UNIVERSITY OF SASKATCHEWAN

Numerical Modelling for Environmental Engineers and Scientists

Groundwater processes

Lecture 4

Andrew Ireson

andrew.ireson@usask.ca

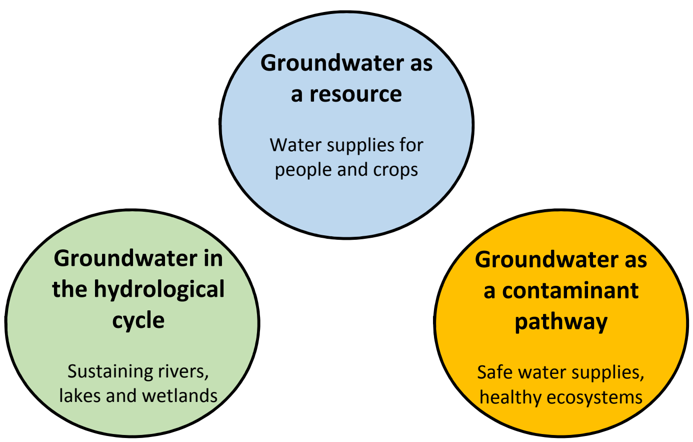
Learning objectives

You should be able to:

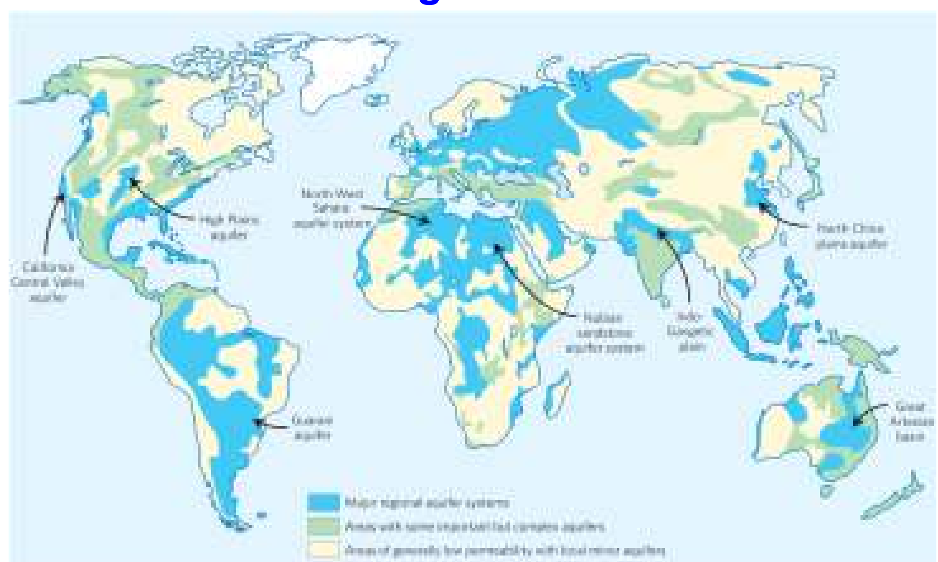
- Explain the ways that groundwater is important
- Describe of the global distribution of groundwater
- Define "*groundwater*", and describe the different forms that it takes
- Understand the basics of storage and movement of water in porous media, with particular focus on unconfined aquifers

The importance of groundwater

Groundwater is important for three primary reasons:



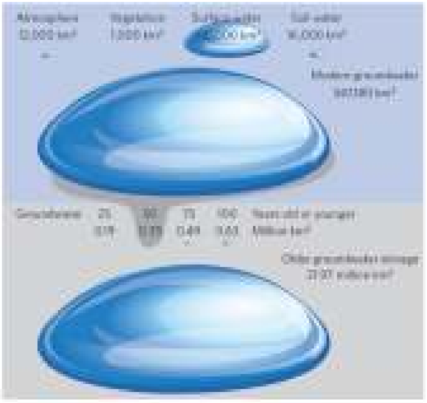
Global groundwater



Taylor et al, Groundwater and Climate Change, Nature Climate Change, Vol 3, 2013.

Global Groundwater

A recent assessment by Gleeson et al (2015) of global groundwater improves estimates of the amount of groundwater, globally, and the age distribution of groundwater.

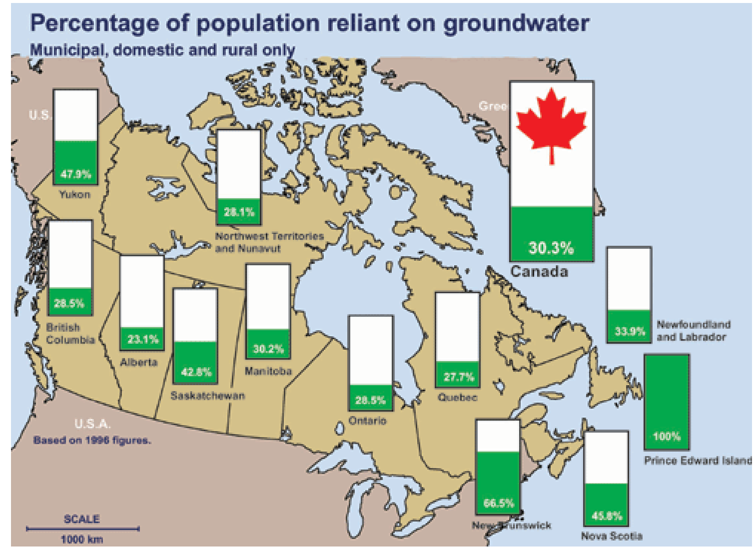


Key findings about:

- The vast majority of groundwater is not modern (>50 years old and non-renewable if exploited)
- Modern groundwater volume is equivalent to 3 m depth over all the continents – still a huge amount
- Modern groundwater is renewable, better quality and a usable, sustainable resource
- It is an active part of the hydrological and biogeochemical cycles, but vulnerable to vulnerable to contamination and changing recharge

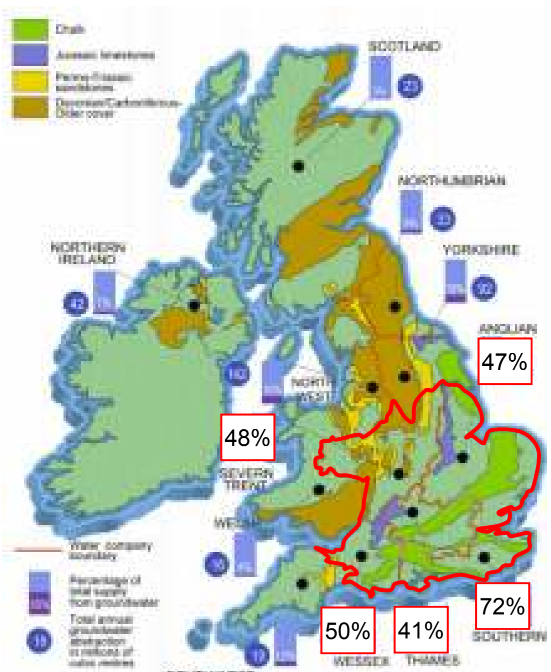
Gleeson et al, The global volume and distribution of modern groundwater, Nature Geoscience, 2015.

Groundwater in Canada



Environment Canada http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=300688DC-1

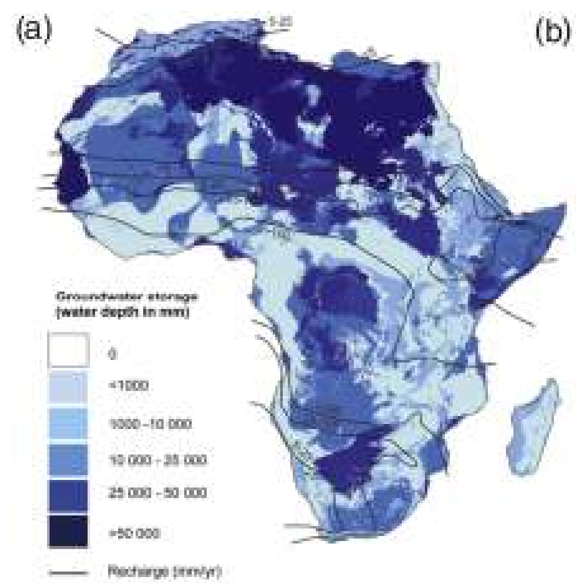
Groundwater in the UK



(after the UK Groundwater Forum, 2004)

In the midlands and southeast, groundwater represents 41% to 72 % of total water supply

Groundwater in Africa



MacDonald et al., 2012. Quantitative maps of groundwater resources in Africa, Env. Res. Let. 7

Groundwater in rural Ghana

Surface water in rural Ghana

It is estimated that 320 million African's, and 25% of Ghanaian's, are relying on unsafe surface waters, as depicted here:

Adelana and MacDonald, 2008. Applied Groundwater Studies in Africa. CRC Press

What is groundwater?

Simple: Groundwater can be defined as water under the ground!

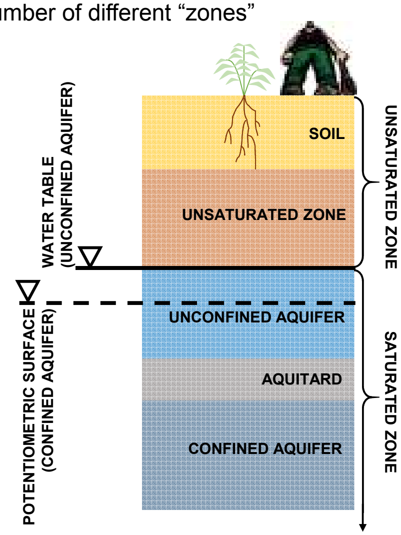
Complicated: Groundwater exists in a number of different "zones"

Useful to consider the zones separately, because the behavior of each is distinctly different.

Soil moisture: unsaturated, root water uptake, soil horizons dominate material properties.

Unsaturated zone: unsaturated, but typically no roots, gravity drainage dominates.

Saturated zone: saturated, variable flow directions and magnitudes, further divided into aquifers, aquitards and aquicludes



The saturated zone

AQUIFER A saturated permeable geological unit that stores **groundwater** and allows it to **flow** under normal conditions.

AQUICLUDE A saturated geological unit that is **incapable** of transmitting significant quantities of water.

AQUITARD A '**less permeable**' bed in a **stratigraphic** sequence (may be significant in a regional groundwater balance, but insignificant for a local production well).

N.B. These terms are relative!

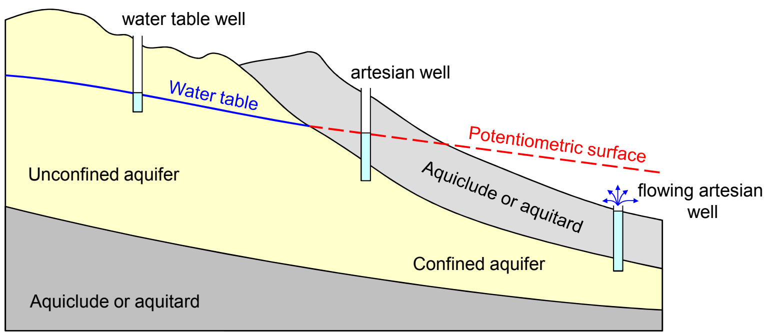
Aquifer types

Unconfined Aquifer

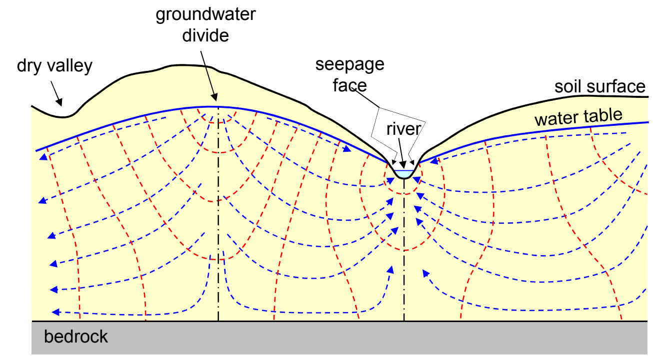
An aquifer with a free water surface as the upper boundary (the water table or phreatic surface) at which pressure is atmospheric.

Confined Aquifer

An aquifer confined between two aquitards or aquicludes, such that pressures in the aquifer are everywhere greater than atmospheric.

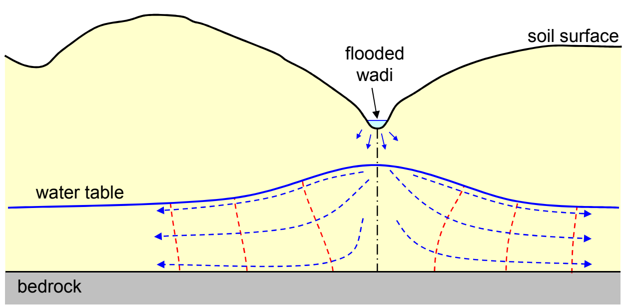


Valley aquifers



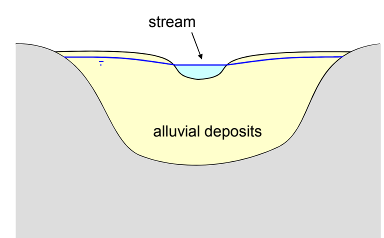
- Generally found in temperate climates where the soil is porous and permeable.
- Rainfall infiltrates and staturates the rock up to a level called the phreatic surface or water table.
- Groundwater drains to topographic lows and exits as springs or streams.

Valley aquifers in arid zones



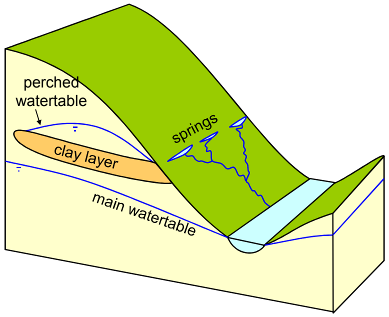
- In arid areas rainfall is much lower than potential evapotranspiration and surface recharge is almost zero.
- However, valleys may carry water from mountainous areas or from flash floods, which bring large quantities of water for a short time.
- This water usually infiltrates through the river bed into the aquifer and constitutes the only recharge mechanism.
- Therefore, the water table is higher beneath the valleys than elsewhere.

Alluvial aquifers



- Unconfined aquifer situated in alluvial deposits found along the course of a stream or river.
- Water in aquifer is generally in equilibrium with that of the stream, which alternately drains and recharges it (e.g. Rhine, Danube rivers).

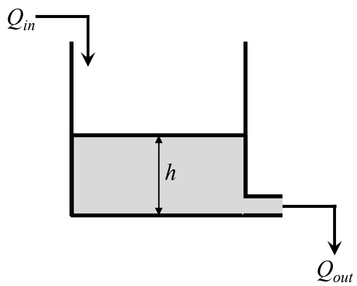
Perched aquifers



- A saturated lens of relatively low permeability bounded by a perched water table.
- Perched aquifers can provide minor sources of supply but can suffer rapid changes in water level since the storage involved is usually relatively small.
- Unconsolidated sediments (e.g. sands, silts, clays) are commonly inter-bedded, making the determination of the 'true' water table sometimes very difficult in practice.

Fundamentals of groundwater flow processes

Flow and storage in porous media



Recall the bucket model from the last lecture.

The volume of water in the bucket is:

$$V = h.A$$

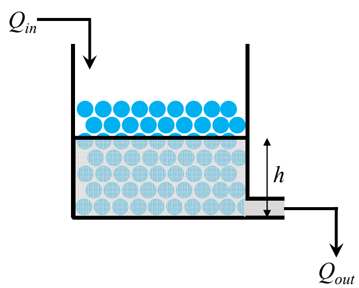
The discharge from the bucket was assumed to be:

$$Q_{out} = k.h$$

Now, imagine that the bucket contains glass beads. This will have two effects:

1. The volume of water in the bucket is now lower
2. The discharge from the bucket will be slower

These are the basic features of porous medium – we need to characterize the properties related to storage and flow.



Porosity

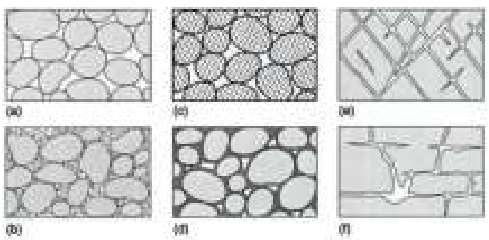
Porosity

In porous materials, i.e. soils and rocks, water is stored in and flows through the voids, or pore spaces.

Porosity, n, is a measure of the volume of voids relative to the volume of rock, i.e.

$$n = \frac{\text{volume of voids}}{\text{total volume of the rock}} \quad [-]$$

The nature of the porosity is different in different materials



a) well sorted sedimentary deposit with high porosity; **b)** poorly sorted sedimentary deposit with low porosity; **c)** as a) but with porous pebbles; **d)** as a) but with diminished porosity from mineral desposits; **e)** porosity from fracturing; **f)** porosity from solution of rock.

Reproduced from Kresic (2007) page 13. Originally from Meinzer, O.E., USGS Water-Supply Paper 489, 1923.

Hydraulic Head

The potential mechanical energy per unit weight of a fluid relative to some datum is known as hydraulic head, h, where:

Assumed negligible for flow through porous media

$$h = \underbrace{\frac{P}{\rho g}}_{\text{Pressure head, } \psi} + \cancel{\frac{u^2}{2g}} + z$$

Units of length, L

Elevation head, z

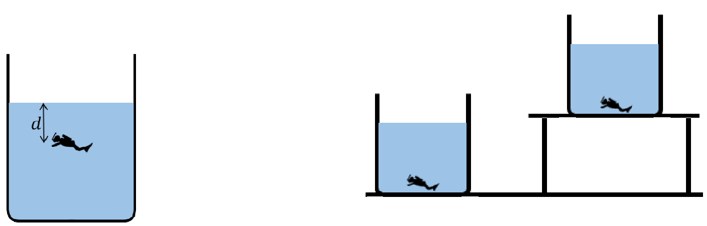
Therefore $$h = \psi + z$$

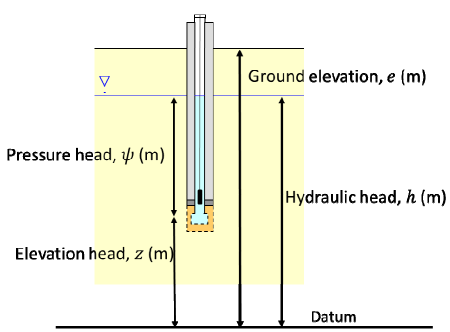
Fundamental concept: Fluid moves from high to low hydraulic head.

In other words: Flow is driven by a negative hydraulic head gradient.

This is expressed in Darcy's Law: $$Q = -KA\frac{\Delta h}{\Delta x}$$

Hydraulic, pressure and elevation head





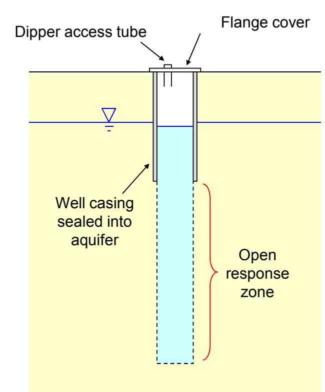
Measuring hydraulic head

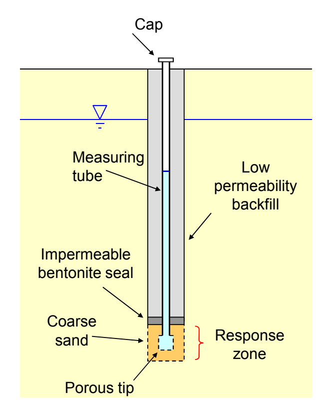
Observation well

Essentially an open borehole. Water level in such a well represents the average hydraulic head over the length of the open section. In unconfined aquifers, the water level in an observation well is often assumed to be the level of the prevailing watertable.

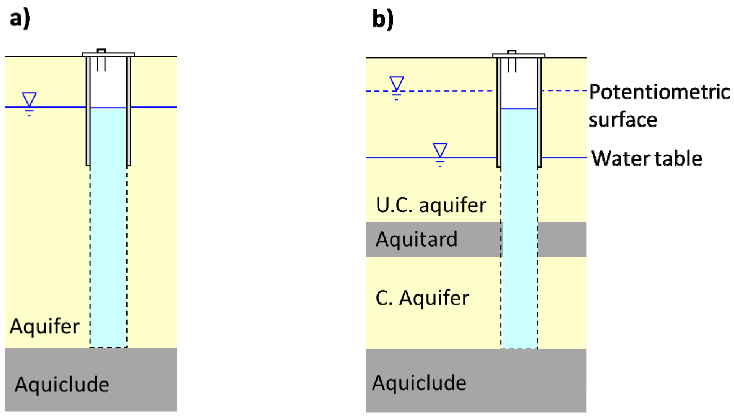
Piezometer

A device for measuring hydraulic head at a point (or averaged over a relatively small depth) in the ground. The water level in an open piezometer well is not necessarily the same as the water table level in unconfined conditions.

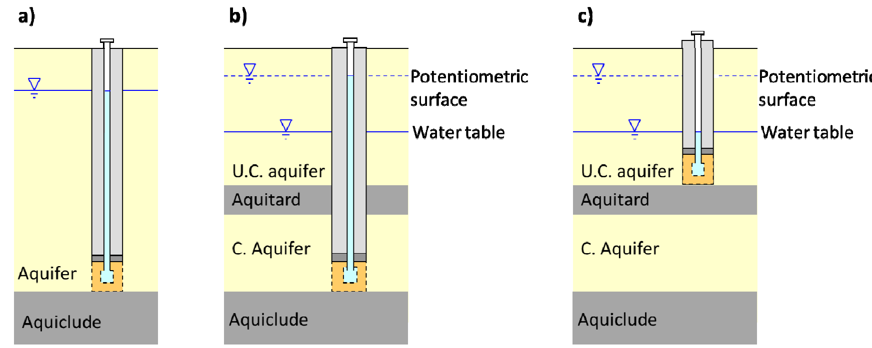




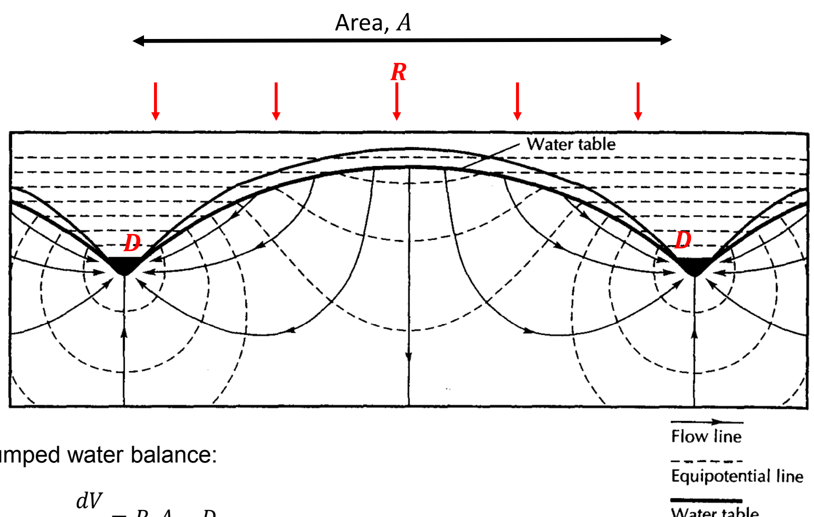
Observations wells



Piezometers



Flow in an idealized unconfined aquifer



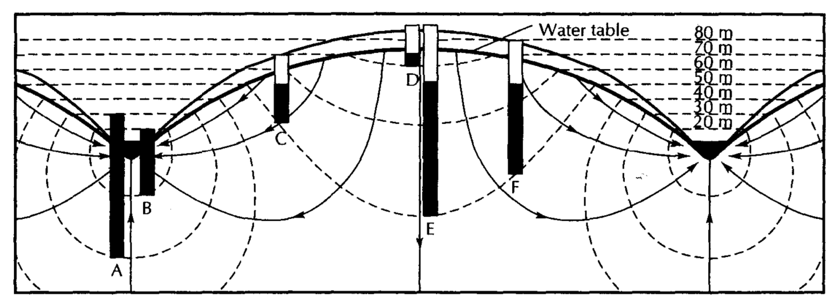
Lumped water balance:

$$\frac{dV}{dt} = R.A - D$$

Fetter, Applied hydrogeology, p 238.

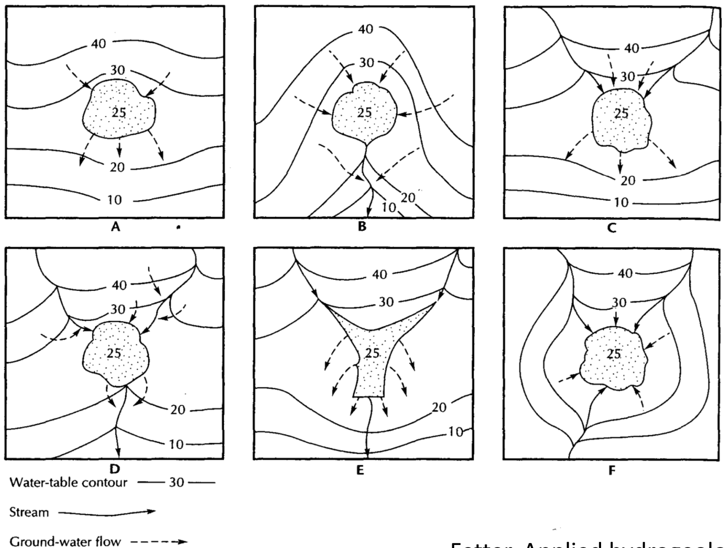
Flow in an idealized unconfined aquifer

Piezometer readings:



Fetter, Applied hydrogeology, p 238.

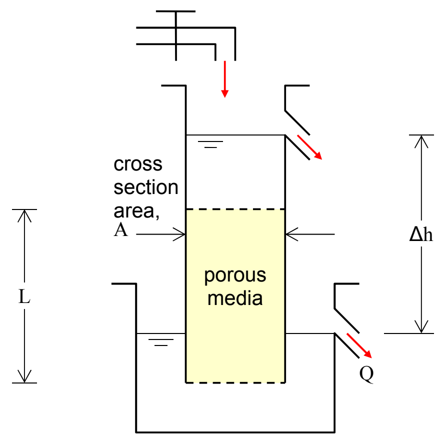
Mapping groundwater flow

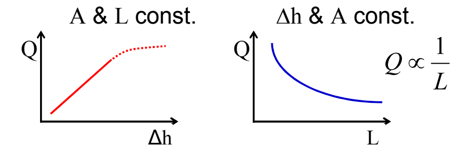


Fetter, Applied hydrogeology, p 274.

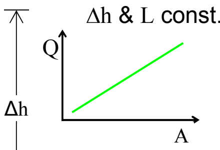
Darcy's law

Darcy's experiments:





$Q \propto \dfrac{1}{L}$



Therefore Darcy found:

$$Q \propto \Delta h \frac{1}{L} A$$

The constant of proportionality is what we call **hydraulic conductivity**, K [L/T].

Hence, we have Darcy's Law: $Q = KA\dfrac{\Delta h}{L}$ or: $\boxed{q = -K\dfrac{dh}{dz}}$

Darcy flux [LT^{-1}] = Q/A

Note, minus sign

Hydraulic gradient [LL^{-1}]

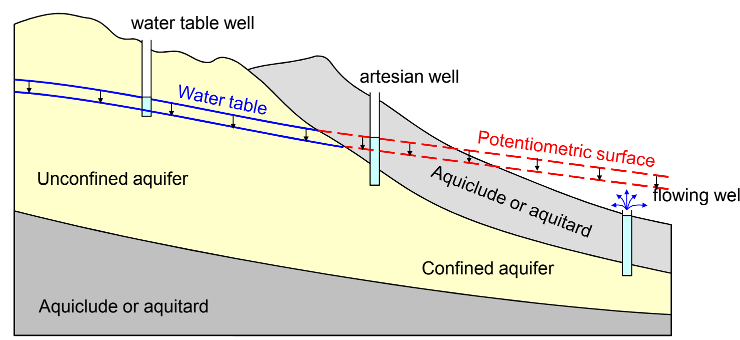
Some typical values

Material	Porosity (%)	K (m/s)	K (m/d)
Sedimentary			
Gravel	24 – 38	3.0E-4 –3.0E-2	26 – 2600
Sand	26 – 53	2.0E-7 – 6.0E-3	0.01 – 500
Silt	34 – 61	1.0E-9 – 2.0E-5	1E-4 – 2
Clay	34 – 60	1.0E-13 – 4.7E-9	1E-8 – 4E-4
Sedimentary Rocks			
Sandstone	5 – 30	3.0E-10 – 6.0E-6	3E-5 – 0.5
Siltstone	21 – 40	1.0E-11 – 1.4E-8	1E-6 – 1E-3
Shale	0 – 10	1.0E-13 – 2.0E-9	1E-8 – 2E-4
Limestone	0 – 40	1.0E-9 – 2.0E-2	1E-4 – 2000
Crystalline Rocks			
Fractured crystalline rocks	0 – 10	8.0E-9 – 3.0E-4	7E-4 – 30
Unfractured crystalline rocks	0 – 5	3.0E-14 – 2.0E-10	3E-9 – 2E-5
Weathered granite	34 – 47	3.3E-6 – 5.2E-5	0.3 – 4
Weathered gabbro	42 – 45	5.5E-7 – 3.8E-6	0.05 – 0.3
Basalt	3 – 35	2.0E-11 – 4.2E-7	2E-6 – 0.04

After Schwartz and Zhang (2003, Fundamentals of Ground Water, Wiley, p.44 and 51)

Storage in groundwater

- In aquifers, the total porosity that we previously discussed is not the relevant storage parameter, since the rock is never completely drained.
- Groundwater in/out flow results in an increase/decrease in pressure. For example, groundwater discharge will result in a drop in pressure, which corresponds to a drop in the water table/potentiometric surface.
- In unconfined aquifers, when the water table drops, the pore space is partially drained
- In confined aquifers, when the potentiometric surface drops, the rock and the water expand (very slightly) to release water

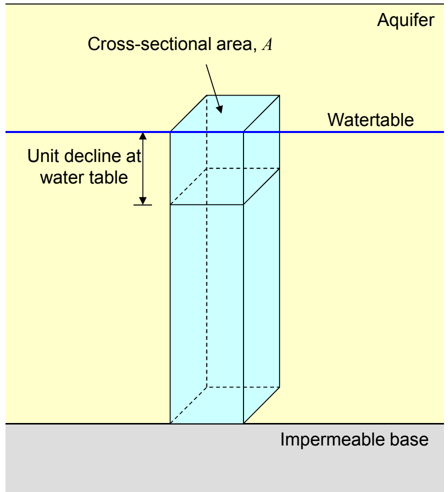


Unconfined aquifers: Specific yield

- Specific yield, S_y [-]
- Volume of water released per unit area as a result of a unit fall in the water table elevation.
- The water arises from the dewatering of the pores as the water table is lowered.
- This is similar to the previous bucket analogy
- Total yield from the aquifer is

$$\Delta V = S_y(\Delta h)A$$

Of the order of the porosity, or 0.01 – 0.6



Confined aquifers: Specific storage

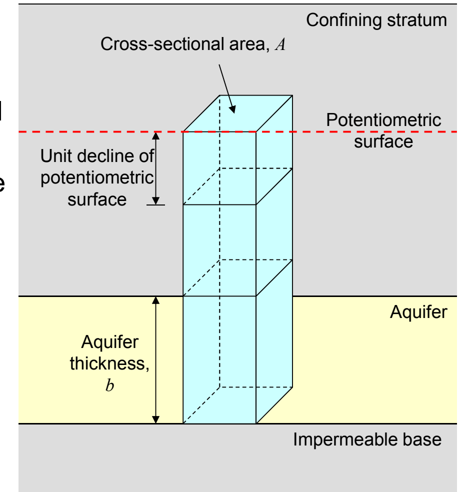
- Specific storage, S_s [L^{-1}]
- Volume of water released per unit volume of saturated formation as a result of a unit fall in the potentiometric surface
- Release is from expansion of the water and rock which result from the drop in fluid pressure.

$$S_s = \rho g(\alpha + n\beta)$$

- Total yield from the aquifer is

$$\Delta V = S_s b(\Delta h)A$$

Much smaller than porosity, of the order of 0.005 or less



Summary

- We looked at the importance of groundwater and the global occurrence of groundwater
- We defined groundwater, and saw the different forms that it can take in different parts of the ground
- We learnt about confined and unconfined aquifers, aquitards and aquicludes
- We leant about the basic properties of porous media and the way in which water is stored and transmitted through porous media
- In class we will focus on two activities:
  a) Look at some lab experiments to better understand hydraulic head, specific yield and hydraulic conductivity
  b) Use the understanding we have developed to derive governing equations for groundwater flow in unconfined aquifers, and solve these equations analytically and numerically

Keywords

Aquifer	
Aquiclude	
Aquitard	
Confined aquifer	
Unconfined aquifer	
Water table	
Pontentiometric surface	
Continuity equation	
Darcy's Law	
Hydraulic head	
Porosity	
Hydraulic conductivity	
Specific Yield	
Specific storage	