**Earth’s Water**

- Water in, on, and above Earth is ~ 1.36 billion km$^3$ (326 million mile$^3$) and this amount is fairly constant.

- The continuous circulation of water through the ocean, land, and the atmosphere is the process called the hydrologic cycle.

- Distribution of Earth’s water:
  - 97.2% in ocean; 2.15% ice/glacier; 0.65% Lakes, Streams, Groundwater, Atmosphere.

- Types of water:
  - Juvenile—initial Earth’s water
  - Meteoric—nearly all surface water originates in the atmosphere.
Distribution of Water on Earth

Percentages and sources of fresh and salt water in world

- Saltwater in oceans and seas 97.4%
- Freshwater 2.6%
- Groundwater 0.59%
- Ice caps and glaciers 1.98%
- Atmosphere, rivers, plants, animals 0.001%
- Soil moisture 0.005%
- Lakes 0.007%

Water Content of Organisms and Food

<table>
<thead>
<tr>
<th>Organisms</th>
<th>Percentage of Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine invertebrates</td>
<td>97</td>
</tr>
<tr>
<td>Human fetus (1 month)</td>
<td>93</td>
</tr>
<tr>
<td>Fish</td>
<td>82</td>
</tr>
<tr>
<td>Human adult</td>
<td>70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Foods</th>
<th>Percentage of Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broccoli</td>
<td>90</td>
</tr>
<tr>
<td>Milk</td>
<td>88</td>
</tr>
<tr>
<td>Apples</td>
<td>85</td>
</tr>
<tr>
<td>Grapes</td>
<td>80</td>
</tr>
<tr>
<td>Eggs</td>
<td>75</td>
</tr>
<tr>
<td>Potatoes</td>
<td>75</td>
</tr>
<tr>
<td>Steak</td>
<td>73</td>
</tr>
<tr>
<td>Cheese</td>
<td>35</td>
</tr>
</tbody>
</table>
Streams: Transport to the Ocean

Streams:
Transport to the Ocean

Streams:
Transport to the Ocean

Rivers and streams

Stream: body of water flowing in a channel

The floor of the channel is called the bed

When rainfall is very heavy or snow melts rapidly, bodies of water overflow their banks and water covers the adjacent land called the floodplain
Rivers and streams

- Carry away runoff to lakes and seas
- Erode land (degradation)
- Transport and deposit sedimentary debris

Stream behavior

- Mostly determined by velocity and shape of channel
- These factors combine to allow either laminar or turbulent flow
- Turbulent flow is much more erosive
- Stream velocities may vary from 0.25 to 7 m/s
Laminar flow

- Smooth sheet-like flow at a low velocity
- Usually confined to edges and top of stream

Turbulent flow

- Irregular swirling flow
- Occurs at most rates of stream flow
- Keeps particles in suspension
**Laminar flow**

- Streamlines do not cross
- No mixing between layers
- Channel walls

**Turbulent flow**

- Streamlines cross
- Extensive mixing of fluid
Laminar to turbulent transition

Laminar flow

Turbulent flow

Streams move material in three forms

• Dissolved load
• Suspended load
• Bed load (traction and saltation)
Sediment Transport

Flow surface
- Finest clay particles dispersed throughout flow
- Finer particles temporarily suspended in flow.

Suspended load
- Coarsest particles rolling and sliding on bottom as bed load

Saltation
Saltation of sand-sized bed load

Stream terms

*competence*: measure of the largest particles a stream can transport

*capacity*: maximum quantity of sediment carried by stream

 proportional to discharge ($Q$) and velocity ($v$)
Grain Size and Flow Velocity

Lower Velocities Form Ripples
Higher Velocities Form Dunes

(b) Higher velocity

Flow of water and ripples and dunes

Pebbles Caught in Eddies Form Potholes
Waterfall Retreating Upriver

Parts of a River System

Channel and floodplain deposits of gravel, sand, and clay
Two important stream types

1. Meandering Streams
   • Gentle gradients, fine-grained alluvium
   • Minimizes resistance to flow and dissipates energy as uniformly as possible (equilibrium)
   • Examples: point bars, oxbow lake, migrating meanders

2. Braided Streams
Meandering River

Point Bar

Incised Meanders, Utah
Stream velocity distributions in cross sections through a meandering channel

Meandering River Over Time

- **Erosion at outside bend**
- **Deposition of point bar at inside bend**
- **Position of strongest current (blue arrow) shifts from side to side**
- **Direction of meander migration**
  - A: Maximum velocity
  - B: Deposition

- **Site and clay deposits in former channel connections**
Lateral migration by erosion at the outside & deposition on the inside of the river

Two important stream types

2. Braided Streams

• Sediment supply greater than amount stream can support

• At any one moment the active channels may account for only a small proportion of the area of the channel system, but essentially all is used over one season

• Common in glacial, deserts, and mountain regions
Braided River

Discharge

Total amount of water that passes a given point in a stream per unit time

\[ Q = w d v \]
Discharge

Discharge \( (m^3/s) = \text{width (m)} \times \text{depth (m)} \times \text{average velocity (m/s)} \)

In the U.S., this is expressed as cubic feet per second (cfs):

\[ 1 \, m^3/s = 35.9 \, ft^3/s \]

River at Low Discharge

(a) River at average level

- Cross-sectional area low:
  \[ 1.2 \, \text{feet} \times 59 \, \text{feet} = 70.8 \, \text{feet}^2 \]
- Velocity low: 1.5 feet/s
- Discharge low:
  \[ 70.8 \, \text{feet}^2 \times 1.5 \, \text{feet/s} = 106.2 \, \text{feet}^3/s \]
River at High Discharge

(b) River at high level

Cross-sectional area high:
3.1 feet × 62 feet = 194.2 feet³

Velocity high: 3.1 feet/s

Discharge high:
194.2 feet³ × 3.1 feet/s = 601.02 feet³/s
Flooding

- Water in the stream is greater than the volume of the channel
- Interval between floods depends on the climate of the region and the size of the channel
- Since $Q = w d v$, greatest erosion and transport of sediment occurs during periods of high water associated with floods

City Built on a Floodplain
Formation of Natural Levees

Recurrence interval

Average time between the occurrences of a given event

The recurrence interval of a flood of a given size at a given place depends on:

- climate of the region
- width of the floodplain
- size of the channel
Base level

Elevation at which a stream enters a large body of water such as a lake or ocean
Role of Base Level in Controlling Longitudinal Profile of Rivers

Effects of Building a Dam
Original Profile Graded to Regional Base Level
Effects of Building a Dam

**Dam Forms New Local Base Level**

- Dam is built, impounding reservoir or lake behind it.

**Deposition Upstream and Erosion Downstream**

- New, higher profile by sedimentation
- New, lower profile by erosion
Geologic evidence of changes in stream equilibrium

- Alluvial fans
- Terraces: erosional remnants of former floodplains

Alluvial Fans
Formation of River Terraces

Drainage basin

Area of land surrounded by topographic divides in which all the water is directed to a single point
Drainage Basin of the Colorado River

Drainage divides separate adjacent drainage basins.
Typical Drainage Networks

(a) Dendritic drainage
(b) Rectangular drainage
(c) Trellis drainage
(d) Radial drainage

Delta

Location of significant sedimentation where a river meet a still body of water such as a lake, inland sea or the ocean
Mississippi River Delta

Typical Large Marine Delta
Shifting Mississippi River Delta Over the Past 6000 Years

Water Resources

- Over the last century
  - Human population has increased 3x
  - Global water withdrawal has increased 7x
  - Per capita water withdrawal has increased 4x
  - About one-sixth of the world’s people don’t have easy access to safe water
  - Most water resources are owned by governments and are managed as publicly owned resources
### Daily Water Use (per capita)

#### Table 10.4 Average Per Capita Daily Water Use in the United States

<table>
<thead>
<tr>
<th>Use</th>
<th>Rate (gallons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flushing toilets</td>
<td>30</td>
</tr>
<tr>
<td>Bathing</td>
<td>23</td>
</tr>
<tr>
<td>Laundry</td>
<td>11</td>
</tr>
<tr>
<td>Drinking and cooking</td>
<td>10</td>
</tr>
<tr>
<td>Washing dishes</td>
<td>6</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>90</strong></td>
</tr>
</tbody>
</table>

### Too Little Water

- **Dry climate**
- **Drought**
- **Desiccation**
- **Water stress**

Map showing water stress in the United States with layers for acute shortage, adequate supply, shortage, and metropolitan regions with population greater than 1 million.
National Drinking Water Standards

### Maximum Permissible Levels for Metals in Drinking Water

**Table 10.6 Maximum Permissible Levels for Metals in Drinking Water**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Maximum Level (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antimony</td>
<td>6</td>
</tr>
<tr>
<td>Arsenic*</td>
<td>50</td>
</tr>
<tr>
<td>Barium</td>
<td>2000</td>
</tr>
<tr>
<td>Beryllium</td>
<td>4</td>
</tr>
<tr>
<td>Cadmium</td>
<td>5</td>
</tr>
<tr>
<td>Chromium (total)</td>
<td>100</td>
</tr>
<tr>
<td>Copper</td>
<td>1300</td>
</tr>
<tr>
<td>Lead</td>
<td>15</td>
</tr>
<tr>
<td>Mercury (inorganic)</td>
<td>2</td>
</tr>
<tr>
<td>Selenium</td>
<td>50</td>
</tr>
<tr>
<td>Thallium</td>
<td>2</td>
</tr>
</tbody>
</table>
Human water needs

- A person needs about 1 gallon water/day for hydration
- In the US each person uses about 90 gallons/day
- An additional 660 gallons/person/day are used for irrigation, industrial use.
- Total per capita use is about 2000 gal/person/day
- If world’s water supply were 100 liters, the usable supply would be about 0.5 tsp
- US has highest per capita water withdrawal, followed by Canada, Australia, Russia, Japan

How Water is Used

- Public supply, 11 percent
- Domestic, less than 1 percent
- Irrigation, 30 percent
- Livestock, less than 1 percent
- Aquaculture, less than 1 percent
- Industrial, 5 percent
- Mining, less than 1 percent
- Thermoelectric power, 40 percent
- Other, less than 1 percent
Canada is the Saudi Arabia of fresh water

- Canada has 20% of the world’s fresh water!

Water Pollution

Humans depend on very small reservoirs of water for all our needs.

These reservoirs cycle/turnover very quickly.

As they cycle they can either

- collect pollution from other sources, or
- be cleaned by passing through functioning ecosystems.
What is in water?

- Microbial organisms
  - bacteria, archaea, viruses, parasites

- Minerals (inorganic species)
  - soluble salts
    - positive and negative ions
      - e.g. Na⁺, Cl⁻, CO₃²⁻, Ca²⁺
    - insoluble suspended particles (colloids)

- Organic species
  - lower concentrations than minerals
  - mostly C, H, O, N, P based compounds
  - e.g. organic acids, tannins, detergents, pesticides

When is water “polluted”? 

- When it is unsuitable for drinking?
  - Microbial content
    - *E. coli*
  - Metals
    - Lead, mercury, arsenic, ...
  - Organics
    - pesticides, hydrocarbons,...

- When it is unsuitable for aquatic organisms?
  - Oxygen content is critical!

- When it is unsuitable for agriculture?
  - High salinity is bad!
What is “pollution”? 

- Is the ocean “polluted” with salt (NaCl)?
- If a large amount of salt is dumped in a small mountain stream does the stream become “polluted”? 
- Tap water can be considered “polluted” with copper for some aquatic organisms

A personal look at water

- What happens to your water before you drink it?
  - Vast majority of America's population get their water delivered from a public-supply system
  - Surface water and groundwater (groundwater is filtered to remove solids and small contaminants (e.g., viruses), most add chlorine to disinfect water, organic chemical may be removed by activated charcoal filters)

- What happens to your water after you dispose of it?
  - Approximately 99% of Swedes are served by wastewater treatment plants, 86.5% of Germans, 74% of Americans, and 57% of Canadians.
What constitutes quality drinking water?

- Free of pollutants
- Tastes good
  - Want Sodium Bicarbonate and Calcium Sulfate in same concentrations as found in saliva
  - 10°C
  - As little chlorination as possible
- Calcium & magnesium account for most water hardness, death rates (cardiovascular disease) higher in soft water areas than in hard water areas
- Copper needed to absorb & metabolism iron, but >1mg/liter makes water unpalatable
- Does taste correlate with presence of toxic compounds?

Water Pollution
Water Pollution

• 1.2 billion people worldwide do not have access to clean water

• Each day almost 10,000 children <5 years old in Third World countries die as a result of illnesses contracted by use of impure water

Water Pollution

• Water Pollution = degradation of water quality (biological, chemical, or physical)
  - Judged according to the use of the water
• Pollutant = any substance that in excess is known to be harmful to life
Water Pollution: Many Forms

- **Disease:** In developing nations, 80% of diseases are water-related.
- **Synthetic Organic Compounds**
- **Inorganic Compounds & Mineral Substances** such as Acids, etc.
- **Radioactive substances**
- **Oxygen-demanding wastes**
- **Plant Nutrients**
- **Sediments**
- **Thermal Discharges**
Water Pollution

Two major classifications

• Point Source
• Non-point Source

Surface-Water Pollution & Treatment

• Point Source = specific, confined pollution
  - On-site clean-up; regulated by permit
Point Source - Example

- LUST - Leaky Underground Storage Tanks
- 22% of the 1.2 million UST are LUSTy

Point source examples
Surface-Water Pollution

- Non-point Source = diffuse, intermittent pollution
  - Automobiles
  - Fertilizer on fields
    - Influenced by:
      - Land-use Hydrology
      - Native vegetation
      - Topography
      - Geology

- Difficult to control, contains multiple pollutants

Non point source examples
Non-point source pollutants - nutrients

Point and Nonpoint Sources of Water Pollution
Examples of Polluted Waters

Forms of Pollution – Details

- **Inorganic** – acids, salts, toxic metals
- **One gram of lead in 20,000 liters of water** makes it unfit for drinking. Lead is often found in the pipes of older homes
- **What is the safe drinking water limit for arsenic? For lead?**
Forms of Pollution – Details

- Organic: sewage, pesticides, plastics, etc.
- One drop of oil can render up to 25 liters of water unfit for drinking
- One gram of 2,4-Dichlorophenoxyacetic acid (2,4-D) can contaminate 10 million liters of drinking water!
- One gram of PCBs can make 1 billion liters of water unsuitable for freshwater aquatic life!

Pollutants

- Oxygen-demanding waste
- Disease causing organisms
- Nutrients
- Oil
- Hazardous Chemicals
- Heavy Metals
- Radioactive Materials
- Thermal Pollution
**Oxygen-Demanding Waste**

- Bacteria in water consume organic matter and use oxygen in the process
- Too much bacteria in the water causes oxygen shortage so fish and other organisms die
- Urban sewage is prime breeding ground for bacteria
  - may wash into natural systems via flood, earthquake, human error, etc.

**Oxygen and Water**

- Biochemical Oxygen Demand – What does this mean?
  - Anything in the water that bacteria can break down.
  - Bacteria will use up oxygen in the water
  - Other aerobic organisms will die
Oxygen and Water

• What else can affect the amount of O₂ in the water?
  - Temperature
  - Speed of water flow
  - Roughness of surface over which water flows

Dissolved oxygen

• One of the most important substances for aquatic organisms
• At least 5 ppm DO generally needed by fish
• DO decreases as Temperature increases
• Less DO at higher altitudes
• DO used up by aerobic bacteria during decomposition of organic matter
The Solubility of Oxygen in Water

Reduction in Dissolved Oxygen by Pollutants
Pathogenic Organisms

- Microscopic
- Disease-causing: cholera, typhoid, hepatitis, dysentery
- Monitor: *E. coli*
  - Found in human or animal waste
- May wash into natural systems via flood, earthquake, human error, etc.
  - Ex: Northridge, 1994

Nutrients

- Phosphorus & nitrogen
  - used in fertilizers, detergents, sewage-treatment plants
- Results in rapid growth of algae which:
  - covers water surface blocking light from reaching plants below
  - Upon death consumes oxygen, killing off aerobic organisms

The green color along the coast is an algal bloom-Fish die
**Nutrients**

- **Mississippi Dead Zone**
  - Offshore in Gulf of Mexico
  - Area ~size of New Jersey every summer
  - Mississippi River drains ~40% of continental U.S. – high levels of nutrients

**Oil**

- **Exxon Valdez, Alaska**
  - March 1989
  - Worst oil spill in U.S. history
  - Ran aground
  - >250,000 barrels of oil spilled
  - Area was one of most pristine and ecologically rich in world
  - Short-term impacts:
    - Many seabirds and mammals were killed
    - Fishing and tourism disrupted
  - Long-term impacts: ???
Hazardous Chemicals

- Clean Air Act 1990
  - Required use of oxygen additives to reduce automobile emissions
- Methyl tertiary butyl ether (MTBE, C₅H₁₂O) additive leaking into groundwater:
  - Underground gas leaks
  - Storm runoff from gas tanks/leaks on surface
- Santa Monica, California, 1997
  - MTBE pollution forced city to stop pumping groundwater eliminating 50% of drinking water supply

Harmful health effects of organic compounds

- The main problem is that there are so many synthetic organics and that we know so little about the toxicity of the vast majority of them
- It has also been discovered that many are toxic in very low concentrations and are persistent in the environment
Heavy Metals

• Lead, mercury, zinc, and cadmium
  – metals can dissolve and become incorporated into plants, crops, and thus animals and humans
• Sources: some natural, others burning fossil fuels, incinerating waste, processing metals
• Human activity has increased mercury levels in the atmosphere 2-3x and 1.5% per year
  – Particles in the atmosphere get rained out and soak into soil

Heavy Metals

• What characteristic of the so-called heavy metals causes them to be especially hazardous to humans and other animals high in food chains?
• The heavy metals accumulate in the body; they are not readily excreted. Therefore, their concentrations tend to increase going up a food chain.
Bioaccumulation

Bioaccumulation in aquatic food chain

- Fish-eating birds
- Larger fish
- Small fish
- Zooplankton

Increasing concentration of heavy substance in food chain.

Deposition of inorganic mercury $\text{Hg}^{2+}$

Methylation (Methylmercury/CH$_3$Hg$^+$)

Biomagnification (Bioaccumulation)

Sedimentation
**Hg in Hawaii Pelagic Fish**

Median Depth of Occurrence (m)

- **X. gladius** (66.7 kg)
- **L. guttatus** (40.9 kg)
- **T. obesus** (39.3 kg)
- **K. pelamis** (7.61 kg)
- **T. albacares** (21.1 kg)
- **C. hippurus** (6.1 kg)

**Arsenic in U.S. Ground Water**

- Counties with arsenic concentrations exceeding 10 μg/L in 10% or more of samples.
- Counties with arsenic concentrations exceeding 5 μg/L in 10% or more of samples.
- Counties with arsenic concentrations exceeding 3 μg/L in 10% or more of samples.
- Counties with fewer than 10% of samples exceeding 3 μg/L, representing areas of lowest concentration.
- Counties with insufficient data in the USGS database to make estimates.
Sediments

- THE largest form of water pollution
- Erosion is source – we’ve sped up rate of erosion, e.g. during urban construction can lose up to 43 tons of topsoil/acre/year
- Natural rates of erosion: leads to aquatic succession

Thermal Pollution

- Thermal pollution = artificial heating of water
  - Caused primarily by hot-water emissions from industrial operations and power plants
- Problems:
  - Contains less oxygen
  - Favors different species
  - May increase growth rates of undesirable species
  - May benefit some desirable species especially in winter
**Thermal pollution**

- 48% of water in U.S. is affected by this
- Up to a point of adding heated water, you can get thermal enrichment
- Adding more heat, you get thermal pollution

**We can also have cold water pollution**

In many areas fish and other river organisms are adapted to relatively warm water.

Building a dam results in very cold water released downstream killing organisms and changing species.