



Groundwater Modelling

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What do I expect to teach (and you to learn)

- Understand the importance of groundwater for civil and environmental applications
- Study and apply fundamental principles of groundwater flow and well hydraulics
 - Darcy's law
 - Radial flow to wells (steady and transient conditions)
 - Governing groundwater flow equations in 1, 2 and 3 dimensions
- How do groundwater systems interact with the rest of the hydrologic cycle
 - Surface water-groundwater interactions
- Human influences on groundwater
 - Pumping, subsidence, saltwater intrusion, water quality

In addition to lectures and assigned readings from the textbook, I will post demonstration videos for projects and analysis using EXCEL and other software

Recap

- Water Balance
 - Accumulation = In – Out $\pm$ Source/Sinks
- Groundwater-surface water interactions
 - Recharge = Discharge
 - Recharge = Pumping
 - Safe Yield
- Groundwater management doctrines
 - Rule of capture
 - Stakeholder driven management

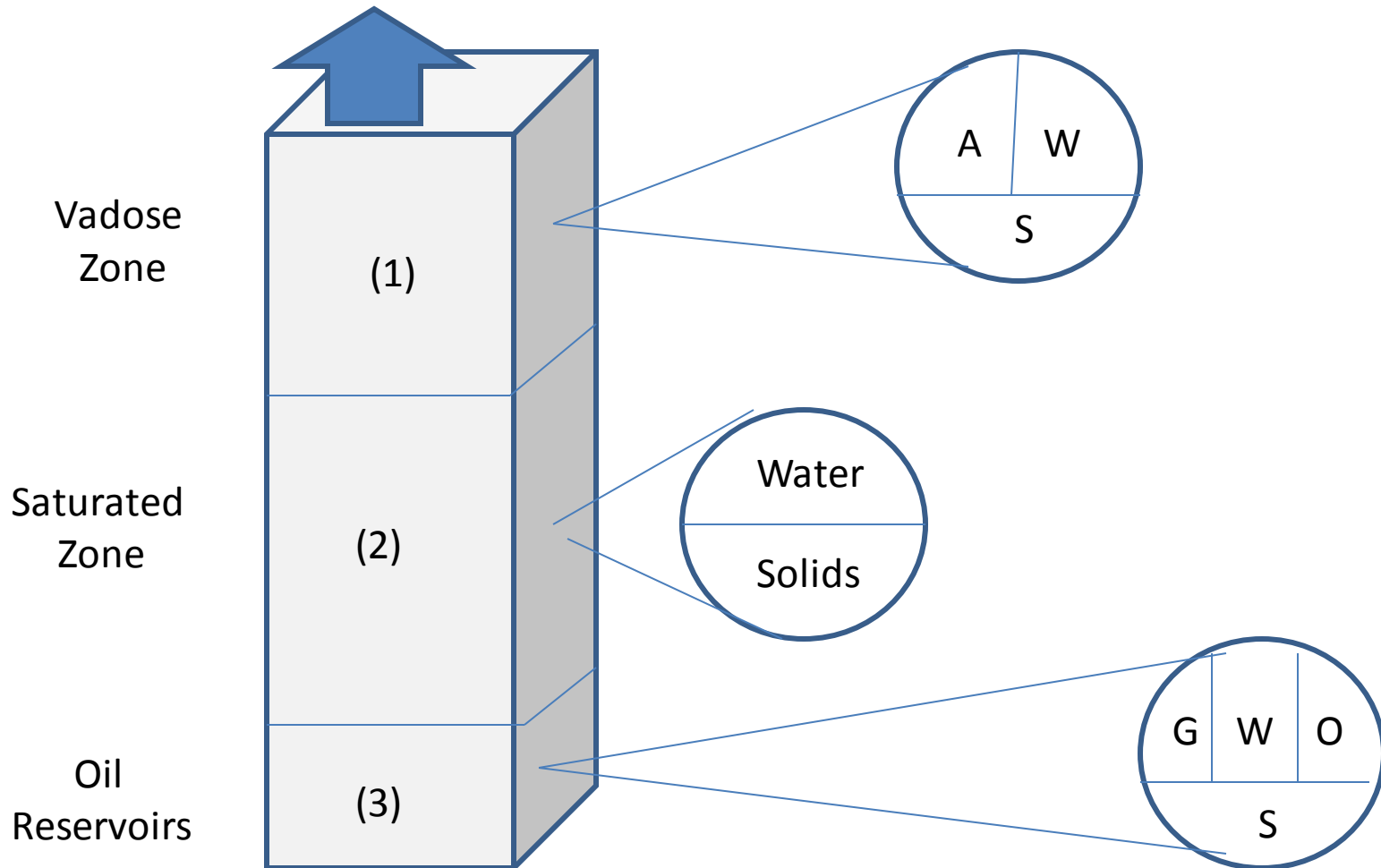
Recap

- Importance of groundwater
 - Accessibility, buffer against droughts
 - Groundwater accumulated over millions of years
 - Advancements in pumping technologies and rural electrification have intensified its use
 - Increased use in the US since 1940s
- Subsurface Systems
 - Vadose zone; Aquifers, Aquifuge, Aquiclude; Aquitard

The Subsurface Environment

- Subsurface refers to the zone below the land surface
 - Extends all the way to the center of the earth
 - But our focus is limited to tens to a few thousand feet at best
- We can classify the subsurface into three broad compartments(sections):
 - Vadose or the unsaturated zone
 - The saturated zone or the aquifer
 - Deep aquifers and oil bearing reservoirs

The Subsurface Environment

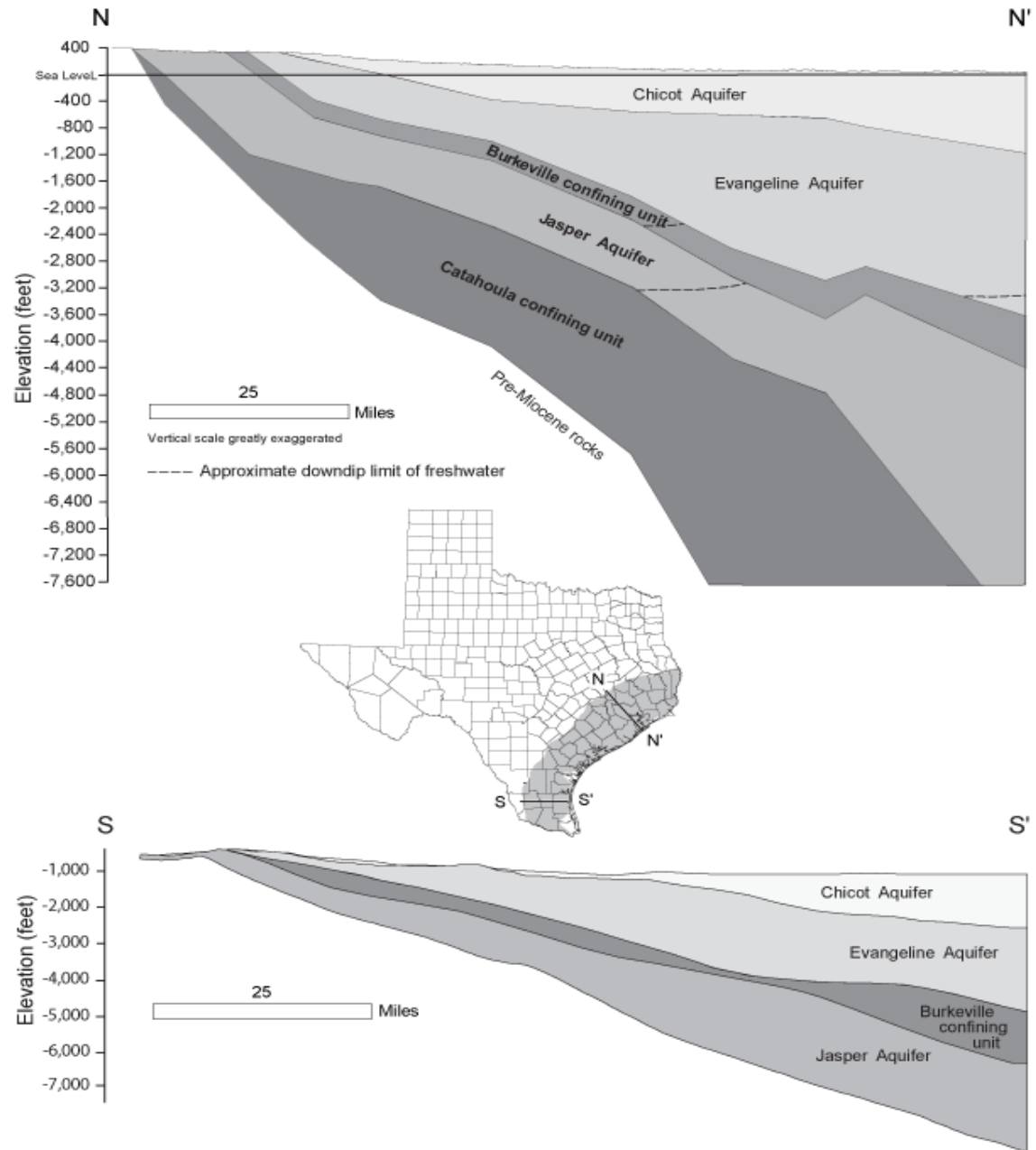


Aquifers and Groundwater

- Aquifers are geologic formations
 - Where the pores are fully saturated with water
 - One fluid and one solid phase
 - Water can be extracted sustainably and in sufficient quantities for human use
 - Permeable formation
- Aquiclude – Saturated geologic formation but do not yield appreciable amount of water (i.e., relatively impermeable)
 - Clay beds
- Aquifuge – relatively impermeable formation does not contain or transmit water
 - Solid Granite
- Aquitard – Saturated but poorly permeable formation
 - Can transmit water to layers above and below
 - But generally does not yield significant amount of water for human use

Aquifer Example

- Aquifers are geological depositional environments
 - Are formed over millions of years
 - Typically tend to be layered



Geologic time-scale

Palentology plays a major role
in aquifer classification

Groundwater was
deposited over millions
of years

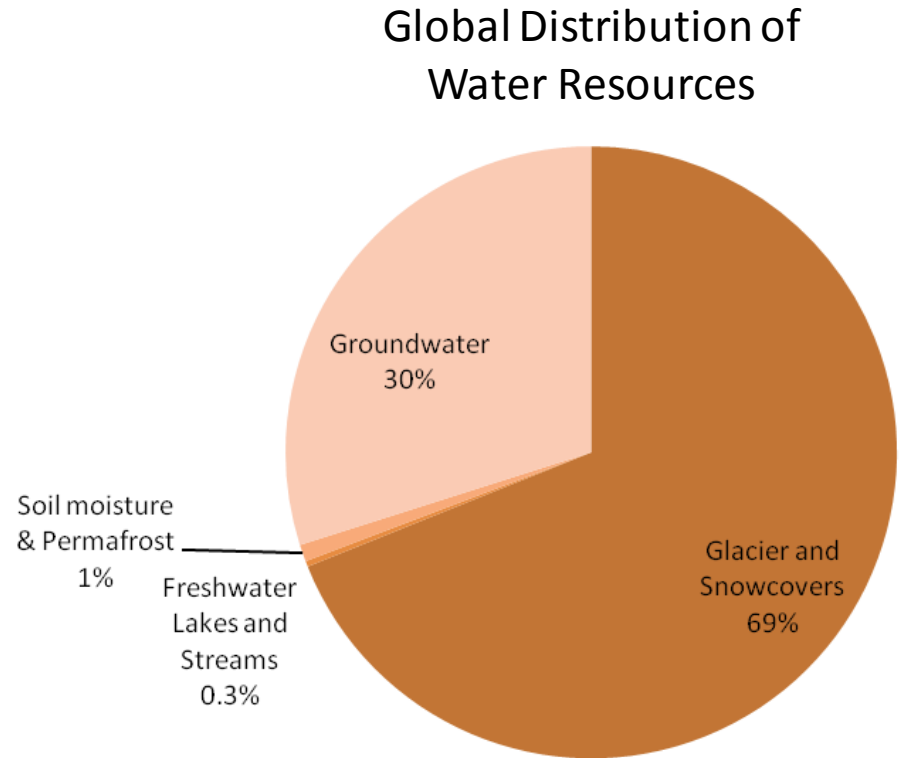
Advances in drilling
technologies help us tap
into deeper formations
(Good or Bad?)

Engineering Hydrologists work
closely with geologists to
solve groundwater issues

Eon	Era	Period	Epoch	MYBP*	Major Events in Evolution	
P H A N E R O Z O I C E O N	C E N O Z O I C	Quaternary	Recent	0.01	🦕 First written language, beginning of human history	
			Pleistocene	1.6	🦕 Modern humans 🦕 Many extinctions	
		Tertiary	Pliocene	5	🦕 First hominids	
			Miocene	23	🦕 MEGALODON and WHITE SHARK 🦕 FIRST HAMMERHEAD SHARKS	
			Oligocene	35	🦕 RADIATION OF MODERN SHARKS 🦕 Modern mammal families	
			Eocene	57	🦕 First whales	
			Paleocene	65		
			M E S O Z O I C	Cretaceous		145
	Jurassic			208	🦕 FIRST BATOIDS 🦕 First birds 🦕 Dinosaurs diversify	
	Triassic			245	🦕 FIRST NEOSELACHIANS, teleosts 🦕 First dinosaurs and mammals	
	P A L E O Z O I C	Permian		290	🦕 Many extinctions 🦕 First mammal-like reptiles	
		Carboniferous		360	🦕 "GOLDEN AGE OF SHARKS" 🦕 First tetrapods	
		Devonian		408	🦕 CLADOSELACHE 🦕 First insects	
		Silurian		440	🦕 FIRST SHARKS, ray-fins, placoderms	
		Ordovician		510	🦕 First fishes with jaws 🦕 First fishes with cranium	
		Cambrian		570	🦕 Oldest bone fragments 🦕 Oldest chordates	
	P R E C A M B R I A N			4 650	🦕 First multicellular life - 580 🦕 First cells with nucleus - 2 200g 🦕 Oldest life on Earth - 3 800	

Groundwater Resources

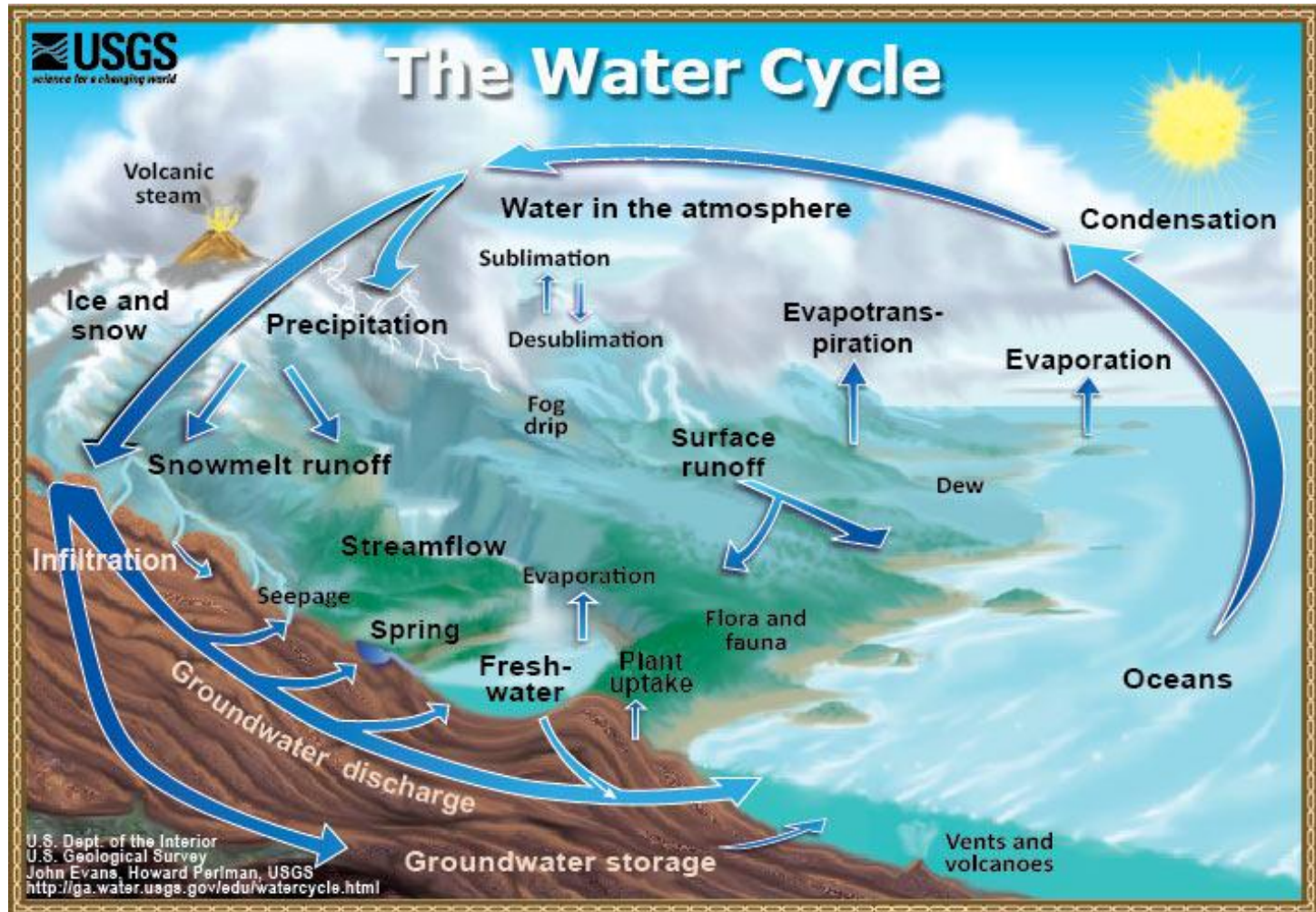
- Groundwater is a major source of freshwater both in the world and the US
 - Reliable
- More accessible particularly with availability of energy
 - Susceptible to over-exploitation
- Sole source of drinking water in most arid and semi-arid regions



Data: Gleick, 2010

Groundwater is often viewed as a buffer against droughts

Groundwater & Hydrologic Cycle



Approximately 1% of the precipitation ends up recharging the aquifers

Global Water Budget

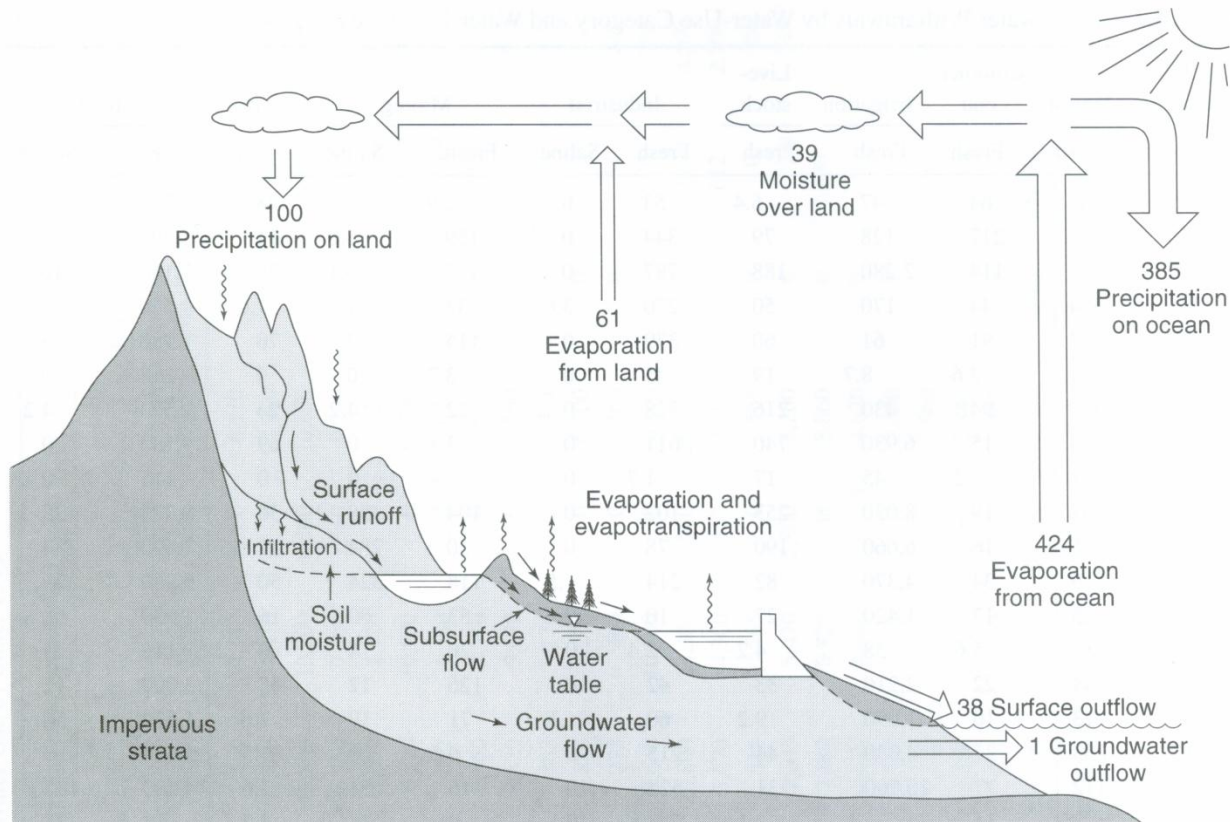
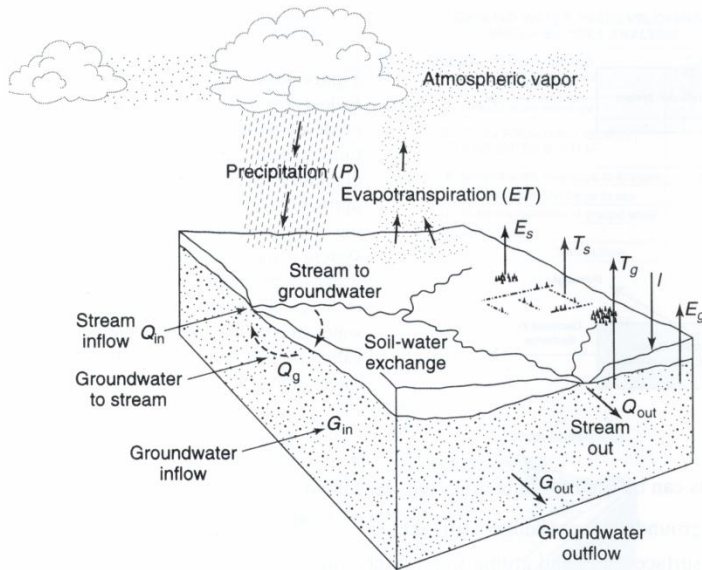


Figure 1.5.1. Hydrologic cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land.²²

Water Balance



Surface Water System Hydrologic Budget

$$P + Q_{in} - Q_{out} + Q_g - E_s - T_s - I = \Delta S_s, \quad (1.6.1)$$

where P is the precipitation, Q_{in} is the surface water flow into the system, Q_{out} is the surface water flow out of the system, Q_g is the groundwater flow into the stream, E_s is the surface evaporation, T_s is the transpiration, I is the infiltration, and ΔS_s is the change in water storage of the surface water system.

Groundwater System Hydrologic Budget

$$I + G_{in} - G_{out} - Q_g - E_g - T_g = \Delta S_g, \quad (1.6.2)$$

where G_{in} is the groundwater flow into the system, G_{out} is the groundwater flow out of the system, and ΔS_g is the change in groundwater storage. The evaporation, E_g , and the transpiration, T_g , can be significant if the water table is near the ground surface.

System Hydrologic Budget

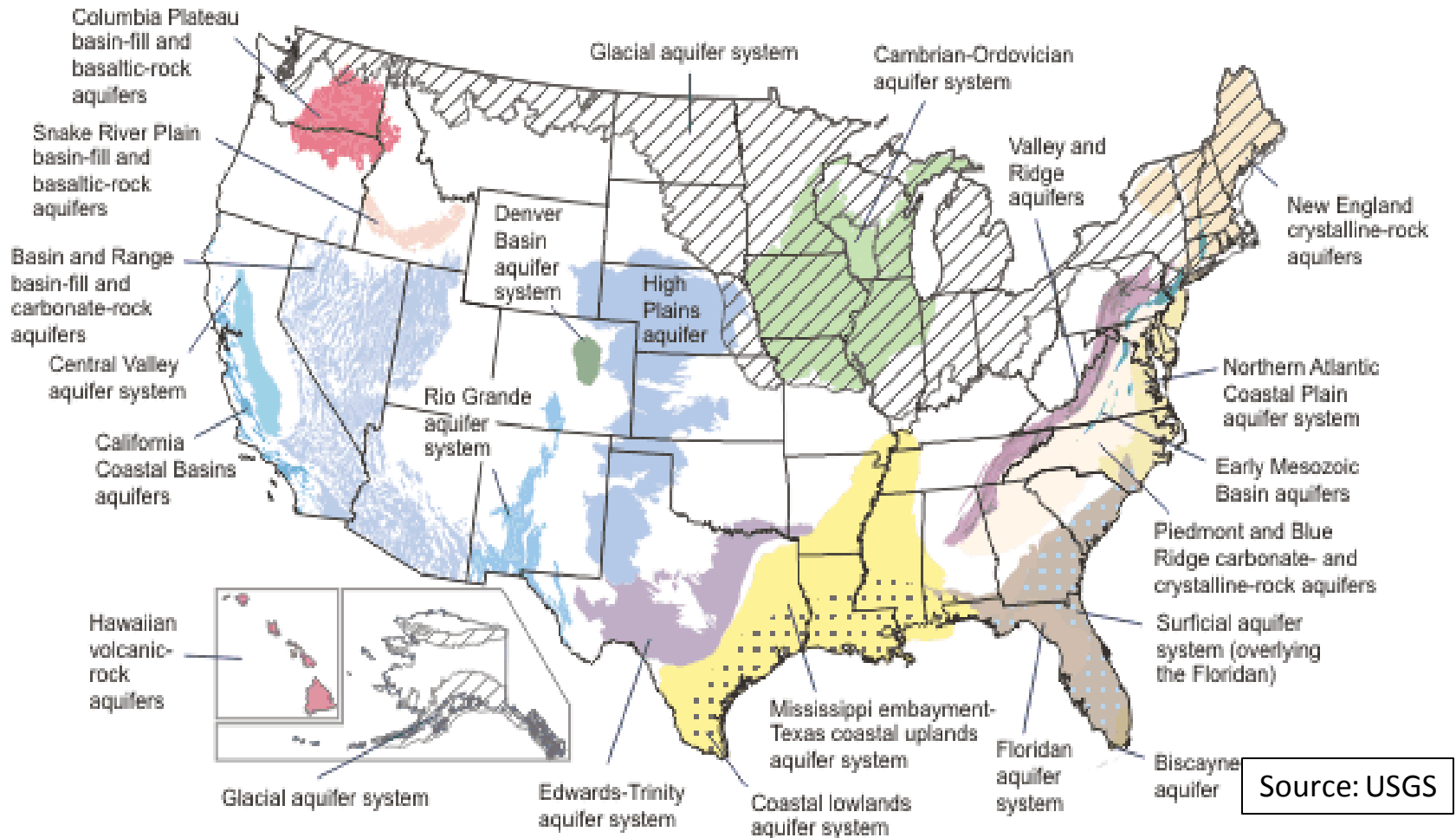
The system hydrologic budget is developed by adding the above two budgets together:

$$P - (Q_{out} - Q_{in}) - (E_s + E_g) - (T_s + T_g) - (G_{out} - G_{in}) = \Delta(S_s + S_g) \quad (1.6.3)$$

Using net mass exchanges, the above system hydrologic budget can be expressed as

$$P - Q - G - E - T = \Delta S \quad (1.6.4)$$

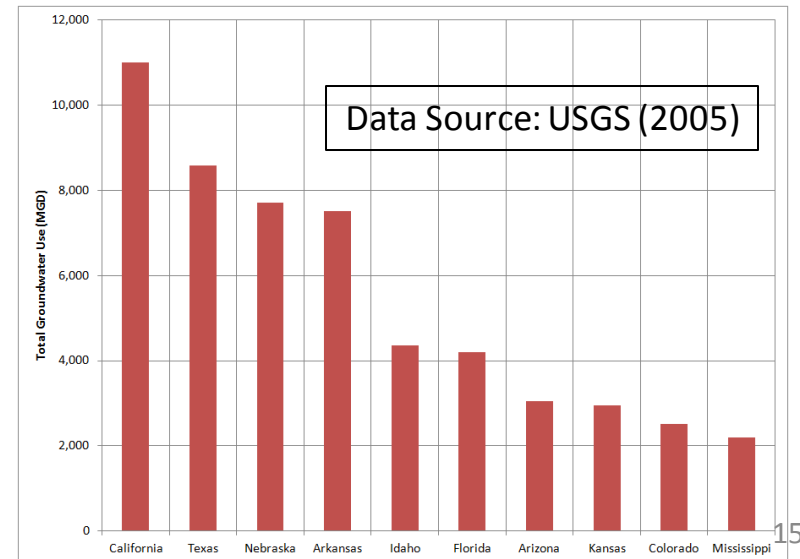
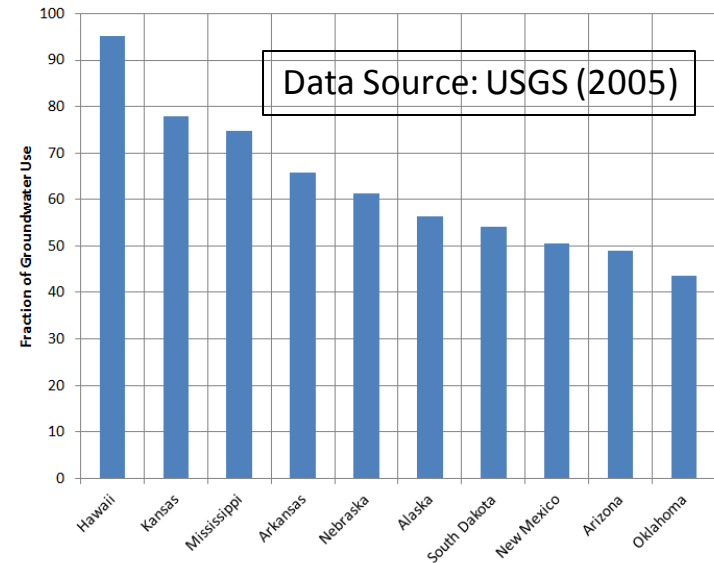
Groundwater in the US



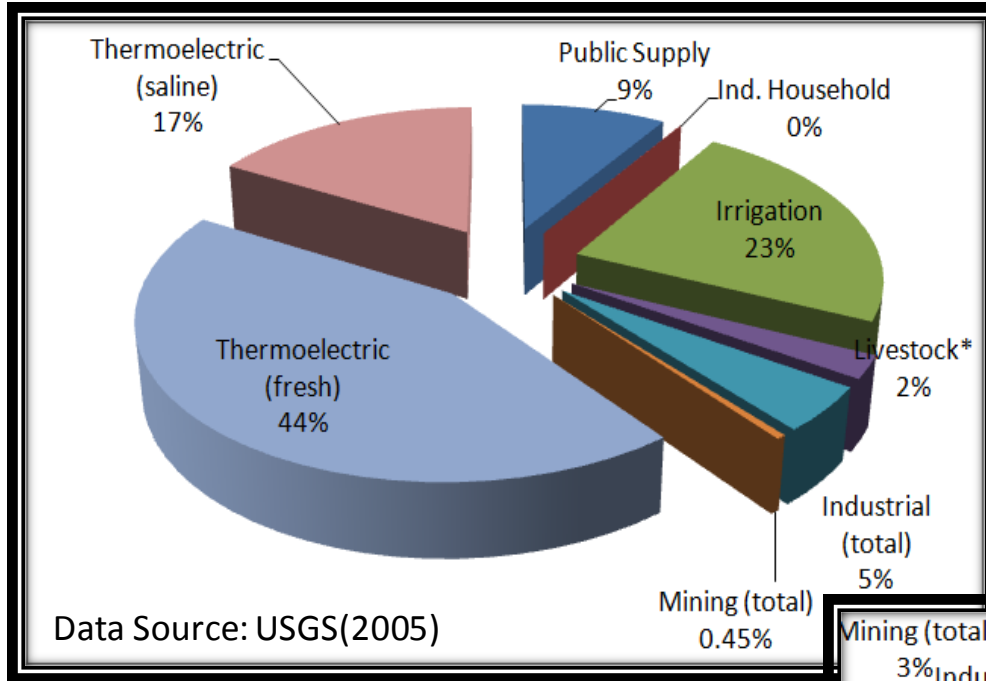
62 Principal aquifers in the US and many minor aquifer formations

US Groundwater Use Estimates

- Approximately 26% of the water withdrawn in the US is groundwater
 - Varies from 95% in Hawaii to 3% (Montana & W. Virginia)
- California and Texas are the largest groundwater users in terms of volume
- Nebraska and Idaho have the largest withdrawal per-capita
- Over 15 million wells nationwide
- Over one million wells in Michigan
- Texas probably has a few million



Differences in Surface & GW Uses

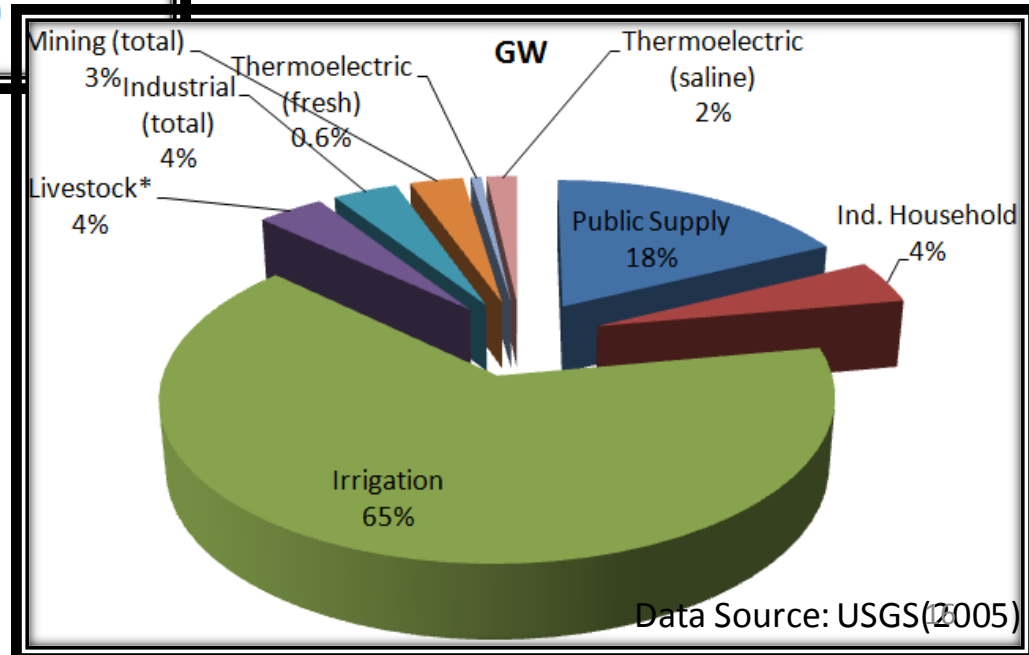


Surface water is most used for Thermoelectric needs

Groundwater most used for Irrigation and potable water

Over 95% of individual Household Use served by Groundwater

Sustaining Groundwater Resources is Critical for Water and Food Security



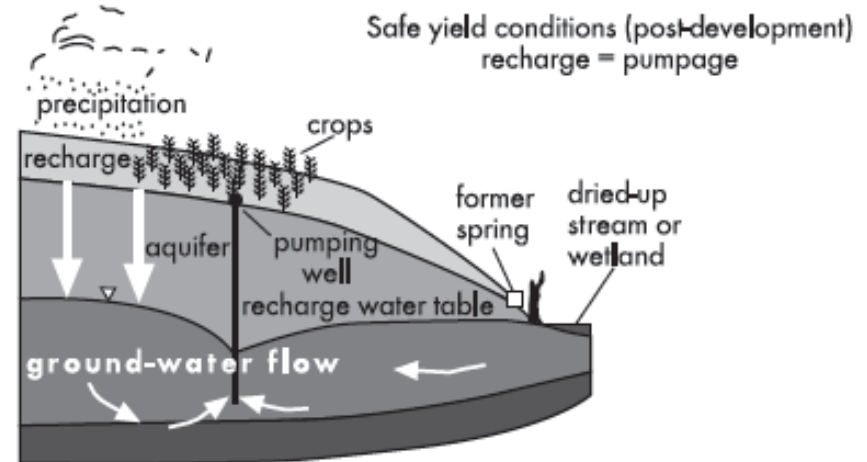
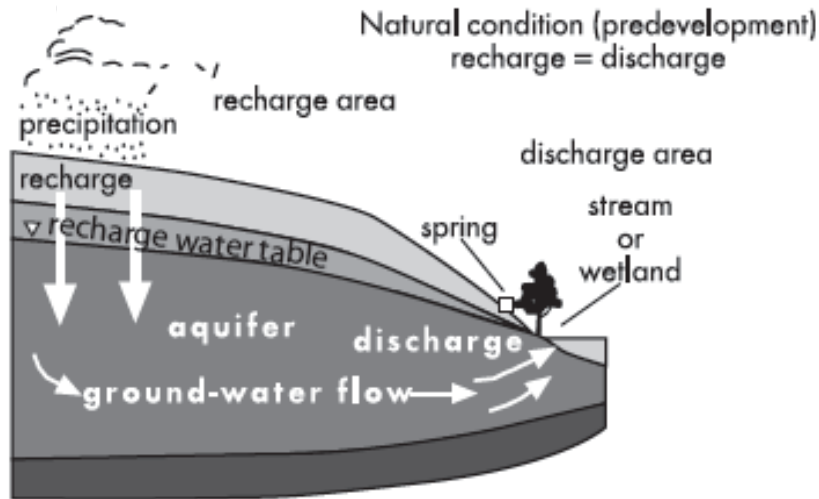


Groundwater & the Environment

- Groundwater sustains flows in perennial streams and rivers
 - 30% - 40% of the flows in streams is due to groundwater
 - Ecological and Recreational values of streams and lakes depend upon groundwater discharges
- Some groundwater systems are home to endangered species
 - Texas Blind Salamander in the Edwards Aquifer of Texas



Credit: Google Images



Recharge

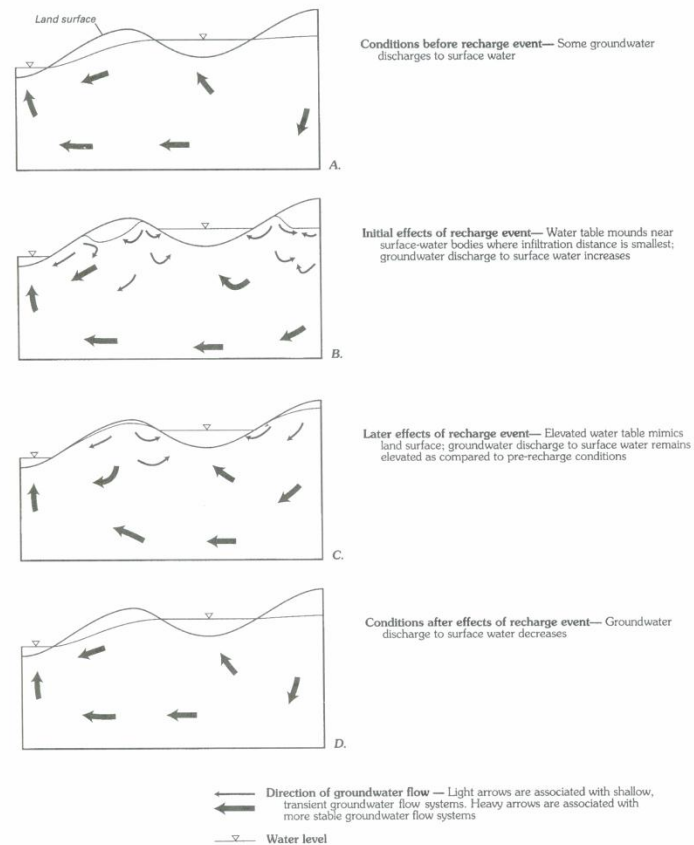
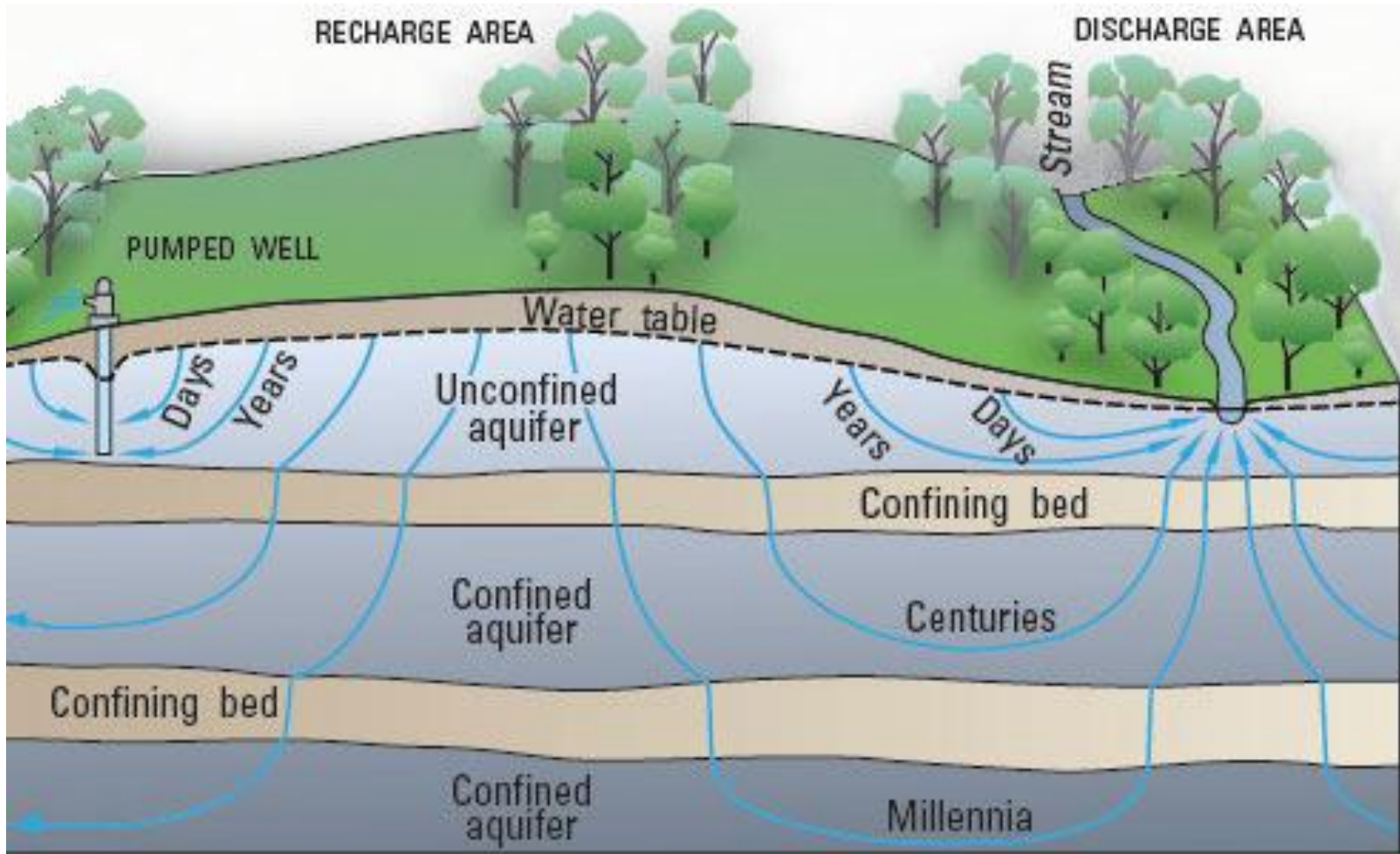


Figure 1.5.4. Diagrams showing the effect of transient recharge from precipitation on the configuration of a water table and associated groundwater flow.³³

Surface Water Groundwater Interactions

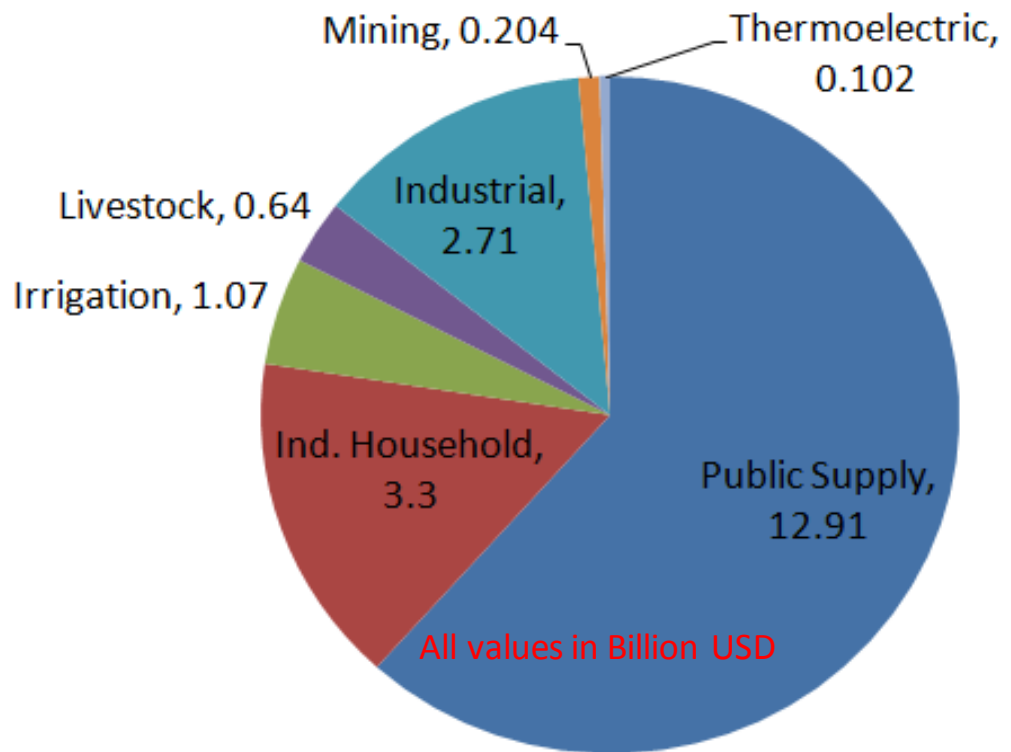


Groundwater Economic Impacts

- Estimated value of produced groundwater
 - \$ 20.9 Billion (Year 2004 estimates)
- Estimated value of Groundwater-related Infrastructure
 - \$75 Billion (Year 2003 estimates)

Groundwater Infrastructure	
WUG	Value (Billion USD)
Public Supply	3.73
Ind. Household	64.31
Irrigation	6.00

Increased push to move water from low valued users to high valued users (Ag → Urban)



Source NGWA

Groundwater Economic Impacts

- Estimated sales of Groundwater Related Businesses in the US
 - ~ 15.83 Billion USD¹
- Estimated sales of American Groundwater Related Manufacturing
 - 353.00 Million USD (2010 estimate)

American companies sold Nearly 1.5 Million pumps in the year 2010

1.5 Million Pretzels served each year in Walt Disney World

~ 50 gallons of virtual water per pretzel

Category	Estimated Sales (Billion USD)
<i>American Groundwater-Related Businesses</i>	
Consulting Services	6.5
Remediation Services	6.5
Well Construction & Services	2.73
<i>American Groundwater-Related Manufacturing</i>	
Drilling Machines	0.912
Pumps	0.262

¹ Likely includes some non-groundwater related business as well

Groundwater Societal Impacts

- 8085 Drilling Services firms in the US
 - Employ estimated 44,358 people
 - Many firms are multi-generational family owned businesses
- 9,747 Environmental Services firms
 - Employ an estimated 83,631 people
- 3,833 Remediation firms
 - Employ an estimated 73,332 people
- 38,588 community water systems rely upon groundwater across the United States,
 - Employ an estimated 211,989 professionals
- Thousands of Groundwater Scientists and Engineers are employed in Government, Research Labs and Universities

Source: NGWA (2012)

Estimates Likely includes some non-groundwater related business as well

Groundwater Sustainability Challenges

- On a macro-scale, the nation appears to have ample groundwater resources
 - Current use estimated at ~ 80 billion gallons/day
 - Natural recharge ~ 1 trillion gallons/day (Nace, 1960)
 - 26% of annual use is from groundwater
- Groundwater resources exhibit considerable spatial variability
 - Areas where production exceeds replenishment

Groundwater is a (slowly) renewable resource

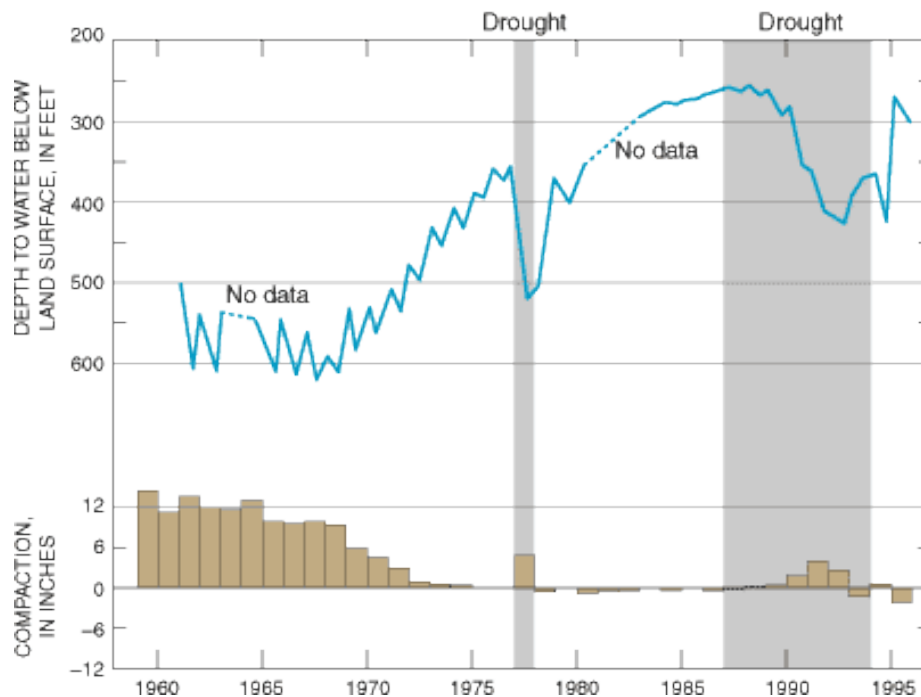
Human Influences on Groundwater Sustainability

- Over-exploitation of groundwater resources
 - Borrowing from the future
 - Inter-generational equity
 - Land Subsidence due to groundwater overdraft
- Insufficient/Improper planning & management
 - Inequitable distribution of the resource
 - Intra-generational equity
- Slow (no) technological adaptations
 - Inefficient water use

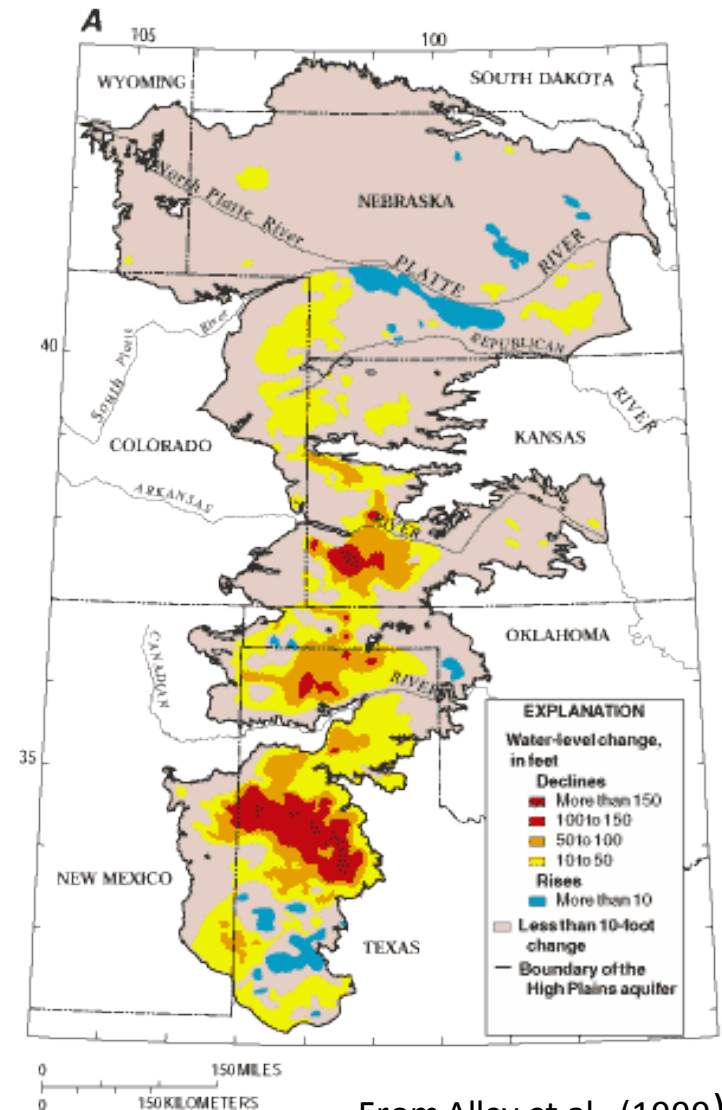
Human influences are generally improper adaptation to climatic effects

Challenges to Aquifer Sustainability

- Coupled human-climate impacts on aquifers can have severe economic consequences



Subsidence in San Joaquin Valley, CA

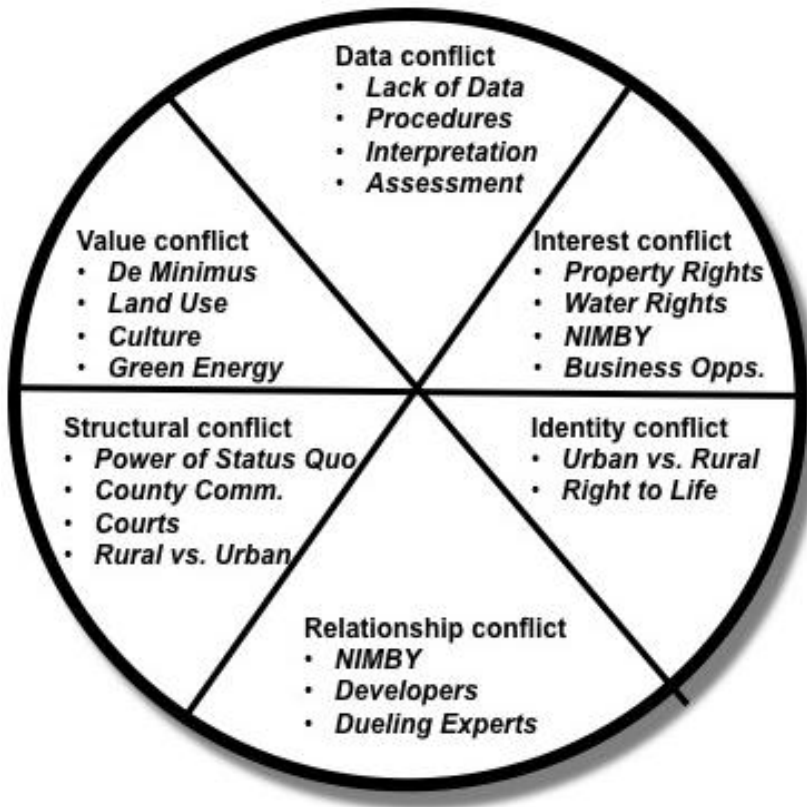


From Alley et al., (1999)

Groundwater Regulatory Framework

- Groundwater is a diffuse resource
 - Typically not amenable to top-down management
 - People values on groundwater are diverse
- Multiple legal doctrines currently in use
 - Absolute Ownership
 - Reasonable use
 - Correlative Rights
 - Prior appropriation
- Shift towards participatory groundwater management
 - Multi-stakeholder settings
- Aquifers do not recognize administrative boundaries
 - Conflicts between groundwater institutions
- Scientific limitations and data gaps compound the management challenges

Groundwater Conflicts



- Increase in groundwater conflicts
- From Disputes between domestic well owners
- Billion-dollar lawsuit between the State of Mississippi and the City of Memphis

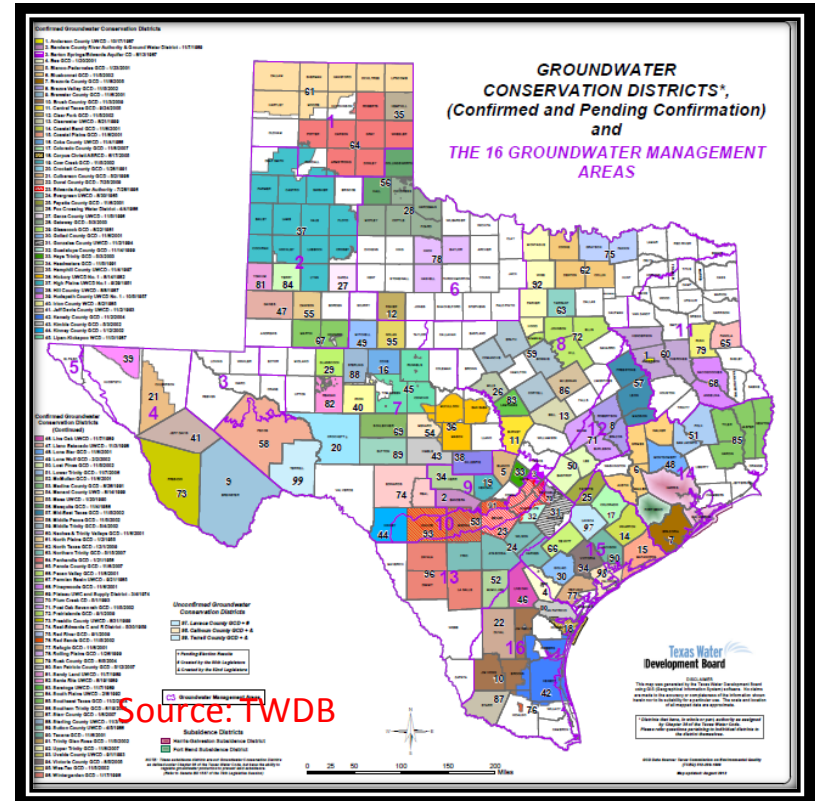
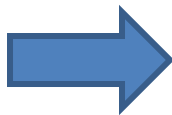
From Vinett and Jarvis, 2012

Groundwater Management

- Groundwater management is continually evolving
 - Rule of capture or absolute ownership
 - Participatory Groundwater Management



From Shotguns to Sustainability



Current Groundwater Framework in Texas where nearly 100 Groundwater Conservation Districts (GCDs) with regulatory authority are divided into 16 Planning Groups (Groundwater Management Areas or GMA)

Wrap Up

- Groundwater is an important natural resource
 - Slowly replenished
 - Aging infrastructure can pose risks
- Sustainable management of this resource is vital from several fronts
 - Food security, ecological integrity, economic development
- Sustainable management however requires a sound understanding of this resource from scientific as well as socio-economic perspectives
 - Disseminating this knowledge to broad range of audiences is also critical for developing successful solutions

Balance Economic and Environmental Objectives for Responsible Use of Groundwater Resources