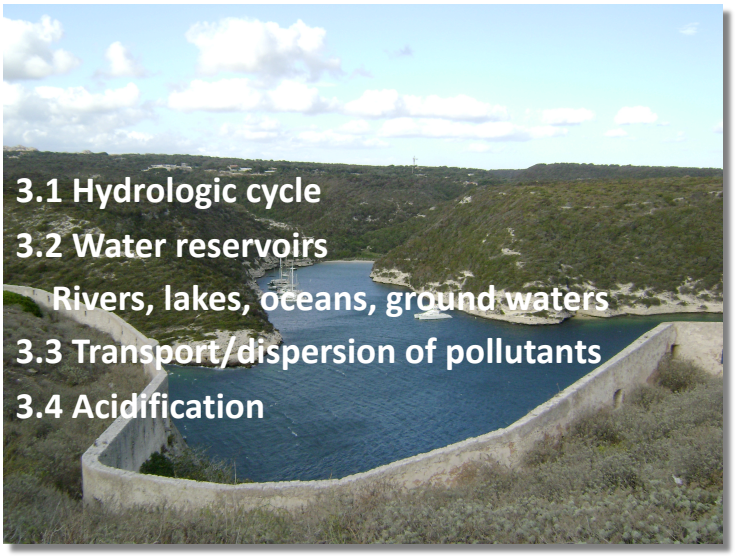
Chapter 3: Hydrosphere



Earth - A Blue Planet

"How inappropriate to call this planet Earth, when clearly it is Ocean."

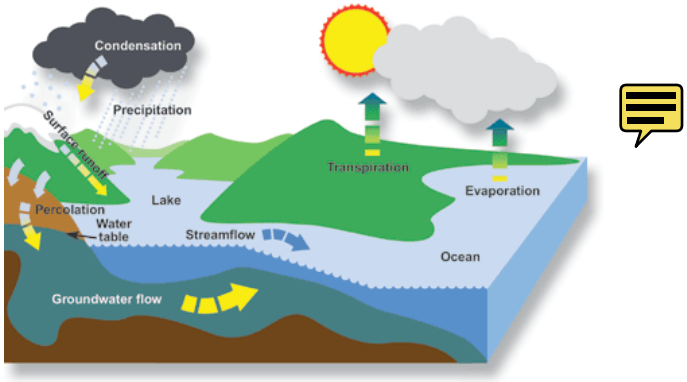
Arthur C. Clarke

•70% of Earth's surface is covered with water

3.1 Hydrologic cycle

70% of the earth's surface is covered with water
10% is covered with ice
97% of water is in the oceans
2% is in the ice
1% is freshwater (lakes, rivers, ground waters, soils)

Hydrologic cycle (Fig. 3.2)



http://www.ec.gc.ca/water/en/nature/prop/e_cycle.htm

Water as a resource

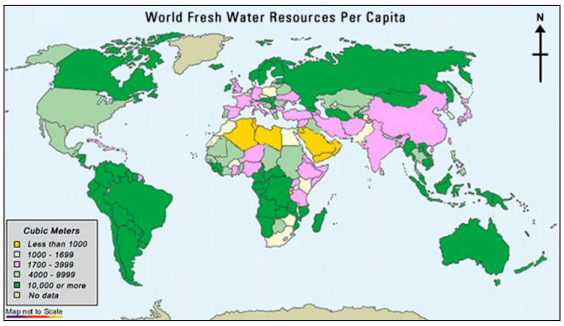
- Water is a renewable resource essential to support life on Earth
- Surface waters (lakes, rivers, streams) can be used as a source of drinking water, for irrigation, for hydroelectricity and recreational activities
- Groundwaters are present in aquifers. Recharge is achieved through precipitation
- Water resources are related to the climate: low or high precipitation
- Surface and ground waters are threatened by pollution

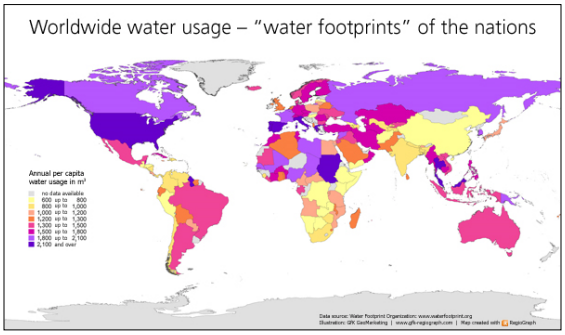
Water usage

- Regions of the world with the smallest water resources per capita are Asia, Africa and Europe, whereas America has the largest resources
- North America consumes the most water per capita, whereas under-developed countries consume the least
- In Canada, water is mainly used by the industries (including the power plants), whereas in the U.S., water is mainly used for irrigation
- Canadians use 5.4 billions m^3/yr of water (surface and groundwaters)
- Only 4 % of the water is from aquifers

Water usage worldwide

- Regions of the world with the smallest water resources per capita are Asia, Africa and Europe, whereas Americas have the largest resources
- North America consumes the most water per capita, whereas under-developed countries consume the least
- Agriculture accounts for bulk of worldwide water usage (73%)





Water usage - Canada

- In Canada, water is mainly used by the industries (including the power plants), whereas in the U.S., water is mainly used for irrigation
- Canadians use 5.4 billion m^3/yr of water (surface and groundwaters)
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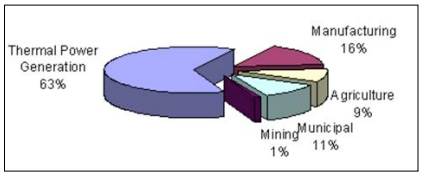
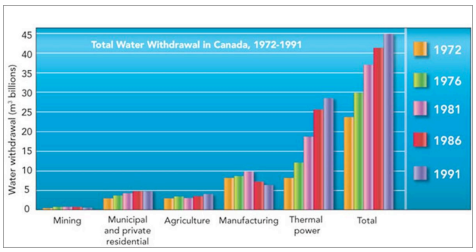
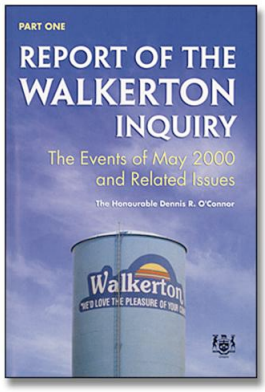




Groundwater supplies

- Groundwaters are used for domestic purposes in rural areas (wells)
  - Supplies 4% of Canadians

- Pollution can be a problem:
  - Walkerton, ON (May 2000)
    - Farm animal waste washed into vulnerable well
    - Groundwater supply contaminated with *E. coli 0157:H7*
    - 7 died, 2300 made ill
    - Failures in adequate water testing → *Safe Drinking Water Act*, ON (2002)



Water conservation

- Canada 2nd worst developed nation for water consumption

- In the prairies, 58% of the water is used for agriculture
  - Improved irrigation could reduce agricultural withdrawals by 20-30%
    - Price agricultural water to encourage conservation
    - Use lined or covered canals to prevent evaporation
    - Irrigate at times when evaporation is minimal (night, early morning)
    - Use better irrigation systems: sprinklers, etc
    - Improve the quality of the soil: better infiltration
    - Plant crops that require little water

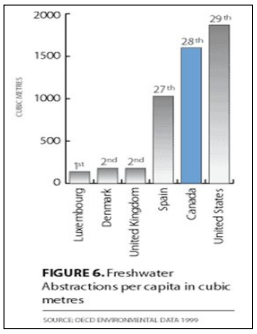
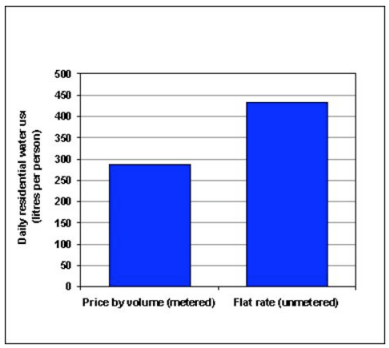


FIGURE 6. Freshwater Abstractions per capita in cubic metres

SOURCE: OECD ENVIRONMENTAL DATA 1999



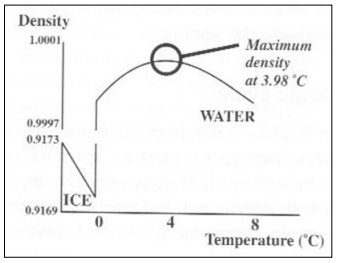
Water reservoirs

Rainwater

- 83% of rainwater is generated by evaporation from the oceans
- Contains dissolved solids (Na, K, Ca, Cl, HCO_3, SO_4, etc.)
  - Total dissolved solids (TDS) = 7 mg/L
- Contains dust particles

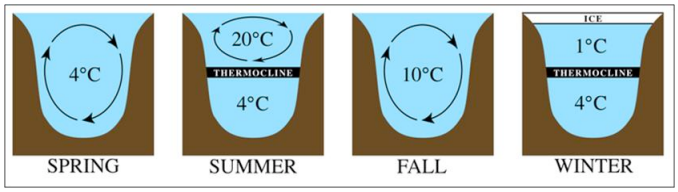
Lakes

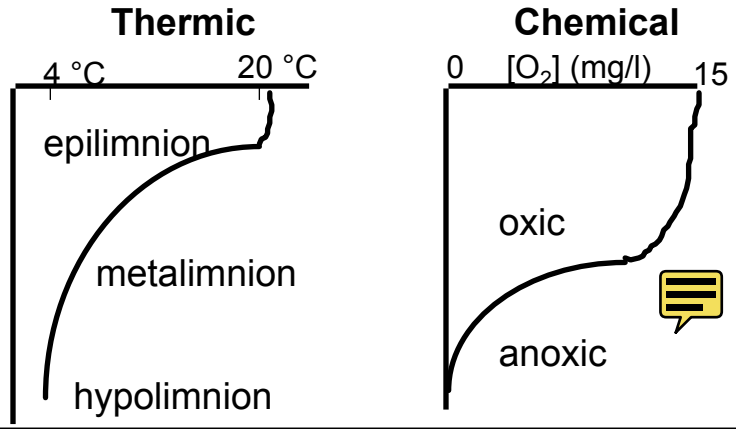
- Water composition is determined by the river water that flows into them
- Contain solids (from the watershed) and dissolved solids
- Water is mixed by the action of the wind
- Often stratified
  - Thermal stratification
    - Max density of water: 4 ˚C
  - Chemical stratification



Howard (1998) Aquatic Environmental Chemistry

Lake stratification

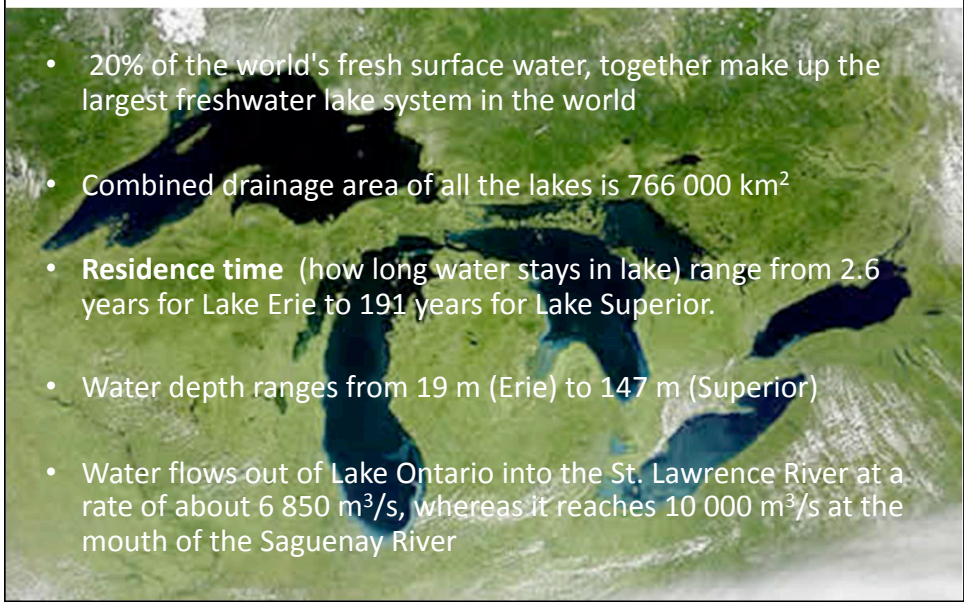




Lake stratification

- **Monomictic** or **dimictic** lakes turnover once or twice a year, respectively
- **Meromictic** lakes do NOT turnover
  - Permanently stratified
  - E.g. Pink Lake, Gatineau Park
  - Lake Nyos, Cameroon

Great Lakes and St-Lawrence River



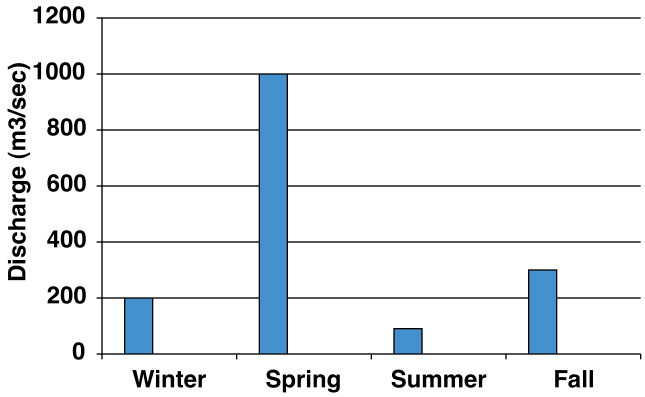
- 20% of the world's fresh surface water, together make up the largest freshwater lake system in the world
- Combined drainage area of all the lakes is 766 000 km^2
- **Residence time** (how long water stays in lake) range from 2.6 years for Lake Erie to 191 years for Lake Superior.
- Water depth ranges from 19 m (Erie) to 147 m (Superior)
- Water flows out of Lake Ontario into the St. Lawrence River at a rate of about 6 850 m^3/s, whereas it reaches 10 000 m^3/s at the mouth of the Saguenay River

3.2.2 Rivers

- Derived from rainwater that has either run off or run through its surrounding rocks
- TDS = 118 mg/L
- Suspended and dissolved material is transported downstream by gravity
- Physical characteristics: Discharge (Q)

$Q = AV$ (m^3/sec)
A: cross-sectional area (m^2)
V: average velocity (m/sec)

Hydrograph



Contaminants

- Metals: Cu, Zn, Cd, Cr, Al, Hg, etc
- Organic compounds and organo-chlorinated compounds
- Fertilizers
- Sources: industrial effluents, mines, agriculture, surface runoff, etc.

Point-source contamination

Logging

Coal mining activity

Toxic heavy metals and low pH

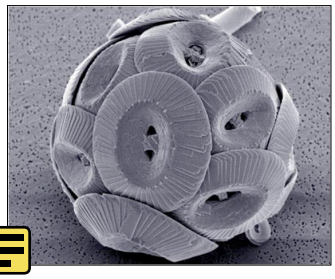
Drinking water guidelines in Canada

Toxic metals	Concentration (mg/L)
As	0.025
Pb	0.010
Hg	0.001
Volatile Organic chemicals	
Benzene	0.005
CCl_4	0.005
Microorganisms	
E. coli	none

3.2.3 Oceans

- contains dissolved and suspended solids
- TDS = 35 g/L (33-37 g/L) (rich in Na and Cl)
- dissolved and suspended solids are added to the oceans by the action of rivers, rain, marine volcanoes, ice and underground water flow
- material is lost from the oceans by evaporation (sea mist) and precipitation (silica, carbonates, etc.)

Chemical precipitation



Evaporative processes:

$Na^+ + Cl^- = NaCl$

$Ca^{2+} + SO_4^{2-} = CaSO_4$

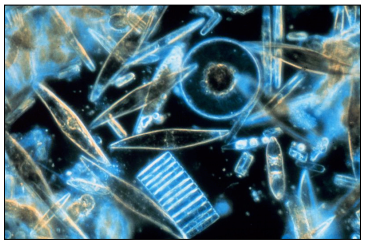
Carbonate precipitation:

$Ca^{2+} + 2HCO_3^- = CaCO_3 + CO_2 + H_2O$

$Mg^{2+} + 2HCO_3^- = MgCO_3 + H_2O + CO_2$

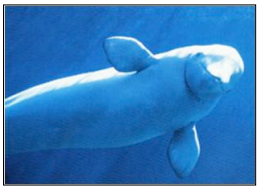
Silica formation:

$H_4SiO_4 = SiO_2 + H_2O$



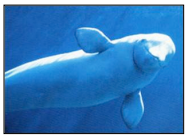
Pollutants: PAH

- PAH (polycyclic aromatic hydrocarbons)
  - Fused aromatic rings
  - By-product of incomplete fuel combustion (coal, oil, biomass)
  - Carcinogen, mutagen, teratogen
  - Lipophilic
- Hamilton harbour and Sydney Tar ponds
  - PAH, heavy metals, tar, PCBs...
- St. Lawrence beluga whale



Persistent Organic Pollutants: PCBs etc

- PCB (polychlorinated biphenyl) and other **synthetic** organochlorines commonly contaminate the sediments of harbours and major river systems discharging to the sea
- Virtually all the PCBs that have escaped into the environment are still there
  - **Persistent** organic pollutant (POP)
  - Lipophilic, carcinogenic



- PCBs are widespread in the Atlantic coastal region
  - several hundred parts per million (ppm) found in Beluga whales
  - found in edible crab, fillets of flounder, salmon etc (2 ppm Health Canada limit)
- Sydney Tar ponds
  - Waste from steel mill
  - 3.8 tonnes PCBs!

Heavy metal pollutants

- Natural and anthropogenic sources
- Anthropogenic sources include
  - Offshore oil and gas development
  - Industrial effluents
  - Municipal wastewater discharges
  - Urban runoff
  - Volatile emissions from incineration and combustion that reach the oceans via the atmosphere
  - Mining facilities
  - Ocean dumping (Rupert Inlet, BC; 400 Mt deposited)

Minamata mercury

- Hg
  - Lipophilic
  - Biomagnifies up food chain
- Minamata
  - 1950's Japan
  - Inorganic Hg & methylmercury discharged into Minamata fishing bay by chemical factory
  - Taken up by shellfish/fish → food chain to humans
  - Led to neurological disease

Tomoko in the Bath

Spills

- Ocean traffic and industrial operations along the coast (e.g., pulp and paper mills) are the source of most spills.
- In the Arctic, the annual sea lift of fuel and other supplies to remote communities and industries constitutes one of the largest sources of oil contamination.
- Elevated levels of hydrocarbon contamination have been documented for specific Arctic areas, and bioaccumulation in benthic fish species such as flounder has been

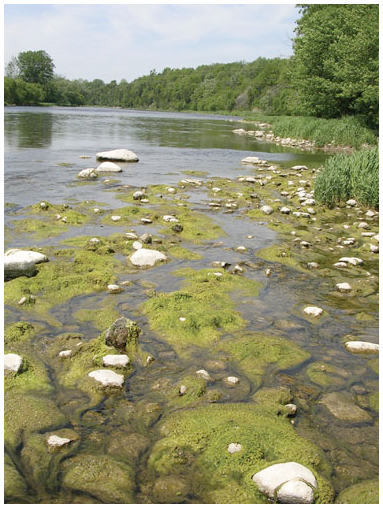
Pulp and paper mill discharges

- Buildup of wood fiber in the receiving waters.
- Depending on the production process, pulp and paper mills may also be major sources of toxic chemicals, including dioxins and furans.
- These chemicals have been found in the fatty tissue and muscle of crab and other shellfish in the Pacific region, with the result that some commercial and noncommercial fisheries were closed, beginning in the late 1980s

Nutrients, eutrophication and toxins

- Runoff of agricultural fertilizers and animal wastes, aquacultural operations (hatcheries and cage sites), municipal effluents, and industrial wastewater(e.g., from the food-processing industry), are primary sources of elevated levels of nutrients such as nitrogen and phosphorus in the oceans.
- P is a limiting nutrient in freshwaters
- N is limiting in the oceans

Eutrophication



continued

- Eutrophic waters can contain large amounts of cyanobacteria and algae which can affect the taste
- Some microorganisms can also produce toxins
- Excessive algal growth can lead to anoxia (O_2 depletion)
- Anoxia creates a stress amongst aquatic species and can also be responsible for the formation of H_2S, which is toxic
- Water quality is degraded and fisheries are affected
- Experimental lakes in Ontario

Experimental lake area (ELA)

Lake 226 in 1973

Lake 227 in 1994 (green) and lake 305 (blue)

Sources of phosphorus

- Laundry detergents have been a major source of phosphorus in freshwaters
- Between 1960 and 1970, most detergents contained 50-65% (per weight) of Na-tripolyphosphate
- Used as a surfactant
- Between 1960-1970, 3 millions kg/yr of detergent were used
- Surface waters (lakes and rivers) turned green
- Present-day detergents do not contain P (1973)
- Lake Erie
- http://www.dfo-mpo.gc.ca/regions/central/science/enviro/ela-rle_e.htm

Toxins

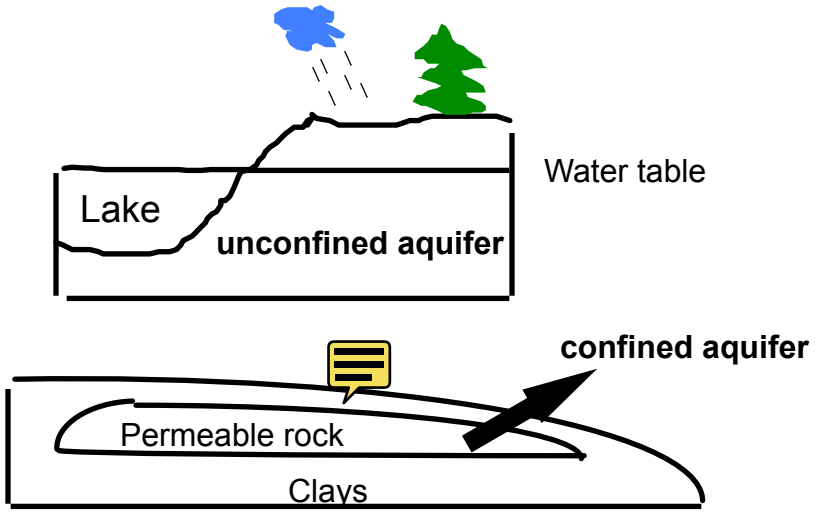
- Certain species of phytoplancton produce toxins during excessive algal growth
- Generally non-toxic for aquatic life, but some can be highly toxic once introduced in the trophic chain, especially for humans
- Intoxication by mussels is one example

Municipal waters

- Municipal wastewater is still one of the major sources of marine contamination in Canada.
- **Municipal wastewaters** (including storm sewers) are a source of organic and metal toxic substances.
- Inadequately treated municipal wastewaters contain bacteria, viruses, and protozoans, which become concentrated in filter-feeding organisms such as clams and oysters, making them unfit for human consumption.

3.2.4 Groundwaters

- a small proportion of freshwater is held in aquifers
- **Aquifer**: geological unit that allows the transport of water (porous, permeable): sand
- **Aquiclude**: geological unit that does not allow the transport of water (impermeable)



(See Fig. 12.5)

Mass balance concept (p.28)

- 3 possible outcomes for a pollutant in a specific location in the environment:
  - can remain at the location
  - can be transported
  - can be eliminated or transformed

Change in storage of mass = mass transported in – mass transported out = mass eliminated by sinks or produced

input rate = output rate + decay rate + accumulation rate

- steady state: input rate = output rate (no storage change)

Sources of contamination

- **non-point sources**:

  - fertilizers. pesticides, acid rain, atmospheric fallout, surface runoff, etc
- **point sources**: waste disposal:

  - sewage sludges, landfills, livestock wastes, mine tailings, wells for disposal of liquid wastes, fly ash from coal-fired power plants, etc
- **point sources**: leaks and spills

  - manufacturing facilities, leaky tanks and pipelines, wood preservation facilities, etc.

3.3 Transport and dispersion

- soluble and particulate pollutants
- Physical transport
  - advection: bulk movement of water or air

flux density (J) = rate at which a chemical is transported by unit area

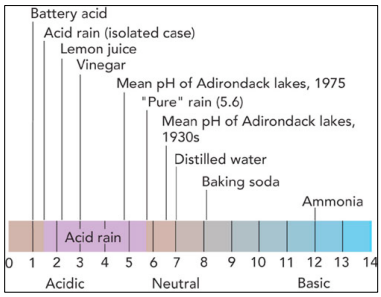
J = CV

C: chemical concentration

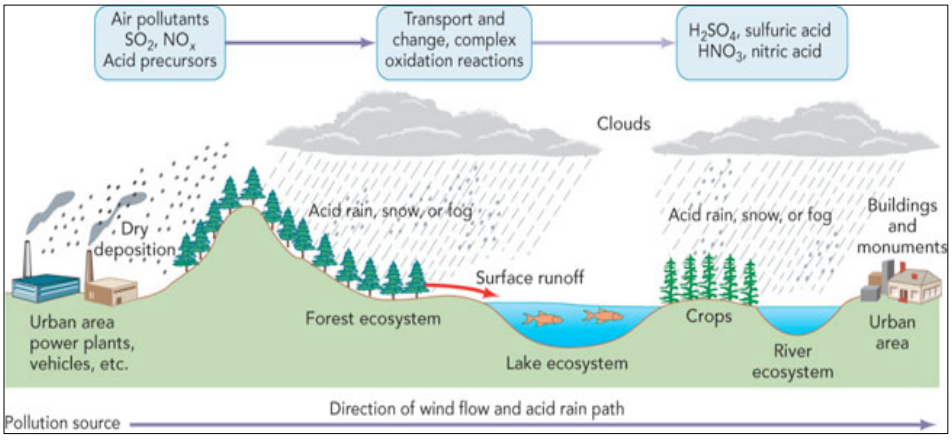
V: fluid/air velocity

Acidification

- Characterized by an increase of the concentration of protons ([H^+])
  - Recall pH = -log[H^+]
- Caused by acid rain and acid mine drainage (acidic leachate rich in metals)
- Acid rain is produced when SO_2 and NO_x and their oxidation products are present in the atmosphere
- The main acidifying species are H_2SO_3, H_2SO_4 and HNO_3 and they are returned to the earth by a process known as wet deposition (rain, snow)



Cycling of acidifying species



Acid rain

- Normal unpolluted rain is slightly acidic and the pH is around 5.6
  - Due to the equilibrium between CO_2 and H_2O

$$CO_2\,(g) + H_2O\,(l) = H_2CO_3\,(aq)$$

$$H_2CO_3\,(aq) = \mathbf{H^+}\,(aq) + HCO_3^-\,(aq)$$

- An extreme case of acidification in Canada is in Dorset, Ontario, an area submitted to intense acid precipitations
  - Rainwater is pH = 4.1 due to SO_2 & NO_x emissions

Acid rain

- Rain is classified as acid rain when the pH < 5.6
- Susceptibility of a certain water body to acid rain depends on its capacity to act as a buffer or to neutralize the effects of the acidity
  - Depends on the composition of the underlying rocks and soils
  - Carbonate rocks are good buffers, but granitic rocks are not

$$\mathbf{H^+}\,(aq) + HCO_3^-\,(aq) = H_2CO_3\,(aq)$$

$$H_2CO_3\,(aq) = CO_2\,(g) + H_2O\,(l)$$

Sources of SO_2 and NO_x

SO_2

- **Natural**
  - Forest fires
  - Volcanic eruptions (e.g. Mt. Pinatubo)
- **Anthropogenic**
  - Coal-fired power stations
  - Smelters of sulfide-bearing ores

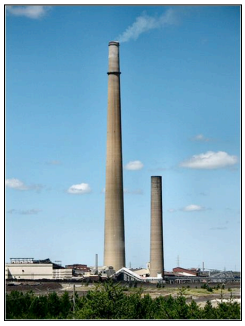
NO_x

- **Natural**
  - Forest fires
  - Soil gases
  - Lightning
- **Anthropogenic**
  - Power plants
  - Motor vehicle emissions

Dry deposition

- Dry deposition episodes occur between wet deposition periods
- Vegetation, soils and water absorb SO_2 and NO_x gases and particular material
- Once incorporated, those compounds are transformed in acidic species (SO_2 in SO_4^{2-} and NO_x in NO_3^-)
- 40 km away from Sudbury, 55% of the S atmospheric deposition originates from dry deposition

Sudbury – Inco superstack

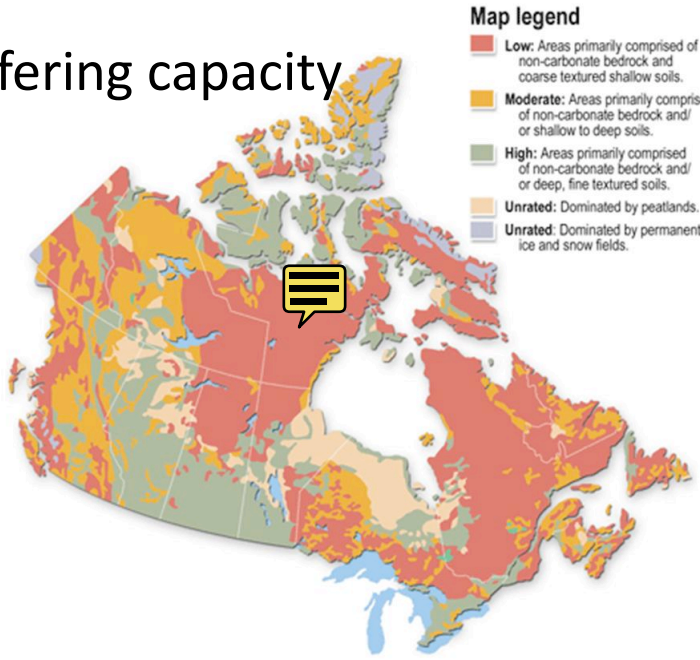


- Acid pollution from smelters
  - 1969
    - Govt. Ontario told Inco (main mining company & polluter) to reduce emissions
    - INCO built the "Superstack", 380 m
    - Dilute and disperse?
    - Just contaminated a larger area
      - >7000 lakes in ON, QC
    - Today, SO_2 emissions 90% lower
      - SO_2 "scrubbed" out before emitted

Acidification in Canada

- The Canadian Shield region of eastern Canada (west of Kenora (pH 4.7)) and parts of the Appalachians or Atlantic Maritime ecozone (Kejimkujic (pH 4.6)) are vulnerable to acidification
  - Thin soils and granitic bedroc: little natural buffering capacity for neutralizing acid deposition
    - Buffer – resist changes to pH upon addition of acid/ base
- Deposition from:
  - Smelters in northern MB, ON, QC
  - Thermal generating stations in ON, NB, NS and USA

Buffering capacity



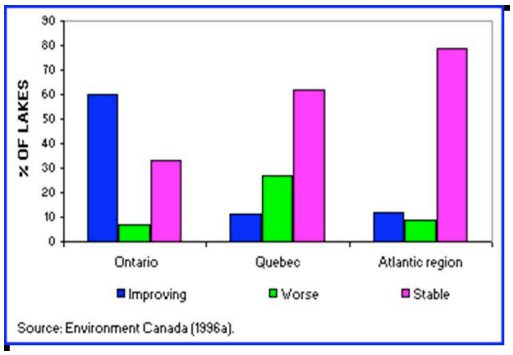
Environment Canada

Lake acidity

- In the Sudbury region, the majority of monitored lakes showed an improvement in acidity
  - Attributed to the substantial control of SO_2 emissions from Sudbury's nickel smelters
- Despite significant SO_2 controls in eastern Canada, the acidity of most lakes showed little change (stable) in the remainder of ON & QC

Trends in Lake Acidity

- SO_4 lake levels lower (lower SO_2 emissions from scrubbing etc), but lakes still acidified
- NO_x emissions changed little
- ON, QC and the Atlantic region also affected by continuing transboundary flow of acidifying emissions from the United States.



Bio-indicators of acidity

- Certain phytoplankton species (diatoms) can be used as indicators
  - Acidic waters: *Eunotia pectinatus, Fragilaria acidobionta, Pinnularia subcatica, Tabellaria quadriseptata*
  - Acidic and metals (Cu, Zn): *Eunotia exiga, E. tenella, Frustulina rhoboides saxonica, Pinnularia bilseana*
  - Non-acidic waters: *Cyclotella meneghiniana, Fragilaria construens, F. crotonensis*
- Diatoms can remain in sediments and be used as paleo-indicators to reconstruct acidity patterns

Impacts of Lake Acidification

- Change of algal species, but the population density remains the same
- Certain aquatic plants (macrophytes) can take over in acidic waters (*Sphagnum*)
- Invertebrate benthic organisms decrease in number at low pH (mussels are affected)
- Fish like salmon, trout, etc. are highly sensitive

Reducing acidity

- The acidification of surface waters can be neutralized by the addition of carbonates and lime
- Neutralization at higher pH promotes metal precipitation
  - Great for water quality, but some side effects (Al + fish gills)
- Diminution of gas emissions
  - Requires an agreement between countries, governments, industries and a respect of the agreement