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Civil Engineering

Week 1: Groundwater fundamentals

Groundwater around us

CIV5881/6881: Groundwater Hydrology

Dr Tim Peterson

GROUP OF EIGHT AUSTRALIA

Week 1: Learning Outcomes

- **Identify** **the influence of groundwater in the natural world and human history.**
- **Understand** the importance of groundwater and its role in the hydrological cycle.
- **Explain** how groundwater level is measured and apply measurements to estimate flow directions.
- **Identify** the major groundwater aquifer types.
- **Understand** how water is stored in aquifers.

The influence of groundwater on the landscape…

Source: https://www.flickr.com/photos/phunnyfotos/15298366848/sizes/k/

Source: https://www.evergraze.com.au/library-content/ne-manage-salinity/

Source: https://goo.gl/maps/EQegLY8GZu22

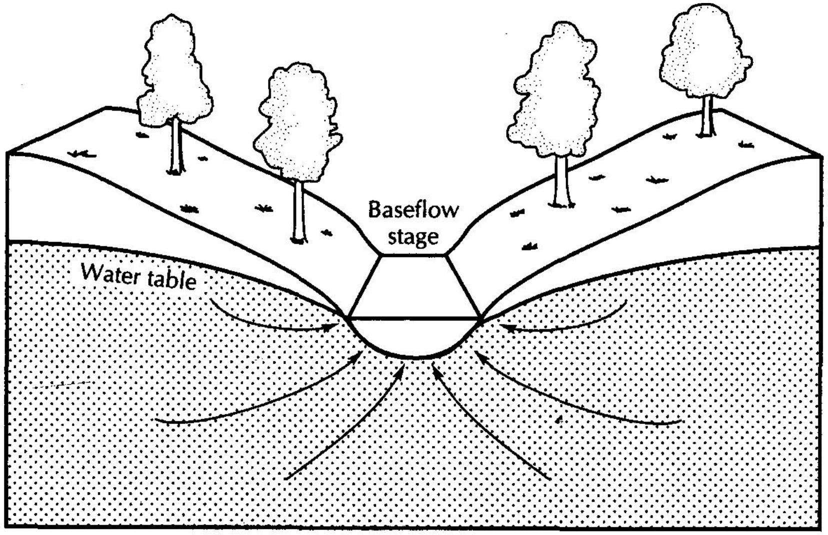
Source: https://ca.water.usgs.gov/land_subsidence/

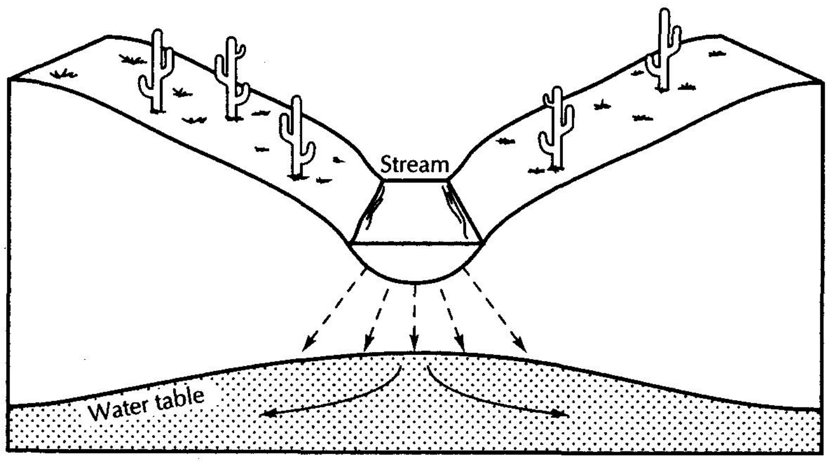
Groundwater shapes rivers

Source: http://www.namibian.org/travel/namibia/rivers.html

Source: By Stephen Reynolds User:Tophonic - Own work, CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=57306377

Groundwater shapes rivers …. and influences when they flow





Gaining: groundwater flows to the river:

- Stream flows in dry seasons.
- Low streamflow variability

Source: Fetter (2001). Applied Hydrogeology, p47

Losing: river water flows to the groundwater:

- Stream dry in dry seasons.
- High streamflow variability

So, what is groundwater?

Groundwater is water located in the saturated zone below the earth's surface.

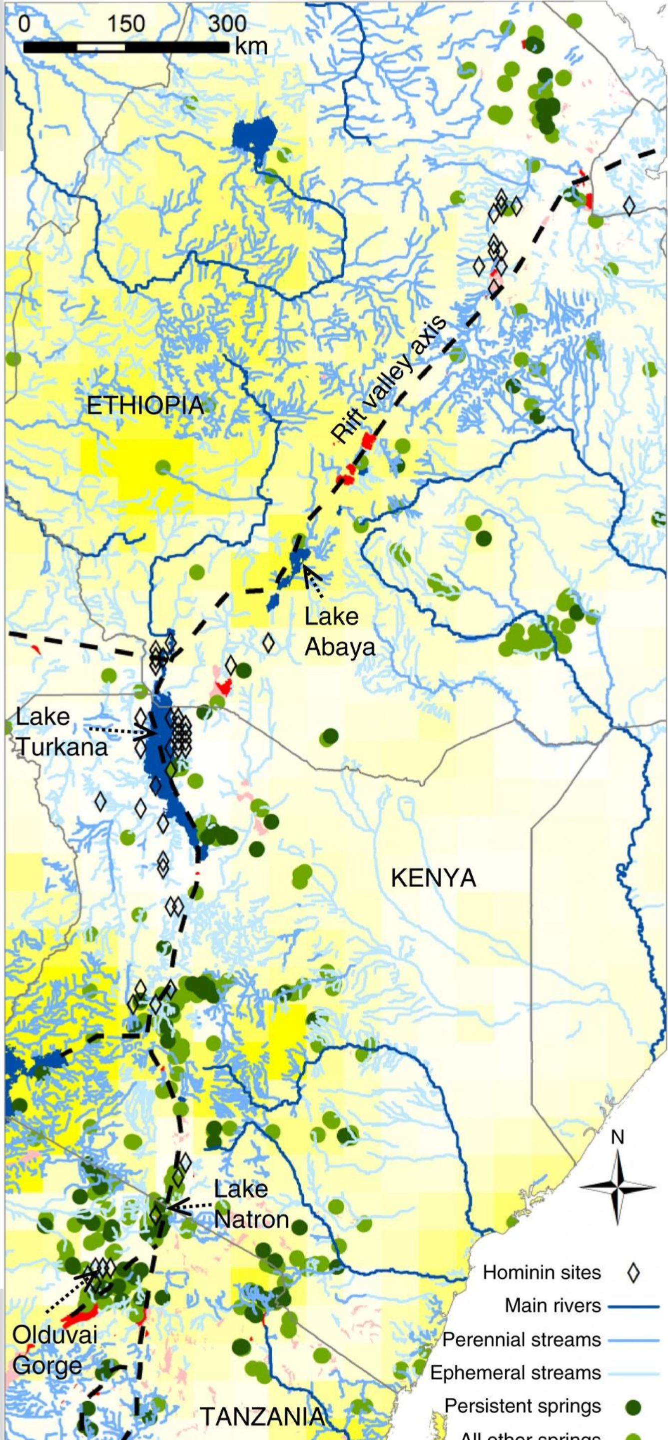
Groundwater is water that has migrated from the surface through the ground and become stored in porous soils and rocks.

Groundwater comes from the two primary sources: rain and surface water.

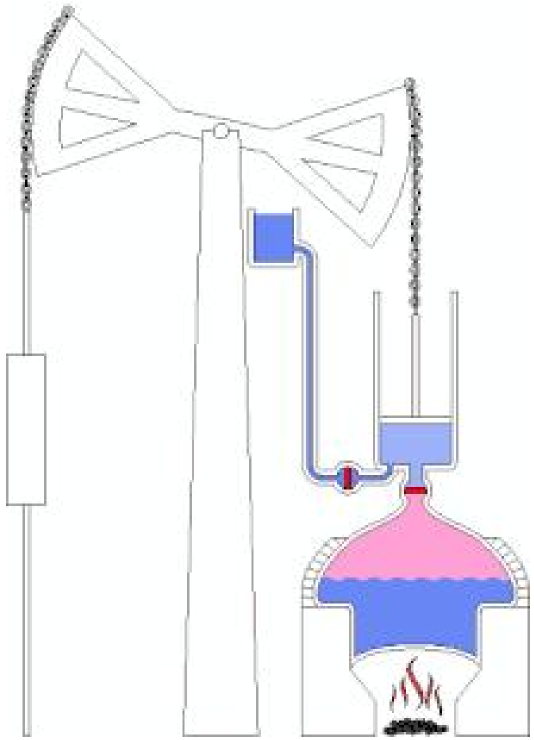
Groundwater shaped human evolution

- Hominin sites are closely associated with the rift valley axis.
- Hundreds of persistent springs distributed across East Africa could function as persistent groundwater hydro-refugia through orbital-scale climate cycles.
- That is, groundwater may have allowed early humans to survive 1,000 year+ dry periods!

Source: Cuthbert, M., Gleeson, T., Reynolds, S. *et al.* Modelling the role of groundwater hydro-refugia in East African hominin evolution and dispersal. *Nat Commun* **8,** 15696 (2017). https://doi.org/10.1038/ncomms15696



Groundwater shaped the early industrial revolution: the first engine was built to control groundwater in U.K. mines

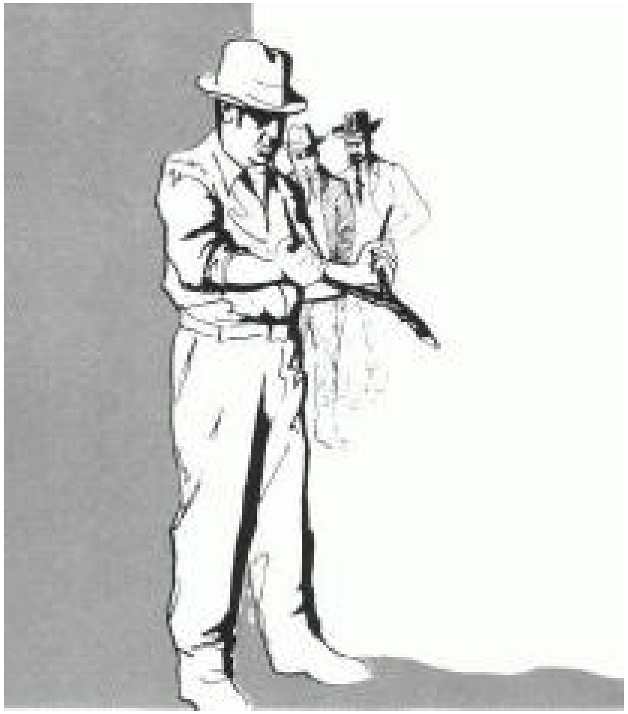


Schematic Newcomen engine.
– Steam (pink), water (blue)
– Valves open (blue), valves closed (red)

Source:https://en.wikipedia.org/wiki/File:Newcomen_atmospheric_engine_animation.gif

Source: https://www.alamy.com/stock-photo-coal-mine-in-the-midlands-in-the-1790s-featuring-a-newcomen-engine-138029014.html

But how can we find groundwater? Some believe *Water Divining* can identify underground *"rivers"*



Dowsing Challenge
https://en.wikipedia.org/wiki/One_Million_Dollar_Paranormal_Challenge

Source https://water.usgs.gov/edu/dowsing.html

Poor location of windmills may be explained by the use of divining.

Source:https://www.picfair.com/pics/09721666-windmill-and-rustic-water-tank

Source: https://www.pikist.com/free-photo-ihpfe

But indigenous cultures often "*read*" the landscape to find groundwater …

But indigenous cultures often "*read*" the landscape to find groundwater …

Key knowledge from this module

- **Learning Outcome:** identify the influence of groundwater in the natural world and human history.
  - Identify some ways that groundwater shapes the landscape.
  - Appreciate the role of groundwater in human history.
  - Appreciate the importance of groundwater to indigenous cultures.

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Hydrological Cycle

CIV5881/6881: Groundwater Hydrology

Dr Tim Peterson

GROUP OF EIGHT AUSTRALIA

Adapted from those by Christian Urich

Week 1: Learning Outcomes

Identify	the influence of groundwater in the natural world and human history.
Understand	**the importance of groundwater and its role in the hydrological cycle.**
Explain	how groundwater level is measured and apply measurements to estimate flow directions.
Identify	the major groundwater aquifer types.
Understand	how water is stored in aquifers.

Why is groundwater important?

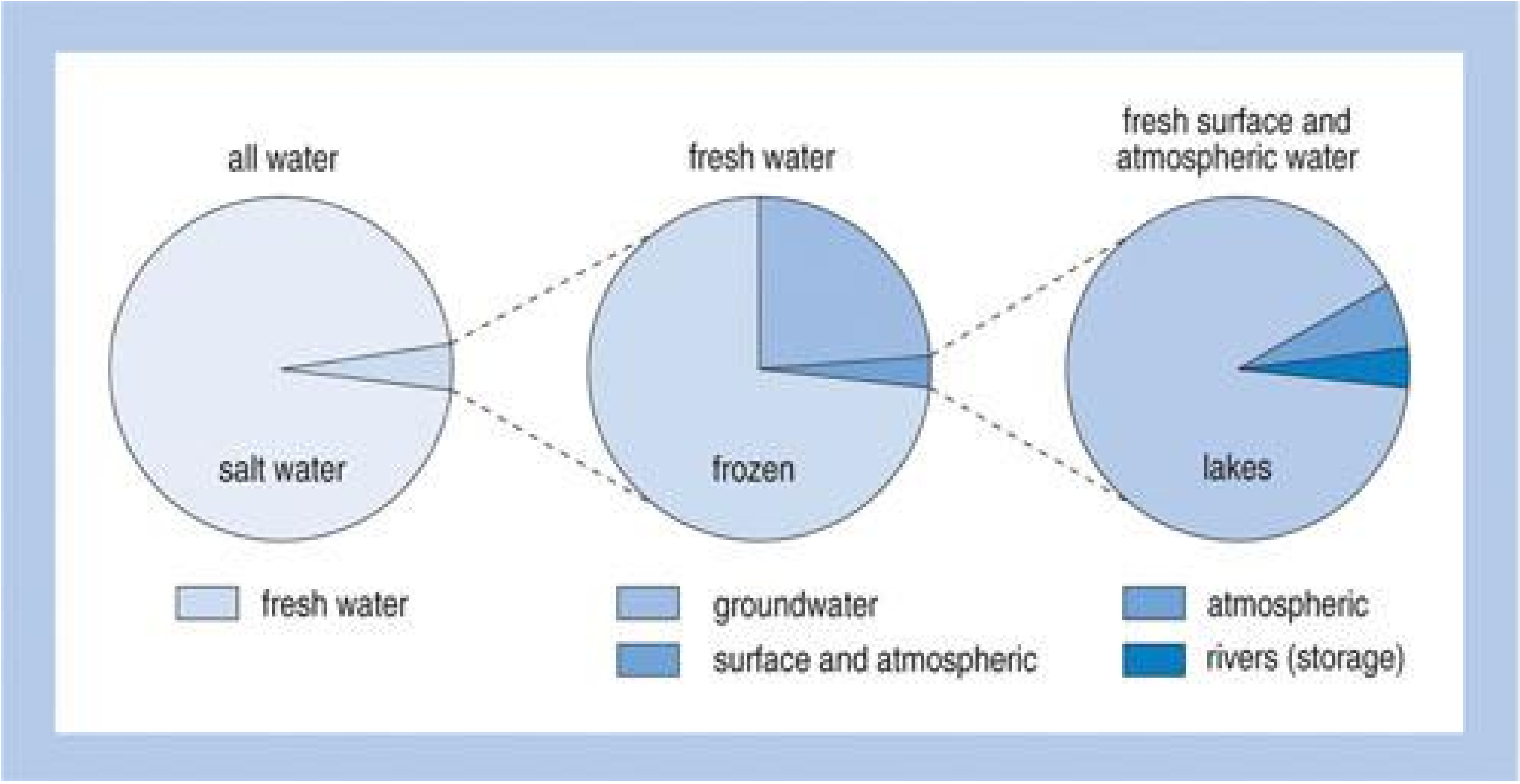
Groundwater makes up approximately 98% of the earth's available freshwater.

It is 60 times as plentiful as freshwater found in all of the earth's lakes and streams combined.

Groundwater makes up about 17% of Australia's accessible water resources and may account for up to 70% of total consumption in particular regions.

Groundwater is a finite resource. It is replenished only when surface water seeps into aquifers.

Why is groundwater important?



http://www.open.edu/openlearnworks/mod/oucontent/view.php?id=200&extra=thumbnail_idp43241920

Groundwater use

Domestic supply to cities and towns:

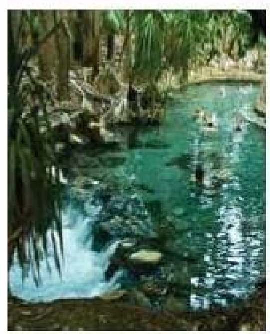
- Daylesford spa
- Mineral springs

Green spaces in the community

Irrigation

Industrial use

Salt harvesting

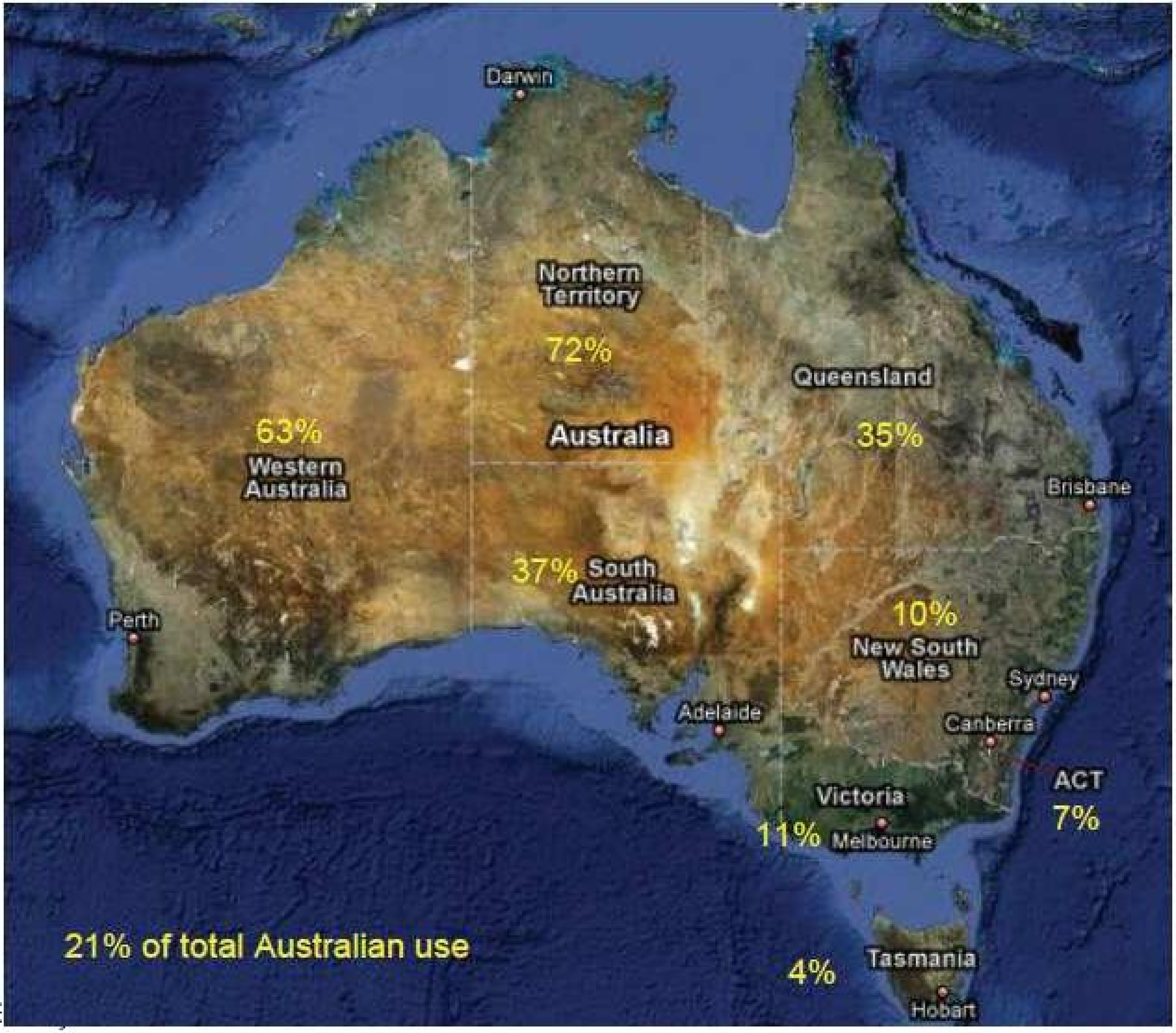


Thermal springs

Wells in remote regions

Geothermal Power

Proportion of groundwater use – by states

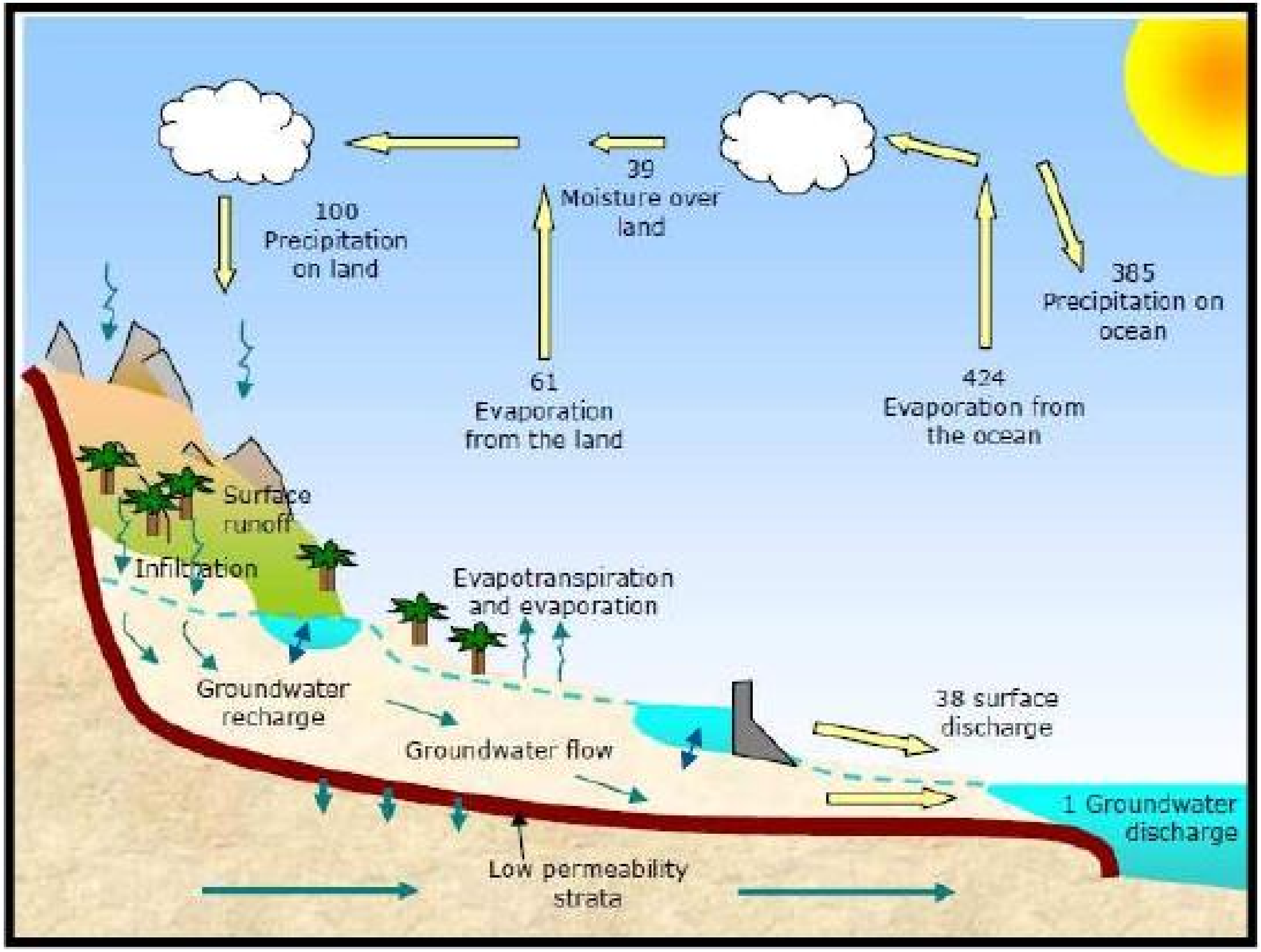


Proportion of groundwater use – by states

TABLE 6.1 MEAN ANNUAL GROUNDWATER USE (GL) BY USE CATEGORIES

State / Territory	Irrigation	Urban/ Industrial	Rural	In situ	Total
NSW	643	160	205	0	1 008
VIC	431	127	54	10	622
QLD	816	265	541	0	1 622
WA	280	821	37	0	1 138
SA	354	23	42	24	419
TAS	9	7	4	0	20
NT	47	48	33	0	128
ACT	2	0	3	0	5
Total	2 582	1 451	919	34	4 962

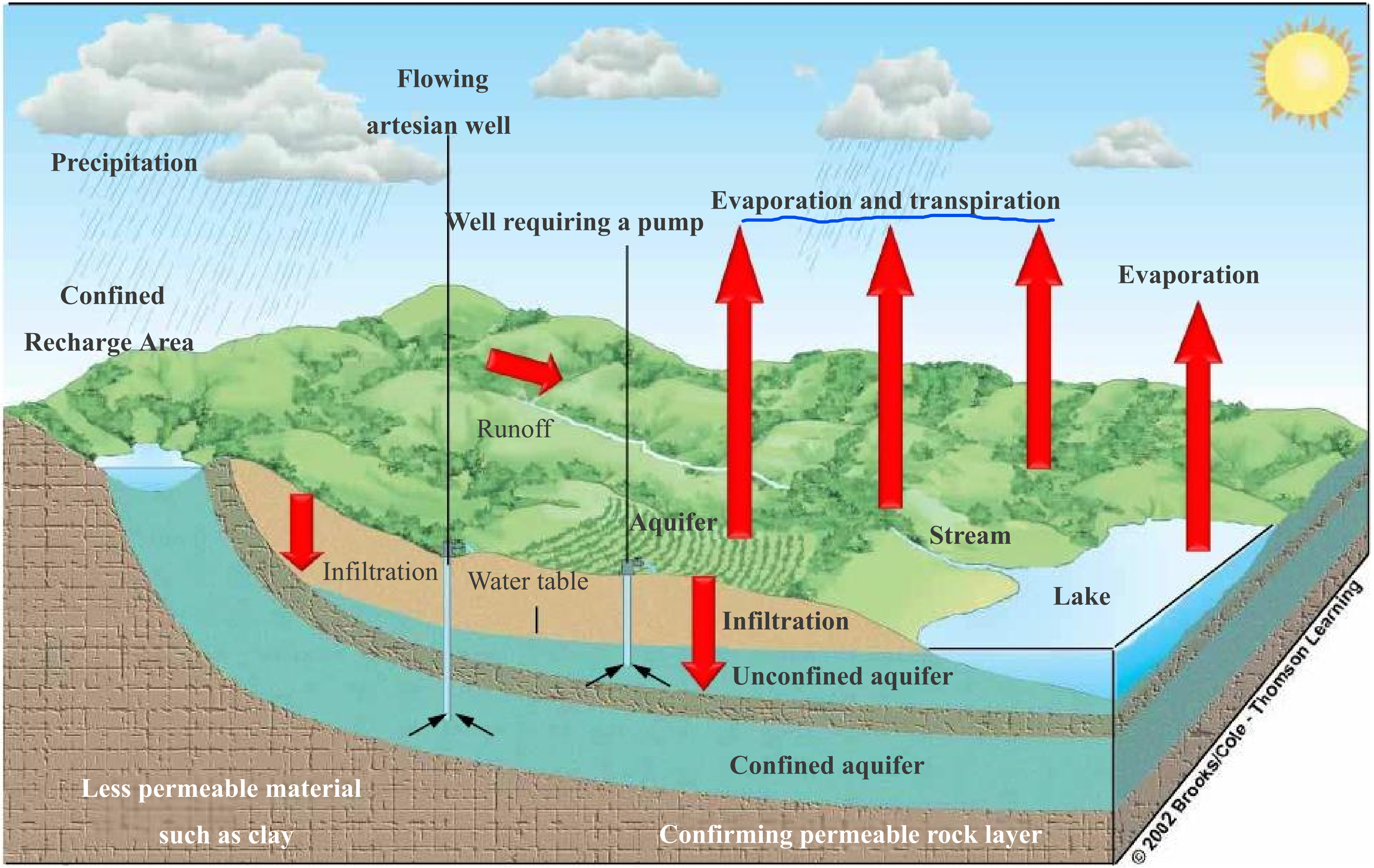
Hydrological cycle (Water cycle)



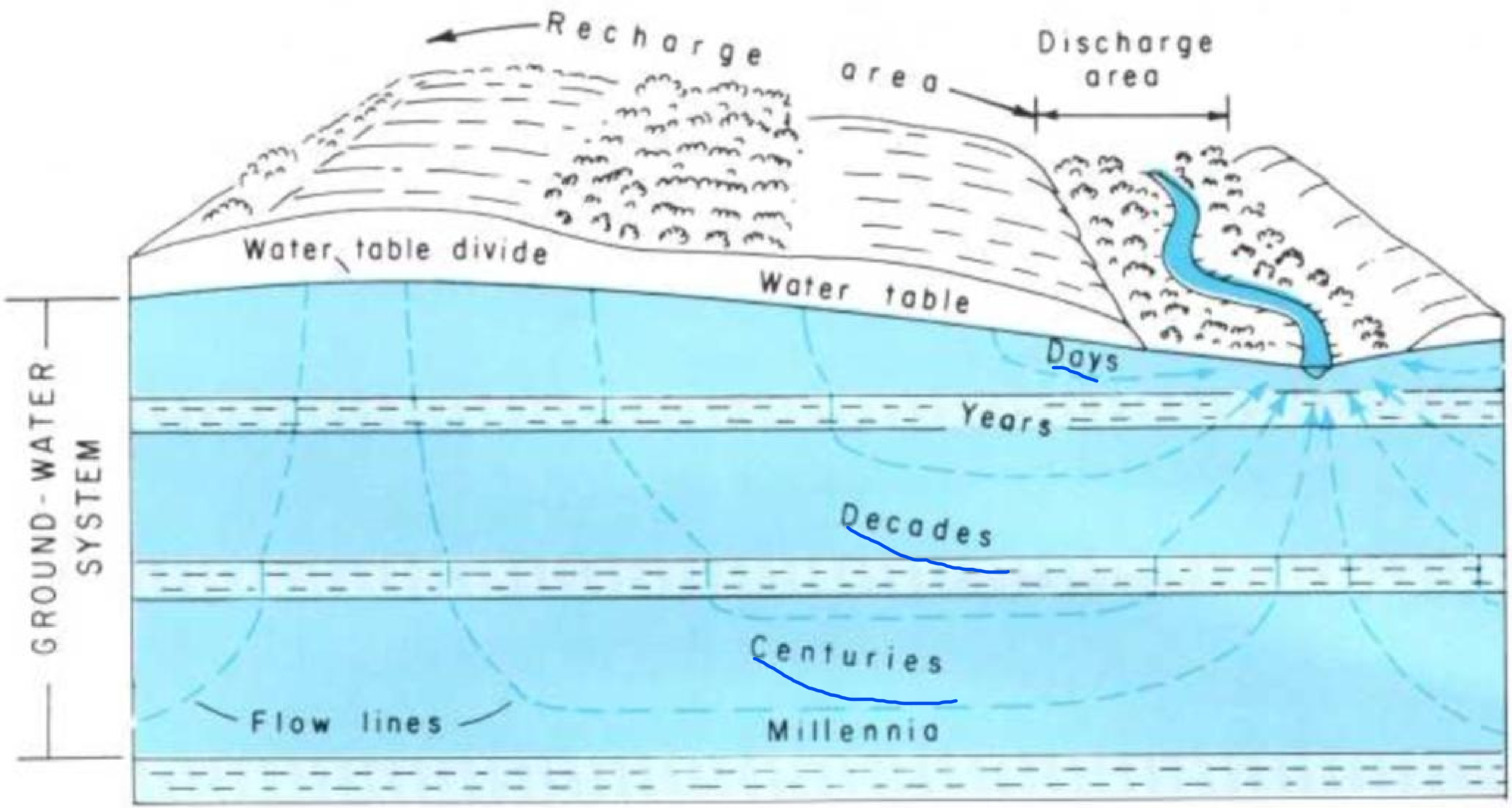
- ❑ Evaporation
- ❑ Transpiration
- ❑ Condensation
- ❑ Precipitation
- ❑ Infiltration

Yearly flow volumes based on annual surface precipitation on earth, ~ 100,000 km^3 / year

Hydrological cycle (Water cycle) … focusing on groundwater



Groundwater residence time

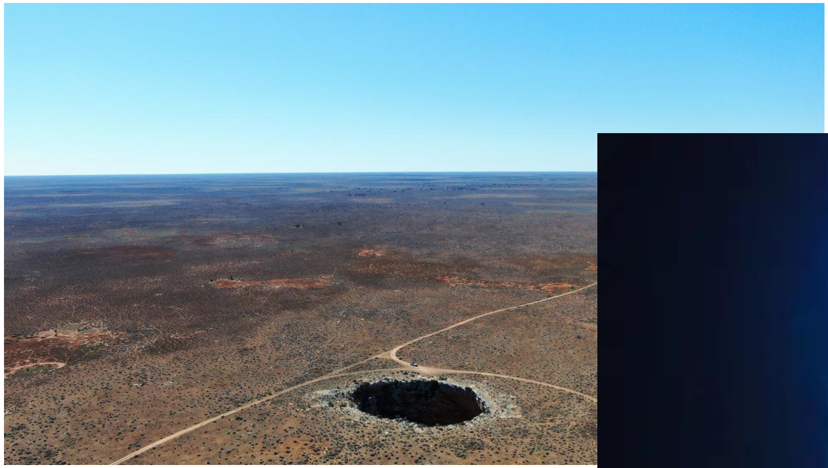


Source: Health, 2004 https://pubs.er.usgs.gov/publication/wsp2220

Groundwater residence time … in context

Reservoir	Approximate Residence Time
Glaciers	40 years
Seasonal Snow Cover	0.4 years
Soil Moisture	0.2 years
Groundwater: Shallow	200 years
Groundwater: Deep	10,000 years
Lakes	100 years
Rivers	0.04 years

Nullarbor Plains (W.A.) groundwater is 40,000 – 180,000 years old!



https://cdn.newsapi.com.au/image/v1/0cb544320be5

https://www.vice.com/en/article/yvx875/cave-diving-in-the-nullarbor-is-like-floating-in-space

Key knowledge from this module

- **Learning Outcome**: understand the importance of groundwater and its role in the hydrological cycle.
  - Groundwater is a vital source of water for society and nature.
  - Groundwater supports irrigation, urban supply, agriculture and mining.
  - Groundwater interacts with the climate, lakes & rivers and the ocean, but this changes with the depth of the aquifer.
  - Groundwater can be the oldest water on earth, and this has major implications for its sustainability.

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The concept of head
CIV5881/6881: Groundwater Hydrology

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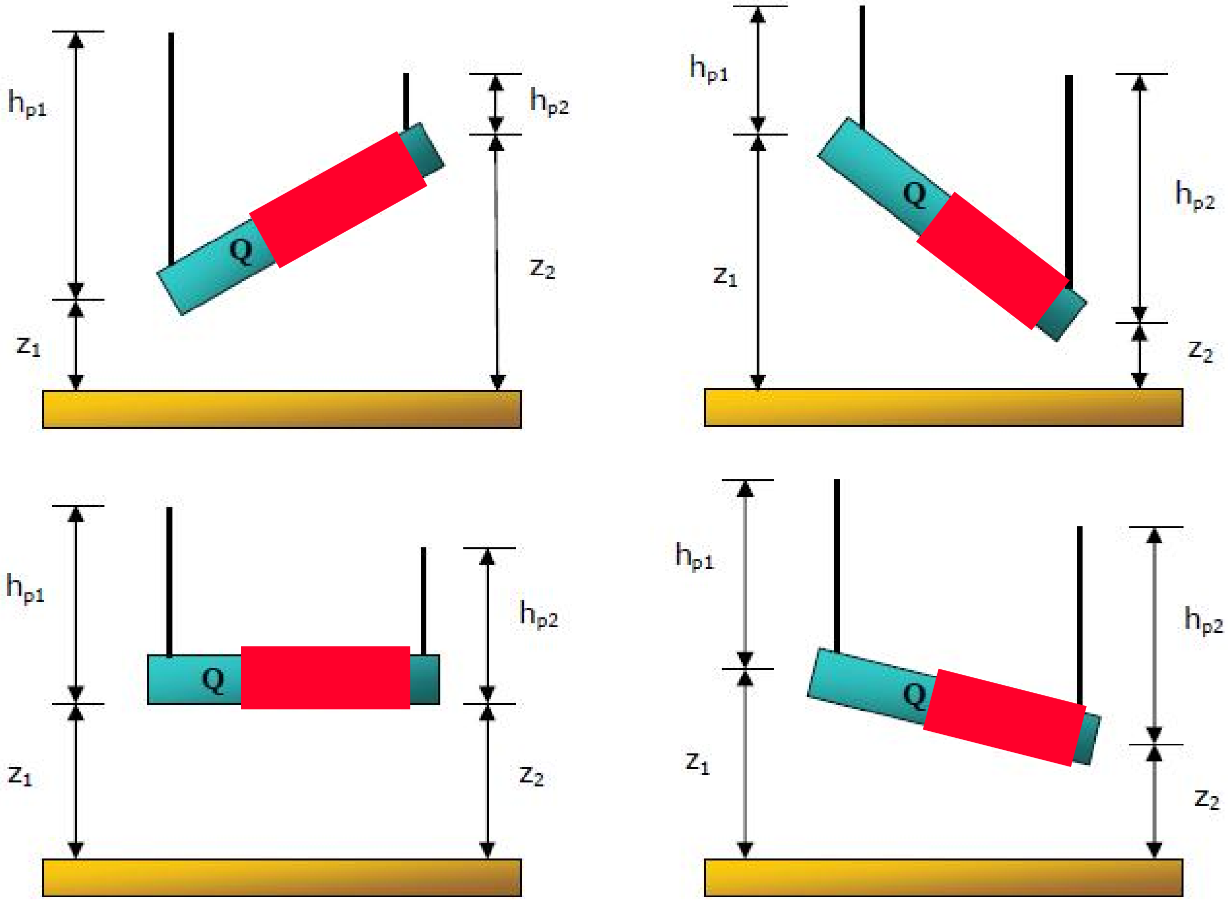
Which way does water flow?



Like any matter in nature, water is associated with energy

Energy is be balanced and conserved (energy conservation law)

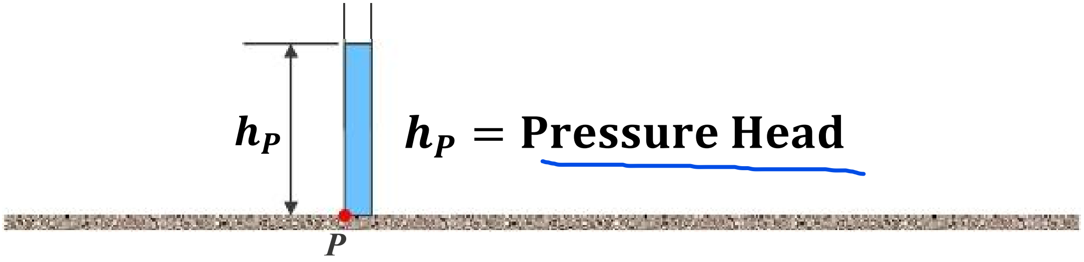
So, water flows from locations of higher energy to those of low energy

Thus, the key to understanding the flow of water in soils is to know the energy associated with water at different locations

A concept that relates the energy in an incompressible fluid to the height of an equivalent static column of that fluid. (Head expresses an amount of energy per unit weight of fluid)

Flow of water in soils is considered incompressible, because density changes can be neglected at ordinary stress levels.

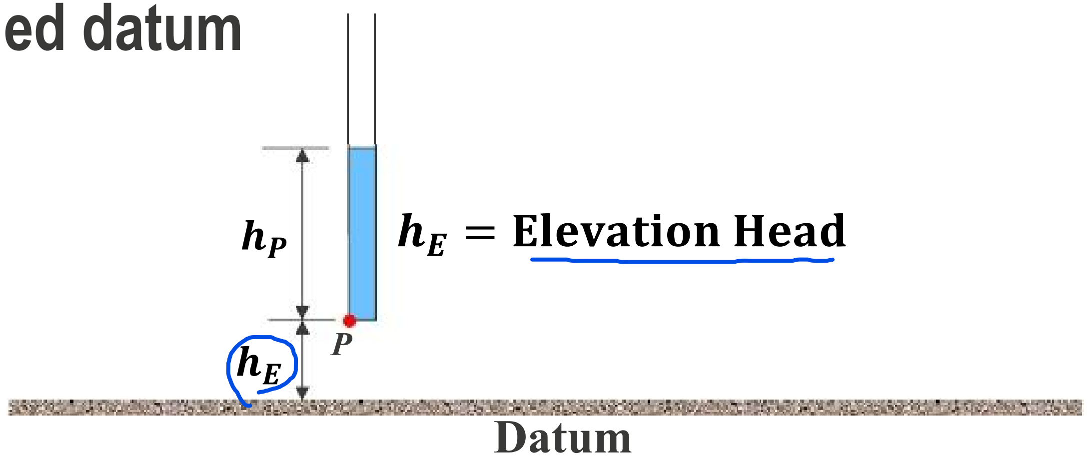
Pressure energy: due to static pressure in a water mass



h_P = Pressure Head

Groundwater head: datum and flow velocity

Elevation energy: due to elevation of water above a specified datum



Kinetic energy: due to movement of water

If water flows through the tube with a velocity v, then we have an additional head due to velocity given as

$$\frac{v^2}{2g}$$

acceleration of gravity

Groundwater head: combine the terms gives us Bernoulli's eqn

Total head according to Bernoulli's principle is

$$H = h_E + h_P + \frac{v^2}{2g}$$

The velocity of flow through soils is generally small [1 cm/s], we usually neglect the velocity head. The total head in soils is then

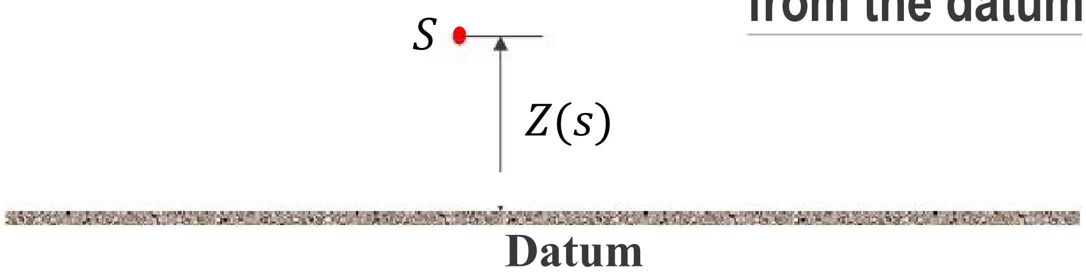
$$P = h \cdot \gamma_w$$

$$H = h_E + h_P + \cancel{\frac{v^2}{2g}} = h_E + \frac{P}{\gamma_W}$$

where *P* is the pore pressure, and γ_W is specific weight (i.e. density times acceleration of gravity).

Groundwater head: estimating the head at a point

$$\boldsymbol{h(s) = \frac{P(s)}{\gamma_W} + Z(s)}$$

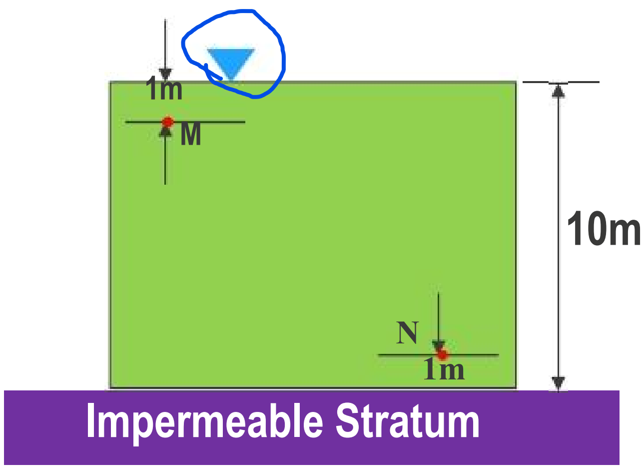


Note: Z is measured vertically up from the datum

Groundwater head: estimating the static water table elevation

Calculation of head at point M and N

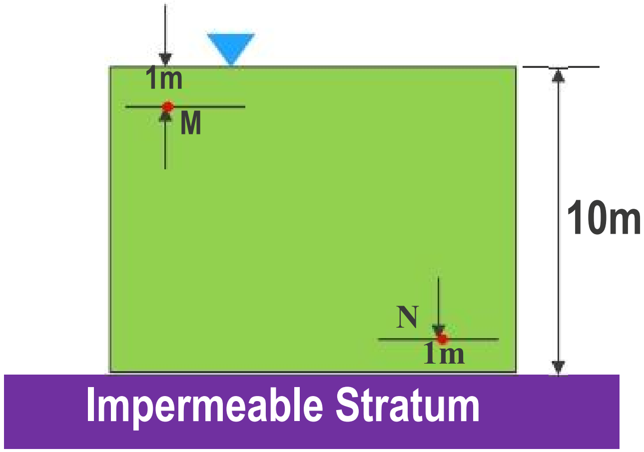
$$h(s) = \frac{P(s)}{\gamma_W} + Z(s)$$



Groundwater head: estimating the static water table elevation

Calculation of head at point M and N

$$h(s) = \frac{P(s)}{\gamma_W} + Z(s)$$



How about choosing datum at the water table?

Choose datum at the top of the impermeable layer

$$P(M) = 1\gamma_W$$

$$Z(M) = 9\text{m}$$

$$h(M) = \frac{1\gamma_W}{\gamma_W} + 9 = 10\text{m}$$

$$h(N) = \frac{9\gamma_W}{\gamma_W} + 1 = 10\text{m}$$

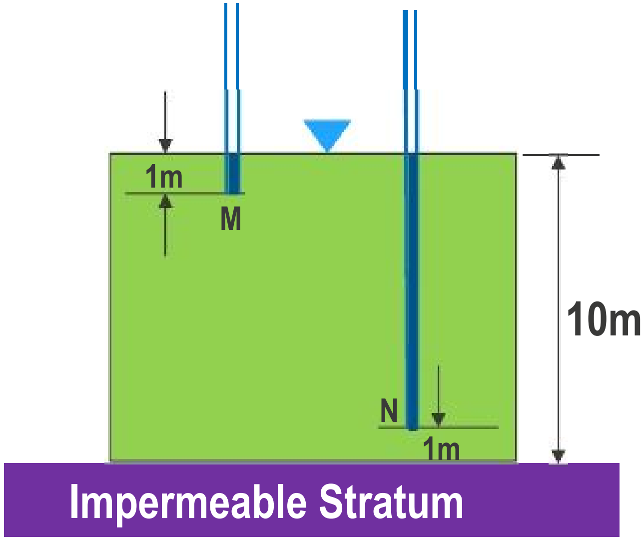
$$P(N) = 9\gamma_W$$

$$Z(N) = 1\text{m}$$

Groundwater head: estimating the static water table elevation

The value of the total head depends on the choice of datum

Differences in total head are required for flow [not pressure]



It can be helpful to consider imaginary pipes (i.e. piezometers) placed in the soil at the points where the head is required

The head is the elevation of the water level in the groundwater piezometer above the datum

Groundwater head: a recap

The following three heads must be considered in problems involving fluid flow in soil:

Elevation Head, h_E : the distance from the datum

Pressure Head, h_P: the pressure divided by the specific weight

Total Head, H : the sum of elevation head and pressure head

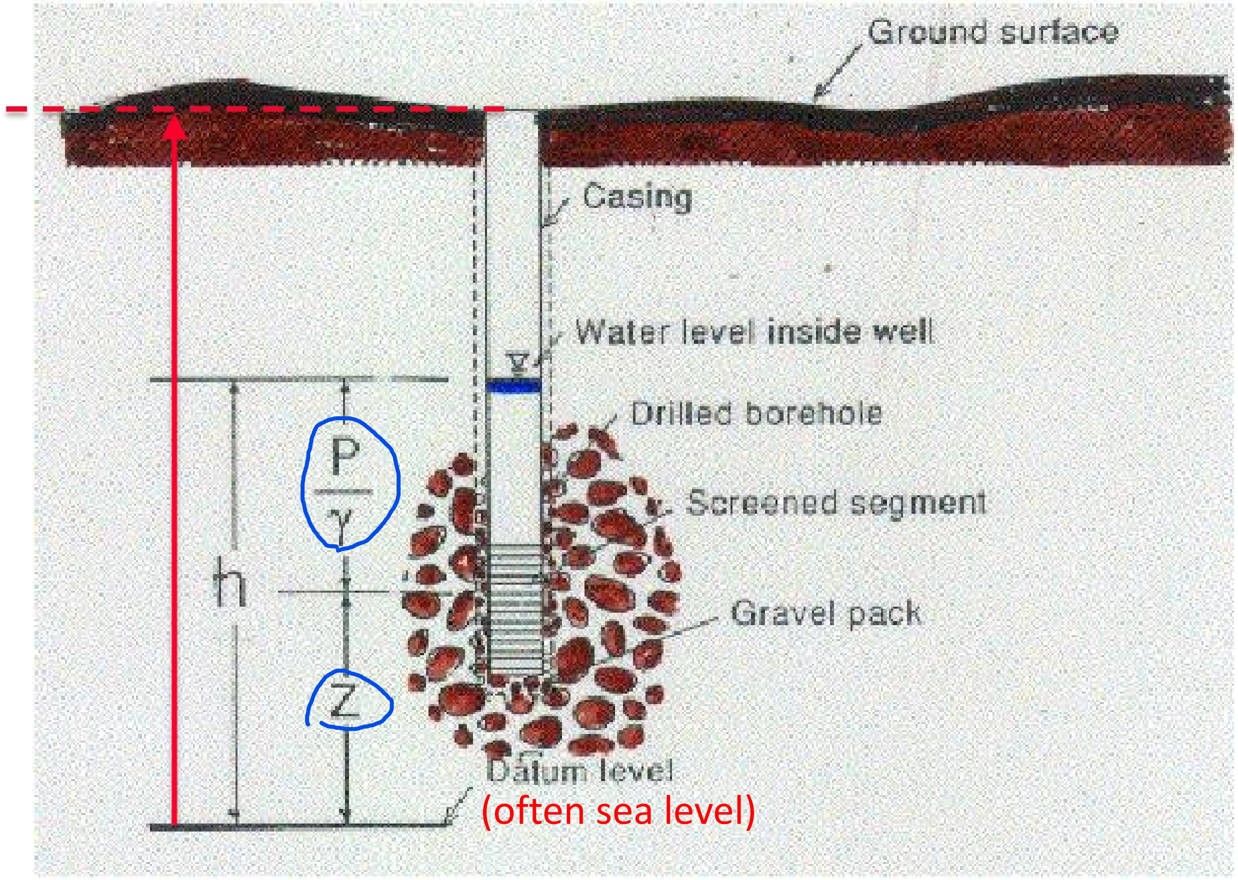
Hydraulic/Piezometric Head = Total Head

The height of the water surface in a groundwater piezometer relative to a common datum

Measuring a groundwater piezometer

Measuring a groundwater piezometer

The height of the water surface in a piezometer relative to a common datum, which is almost always the land surface elevation



Example piezometer head calculation

A well's screen is located at an elevation 180 m above sea level. The length of the water column in the well is 27 m.

Question: What is the piezometric head at the well, if we use the plane at 20 m above sea level as the datum level?

$$\boldsymbol{H = h_E + h_P}$$

Example piezometer head calculation

A well's screen is located at an elevation 180 m above sea level. The length of the water column in the well is 27 m.

Question: What is the piezometric head at the well, if we use the plane at 20 m above sea level as the datum level?

基准线

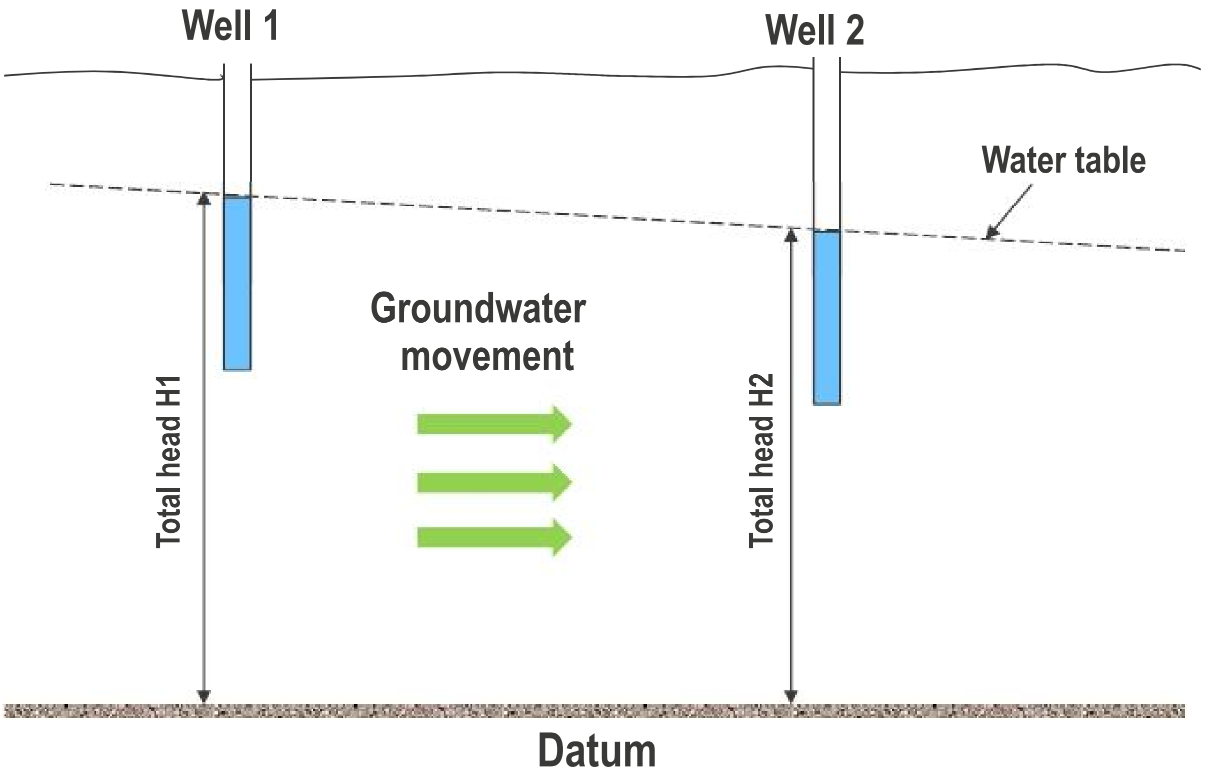
$$H = h_E + h_P$$

$$h_E = 180 - 20 = 160m$$

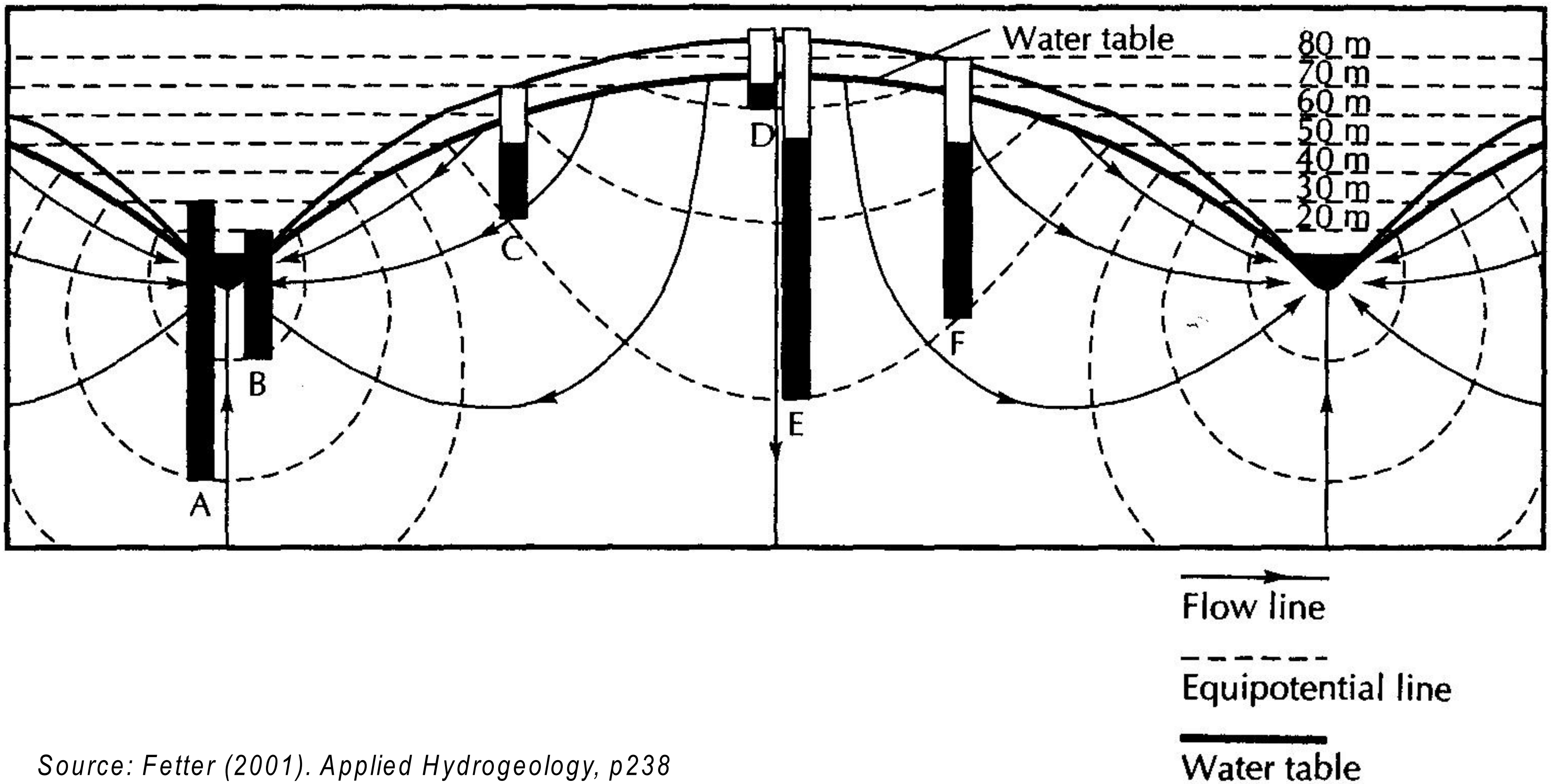
$$h_P = 27m$$

$$H = h_E + h_P = 187m$$

Groundwater head observations tells us about groundwater flow direction

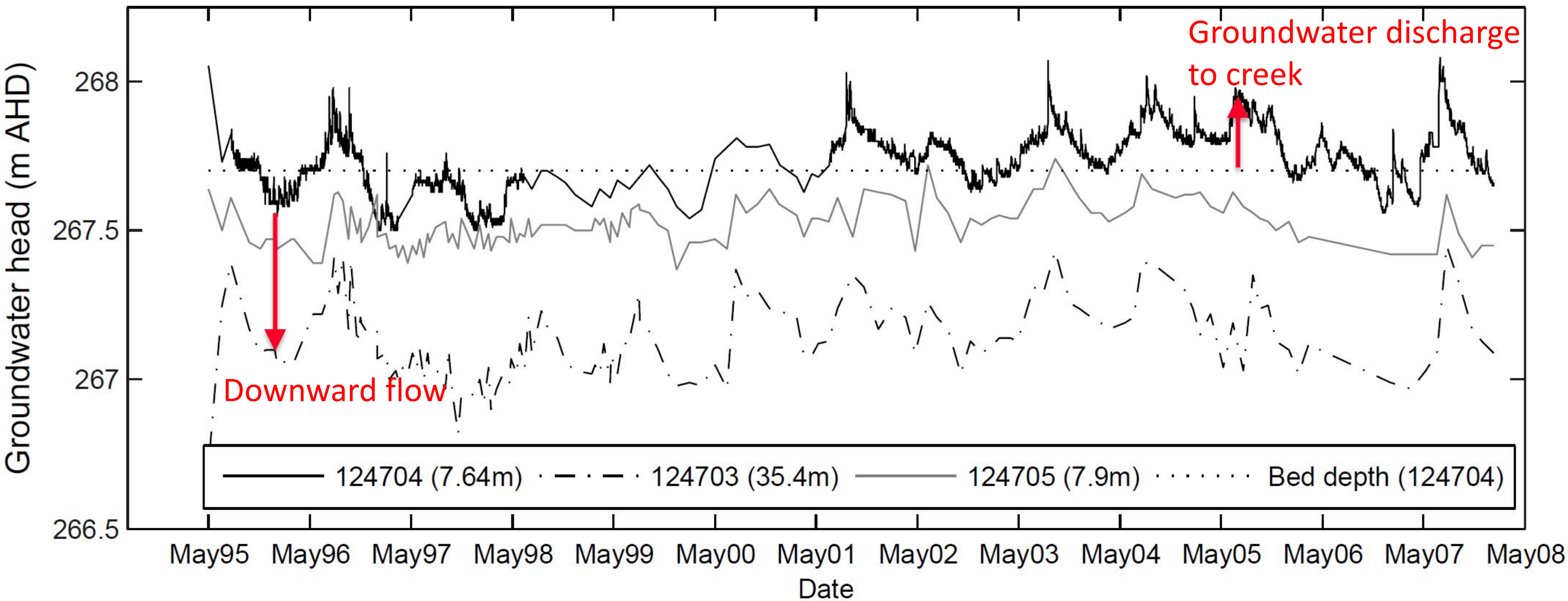


But groundwater head changes with depth, producing vertical and horizontal flow paths



Source: Fetter (2001). Applied Hydrogeology, p238

Groundwater head changes with depth: an example



Source: Peterson, 2009, fig 7.9 https://minerva-access.unimelb.edu.au/handle/11343/35439

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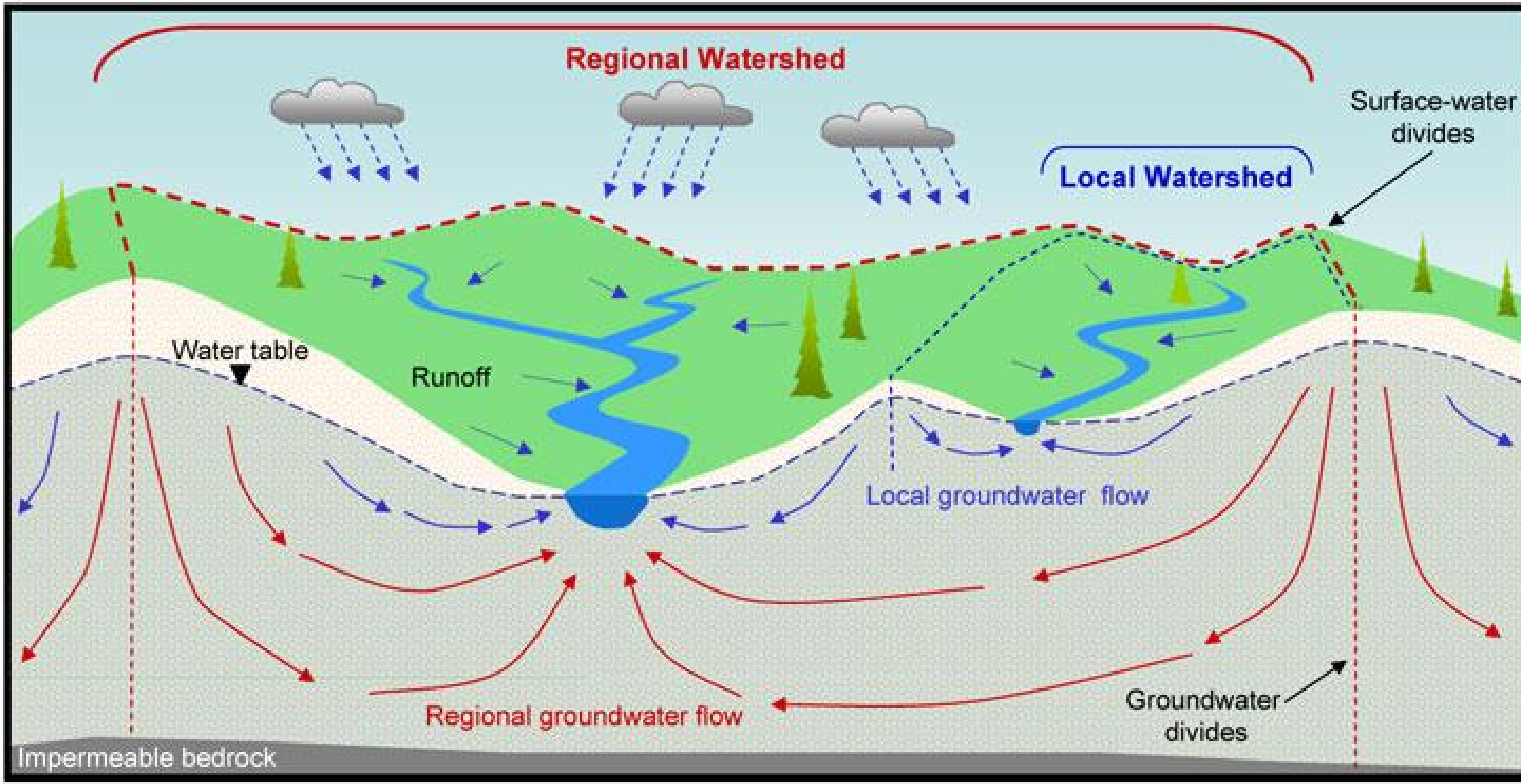
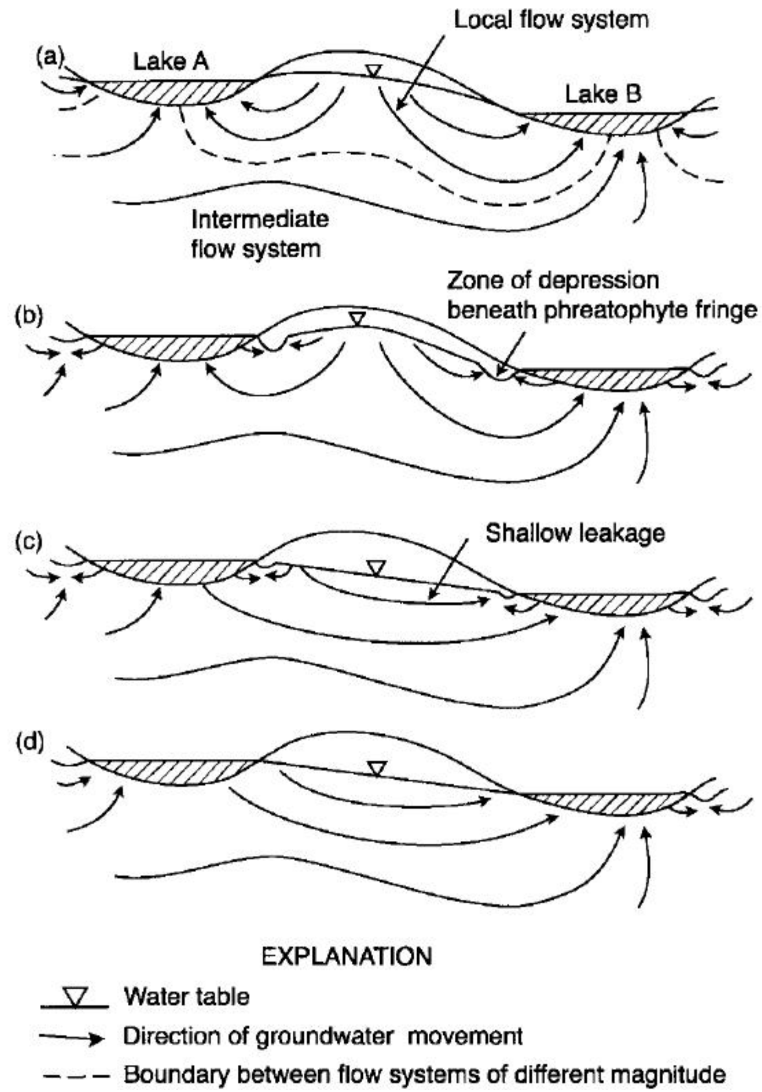
Complex groundwater flow paths feed rivers & lakes and define catchment boundaries



Source: Kevin Masarik, Central Wisconsin Groundwater Center

Complex groundwater flow paths feed rivers & lakes and define catchment boundaries



Local recharge and regional flow supply lakes

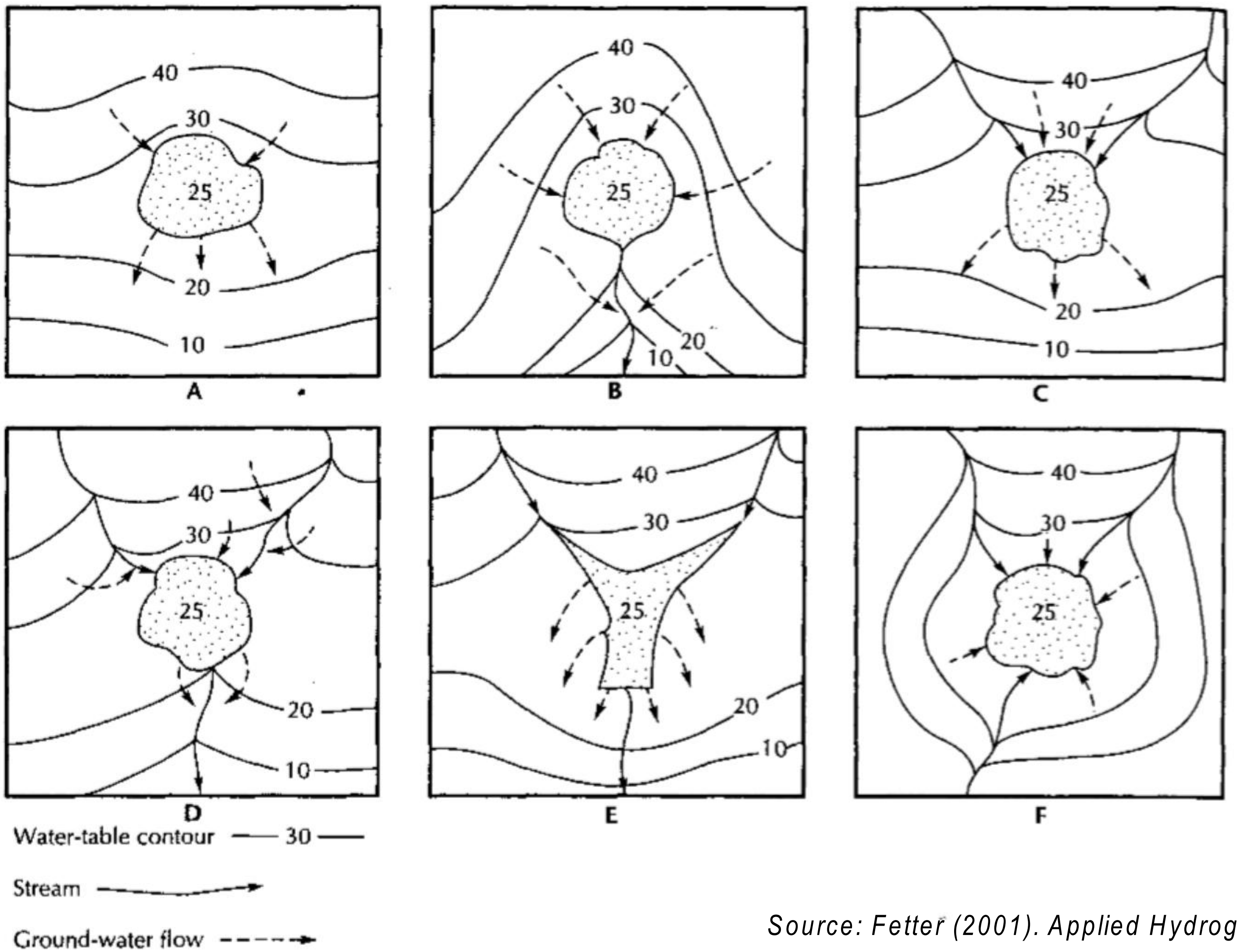
Local recharge is transpired, causing flow from the lake. Most of the lake inflows are from regional flow.

No local recharge causes water from the left lake to flow into the right lake, but some water is lost to transpiration.

No local recharge causes water from the left lake to flow into the right lake. None is lost to transpiration.

Source: Sophocleous 2020
DOI 10.1007/s10040-001-0170-8

Groundwater flow paths tells us when groundwater flows into or out of lakes and rivers!



Source: Fetter (2001). Applied Hydrogeology, p274

Key knowledge from this module

- **Learning Outcome**: Explain how groundwater level is measured and apply measurements to estimate flow directions.
  - Estimating groundwater head from piezometers.
  - Differences in head cause groundwater flow.
  - Head often changes with depth because groundwater flows vertically and horizontally.
  - Groundwater head contours around lakes and rivers tell us how surface and groundwater interact.

Aquifer Type

Dr Tim Peterson

Adapted from those by Christian Urich

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Identify	**the major groundwater aquifer types.** 含水层
Understand	how water is stored in aquifers.

Some key definitions…

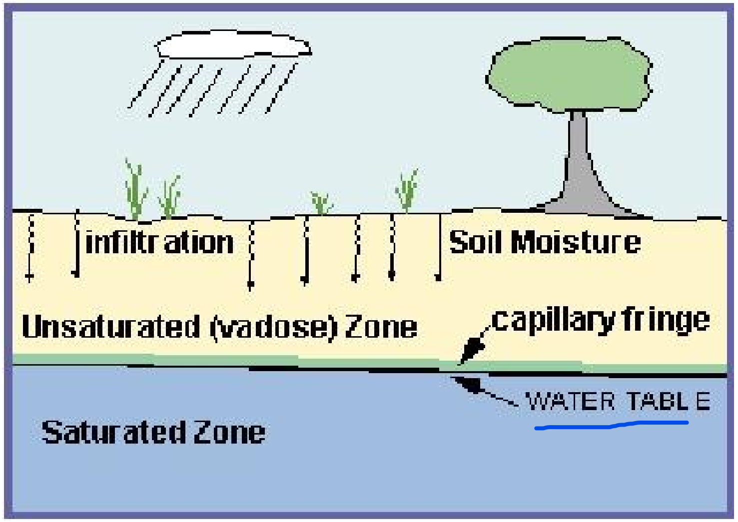
Aquifer: A geologic unit that **stores** and **transmits** water

Water Table: Top of saturated zone

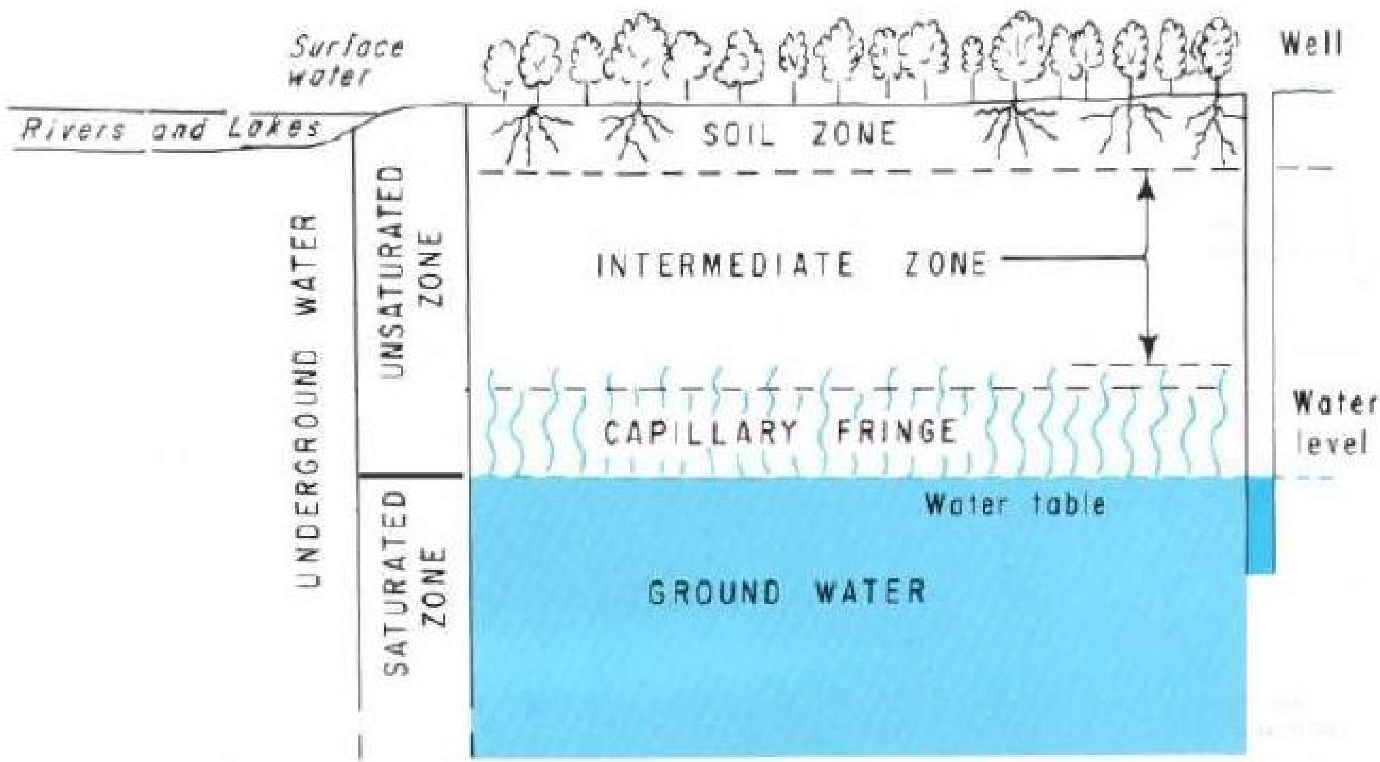
Unsaturated (Vadose) Zone: Region between water table and ground surface

Capillary Fringe: Region above water table where water rises due to capillary forces in the porous medium

毛细区



Vertical distribution of water subsurface water

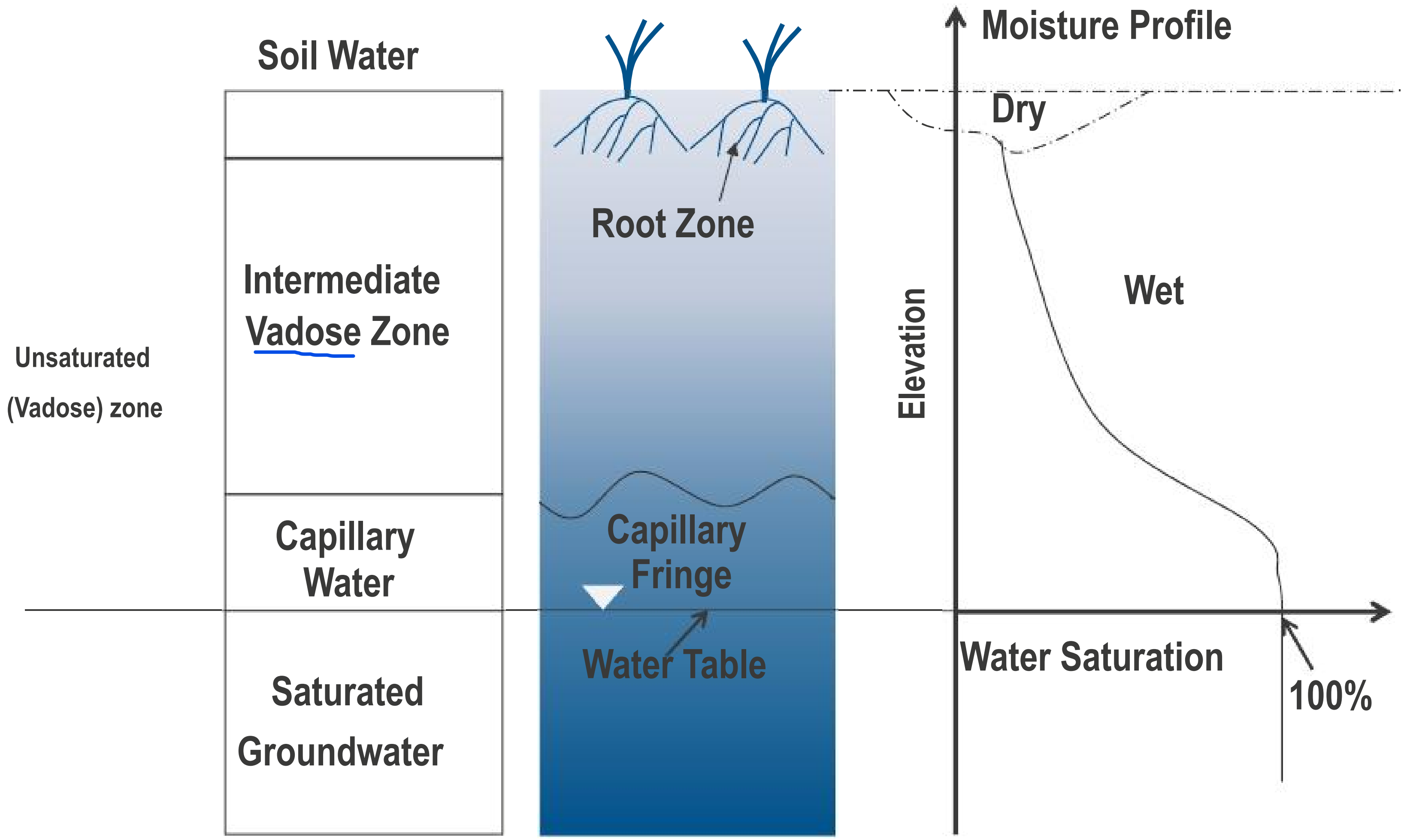


Source: Heath (2004), Basic groundwater hydrology

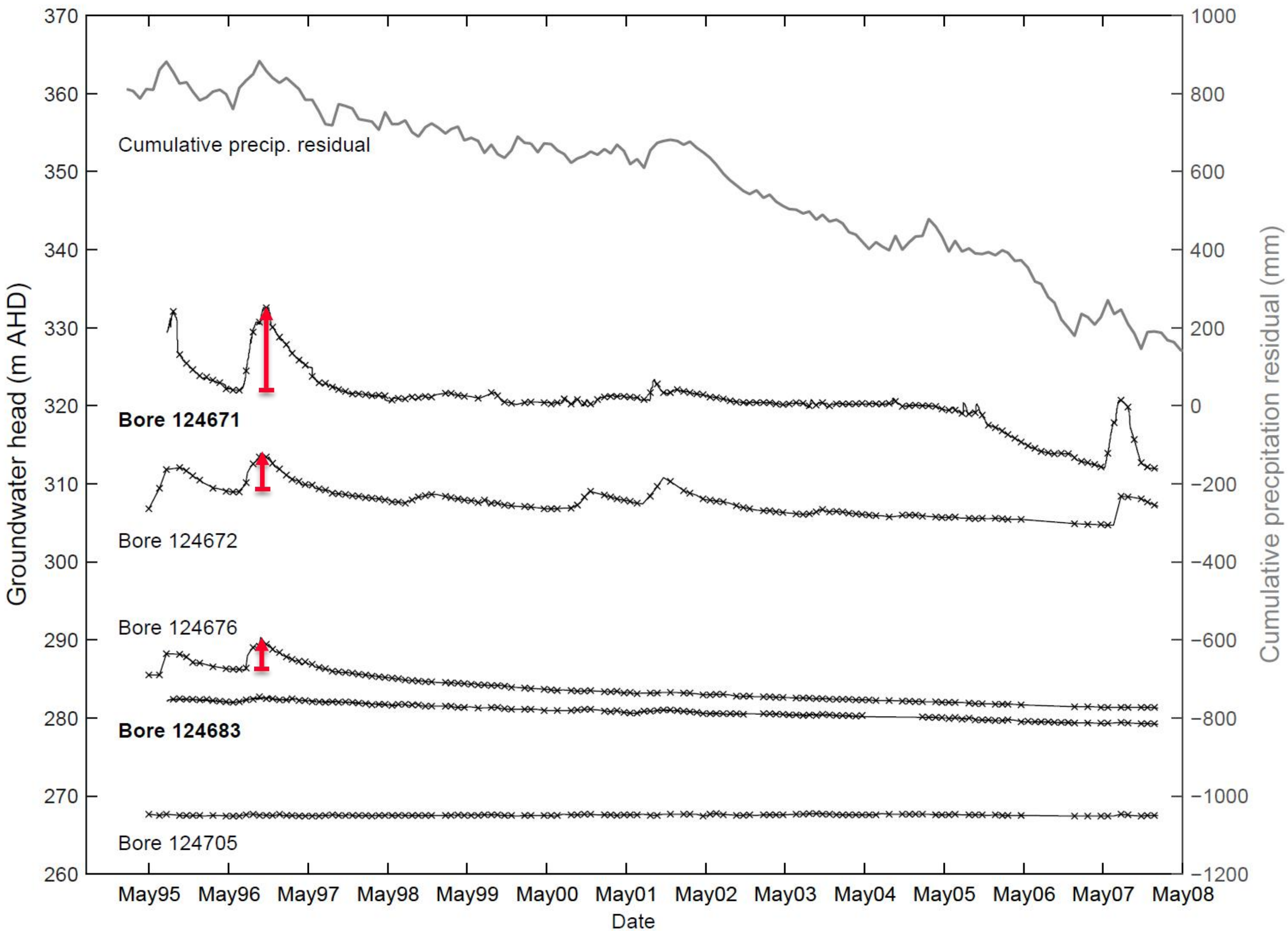
- ❑ **Unsaturated zone**
- ❑ **Saturated zone**
- ❑ **Intermediate zone**
- ❑ **Capillary fringe**
- ❑ **Water table**

The thickness of the capillary fringe depends on the soil's texture and homogeneity

Vertical distribution of water subsurface water



Vertical distribution of water subsurface water: Example recharge events



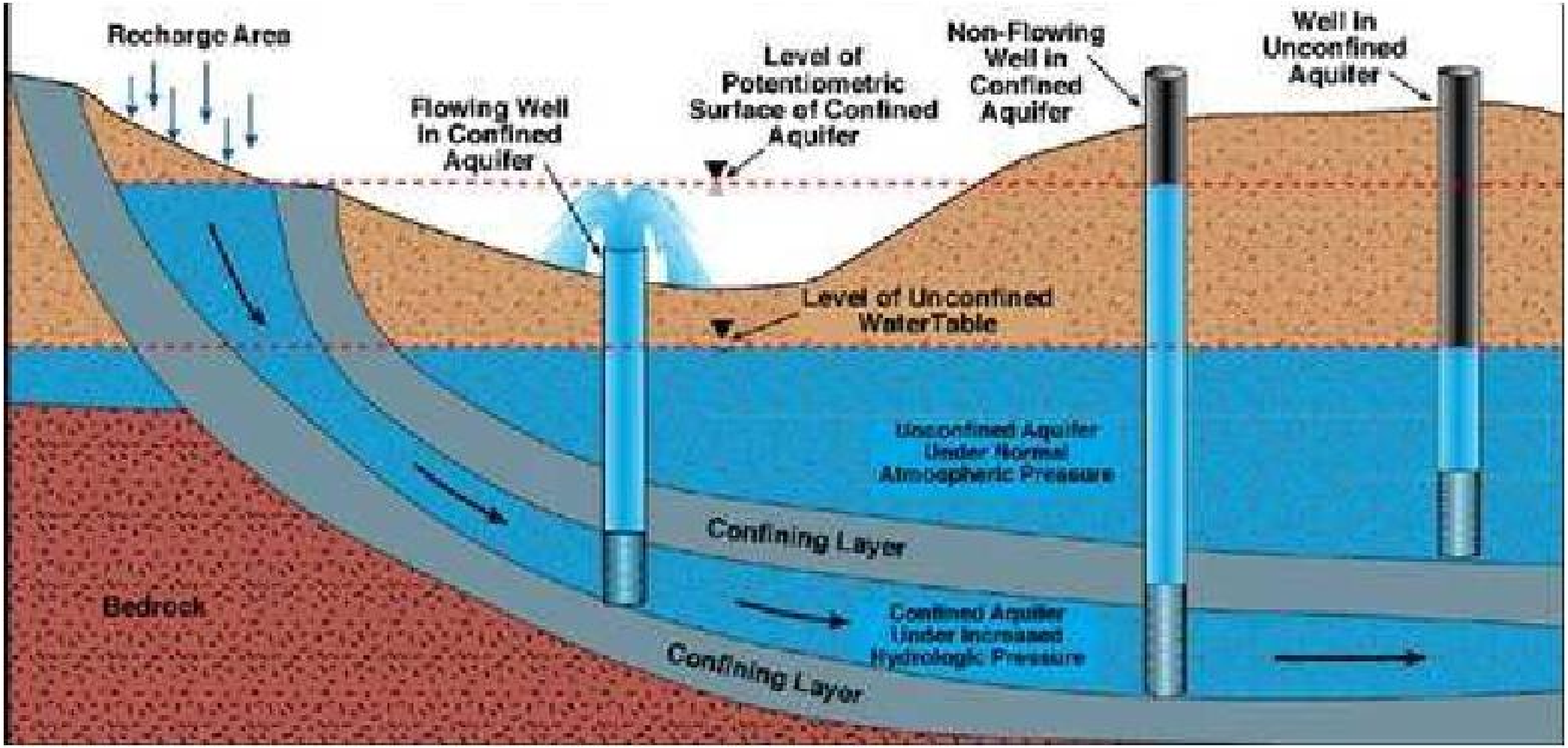
Source: Peterson, 2009, fig 7.7 https://minerva-access.unimelb.edu.au/handle/11343/35439

Aquifer Types: overview

Three types of aquifers: based on the nature of confining beds

承压水层

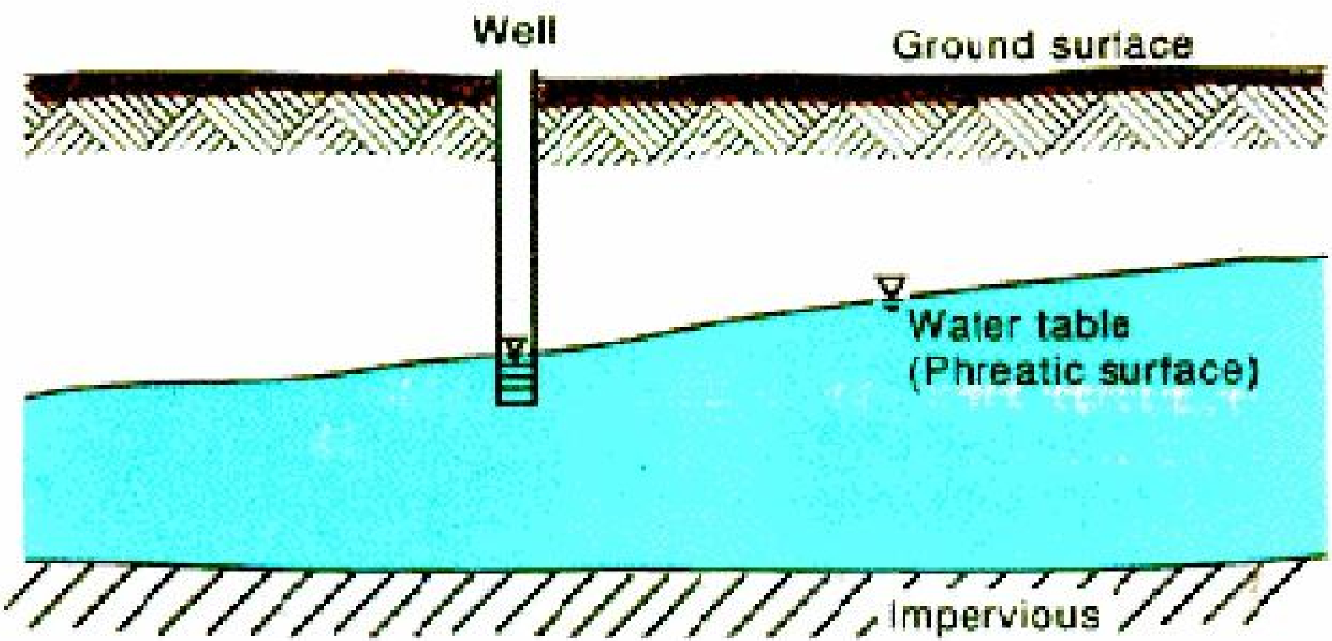
Confined Aquifer: bounded above and below by an impermeable layer.



Aquifer Types: unconfined aquifer

Unconfined Aquifer: has a surface pressure equal to the atmosphere and has the water table as its upper boundary.

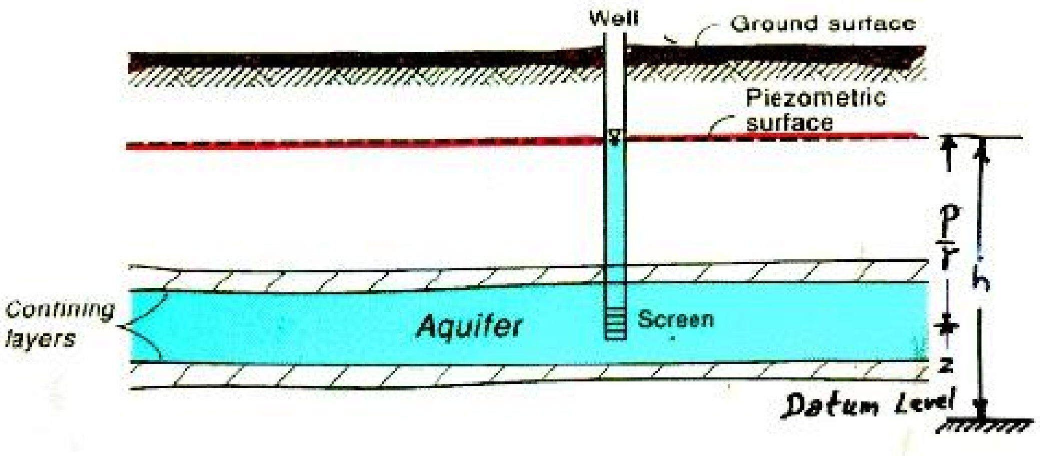
Additional water is stored by an increase the aquifer saturated volume. Evapotranspiration and runoff keeps the water table at or below the land surface.

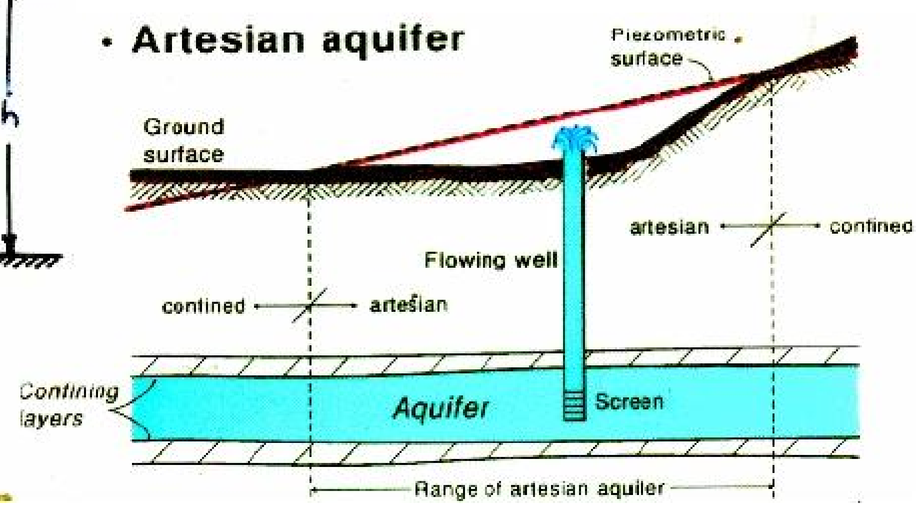


Confined Aquifer: has a pressure greater than the atmosphere, causing the head to be above the upper confining layer.

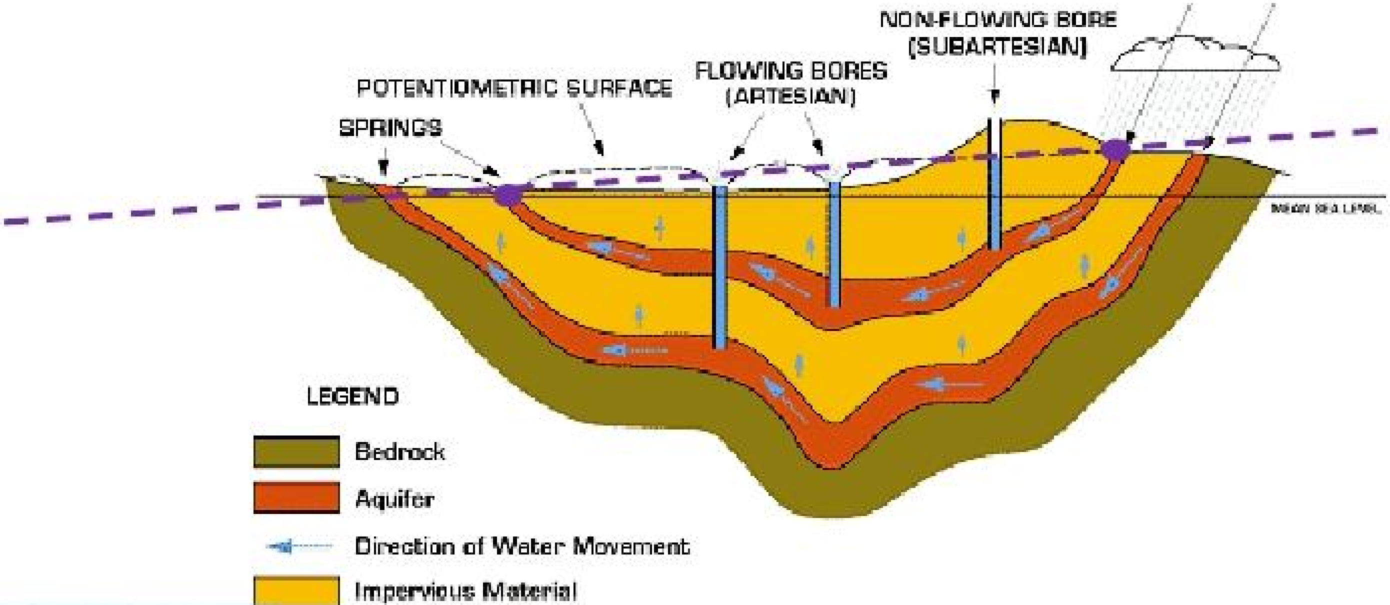
Additional water is stored by an increase in the water pressure, not an increase the aquifer saturated volume.

Confined aquifer Vs. Artesian aquifer





Great Artesian Basin



Underlies 22% or 1.7 million km^2 of Australia.

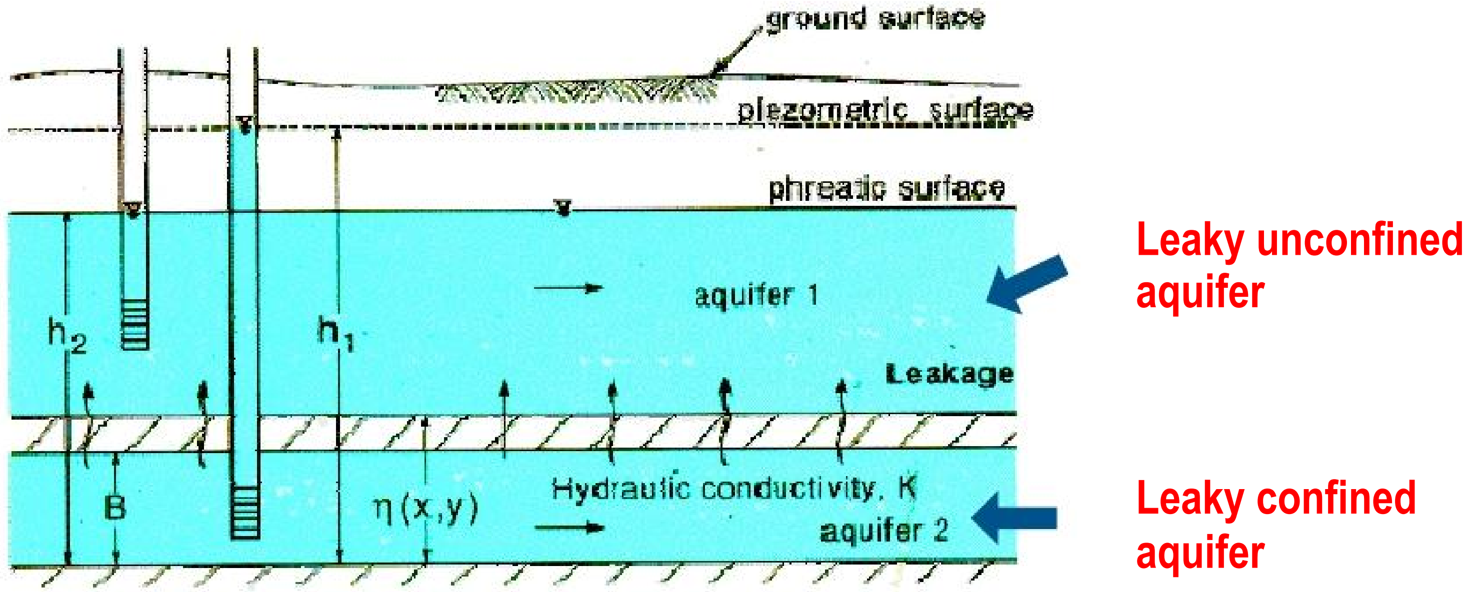
Includes QLD, NSW, SA & NT.

Mostly semi-arid to arid regions.

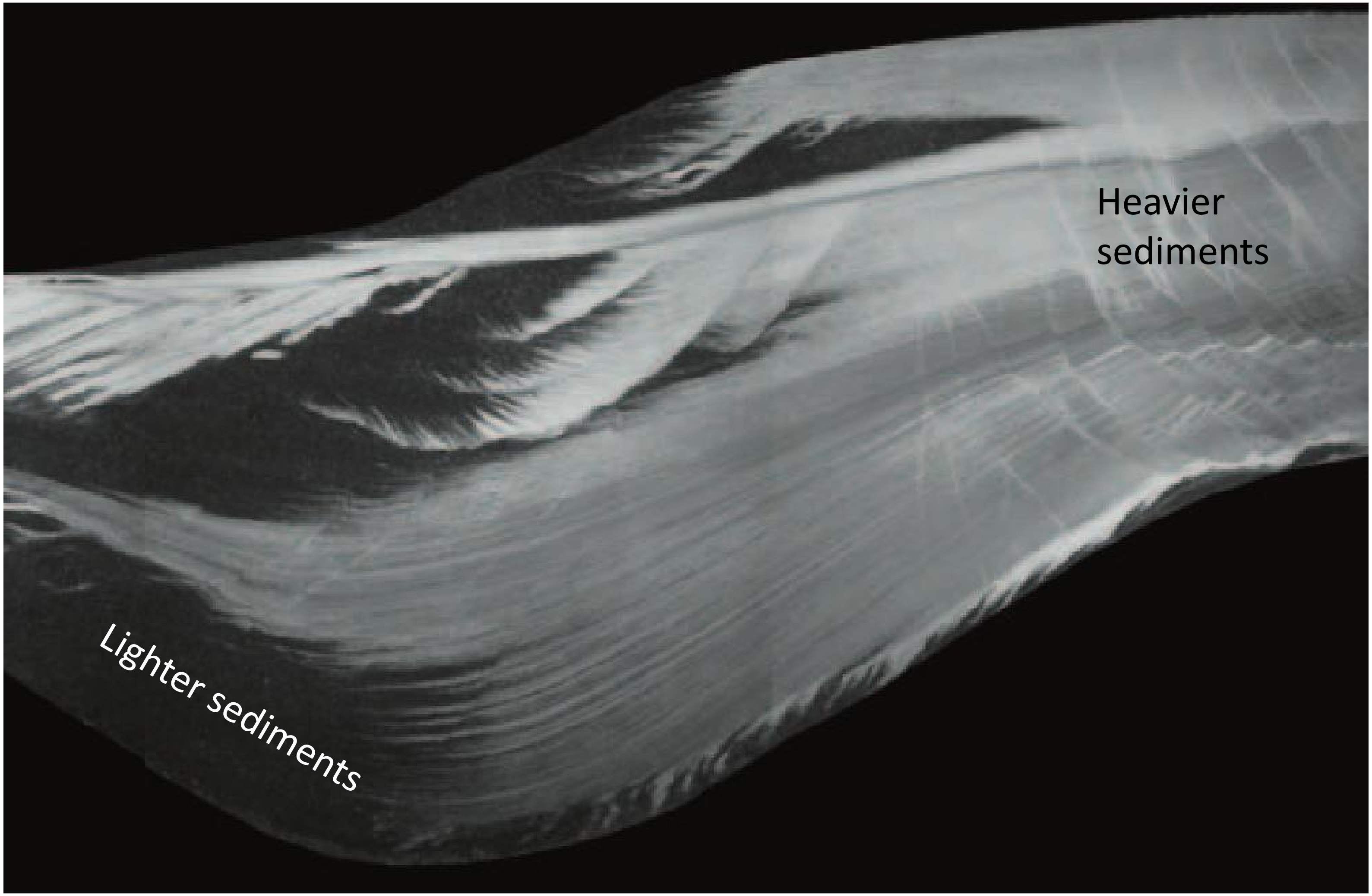
Up to 3 km deep.

Aquifer Types: leaky aquifer

Leaky Aquifer (or semi-confined aquifer): is like a confined aquifer but one of the confining layers is semi-permeability to vertical flow. This allows flow from another aquifer, often an overlying unconfined aquifer, when the semi-confined head declines, e.g. when pumped.



But aquifers are not so simple. In reality, the boundaries and extent of aquifers are often poorly defined.



Source: Paola, et al. 2001, Experimental stratigraphy, *GSA Today*, p4-9

- **Learning Outcome**: identify the major groundwater aquifer types.
  - The unsaturated zone and water table interact, primarily through recharge.
  - Confined aquifers are bounded, can be artesian and are recharged from a distance.
  - Unconfined aquifer have no upper bound and often received recharge from the unsaturated zone.
  - Leaky aquifers are like a confined aquifer, but water can infiltrate through the bounds.

MONASH University

MONASH
Civil Engineering

Storage of water in aquifers
CIV5881/6881: Groundwater Hydrology

Dr Tim Peterson

GROUP OF EIGHT AUSTRALIA

Adapted from those by Christian Urich

Week 1: Learning Outcomes

Identify	the influence of groundwater in the natural world and human history.
Understand	the importance of groundwater and its role in the hydrological cycle.
Explain	how groundwater level is measured and apply measurements to estimate flow directions.
Identify	the major groundwater aquifer types.
Understand	**how water is stored in aquifers.**

Subsurface openings

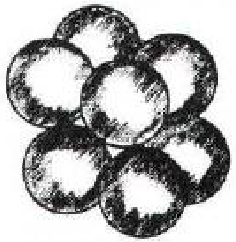
Our impression of a “solid” Earth, from observations on the land surface

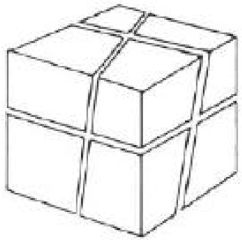
Can’t sense the presence of subsurface openings

Volume of subsurface openings is actually quite big (total: 521,000 km3)

Large enough to yield water in a usable quantity to wells and springs and make groundwater one of the most widely available natural resources.

Subsurface openings





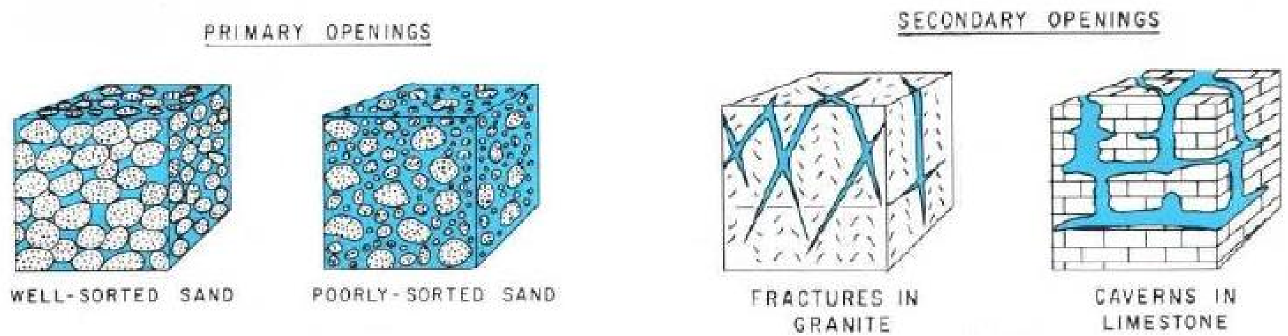
Most of the rocks near the Earth's surface are composed of solids and voids.

Water-bearing material consist either of unconsolidated deposits (soil-like) or consolidated rocks.

Unconsolidated deposits include clay, silt, sand, and gravel (in order of increasing grain size). Most unconsolidated deposits consist of material derived from the disintegration of consolidated rocks.

Consolidated rocks include igneous (e.g. basalt), metamorphic (e.g. granite and marble) and sedimentary rock (e.g. sandstone and limestone). When such rocks are deep, they're often referred to as bedrock.

Subsurface openings



Different kinds of voids in rocks: primary and secondary openings (in terms of formation time)

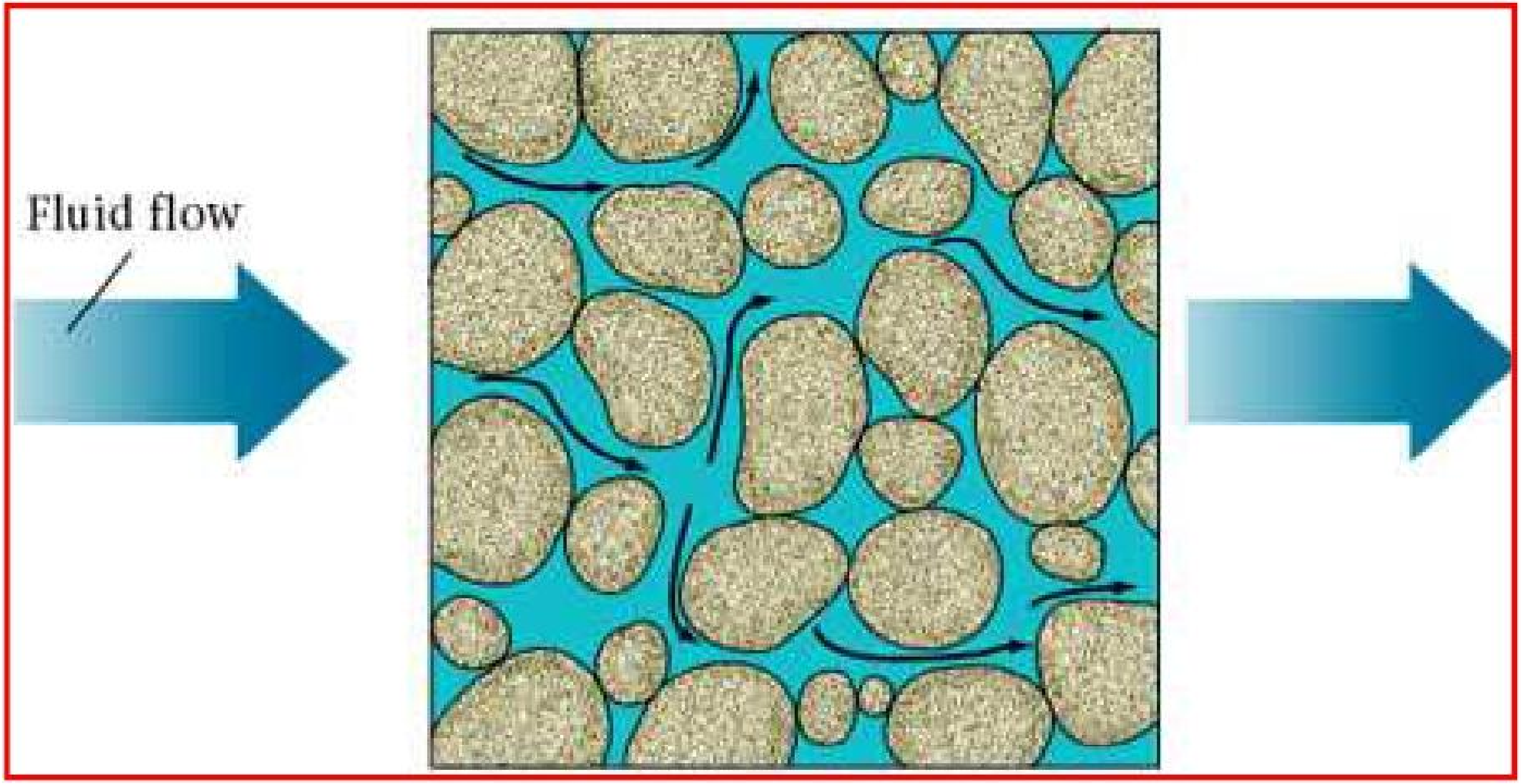
If the voids were formed at the same time as the rock: primary openings, such as the pores in sand and gravel and in other unconsolidated deposits.

If the voids were formed after the rock was formed: secondary openings, such as the fractures in granite and in consolidated sedimentary rocks.

Voids in limestone, formed as groundwater slowly dissolves the rock, are an especially important type of secondary opening.

Karst limestone caves are examples of secondary openings

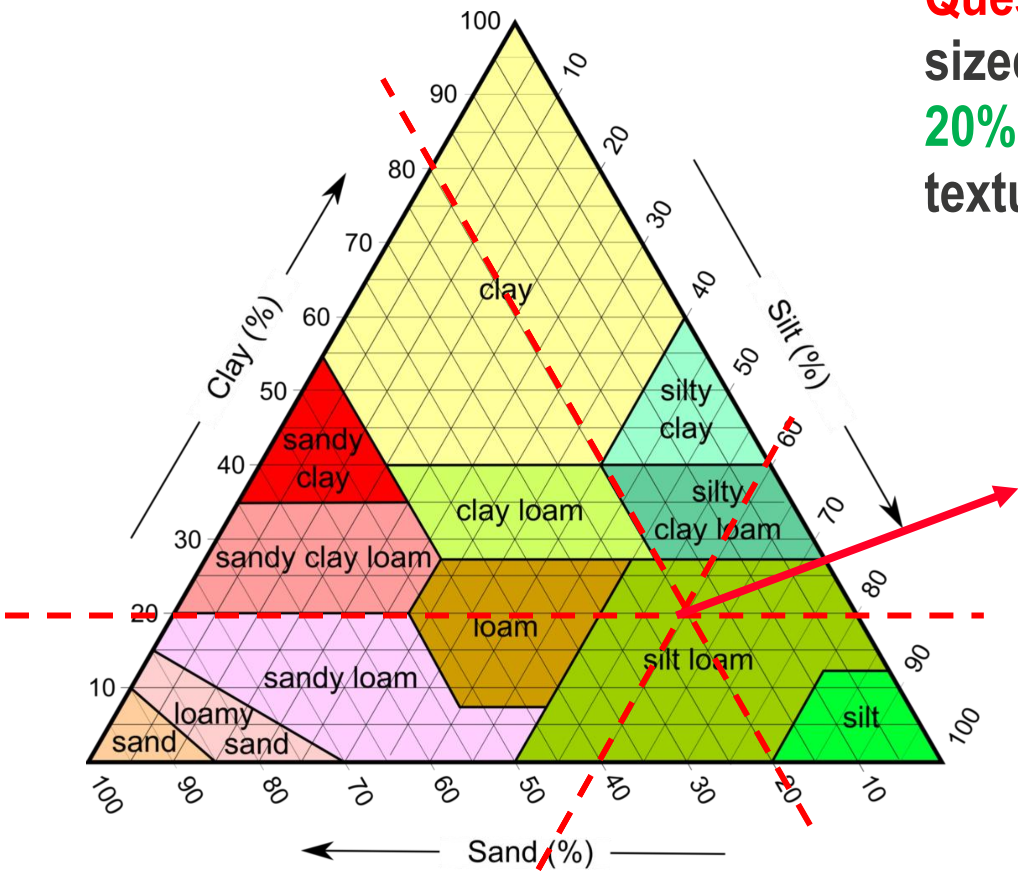
Water-bearing rocks



USDA Classification of Soil Particles

CLASS	Diameter (mm)
Gravel	> 2
Sand	0.05 - 2
Very coarse	1 - 2
Coarse	0.5 - 1
Medium	0.25 – 0.5
Fine	0.1 – 0.25
Very Fine	0.05 – 0.1
Silt	0.002 – 0.05
Clay	< 0.002

Texture triangle (USDA)

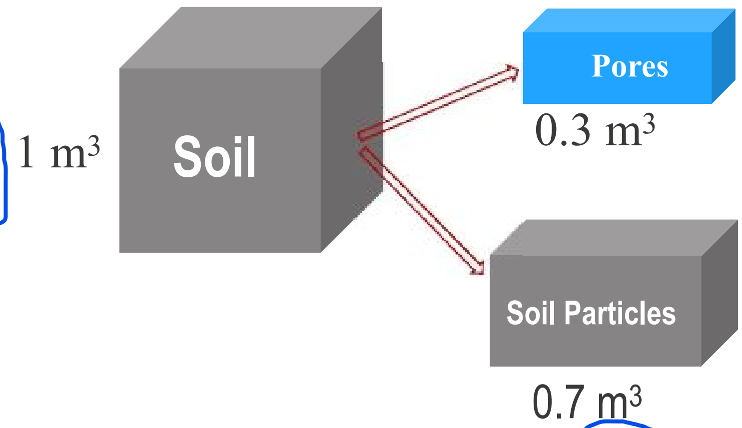


Question: A soil of **20% sand**-sized particles, **60% silt**, and **20% clay**. What is its texture classification?

Silt loam

Porosity:

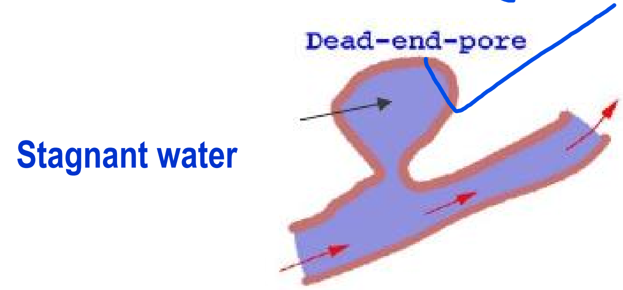
$$n = \frac{Volume\ of\ pores}{Bulk\ Volume} = \frac{V_P}{V_B}$$



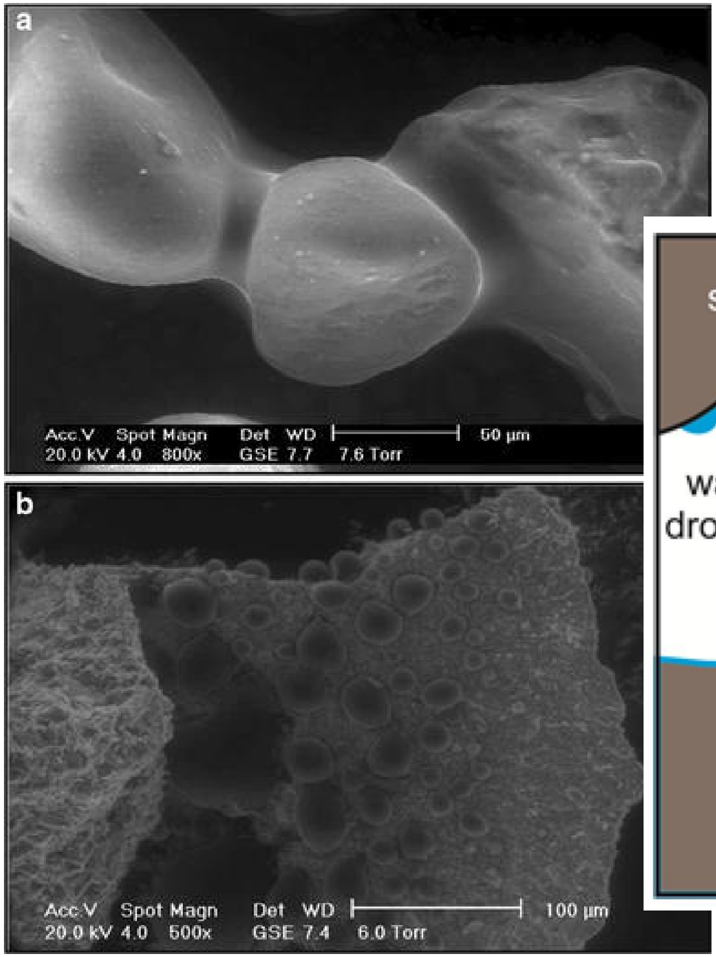
Effective Porosity:

$$n_e = \frac{Volume\ of\ pores\ where\ liquid\ is\ free\ to\ move}{Bulk\ Volume} = \frac{V_{PW}}{V_B}$$

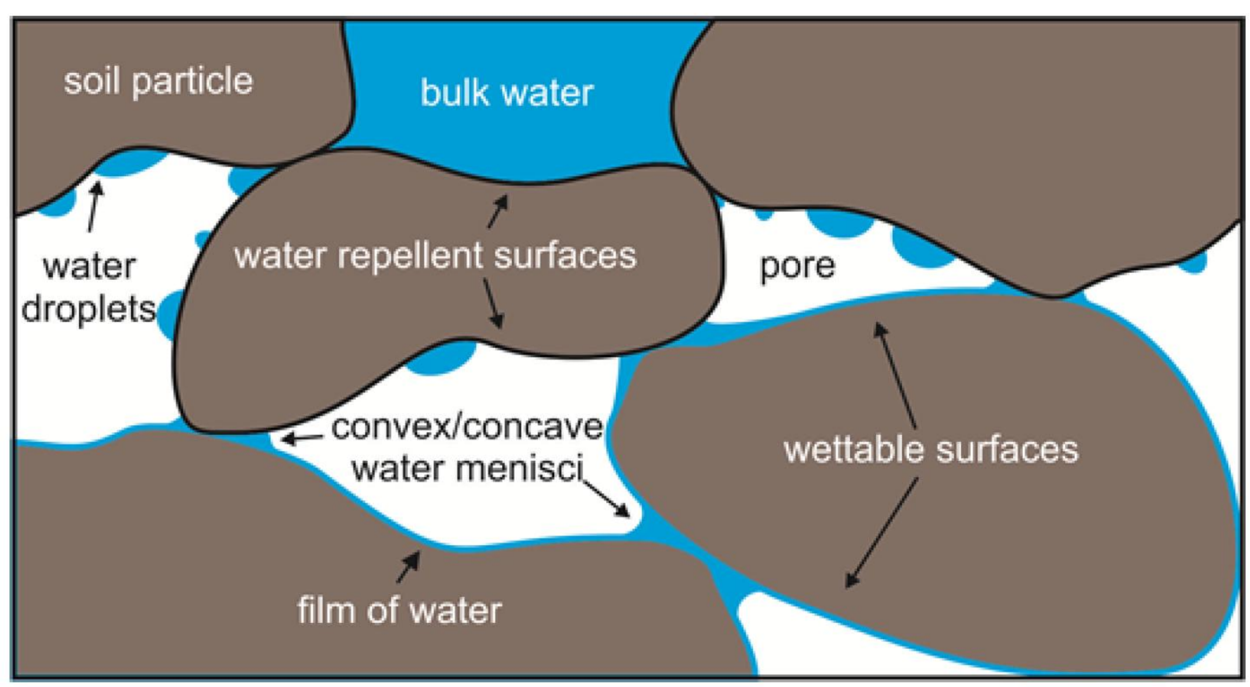
$$n \geq n_e$$



But surface tension of water can exceed gravitational forces, causing it to cling to soil (i.e. pendular water).



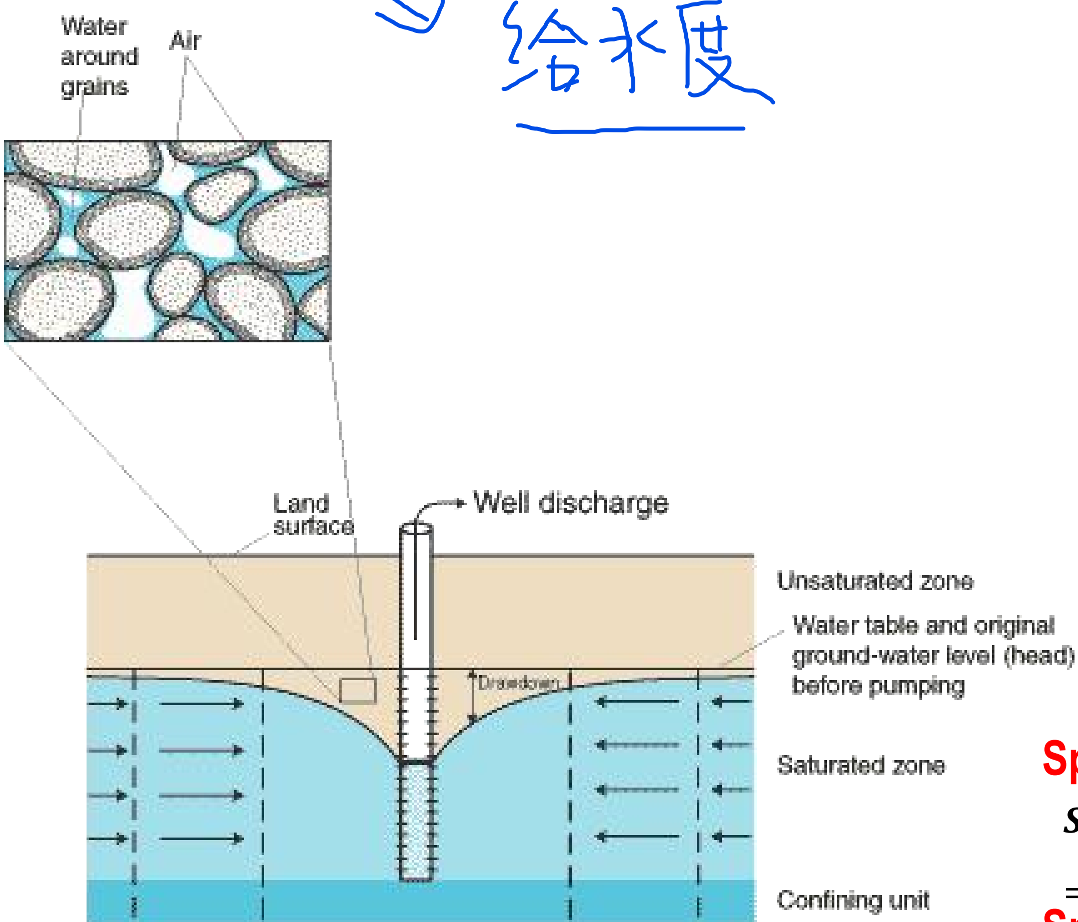
Microphotographs of minerals by environmental scanning electron microscopy, **a** wettable sand particles; **b** water-repellent malachite particles
Source: Lourenço, et al. (2018) *Acta Geotech*



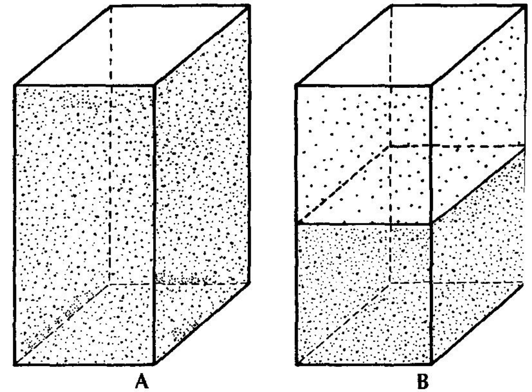
Source: Lourenço, et al., (2015) Geotechnical Society Special Publication

Specific yield explains how rapidly an unconfined aquifer drains

给水度



Source: Alley, et al., (1999) Sustainability of Ground-Water Resources, U.S. Geological Survey Circular 1186



► FIGURE 3.8
A. A volume of rock saturated with water.
B. After gravity drainage, 1 unit volume of the rock has been dewatered with a corresponding lowering of the level of saturation. Specific yield is the ratio of the volume of water that drained from the rock, owing to gravity, to the total rock volume.

Source: Fetter (2001) Applied Hydrogeology

Specific yield:

$$S_y = \frac{Volume\ of\ water\ drainged\ under\ gravity}{Volume\ of\ soil}$$

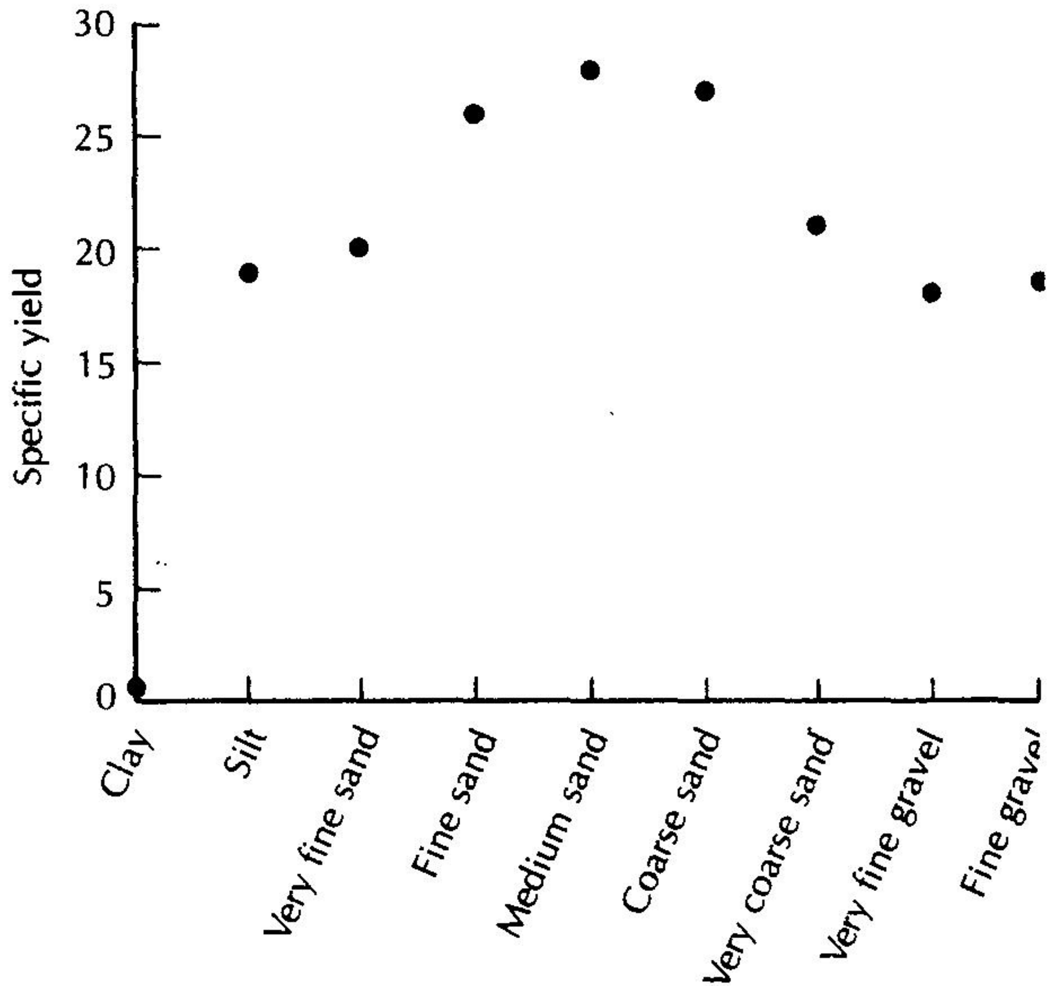
Specific retardation:

$$S_r = \frac{Volume\ of\ water\ retained\ under\ gravity}{Volume\ of\ soil}$$

$$n = S_y + Sr$$

Specific yield is only partially explained by porosity

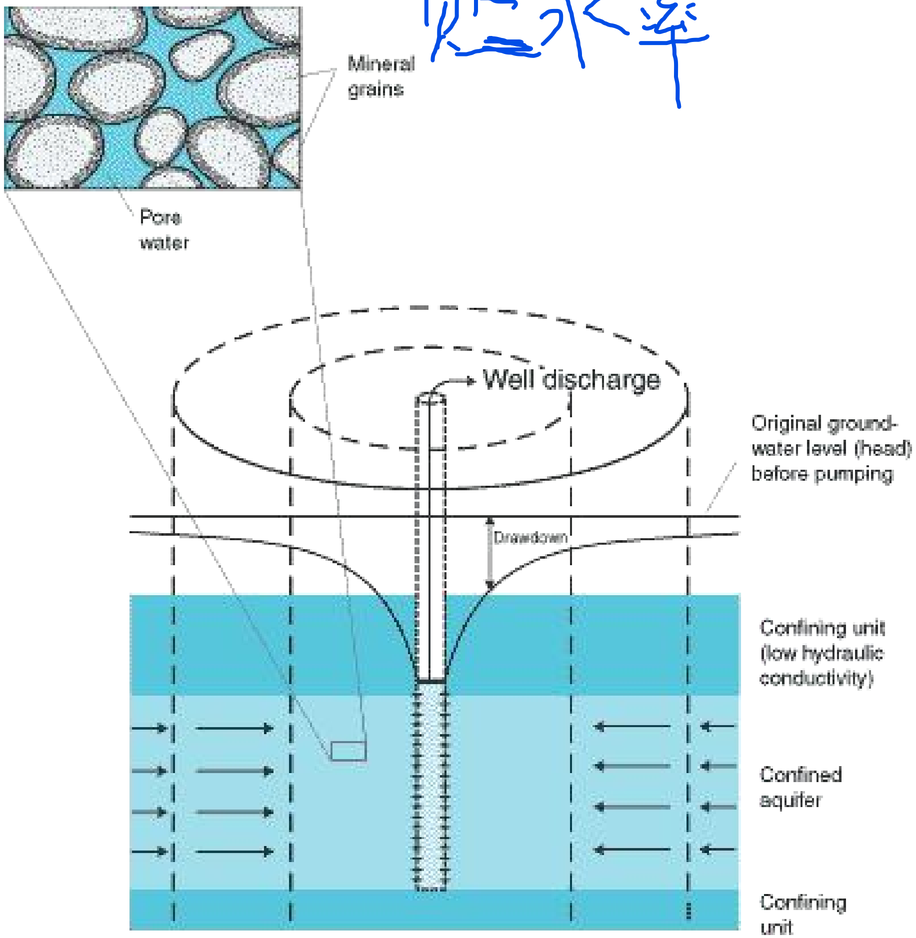
▶ **FIGURE 3.10**
Specific yield of sediments from the Humboldt River Valley of Nevada as a function of the median grain size.
Source: Data from P. Cohen, U.S. Geological Survey Water-Supply Paper *1975, 1965.*



Source: Fetter (2001) Applied Hydrogeology

Specific storage explains how rapidly pressure declines in a confined aquifer

贮水率



Source: Alley, et al., (1999) Sustainability of Ground-Water Resources, U.S. Geological Survey Circular 1186

Specific storage is the amount of water per unit volume of a saturated aquifer that is released from storage owing to the compressibility of the mineral skeleton and pore water per unit change in head.

$$S_s = \rho_w g(\alpha + n\beta)$$ ✓

Where:

Ss is the specific storage per unit of aquifer thickness [1/L]

ρ_w is the density of water

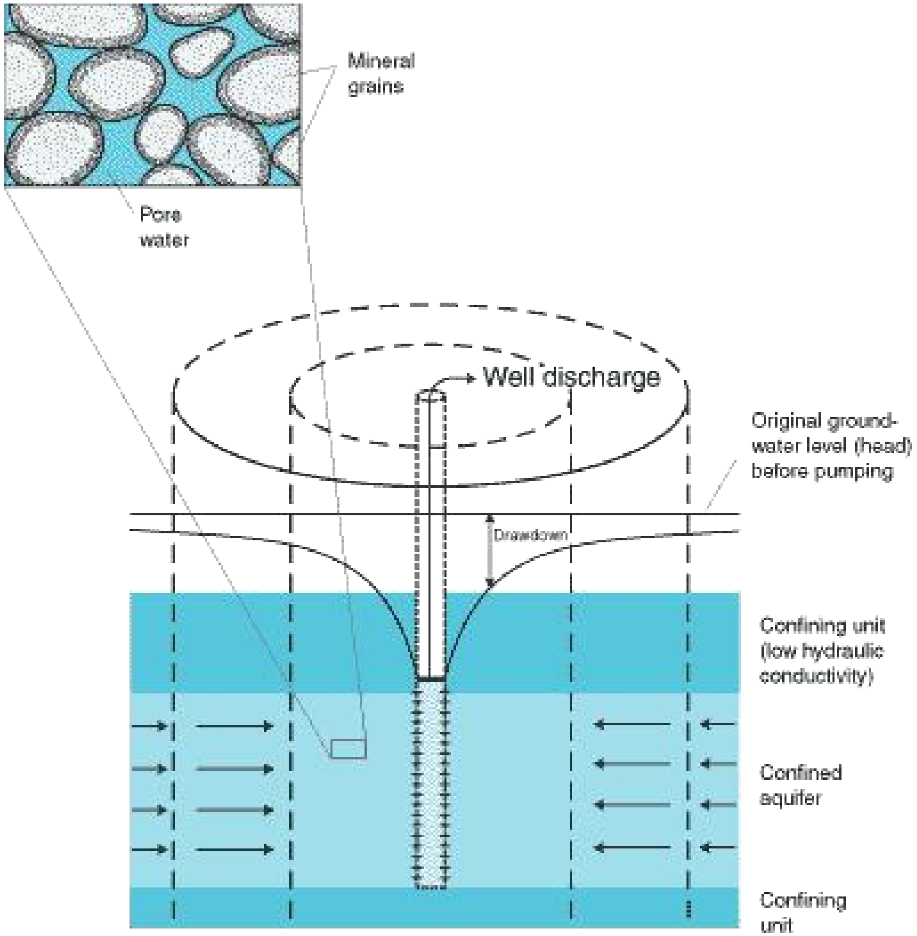
g is the acceleration of gravity

α is the compressibility of the aquifer skeleton

n is the porosity

B is the compressibility of water, typically 4.4E-10 m^2/N

Storativity explains how rapidly pressure declines in a confined aquifer



Storativity is the amount of water per unit area of a saturated aquifer that is released from storage owing to the compressibility of the mineral skeleton and pore water per unit change in head.

$$S = bS_s$$

Where:
S is the storativity [-]
S_s is the specific storage [1/L]
b is the confined aquifer thickness

Source: Alley, et al., (1999) Sustainability of Ground-Water Resources, U.S. Geological Survey Circular 1186

Typical values of specific storage

Aquifer Material	S_s [1/m]		
Plastic clay	2.38E-04	to	1.89E-03
Stiff clay	1.19E-04	to	2.38E-04
Medium hard clay	8.53E-05	to	1.19E-04
Loose sand	4.57E-05	to	9.45E-05
Dense sand	1.19E-05	to	6.10E-07
Dense sandy gravel	4.57E-06	to	3.05E-07
Rock, fissured	3.05E-07	to	6.40E-06
Rock, sound	<1.00E-06		

Source: Freeze, R.A. and J.A. Cherry, 1979. *Groundwater*, Prentice Hall, Englewood Cliffs, New Jersey, 604p.

- **Learning Outcome**: understand how water is stored in aquifers.
  - Aquifer water is stored with primary and secondary openings.
  - Soil texture heavily influences porosity.
  - Specific yield, S_y, defines how the head changes within an unconfined aquifer.
  - Specific storage , S_s, and storativity, S, define how the head changes within a confined aquifer.
  - Generally, $S_y > S$