Water & Waste Water

Meghan F. Davis, DVM MPH PhD
Associate Professor
Environmental Health and Engineering
mdavis65@jhu.edu

JOHNS HOPKINS BLOOMBERG SCHOOL OF PUBLIC HEALTH
Current Water Issues

• Vulnerability of surface water to:
  – drought (not replenished)
  – diversion of rivers for agricultural and urban use

• Declining groundwater levels
  – failure to replenish
  – compaction of aquifers
  – saltwater intrusion

• Surface and groundwater pollution from non-point sources

• Increasing competition for water supplies

Slide courtesy of John Groopman
Gold King Mine

Toxic, acid waste water release on August 5, 2015

Source: Denver Post

Source: LA Times
The Age of U.S. Water Pipes
From pre-Civil War to Civil Rights era, U.S. water systems reflect a range of ages.

240,000 water main breaks a year in US, pipes have 75 year life span

Slide courtesy of John Groopman
Lead and Flint, MI

Slide courtesy of John Groopman
Falling

The pH of treated Flint River water dropped over much of 2015, suggesting water officials didn’t have a target pH to control for corrosion.

<table>
<thead>
<tr>
<th>Treated Flint River water pH</th>
<th>8.5</th>
<th>8.0</th>
<th>7.5</th>
<th>7.0</th>
</tr>
</thead>
</table>

**February 2015:** City finds >100-ppb lead levels in one resident’s home.

**January 2015:** Detroit offers to reconnect its water supply with Flint. Flint city officials decline.

**March 2015:** Veolia, an environmental services company, issues a water quality report for Flint. In it, the firm suggests the city add a corrosion inhibitor to the water.

**August 2015:** Virginia Tech group reports that Flint’s 90th percentile lead level is 25 ppb.

**Source:** Monthly reports from Flint’s water treatment plant

Slide courtesy of John Groopman
How important is sanitation?

Blastocystis hominis protozoal infection
(Also no improvement for Cryptosporidium spp.)
How important is clean water?

**Blastocystis hominis** protozoal infection
(Similar decreases for other protozoa, e.g. *Giardia intestinalis*)

Speich Lancet Infectious Diseases 2016
It takes:

- 50 glasses of water to grow the oranges to provide one glass of OJ
- 30 liters (8 gallons) to grow one tomato
- 450 liters (120 gallons) to produce one chicken egg
- >13,000 liters (3,500 gallons) for a steak
- 225,000 liters (60,000 gallons) for one ton of steel (e.g., the amount in an automobile)

Surface water (fresh) 270000
Surface water (saline) 59000
Groundwater (fresh) 80000
Groundwater (saline) 1600

Public Supply 44000
Domestic 29000
Commercial/Industrial 37000
Mining 4000
Aquaculture 8800
Livestock 2100

Irrigation 130000
Thermo-Electric Cooling 200000

Discharge to Surface Water 230000
Discharge to Ocean 62000
Consumed or Evaporated 120000

Source: LLNL, 2011. Data is based on USGS Circular 1344, October 2000. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. All quantities are rounded to 2 significant digits and annual flows of less than 0.05 MGCy/day are not included. Totals may not equal sum of flows due to independent rounding. Further detail on how all flows are calculated can be found at http://flowcharts.llnl.gov. LLNL-TM-73772.
Estimated Maryland Water Flow in 2005:
7500 Million Gallons/Day

Source: LLNL 2011. Data is based on USGS Circular 1244, October 2006. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. All quantities are rounded to 2 significant digits and annual flows of less than 0.05 MGCaL/day are not included. Totals may not equal sum of flows due to independent rounding. Further details on how all flows are calculated can be found at http://flowcharts.llnl.gov. LLNL TR-475772.
Drinking Water:

• Baltimore region uses 275 million gallons per day

• A one inch rainfall on Baltimore City is 1.6 Billion gallons of water (92 square miles)

Slide courtesy of John Groopman
Simplified Flowchart of Drinking Water Treatment

DRINKING WATER SOURCE (RAW WATER) →

COAGULATION, THEN FLOCCULATION
   Chemical treatment to form floc, which is allowed to settle from water →

SEDIMENTATION →

FILTRATION
   To remove remaining solids →

DISINFECTION
   Chlorine to kill microorganisms →

DISTRIBUTION SYSTEM

Slide courtesy of John Groopman
Coagulation

Chemicals are added to the water to create a coagulant. The chemical most commonly used in the US is $\text{Al}_2(\text{SO}_4)_3:14\text{H}_2\text{O}$ (alum). The highly positively charged Aluminum$^{+++}$ attracts the negatively charged colloidal suspended particles in the water and together forms a gelatinous mass called *floc*.

Slide courtesy of John Groopman
Flocculation and Sedimentation

Once flocculation has been established by rapid mixing, the water is slowly and gently stirred to enable the finely divided floc to agglomerate into larger particles (including pathogens) that will rapidly settle.

– Dissolved contaminants are not removed.
– The settled floc or sludge is removed for the bottom of the settling tank and sent to disposal.
Sedimentation Bed

Photo: J. Jacangelo
Drained Sedimentation Bed

Photo: J. Jacangelo
Filtration

- Settled water is further treated by filtration
  - Sand filtration common in U.S.
  - Filters typically contain a dual bed media consisting of coal (anthracite) and sand 2 – 4 feet deep.
  - Filters become clogged after 12 to 72 hours of filtration and must be backwashed to clean the filter.
  - Backwash water must be discharged into the sewer.
Interior Rapid Sand Filtration Gallery

Photo: J. Jacangelo
Filter Backwash
Water Disinfection Requirements

• Must be reasonable in cost and safe and easy to store, transport, handle, and apply.
• Residual concentration in the treated water must be easily determinable.
• Must be sufficiently persistent so that the disappearance of the residual would be a warning of contamination.
• Must destroy bacteria, viruses and amebic cysts in water within a reasonable time despite all variations in water temperature, composition, and concentration of contaminants.

Slide courtesy of John Groopman
Drinking Water Disinfectants

- **Chlorine**
  - *Pros* – cheap, good disinfectant, provides residual
  - *Cons* – relatively unstable, forms disinfection by products (DBPs) that are potentially carcinogenic

- **Ozone**
  - *Pros* – good disinfectant, no DBPs
  - *Cons* – no residual, expensive

- **Ultraviolet Radiation**
  - *Pros* – effective on cryptosporidium, no DBPs, no storage problems
  - *Cons* – no residual, interference by solids and turbidity

Slide courtesy of John Groopman
Chlorine as a Disinfectant

• A vast majority of drinking water treatment plants use chlorine as the primary disinfectant.

• Chlorine can effectively inactivate many types of microorganisms.

• Chlorine provides a strong residual (unused Cl that can protect the water from additional microbial contamination in the distribution system).

Slide courtesy of John Groopman
Chlorine is the Favored Disinfectant for Water Supplies

Chlorine kills microorganisms

Chlorine reacts with ammonia and other substances

Remaining chlorine termed “free” is available to disinfect any new input of microorganisms

Slide courtesy of John Groopman

ReVelle P (adapted)
A MASSIVE OUTBREAK IN MILWAUKEE OF CRYPTOSPORIDIOUM INFECTION TRANSMITTED THROUGH THE PUBLIC WATER SUPPLY

WILLIAM R. MAC KENZIE, M.D., NEIL J. HOXIE, M.S., MARY E. PROCTOR, PH.D., M.P.H.,
M. STEPHEN GRADUS, PH.D., KATHLEEN A. BLAIR, M.S., R.N., DAN E. PETERSON, M.D., M.P.H.,
JAMES J. KAZMIERczAK, D.V.M., DAVID G. ADDISS, M.D., M.P.H., KIM R. FOX, P.E.,
JOAN B. ROSE, PH.D., AND JEFFREY P. DAVIS, M.D.

Abstract  Background. Early in the spring of 1993 there was a widespread outbreak of acute watery diarrhea among the residents of Milwaukee.

Methods. We investigated the two Milwaukee water-treatment plants, gathered data from clinical laboratories on the results of tests for enteric pathogens, and examined ice made during the time of the outbreak for cryptosporidium oocysts. We surveyed residents with confirmed cryptosporidium infection and a sample of those with acute watery diarrhea consistent with cryptosporidium infection. To estimate the magnitude of the outbreak, we also conducted a survey using randomly selected telephone numbers in Milwaukee and four surrounding counties.

Results. There were marked increases in the turbidity of treated water at the city’s southern water-treatment plant from March 23 until April 9, when the plant was shut down. Cryptosporidium oocysts were identified in water from ice made in southern Milwaukee during these weeks. The rates of isolation of other enteric pathogens remained stable, but there was more than a 100-fold increase in the rate of isolation of cryptosporidium. The median duration of illness was 9 days (range, 1 to 55). The median maximal number of stools per day was 12 (range, 1 to 90). Among 285 people surveyed who had laboratory-confirmed cryptosporidiosis, the clinical manifestations included watery diarrhea (in 93 percent), abdominal cramps (in 84 percent), fever (in 57 percent), and vomiting (in 48 percent). We estimate that 403,000 people had watery diarrhea attributable to this outbreak.

Conclusions. This massive outbreak of watery diarrhea was caused by cryptosporidium oocysts that passed through the filtration system of one of the city’s water-treatment plants. Water-quality standards and the testing of patients for cryptosporidium were not adequate to detect this outbreak. (N Engl J Med 1994;331:161-7.)
Disinfection By-Products (DBPs)

• When chlorine reacts with naturally occurring dissolved organic material (humics) in water, potentially carcinogenic by-products such as trihalomethanes (THMs) are generated.

• Major efforts in the drinking water field are focused on reducing DBPs while still providing adequate microbial protection.

Slide courtesy of John Groopman
Kinetics of Disinfection

• Inactivation of microorganisms is a gradual process that involves a series of physical-chemical and biochemical steps.

• Disinfectant effectiveness can be expressed as $C \times t$
  – $C$ is the disinfectant concentration
  – $t$ is the time required to inactivate a certain percentage of the population under specific conditions (pH and temperature)

In general, the lower the $Ct$ value, the more effective the disinfectant.
# Microbial Inactivation by Chlorine: 
Ct Values*

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Chlorine Conc., mg/L</th>
<th>Inactivation time (min)</th>
<th>Ct</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. coli</td>
<td>0.1</td>
<td>0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>Poliovirus</td>
<td>1.0</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>E. histolytica cysts</td>
<td>5.0</td>
<td>18</td>
<td>90</td>
</tr>
<tr>
<td>G. lamblia cysts</td>
<td>5.5</td>
<td>100</td>
<td>550</td>
</tr>
<tr>
<td>Cryptosporidium</td>
<td></td>
<td></td>
<td>&gt;250</td>
</tr>
</tbody>
</table>

* 99.9% kill; Temp. - 5°C; pH = 6.0 

Bitton G
# Microbial Inactivation by Chlorine

(99.9% of Organisms Killed)

<table>
<thead>
<tr>
<th>Chlorine Concentration (mg/L)</th>
<th>Inactivation Time (min)</th>
<th>Ct (concentration x time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2.0</td>
<td>0.25</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Note: The organism, temperature and pH are the same
Distribution

• Maintaining a residual disinfectant in the distribution pipes is critical.
  – Cross connections between sewer and water lines
  – Back siphoning due to pressure changes
  – Reduction of biofilm growth on the interior of the pipes
  – Ortho-Phosphate: lead and copper leaching

• System is under pressure; water delivery and fire fighting.

Slide courtesy of John Groopman
Waste Water Systems
Wastewater Components

Wastewater Components of Concern

- Pathogens
  - Suspended Solids
- BOD
- Nutrients (N & P)
  - Toxic Chemicals

Slide courtesy of John Groopman
Wastewater Treatment

The aim of sewage treatment is to improve the quality of wastewater to the point that it can be discharged into a waterway without seriously disrupting the aquatic environment or causing human health problems in the form of waterborne disease.

Slide courtesy of John Groopman
Composition of Domestic Wastewater

• Domestic wastewater is primarily a combination of human feces, urine, and “graywater” (water from washing, bathing and meal preparation).

• Water from various industries and businesses may also enter the system.

• People excrete 100-500 grams wet weight of feces and 1-1.3 liters of urine per person per day.

Slide courtesy of John Groopman
An Example of the Number of Microorganisms shed from an Ill Individual

- Ingesting 1-10 norovirus can make you sick
- A single 500 mL diarrhea stool can contain over 1 billion noroviruses (7 million per mL)
  - Many ill individuals have 10-20 diarrheal stools per day
  - $20 \times 10^9 = 2 \times 10^{10}$ 20 billion virions from one sick individual in one day

Slide courtesy of John Groopman
Impact of Gastroenteritis (GE)

- 200 million people experience GE daily

- The volume of diarrheal discharge into the environment each day equals the volume of water flowing over Victoria Falls every two minutes (200,000 m$^3$ of fluid)

Courtesy of K. Schwab
# Primary Constituents of Municipal Sewage

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Potential Sources</th>
<th>Effects in Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂-demanding substances</td>
<td>Organic material (human feces)</td>
<td>Consumes dissolved O₂</td>
</tr>
<tr>
<td>Pathogens</td>
<td>Human waste</td>
<td>Cause disease</td>
</tr>
<tr>
<td>Nutrients</td>
<td>Detergents</td>
<td>Algal nutrients</td>
</tr>
<tr>
<td>Toxic chemicals</td>
<td>Industrial waste</td>
<td>Toxicity</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>Silt</td>
<td>Interferes with disinfection</td>
</tr>
</tbody>
</table>
Biological Oxygen Demand (BOD$_5$)

- Organic decomposition requires oxygen
- BOD = the amount of oxygen used by organisms in a body of water to carry out decomposition
- Amount of oxygen utilized by micro-organisms to oxidize organic compounds in the dark at 20ºC in 5 days (BOD$_5$)

\[
\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2
\]

*bacteria*

Slide courtesy of John Groopman
Biological Oxygen Demand ($\text{BOD}_5$)

- When bacteria act upon organic matter in sewage, large amounts of dissolved oxygen are rapidly used up
  
  - No oxygen = fish kills

- BOD indicates how much organic material is present in the water
  
  - low BOD = good water quality
  
  - high BOD = polluted conditions
<table>
<thead>
<tr>
<th>Source</th>
<th>$\text{BOD}_5$ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pristine river</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Domestic sewage</td>
<td></td>
</tr>
<tr>
<td>raw</td>
<td>300</td>
</tr>
<tr>
<td>treated</td>
<td>10</td>
</tr>
<tr>
<td>Textile-dyeing</td>
<td>660</td>
</tr>
<tr>
<td>Dairy wastewater</td>
<td>900</td>
</tr>
<tr>
<td>Slaughterhouse wastewater</td>
<td>2,000</td>
</tr>
<tr>
<td>Rubber factory</td>
<td>3,300</td>
</tr>
<tr>
<td>Distillery vinasse (sugar by-product)</td>
<td>30,000</td>
</tr>
<tr>
<td>Swine lagoon</td>
<td>800</td>
</tr>
<tr>
<td>Open feedlot runoff</td>
<td>1,000</td>
</tr>
<tr>
<td>Raw swine manure</td>
<td>50,000</td>
</tr>
</tbody>
</table>
Clean Water Act

• Enacted in 1972
• The Act consists of two major parts:
  – regulatory provisions that impose progressively more stringent requirements on industries and cities in order to meet the statutory goal of zero discharge of pollutants
  – provisions that authorize federal financial assistance for municipal wastewater treatment construction.
• The Goal of the Act is to make all waters fishable and swimmable

Slide adapted from John Groopman
Total Maximum Daily Loads (TMDLs)

Section 303(d) of the Clean Water Act requires states to identify pollutant-impaired water segments and develop "total maximum daily loads" (TMDLs) that set the maximum amount of pollution that a water body can receive without violating water quality standards.
Safe Drinking Water Act (SDWA)

- Passed by Congress in 1974 to protect public health by regulating the nation’s water supply.
- Authorizes the USEPA to set legally enforceable national health-based standards to protect against both naturally-occurring and man-made contaminants that may be found in drinking water.

Slide courtesy of John Groopman
Safe Drinking Water Act (SDWA)

• SDWA applies to every public water system in the US
• A public water system must have at least 15 service connections or serve at least 25 people per day for 60 days of the year.
  – 170,000 public water systems
    • 55,000 Community water systems (cities, towns, mobile home parks)
    • 135,000 Non-community water systems
      – Schools
      – Rest areas, campgrounds

Slide courtesy of John Groopman
Wastewater sewer systems operate primarily by gravity flow from source to treatment plant. (Drinking water delivery is under pressure)

There are approximately 19,500 sewer systems nationwide.

These systems contain 500,000 miles of sewer lines designed to handle an average daily flow of roughly 36 billion gallons of raw sewage.

Slide adapted from John Groopman
Modern Wastewater Treatment

• **Primary treatment**
  – A physical process that involves the separation of large debris, followed by sedimentation

• **Secondary treatment**
  – A biological oxidation process that is carried out by microorganisms

• **Tertiary treatment**
  – A physicochemical process that removes turbidity caused by the presence of nutrients (e.g., nitrogen and phosphorus), dissolved organic matter, metals, or pathogens

Slide courtesy of John Groopman
Wastewater Pretreatment
- Physical methods to remove solid materials
  - Sedimentation
    - Suspended solids allowed to settle
  - BIOLOGICAL TREATMENT
    - Uses microorganisms to digest soluble substances
      - SEDIMENTATION
        - Secondary sludge
  - Tertiary
    - SPECIALIZED TREATMENT
      - Removes phosphorus and nitrogen
        - DISINFECTION
          - DISCHARGE OF EFFLUENTS TO RECEIVING STREAM
Conceptual diagram illustrating a modern central collection and wastewater treatment plant, which can remove nutrients from wastewater to very low levels (i.e., tertiary treatment) and provide recycled water for agricultural and landscape uses.

Treatment of Wastewater

- Pretreatment of wastewater – Bar screens
- Grit Removal Chamber – Grit to landfill
- Primary Clarifiers – separates floatables (lipids) and sludge; sludge to anaerobic digesters
- Aeration and Biological Treatment (Aeration Basins) – air is bubbled in and microorganisms decompose organic compounds
- Secondary Clarifiers – settles out solids which go to the anaerobic digesters
- Chlorination/Dechlorination (SO₂)/Aeration

Slide courtesy of John Groopman
Current Issues for Water / Wastewater

• Sanitary sewer overflows
  – Rain events v. infrastructure capacity

• Planned v. de facto reuse scenarios
  – Upstream wastewater discharge ➔ downstream water treatment (de facto)
  – Toilet-to-Tap (planned reuse)
Sanitary Sewer Overflows

– There are on average 143 breaks per 1,000 miles of sewer line (500,000 miles) = 71,500 SSOs/year.

– EPA estimates that annually there are at least: 400,000 basement backups.

– Much of the nation's sewage collection infrastructure is between 30 and 100 years old, placing them at increased risk for leaks, blockages and malfunctions due to deterioration.

Slide adapted from John Groopman
Environmental Impacts of Overflows: Emergent Properties

• Contribute to general loading of pathogens in the environment

• Contribute to nitrogen and phosphorous loading of surface waters
  – Accelerate eutrophication
  – Hypoxia (low dissolved oxygen in water)

• Contribute to presence of industrial chemicals and heavy metals in water, sediments and aquatic wildlife

• Release human drugs into natural waters and ecosystems

• Contaminate shellfish and “bottom” feeding fish.

Slide courtesy of John Groopman
Magnitude of de facto wastewater reuse occurrence in large drinking water surface intakes across the U.S. (Scenario 1).

Published in: Jacelyn Rice; Paul Westerhoff; Environ. Sci. Technol. 2015, 49, 982-989.
DOI: 10.1021/es5048057
Copyright © 2014 American Chemical Society
Planned Reuse: Toilet-to-Tap

Solving the global water challenge through innovation, education, and collaboration.