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The Economic Benefits of Chlorine Chemistry in Water Treatment in the United States and Canada

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Executive summary

Most households in the United States and Canada benefit from the use of chlorine chemistry when they consume safe drinking water and when properly treated wastewater is returned to the environment. They benefit most generally by avoiding public health risks that would result from the consumption or dissemination of pathogen-containing water that could spread disease, as well as by avoiding all of the personal loss and costs of treating the diseases. These benefits accrue to consumers regardless of the specific technology used in the disinfection process. However, the public benefits specifically from chlorine chemistry in water treatment because it is more cost effective than the use of alternative disinfection techniques. Primary disinfection of drinking water kills or inactivates harmful microorganisms in the treatment plant, while secondary disinfection provides longer-lasting water treatment as the water moves through pipes to the consumer. Only chlorine-based disinfectants provide "residual disinfectant" levels that prevent microbial re-growth and help protect treated water as it journeys from the treatment plant to the tap. The extent of the benefits can be quantified by determining the additional costs that would have to be borne if all of the treatment plants that currently use chlorine chemistry in disinfection substituted alternative technologies, such as disinfection by UV radiation or ozone. UV radiation and ozone have seen increased use for primary disinfection, but these methods are unsuitable for secondary treatment.

We estimate there are approximately 52,500 drinking water and 16,800 wastewater treatment facilities operating in the United States and Canada. The capital requirements to deploy alternative disinfection technologies for existing chlorine-based disinfection in drinking and wastewater treatment plants would be about $48.6 billion. We estimate the breakdown in the incremental capital requirements for treatment plants in the US would amount to $44.9 billion and capital requirement for the plants in Canada would be $3.7 billion. Over 80% of these one-time capital costs would be borne by small and medium sized community water systems serving less than 100,000 people, and nearly 20% of these costs would fall on large systems. The substitution would cost consumers an additional $5.1 billion per year. To break this down further, the substitution costs would increase the outlay for US consumers by $4.7 billion per year and the outlay for Canadian consumers by $0.4 billion per year. These costs are significant compared with the existing infrastructure needs of the nation's drinking water and wastewater utilities. According to the latest surveys, the US Environmental Protection Agency (EPA) estimates that utilities in the US will require an average of $19 billion per year for drinking water capital improvement projects[1] and an average of $15 billion per year for wastewater capital improvement projects[2] over the next 20 years in addition to the nearly $5 billion per year spent to operate them. These estimates assume that, in most cases, the retrofit costs will be reduced by the availability of functional components of the existing plant and infrastructure. Costs are lower for the wastewater treatment system retrofits because there are fewer of them. If consumers were to install and operate the most basic types of point-of-use disinfection systems to protect against recontamination of water supplies that were not protected by residual levels of chlorine, at least an additional $20 billion could be required to purchase and install the systems and then annual operating costs could be at least $5 billion per year.

While alternatives to the use of chlorine chemistry exist for the treatment of drinking water and wastewater, all the alternatives have limitations with respect to either effectiveness against certain pathogens, the ability to provide residual disinfection, or cost. The need to substitute alternative disinfection technologies for the chlorine-based ones currently in use would burden consumers with high costs both to construct and operate the treatment systems that use the substitutes. The greatest increase in costs would fall most heavily on consumers served by the smaller systems.

1 "Drinking Water Infrastructure Needs Survey and Assessment, Fifth Report to Congress," U.S. Environmental Protection Agency, April 2013; Clean Watersheds Needs Survey, EPA, 2008.

2 "Clean Watersheds Needs Survey 2008: Report to Congress," U.S. Environmental Protection Agency, 2014.

Introduction

Chlorine, and compounds that contain chlorine, are the chemicals most widely used to treat both water for human consumption and to treat wastewater prior to discharge. Chlorine chemistry is relied upon in more than 85% of water treatment plants in the United States and Canada.[3] Chlorine is widely accepted in these applications because the technology required for its use is simple, highly reliable, and can be employed in systems that range in size from those serving small communities to those serving the largest metropolitan areas. It is also low in cost, easy to use, and, most importantly, has been shown to be extremely effective in protecting and preserving the public health by destroying the water-borne pathogens that can cause a range of diseases. In addition to being effective in the primary water treatment facility, only chlorine-based disinfectants provide residual disinfectant levels to help protect treated water as it journeys from the treatment plant to the tap. Chlorine-based disinfectants that produce "free chlorine" in water include elemental chlorine gas, sodium hypochlorite, calcium hypochlorite and chlorinated isocyanurates.[4] Chlorine-based alternative disinfectants, which do not produce "free chlorine," are chloramine and chlorine dioxide. Non-chlorine alternative disinfectants include ozone and ultraviolet radiation.

Consumers in the United States and Canada usually take the availability of safe drinking water and the proper treatment of wastewater for granted because the treatment plants that perform these functions operate so reliably and generally are out of the public's eye. Nevertheless, severe public health problems can arise when water is not treated properly. In 1993, one of Milwaukee's two water treatment plants became contaminated with *Cryptosporidium*, a protozoan pathogen that causes dehydration, fever, stomach cramps, and diarrhea. About 403,000 people became ill, and more than 100 people died, making it the largest waterborne outbreak in US history.[5] In another incident, contamination of the water supply in Walkerton, Ontario by *E. coli* in 2000 caused seven deaths, made 2,000 people ill, and imposed costs on the community that amounted to about $45 million. These examples illustrate the importance of protecting the water supply and justify the stringent requirements imposed on the treatment plants by various regulatory authorities to preserve and protect the health of the general public.

Some 40 years ago, the US EPA imposed limits on the maximum allowable concentrations of so-called trihalomethanes (THMs) in the drinking water supplies provided by treatment systems serving more than 10,000 customers. THMs are an example of a larger class of compounds known as disinfection byproducts which are formed when disinfectants applied to drinking water to destroy pathogens react with organic matter that is also present in the water. Additional regulations have been promulgated since that time, strengthening THM limits and extending the application of limits on disinfection byproducts to specific classes of compounds, such as halogenic acetic acids (HAAs), chlorites, and bromates. Similar regulatory approaches have been adopted by Environment Canada and the Canadian provinces. In the US, one result of increasingly stringent limits on disinfection byproducts in drinking water has been a shift from chlorine to chloramine disinfection. Chloramine, produced by combining chlorine and ammonia, produces lower levels of regulated disinfection byproducts. Furthermore, primary treatment practices have changed to use chlorine later in the process, after the removal of organic precursors to disinfection byproducts, reducing levels of disinfection byproducts in finished drinking water.

More recently, concerns about the transportation, storage, and use of large volumes of hazardous materials have served to initiate reviews of water treatment plant technologies and operating practices to minimize these risks. The reviews have resulted in improved operating and management practices.

3 "Committee Report: Disinfection Survey, Part 2 – Alternatives, Experiences, and Future Plans," Journal AWWA, Peer-Reviewed, American Water Works Association, November 2008. See also "Committee Report: Disinfection Survey, Part 1 – Recent Changes, Current Practices, and Water Quality, Journal AWWA, October 2008. This decennial survey is scheduled to be updated in 2017.

4 "Free chlorine" is a combination of hypochlorous acid and hypochlorite ion. These two chemical species form when chlorine gas, sodium hypochlorite, calcium hypochlorite or chlorinated isocyanurate disinfectants are added to water.

5 Centers for Disease Control and Prevention, August 12, 1994, http://www.cdc.gov/mmwr/preview/mmwrhtml/00032242.htm3; William R. Mac Kenzie et al., "A Massive Outbreak in Milwaukee of *Cryptosporidium Infection Transmitted through the Public Water Supply," New England Journal of Medicine, Volume 331:161-167, July 21, 1994.*

In the following sections we discuss the requirements that water treatment facilities must meet to protect the public health and safety, the technology options that are available to them, and the economic benefits of chlorine chemistry to consumers in the United States and Canada.

The treatment of drinking water and wastewater

The technology chosen to treat raw drinking water to produce potable water at a particular site depends on a number of factors, including the quality of the raw water, whether it is drawn from surface or underground sources, the volume of water to be treated, the number of customers served, and the financial and human resources available to the system operator. The process of treating drinking water usually involves raw water storage and sedimentation to remove gross particulates. The process may also entail aeration to oxidize both inorganic and organic constituents and to reduce objectionable odors. The water is typically treated by coagulation and sedimentation to remove most of the contained particulate matter and then may be subjected to a number of additional filtration and other treatment steps to reduce the concentrations of solids and dissolved compounds still further. Hard water, which contains high levels of dissolved minerals, may be treated chemically to soften it by reducing calcium and magnesium contents. The removal of objectionable elements such as iron and manganese is accomplished by chemical treatment to oxidize them. Additional treatment steps may include filtration through beds of sand, membranes, or activated carbon; the addition of fluoride and corrosion inhibitors; and pH adjustment.

These measures can greatly improve the aesthetics of potable water, and careful filtration can reduce the content of pathogens in the water since many of them are associated with the particulate matter that is present. However, even a high degree of pathogen removal by physical means other than nanofiltration may not be sufficient to completely protect the drinking water supply because the remaining pathogen population can reestablish itself quickly. *E. coli*, for example, can double its population within one half hour under favorable circumstances. To prevent re-growth of *E. coli* or other pathogens as the water passes through the distribution system to consumers, complete inactivation is required at the treatment plant followed by maintaining a residual level of disinfectant in the distribution system. Effective inactivation of viral, bacterial, and protozoan pathogens results in a modification to the pathogen's cellular structure or metabolism, causing death or impairment of reproductive capacity. Different disinfection practices may be required to treat the different types of pathogens effectively.

Chemical inactivation of pathogens

Historically, chlorine has been the chemical of choice to disinfect both drinking water and wastewater. It was first used in the United States in 1908, just 25 years after Pasteur's identification of the significance of microbial activity. The normal practice is to mix chlorine gas with the water being treated at sufficient dosage and for a sufficient contact time to destroy the pathogens. The amount of chlorine and contact time required depends on the degree of destruction required, the mixing efficiency, the types and amounts of microorganisms present, and the temperature and pH of the water being treated. Current EPA regulations require that the concentration of viruses in treated water be reduced by a factor of 10,000, which typically requires a dosage-contact time of 4 mg-min/ml for chlorine. In addition to destroying viruses, these conditions also essentially destroy any bacteria present, but would not destroy protozoa to the same degree. Sufficient chlorine is normally added to ensure that the residual chlorine content of the treated water is in the range of 0.1 to less than 1 mg/l (0.1 to <1 ppm), which is sufficient to provide continued or residual disinfection capability.

Chlorine generally is shipped and stored in bulk quantities at large treatment facilities and in cylinders at smaller facilities, but it may also be generated on site by electrolysis of salt solutions. Disinfection using other chlorine-containing compounds is also practiced widely. Compounds, such as chlorine dioxide, sodium hypochlorite, and chloramines, are also efficient and cost effective disinfectants that may be produced on site or purchased as circumstances warrant. Free chlorine-generating hypochlorites function in the same way that elemental chlorine does because the active agent, hypochlorous acid, is the same for both. This acid destroys pathogens by oxidizing viruses and penetrating the cell walls of bacteria and protozoa to disrupt their metabolism. Its effectiveness against protozoa such as *Cryptosporidium* and *Giardia lamblia*, however, is limited.

Chlorine dioxide is more efficacious than chlorine against parasitic pathogens, such as *Cryptosporidium* and *Giardia lamblia*. The disinfectant must be generated on-site, however. Disinfection with chlorine dioxide is only slightly affected by pH, unlike chlorine disinfectants, which are quite pH-dependent. Operating costs of using chlorine dioxide are high compared to chlorine and hypochlorites. Chloramines are less reactive than free chlorine, but they provide extended residual disinfection and lower levels of regulated disinfection byproducts.[6] Chloramine is used almost exclusively as a secondary disinfectant. Its use has increased in recent years due to the EPA's more stringent regulation of disinfection byproducts.

Many water treatment plants use both chlorine and chloramines sequentially, for example, to maximize pathogen destruction efficiency while providing residual disinfection with minimum formation of disinfection byproducts. A different approach is used by anodic oxidation processes. This technology electrolyzes solutions of salt water directly to generate a mixture of hypochlorous acid, chlorine dioxide, and hydrogen peroxide. This mixture has been shown to be quite effective in the destruction of pathogens, including the protozoa *Giardia* and *Cryptosporidium*, while reducing the formation of disinfection byproducts and providing the continued protection of residual disinfection.[7]

Chlorine and chlorine-containing compounds are used to treat the effluents from wastewater treatment plants in a similar way in order to prevent the introduction of pathogens into the water bodies that receive the plant discharges. Wastewater treatment plants typically use a sequence of steps to treat the water to remove bulk matter and fine particulates prior to removing the soluble and insoluble materials present. Removal of organic wastes is most commonly achieved by aerobic destruction using an activated sludge process, but other aerobic and anaerobic processes have been used as well. However, these processes may not produce the required degree of destruction of pathogens, so post-treatment disinfection may be required. The most widely used wastewater disinfection technologies involve the use of chlorine, sodium hypochlorite, and UV radiation. In general, the required application rate of chlorine to wastewater is higher than for potable water because the concentration of organics and pathogens to be removed is higher; however, with proper plant design and operation, the treatment is just as effective. When relatively high doses of chlorine are required to destroy the pathogens, it may be necessary to de-chlorinate the treated water prior to its release to meet emission limits. This is usually done by adding small amounts of reagents such as sodium bisulfate, thiosulfate, or sulfur dioxide.

Oxidants other than chlorine can be and are being used to treat drinking water and wastewater. Chemical oxidants such as potassium permanganate are used in small amounts, usually in the initial stages of treatment, to remove iron and manganese rather than as final stage disinfectants. Systems that generate ozone, a powerful oxidant, from air or purified oxygen are used in treatment plants to oxidize iron and manganese, as well as to destroy pathogens in much the same way that chlorine does. It reacts with pathogens more rapidly than chlorine, requires only about one fifth the dosage-contact times, and has been found to be effective against such refractory organisms as *Giardia lamblia*. Disinfection by ozonation is used currently in about 2% of the potable water treatment plants in the United States and Canada, but this technology is not used widely to treat wastewater because more cost effective approaches are available.[8]

Because ozone has short life in treated water before decomposing, it provides no residual disinfection nor does it protect against subsequent recontamination in the water distribution system. Thus, the application of ozone is usually followed by booster disinfection with small amounts of chlorine or chlorine-containing compounds, usually chloramines, in the distribution system. Ozone, like other disinfectants, reacts with organic material present in the water to form disinfection byproducts, although not normally chlorinated ones. Treatment plant operating regulations require that the treated water be monitored for these materials, and some plants reduce

6 "Disinfection Technologies for Potable Water and Wastewater Treatment: Alternatives to Chlorine," Pacific Northwest Laboratories, 1998.

7 "Technology and Cost Document for the Final Groundwater Rule," United States Environmental Protection Agency, October, 2006, section 2, pages 17-18.

8 AWWA, op. cit., November 2008.

their concentration by using additional treatment steps. While another strong oxidant, hydrogen peroxide, has been used as a disinfectant in other applications, it is not used in water treatment because of its higher cost. The peroxone process uses a combination of ozone and peroxide to treat water contaminated with small amounts of pollutants or to improve taste and odor, but this process is not in widespread use because of the higher cost.

Alternative methods for pathogen removal or inactivation

Pathogens may also be removed or destroyed by physical means as well as by chemical processes. Water purification by ultrafiltration, or nanofiltration, is practiced in industrial settings for the production of relatively small amounts of highly purified water from water that is already of reasonably good quality. The pores of nanofilter membranes can have average diameters as small as 10 nanometers, so the membranes act as absolute barriers to microorganisms and even small viruses which are larger than 20 nanometers. However, the treated water must be pre-filtered carefully and the membranes periodically cleaned and disinfected to permit the membrane systems to function at reasonably efficient rates. Under optimum circumstances a nanofilter system containing approximately 20,000 square feet of filter area would be required to provide drinking water to a community of 10,000 people. These systems are complex and operate at high pressure resulting in a high cost to install and operate. They produce very high quality water without the production of disinfection byproducts. However, these systems do not provide residual disinfection.

Other non-chemical technology options include heating water to “pasteurize” it and the use of UV radiation. Pasteurization would be effective and significantly more costly than traditional methods, as would pathogen destruction by the use of ionizing radiation. In addition, the latter might face problems of public acceptance. It has been shown, however, that water-borne pathogens can be destroyed by application of radiation in the ultraviolet range of the spectrum in suitably designed systems. The water must be passed over sources of high intensity UV radiation, typically generated by cylindrical bulbs, and held there for enough time that the radiation disrupts the cellular processes of the organisms. The destruction method involves disruption of the organisms’ RNA and DNA and their ability to reproduce. This approach is highly effective against bacteria when applied at intensities high enough to overcome the organisms’ molecular repair mechanisms. It is less effective against viruses which do not rely on their own DNA for reproduction, but is considered effective against protozoa such as *Cryptosporidium*.

To maintain effectiveness, the allowable contents of dissolved and suspended solids must be limited to insure UV transmittance levels exceeding 50%. Variations of this process in which ozone or hydrogen peroxide are added to the water are even more effective in the inactivation of pathogens and removal of other contaminants, but these methods are considered too expensive for normal use.[9] Currently, about 2% of the drinking water treatment plants in the United States and Canada use UV disinfection. Historically this technology was more commonly deployed in small systems.[10] In 2013, however, New York City began using UV radiation to disinfect up to 2,000 million gallons of drinking water per day delivered by pipe from the Kensico Reservoir in upstate New York; and, in 2014, Los Angeles commissioned a new UV water treatment plant in Sylmar, California that has a design capacity of 600 million gallons of drinking water per day. Ultraviolet radiation technology is used in more than a third of the wastewater treatment plants in the United States and Canada, as well as for water purification in small industrial and commercial establishments. Small UV systems are available to homeowners whose water supply must be disinfected at the point of use. This process does not produce disinfection byproducts at levels of concern, but it does not provide residual disinfection benefits, and chlorine or a chlorine-containing disinfectant is always used in conjunction with UV in drinking water disinfection.

9 Journal of Environmental Science, Vol. 1, 2002, p 247.

10 AWWA, op. cit., November 2008.

Cost effectiveness of different technologies

Efficient and cost effective disinfection of drinking water and wastewater to protect the public health and safety requires a high degree of removal of dangerous pathogens. Current practices using various treatment options are straightforward and reliable. Disinfection may be carried out by chemical means using elemental chlorine, chlorine-containing compounds, or ozone, or by physical means using UV radiation or nanofiltration. All the chemical and physical disinfection processes described above have limitations with respect to effectiveness against certain types of pathogens, cost, ease of operation, or possible environmental or health impacts by the creation of disinfection byproducts. Nevertheless, use of chlorine chemistry has been demonstrated to be a reliable and cost effective approach to water disinfection, and it is by far the method preferred in the United States and Canada. Furthermore, only chlorine-base disinfectants provide "residual disinfectant" levels that prevent microbial re-growth and adverse health effects as the water moves through the distribution system to the consumer. Estimates of the capital requirements and operating costs for drinking water treatment systems using these technologies are shown in the table and chart.

Estimated cost of drinking water disinfection technologies

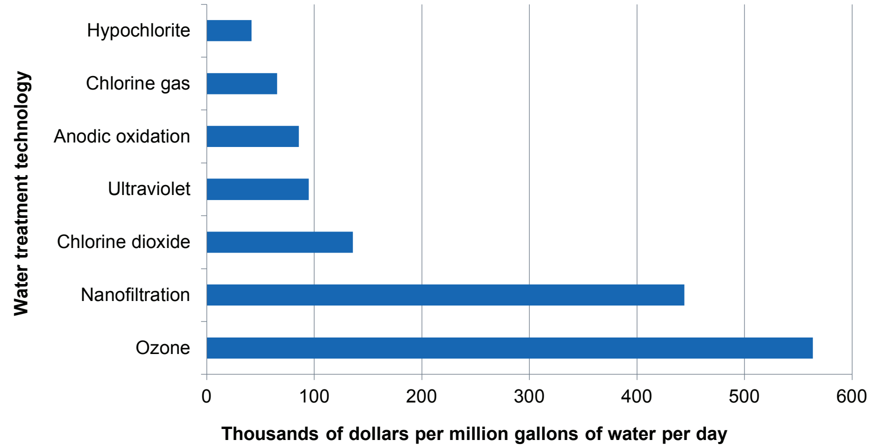
Disinfectant	Treatment plant size*	Investment ('000 $)	Operating costs ('000 $ per year)
Chlorine	Small	110	11
	Medium	1,250	40
	Large	8,500	270
Hypochlorite	Small	65	7
	Medium	500	56
	Large	1,950	720
Chlorine dioxide	Small	60	23
	Medium	330	47
	Large	890	200
Anodic oxidation mixture	Small	250	14
	Medium	2,670	92
	Large	12,600	860
Ultraviolet	Small	460	15
	Medium	3,220	54
	Large	12,200	140
Ozone	Small	770	93
	Medium	4,470	470
	Large	24,600	5,100
Nanofiltration	Small	710	74
	Medium	13,900	1,600
	Large	109,000	18,000

* Small plants serve populations of less than 10,000 people; medium sized plants serve populations between 10,000 and 100,000; large plants serve populations greater than 100,000. These costs are averages for sizes within each range. They have been escalated to 2014 values using the Chemical Engineering Plant Cost Index for investment, BLS producer price indices for chemical manufacturing and employment costs, and EIA data for electricity costs.

Source: "Technology and Cost Document for the Final Groundwater Rule," United States Environmental Protection Agency, October, 2006, and "Treatment Alternatives for Compliance with the Stage 2 D/DDPBR: An Economic Update", A. J. Roy, AWWA Journal, March 2010, p 44

The annual cost of chlorine-based disinfection technologies for small water treatment systems varies greatly. Over 90% of the water treatment systems in North America are small – each serving a population of less than 10,000. It is significantly more costly per unit of water treated to construct and operate treatment plants for small communities than for medium sized or larger ones, and the costs of disinfection using chlorine chemistry are significantly lower for plants in all size categories than for other technologies, except for UV.

Estimated annual cost of constructing and operating small water treatment systems, 2014



Notes: The annual cost is the sum of estimated cash operating expenses plus an allowance for the cost of capital.
Source: IHS
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The benefits of chlorine chemistry in water treatment

Nearly every household in the United States and Canada benefits from the use of chlorine chemistry when they consume safe drinking water and when properly treated wastewater is returned to the environment. They benefit most generally by avoiding public health risks that would result from the consumption or dissemination of pathogen-containing water that could spread disease, as well as by avoiding the personal loss and costs of treating those diseases. These general benefits accrue to consumers regardless of the specific technology used in the disinfection process. However, the public benefits specifically from chlorine chemistry in water treatment because it is more cost effective than the use of alternative disinfection techniques. The extent of the benefits can be quantified by determining the additional costs that would have to be borne if all of the treatment plants that currently use chlorine chemistry in disinfection were substituted alternative technologies, such as disinfection by ozone or UV radiation.

The total number of drinking water treatment systems in the United States and Canada is more than 52,500. More than 90% of them are small, serving less than 10,000 customers, about 8.5% are midsized, and slightly more than 1% are large, serving more than 100,000 customers. Nearly 75% of the community water systems rely primarily on ground water and 9% rely primarily on surface water. The remaining 18% purchase finished, partially treated, or untreated water. Between 2% and 3% of systems disinfect with UV, while less than 2 % of systems disinfect with ozone and almost all of those treat surface water. The remaining 95% of systems use chlorine, chlorine dioxide and other chlorine-containing compounds to disinfect both surface and ground water.[11]

The total number of wastewater treatment facilities in the United States and Canada is about 16,800, and more than 20% of them serve customers from mid- and large-sized communities that have municipal wastewater treatment systems. About 63% of these facilities use chlorine chemistry for disinfection. UV disinfection is used in about 36% of the systems and less than 1% use ozone or other oxidants. Many of the systems that use chlorine chemistry for disinfection de-chlorinate the treated water to remove residual chlorine prior to discharge into sensitive aquatic waters.

In the absence of chlorine chemistry for primary disinfection, essentially all drinking water and about two-thirds of the wastewater treatment systems would need to retrofit their systems to employ alternative disinfection technologies. Considering the relative costs of different disinfection technologies and the current

11 "2006 Community Water System Survey," Volume II, Detailed Tables and Survey Methodology, United States Environmental Protection Agency, May 2009; "Survey of Drinking Water Plants," Statistics Canada, 2011; IHS estimates.

practices in water treatment plants, we believe that few systems would adopt nanofiltration technology. Use of ultraviolet radiation would most likely be preferred for most drinking water treatment plants, with ozone treatment used where special circumstances justified its higher costs. Wastewater disinfection would probably be done by UV in most cases. In most cases, modular ozone generation and UV plants could most likely be retrofit within the confines of existing plants, and most of the existing pre-treatment facilities would still be used. In some cases, however, constraints on available space or the inadequacy of existing pre-treatment systems would complicate the retrofit process and could increase costs significantly.

We estimate that the capital requirements to substitute ozone and UV disinfection for chlorine-based disinfection in drinking and wastewater treatment plants in the United States and Canada would amount to about $48.6 billion. We estimate the breakdown in the incremental capital requirements for treatment plants in the US would amount to $44.9 billion and capital requirement for the plants in Canada would be $3.7 billion. These costs are significant compared with the existing infrastructure needs of the nation's drinking water and wastewater utilities. According to the latest surveys, the EPA estimates that utilities in the US will require an average of $19 billion per year for drinking water capital improvement projects[12] and an average of $15 billion per year for wastewater capital improvement projects[13] over the next 20 years. The capital improvement projects include infrastructure investments in treatment plants, pipes, storage tanks, and other key assets. The cost to substitute ozone and UV disinfection would also raise the operating costs of treatment plants and would cost consumers in the US and Canada an additional $5.1 billion per year. To break this down further, the substitution costs would increase the outlay for US consumers by $4.7 billion per year and the outlay for Canadian consumers by $0.4 billion per year.

12 "Drinking Water Infrastructure Needs Survey and Assessment, Fifth Report to Congress," U.S. Environmental Protection Agency, April 2013; Clean Watersheds Needs Survey, EPA, 2008.

13 "Clean Watersheds Needs Survey 2008: Report to Congress," U.S. Environmental Protection Agency, 2014.

Economic benefit of chlorine in water treatment, 2014

	Small plants	Medium plants	Large plants	Total
New capital investment ($MM)				
Drinking water				
United States	20,342	10,955	6,033	37,330
Canada	1,189	717	488	2,394
Subtotal	**21,531**	**11,672**	**6,521**	**39,724**
Wastewater				
United States	3,250	1,871	2,492	7,614
Canada	876	311	113	1,300
Subtotal	**4,127**	**2,182**	**2,605**	**8,913**
Total new capital investment	**25,658**	**13,854**	**9,126**	**48,637**
Incremental cash operating cost ($MM per year)				
Drinking water				
United States	307	10	-103	215
Canada	16	5	-2	18
Subtotal	**323**	**15**	**-105**	**233**
Wastewater				
United States	3	24	-42	-16
Canada	-1	1	-2	-2
Subtotal	**2**	**25**	**-45**	**-18**
Total incremental cash operating cost	**325**	**40**	**-150**	**215**
Cost of substitution ($MM per year)*				
Drinking water				
United States	2,341	1,106	500	3,948
Canada	135	76	46	258
Subtotal	**2,476**	**1,182**	**547**	**4,205**
Wastewater				
United States	328	211	207	746
Canada	86	32	9	128
Subtotal	**415**	**243**	**216**	**873**
Total cost of substitution	**2,891**	**1,425**	**763**	**5,079**

*Notes: We compute the total cost of substitution to be the incremental cash operating cost per year plus a return on investment of 10% of the new capital required.

Source: IHS

In the absence of chlorine chemistry for primary disinfection, approximately 80% of the new investments would be targeted to retrofit the drinking water treatment systems and 20% for the wastewater treatment systems. These estimates follow directly from the higher costs of the substitute systems shown above, even when allowances are made for the expectation that, in most cases, the retrofit costs would be reduced by the availability of functional components of the existing plant and infrastructure. Similar cost shares apply to the ongoing total costs of substitution in drinking water plants as well. Costs are lower for the wastewater treatment system retrofits because there are fewer of them, and the consumers served by small systems bear less than 50% of the total costs because there are relatively more mid-sized and large wastewater treatment systems.

None of the chlorine-free technologies provide the residual disinfectant properties of chlorine in their water distribution systems. In the absence of residual chlorine in drinking water, waterborne pathogens could re-enter the water supply and increase the risk of adverse health effects, resulting in waterborne illness outbreaks. Water distribution systems would need to be upgraded significantly and better maintained, and consumers could be required to add point-of-use treatment options at the tap to ensure that the water they receive had not been re-contaminated in the distribution system. Point-of use options include installation of home filtration systems and home UV systems and boiling all water prior to its consumption. The latter option is appropriate only for emergencies caused by a temporary malfunction in the treatment and distribution system.

Home filtration systems are available for as little as $50-150, but they are difficult to maintain and cannot remove very small particulates, and so are effective only against larger microorganisms such as microbial cysts; bacteria and viruses would pass through these filters. Home UV systems also require continuous maintenance, but can be effective against a wider range of pathogens. They are available from a variety of sources at prices ranging from about $300 to $600, with annual fittings and lamp replacement costing around $150.[14] If the basic filtration systems were installed in all of the more than 137 million households in the United States and Canada, as well as all of the commercial, institutional and industrial systems served by central water treatment facilities, the total installed costs could exceed $20 billion, approximately 40% of the costs of substituting alternative processes for chlorine chemistry in the treatment plants themselves. Annual costs for filter element replacement would exceed $5 billion per year or about the same as the cost of process substitution in the treatment plants. Use of the more effective, expensive UV systems would increase both the initial and ongoing costs by five times. Point-of-use costs at hundreds of millions of sites must be higher than those at central treatment plants because of the diseconomies of scale inherent in the installation of such small systems.

In summary, while alternatives to the use of chlorine chemistry exist for the treatment of drinking water and wastewater, all the alternatives have limitations with respect to either effectiveness against certain pathogens, the ability to provide residual disinfection capability, or cost. The need to substitute alternative disinfection technologies for the chlorine-based technologies currently in use would burden consumers with high costs both to construct and operate the treatment systems that use the substitutes. The greatest increase in costs would fall most heavily on consumers served by the smaller systems.

14 These estimates are based on price information published by various manufacturers in the fourth quarter of 2015.

Chlorine and safe drinking water

In 1774, a Swedish scientist – Carl W. Scheele – treated manganese dioxide with hydrochloric acid which released a yellowish-green gas, and chlorine was discovered. It was determined to be an element in 1810 and aptly named by Sir Humphry Davy ("chloros" is Greek for pale green) Use of chlorine as a disinfectant was first introduced in 1846 by Austrian-Hungarian physician, Ignaz Philipp Semmelweis, on the maternity ward of the Vienna General Hospital to clean the hands of medical staff and prevent puerperal fever. In 1881, German physician Robert Koch showed that pure cultures of bacteria were destroyed by hypochlorites.

Prior to the use of chlorine in water treatment, cholera, typhoid fever, dysentery, and hepatitis A were common diseases. Right up to 1900, typhoid fever alone killed thousands of North Americans every year. England was one of the first countries to treat drinking water with chlorine, and in 1908, Jersey City in the US followed suit. In 1916, Canada began using chlorine to disinfect its water supply. Considered one of the most significant public health advances in the 20th century, drinking water chlorination has virtually eliminated waterborne diseases such as cholera, typhoid, and dysentery in North America. The effectiveness of chlorine as a disinfectant also has been demonstrated by its widespread use in drinking water treatment for nearly one hundred years.

In January 1991, the Peruvian Ministry of Health received reports of increased gastroenteritis in Chancay, a coastal district north of Lima. This was soon identified as cholera. The epidemic spread quickly and, within days, reached all of Peru's coastal departments. Within 29 days, the mountain and tropical forest regions were affected as well. From Peru, the disease spread rapidly to other Latin American countries – nineteen in all. A five-year epidemic of cholera resulted, the disease's first appearance in the Americas in the 20th century. About one million illnesses and 12,000 deaths occurred. The major cause was determined to be inadequate chlorination of drinking water.

One of the advantages of chlorination as a method of disinfecting potable water is the ease of application and portability. On December 26, 2004, an earthquake off the Indonesian island of Sumatra triggered massive tsunamis which devastated coastal regions of eleven countries around the Indian Ocean. At least five million people were affected. The death toll exceeded 280,000 people, and more than one million persons were displaced as a result of the destruction. Moreover, drinking water infrastructure was destroyed, placing over 500,000 displaced persons at increased risk of waterborne disease. Millions of chlorine tablets and bottles of sodium hypochlorite were shipped to the affected areas that allowed immediate and effective disinfection of drinking water during the early phases of the emergency. According to a study in the *American Journal of Tropical Medicine and Hygiene*, chlorination is the most effective strategy to improve water quality and protect human health in these types of post-disaster situations.

Source: Public Health Agency of Canada; Department of Geography, University of Texas. Cholera in Peru. Retrieved from http://www.colorado.edu/geography/gcraft/warmup/cholera/cholera_f.html; Clasen, T., Smith, L. The Drinking Water Response to the Indian Ocean Tsunami Including the Role of Household Water Treatment. World Health Organization Sustainable Development and Healthy Environments. 2005; Gupta SK, Suantio A, Gray A, Widyastuti E, Jain N, Rolos R, Hoekstra RM, Quick R. Factors associated with E. coli contamination of household drinking water among tsunami and earthquake survivors, Indonesia. American Journal of Tropical Medicine and Hygiene. 2007 Jun;76(6):1158-62.