Fundamentals of Earth Sciences (ESO 213A)

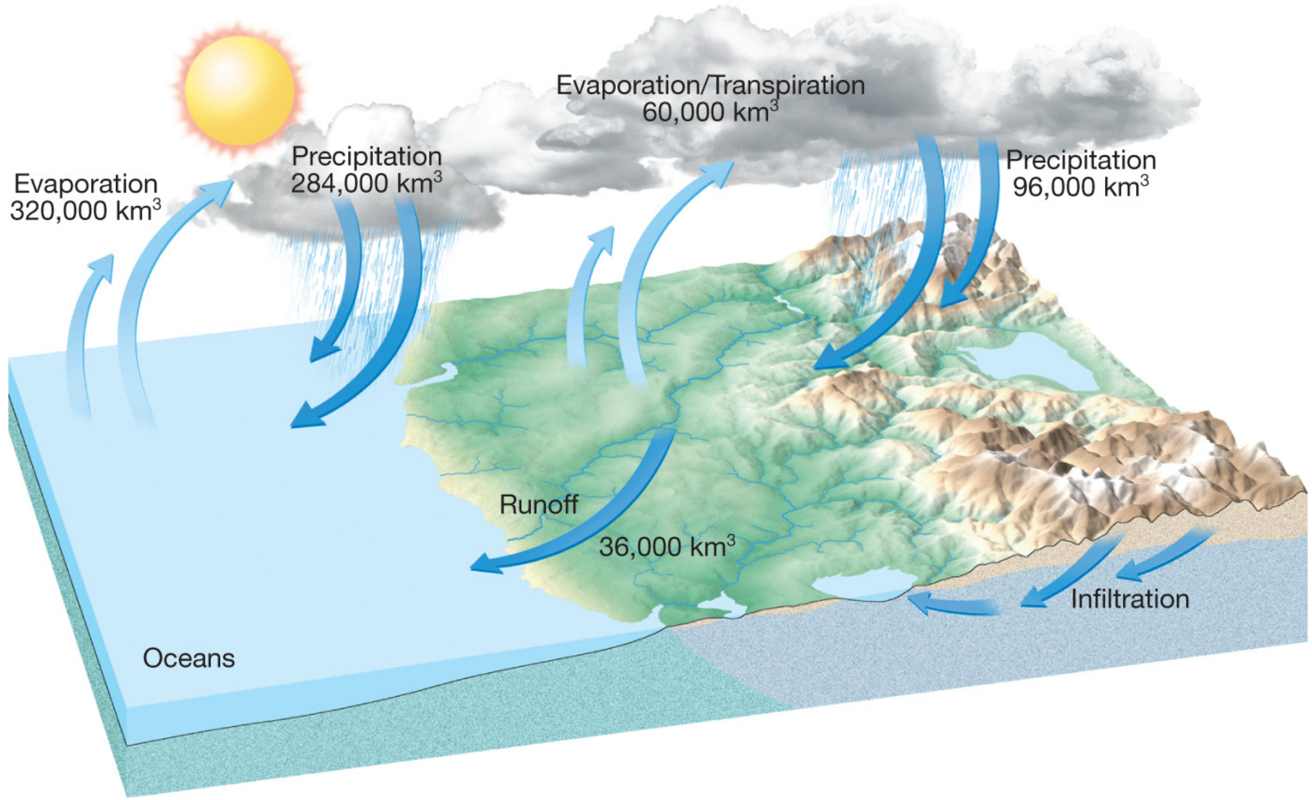
Dibakar Ghosal
Department of Earth Sciences

Groundwater

Previous Class: Glaciers

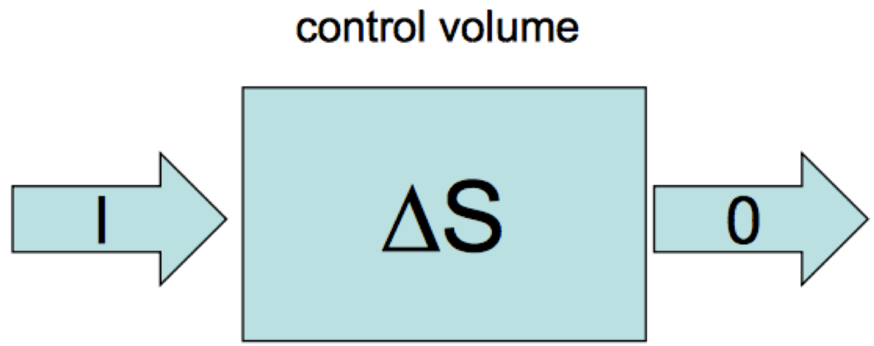
Ground Water

- *Ground Water* lies beneath the ground surface, filling pores in sediments and sedimentary rocks and fractures in other rock types
- Represents *0.6%* of the hydrosphere
  - Resupplied by slow *infiltration of precipitation*
  - Generally cleaner than surface water
  - Accessed by *wells*

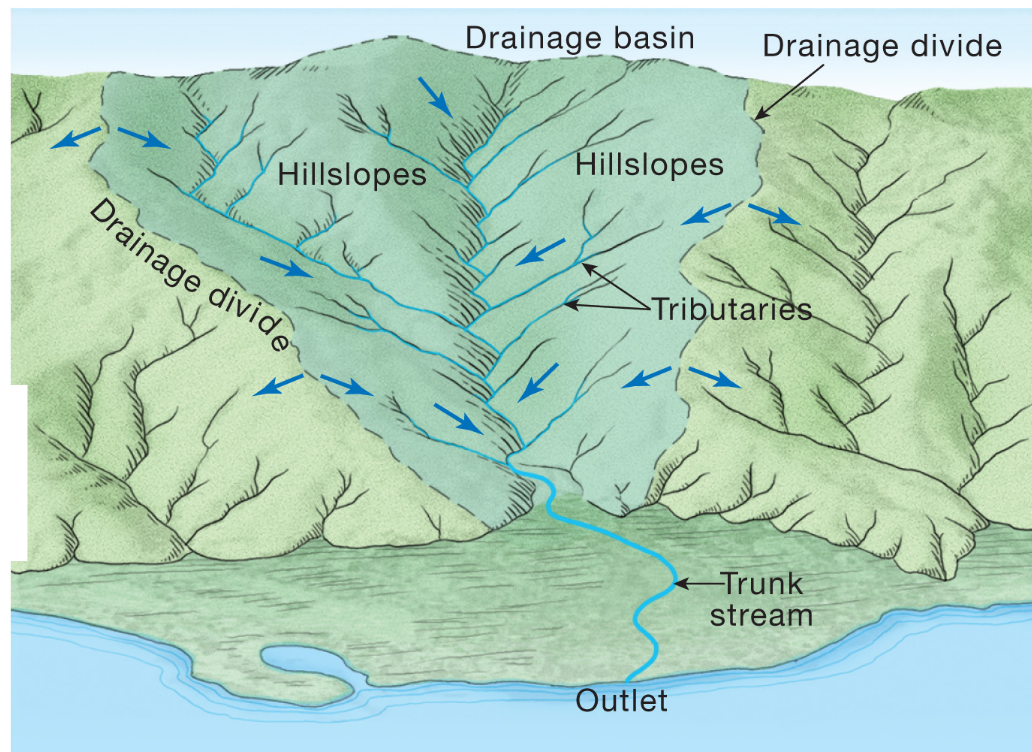


The water balance and principle of conservation

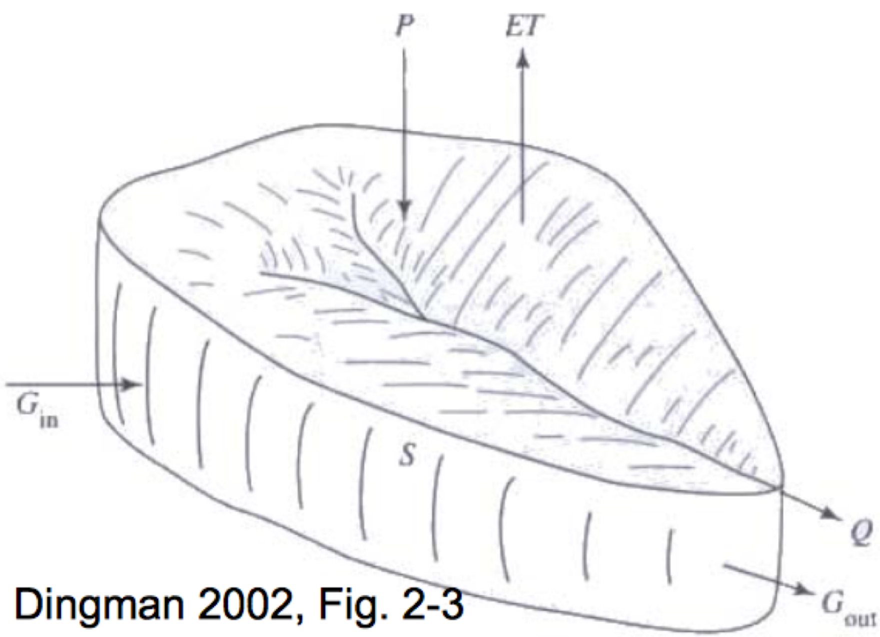
Conservation: inputs (I) – outputs (O) = change in storage (S)



$$I - O = \Delta S$$



The water balance of a watershed



Dingman 2002, Fig. 2-3

Inputs (I), outputs (O) and storage (S):
I: Precipitation (P)
Groundwater in (G_{in})
O: Evapotranspiration (ET)
Groundwater out (G_{out})
River discharge (Q)
Storage (S): In groundwater, rivers and lakes

$\Delta S = P + G_{in} - (Q + ET + G_{out})$

If we assume that G_{in} and G_{out} are negligible, and that for the long-term annual mean, ΔS is zero, then:

$P = ET + Q$, or $ET = P - Q$

What can we usually measure?

P: rain gauges
Q: stream gauges
ET: hard to get except local values
G_{in}: hard to get, assume zero
G_{out}: hard to get, assume zero
S: often hard to get

Dimensions and Units

Length = L (meters)

Volume = V

V = L^3 , typically m^{-3} or km^{-3}

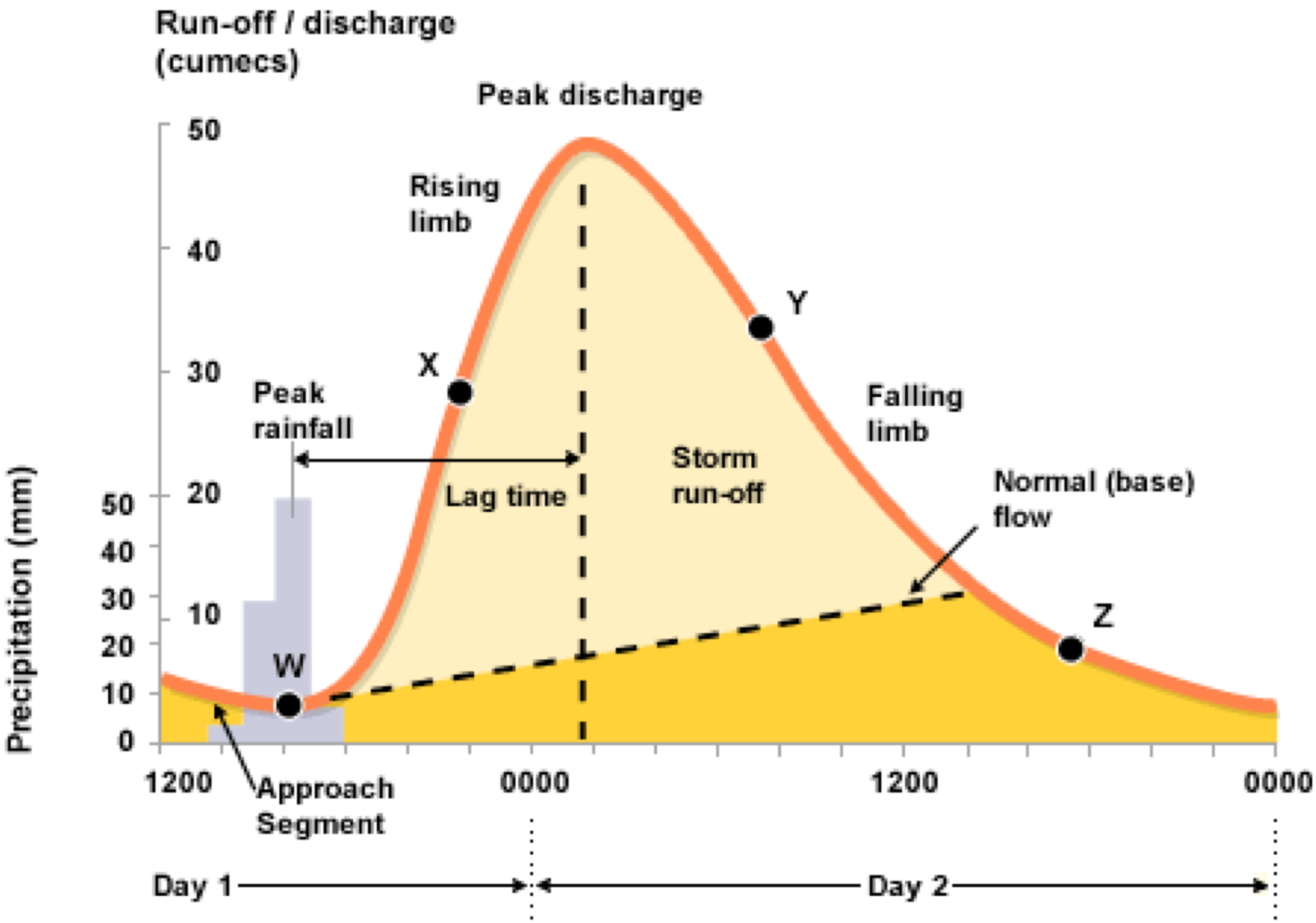
Mass = m (kilograms)

Density (ρ) is often assumed to be constant for liquid water (1000 kg m^{-3}) hence water mass m = ρ V (this means that conservation of mass equals conservation of volume)

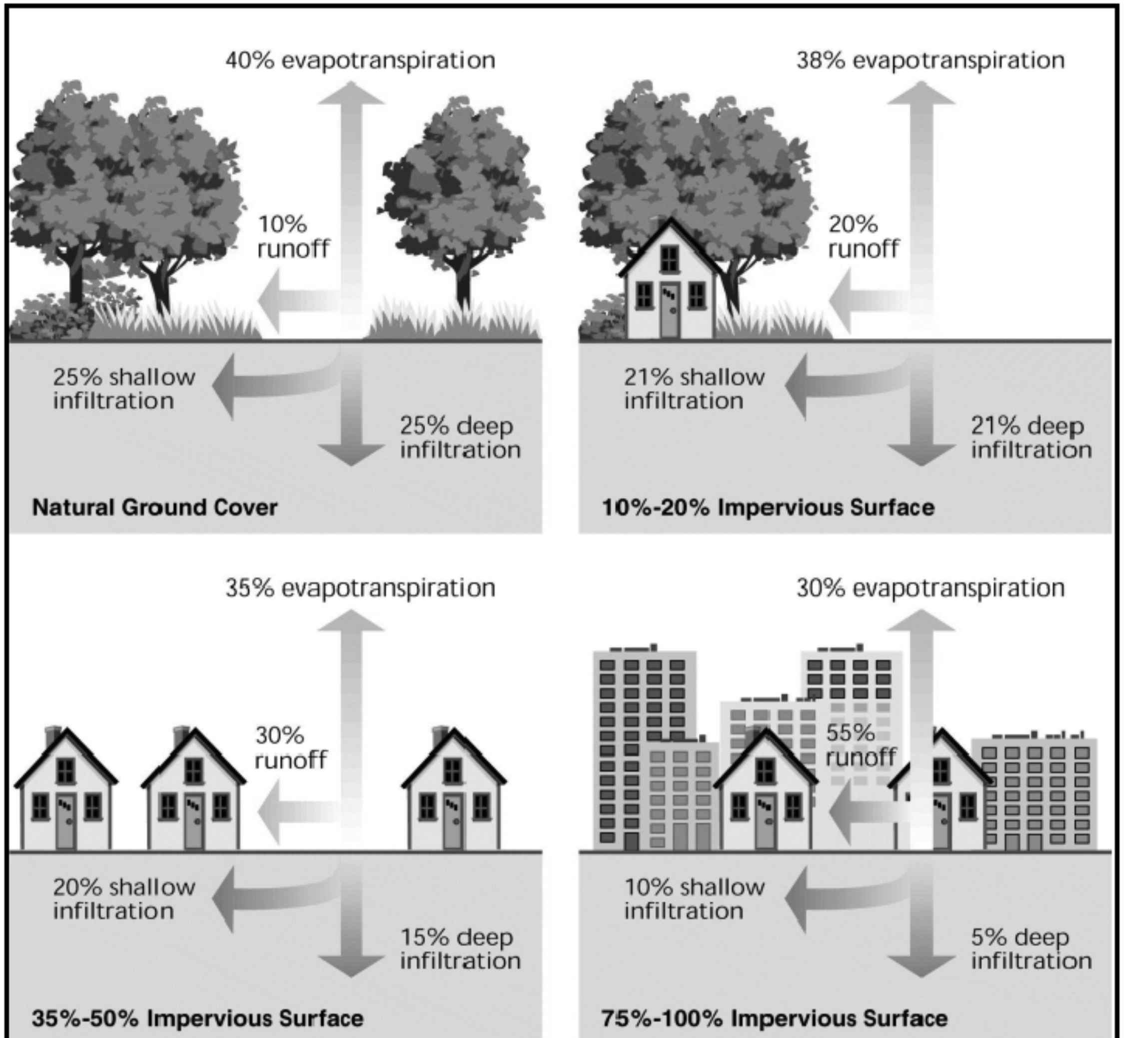
Inputs (I) and outputs (O) are often expressed as rates of fluxes, or volume/time (e.g., $m^{-3}\ s^{-1}$); storage changes must have the same units.

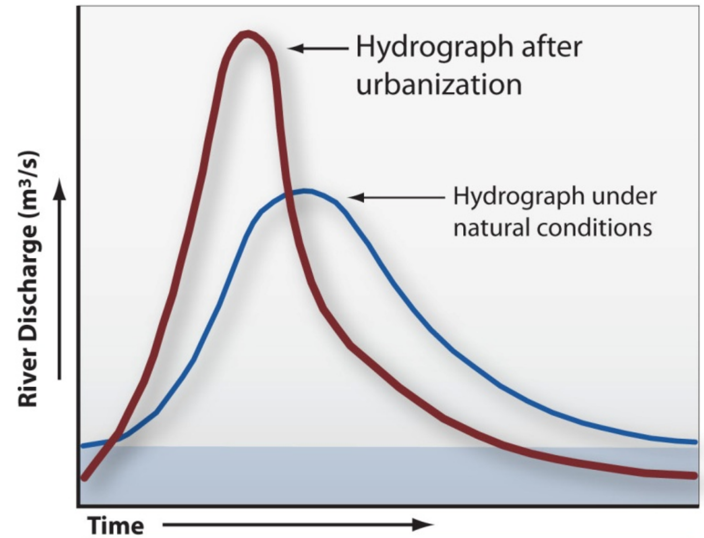
Inputs, outputs and storage changes can also be expressed as a change in water depth (m) averaged over the watershed. Simply divide by the area of the watershed ($m^{-3}\ s^{-1} / m^2 = m\ s^{-1}$). In this case, instead of discharge Q we speak of runoff R.

A Typical Hydrograph (water flow in streams)



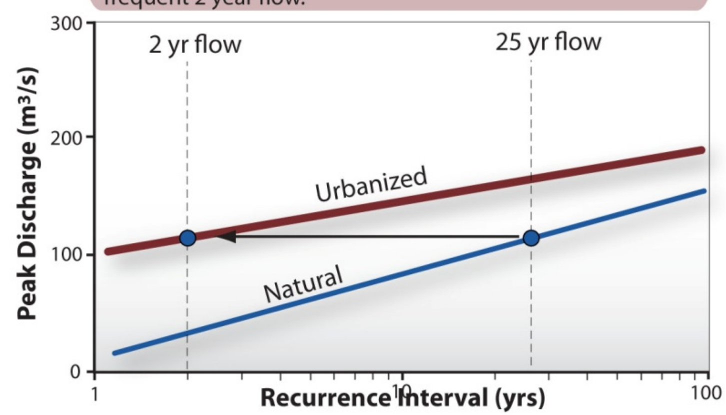
Watershed Urbanization

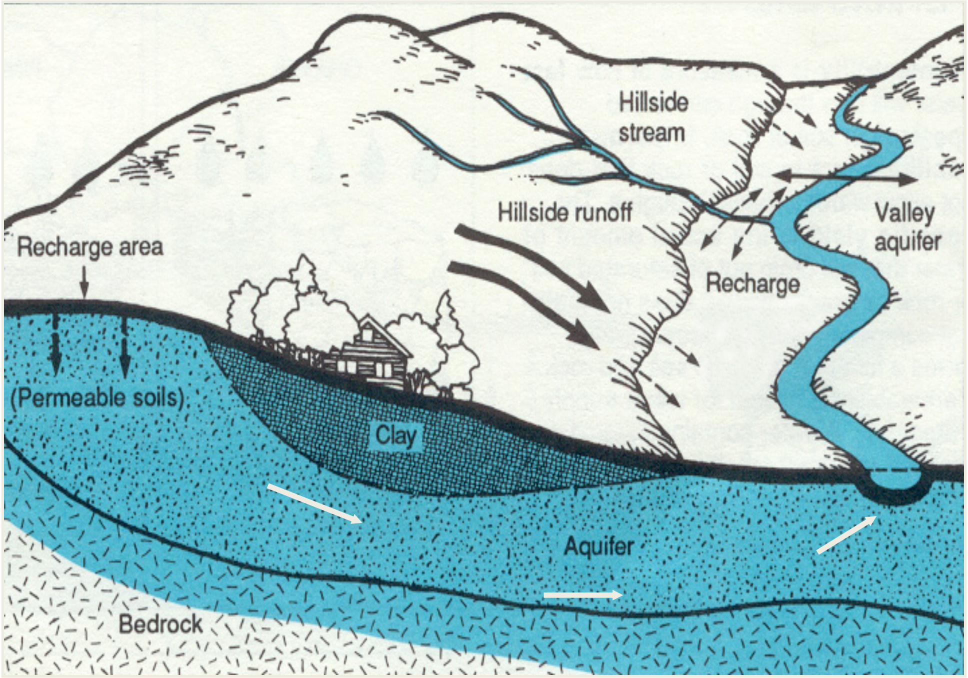




Before development, rainfall followed a more convoluted path through the landscape - held in detention storage by pit and mound topography, infiltrating into organic-rich forest soil and moving slowly to the channel. The infiltrating water fed baseflow during times when it was not raining. Flood peaks were lower and came later.

After urbanization, rainfall moves rapidly to the channel with little chance to infiltrate during storms, thus baseflow is reduced. Flowing directly off impervious surfaces such as parking lots, runoff enters streams quickly raising their level. Flood peaks now come sooner and are higher, increasing flood hazards and the tempo of geomorphic change. For example, the natural 25 yr flow becomes the much more frequent 2 year flow.

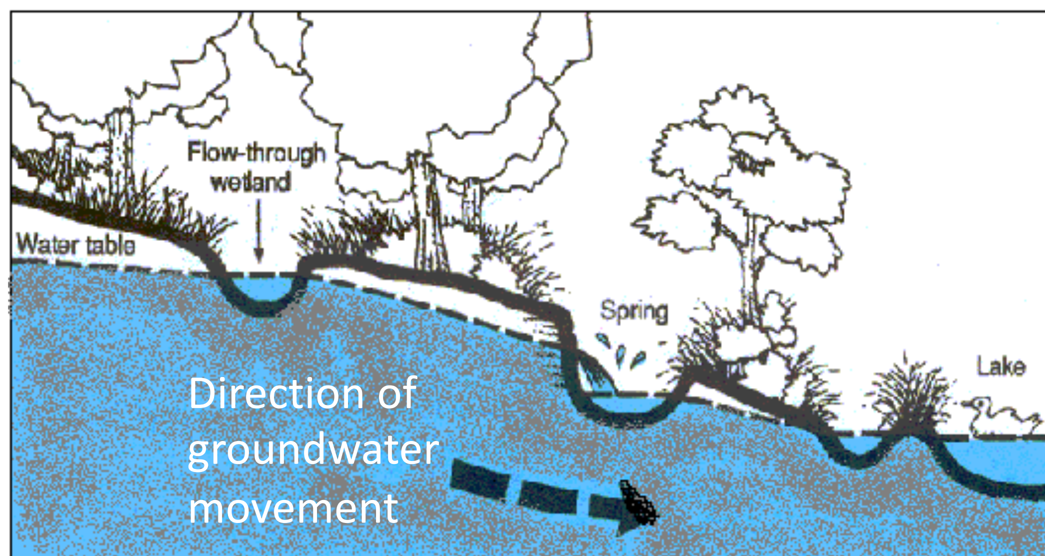




Groundwater Basics

- Groundwater occurs **almost everywhere** within the pore spaces of saturated rock beneath the land surface.

- Groundwater is not like an underground river or lake. In fact, groundwater is more like the **water in a sponge**, held within the tiny pores.



Porosity, Permeability, Specific yield and Specific retention

Porosity - the percentage of rock or sediment that consists of voids or openings

- Measurement of a rock's ability to hold water
- Loose sand has ~30-50% porosity
- Compacted sandstone may have only 10-20% porosity

Permeability - the capacity of a rock to transmit fluid through pores and fractures

- Interconnectedness of pore spaces
- Most sandstones and conglomerates are porous *and* permeable
- Granites, schists, unfractured limestones are *impermeable*

The beaker on the left is filled with 1000 ml of sediment. The beaker on the right is filled with 1000 ml of water.

The sediment-filled beaker now contains 500 ml of water. Pore spaces (porosity) must represent 50 percent of the volume of the sediment.

Specific yield: the portion that will drain under the influence of gravity.

Specific retention: the part that is retained as a film on particle and rock surfaces and in tiny openings.

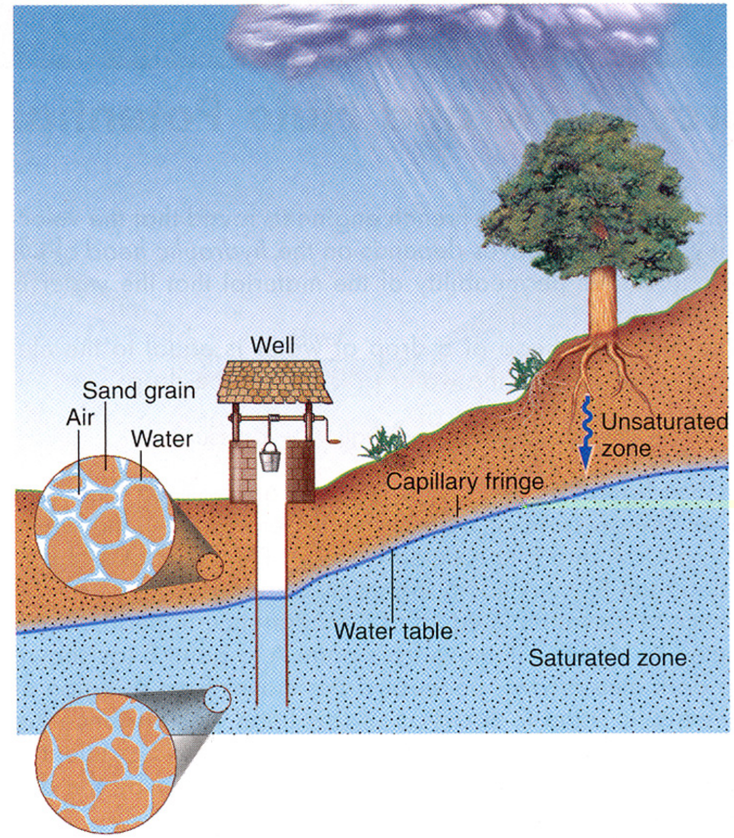
TABLE 17.1 Selected Values of Porosity, Specific Yield, and Specific Retention*

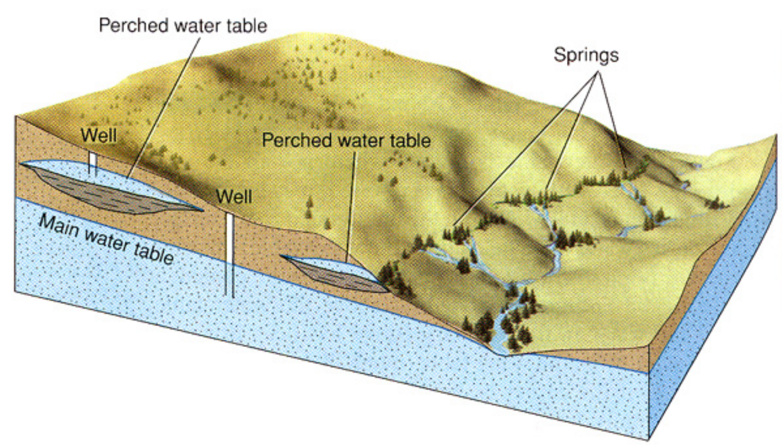
Material	Porosity	Specific Yield	Specific Retention
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (semiconsolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (fresh)	11	8	3

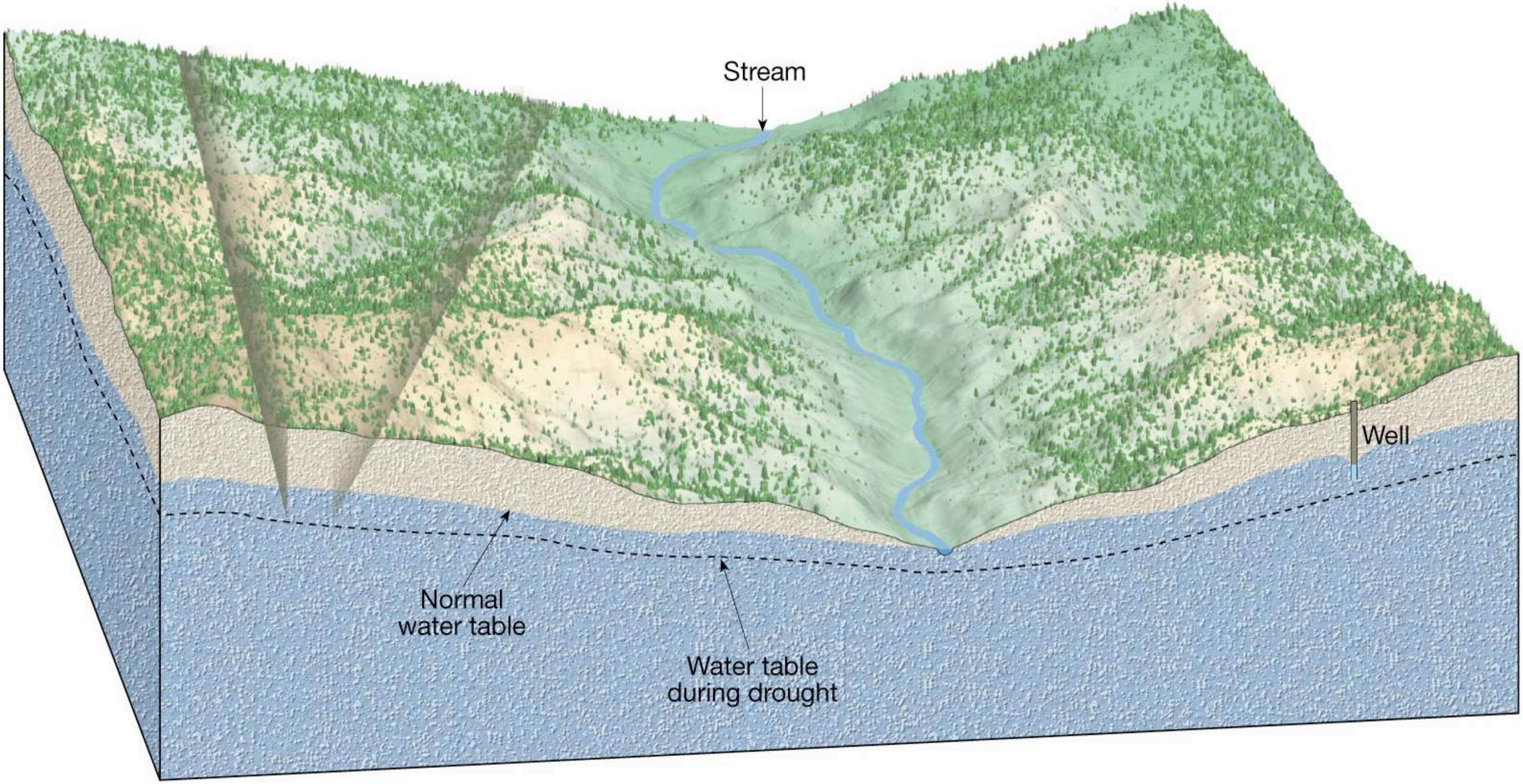
*Values in percent by volume.

Zones and Water Table

- *Well* - a deep hole dug or drilled into the ground to obtain water from an aquifer
- Subsurface zone in which all rock openings are filled with water is the *phreatic, or saturated zone*
- Top of the saturated zone is the *water table*
  - Water level at surface of most lakes and rivers corresponds to local water table
- Above the water table is an *unsaturated* region (*zone of aeration*) called the *vadose zone*
- A *perched water table* is above and separated from main water table by an unsaturated zone
  - Commonly produced by thin lenses of impermeable rock (e.g., shales or clays) within permeable ones



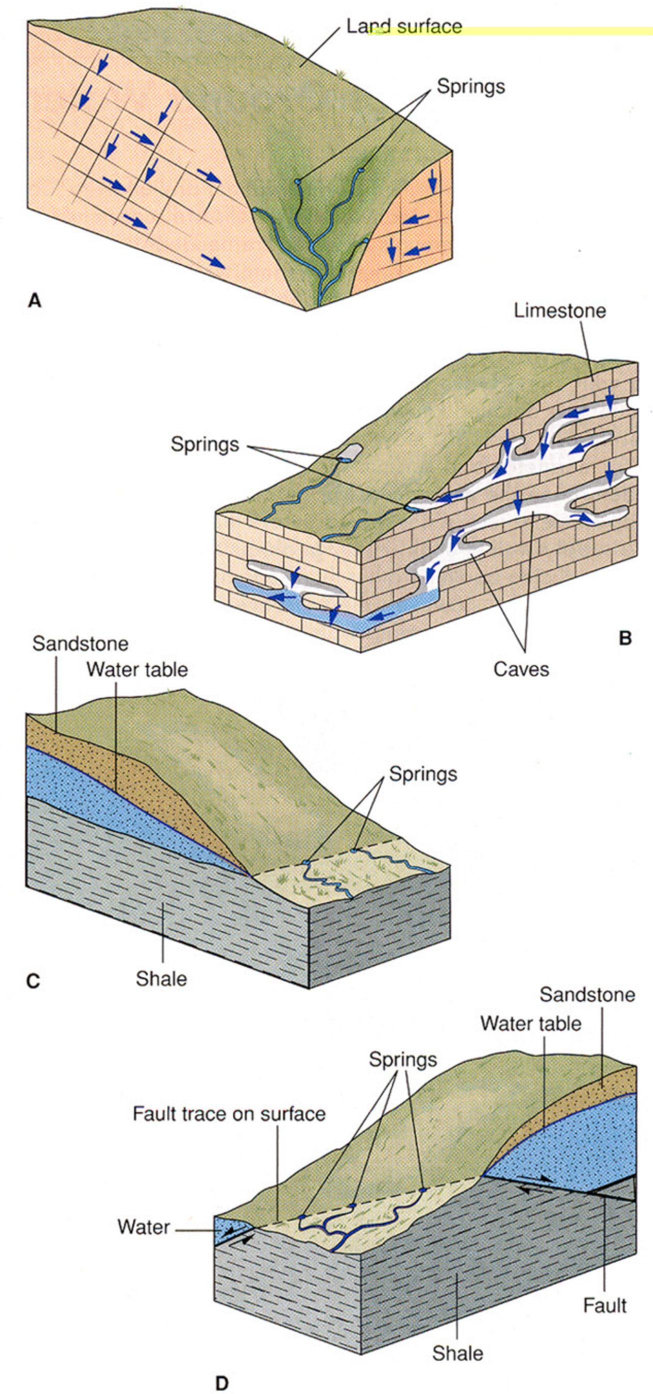




The *water table* separates the saturated and unsaturated zones. The water table is exposed at the surface in streams and lakes. The water table rises and falls as the balance between precipitation and evaporation changes.

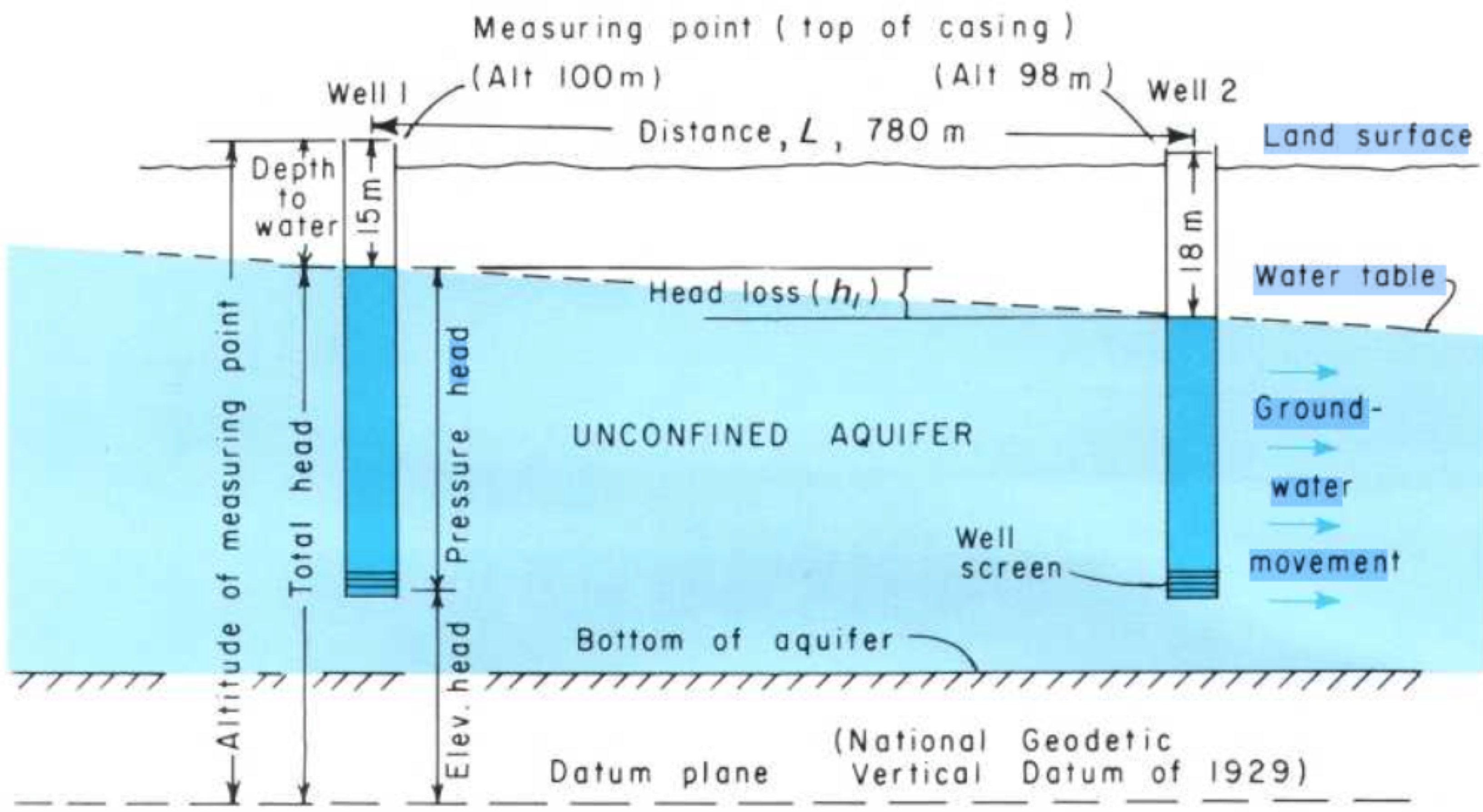
Springs

- *Spring* - a place where water flows naturally from rock or sediment onto the ground surface



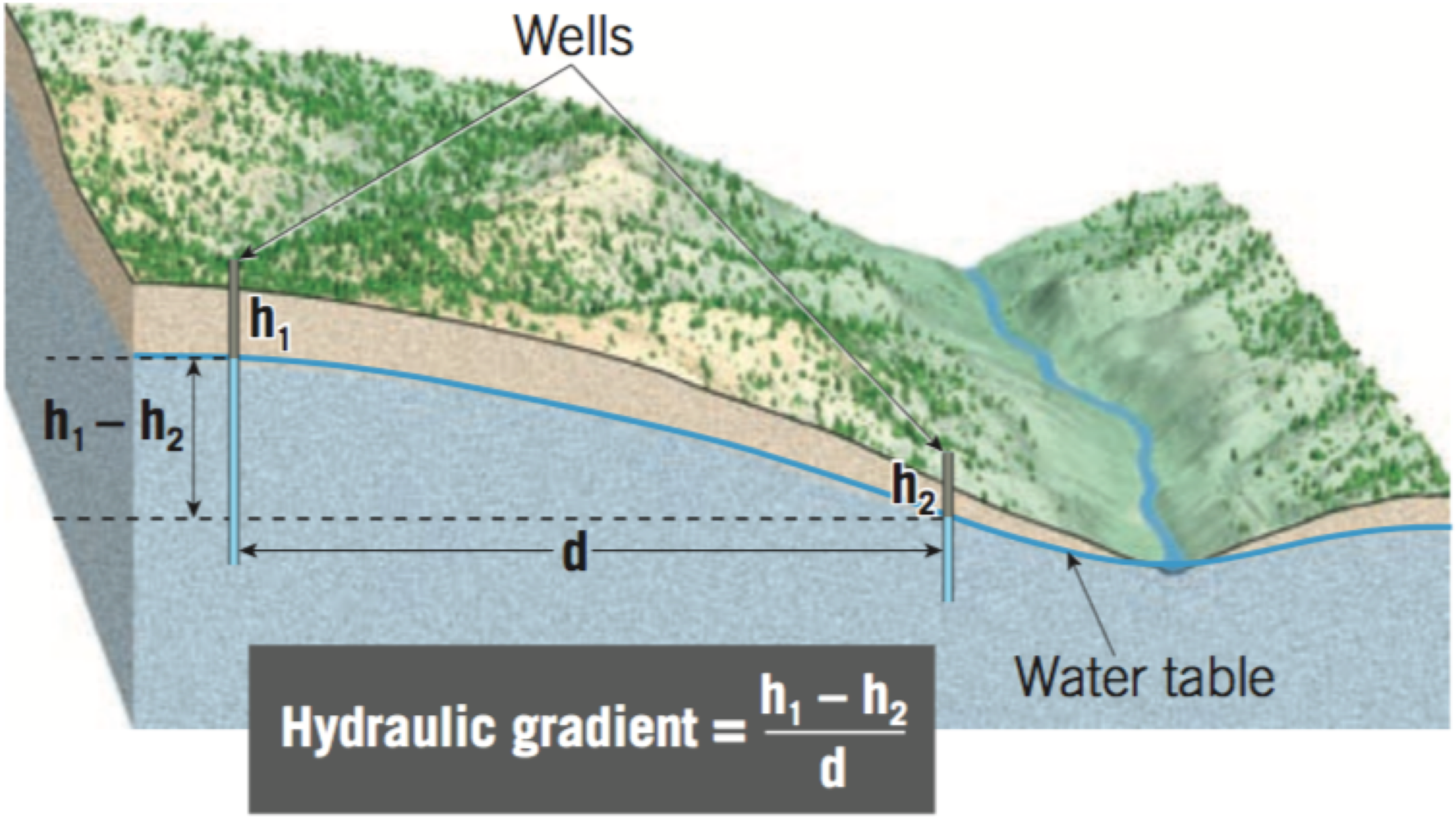
How Ground water flows? Head and Gradient

Total Head = Elevation head + pressure head



Hydraulic Gradient = h_L/L

$$\frac{h_L}{L} = \frac{(100\text{ m} - 15\text{ m}) - (98\text{ m} - 18\text{ m})}{780\text{ m}} = \frac{85\text{ m} - 80\text{ m}}{780\text{ m}} = \frac{5\text{ m}}{780\text{ m}}$$

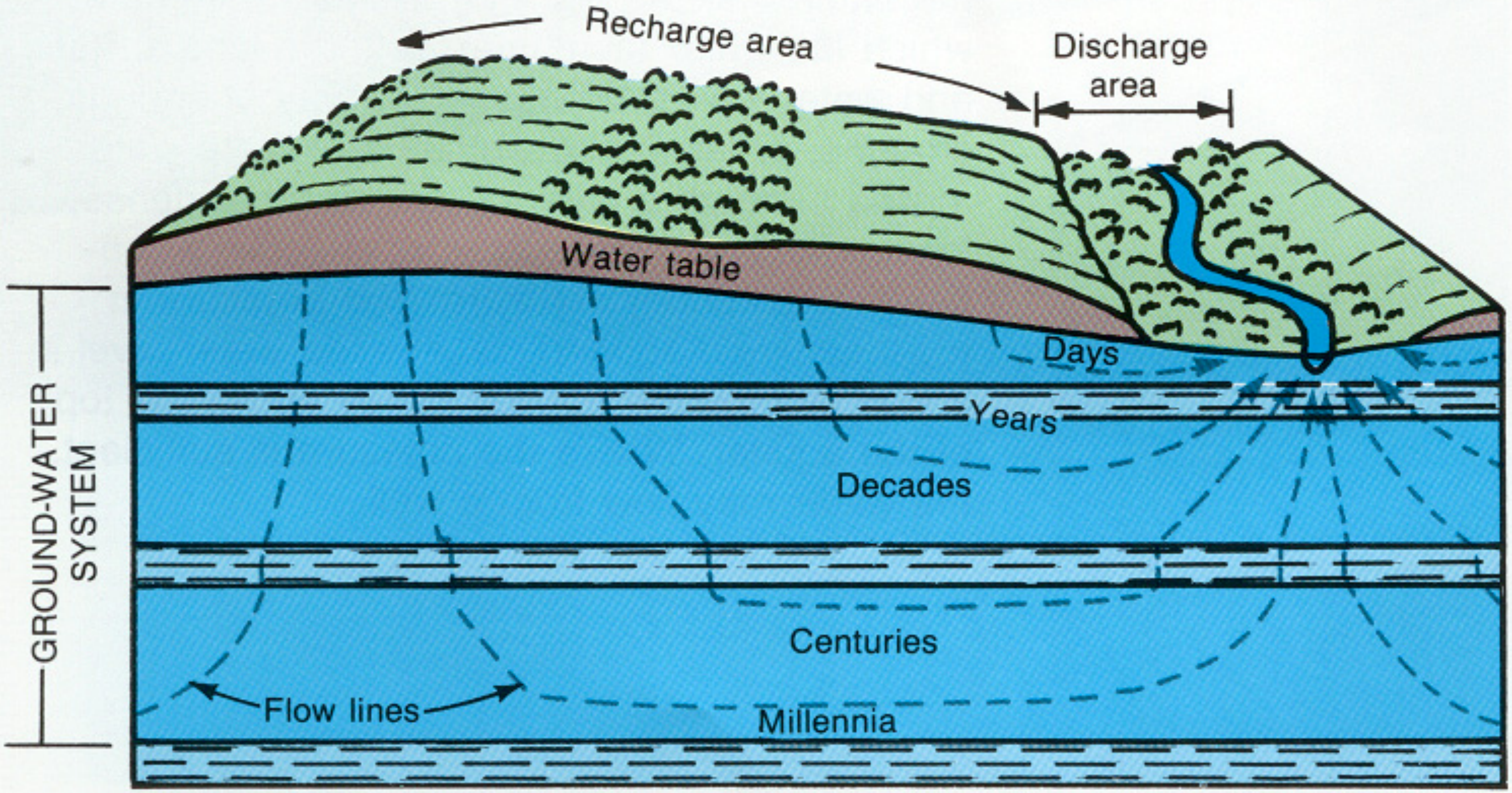


Rate of groundwater flow is proportional to: 1) the hydraulic gradient
2) the hydraulic conductivity

Darcy's law: Q=K*A*I

K= hydraulic conductivity
A= cross-sectional area
I = hydraulic gradient [a measure of change of head between two wells located at a given distance [dh/dl]

Groundwater

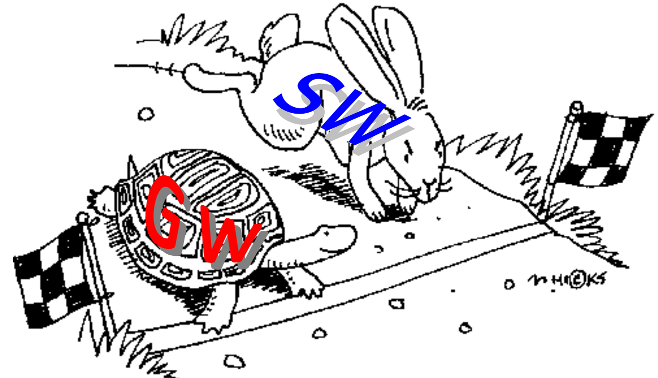


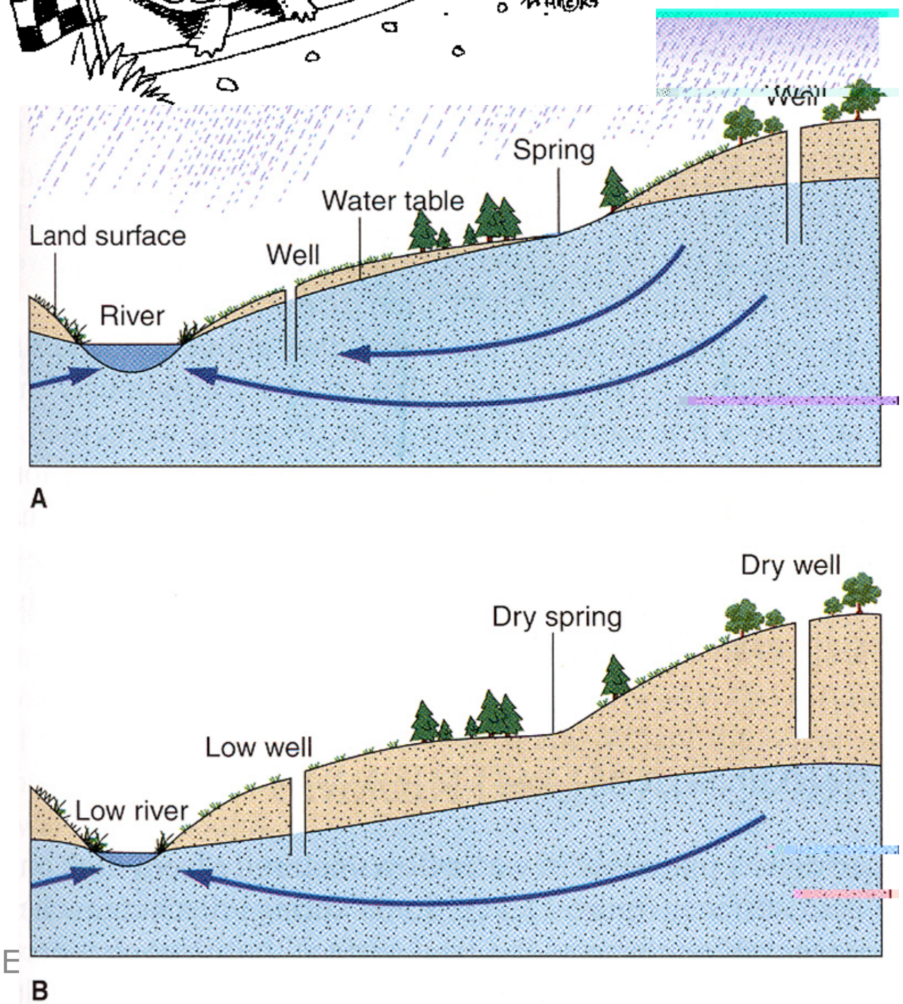
Direction and rate of ground-water movement.

Ground Water Movement

- Movement of ground water through pores and fractures is *relatively slow* (cms to meters/day) compared to flow

  of water in surface streams
  - Flow velocities in cavernous limestones can be much higher (kms/day)





- Flow velocity depends upon:
  - *Slope* of the water table
  - *Permeability* of the rock or sediment

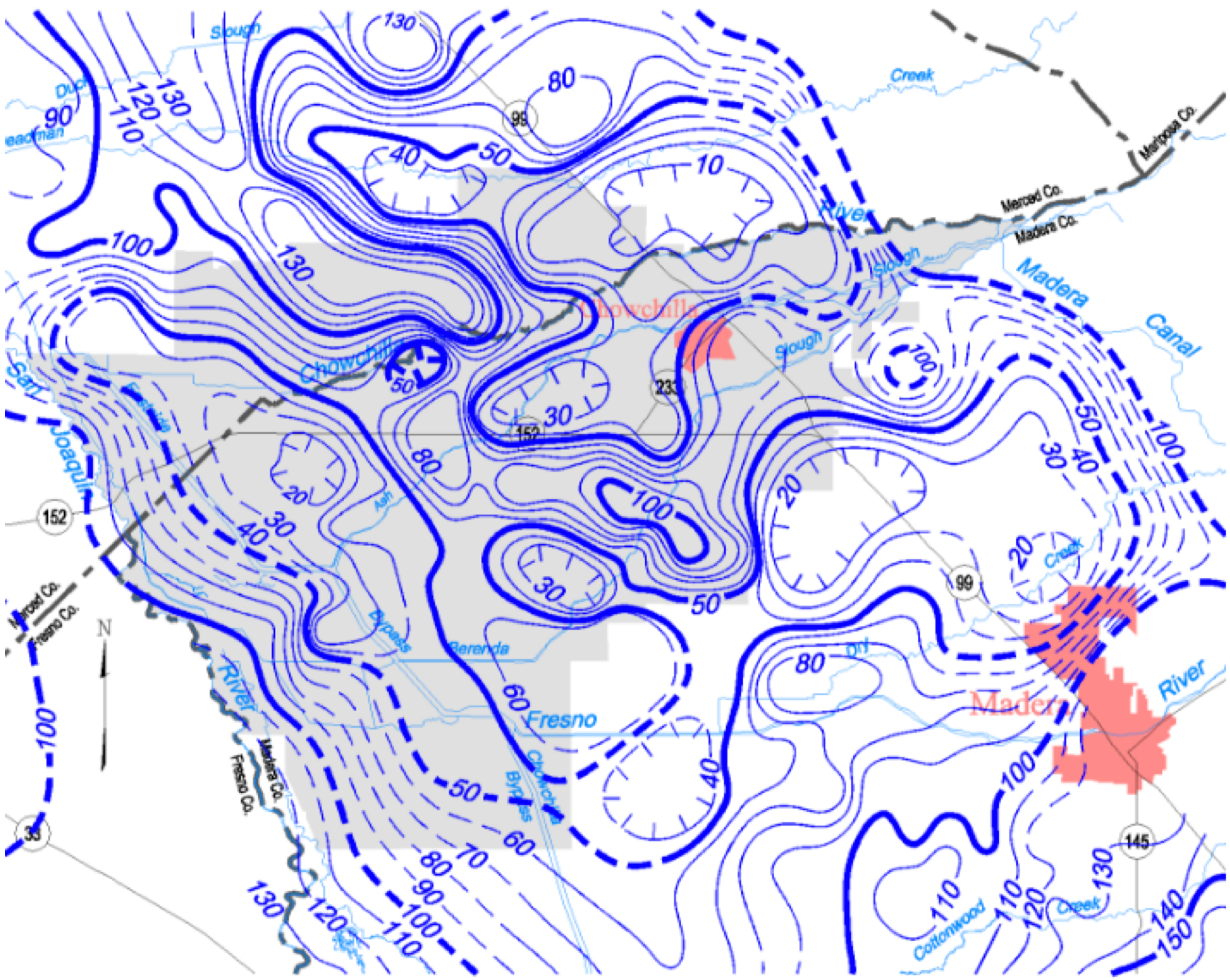
Chowchilla Groundwater Basin

Spring 2008, Lines of Equal Elevation of Water in Wells, Unconfined Aquifer

Indra Sekhar Sen

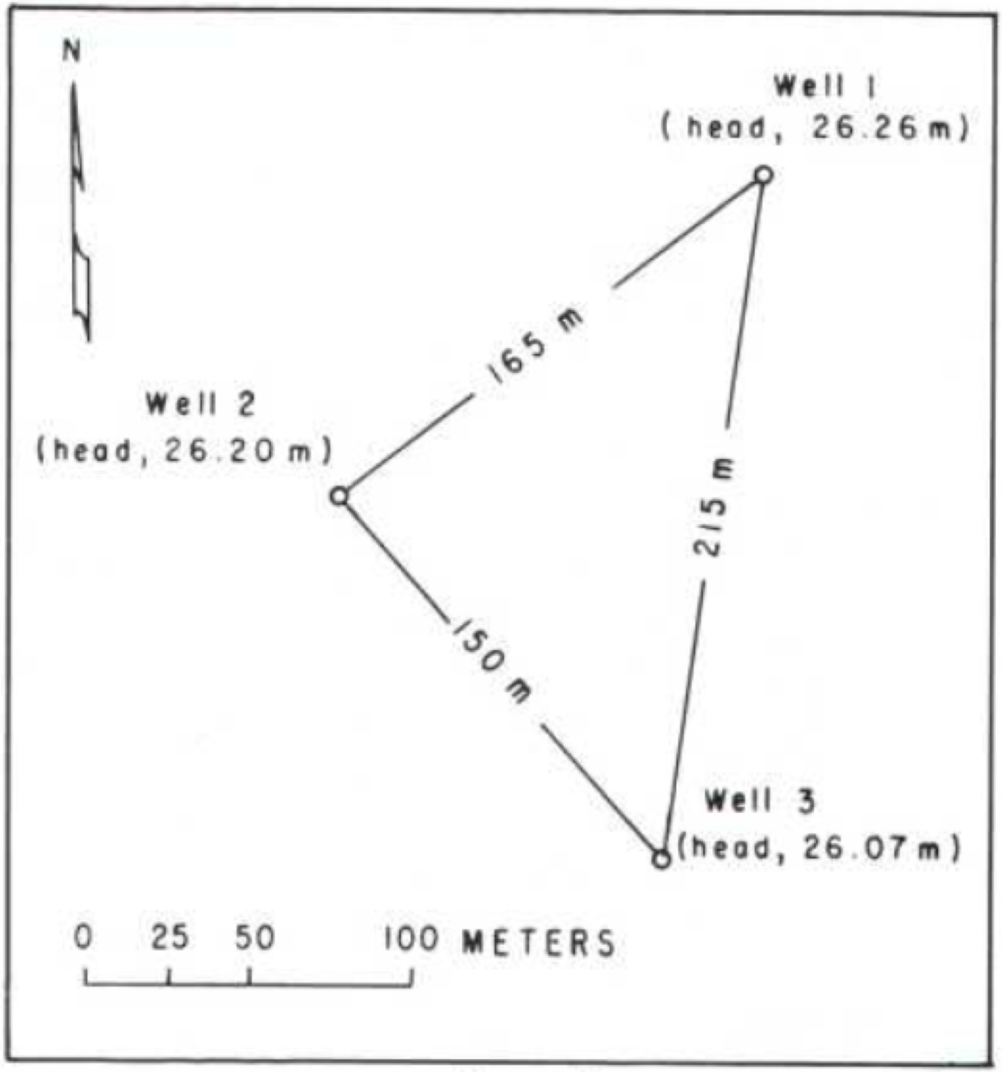
Scale of Miles

2 0 2 4 6



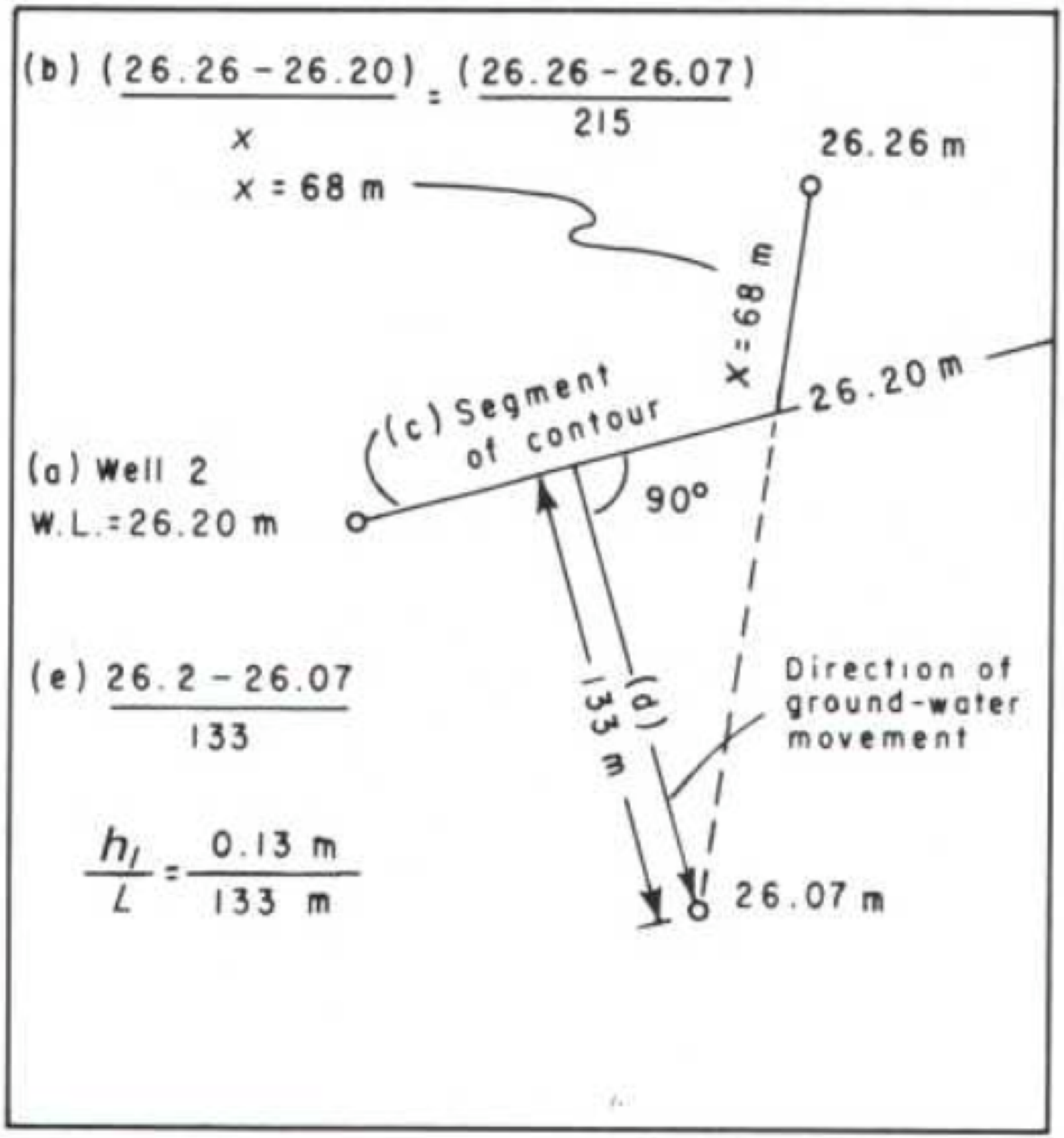
Contours are dashed where inferred. Contour interval is 10 feet.

Water-Level Contour Map



Questions -

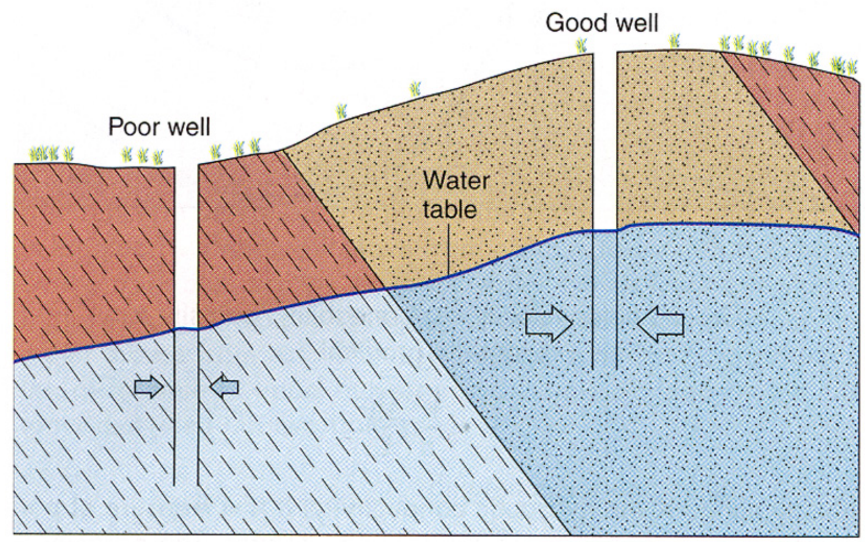
1. Identify the well that has the intermediate water level
2.Calculate the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well.
Draw a water level contour along which the total head is the same as that in the intermediate well



What is the hydraulic gradient between water-level contour and well 3?

Aquifers and Aquitards

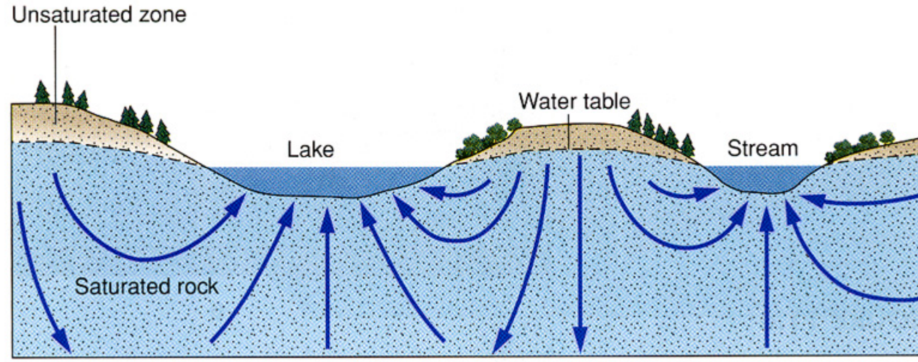
- *Aquifer* - Aquifers are water-bearing layers of rock or sediment that contain **usable quantities of water** that can move easily
  - Sandstone
  - Conglomerate
  - Well-jointed limestone
  - Sand and gravel
  - Highly fractured volcanic rock



- *Aquitard* - rock/sediment that retards ground water flow due to low porosity and/or permeability
  - Shale, clay, unfractured crystalline rocks

Unconfined vs. Confined Aquifers

- *Unconfined Aquifer*
  - Has a water table, and is only partly filled with water
  - Rapidly *recharged* by precipitation infiltrating down to the saturated zone

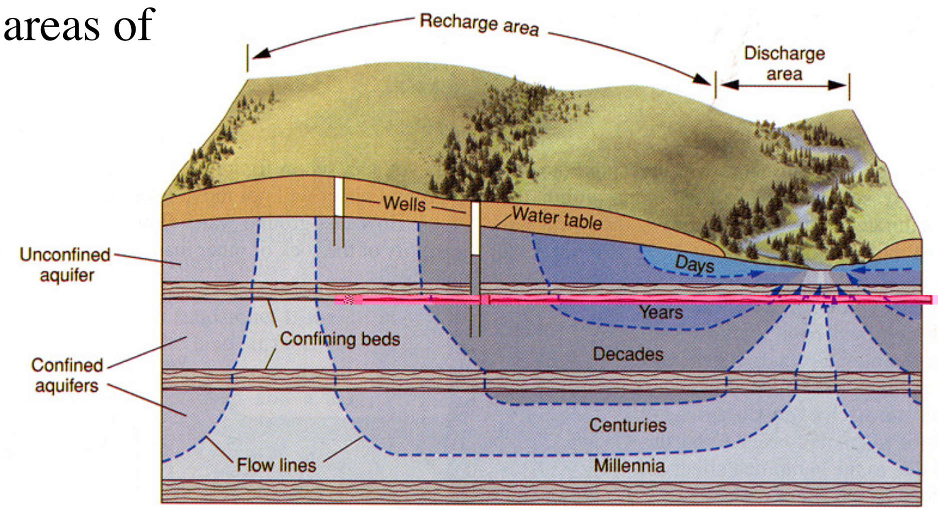


-- Influenced by **gravity** and flows from higher to lower groundwater elevations, much like river water.

--The steeper the slope of the groundwater "table," the faster the groundwater will flow.

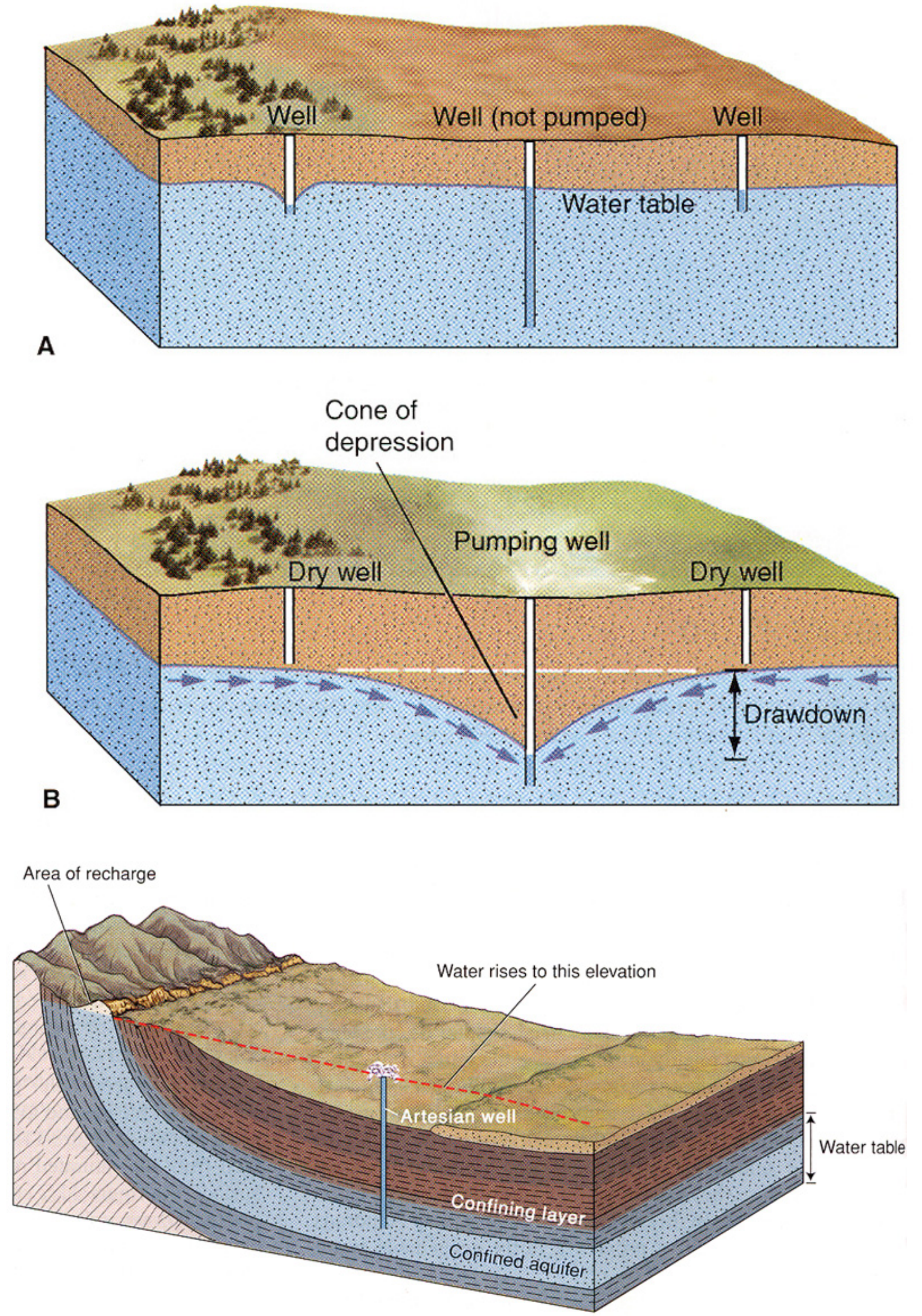
--**Pressure**, rather than gravity, makes water move in confined aquifers. Water moves from areas of high to low pressure.

- *Confined Aquifer*
  - Completely filled with water under pressure (*hydrostatic head*)
  - Separated from surface by impermeable *confining layer/aquitard*
  - *Very slowly* recharged



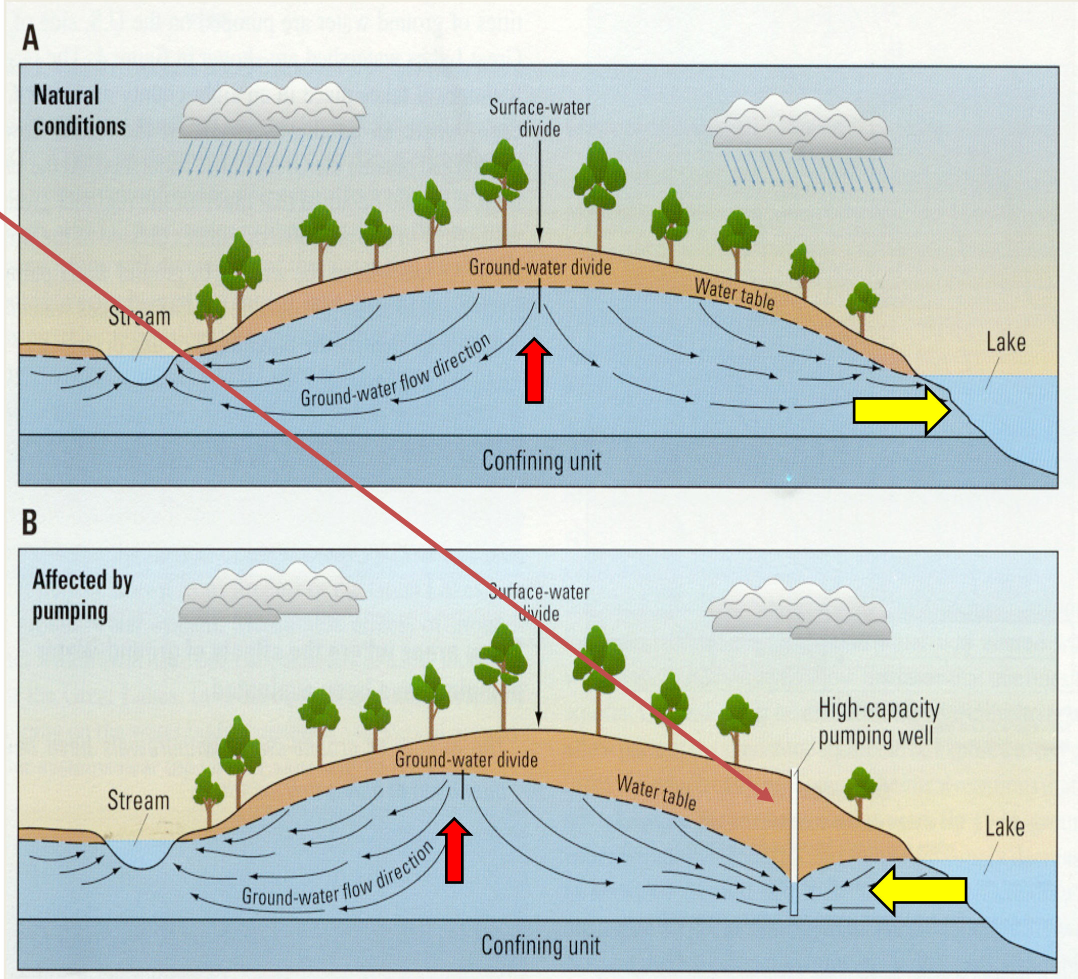
Cone of depression and storativity

- For wells in unconfined aquifers, water level before pumping is the water table
- Water table can be lowered by pumping, a process known as *drawdown* and create a **cone of depression**.
- Water flows toward the cone of depression. The area affected by the well is called the **area of influence**.
- Water may rise to a level above the top of a confined aquifer, producing an *artesian well*
- *Storativity (S):* Aquifer storage is measured by storativity, which is a volume of water that aquifer releases per unit area per unit pressure drop
- Transmisivity (T): Product of hydraulic conductivity (K) and thickness of acquifer (b) (T=Kb)



Pumping Water from Wells

- Pumping water from aquifers can lower groundwater levels.
- Pumping changes groundwater flow patterns.
- For example, water used to flow from groundwater to lake. Now flowing from lake to groundwater.
- Could lead to change in groundwater quality.

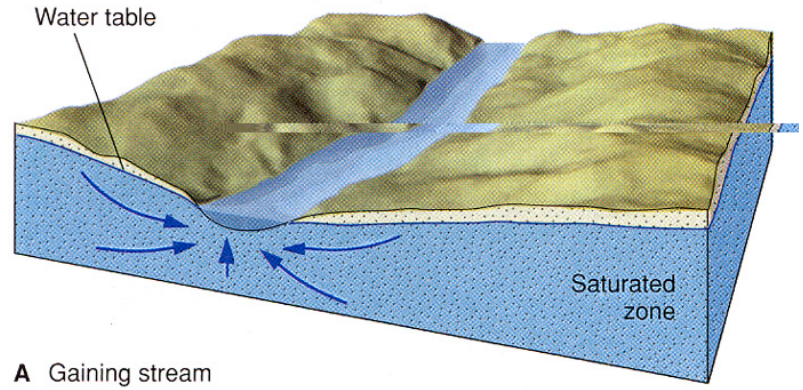


Generalized ground-water flow (A) under natural conditions and (B) affected by pumping (Note that surface- and ground-water divides are coincident in A but not in B).

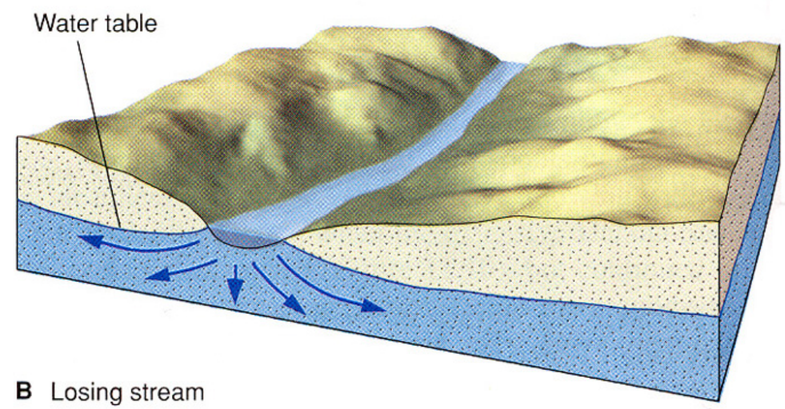
Streams and Groundwater

- *Gaining streams* - receive water from the saturated zone
  - Gaining stream surface is local water table

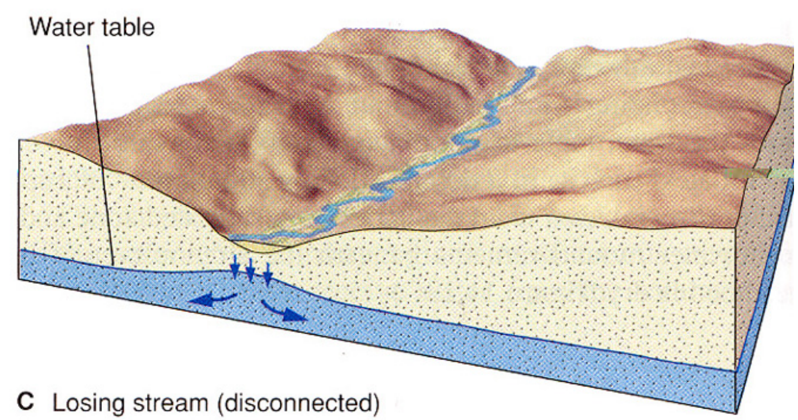
- *Losing streams* - lose water to the saturated zone
  - Stream beds lie above the water table
  - Maximum *infiltration* occurs through streambed, producing permanent "mound" in the water table beneath dry channel



A Gaining stream



B Losing stream



C Losing stream (disconnected)

Residence time of water?

- **Rate of movement varies greatly in each component**
  - **Atmospheric water: 100's kms /day**
  - **Stream water: only a few tens of kms/day;**
  - **Water in glaciers: cm-meters/day**
  - **Underground water: meters or less/ year.**

- **MRT [Mean Residence Time] – amount of time an average water molecule spends within any one reservoir before moving to another reservoir.**

MRT' S OF RESERVOIRS

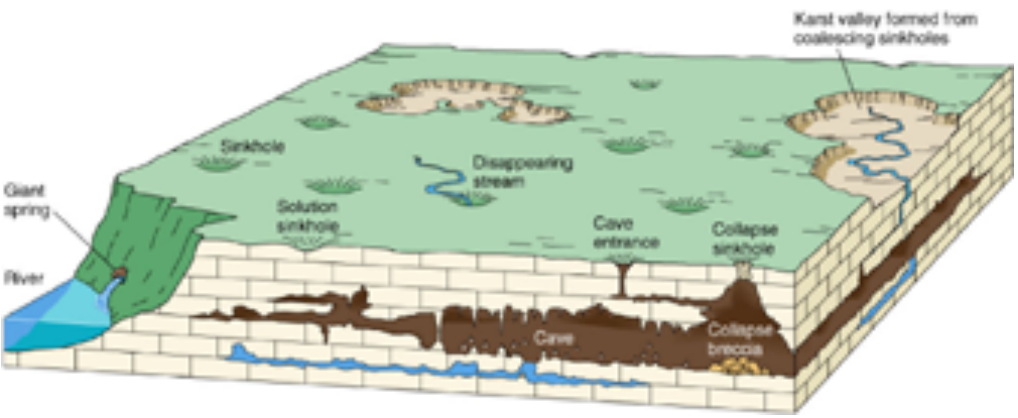
- ATMOSPHERIC WATER: ~ 8-10 DAYS

- OCEANS (on average): > 3000 Years
  - Shallow oceans: Few days to weeks
  - Deep ocean water: 100' s – 1000' s years

- GROUNDWATER (on average): 10,000 Years
  - Shallow aquifers: 1-5 Years
  - Deep aquifers: 10,000-100,000 Years]

Caves, Sinkholes, and Karst

- *Caves* - naturally-formed underground chambers
  - Acidic ground water dissolves limestone along joints and bedding planes
- Caves near the surface may collapse and produce *sinkholes*
- Rolling hills, disappearing streams, and sinkholes are common in areas with *karst topography*



Hot Water Underground

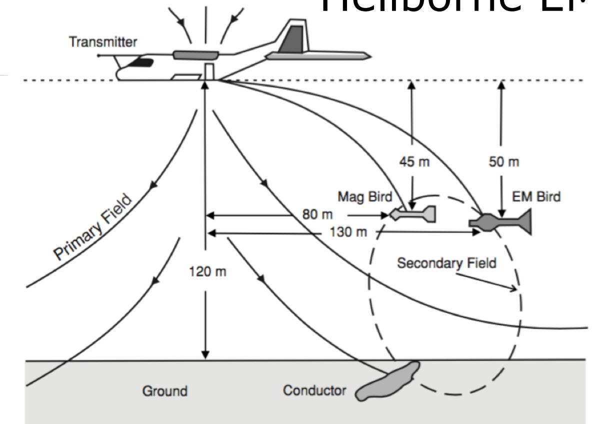
- *Hot springs* - springs in which the water is warmer than human body temperature
  - Ground water heated by nearby magma bodies or circulation to unusually deep (and warm) levels within the crust
  - Hot water is less dense than cool water and thus rises back to the surface on its own
- *Geysers* - hot springs that periodically erupt hot water and steam
  - Minerals often precipitate around geysers as hot water cools rapidly in the air

Geothermal Energy

- *Geothermal energy* is produced using natural steam or superheated water
  - No CO_2 or acid rain are produced (*clean* energy source)
  - Some toxic gases given off (e.g., sulfur compounds)
  - Can be used directly to heat buildings
  - Superheated water can be very corrosive to pipes and equipment

Indian Ground water scenerio

Heliborne EM



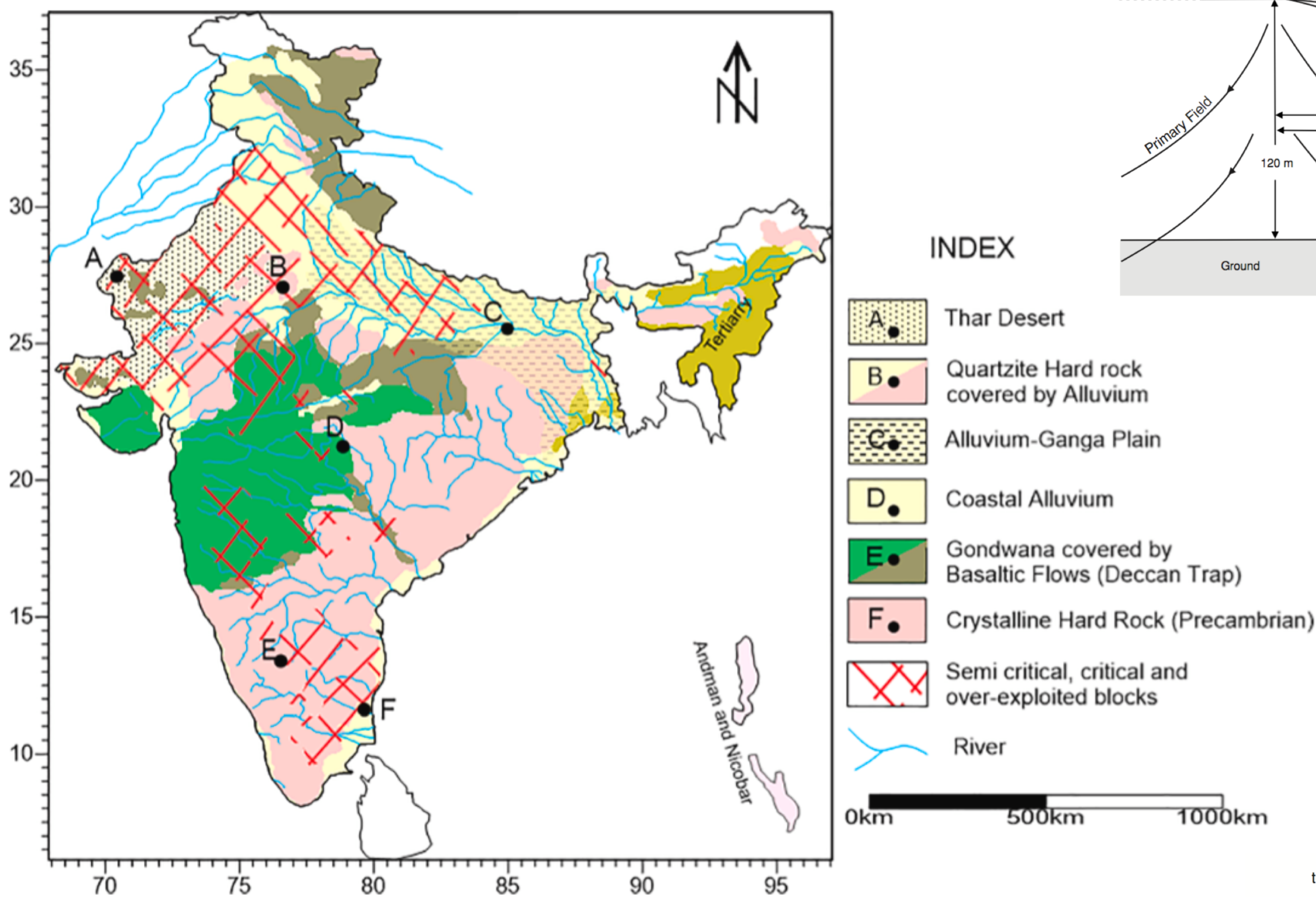
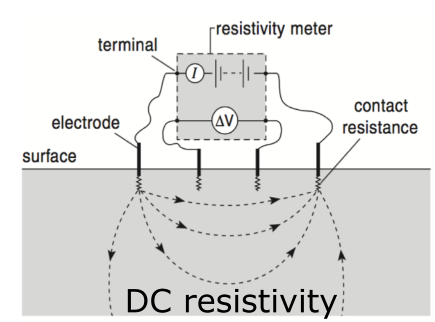
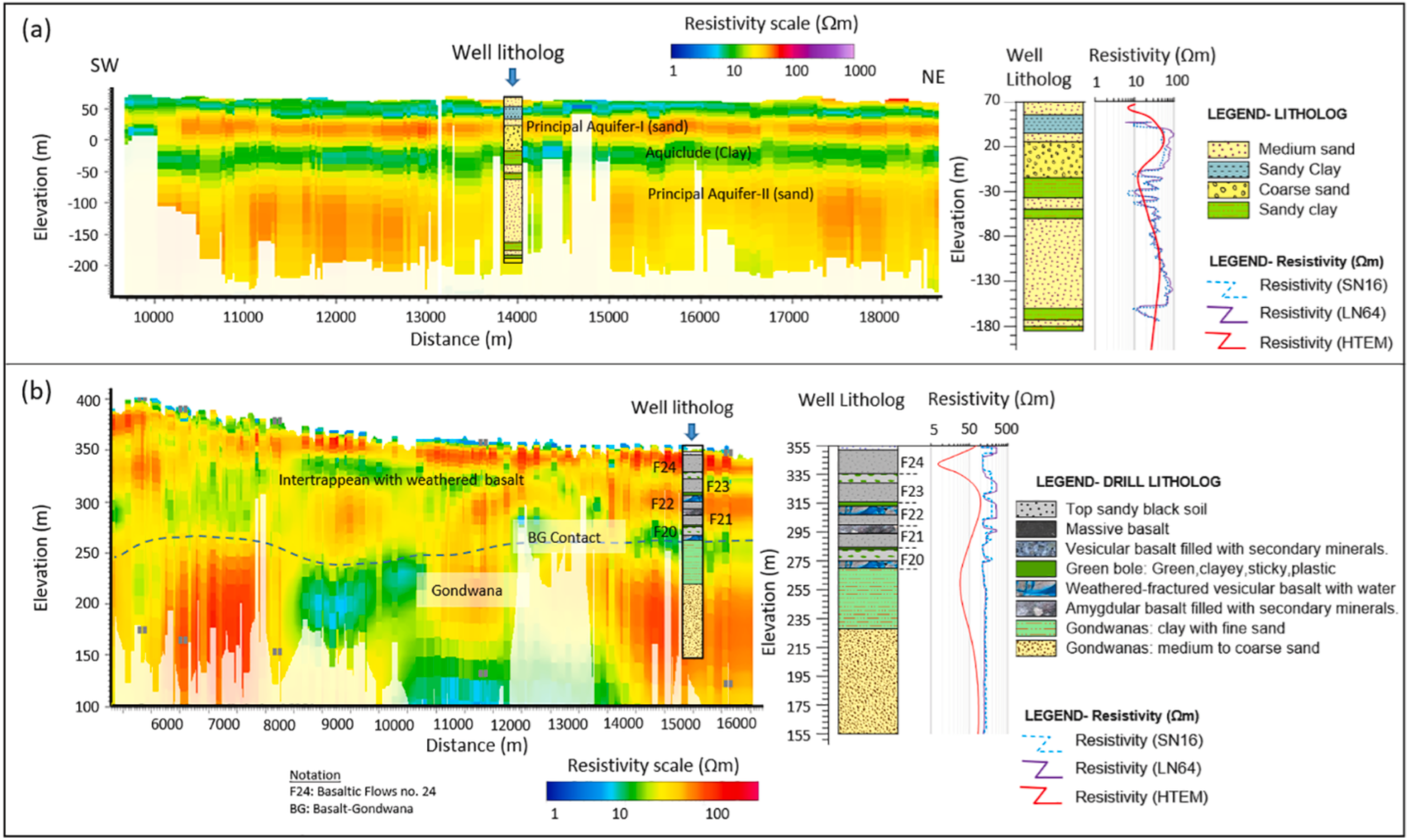


Fig. 1. Pilot study areas located in representative hydrogeological settings of India.



Chandra et al., 2022

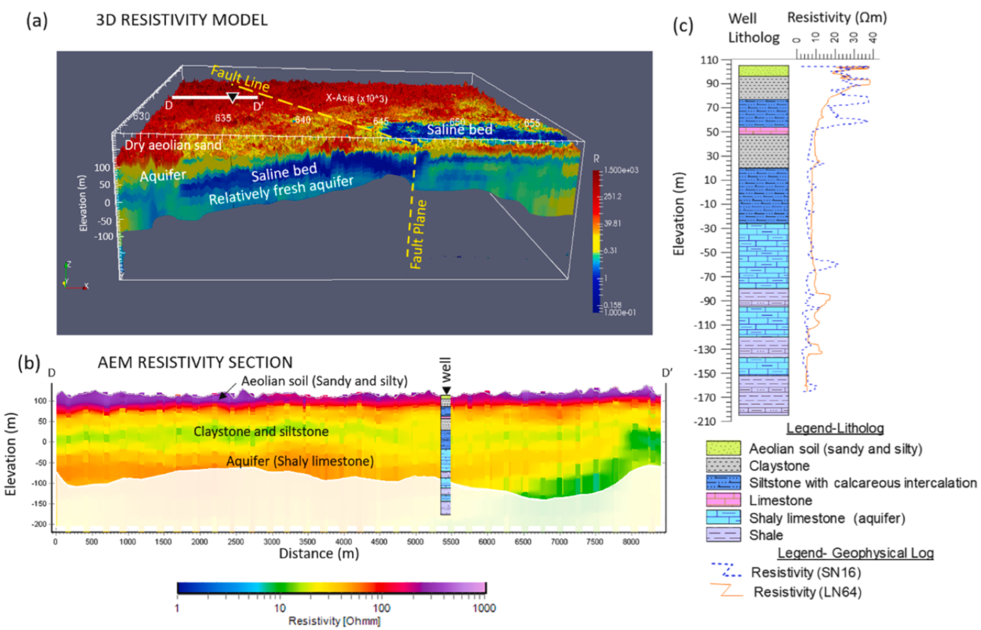
Resistivity-EM results



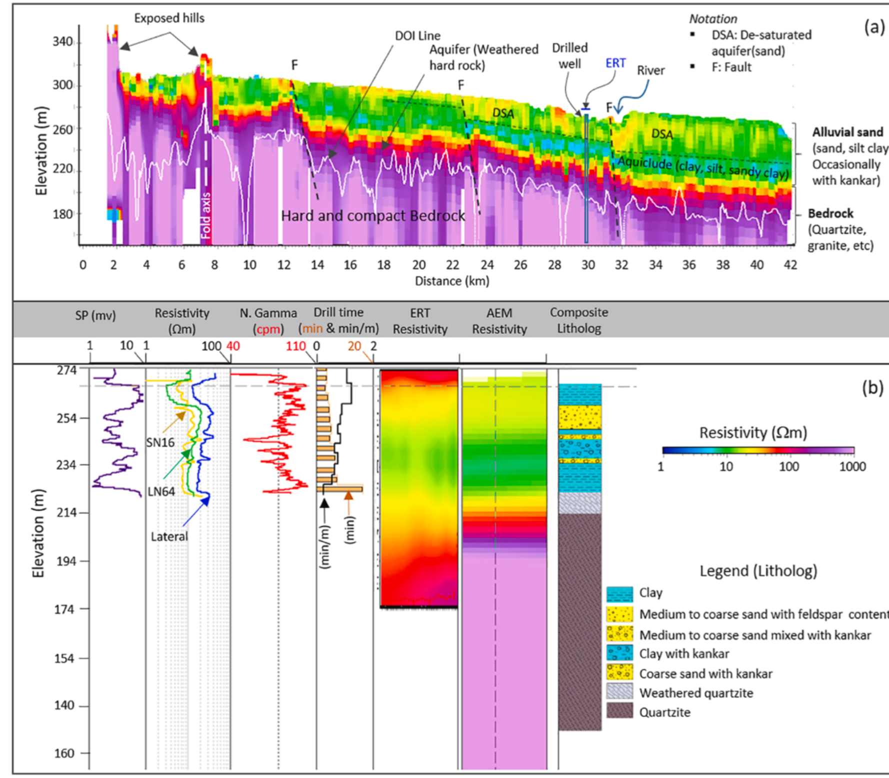
(a) HTEM resistivity sections of Ganga Alluvium, Patna (Bihar) with well litholog and borehole resistivity (SN16 & LN64) logs located almost at the center of the pro le; (b) HTEM resistivity sections Deccan basalt near Nagpur (Maharashtra) with well litholog and borehole resistivity (SN16 & LN64) logs.

Chandra et al., 2022

Resistivity-EM results



HTEM results of Thar desert, Jaisalmer showing: (a) 3D Resistivity model; (b) resistivity section along DD' pro le line with borehole litholog; and (c) drilling litholog and electrical resistivity (SN16 & LN64) logs.



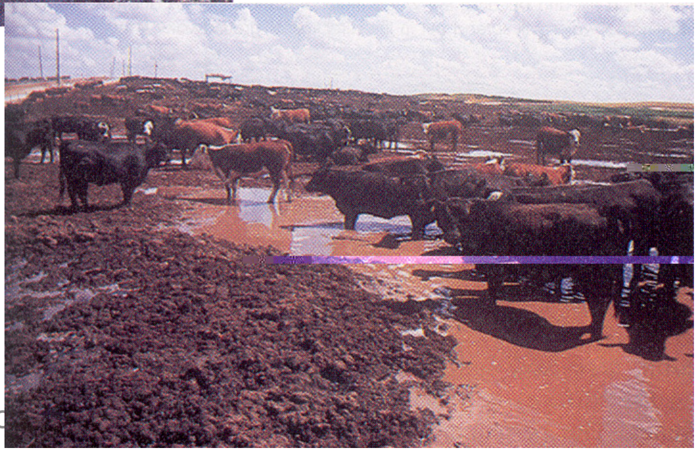
(a) HTEM resistivity pro le of Dausa district, Rajasthan; and (b) comparative plot of HTEM resistivity, ERT, borehole geophysical logs and drilling litholog at the drilled well site

Chandra et al., 2022

Ground Water Contamination

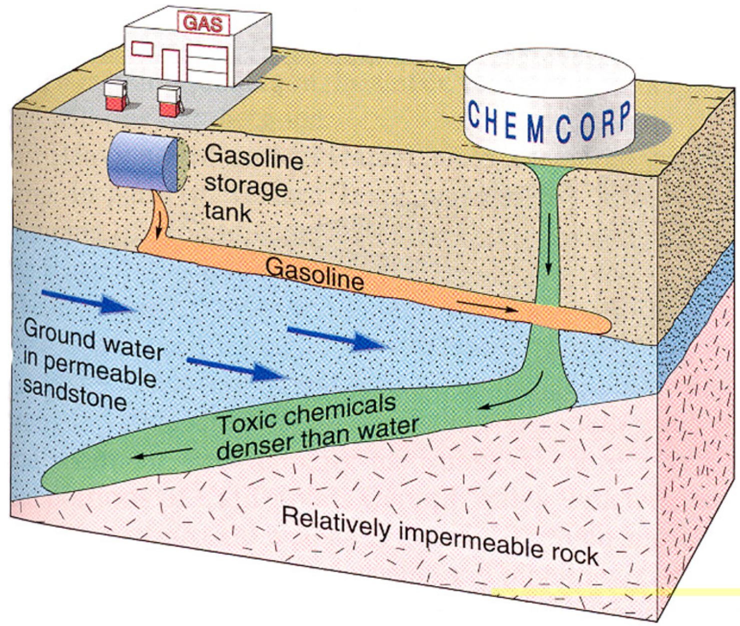
Infiltrating water may bring contaminants down to the *water table*, including (but not limited to):

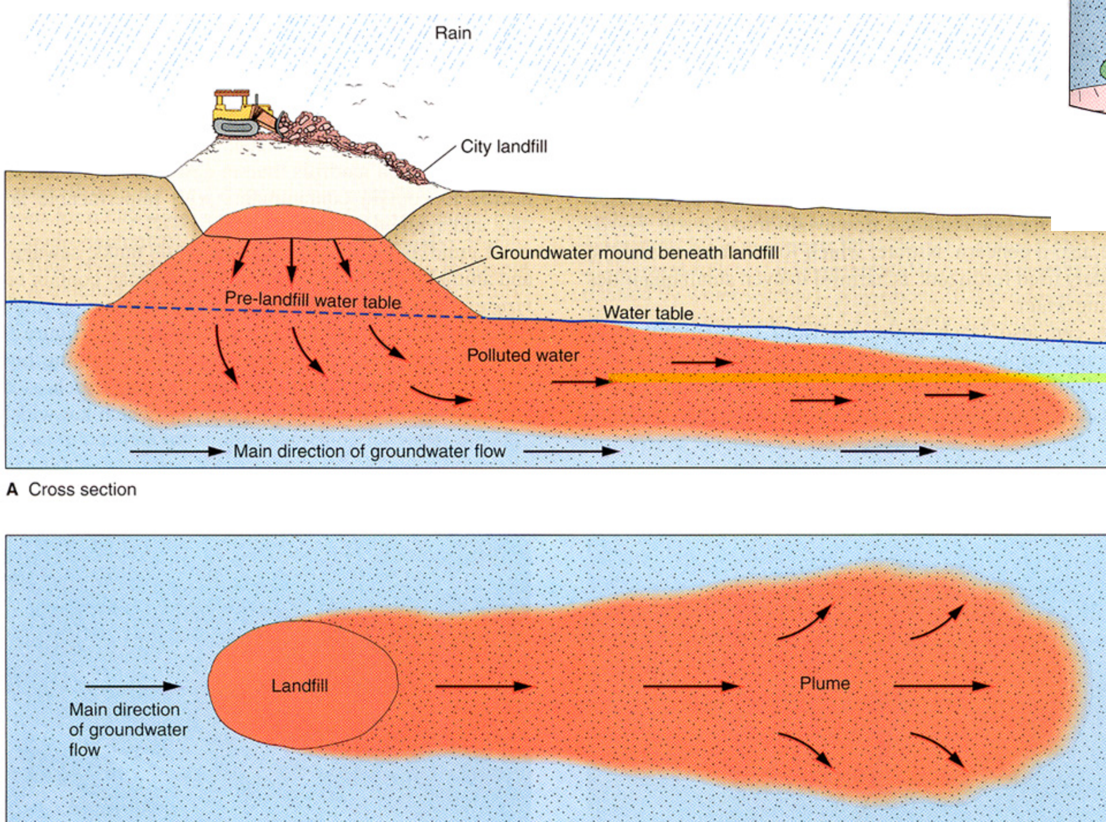
- Pharmaceuticals
- Pesticides/herbicides
- Fertilizers
- Feed lots
- Mercury and gold mining
- Landfill pollutants
- Heavy metals
- Bacteria, viruses and parasites from sewage
- Industrial chemicals (PCBs, TCE)
- Acid mine drainage
- Radioactive waste
- Oil and gasoline



Ground Water Contamination

- *Contaminated ground water* can be *extremely difficult and expensive* to clean up





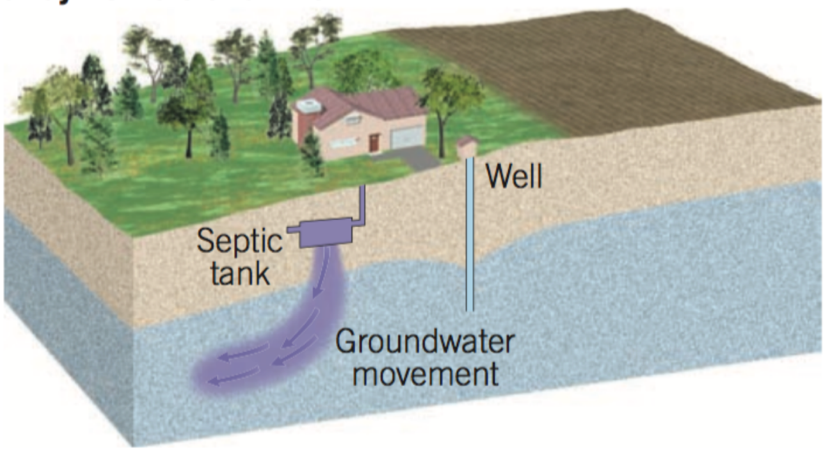
A Cross section

Inc.

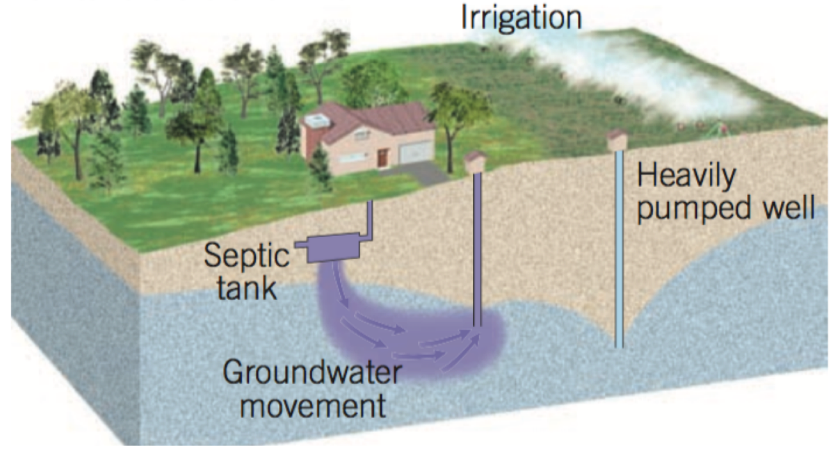
How Does Pumping Water from Wells Influence Water Quality?

- Pumping water from a well draws the water table down and can pull in contaminants from the well's **area of influence**.

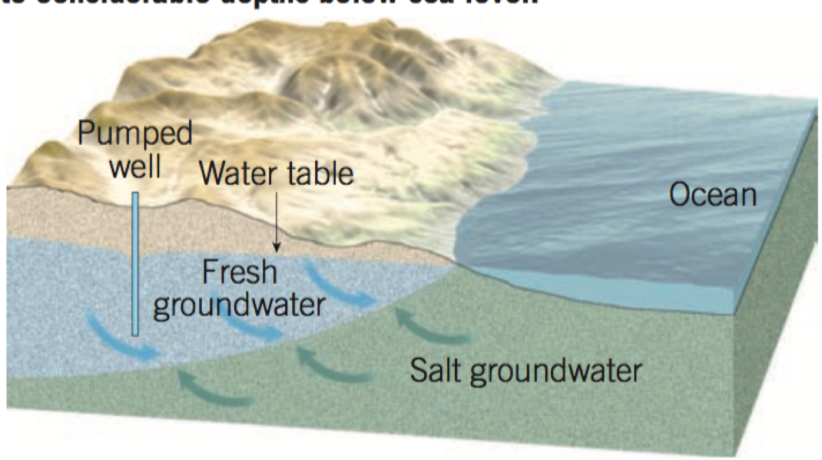
Originally the outflow from the septic tank moved away from the small well.



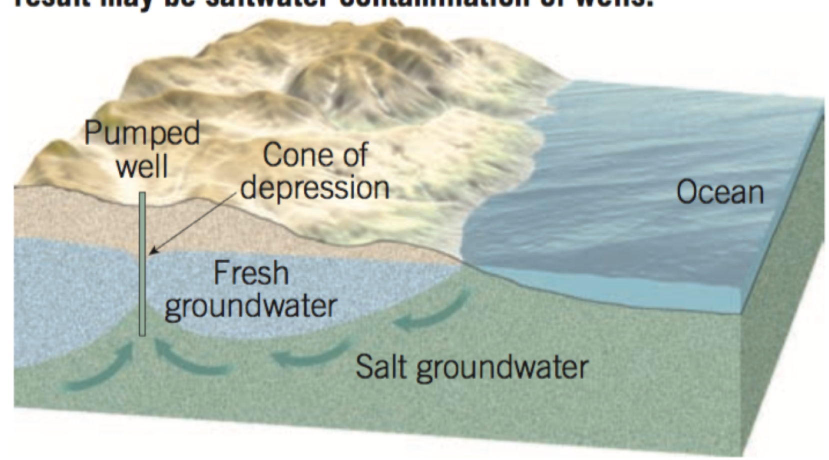
The heavily pumped well changed the slope of the water table, causing contaminated groundwater to flow toward the small well.



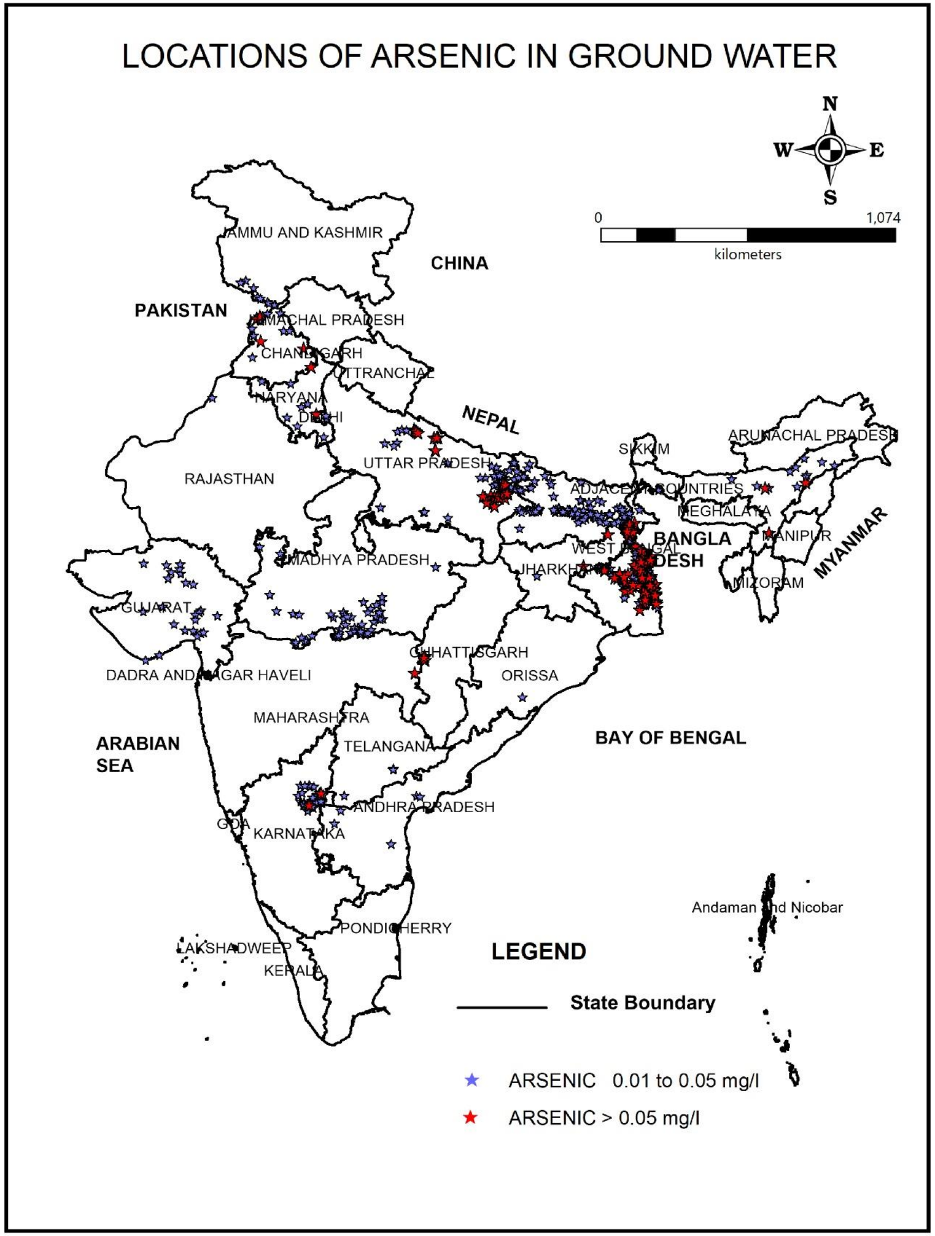
Because freshwater is less dense than saltwater, it floats on the saltwater and forms a lens-shaped body that may extend to considerable depths below sea level.



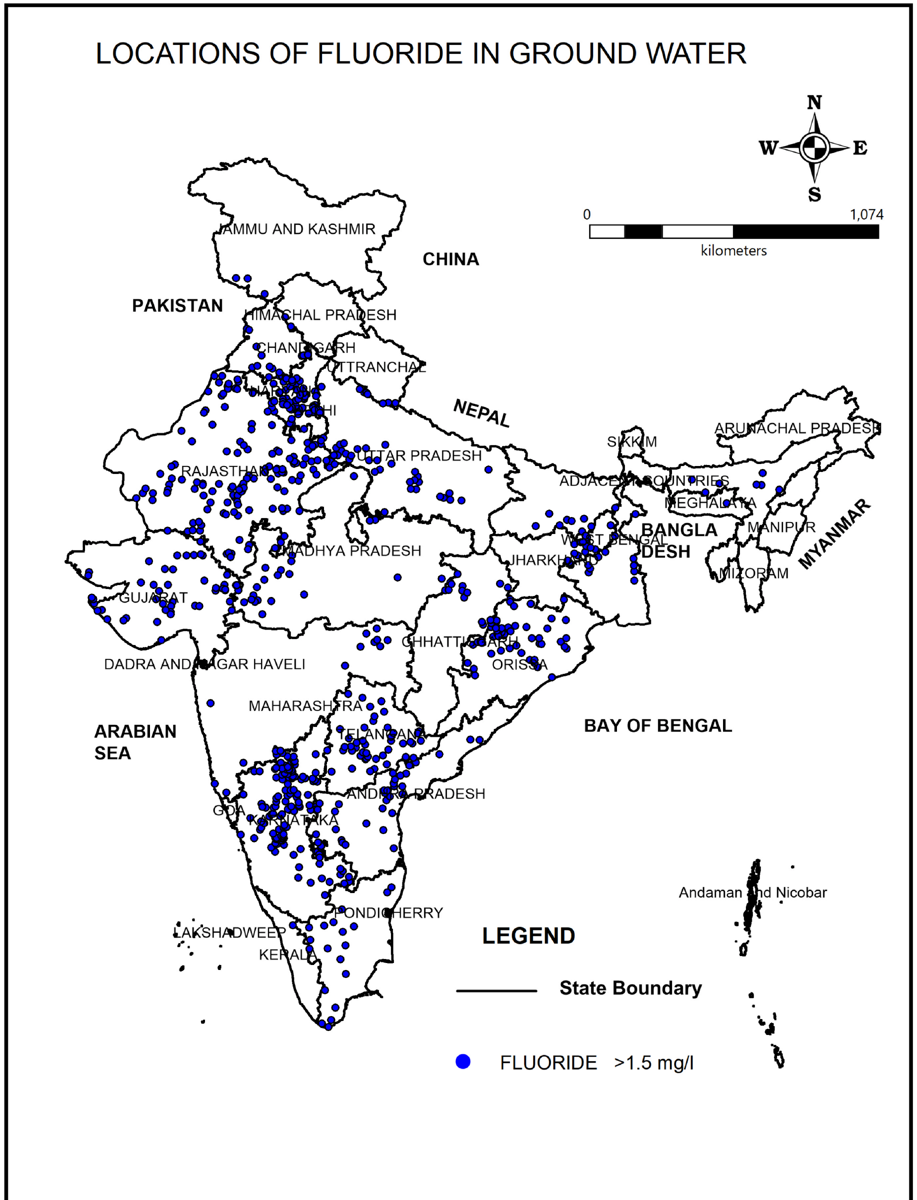
If excessive pumping lowers the water table, the base of the freshwater zone will rise 40 times that amount. The result may be saltwater contamination of wells.

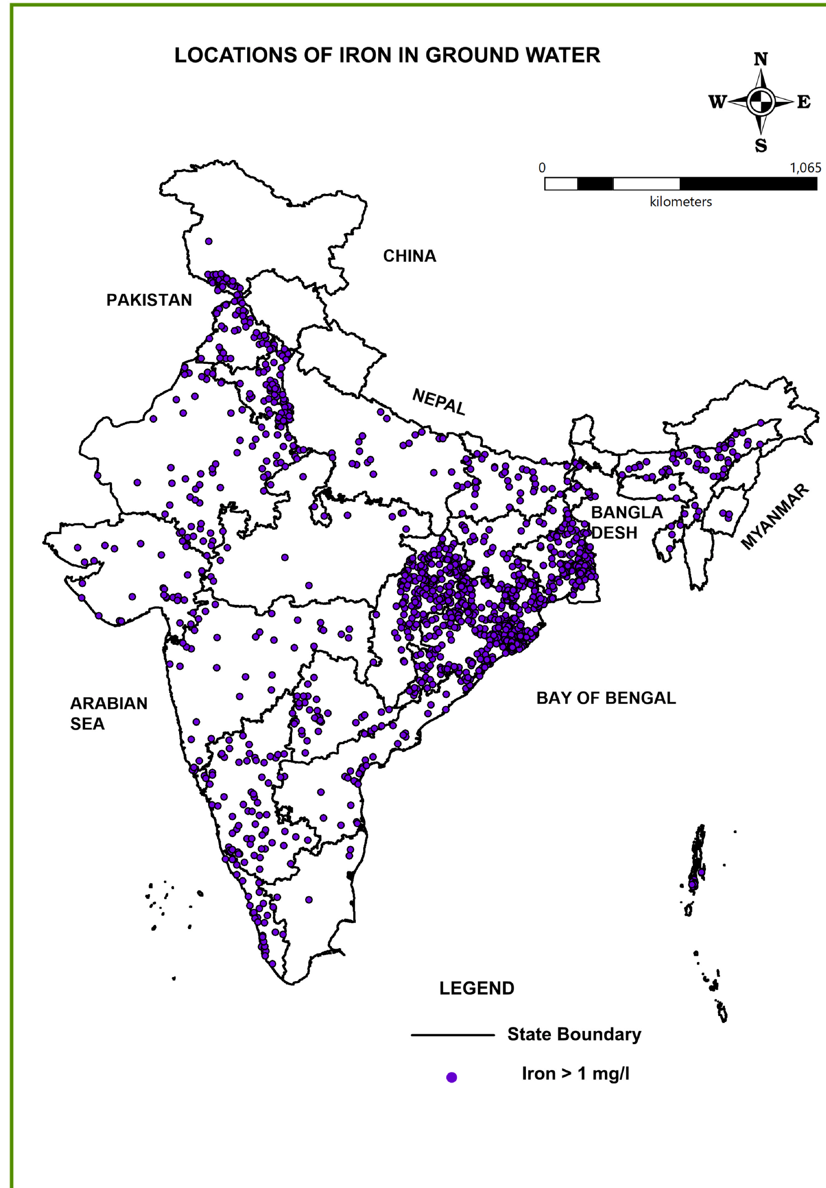


Arsenic is a naturally occurring trace element found in rocks, soils and the water in contact with them. Arsenic has been recognized as a toxic element and is considered a human health hazard.

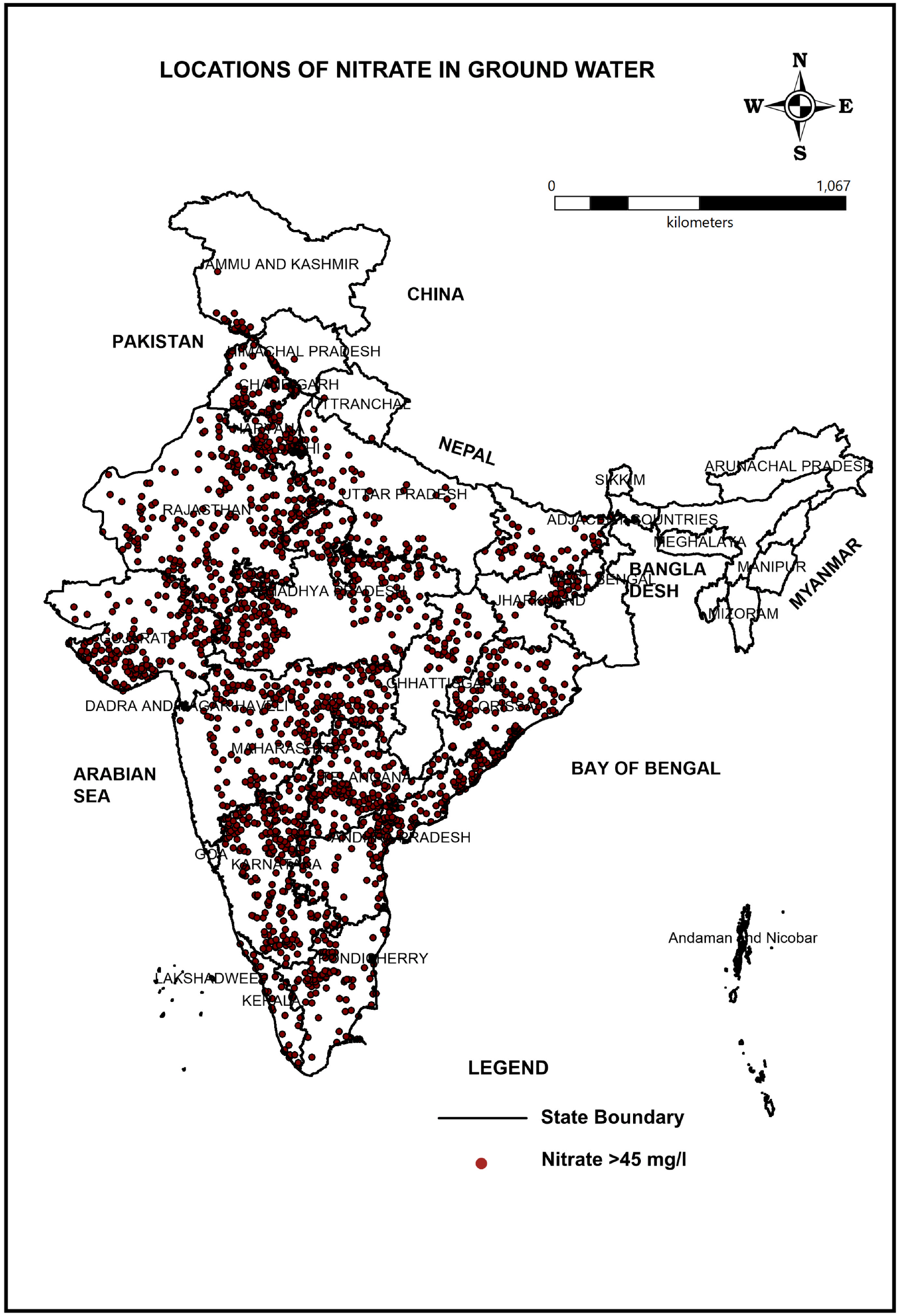


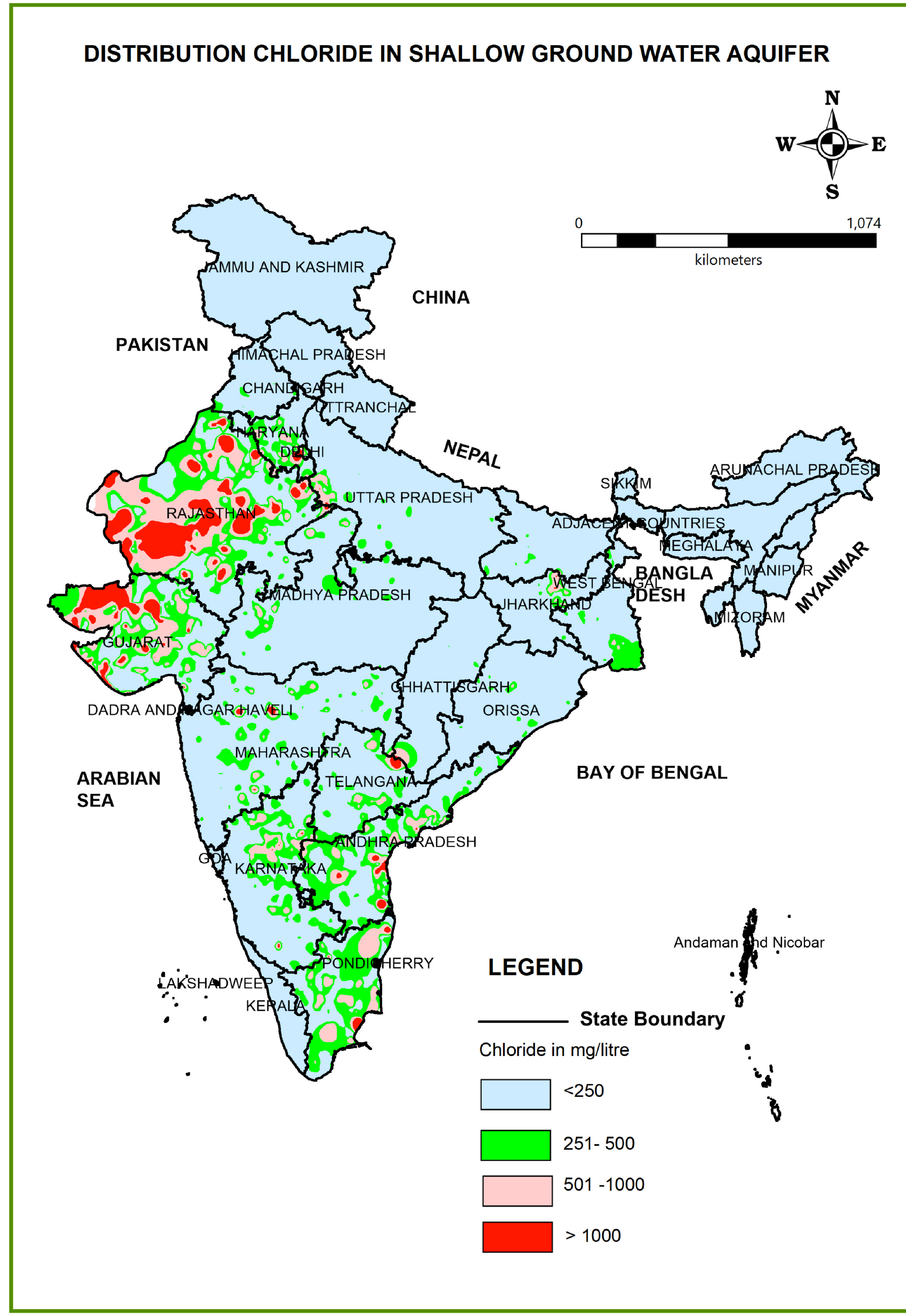
Source:CGWB


LOCATIONS OF FLUORIDE IN GROUND WATER
N
W
E
S
0
1,074
kilometers
JAMMU AND KASHMIR
CHINA
PAKISTAN
HIMACHAL PRADESH
CHANDIGARH
UTTRANCHAL
NEPAL
UTTAR PRADESH
RAJASTHAN
SIKKIM
ARUNACHAL PRADESH
ADJACENT COUNTRIES
MEGHALAYA
BANGLA DESH
MANIPUR
MYANMAR
WEST BENGAL
MADHYA PRADESH
JHARKHAND
MIZORAM
GUJARAT
CHHATTISGARH
ORISSA
DADRA AND NAGAR HAVELI
MAHARASHTRA
ARABIAN SEA
BAY OF BENGAL
TELANGANA
ANDHRA PRADESH
GOA
KARNATAKA
Andaman and Nicobar
PONDICHERRY
LAKSHADWEEP
KERALA
LEGEND
State Boundary
FLUORIDE >1.5 mg/l


LOCATIONS OF IRON IN GROUND WATER
N
W
E
S
0
1,065
kilometers
CHINA
PAKISTAN
NEPAL
BANGLA DESH
MYANMAR
ARABIAN SEA
BAY OF BENGAL
LEGEND
State Boundary
Iron > 1 mg/l

Source:CGWB

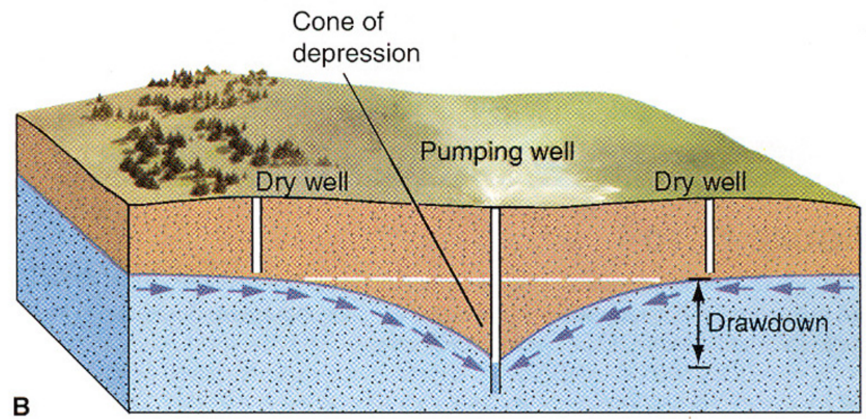

LOCATIONS OF NITRATE IN GROUND WATER
N
W
E
S
0
1,067
kilometers
JAMMU AND KASHMIR
CHINA
PAKISTAN
HIMACHAL PRADESH
CHANDIGARH
UTTRANCHAL
HARYANA
DELHI
NEPAL
RAJASTHAN
UTTAR PRADESH
SIKKIM
ARUNACHAL PRADESH
ADJACENT COUNTRIES
MEGHALAYA
BANGLA DESH
MANIPUR
MYANMAR
MADHYA PRADESH
WEST BENGAL
JHARKHAND
MIZORAM
GUJARAT
CHHATTISGARH
ORISSA
DADRA AND NAGAR HAVELI
MAHARASHTRA
BAY OF BENGAL
ARABIAN SEA
TELANGANA
ANDHRA PRADESH
GOA
KARNATAKA
Andaman and Nicobar
PONDICHERRY
LAKSHADWEEP
KERALA
LEGEND
State Boundary
Nitrate >45 mg/l


DISTRIBUTION CHLORIDE IN SHALLOW GROUND WATER AQUIFER
N
W
E
S
0
1,074
kilometers
JAMMU AND KASHMIR
CHINA
PAKISTAN
HIMACHAL PRADESH
CHANDIGARH
UTTRANCHAL
HARYANA
DELHI
NEPAL
RAJASTHAN
UTTAR PRADESH
SIKKIM
ARUNACHAL PRADESH
ADJACENT COUNTRIES
MEGHALAYA
BANGLA DESH
MANIPUR
MYANMAR
MADHYA PRADESH
WEST BENGAL
JHARKHAND
MIZORAM
GUJARAT
CHHATTISGARH
ORISSA
DADRA AND NAGAR HAVELI
MAHARASHTRA
TELANGANA
BAY OF BENGAL
ARABIAN SEA
ANDHRA PRADESH
GOA
KARNATAKA
Andaman and Nicobar
PONDICHERRY
LAKSHADWEEP
KERALA
LEGEND
State Boundary
Chloride in mg/litre
<250
251- 500
501 -1000
> 1000

Source:CGWB

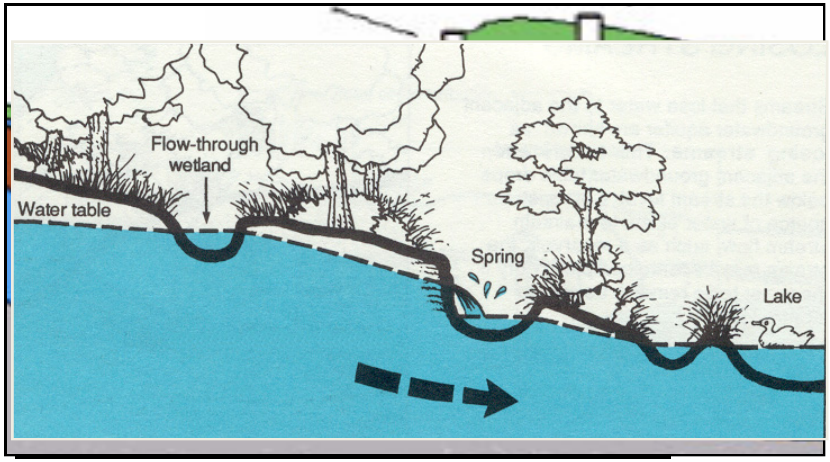
Balancing Withdrawal and Recharge

- If ground water is withdrawn more rapidly than it is recharged, the *water table* will drop
  - Dropping water table can lead to ground *subsidence*
    - surface of the ground drops as buoyancy from ground water is removed, allowing rock or sediment to compact and sink
  - Subsidence can crack foundations, roads and pipelines
  - Areas of extremely high *ground water pumping* (such as for crop irrigation in dry regions) have subsided 7-9 meters



Groundwater Susceptibility

Things to keep in mind:



- Unconfined aquifers with no cover of dense material are susceptible to contamination.
- Bedrock with large fractures is susceptible, because the fractures provide pathways for contaminants.
- Confined, deep aquifers tend to be better protected than surface aquifers with a dense layer of clay material.
- Wells that connect two aquifers increase the chance of cross contamination between the aquifers.