Chapter 7 Drinking Water Distribution Systems

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Chapter 7 Drinking Water Distribution Systems

7.1 Introduction

The distribution system is the final barrier before delivery to the consumer's tap. Even when the water leaving the treatment plant is of the highest quality, if precautions are not taken its quality can seriously deteriorate. In extreme cases, dangerous contamination can occur.

Distribution systems are composed of watermains, valves, hydrants, service lines, and storage facilities. This infrastructure is expensive but long-lived. Because it is largely out of sight, distribution infrastructure tends not to be a top priority in the management and financing of water systems. But as populations shift and pipes corrode, substantial ongoing investments are necessary.

This chapter is essentially descriptive and includes only two formal recommendations. It describes the various threats to the integrity of distribution systems and discusses practices relating to their construction, repair, and maintenance. In this discussion, I have tried to summarize the best current thinking on both topics, in the hope that this will assist water system owners, operators, and regulators.

7.2 The High-Quality Distribution System

A high-quality distribution system is reliable, providing a continuous supply of potable water at adequate pressure. Reservoirs within the system balance pressure and cope with peak demands, fire protection, and other emergencies without causing undue water retention, while looped watermains prevent stagnation and minimize customer inconvenience during repairs. Since water quality declines with the length of time the water remains in the system, and the rate of decline depends partly on the attributes of the distribution system, a high-quality system has as few dead ends as possible and maintains adequate flow and turnover.

A well-maintained distribution system is a critical component of a safe drinking water system. It is essential that water providers have adequate financing mechanisms in place so that their distribution systems can be properly maintained and renewed. In Chapter 10 of this report, I recommend that every municipal water provider should produce a sustainable asset management plan as part of its comprehensive financial plan. The sustainable asset management plan should include, at a minimum, an accurate characterization of all parts of the system by age, size, location, materials, maintenance history, scheduled repairs, planned capital maintenance, refurbishment, and replacement. The design of system extensions should take advantage of opportunities to optimize hydraulic characteristics and eliminate dead water.

In a well-managed system, routine maintenance and system extensions are adequately financed to minimize costs and reduce risks to public health over the asset's lifetime. Routine maintenance includes flushing, cleaning, valve exercising, and inspection.[1] Less frequent maintenance might include mechanical scraping, pigging, swabbing, chemical cleaning, or flow jetting.[2] Capital maintenance might include relining pipes, replacing valves, and repairing pumps. All maintenance is programmed through a computerized asset management system for best efficiency.

The continuous monitoring of water quality, hydraulics, and system condition is undertaken with up-to-date Supervisory Control and Data Acquisition (SCADA) systems. Data are centrally archived and used for infrastructure management. Computer models of the distribution system allow informed decisions to be made about priorities for replacement or rehabilitation. Emergency procedures are documented, and standby power is provided.

Backflow preventers stop the inflow of contaminants from cross-connections, dead ends,[3] and pipe breaks, and all customers are metered. Although meters must be replaced periodically,[4] their mere presence has been shown to reduce water demand by as much as 15% to 20%,[5] thus reducing the size and cost of distribution systems.

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[1] E. Doyle, 2002, "Production and distribution of drinking water," Walkerton Inquiry Commissioned Paper 8, p. 76.

[2] G.J. Kirmeyer et al., 2001, "Practical guidelines for maintaining distribution system water quality," *Journal of the American Water Works Association*, vol. 93, no. 7, pp. 62–73.

[3] A special case is fire sprinkler systems, whose stagnant waters may accumulate heavy metals: S.J. Duranceau et al., 1999, "Wet-pipe fire sprinklers and water quality," *Journal of the American Water Works Association,* vol. 91, no. 7, pp. 78–90.

[4] Perhaps every 30 years for brass meters and every 15 years for plastic: M.D. Yee, 1999, "Economic analysis for replacing residential meters," *Journal of the American Water Works Association*, vol. 91, no. 7, pp. 72–77.

[5] D.M. Tate, 1990, *Water Demand Management in Canada: A State of the Art Review*, Social Science Series 23 (Ottawa: Environment Canada, Inland Waters Directorate).

7.3 Threats to System Integrity

Physical, biological, and chemical changes gradually occur as water is transported through the distribution system.[6] The causes for such changes vary; some can be prevented through changes in treatment or operating procedures, whereas changes that result from the age and quality of the infrastructure may require large capital investments.

7.3.1 Pipe Age

As pipes age, they become prone to leaks and breaks as a result of bedding failure, corrosion, the development of capacity-limiting scale or biofilm, and subtle changes in the pipe's chemical or physical properties. Coatings and cathodic protection can assist in coping with corrosive water, stray ground currents, or acidic ground conditions, but entropy always wins in the end.

Frost, traffic vibrations, the erosion of supporting ground materials, and even Ontario's mild earth tremors can cause pipes that have become weakened by age to fail. Unattended leaks may allow incursions of contaminants and result in the loss of treated water. Moreover, leaks undermine supporting ground materials, thus creating a potential for further failure of the pipes.[7]

In addition, as part of their comprehensive distribution system program, water providers should have active programs, working together with building inspectors and public health agencies, to detect and deter cross-contamination. The primary program responsibility should lie with the provider, which should develop a risk-based schedule of visits to sites that are known to pose threats. Such sites include industrial operations, car washes, interconnecting cisterns, hospitals, clinics, funeral homes, and meat and food packing plants.

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[6] M.-C. Besner et al., 2001, "Understanding distribution system water quality," *Journal of the American Water Works Association*, vol. 93, no. 7, pp. 101–114.

[7] Finding leaks is not as difficult as it might seem. A variety of non-intrusive methods are available for doing so, including "listening" to and triangulating on the sound of leaking water. See A.N. Tafuri, 2000, "Locating leaks with acoustic technology," *Journal of the American Water Works Association*, vol. 92, no. 7, pp. 57–66; J. Makar and N. Chagnon, 1999, "Inspecting systems for leaks, pits and corrosion," *Journal of the American Water Works Association*, vol. 91, no. 7, pp. 36–46; and O. Hunaidi et al., 2000, "Detecting leaks in plastic pipes," *Journal of the American Water Works Association*, vol. 92, no. 2, pp. 82–94.

Distribution systems should have regularly tested backflow prevention valves that can prevent or at least isolate incursions. Pressure should always be higher than ambient, and distribution systems should have pressure-monitoring equipment that can detect fluctuations or drops in pressure and alert the operator when they occur.

Infrastructure is also vulnerable to amateur cross-connections and their attendant risks of contamination. It is common in areas of Ontario that depend on hard groundwater for households to use roof-fed cisterns. Such water can contain bird and rodent fecal matter as well as air-deposited contaminants. If, as frequently happens, the householder connects this supply to the household service without installing functional check valves or other backflow-preventing devices, the communal distribution system can become contaminated.[8]

As I point out in Chapter 13 of this report, the *Safe Drinking Water Act* should expressly allow for the inspection of private premises by the water provider, for emergency disconnection in the event of a public health threat, and for the refusal of service if a customer or property owner does not address the problem.

The expensive replacement of aging infrastructure can be deferred, often for many years, if repairs and rehabilitation are performed before systems deteriorate too far. Asset management planning to monitor infrastructure age and condition allows the scheduling of rehabilitation projects in advance. Sustainable asset management in relation to municipal water systems is discussed in more detail in Chapter 10 of this report.

7.3.2 Materials

Recommendation 34: The provincial government should encourage the federal government, working with the Standards Council of Canada and with advice from municipalities, the water industry, and other stakeholders, to develop standards for materials, including piping, valves, storage tanks, and bulk chemicals, that come into contact with drinking water.

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[8] This risk is critical to system integrity: seven of the 12 largest water-borne disease outbreaks caused by distribution system contamination in the United States between 1971 and 1998 were caused by cross-connections. See G.F. Craun and R.L. Calderon, 2001, "Waterborne disease outbreaks caused by distribution system deficiencies," *Journal of the American Water Works Association*, vol. 93, no. 9, Table 5, p. 69.

Standards for materials used in water systems are necessary to guard against untested materials that provide a pathway for, or a source of, contaminants. There is no need to await a comprehensive federal law regarding materials that come into contact with all products ingested by humans. Matters specific to drinking water can be dealt with through existing mechanisms. Several major industry associations are already active in this regard. Only where existing standards fall short should effort be devoted to creating a "made in Ontario" standard.

These standards should be incorporated into building and plumbing codes as appropriate and into Certificates of Approval for new or upgraded facilities. Because the federal government has a considerable research establishment working on these topics, it makes little sense to duplicate their efforts at the provincial level, though this of course should not preclude a cooperative approach, with specific laboratories undertaking work for the benefit of all where they have established capability. Work done by Health Canada and the National Research Council (NRC) for the abandoned Bill C-76/C-14[9] should be brought forward and made part of the NRC's advisory work on building and plumbing codes, which provide an efficient and well-understood method for putting the results into practice.

Typical considerations when selecting piping material include corrosion resistance, internal surface roughness, compatibility with existing materials, susceptibility to chemical leaching or biofilm growth, cost, and use. Materials suitable for transmission may be weakened if tapped for service delivery. Mains tend to be made of cast iron or ductile iron. Occasionally they are made of wrapped steel or, in recent years, plastic. Service lines into homes are often zinc-coated iron (which may react galvanically with brass, bronze, or copper fittings), copper tubing, or in some older systems, lead pipe.

Recommendation 35: As part of an asset management program, lead service lines should be located and replaced over time with safer materials.

Human exposure to lead, especially where children are involved, has been a public health concern for several decades. The most important sources of lead used to be lead-based paint and leaded gasoline. However, lead was also frequently used in the service lines that connect homes with water mains and

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[9] *Drinking Water Materials Safety Act*, introduced as Bill C-76 in House of Commons on December 11, 1996. Reintroduced as Bill C-14 on October 30, 1997.

in the solder used in copper plumbing. As a result, in Canada, municipalities have been phasing lead materials out of drinking water systems for a decade, and tin solder is now generally used in plumbing. Ontario's building code requires a lead content of less than 0.2% for plumbing solder used in water systems. Ontario Regulation 459/00 establishes an upper limit for lead in drinking water of 0.01 mg/L at the point of consumption. If higher levels remain after pipes have been flushed, the municipality is required to replace any lead service lines into a house. The risks are posed by a combination of lead piping and the corrosiveness of water: soft water poses a higher risk than does scale-forming hard water.

The presence of lead in drinking water is a significant health risk because even minute quantities are believed to cause neurological problems in infants and children. The U.S. Environmental Protection Agency estimates that, on average, lead in drinking water accounts for approximately 20% of all human exposure to lead.[10] In the United States, lead-free solder and piping have been required since 1986, and the 1991 Lead and Copper Rule (LCR), revised in 2000, requires the phased replacement of existing lead pipes.[11] The LCR establishes action levels (i.e., maximum limits that, if exceeded, require corrective action to be taken) of 0.015 mg/L for lead and 1.3 mg/L for copper. Maximum Contaminant Level Goals (the standard that will eventually apply in the United States when old lead pipes have all been replaced) are 0 mg/L for lead and 1.3 mg/L for copper. Techniques for addressing concerns about lead and copper include minimizing corrosion in pipes, treating source water where appropriate, investing in public education, and replacing lead service lines if levels in water exceed the action level.[12] People should be informed if the buildings they live or work in are suspected of being serviced by lead pipes so that they can check their end of the line for lead pipe as well.

7.3.3 System Design

The design of the water distribution system, including the size of the pipes, also affects integrity. The larger the diameter of the pipe, the greater the ratio

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[10] U.S. Environmental Protection Agency, Office of Water, 2001, *Lead and Copper* <www.epa.gov/safewater/leadcop.html> [accessed May 2, 2002].

[11] G.R. Boyd et al., 2001, "Selecting lead pipe rehabilitation and replacement technologies," *Journal of the American Water Works Association*, vol. 93, no. 7, p. 75.

[12] U.S. Environmental Protection Agency, Office of Water, 1999, *Lead and Copper Rule Minor Revisions: Fact Sheet* <www.epa.gov/safewater/standard/leadfs.html> [accessed May 2, 2002].

between volume and surface area and thus the less contact between pipe material and water. But having larger-diameter pipes also slows water flow, thus increasing the risk of stagnation. The system's three-dimensional layout (e.g., the number and length of branches, slopes, curves, and so on) also affects the flow and thus influences hydraulic properties.[13] Designers must clearly balance many factors to obtain optimal performance. This task is complicated by the ever-changing size of the system and the demands placed on it.

Some elements of design are constant, however. The water distribution system should always be under a minimum of 20 psi (138 kPa) pressure[14] to prevent incursions at cracks or joints. Good pressure is facilitated by maintaining relatively constant flow rates, which also reduces pipe scouring. Curves should be minimized, with thrust restraint (usually a mass of concrete) provided where abrupt changes of direction are unavoidable. Pipes should be below the frost line, now and decades from now. High points should be equipped with air relief valves. Dead ends should be minimized, but where they are unavoidable, they should be equipped with blow-off valves for line flushing. Capacity (and hydrant spacing) should be sufficient for fire suppression, but should not lower water turnover to an extent that imperils the water's quality for drinking.

Valves are critically important components of the water delivery system and therefore need proper maintenance to avoid expensive and dangerous situations.[15] When they are working correctly, valves allow the measurement and management of water flows and the locating of leaks. Backflow preventers keep contaminants isolated. But valves can and do malfunction, often as a result of underuse. Scale, biofilm, and corrosion products occlude them. Valves that are stuck shut, broken, or not operating properly – a common problem where they are not exercised frequently – may force water to travel much farther than necessary, reducing pressure and increasing retention times.

Low pressure is particularly problematic during the peak demands caused by firefighting. Even under ordinary demand conditions, extra power may be necessary for pumping. Sometimes the hydraulic conditions in the system can lead to transient zones where pressure is lower than that in the atmosphere, with the result that pollutants are actively sucked in. In extreme cases, such

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[13] Besner et al., pp. 101–113.

[14] Kirmeyer et al., p. 66.

[15] B. Gauley, 2000, "Valve maintenance an important 'best management practice,'" *Ontario Pipeline*, April, p. 8.

conditions can cause pipes to buckle or collapse.[16] Three-dimensional hydraulic models of a particular system can aid in identifying problems and help to maintain proper hydraulic conditions within the system.

7.3.4 Storage

Treated water is often stored in reservoirs or standpipes (water towers) before delivery. This approach may have both public health and economic advantages in allowing for treatment system optimization independent of short-term fluctuations in demand. It may also improve contact times for chemical disinfection. Although distribution system pressure is readily maintained through the use of elevated or pressurized reservoirs, the reservoir materials must not give rise to or allow contamination, reservoirs must be covered and inaccessible to the public, and retention times must not be overly long.

7.3.5 Corrosion

Most mains in Ontario are made of cast or ductile iron or, less frequently, steel. Consequently, corrosion is the most common problem in distribution systems. In addition to weakening pipe walls, corrosion can lead to the development of large tubercles (collections of material that may include scale, algae, and bacteria) inside the pipes, reducing water capacity and water pressure, which in turn increases residence times (the amount of time the water stays in the pipes) and reinforces corrosion. Meanwhile, the aesthetic quality of the water can be reduced through the release of soluble or particulate corrosion by-products. In systems using hard water, this is especially the case with new pipes, before a protective layer of scale builds up on the interior surfaces. Corrosion does not necessarily affect the safety of drinking water directly, but it will reduce the life of the pipes and, in older pipes, increase the probability of leaks, breaks, and contamination.

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[16] A.T.K. Fok, for Environmental Hydraulics Group Inc., 2002, Walkerton Inquiry Submission.

7.3.6 Scale

Scale is usually composed of carbonate precipitates that form on pipe walls. Over time, scale will reduce flow volumes and increase headloss. Its presence, and the inclusions within it, can affect corrosion rates.

7.3.7 Sedimentation

When water is moving slowly through a pipe, particles suspended in the water may settle out into the pipe. The accumulated sediment reduces the pipe's capacity. This problem is most common in source water pipes that are situated upstream of a treatment plant, because proper treatment eliminates suspended particles. But if the water has not been treated properly, allowing excess turbidity in product water, sedimentation may also occur in the distribution system. However, even slight overtreatment of water can result in post-treatment precipitation. Thus, overdosing the water with flocculant chemicals can have the same effect as underdosing it.[17]

7.3.8 Biological Growth

Information on water retention time in every part of the storage and distribution system needs to be developed and used to schedule additional flushing in slow-flow areas in order to slow biofilm development.

Biofilm results from the growth of bacteria that can thrive in water distribution systems. Decaying algae from algal growth in insufficiently filtered surface waters is one of many possible sources of dissolved organic matter that may provide a good food source for bacterial growth. Anaerobic groundwater containing soluble iron and sulphur is a food source for two bacterial species that cause a number of aesthetic problems involving odour.[18]

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[17] American Water Works Association, 2001, *Rehabilitation of Water Mains: Manual of Water Supply Practices, Manual M28*, 2nd ed. (Denver: AWWA), p. 1.

[18] G.C. White, 1999, *Handbook of Chlorination and Alternative Disinfectants*, 4th ed. (New York: Wiley), pp. 447–451.

Bacteria adhere to pipe walls, and their metabolic products both increase adhesion and protect the bacteria from the residual disinfectant.[19] Their biological activity can increase corrosion.[20] Further, bacteria that are adapted to low-nutrient conditions, such as can occur in distribution systems, are less susceptible to disinfectants. Once they are established, they are all but impossible to eradicate through the use of chlorine or chloramines.[21]

The regrowth of bacteria may be affected by time, temperature, sediments, and the materials used in the system. There is a direct threat to people from pathogens, and indirect threats from likely interference with coliform detection and even from the transfer of antibiotic resistance factors to pathogenic bacteria.[22]

Coliform biofilms can grow or regrow in distribution systems.[23] Age, low disinfectant residuals, warm temperatures, relatively high levels of total organic carbon, old iron pipe, and the insufficient flushing of dead ends all contribute to the growth of biofilms, sometimes to the point where bacteria, including coliforms, are released into the water. Biofilm may support the regrowth of virulent bacteria if treatment failure has occurred at the plant.[24] There are a number of methods for preventing, slowing the growth of, and removing biofilms. Control requires an ongoing, multi-faceted effort that includes monitoring, maintenance, water treatment, and management,[25] and it is not guaranteed by the use of a disinfectant residual alone.[26]

There appear to be limits to the efficacy of chlorine as a guarantor of system integrity.[27] In some ways, it may be regarded as little more than an indirect indicator; rapid changes in its measured value are a signal that something is wrong and that an investigation is required.

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[19] American Water Works Association, 1999, *Waterborne Pathogens Manual, Manual M48* (Denver: AWWA).

[20] White, pp. 451–452.

[21] American Water Works Association, 1999.

[22] L. Evison and N. Sunna, 2001, "Microbial regrowth in household water storage tanks," *Journal of the American Water Works Association*, vol. 93, no. 9, pp. 85–94.

[23] White, pp. 461–462.

[24] P. Payment, 1999, "Poor efficacy of residual chlorine disinfectant in drinking water to inactivate waterborne pathogens in distribution systems," *Canadian Journal of Microbiology*, vol. 45, pp. 709–715.

[25] Kirmeyer et al., p. 68.

[26] R.R. Trussell, 1999, "Safeguarding distribution system integrity," *Journal of the American Water Works Association*, vol. 91, no. 1, pp. 46–54.

[27] Payment, pp. 712–715.

7.3.9 Bulk Water Reactions

Chemical reactions can occur in water as it travels through a distribution system. The longer its residence time in the system, the greater the probability that a variety of reactions will occur. Some reactions – such as the inactivation of micro-organisms by the disinfectant residual – are desirable. Others are not so helpful and can make the water aesthetically displeasing or detrimental to health. The key to avoiding risk is high-quality treatment that ensures the release of chemically stable water into the distribution system. A group of chemical reactions currently at the forefront of research are those that produce disinfection by-products (DBPs: see Chapter 6 of this report). These chemicals, chiefly trihalomethanes and haloacetic acids, may be carcinogenic if consumed over a long period of time. In the concentrations found in drinking water, the risk of becoming ill as a result of consuming DBPs is relatively small – much smaller than the risk from pathogens – but not zero. Minimizing their occurrence in a way that remains consistent with adequate disinfection should be an objective of treatment and distribution system management. DBPs are produced principally through reactions between organic matter and disinfectants, including chlorine, chlorine dioxide, and ozone. Reducing total organic carbon (TOC) in treatment through filtration – biological, granular activated carbon, ultra-, or nano-filtration – is key, as is removing TOC-containing sediment from distribution systems.

As with other aspects of distribution system management, water quality changes with age – both the system's age and the water's age (i.e., its residence time). In New Jersey, research showed that "[d]ifferent by-products responded differently to increasing time in the system."[28] The reactions proceeded more rapidly in warmer months. A study of the Laval, Québec, system demonstrated that the fate of both chlorine and dissolved organic halogens was related to the presence of corrosion by-products, the residence time of the water, and the presence of microbial biomass.[29]

Continuous disinfection should be attained by using only as much chlorine as is necessary.[30] Changing the primary disinfectant from free chlorine to ozone

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[28] W.J. Chen and C.P. Weisel, 1998, "Halogenated DBP concentrations in a distribution system," *Journal of the American Water Works Association*, vol. 90, no. 4, p. 151.

[29] H. Baribeau et al., 2001, "Changes in chlorine and DOX concentrations in distribution systems," *Journal of the American Water Works Association*, vol. 93, no. 12, pp. 102–114.

[30] For some systems based on groundwater of known purity, a chlorine residual may be dispensed with altogether in certain jurisdictions (e.g., the Netherlands and Germany). See B. Hambsch,

or chlorine dioxide can help, as can converting the secondary disinfectant from chlorine to chloramines. Removing TOC during treatment is the optimal approach: it minimizes the consumption of disinfectant in the distribution system by contaminants other than microbes, thus allowing lower initial dosage and possibly avoiding the need for disinfectant top-up later.[31]

7.4 Good Practices in System Operation

A large and rich literature deals with good practices in system operation and maintenance.[32] Drawing together much of what has been said above, good practices in system design, operation, and maintenance include the following:

- Design the system so that it is not so large that slow turnover and high retention times degrade water quality.[33] Distribution systems can be problematic at either end of the size continuum – they can be too small to accommodate fire emergencies or too large to guarantee safe water. Overbuilding a distribution system (i.e., making it too large) can have consequences for both water quality and cost.[34]

- Make regular systematic flushing, with particular attention to dead ends and static zones, part of every maintenance program.

1999, "Distributing groundwater without a disinfectant residual," *Journal of the American Water Works Association*, vol. 91, no. 1, pp. 81–85; D. van der Kooij et al., 1999, "Maintaining quality without a disinfectant residual," *Journal of the American Water Works Association*, vol. 91, no. 1, pp. 55–64; and O. Hydes, 1999, "European regulations on residual disinfection," *Journal of the American Water Works Association*, vol. 91, no. 1, pp. 70–74.

[31] Kirmeyer et al., pp. 66–68.

[32] See, for example, HDR Engineering, pp. 680–741; and the special issue of the *Journal of the American Water Works Association* (vol. 93, no. 7) on distribution systems. Infrastructure Canada, the Federation of Canadian Municipalities, and the National Research Council are collaborating on a guide that will be a "compendium of technical best practices for decision making and investment planning as well as for the construction, maintenance and repair of municipal infrastructure," which is intended to be published in groups of 20 best practices a year for the next five years: see Canada, Treasury Board Secretariat, 2000, *Government of Canada Funds the National Guide to Sustainable Municipal Infrastructures: Innovations and Best Practices* <www.tbs-sct.gc.ca/news2000/1208_e.html> [accessed May 2, 2002].

[33] G. Burlingame, 2001, "A balancing act: Distribution water quality and operations," *Opflow*, vol. 27, no. 7, pp. 14–15.

[34] Strategic Alternatives et al., 2002, "Financing water infrastructure," Walkerton Inquiry Commissioned Paper 16, s. 5.1.

- Operate the system at a steady rate (except during emergencies) that allows for treatment optimization and the minimization of DBPs while maintaining the flexibility to cope with unexpected demand.

- Monitor water flow and basic measures of quality (disinfectant residual, turbidity, and pH, at a minimum) throughout the distribution system on a real-time basis, and adjust flows and treatment to match the changing conditions of demand or system integrity in real time.

- Monitor the condition of the distribution system itself, so that the threats to integrity mentioned above can be managed without threats to public health or excessive loss of water[35] and so that capital repairs and replacement can be scheduled on a rational basis. Timely repair or rehabilitation can often extend the lifetime of infrastructure at modest cost. “Sustainable asset management,” which was recommended by a number of the parties in Part 2 of this Inquiry, is discussed in Chapter 10 of this report. One consequence of this approach is a capacity to work with other utilities to minimize multiple trenching and traffic detours.

- Maintain the network by continually improving techniques for refitting and replacement. New techniques for horizontal drilling, reaming, and pipe lining are available to extend the life of existing pipes.[36]

- Ensure that repair and maintenance crews follow industry-accepted sanitary practices when performing any maintenance activities.

- Maintain computerized models of the system that assist with everything from operational control to optimal capital investment.

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[35] L.M. Buie, 2000, “Accounting for lost water,” *Journal of the American Water Works Association*, vol. 92, no. 7, pp. 67–71.

[36] S.T. Ariaratnam, J.S. Lueke, and E.N. Allouche, 1999, “Utilization of trenchless construction methods by Canadian municipalities,” *Journal of Construction Engineering and Management*, vol. 125, no. 2, pp. 76–86; American Water Works Association, 2001.