Water Treatment

Roberto M. Narbaitz

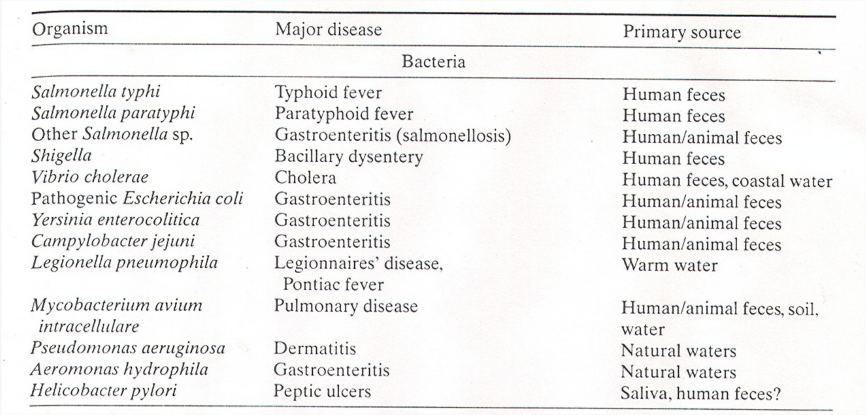
Objective of Drinking Water Treatment:

Supply the population with safe water that is also appealing to drink

What makes a water safe?

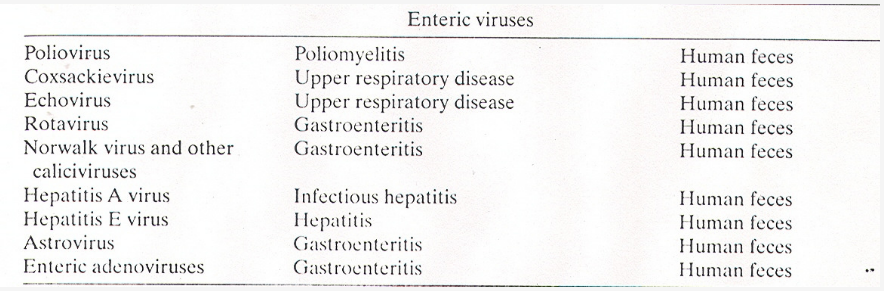
- Free of pathogens (disease causing bacteria, virus, protozoa, etc.)
- Meets standards for toxic chemicals

Pathogenic bacteria possibly found in water



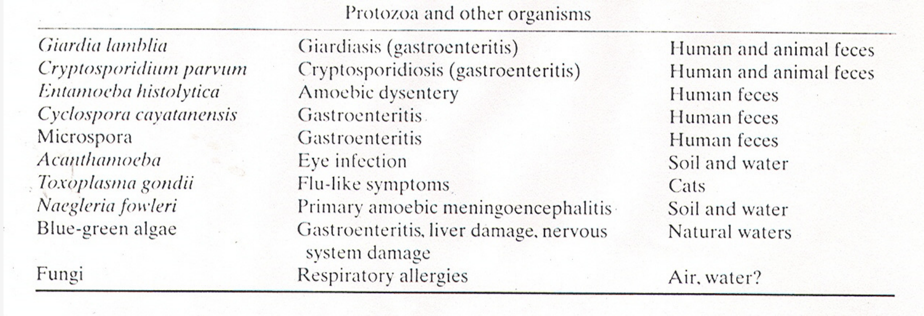
Organism	Major disease	Primary source
	Bacteria	
Salmonella typhi	Typhoid fever	Human feces
Salmonella paratyphi	Paratyphoid fever	Human feces
Other *Salmonella* sp.	Gastroenteritis (salmonellosis)	Human/animal feces
Shigella	Bacillary dysentery	Human feces
Vibrio cholerae	Cholera	Human feces, coastal water
Pathogenic *Escherichia coli*	Gastroenteritis	Human/animal feces
Yersinia enterocolitica	Gastroenteritis	Human/animal feces
Campylobacter jejuni	Gastroenteritis	Human/animal feces
Legionella pneumophila	Legionnaires' disease, Pontiac fever	Warm water
Mycobacterium avium intracellulare	Pulmonary disease	Human/animal feces, soil, water
Pseudomonas aeruginosa	Dermatitis	Natural waters
Aeromonas hydrophila	Gastroenteritis	Natural waters
Helicobacter pylori	Peptic ulcers	Saliva, human feces?

Pathogenic viruses possibly found in water



	Enteric viruses	
Poliovirus	Poliomyelitis	Human feces
Coxsackievirus	Upper respiratory disease	Human feces
Echovirus	Upper respiratory disease	Human feces
Rotavirus	Gastroenteritis	Human feces
Norwalk virus and other caliciviruses	Gastroenteritis	Human feces
Hepatitis A virus	Infectious hepatitis	Human feces
Hepatitis E virus	Hepatitis	Human feces
Astrovirus	Gastroenteritis	Human feces
Enteric adenoviruses	Gastroenteritis	Human feces

Protozoa and other pathogenic organisms possibly found in water



Protozoa and other organisms

Giardia lamblia	Giardiasis (gastroenteritis)	Human and animal feces
Cryptosporidium parvum	Cryptosporidiosis (gastroenteritis)	Human and animal feces
Entamoeba histolytica	Amoebic dysentery	Human feces
Cyclospora cayatanensis	Gastroenteritis	Human feces
Microspora	Gastroenteritis	Human feces
Acanthamoeba	Eye infection	Soil and water
Toxoplasma gondii	Flu-like symptoms	Cats
Naegleria fowleri	Primary amoebic meningoencephalitis	Soil and water
Blue-green algae	Gastroenteritis, liver damage, nervous system damage	Natural waters
Fungi	Respiratory allergies	Air, water?

Evolution of modern water treatment

- **By the 18th century it was established that filtration was an effective way of clarifying water.**
- **In 1804 the first municipal water filtration plant started operation in Scotland**
- **Installation of slow sand filters in London, England in 1829**
- **In 1855, Dr. John Snow was able to prove that cholera was a waterborne disease, by removing the pump handle from the Broad Street pump in London**
- **In the late 1880s Pasteur demonstrated the particulate germ theory of disease**

Evolution of modern water treatment

- First slow sand filters built in the US (1874)
- In 1892 there was a cholera epidemic in Hamburg-Altoona, Germany proved the value of water filtration.
- The first drinking water supply is chlorinated in Middelkerke, Belgium in 1902. In North America, it started in 1908 in Jersey City, NJ
- At that time typhoid fever and cholera epidemics were a relatively frequent event. In Pittsburgh the average death rate from typhoid was 160 per 100,000.

Evolution of modern water treatment

- In 1911 Johnson publishes Hypochlorite Treatment of Public Water Supplies" demonstrating filtration alone is not enough.
- The widespread incorporation of filtration and chlorination form 1910 to 1920 greatly reduced incidence of cholera and typhoid fever.

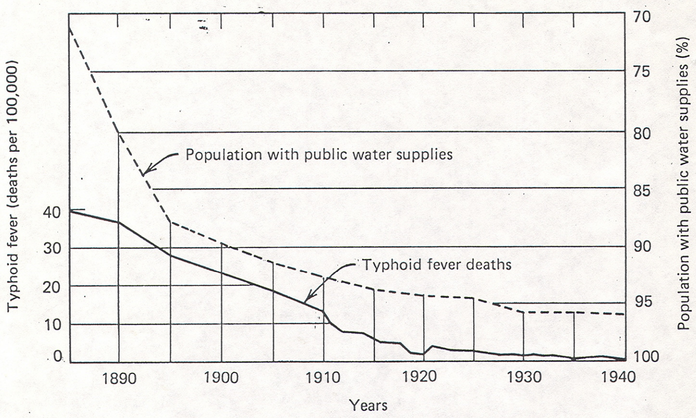


FIGURE 9.1
Typhoid deaths and public water supplies in Massachusetts (1885–1940). From *Water and Wastewater Engineering,* Volume 1, G.M. Fair, J.C. Geyer and D.A. Okun, Copyright © 1966 by John Wiley & Sons, Inc., New York, Page 1–16. Reprinted by permission.

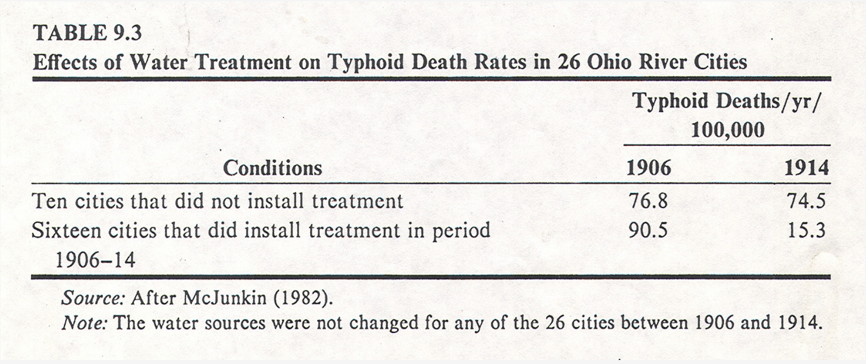
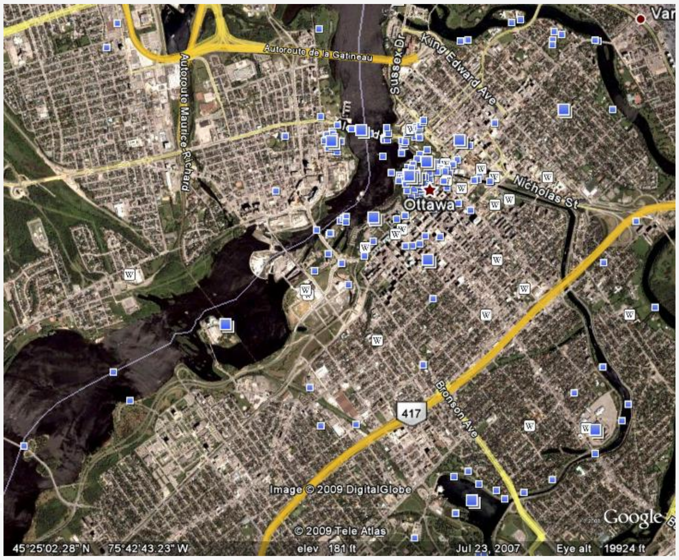


TABLE 9.3
Effects of Water Treatment on Typhoid Death Rates in 26 Ohio River Cities

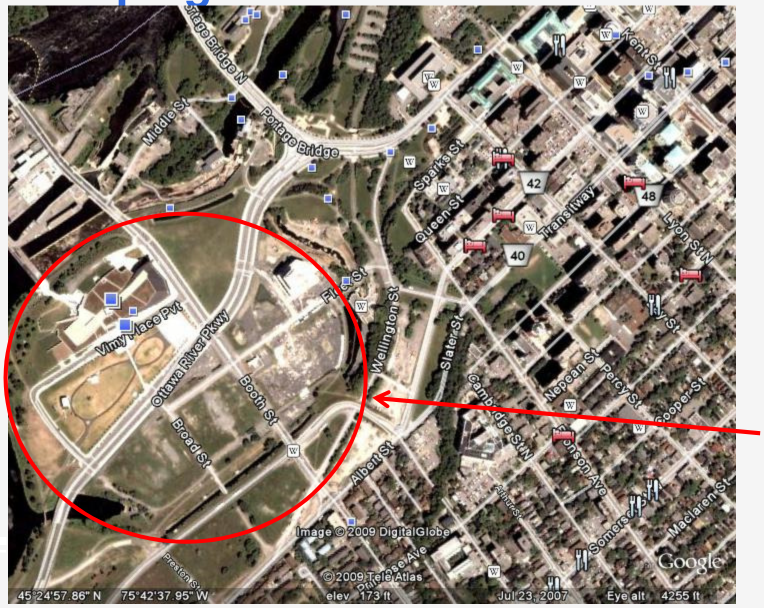
	Typhoid Deaths/yr/ 100,000	
Conditions	**1906**	**1914**
Ten cities that did not install treatment	76.8	74.5
Sixteen cities that did install treatment in period 1906–14	90.5	15.3

Source: After McJunkin (1982).
Note: The water sources were not changed for any of the 26 cities between 1906 and 1914.

Water Supply in Ottawa: Fleet Street Pumping Station built in the 1870s



Water Supply in Ottawa: Fleet Street Pumping Station built in the 1870s

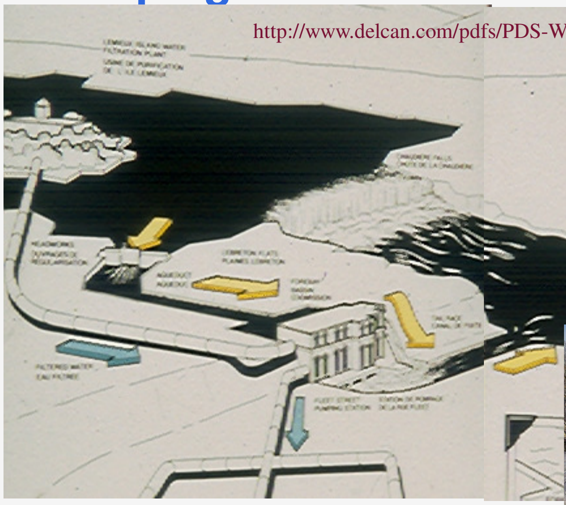


Lebreton's Flat

Water Supply in Ottawa: Fleet Street Pumping Station built in the 1870s

Lebreton's Flat

Water Supply in Ottawa: Fleet Street Pumping Station built in the 1870s

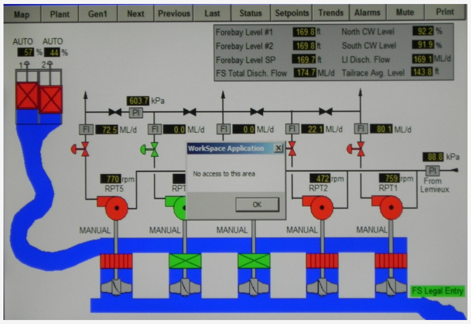


http://www.delcan.com/pdfs/PDS-Water-Infrastructure/PDS-FleetStreet.pdf

Thomas C. Keefer, 1874

Originally pumped untreated river water

Water Supply in Ottawa: Fleet Street Pumping Station built in the 1870s



Forebay Level #1 169.8 ft
Forebay Level #2 169.8 ft
Forebay Level SP 169.7 ft
FS Total Disch. Flow 174.7 ML/d
North CW Level 92.2 %
South CW Level 91.9 %
LI Disch. Flow 169.1 ML/d
Tailrace Avg. Level 143.8 ft

No access to this area

Ottawa water treatment

- First water treatment plant water treatment plant was built at Lemieux Island in 1932.
- This investment was triggered by a Typhoid epidemic

But the bacteriological problems are not over

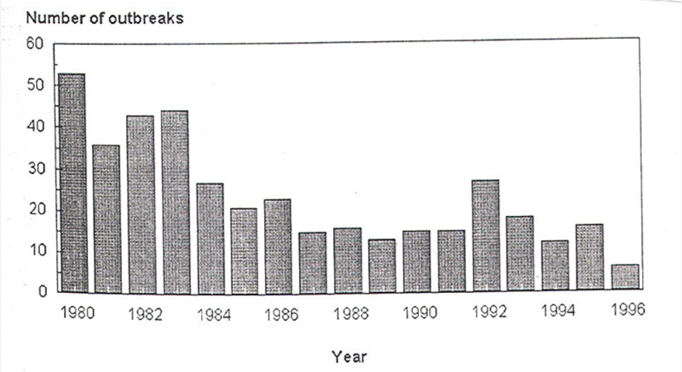


FIGURE 2.1 Waterborne disease outbreaks, 1980 to 1996.

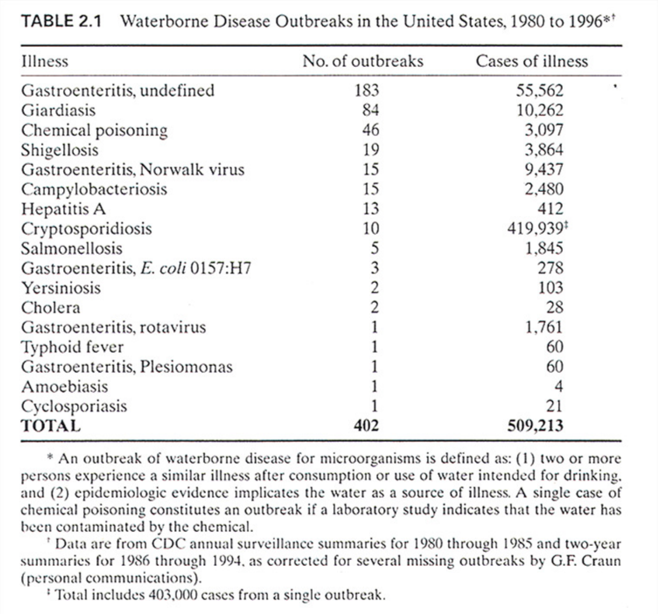


TABLE 2.1 Waterborne Disease Outbreaks in the United States, 1980 to 1996*[†]

Illness	No. of outbreaks	Cases of illness
Gastroenteritis, undefined	183	55,562
Giardiasis	84	10,262
Chemical poisoning	46	3,097
Shigellosis	19	3,864
Gastroenteritis, Norwalk virus	15	9,437
Campylobacteriosis	15	2,480
Hepatitis A	13	412
Cryptosporidiosis	10	419,939[‡]
Salmonellosis	5	1,845
Gastroenteritis, *E. coli* 0157:H7	3	278
Yersiniosis	2	103
Cholera	2	28
Gastroenteritis, rotavirus	1	1,761
Typhoid fever	1	60
Gastroenteritis, Plesiomonas	1	60
Amoebiasis	1	4
Cyclosporiasis	1	21
TOTAL	**402**	**509,213**

* An outbreak of waterborne disease for microorganisms is defined as: (1) two or more persons experience a similar illness after consumption or use of water intended for drinking, and (2) epidemiologic evidence implicates the water as a source of illness. A single case of chemical poisoning constitutes an outbreak if a laboratory study indicates that the water has been contaminated by the chemical.

[†] Data are from CDC annual surveillance summaries for 1980 through 1985 and two-year summaries for 1986 through 1994, as corrected for several missing outbreaks by G.F. Craun (personal communications).

[‡] Total includes 403,000 cases from a single outbreak.

Indicator organisms (after Droste)

- Microorganism are quantified using growth tests. A water of sample is placed into contact with a growth medium, time is allowed for bacterial colonies grow, and finally the colonies are counted.
- Each pathogen has a specific measuring procedure (i.e., using different growth medium, incubation temperature, incubation time).
- To identify and enumerate the pathogens in a water would require an army of microbiologists and excessive time and be prohibitively expensive for analyses on any routine basis.
- Therefore there is a need to find a suitable indicator that would signal the potential presence of pathogenic microorganisms.

Indicator organisms (after Droste)

- The golden rule for an indicator microorganism is: The indicator must be present when pathogens are present and absent when pathogens are absent.

Indicator organisms (after Droste)

Taking into account other practical considerations, the traits of an ideal indicator microorganism would be as follows:

1. The microorganism should only originate in the digestion tract of humans and warm-blooded animals.
2. The microorganism should be easily, rapidly, and reliably identified and enumerated.
3. The analysis should be inexpensive.
4. The indicator should survive longer than pathogens in the extra-intestinal environment.
5. The indicator should occur in high numbers.
6. The indicator should not be pathogenic itself.

Indicator organisms (after Droste)

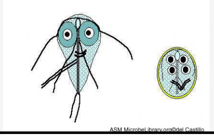
The most common fecal contamination indicator organisms used are **total coliforms and fecal coliforms.**

They have their limitations.

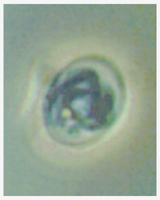
- They take one or two days to have countable bacterial colonies
- Coliforms are killed by chlorine, but harmful protozoa (like cryptosporidium, giardia) and spore-forming bacteria are not. So they are not always capable of quantifying disinfection efficiency.

Why bacteriological problems still occur?

- Our reliance on coliform tests as indicators of contamination/safety and the fact that the survival of some microorganism (such as Giardia lamblia and Cryptosporidium)
- Many treatment systems do not have fail safe characteristics
- Many communities (particularly small ones) do not have the resources or inclination to provide the best level of treatment
- Lax operation and provincial oversight

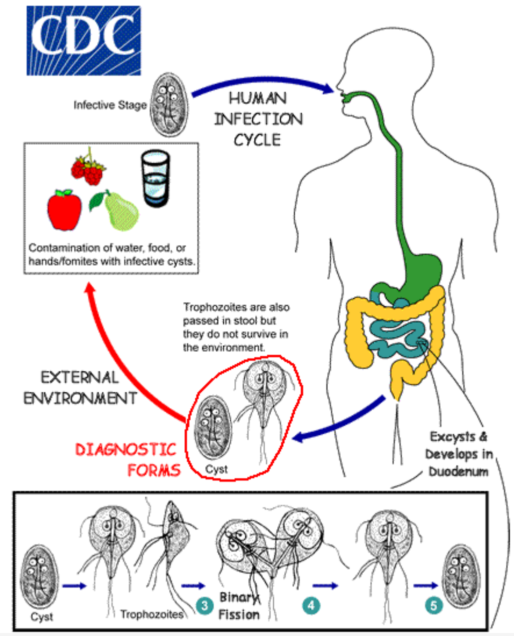


ASM MicrobeLibrary.org©del Castillo



Giardia lamblia –

Beaver fever



Cysts are oval-shaped thin-walled cyst that is 10 to 20 µm in length, 7-10 µm in width and 0.3-0.5 µm thickness. (http://www.phac-aspc.gc.ca/lab-bio/res/psds-ftss/giardia-lamblia-eng.php)

Why bacteriological problems still occur?

Location	When	Organism	# of cases	Hospit. (%)
Kitchener-Waterloo, ON	March 1993	Crypto	193	NA
Collinwood, ON	Feb. 1996	Crypto	39	30
Cranbrook, BC	June 1996	Crypto	29	23
Kelowna, BC	1996	Crypto	100	NA
Walkerton, ON	2000	E. coli	500+	150 people

***Escherichia coli* O157:H7** is an enterohemorrhagic strain of E. coli

---

Other turning points in drinking water treatment evolution

- Many synthetic organic compounds (SOCs) found in the Louisiana portion of the Mississippi River in 1972-73. There has been a lot concern about trace levels of potentially carcinogenic compounds.
- The formation of trihalomethanes (THMs) via the reactions of chlorine with naturally occurring organic matter (NOM) were discovered in the Netherlands in 1974.
- The 1974 Safe Drinking Water Act (SDWA) was passed which made regulations applicable to all public water supplies. Legally enforceable.
- US Standards for THMs established in 1979.

highlights water treatment evolution (cont'd)

- Further surveys in the early 1980s identified widespread problems with synthetic organic compounds (particularly with groundwater systems) and Giardia lamblia in surface waters. 1986 US Safe Drinking Water Act Amendment (includes max levels for
  - Volatile Organic Compounds (VOCs), such as gasoline and solvents
  - Synthetic Organic Compounds (SOCs), such as pesticides
  - giardia removal, CT, mandatory surface water filtration)

- Cryptosporidium becomes a great concern with the 1992 epidemic in Milwaukee, WI (400,000 ill and there were ~80 deaths of immuno-compromised persons).
  - 1996 SWA Amendment. (Regulation of filter backwash, tighter DBP regulations, cryptosporidium control).

---

highlights water treatment evolution (cont'd)

- Cryptosporidium is particularly troublesome because it is highly resistant to chlorination. In a "well" operated conventional treatment plant filtration removes them well because of their size (3 to 7 um) they are removed

- Walkerton epidemic in May 2000 due to E. coli O157:H7 contamination. Led to a severe tightening of Ontario regulations, including legally enforceable standards.

How do we produce safe water?

- By subjecting water to a number of physical separation and chemical processes.
- It must meet standards
  - http://www.ene.gov.on.ca/envision/gp/4449e01.pdf

Ontario Drinking Water Standards

Microbiological Standards	
PARAMETER	**MAX. ALLOWABLE CONCENTRATION**
Escherichia coli (E. coli)	Not detectable (Zero)
Total Coliforms	Not detectable (Zero)
Giardia lamblia	Treatment / disinfection requirements
Cryptosporidium	Treatment / disinfection requirements

The risk of microbiological contamination are higher than those of toxic chemicals

Ontario Drinking Water Standards

- If fecal coliforms are positive, the disinfectant level must be increased, an investigation must be started, the public must be alerted and a boil water must be put in place until the problem is solved.
- As colloidal particles may shield microorganism from the impact of disinfectants, water turbidity is another critical (or primary) drinking standard. The plant effluent has to have a turbidity < 1NTU. However, there is pressure to reduce this to 0.1 NTU. The current operational requirement is that the turbidity is below 0.3 NTU 95% of the time.

Canadian Drinking Water Guidelines and Standards

- Guidelines are not legally enforceable.
- In the division of powers between provincial and federal areas of jurisdiction, the environment falls within the provincial responsibilities.
- The federal government only has jurisdiction of environmental matters over federal lands and interprovincial waterways.
- The federal government creates drinking guidelines through Health Canada in conjunction with the Council of Provincial Minister of the Environment (based in Winnipeg).
- Based on these guidelines, the provinces create their own legally enforceable drinking water standards.

Canadian Drinking Water Guidelines and Standards

- The federal government creates wastewater effluent guidelines through Environment Canada in conjunction with the Council of Provincial Minister of the Environment (based in Winnipeg).
- Based on these guidelines, the provinces create their own legally enforceable wastewater effluent water standards.
- In the US, the federal government, through USEPA, creates legally enforceable regulations. The individual states must create their own legally enforceable regulation that must at least meet the federal regulation.

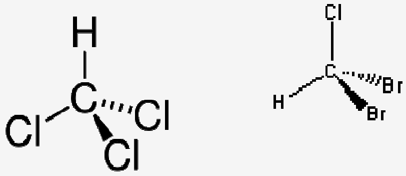
Aesthetic Water Standards

Constituent	Concentration, mg/L		
	Guideline		U.S.[b]
	WHO[c]	Canada	MCL
Aluminum	0.2		0.05–0.2
Ammonia	1.5		
Chloride	250	250	250
Chlorine dioxide	0.4		
Color	15 (units)	15 (units)	15 (units)
Copper	1.0	1.3	TT[e]
Corrosivity			Noncorrosive
Foaming agents			0.5
Hydrogen sulfide	0.05	0.05	
Iron	0.3	0.3	0.3
Manganese	0.1	0.05	0.05
Taste and odor	Inoffensive	Inoffensive	3 TON[d]
pH	Preferably < 8.0	6.5–8.5	6.5–8.5
Silver			0.1
Sodium	200	200	
Tot. dissolved solids	1,000	500	500
Sulfate	250	500	250
Temperature	acceptable	≤15°C	
Turbidity (NTU)	5	1	TT[e]
Zinc	3	5	5

after Droste

DISINFECTION BY-PRODUCTS

- The naturally occurring organic matter (NOM) reacts with the chlorine resulting in the oxidation of some of the NOM and in the formation of a number of potentially harmful disinfection by-products (DBPs).
- The NOM is frequently referred to as DBP precursors.
- The highest concentration DBPs are the Trihalomethanes or THMs
  - chloroform,
  - bromodichloromethane
  - chlorodibromomethane
  - bromoform
  - etc.



NOM + disinfectant $\Rightarrow$ H_2O + CO_2 + Disinfection By- Products (DBPs)
(TOC) + (Cl_2, O_3, etc.)
THMs, Total Haloacetic Acids(THAAs)

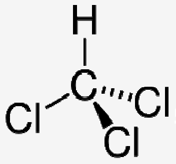
Bromate, NDNA, Chlorate, Chlorite, etc

DISINFECTION BY-PRODUCTS

❑ Chloroform is the THM produced in largest quantities by chlorine treatment.

❑ Chloroform is a suspected human carcinogen. http://www.osha.gov/SLTC/healthguidelines/chloroform/recognition.html

❑ One study of people exposed to chloroform in their drinking water showed a correlation between chloroform concentration and rectal and bladder cancer [Hathaway et al. 1991].



DISINFECTION BY-PRODUCTS

- Haloacetic Acids or HAAs are a second important group of DBPs
- Currently trihalomethane and HAAs concentrations in the distribution systems are regulated in both Canada and the US but to different levels.
- The USA also regulates a number of other DBPs (such as bromate, chlorate, etc.) related to other disinfectants
- Ontario also has DBP standards but they are less strict. (TTHMs 100 versus 80 ug/L) (HAAs 80 versus 60 ug/L)

DISINFECTION BY-PRODUCTS

- In order to minimize potential harmful effects, we try to minimize the formation of DBPs by:
  - Maximizing the removal of the precursors (i.e., NOM),
  - Delaying chlorination to a later point within the treatment plant (i.e., after sedimentation or filtration)
  - Using alternative disinfectants, such as ozone and UV. Alternative disinfectants do produce other disinfection by-products.

- Microfiltration and ultrafiltration membrane processes are becoming more popular because they can disinfect water without the addition of chemical disinfectants, they provide a physical barrier because the pores in the membranes are smaller than the microorganisms.

SOURCES OF RAW WATER SUPPLY

1. Groundwater (wells and springs)
2. Surface water (rivers, lakes, streams, reservoirs)

Groundwater characteristics

- High quality is the norm. Usually requires little or no treatment. The amount of treatment required is unpredictable until the well is installed.
- The water quality is fairly constant
- Pumping is required and may make it expensive
- Generally there is less of a chance of pollution, but when the wells become contaminated it is more difficult to clean up
- High mineral content (hardness, iron and manganese, sulfate, etc.)
- May contain gases (H_2S, CO_2, radon)

Groundwater

Iron stains

Impact of Minerals in Groundwater

Mineral deposit in kettles in a community served by groundwater (Carhue, Argentina)

Groundwater characteristics

- Generally low on suspended solids and turbidity
- Generally has low NOM concentrations (<2 mg TOC/l), so it produces less disinfection by-products. There are exceptions.

Surface water characteristics

- More predictable supply (quantity) on a long term basis
- More variation in the water quality
- More subject to pollution
- In general it is of a lower quality
- Contains more solids and turbidity, particularly rivers and streams
- Contains more microorganisms

Surface water characteristics

- **May have algal related taste and odour problems**
- **Has higher natural organic matter (NOM) content, thus generally higher colour and higher DBP formation**

Coulonge River, Quebec

NOM + disinfectant (TOC) + (Cl_2, O_3, etc.) $\Rightarrow$ H_2O + CO_2 + Disinfection By- Products (DBPs) (THMs, THAAs, etc.)

Surface water characteristics

- **Algal/cyanobacteria related problems**
  - **Taste and odour**
  - **Toxins (neurotoxins, hepatoxins, skin toxins)**

Lake Ontario near
Prince Edward Co., ON

If you see a blue-green film or scum in the water,
it may be Blue-Green Algae.
Some Blue-Green Algae may contain toxins.
People and pets should avoid touching the algae.
If you do come in contact with algae and have a reaction,
please consult your physician.

To report Blue-Green Algae in the Bay of Quinte call the Ministry of the Environment at (613) 962 - 9208 during business hours
(800) 268 - 6060 after hours

A satellite image from NOAA shows an aerial view of Lake Erie's massive 2011 algae bloom.

http://news.nationalgeographic.com/news/2014/08/140804-harmful-algal-bloom-lake-erie-climate-change-science/

http://www.circleofblue.org/waternews/2014/world/choke-point-index-great-lakes-drinking-water-fouled-by-toxic-algae/

How do we treat groundwater?

- ***What is hardness?***
  - Sum of divalent and trivalent positive ions.
  - Primarily Ca^{+2} + Mg^{+2}
- ***What are the different types of hardness?***
  - Total Hardness (TH)
  - Carbonate hardness (CH= min(Alk., TH))
  - Non carbonate hardness (NCH=TH-CH).
- ***What are the levels of hardness?***

Soft water: < 60 mg $CaCO_3$/L
Moderately hard water: 60 – 130 mg $CaCO_3$/L
Hard water: 130 – 300 mg $CaCO_3$/L
Very hard water: > 300 mg $CaCO_3$/L

May consider softening