteriorating state of the infrastructure used to distribute water is therefore a threat to the integrity of distribution systems and increases the vulnerability of distribution system to water contamination. The American Society for Civil Engineers allocated a D- for the poor state of drinking water infrastructures in the U.S. (ASCE, 2005). It is also estimated that about 30% of the produced water in Canadian distribution systems is lost through pipe leaks (Environment Canada, 2005), providing multiple potential entry points for intrusion of microbes into treated drinking water during negative or low pressure events.

Low or negative pressure events have been reported in many studies (Kirmeyer et al., 2001; LeChevallier et al., 2004; Gullick et al., 2004; Gullick et al., 2005; Hooper et al., 2006). These events are usually transient in nature, having a short duration mostly in the range of seconds. It has been stated that a high potential risk of introduction of pathogenic microorganisms into the distribution system exists when transient negative pressure events occur in pipelines (LeChevallier et al., 2003).

The case study presented here is part of a larger study consisting in evaluating the frequency and amplitude of transient low and negative pressures in the distribution system area where Payment et al. (1991; 1997) measured an increased rate of gastrointestinal illnesses associated with the consumption of tap water. These authors indicated that between 14 and 40% of the gastrointestinal illnesses, in the distribution system under study, were related to tap water meeting the current water quality standards and that the distribution system appeared to be partly responsible for this endemic level of illnesses. These findings raised questions about the integrity of distribution systems and the likelihood of their contamination during normal operations.

OBJECTIVES

The main objective of the case study reported here was to determine the magnitude of low and negative pressures induced by the closure and repair of a transmission main. The potential for intrusion and changes in water quality associated with these low/negative pressures were also assessed.

METHODOLOGY

During summer 2006, continuous pressure monitoring of a distribution system area was performed during 80 days using 12 high speed pressure transient data loggers (Figure A-1). This distribution system area is supplied by a single water treatment plant, without any storage tank in the system.

In August 2006, a major planned repair (closure of a 400 mm (16 in.) transmission main) was conducted, affecting about 15,000 customers in a sub-area of the monitored network (Figure A-1). This pipe closure was expected to cause major hydraulic disturbances (flow reversals, low pressures) in this sub-area of the distribution system as water supply would be provided by another treatment plant under the repair conditions (WTP B instead of WTP A). As low pressures were predicted by hydraulic modeling, six additional high-speed pressure data loggers were installed, for a total of 12 pressure sensors in the affected distribution system sub-area.

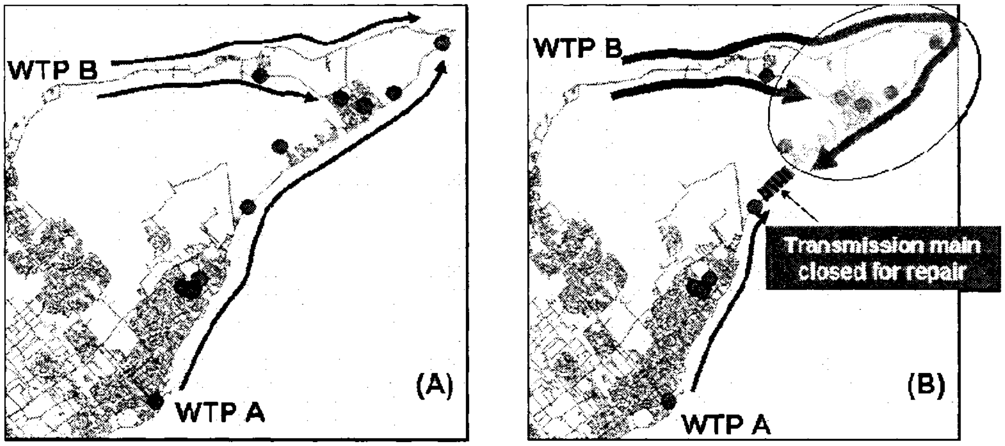

Figure A-1: Distribution system area where continuous pressure monitoring was conducted (pressure loggers are the red dots); (A) Flow conditions under normal system operation; (B) Flow conditions under repair conditions (shaded area represents affected sub-area)

Pressure monitoring was conducted using two types of high-speed pressure transient data loggers. The first type is the RDL 1071L/3 model from Radcom Technologies (Woburn, MA) that can read up to 20 pressure values per second within a range of -103 to 1551 kPa (-15 psi to 225 psi). A Radcom logger was installed directly on one transmission main at the outlet of WTP A and on fire hydrants in the distribution system. The other type of recorder used is the HPR31 model from Telog Instruments (Victor, NY). This logger can read up to 4 pressure values per second within a -103 to 1379 kPa (-15 psi to 200 psi) range and was used to monitor pressure on fire hydrants. The Radcom loggers were zeroed to atmospheric pressure according to the manufacturer's instructions before installation on the field while no specific operation was required for the installation of the Telog loggers.

In order to monitor water quality variations during the closure of the transmission main, four online turbidimeters (1720E Low Range Turbidimeter, Hach, Loveland, CO) were used. Three were installed inside buildings owned by the city and one was installed directly on a fire hydrant (with a continuous purge to allow higher flows out of the hydrant). This last setting is illustrated in Figure A-2.

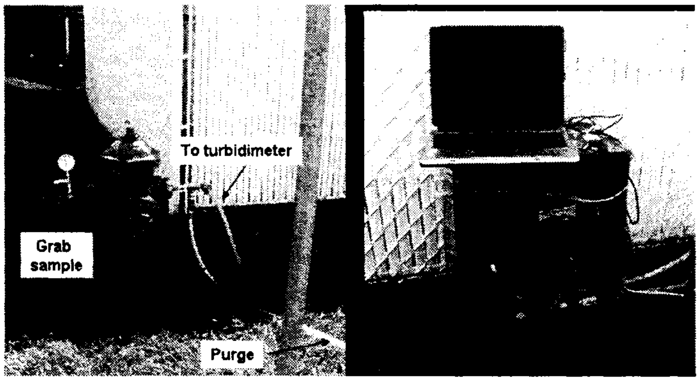

Figure A-2: Hydrant setting used for on-line turbidimeter and grab water samples

Grab samples were also collected at three locations (2 hydrants and 1 routine sampling location) and analyzed for:

- total coliforms and *E. coli* with the Colilert (IDEXX Laboratories) detection method. Instead of the standard 100 ml sample, 1L water samples were used.
- Aerobic endospores (membrane filtration, TSB culture medium, pasteurization at 75°C-15 min, incubation at 35°C-24h), 1L water samples were filtered.
- residual free chlorine, temperature, turbidity and conductivity.

The location of the high-speed transient pressure data loggers, the on-line turbidimeters and the grab sampling are summarized in Figure A-3.

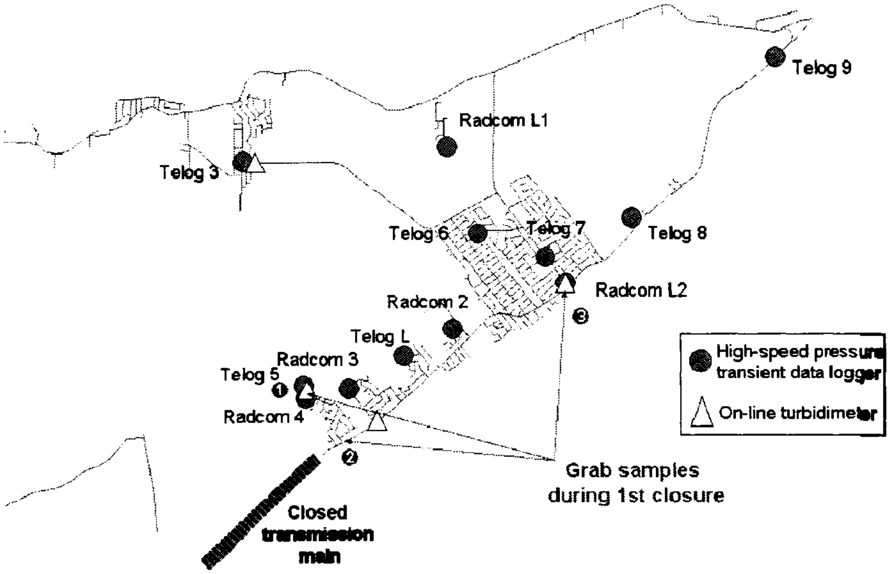

Figure A-3: Location of high-speed transient pressure data loggers, on-line turbidimeters and grab samplings during the 1st transmission main closure.

RESULTS AND DISCUSSION

The initial closure of the transmission main for its repair was performed on August 23 at 23:00 and lasted until 05:40 the following morning. The work was performed at night in order to minimize the impact on the customers and as the demand on the system is lower. The 15,000 customers that were affected by the main closure were put under a preventive boil water order. Because of difficulties encountered during the repair, two successive closures had to be performed. The transmission main was closed from August 24, 23:00 to August 25, 20:00 and again on September 6, from 22:00 to September 8, 15:45. A temporary distribution system was installed consisting of a 200 mm (8 in.) diameter pipe running along the closed transmission main. However, this temporary system was not in place for the 1st closure.

Low and negative pressures

As expected, low pressures were measured in the affected distribution system area during the three closures. Low pressures are considered here as pressure below 138 kPa (20 psi) as it is usually recommended to operate DS at pressure greater than 138 kPa. Negative pressures were also measured for an extensive period of time (Table A-1). The average operating pressure at WTP B was 598 kPa (86.8 psi) during the first closure. This pressure was increased to 625 kPa (90.7 psi) and 647 kPa (93.9 psi) during the 2nd closure but this was not enough to prevent the occurrence of negative pressure in the system.

Table A-1: Duration of low and negative pressures during transmission main repair

	Closure #1		**Closure #2**		**Closure #3**	
	Duration: 6 h 40 min		**Duration: 21 h**		**Duration: 34 h**	
Pressure Logger	**Duration P<20 psi (hh:mm)**	**Duration P<0 psi (hh:mm)**	**Duration P<20 psi (hh:mm)**	**Duration P<0 psi (hh:mm)**	**Duration P<20 psi (hh:mm)**	**Duration P<0 psi (hh:mm)**
Telog 5	00:41	00:13	11:51	00:37	20:49	00:04
Radcom 4	00:41	00:14	11:50	00:14	13:59	00:09
Radcom 3	00:40	00:03	11:00		12:26	
Telog L	00:40	00:01	04:41		11:53	
Radcom 2	00:40		07:54		09:32	
Radcom L2	00:40		06:22		00:00	
Telog 6	00:40		03:07		11:11	
Telog 7	00:39		05:12		07:35	
Telog 8	00:39		04:28		07:16	
Telog 9	00:00		00:21		00:04	
Radcom L1	00:00		00:39		01:27	
Telog 3	00:00		00:21		00:34	
TOTAL (minutes)	**360**	**31**	**4066**	**51**	**5806**	**13**

Two distribution system sites located nearby (Telog 5 and Radcom 4) were particularly affected by the occurrence of negative pressures. These two sites had negative pressures during a total of 91 minutes over the 3 closures (-1 to -28 kPa (-0.2 to -4.1 psi)). These sites were located near the closed transmission main and therefore were the farthest from WTP B. The pressure profiles obtained over the 3 closures at the Telog 5 location are illustrated in Figure A-4.

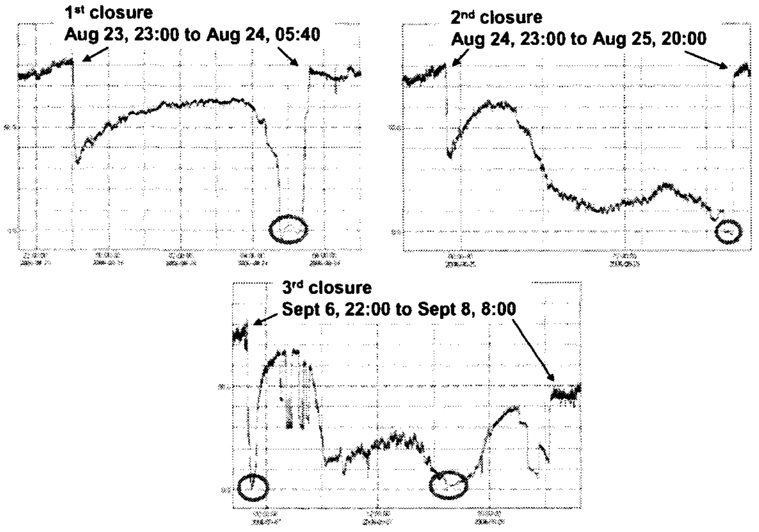

Figure A-4: Pressure profiles at the Telog 5 location

For the first and second closures, the very low and negative pressures were recorded when pipe flushing was conducted before the transmission main was returned to service. For the third closure, negative pressures were recorded 20 minutes after the transmission main was closed and at time of increased water consumption (during the evening peak).

Water quality during first transmission main closure

Detailed water quality monitoring was conducted during the first transmission main closure only. Among the three locations where grab water samples were collected, one was the site #1 (Figure A-3), a fire hydrant that was directly located between the Telog 5 and Radcom 4 locations, a bloc away from each other. These two sites had two periods of negative pressures during the first closure lasting about 6 and 7 minutes each where the flow completely stopped. A total of 11 liters of water were collected at this hydrant over the closure period (before, during and after the closure was performed). For instance, 3 liters of water were collected directly after the 6 and 7 minutes of pressure loss (first flow from the hydrant). Analysis of these samples showed no microbiological contamination (absence of total coliforms and no significant concentration of aerobic endospores (max 1 UFC/L), the two indicators of intrusion that were used). The free chlorine residual after the pressure loss (0.18-0.20 mg/L) was about the same as before the flow was stopped. The water temperature was 21°C.

One on-line turbidimeter was also installed at site #1. The signal obtained showed a peak (max of 2.3 ntu) at the moment of the pressure drop (Figure A-5). This was the maximum turbidity value recorded by the four on-line turbidimeters during the 1st closure. However, it was found very difficult to interpret the turbidity measurements as a signal of potential intrusion into the system. This type of on-line equipment is very sensitive to inflow and usually has to operate within a 200-750 ml/min range. When the inflow stops because of pressure reduction or total loss, turbidity values are still recorded because there is still water into the turbidimeter body. When the pressure is restored and flow is restarted, an increase in turbidity is automatically recorded. Consequently, it is difficult to differentiate a potential turbidity peak that would be related to an intrusion from one due to the equipment operation.

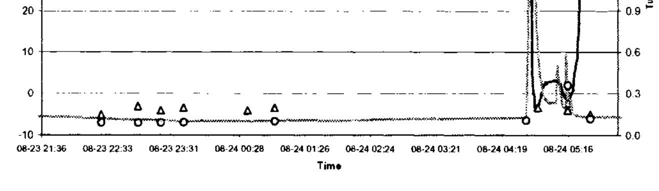

Figure A-5: Pressure and water quality at DS site #1 during first transmission main closure

Out of a total of 34 liters of water analyzed for total coliforms/*E. coli*/aerobic endospores at the 3 distribution system sites where grab samples were collected, only one sample was positive for total coliforms. This sample was collected at site #2, 30 hours after the end of the first closure but still in the middle of the second closure, with a free chlorine residual below the detection level. This site is located directly downstream of the repaired transmission main. During the first closure, this site was characterized by a gradual loss of free chlorine over time (0.86 down to 0.57 mg/L) and a rapid drop to 0.12 mg/L when the transmission main was reopened.

During the period of closures (Aug 23-Sept 8), the conductivity values at WTP B (range 163-177 μS) were significantly higher than at WTP A (range 126-132 μS). While the conductivity measurements at sites #1 and #2 during the 1st transmission main closure were in the same range as those of WTP A, an increase in the conductivity values at site #3 (from 133 to 176 μS) was measured when the transmission main was being flushed at the end of the repair. This indicates that the increase in demand caused by the opening of hydrants to flush the main resulted in the supply by WTP B of the area where site #3 is located.

In the afternoon of August 24, while the transmission main was opened since 5:30 am, a major turbidity peak was recorded at site #1. This peak lasted for about 6 hours (from 12:00 to 18:00) and reached a maximum value of 8.2 ntu at about 15:00. While no other water quality measurements are available at this site during that time, the utility collected nine water samples on August 24 for analysis of total coliforms in the whole area affected and no sample was found positive. Overall, the utility collected 55 water samples during the 3 closures period and no coliforms were detected.

CONCLUSIONS

The closure and repair of a transmission main was found to be the cause of significant and sustained negative pressures in the distribution system under study. However one of the main challenges is to link these negative pressures with intrusion and changes in water quality.

The results obtained regarding water quality point to minimal contamination during this major widely spread negative pressure event related to the transmission main repair. Microbiological analyses of water samples did not reveal significant water contamination. Out of a total of 34 (1L) samples collected by the research team (among which 3 samples were collected right after negative pressure events) and 55 (100 mL) samples collected by the water utility, only one sample was found positive for total coliforms.

However our conclusions may reflect:

- the specific conditions of the distribution system investigated. Negative pressures were recorded in a residential neighborhood supplied by relatively new ductile iron pipes (mostly installed between 1990 and 1995) and where the risk of cross-connection was relatively low.
- the inability to detect contamination in chlorinated systems with the analytical methods used.

This planned transmission main repair represented a unique opportunity for sampling water during a low/negative pressure event in a full-scale distribution system. However, the conclusions cannot be extended to all systems. More field investigations using advanced monitoring approaches and refined detection methods are needed to assess different distribution system conditions.