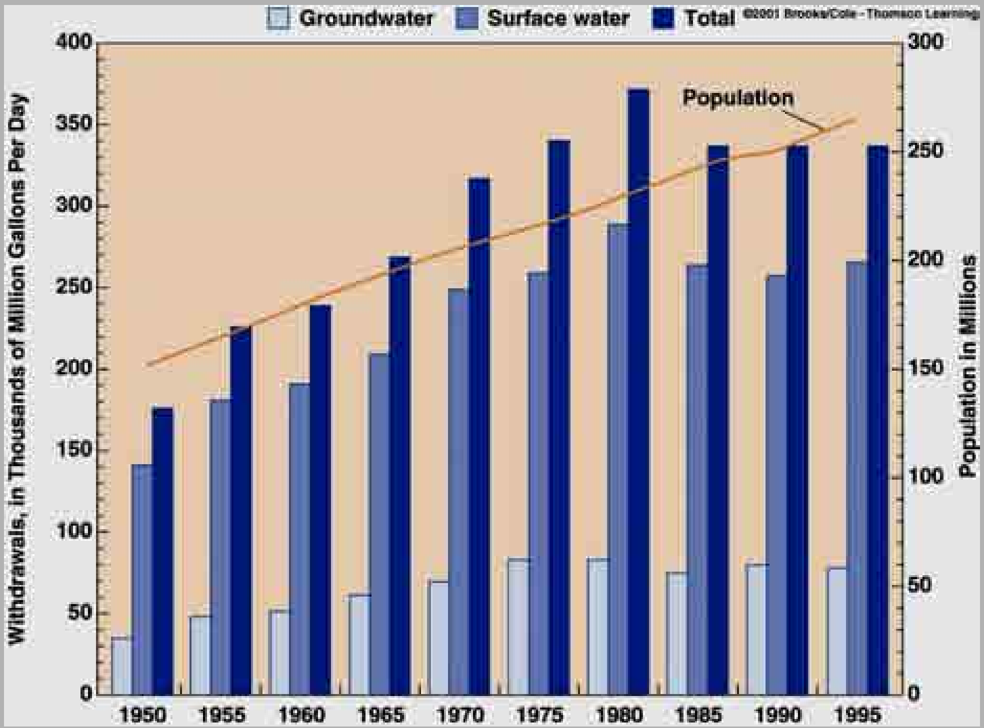
Groundwater Part II

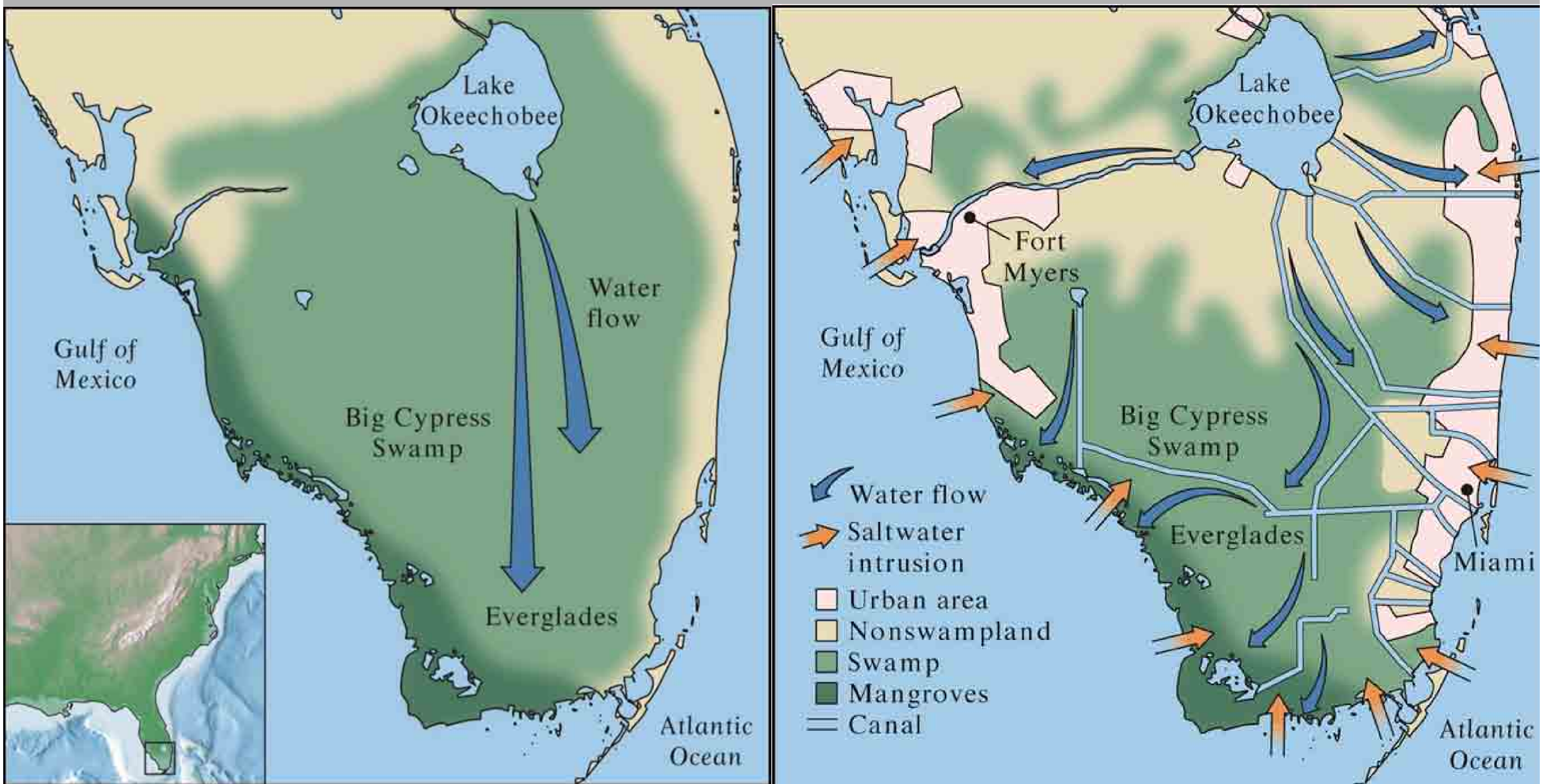
The Human Impact

- Currently, about 40% of all the water used in the U.S. is groundwater. Failure to protect this important resource may result in lowering of the water table, loss of hydrostatic pressure, subsidence, saltwater incursion, and contamination.



Wicander and Monroe (2002)

Human impact

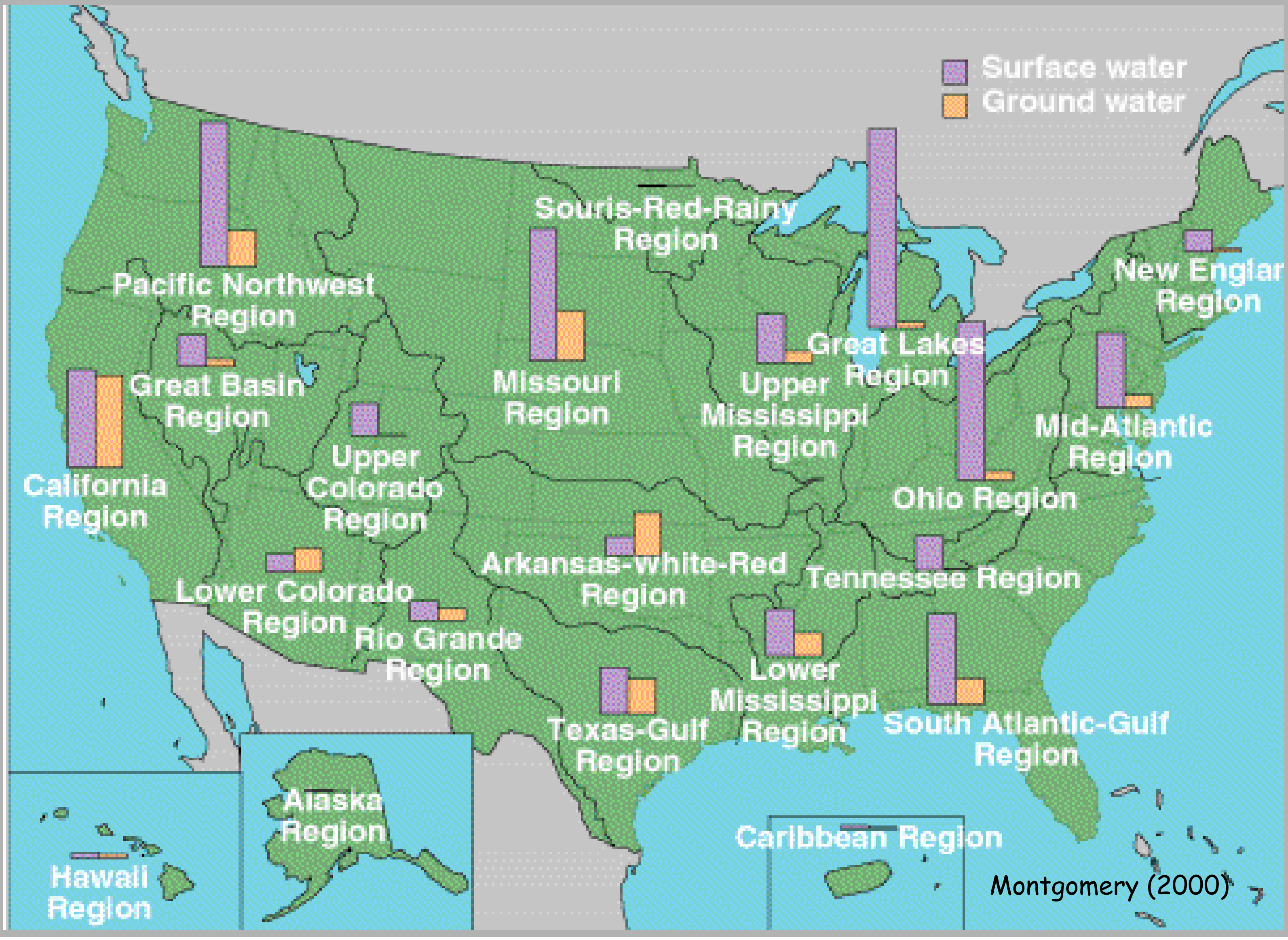


Marshak (2002)

Water use and supply

- Of the 4,200 billion gallons of water that fall on the US each day, 1,400 billion gallons is available for streamflow and groundwater recharge. But this water is often not where it is most needed.
- Humans require 1 gallon of water per person per day, yet in the US 1,800 gallons per person per day are withdrawn from the system for a variety of purposes.

Water withdrawals in the US

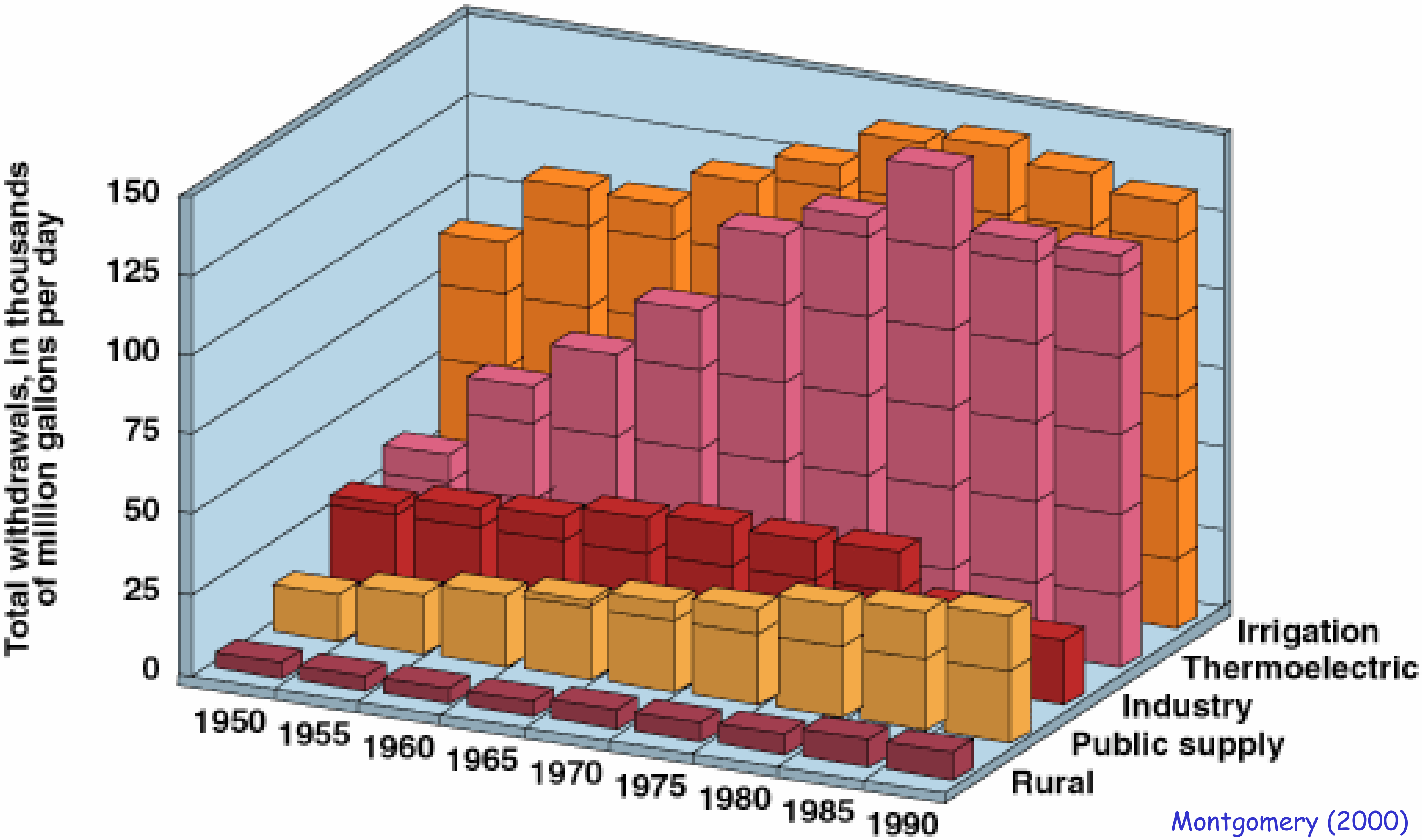


Montgomery (2000)

Water use and supply

- The principal categories of water use are:
  - Municipal supplies (home use)
  - Rural use (rural homes and watering livestock)
  - Irrigation
  - Self-supplied industrial use
  - Thermo-electric power generation

Water withdrawal by sector



Montgomery (2000)

Groundwater withdrawal – the hazards

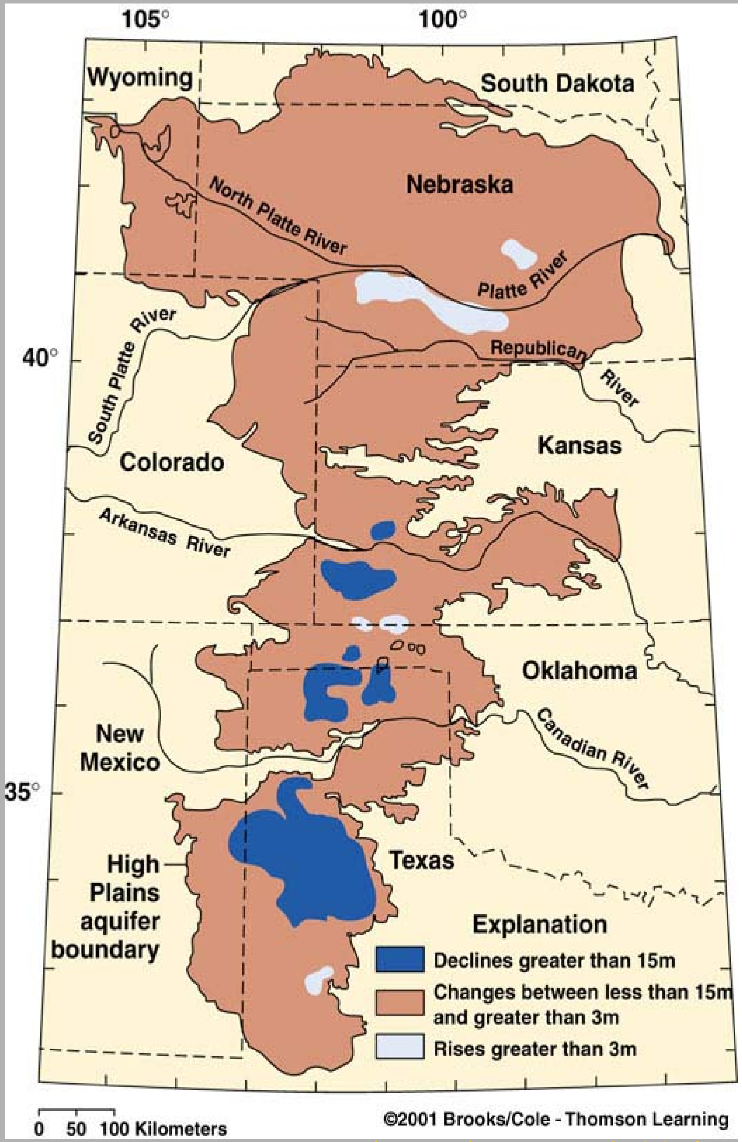
- **Lowering the water table**
  - **Where groundwater is being depleted by high rates of withdrawal which exceed the sustained yield an overdraft condition termed groundwater mining exists**
  - **In parts of Texas overdrafts have reached 95% - 20 times more water is removed than enters the system**

Water 'mining'

Montgomery (2000)

Lowering the Water Table

- Withdrawal of groundwater at a rate in excess of recharge results in lowering of the water table. In some areas of the High Plains water is being withdrawn for irrigation at 2-100 times the recharge rate.
- As a result, the water table in this important agricultural region has dropped greatly.
- Diversion of water from other sources or reduced irrigation will have major economic implications.



Wicander and Monroe (2002)

High Plains Aquifer Example

- The aquifer underlies 480,000km^2 of Kansas, Colorado, Nebraska, Oklahoma and Texas and contains as much water as Lake Huron (3,700km3). Produces 25% of US feed grain exports and 40% of wheat, flour and cotton exports
- Significant withdrawals began in the 50's and by 1980 the water saturated zone had decreased by an average of 3m and up to 30m in places
- A number of factors contributed to the problem:
  - Centre pivot sprinklers use ~4,000 litres per minute 24 hours a day
  - Subsidies encourage growth of water intensive crops like corn, tax breaks favour heavier groundwater use
  - "Use it or lose it" mentality

The solution?

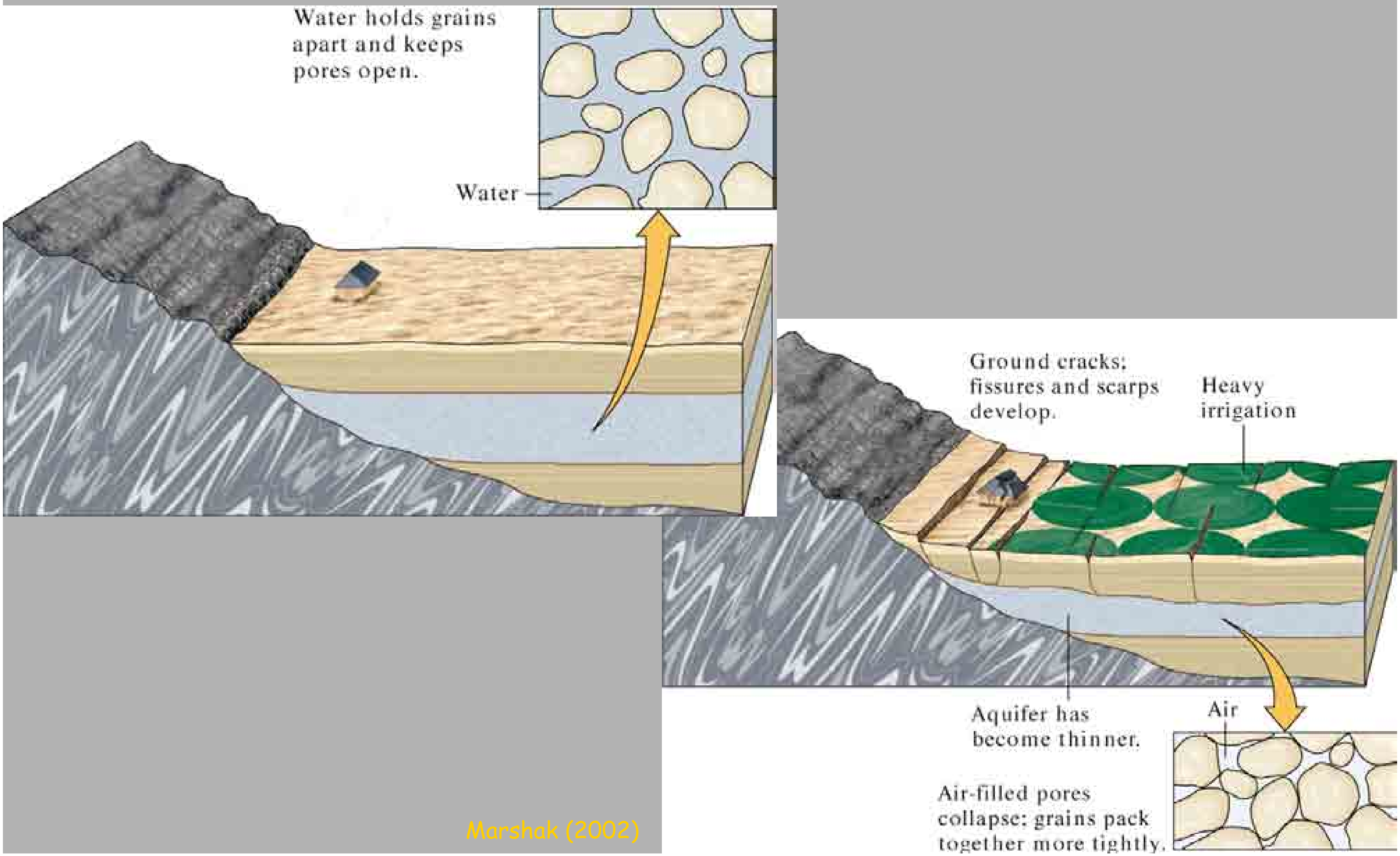
- LEPA – low-energy precision application decrease water use and reduce evaporation by 98%
- Mandatory water meters
- Use of treated waste water for irrigation
- Water diversion programs

Groundwater withdrawal – the hazards

- Compaction and subsidence
  - Removal of water from the aquifer causes the aquifer rocks to be compacted by the weight of the overlying rocks. This permanently reduces their porosity.
  - In addition surface subsidence may occur causing structural damage at high elevations and extensive flooding in low lying regions.
  - Parts of the San Joaquin Valley have subsided up to 9m.
  - While the subsidence can be halted it can rarely be reversed

Wicander and Monroe (2002)

Compaction



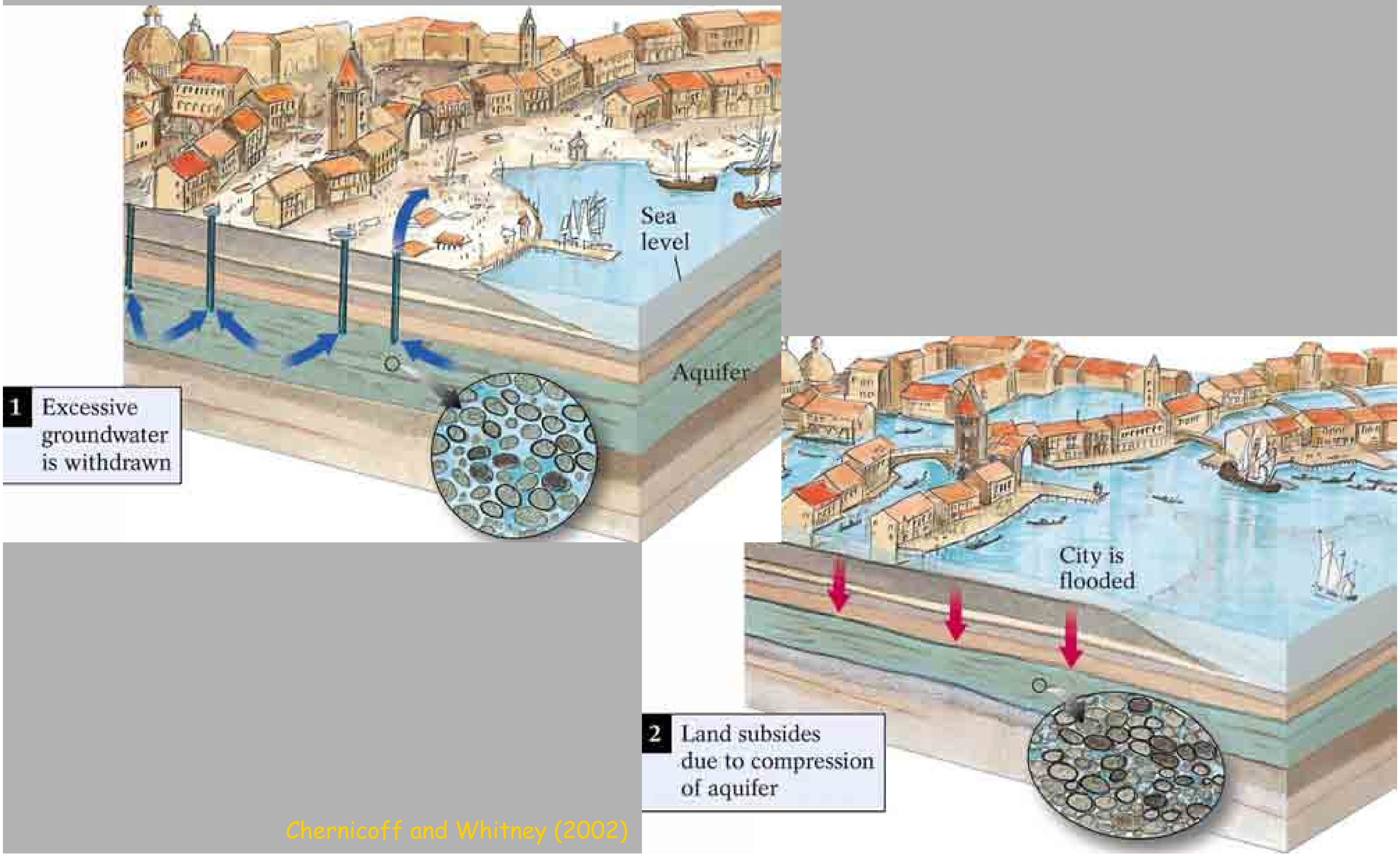
Marshak (2002)

Groundwater withdrawal

- **Groundwater withdrawal is responsible for the flooding and subsequent subsidence that has plagued Venice**

Marshak (2002)

Subsidence in coastal areas.



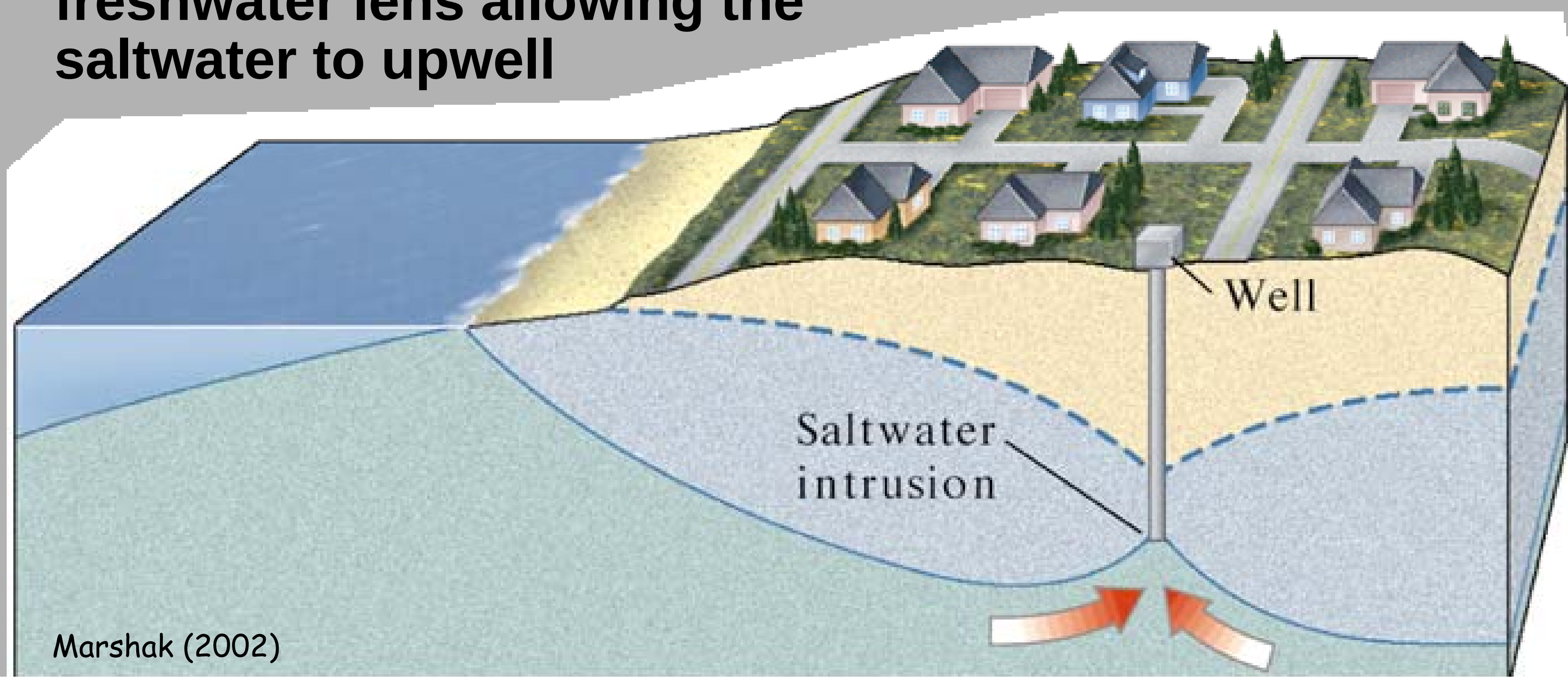
Chernicoff and Whitney (2002)

Subsidence due to groundwater withdrawal

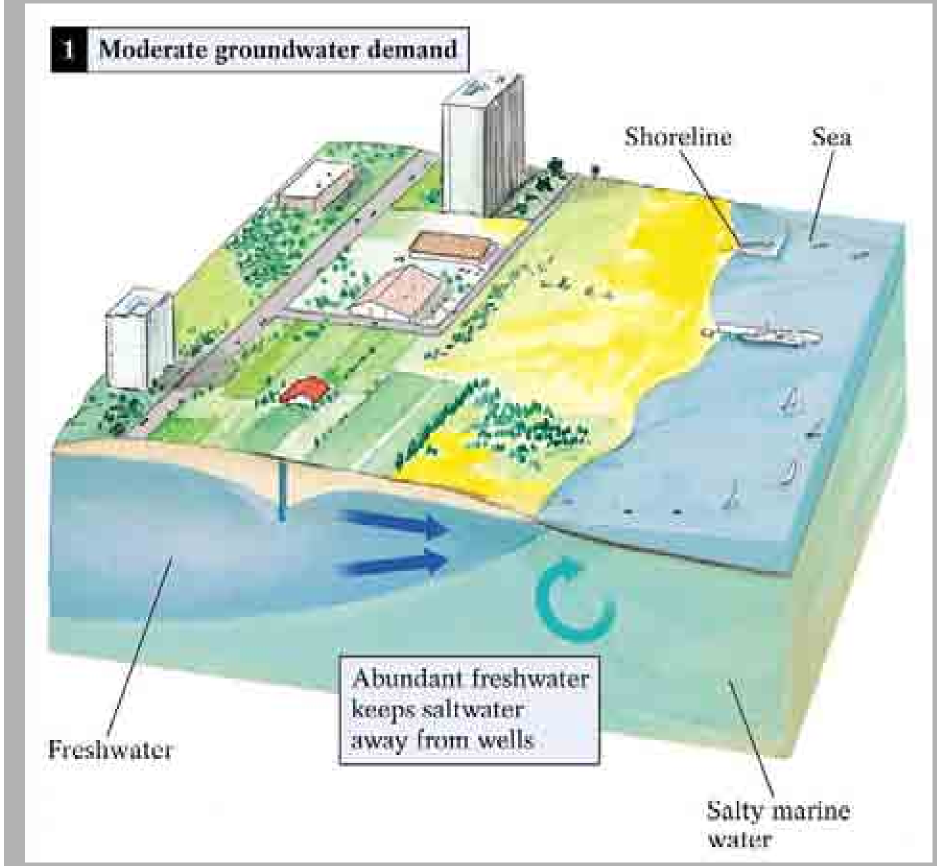
LOCATION	MAX. SUB. (M)	AREA AFFECTED (km^2)
Mexico City, Mexico	8.0	25
Long Beach, Calif.	9.0	50
Taipei Basin, Taiwan	1.0	100
Shanghai, China	2.6	121
Venice, Italy	0.2	150
New Orleans, Lou.	2.0	175
London, England	0.3	295
Las Vegas, Nev.	8.5	500
Santa Clara, Calif.	4.0	600
Bangkok, Thai.	1.0	800
Osaka & Tokyo, Jap.	4.0	3,000
San Joaquin Valley, Calif.	9.0	9,000
Houston, Texas	2.7	12,100

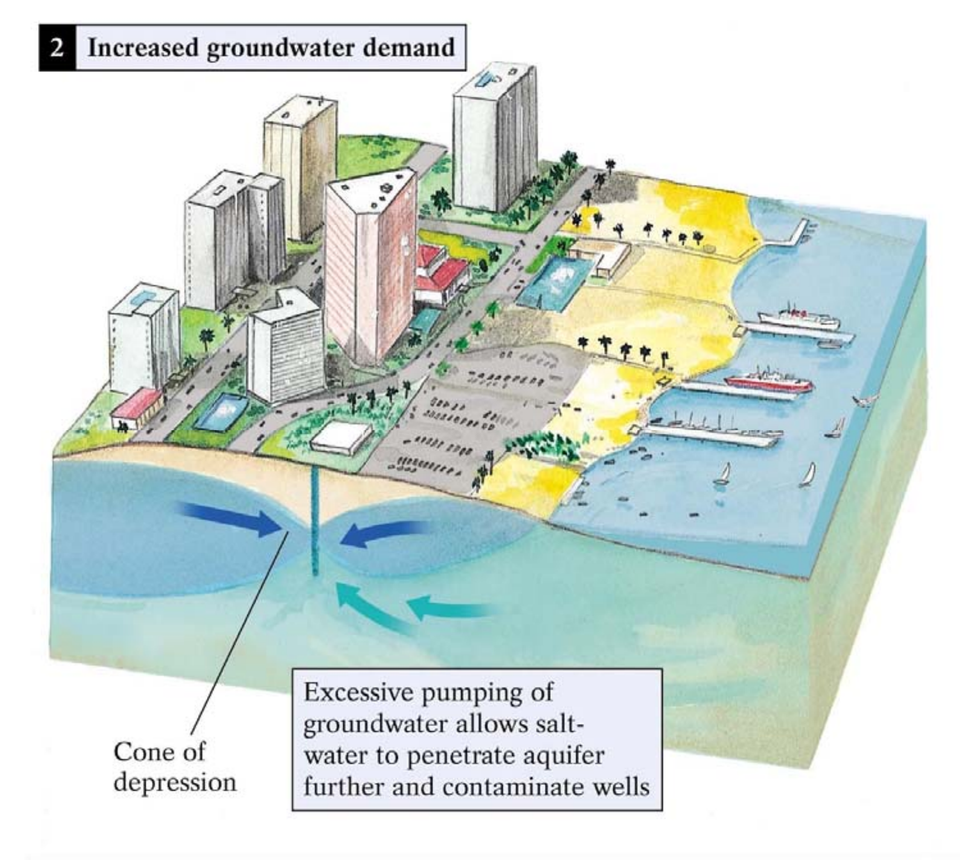
Groundwater withdrawal – the hazards

- **Saltwater intrusion**
  - **This is generally a problem in coastal regions. Because freshwater is less dense than seawater it tends to form a lens above saltwater.**
  - **Excessive depletion of the groundwater will thin the freshwater lens allowing the saltwater to upwell**



Saltwater intrusion.

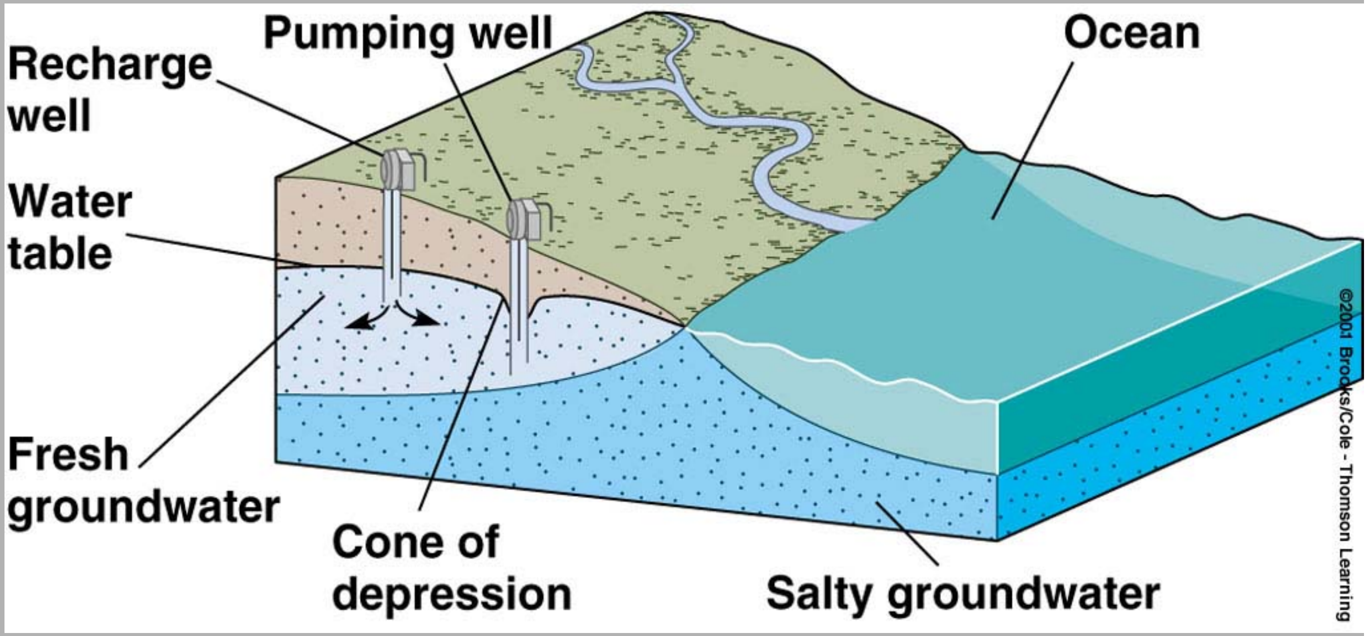




Chernicoff and Whitney (2002)

Remediation

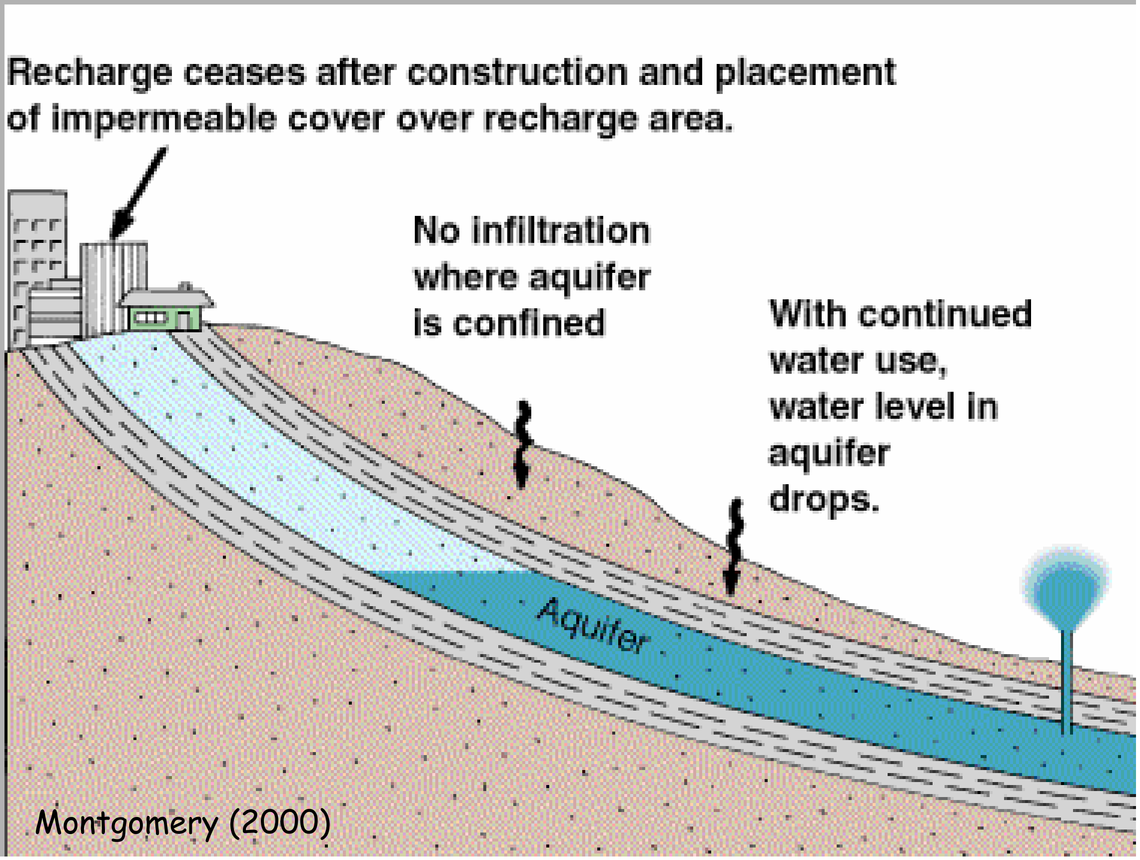
- Recharge wells or ponds are used to recharge the fresh water system and push the fresh-saltwater boundary to a depth beneath the reach of the water wells



Wicander and Monroe (2002)

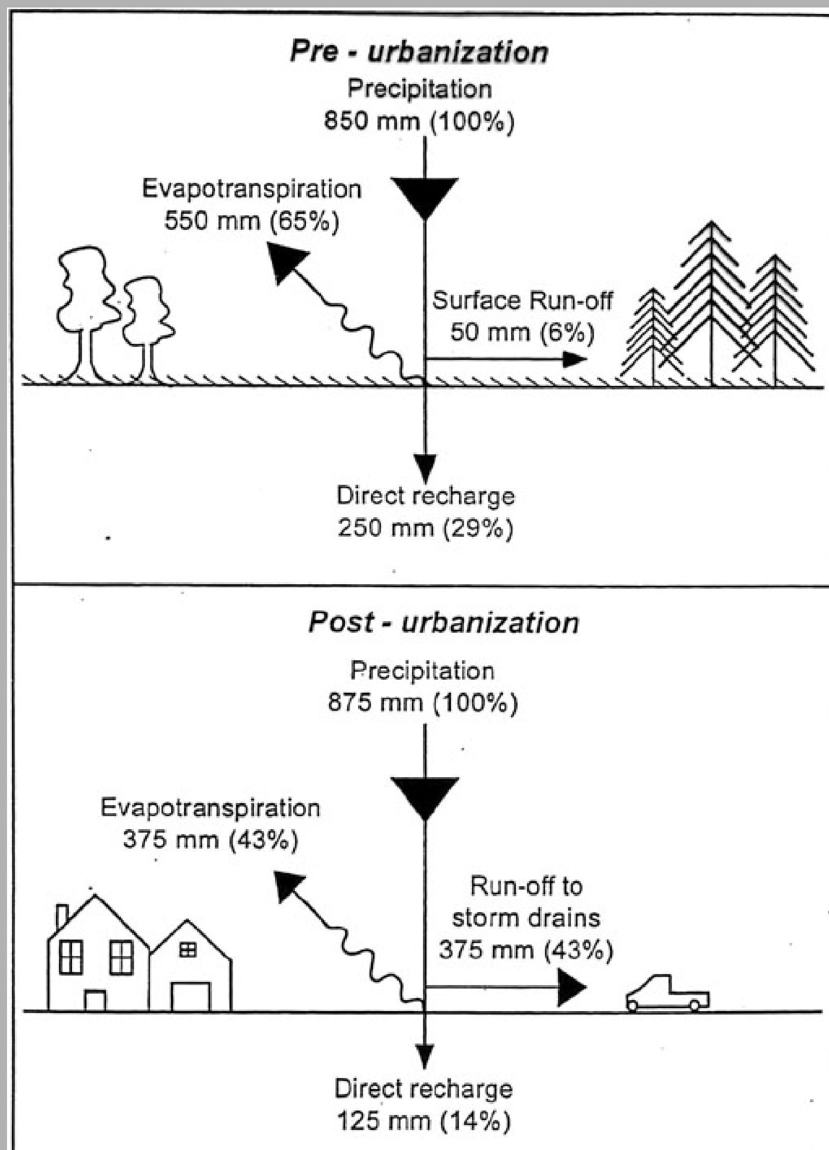
Groundwater withdrawal – the hazards

- **Loss of recharge**
  - Impermeable covers will have little effect on unconstrained aquifers but can be significant for confined aquifers
  - Filling in of wetland areas can also reduce the available recharge

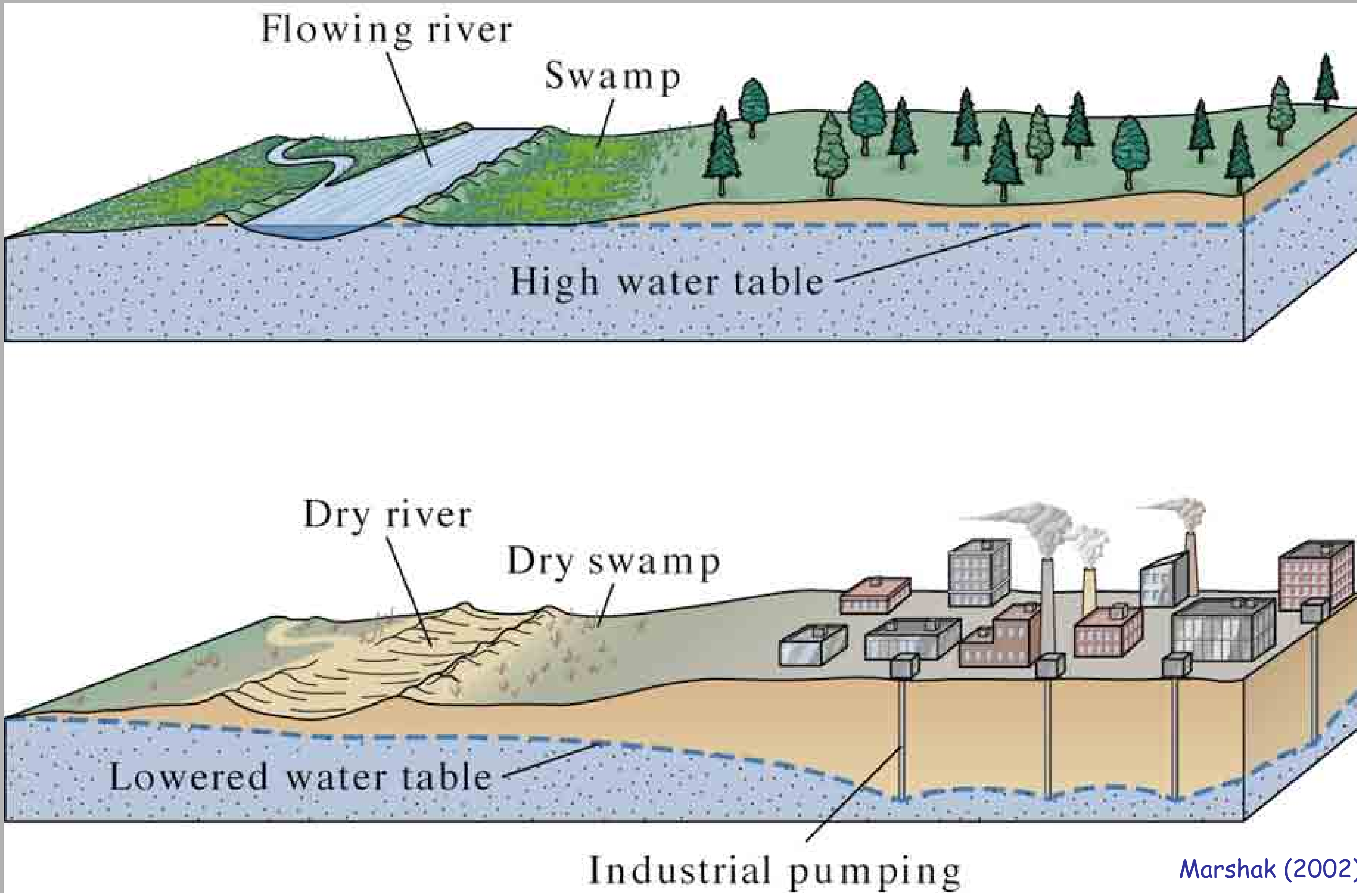


Montgomery (2000)

Urbanization



Water withdrawal



Marshak (2002)

Water quality

- **Stable elements occur as dissolved components in water. The concentration of these elements can either be expressed in terms of weight per volume (mg/L) or weight per weight (ppm or ppb).**
- **For drinking water less than 500 ppm of total dissolved solids (TDS) is preferable. However, the nature of the dissolved material is just as important as the abundance.**
- **Calcite is quite safe at levels up to 1000 ppm whereas many synthetic chemicals are toxic at 1 ppm**

Table 1 World water quality guidelines for drinking water.

Parameter	Canada	United States EPA	World Health Organization	Council of European Communities
INORGANIC				
Aluminum	—	—	0.2*	0.05
Arsenic	0.05	0.050	0.05	0.05
Barium	1.0	2.0	—	0.1
Boron	5.0	—	—	1
Cadmium	0.005	0.005	0.005	0.005
Chloride	250*	—	250*	—
Chromium	0.05	0.1	0.05	0.05
Copper	1.0*	1.3	1.0*	0.1
Cyanide	0.2	0.2	0.1	0.05
Fluoride	1.5	4.0	1.5	0.7
Lead	0.05	0.015	0.05	0.05
Mercury	0.001	0.002	0.001	0.001
Nickel	—	0.0	—	0.05
Nitrate (as N)	10.0	10	10	—
Sodium	200*	—	200	20
Silver	—	0.10*	—	0.01
Sulphate	500	400–500	400*	250
ORGANIC				
Alachlor	—	0.002	—	—
Aldicarb	0.009	0.003	—	—
Atrazene	0.06	0.003	—	—
Benzene	0.005	0.005	0.010	—
Carbon tetrachloride	0.005	0.005	0.003	—
1,2–dichlorobenzene	0.2	—	—	—
1,1–dichloroethane	—	—	0.000	—
1,2–dichloroethane	0.005	0.005	0.01	—
1,2–dichloroethylene	—	0.007	—	—
Ethylbenzene	0.002	0.7	—	—
Tetrachloroethylene	—	0.5	0.01	—
Toluene	0.024	1.0	—	—
Trichloroethylene (TCE)	0.05	0.005	0.030	—
1,1,1–trichloroethane	—	0.2	—	—
Xylene	0.3*	10.0	—	—

Note: all units expressed as $mg \cdot L^{-1}$; * denotes aesthetic objective

Groundwater Quality

- In rural America, up to 90% of the water for domestic use is groundwater. Groundwater is an important part of the water supplies of a number of large cities. Natural factors controlling groundwater quality include: 1) kind of material making up the aquifer, 2) solubility of the aquifer material, and 3) residence time of the water in the aquifer.
- The above factors control the amount and type of dissolved material, such as calcium, iron, and fluoride, in groundwater. Undesirable effects of the dissolved material in some groundwater include plugging of water heaters and pipes, offensive taste or smell, staining of clothing and fixtures, and inhibiting the effectiveness of detergents.

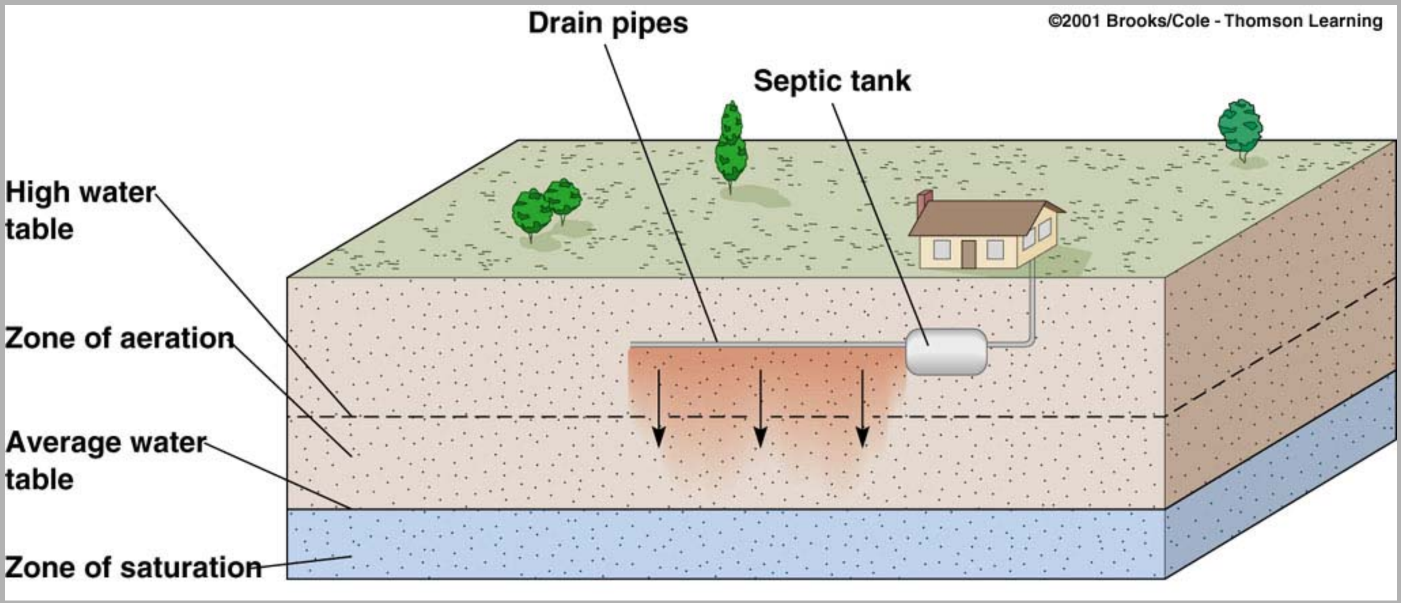
Water Quality

- In addition to geological controls on the water quality (e.g. limestone may generate hard water) human actions can play a significant role. The majority of organic and inorganic contaminants are related to human activity.
- High salt contents (bicarbonate and sulfate) can have a laxative effect
- High Fe or Mn can give water a metallic taste and stain laundry
- >3 ppm Cu can give skin a green tinge
- Fluoride contents of 1-1.5 ppm reduce the occurrence of tooth cavities

INORGANIC POLLUTANT	STANDARD, mg/L	HEALTH EFFECTS
Arsenic	0.05	dermal and nervous-system toxicity effects, paralysis
Barium	1.0	gastrointestinal effects, laxative
Boron	1.0	no effect on humans; damaging to plants and trees, particularly citrus trees
Cadmium	0.01	kidney effects
Copper	1.0	gastrointestinal irritant, liver damage; toxic to many aquatic organisms
Chromium	0.05	liver/kidney effects
Fluoride	4.0	mottled tooth enamel
Lead	0.05	attacks nervous system and kidneys; highly toxic to infants and pregnant women
Mercury	0.002	central-nervous-system disorders, kidney disfunction
Nitrates	10.0	methemoglobinemia ("blue baby syndrome")
Selenium	0.01	gastrointestinal effects
Silver	0.05	skin discoloration (argyria)
Sodium	20–170	hypertension and cardiac difficulties
	70.0	renders irrigation water unusable

Groundwater Contamination

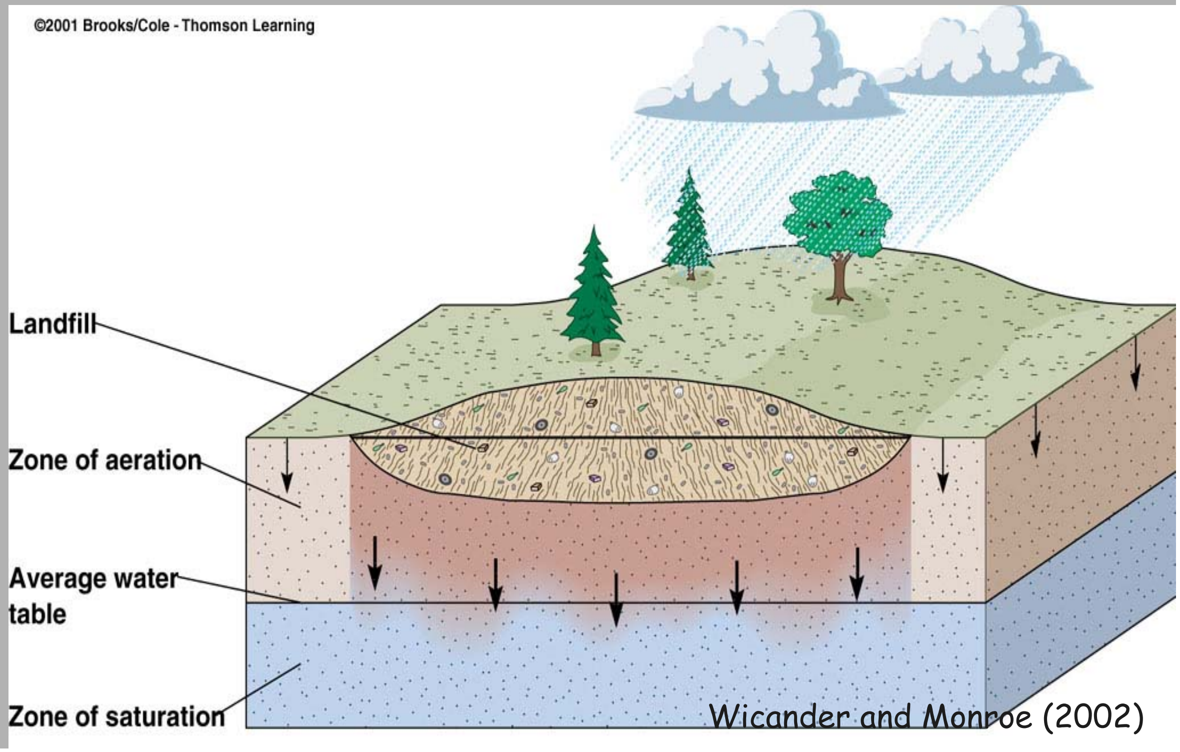
- The most common sources of contamination are sewage, landfills, toxic waste sites, and agriculture. As sewage from septic tanks flows through the zone of aeration, oxidation, bacterial degradation, and filtering cleanse the sewage by the time it reaches the zone of saturation. If the water table is close to the surface or if the sediment or rocks are very permeable, the sewage water may not be cleansed and can contaminate the local groundwater.



Wicander and Monroe (2002)

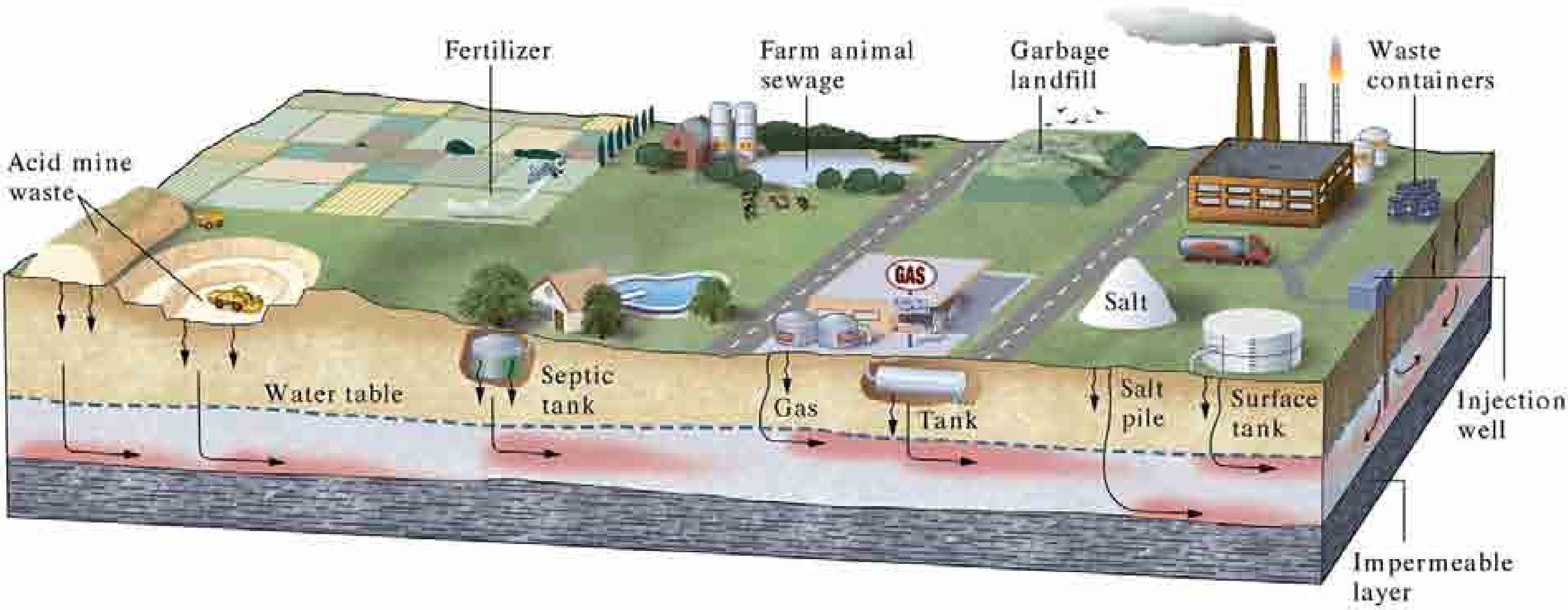
Groundwater Contamination

- Landfills can be a source of groundwater contamination unless carefully designed with impermeable caps and liners. If improperly constructed, toxic substances such as paint, solvents, cleansers, pesticides, and battery acid can be leached from landfills and contaminate groundwater.
- Agricultural runoff and improper disposal of hazardous chemical waste contaminate surface water, soil, & groundwater.



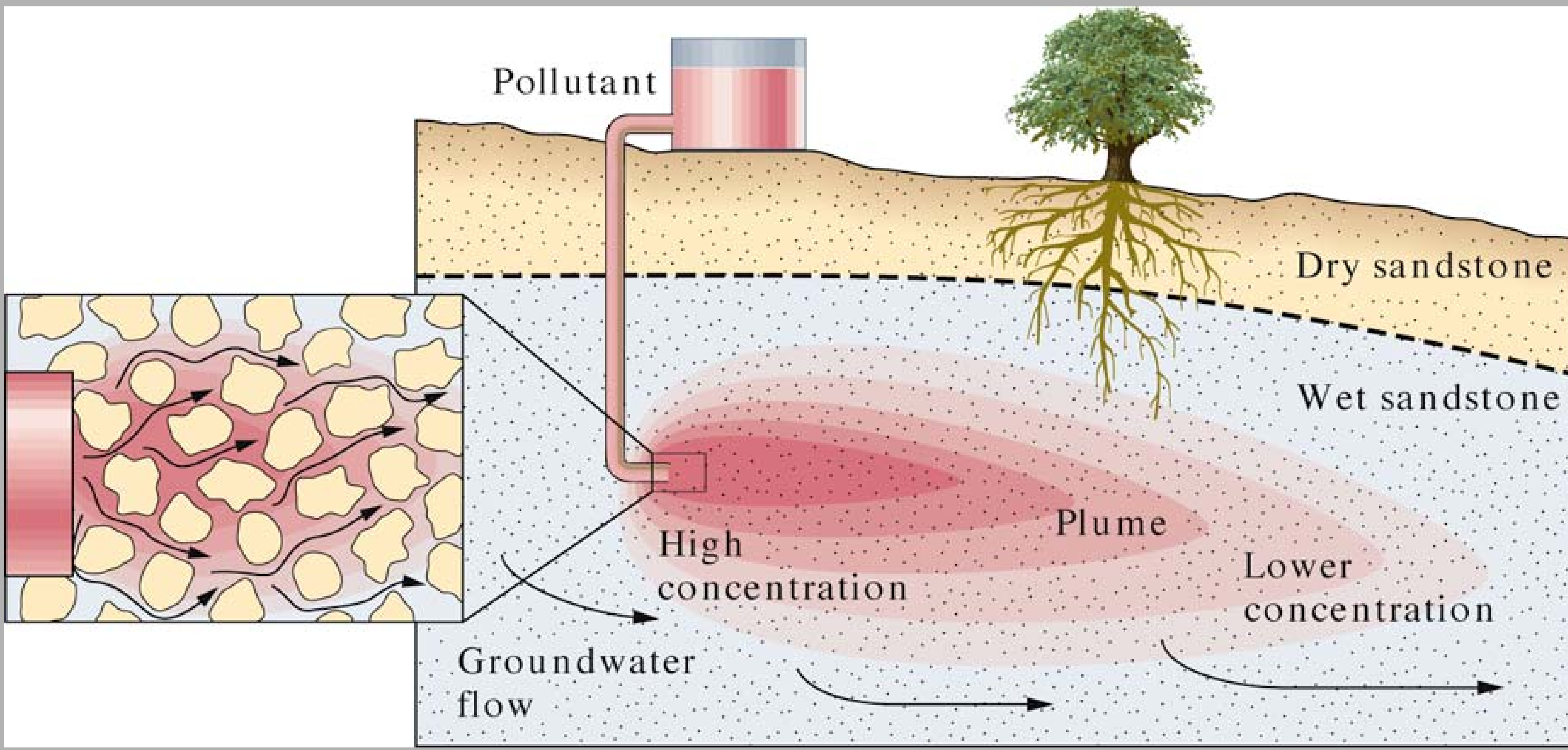
Wicander and Monroe (2002)

Sources of contamination



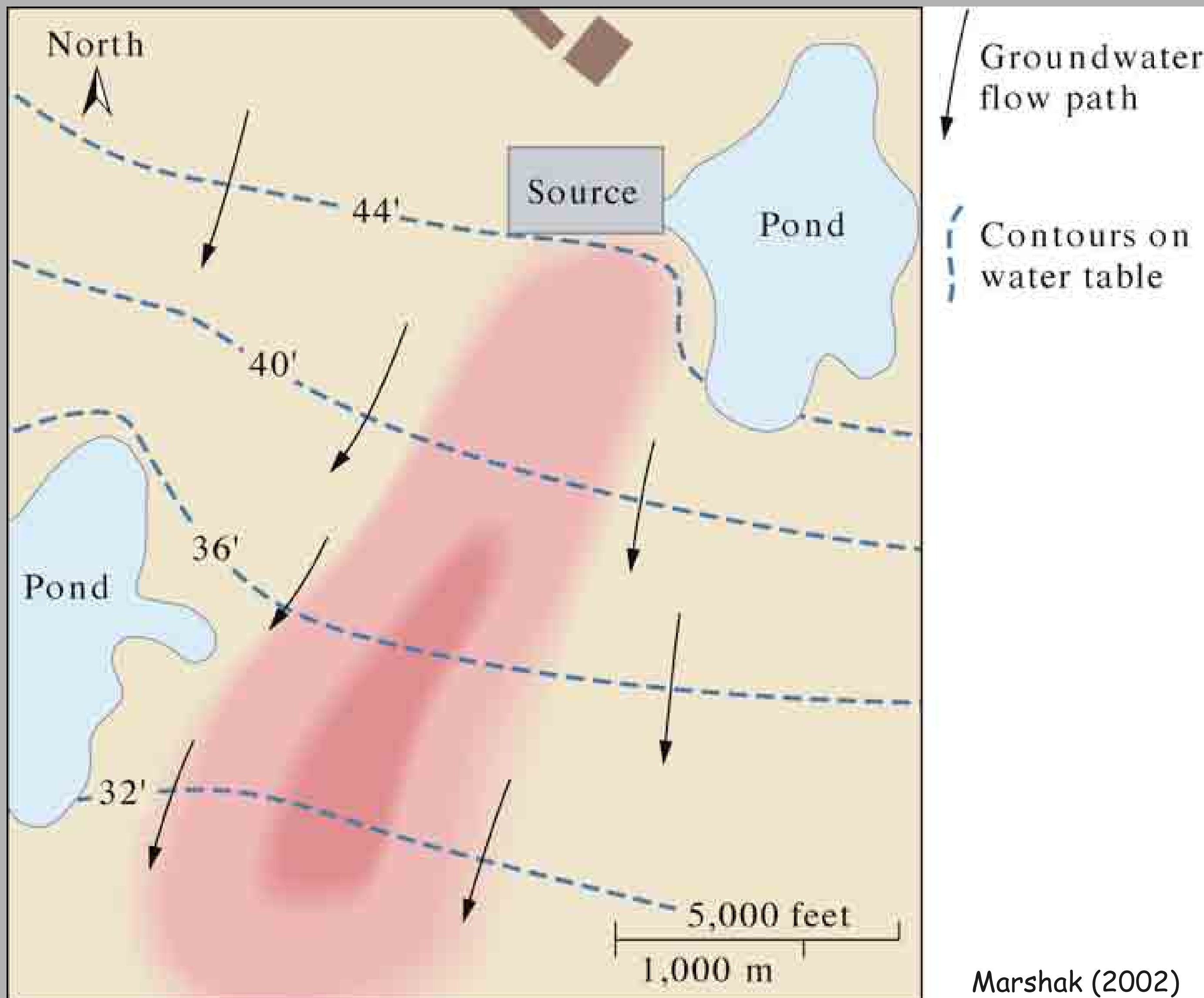
Marshak (2002)

Groundwater contamination



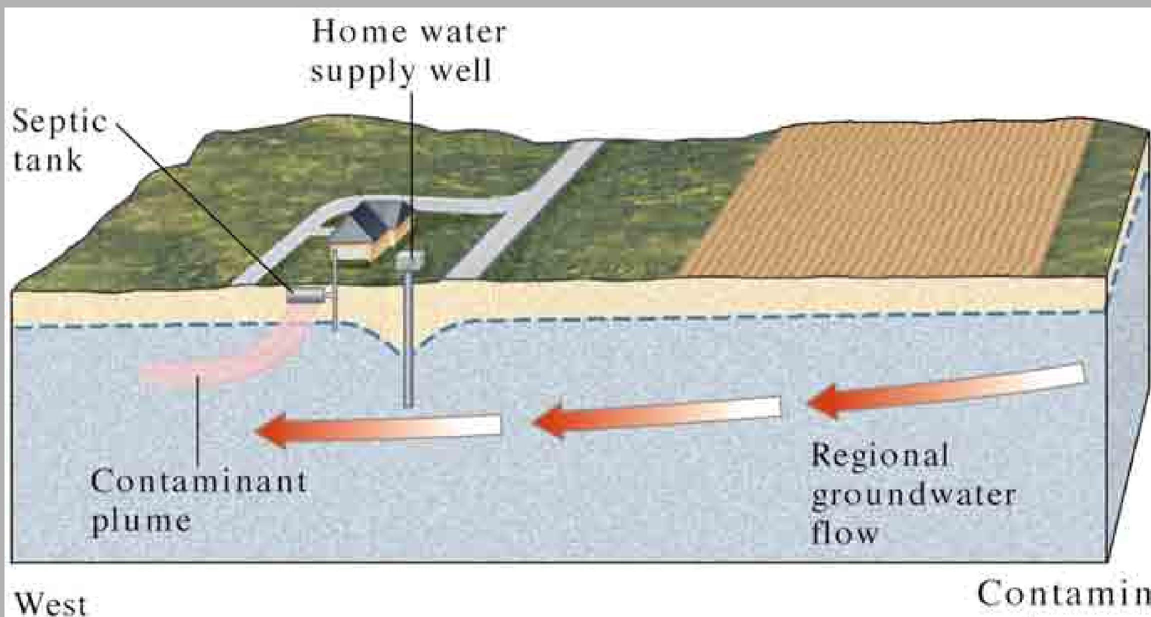
Marshak (2002)

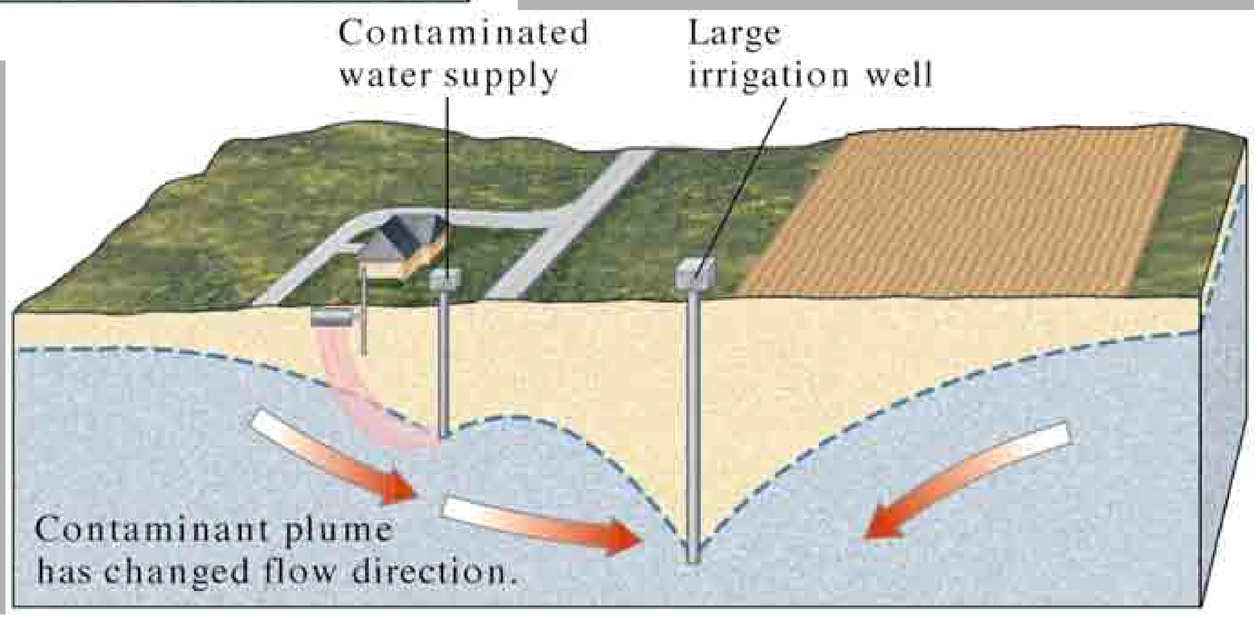
Contamination plume



Marshak (2002)

Contamination plumes





Marshak (2002)

Acid Mine Drainage (AMD) or Acid Rock Drainage (ARD)

- Deals with rocks which contain an abundance of sulfide minerals
- is defined as the the outflow of acidic water
- Usually at metal and coal mines, but can occur anywhere the earth is disturbed…construction sites, subdivisions, transportation corridors
- Partly a natural process via rock weathering, but humans exacerbate this process

- Occurrences:
  - Subsurface mining: happens below water table, therefore water is continuously being pumped out during mining, then mining ceases, water floods back in, and begins the process of AMD.
  - Tailings ponds
  - Exposure to air and water oxidizes the metal sulfides (Ex. Pyrite FeS_2)
  - Acidity increases
  - Copper mines are the worst

Effects

- Yellow boy: a yellow orange precipitate
- Discolors water
- Smothers plants and animal life, destroys/disrupts ecosystems
- The ARD can contain toxics: Ni, Cu, Pb, As, Al, Mn

A stream affected by acid mine drainage…

http://www.depweb.state.pa.us/abandonedminerec/

The Rio Tinto River, Spain… Courtesy of the NASA Ames Research Center

http://www.bucknell.edu/x38124.xml

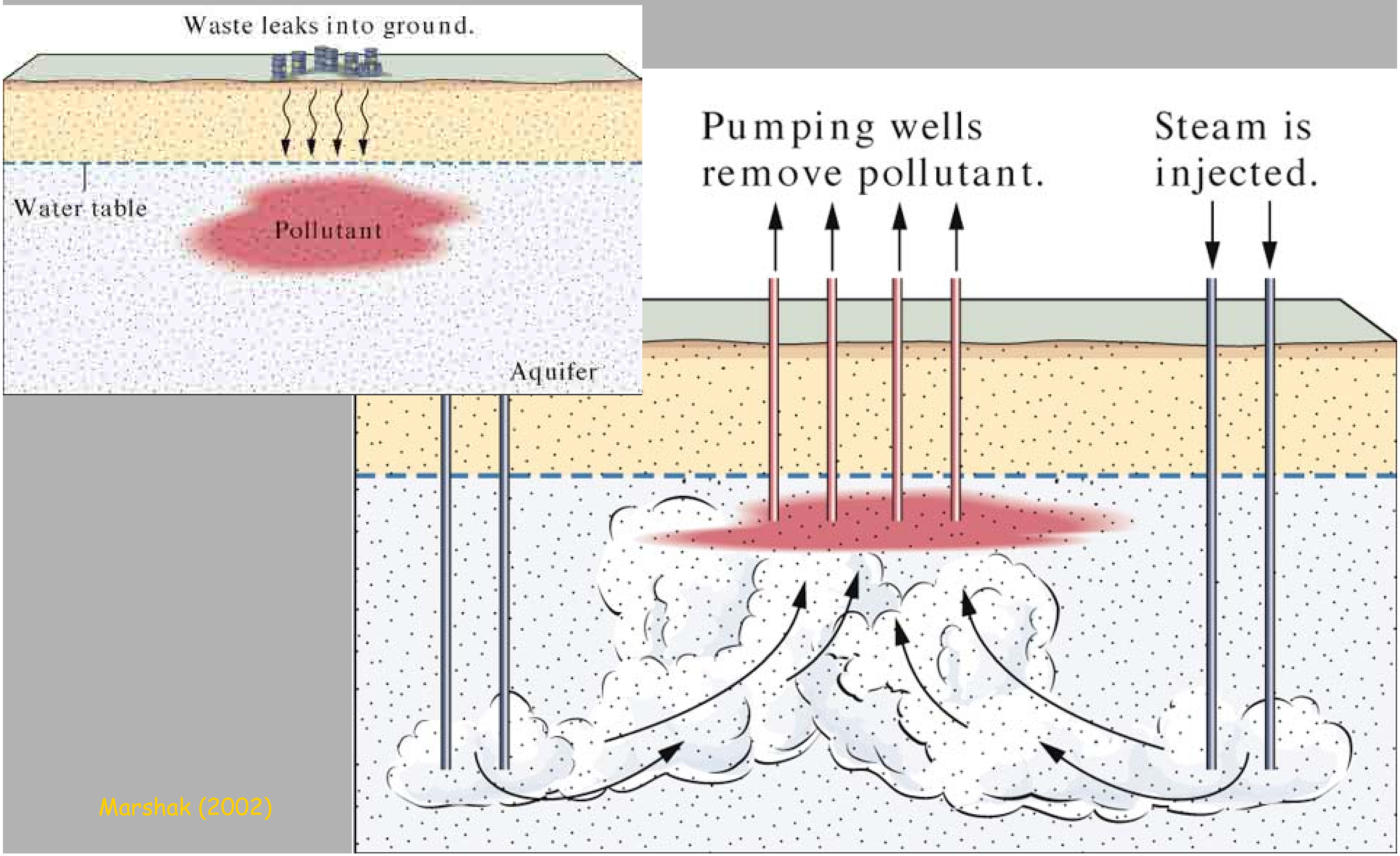
Bucknell University Associate Professor of Geology Carl Kirby paints a bright picture for Pennsylvania's acid mine drainage. Literally. His Volkswagen van bears a coat of paint made from the stuff.

The mine drainage sediment -- commonly called "yellow boy" -- is, essentially, iron hydroxide, or rust.

Treatment (some of many methods used….) of AMD

- Neutralize it!!!
- Canada: MEND Program (Mine Environment Neutral Drainage)
- Carbonate Neutralization with limestone chips
- Ion Exchange
- Constructed wetlands, adding a spectrum of bacteria and some wetland plants….reverses the problem by precipitating out the heavy metals

Remediation of Groundwater

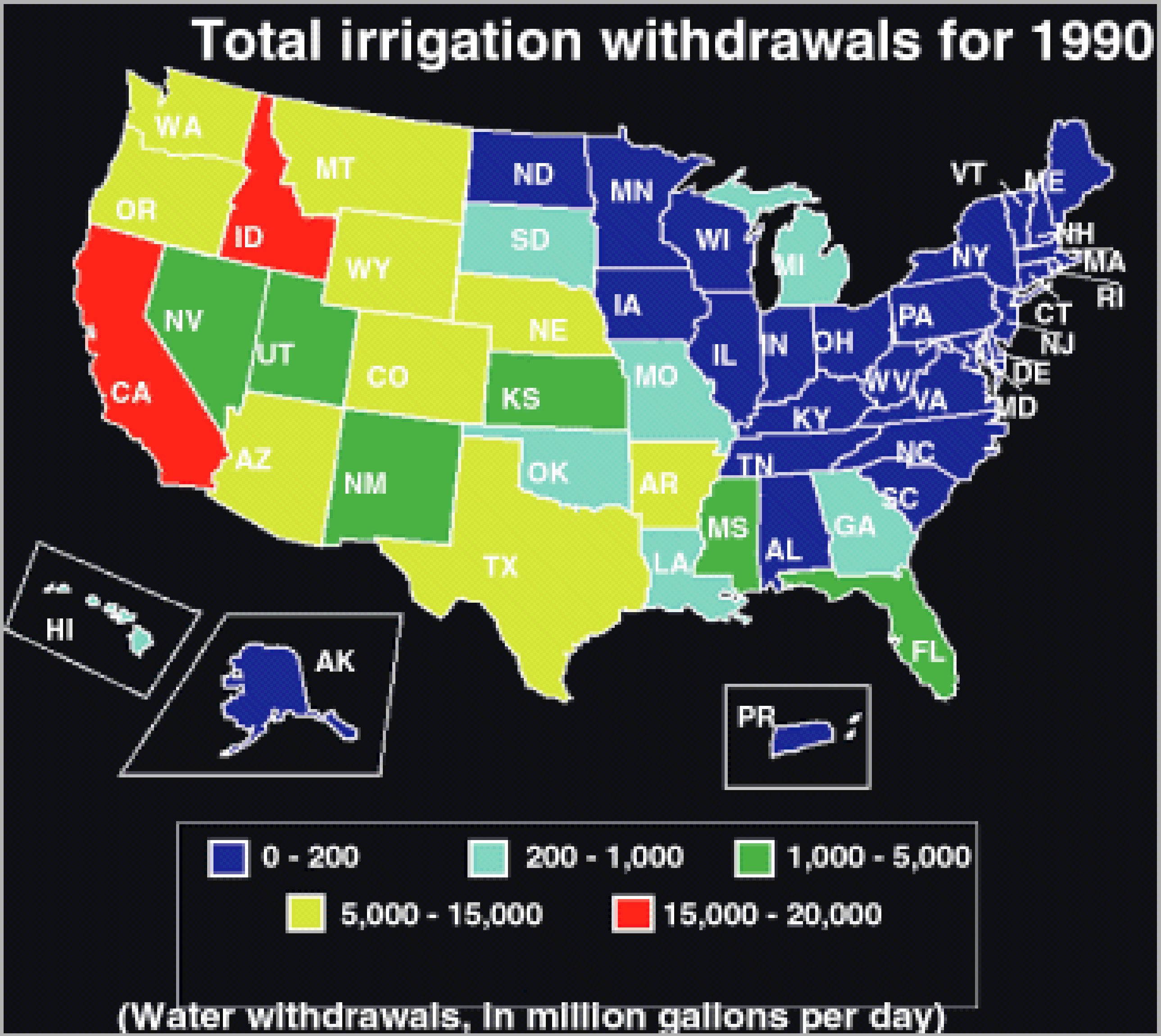


Marshak (2002)

Irrigation

- China, India, Pakistan and the US are the world's top four irrigators.
- In 1900 40 million hectares were irrigated globally, by 1950 the figure was 100 million and by 1995 it was 250 million
- Groundwater has the advantage that it is
  - generally cheaper to exploit (~33% less than surface water according to the World Bank)
  - can provide water on demand
  - is less erratic than surface water and not subject to the evaporation losses common in reservoirs (>10%)
- Groundwater deficits eventually force farmers to take land out of production, this could significantly affect available food supplies in countries like India and China

Water use for irrigation



Montgomery (2000)

Conservation & alternative sources

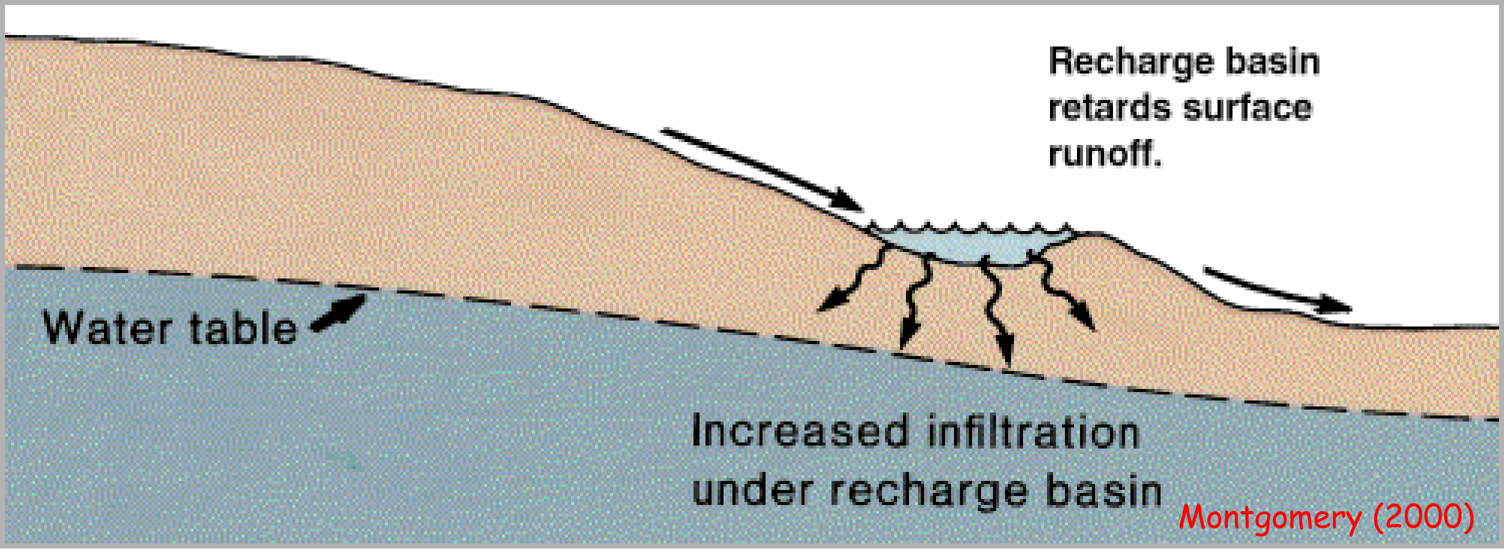
- **Conservation**
  - **Domestic water use is typically wasteful (e.g. lawn watering) but conservation methods will only have a limited effect as domestic water use accounts for only 10%**
  - **Irrigation is the main water user in the US. Improved methods such as drip irrigation can greatly reduce water loss, albeit generally at higher costs**

Conservation & alternative sources

- **Water transfer**
  - Pioneered by California with the construction of the Los Angeles Aqueduct. Completed in 1913 it carried 150 million gallons per day. Numerous other schemes have now greatly increased this total
  - Often faces political opposition, particularly when different states, provinces or countries are involved
  - The North American Water and Power Alliance with a budget of $100 billion is hoping to bring water from little developed areas of Canada to parts of the US and Mexico

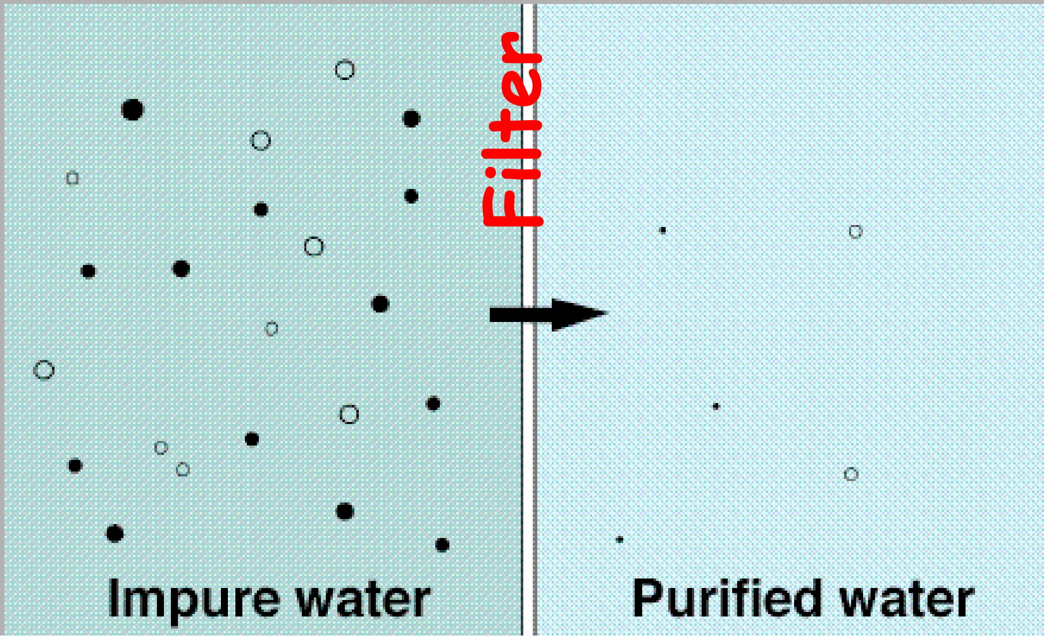
Conservation & alternative sources

- **Artificial recharge**
  - **This involves “banking” water in aquifers during years of heavy rainfall. Water that would normally flow into rivers is diverted into basins where it has time to infiltrate into the aquifer**



Conservation & alternative sources

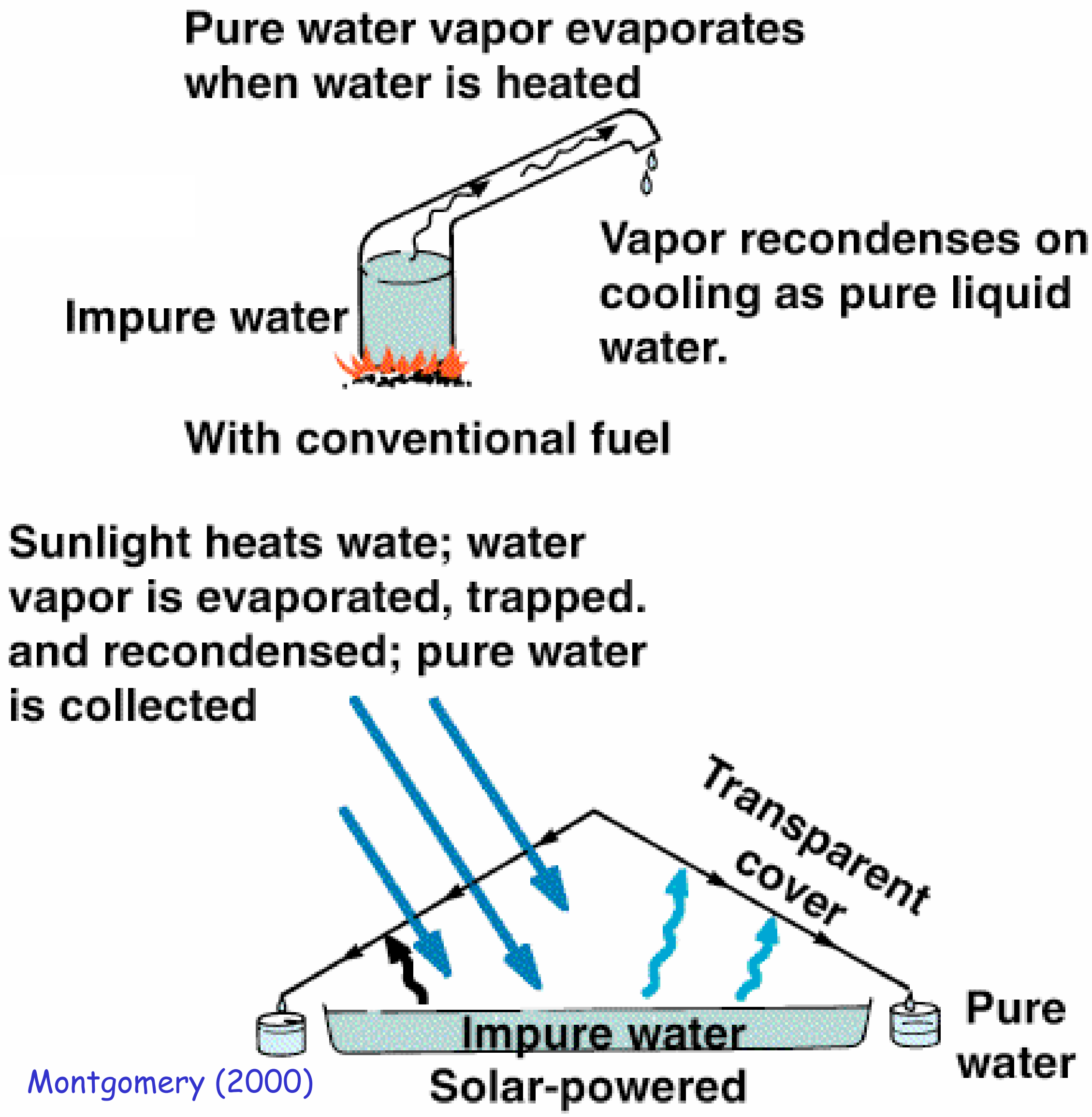
- **Desalination**
  - **This is particularly appropriate for coastal regions but may also be suitable for groundwaters with high TDS contents**
  - **For waters with low TDS filtration techniques can be applied. These can process large volumes at relatively low costs**



Montgomery (2000)

Conservation & alternative sources

Seawater will quickly clog a filtration system but can be purified by distillation. This requires significant heat sources and is consequently expensive (5-10 times more costly than stream water). In addition the coast of pumping the water uphill from the coast to where it is needed often exceeds the cost of production.



Montgomery (2000)

‘Exotic’ water sources – icebergs

- As long ago as 1890 small icebergs were captured and either towed or sailed from Laguna San Rafael, Chile (45°S) to Valparaiso and even Callao, Peru (12°S, 3900km) to provide a source of ice.
- Since the 1970’s a number of ‘serious’ studies have investigated the potential of using icebergs as a water source. The principal problems are:
- Identifying a suitable supply (big and stable). The best are the tabular icebergs derived from Antarctica
- Towing the bergs requires tugs far bigger than exist today, as drag increases with speed they could only be towed slowly. Attaching the tow rope is difficult as wire hawsers would simply melt through the berg under the pressure

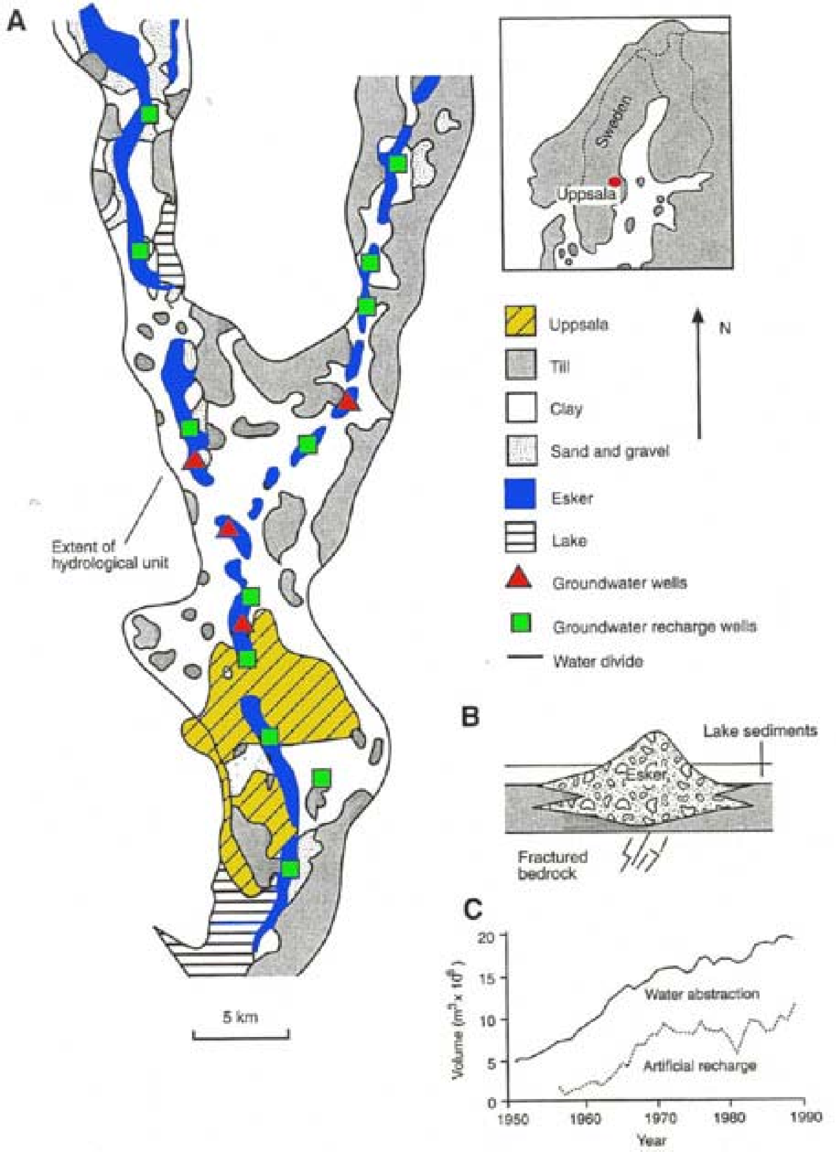
‘Exotic’ water sources – icebergs

- The iceberg will melt during transit. Reducing transit times by taking advantage of ocean currents would help
- Processing of water on arrival, the bergs would ground offshore so it would be necessary to build a processing plant to avoid seawater contamination
- Is it economically feasible ? Too many costs are unknown (tugs & processing) but it looks to be cheaper than desalination

- The technology exists should it become economically feasible

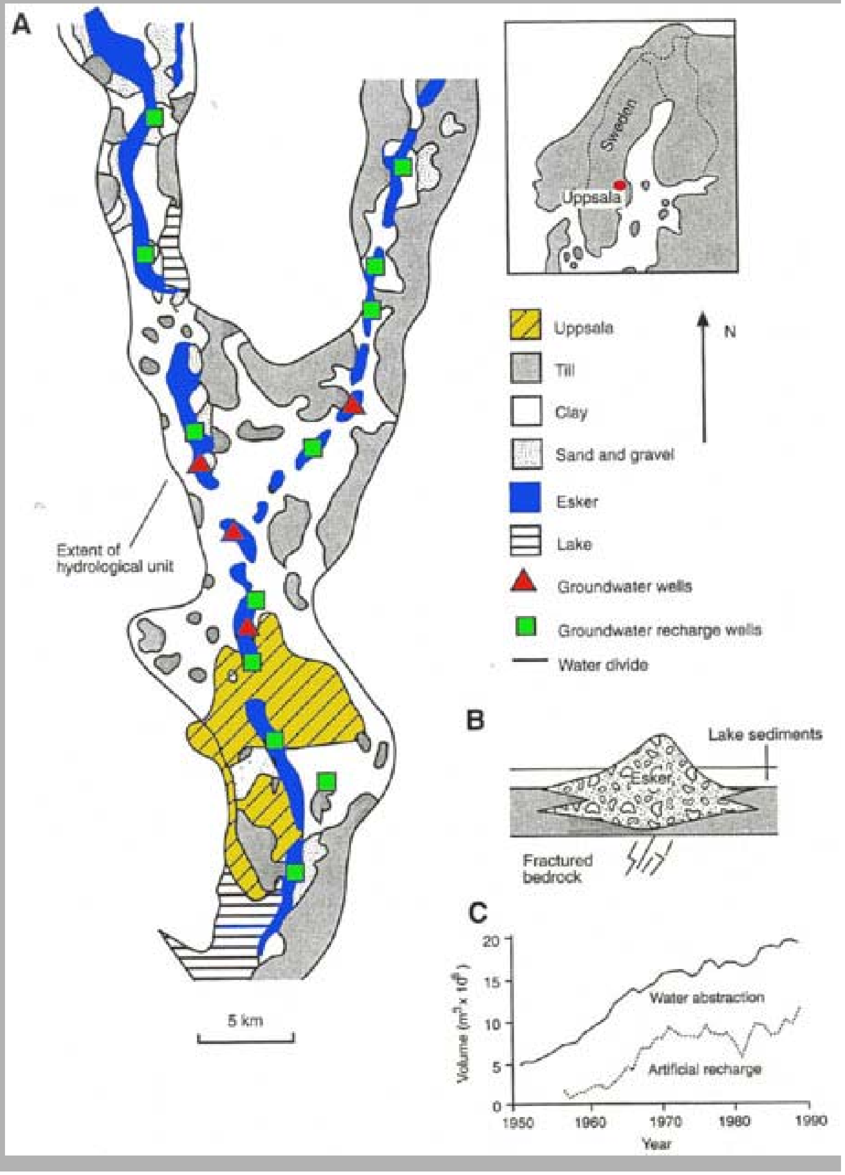
Uppsala aquifer, Sweden

- The city of Uppsala has a population of ~160,000 and derives its municipal water supply entirely from groundwater.
- The aquifer is located in an esker on which the town is partially built. The esker is up to 150m thick and in places stands out from the glacial clays
- The esker was first tapped in 1640 to supply the royal castle located on the esker crest with the modern system initiated in 1872. Current demand is on the order of 60,000m^3 per day



Uppsala aquifer, Sweden

- In the 1950's calculations showed that the aquifer was in danger of becoming seriously overdrawn. This resulted in a program of artificial replenishment. Water from the River Fyris is pumped into wells.
- The water takes ~8 months to reach the extraction wells allowing sufficient time for natural filtration to purify the water
- The groundwater is now a sustainable resource but care is being taken to ensure there is no contamination from the town



Case Study: The Walkerton Water Tragedy

- Canada’s worst case of E.coli contamination
- 7 deaths, 2,300 illnesses
- Walkerton is almost entirely dependent on groundwater for it’s domestic water
- Cattle manure washed into a shallow water supply well
- Campylobacter bacteria E.coli 0151:H7

- A report/assessment in May 2000 cited 3 groundwater sources (Well # 5, 6 and 7) However, Well #5 was the only operational well. Therefore, the town’s only source of water…
- The chlorine shocks neutralize the contaminants, and the operators did not adhere to the protocol.
- Well 5 was beside a cattle farm, and the report noted it’s poor location, and merely concluded that it would have to be continously tested. This did not happen.

The findings of the legal case.

- Insufficient funding
- Inadequate training
- Details were overlooked
- Env. Factors were not considered:
  - Surrounding environments
  - Topography
  - Land use
- Protection barriers needed:
  - Selecting reliable high quality dw
  - Regulating well construction
  - Maintaining and inspecting wells