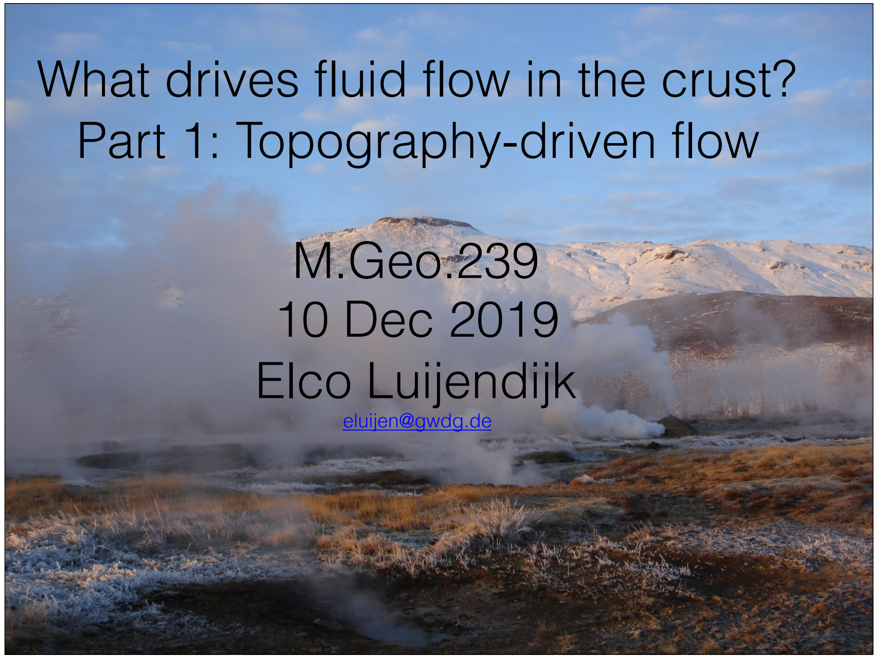

What drives fluid flow in the crust? Part 1: Topography-driven flow

M.Geo.239

10 Dec 2019

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Lectures so far:

- Fluid volumes in the crust
- Diffusion and transport of fluid, heat and solutes in the crust
- Permeability of the crust
- Temperatures and heat flow in the crust

Lectures on driving forces:

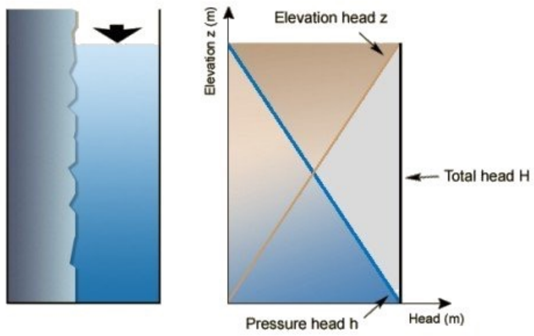
- Today: Driving forces of fluid flow: Topography-driven flow
- 18 Dec: Flow driven by density gradients (convection)
- 8 Jan: Flow driven by compaction

What drives fluid flow: the energy potential of a fluid

- Fluid potential = gravitational potential + elastic energy + kinetic energy: $$E_t = \frac{1}{2}mv^2 + mgz + \frac{mp}{\rho}$$
- Fluid energy potential per unit volume (note mass/volume = density (ρ)): $$E_t = \frac{1}{2}\rho v^2 + \rho g z + p$$
- Fluid potential per unit weight = hydraulic head (m) $$\frac{E_t}{g} = z + \frac{p}{\rho g} = h$$
- h = elevation + pressure head

Hydraulic head & fluid flow

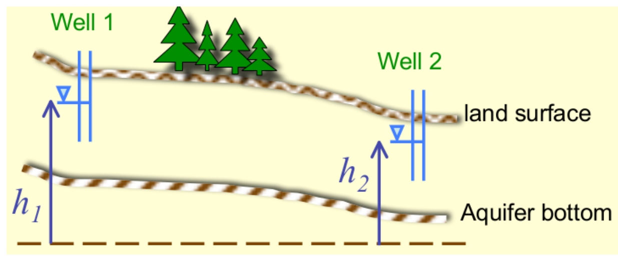
$$h = z + \frac{p}{\rho g}$$



source: C. Harvey, MIT

Hydraulic head & fluid flow

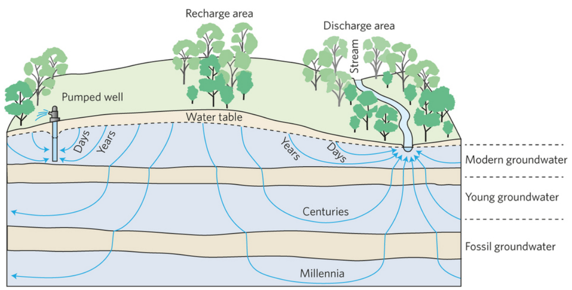
$$h = z + \frac{p}{\rho g}$$



Hydraulic head an aquifer, source: J.L. Wilson, NMT

Topography-driven flow

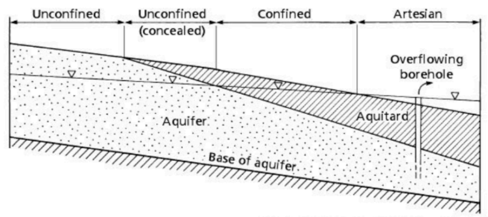
- Fluid flow is driven by the hydraulic gradient:
- The gradient is typically relatively low, 1% on average
- Typical flow velocities are m/yr



Aquifer types

- Differences in permeability give rise to a borad classification of geological units into:
  - aquifers: permeable units
  - aquitards: impermeable units
- Aquifers can be confined or unconfined
- Confined conditions can give rise to artesian wells: wells where the hydraulic head is above the surface (no pump required)

Fig. 2.26 Cross-section showing four types of groundwater conditions. A water table is developed where the aquifer is unconfined or concealed and a potentiometric surface is present where the aquifer experiences confined or artesian conditions.



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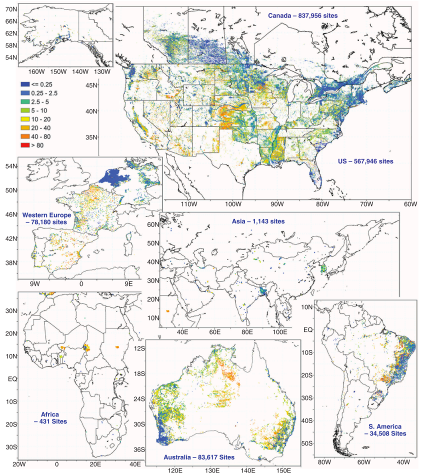
Hiscock and Bense (2014)

Hydraulic gradients

- Hydraulic gradients are typically relatively low, the estimated global average is 1%
- This is slightly lower than the topographic gradient
- -> the groundwater table is a subdued replica of the surface



Global depth of the watertable. Combination of data compilation and model interpretation
Fan et al. (2013) Science

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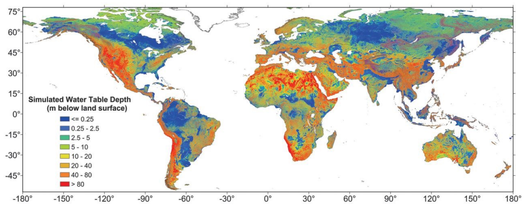
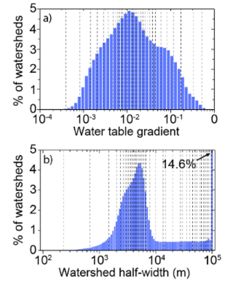


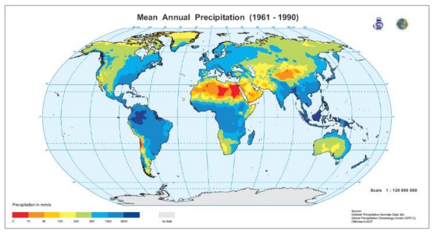
Global depth of the watertable, combination of data compilation and model interpretation
Fan et al. (2013) Science



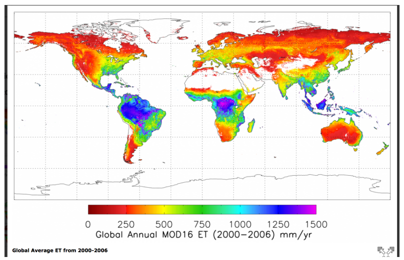
Global average watertable gradients (top) and distance to the nearest stream (bottom)
Gleeson et al. (2016) Nature Geosc.

Groundwater recharge

- Groundwater recharge = precipitation - runoff - evaporation - transpiration
- Runoff: depends on slope and soil properties, typically <5% of precipitation
- Evapotranspiration (ET): can reach values > 1 m/yr in semi-arid and arid regions
- Humid regions: recharge is relatively predictable using models of precipitation, runoff and evapotranspiration
- Semi-arid and arid regions: ET is much higher than precipitation. Recharge depends on infrequent high precipitation events, and favourable recharge flow paths for fluids to escape evapotranspiration



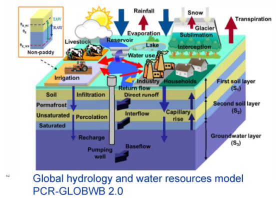
Global average precipitation
(http://www.whymap.org)

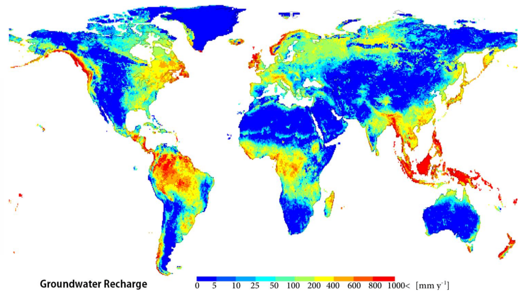


Global ET, source NASA/Univ Montana
(www.ntsg.umt.edu/project/mod16)

Groundwater recharge

- Global models of groundwater recharge exist, but perform much better in humid areas than in semi-arid regions
- Typically models of groundwater recharge consist of a 1D water budget model that combines precipitation, surface runoff, evaporation/transpiration. Remaining budget term=groundwater recharge





Global model of groundwater recharge
De Graaf et al. (2015) HESS

Recharge and precipitation

- There is a rough correlation of recharge with precipitation, but large variation that depends on topography, soil conditions and geology. Recharge is especially variable in semi-arid regions

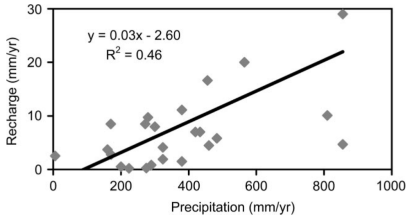


Figure 12. Relationship between recharge and precipitation from studies of large natural areas (40–374 200 km^2) using methods that reflect regional recharge rates (modelling, saturated zone CMB, micro-gravity, and water-table fluctuations) (Leaney and Allison, 1986; Edmunds *et al*., 1988; Bazuhair and Wood, 1996; Sami and Hughes, 1996; de Vries *et al*., 2000; Love *et al*., 2000; Anderholm, 2001; Leduc *et al*., 2001; Flint *et al*., 2002, 2004; Favreau *et al*., 2002b; Harrington *et al*., 2002; Hevesi *et al*., 2003; Goodrich *et al*., 2004; Sanford *et al*., 2004; Heilweil *et al*., 2006; Keese *et al*., 2005)

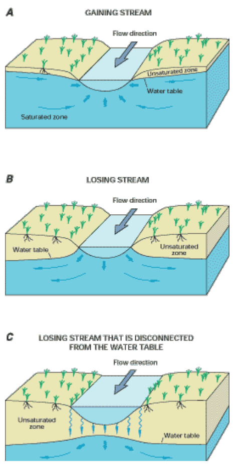
Compilation of regional groundwater recharge estimates.
Scanlon et al. (2006) Hydrol. Proc.

Groundwater discharge

- Groundwater discharges at low elevations where hydraulic head (h) is higher or close to the surface level or the elevation of water bodies
  - h > surface level: seepage, ponding, springs, surface runoff
  - h > water level: discharge to rivers, lakes or oceans
  - h > surface level - ~ 2m: direct evapotranspiration of groundwater and capillary rise

Groundwater discharge

- Groundwater is important in sustaining the baseflow of rivers, ie the steady background flow rate outside of temporal peaks following rainfall events
- Most streams gain water. In arid regions streams can become sources of groundwater when the watertable is located below the level of the stream

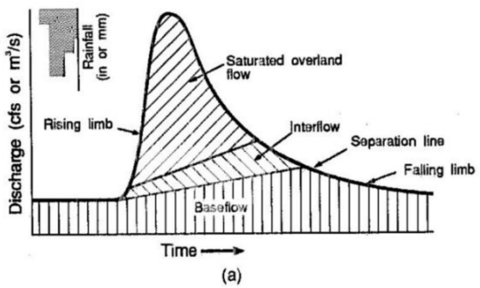


Source: USGS

Groundwater discharge

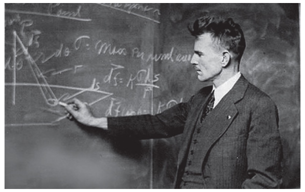
- Groundwater is important in sustaining the baseflow of rivers, ie the steady background flow rate outside of temporal peaks following rainfall events

River discharge over time, and the contribution of groundwater (baseflow) (Maidment 1992)



Topography-driven flow

- What kind of flow systems do we get as a result of recharge and discharge of meteoric water?
- M.K. Hubbert (1940) analytical solution of groundwater flow in a simple topography-driven flow system:



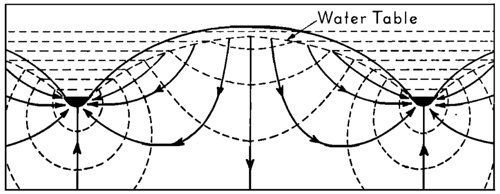
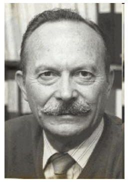


Fig. 4. Approximate flow pattern in uniformly permeable material between the sources tributed over the air-water interface and the valley sinks. (After *Hubbert* [1940].)

Topography-driven flow

- Josef Toth expanded on the work by Hubbert in the 1960s by looking at the response of flow systems to variations in topography in 2D
- Analytical solution to groundwater flow in a system with a sinusoidal watertable



$$\phi = g\Big\{z_0 + \frac{c's}{2} + \frac{a'}{sb'}(1 - \cos b's) + 2\sum_{m=1}^{\infty}\Big[\frac{a'b'(1 - \cos b's \cos m\pi)}{b'^2 - m^2\pi^2/s^2} + \frac{c's^2}{m^2\pi^2}(\cos m\pi - 1)\Big] \cdot \frac{\cos(m\pi x/s)\cosh(m\pi z/s)}{s \cdot \cosh(m\pi z_0/s)}\Big\} \quad (6)$$

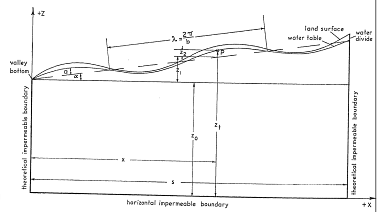


Fig. 1. Idealized cross section of a valley flank in a small drainage basin.

Toth (1963) JGR

Topography-driven flow

- Results: High relief: local flow systems only, all recharge discharges in the nearest stream

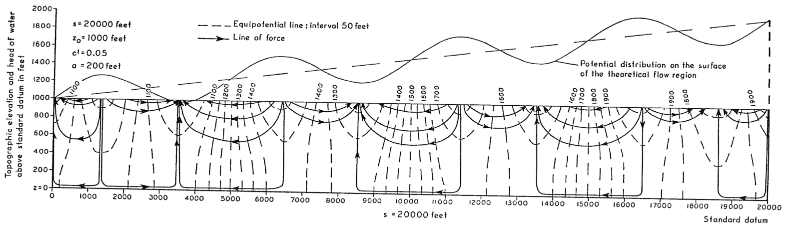


Fig. 2*d*. Potential distribution and flow pattern as obtained by equation 6.

Toth (1963)

Topography-driven flow

- Moderate relief: Some of the groundwater flow is regional, it does not discharge into the nearest river but instead flow to the lowest surface water body in the system
- ie, most groundwater flow systems are a combination of local and regional groundwater flow

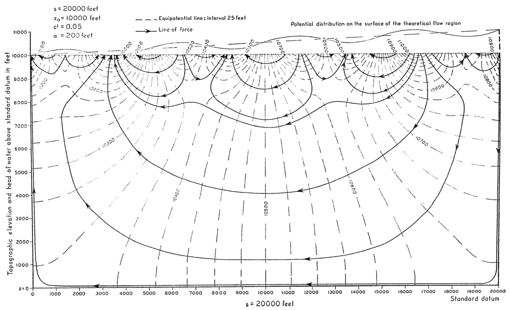


Fig. 2*i*. Potential distribution and flow pattern as obtained by equation 6.

Toth (1963)

Local vs regional flow

- Conceptual model based on Toth's work:

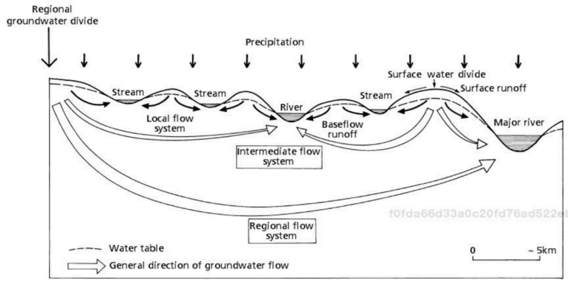


Fig. 2.45 Diagram showing the influence of hummocky topography in producing local, intermediate and regional groundwater flow systems. (Adapted from Tóth 1963. Reproduced with permission of John Wiley & Sons.)

Hiscock and Bense (2014)

Topography-driven flow and relief

- How does topography-driven flow react to variations in relief and hydraulic conductivity
- First numerical models develop in the 1970s by Freeze and Witherspoon
- Results for a homogeneous basin with different values of relief:

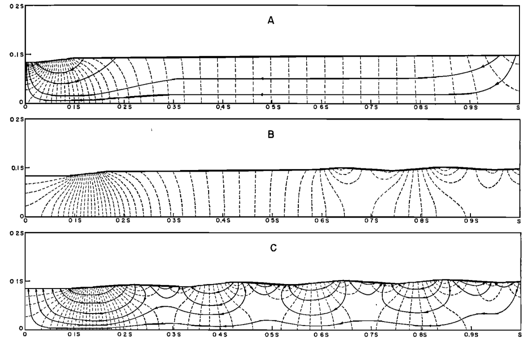
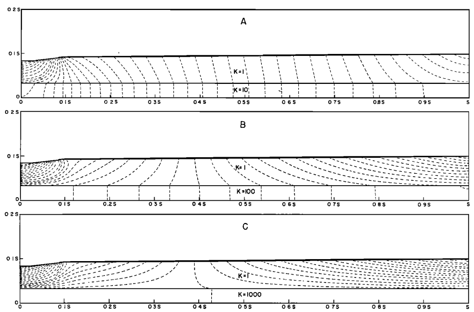


Fig. 1. Effect of water-table configuration on regional groundwater flow through homogeneous isotropic mediums.

 Freeze & Witherspoon (1967) Water Res. Research

Topography-driven flow and conductivity

- Topography-driven flow and hydraulic conductivity
- Slow vertical flow through layers with a low hydraulic conductivity, fast horizontal flow through layers with a high conductivity:



- Flow for two layer system with higher conductivity at the bottom by a factor of 10 (panel A), 100 (B) and 1000 (C)
- Note that the figure shows the equipotential lines only (lines of equal h),
- Flow is always perpendicular to the equipotential lines.
- The wider the equipotential lines are apart, the faster the flow.

Freeze & Witherspoon (1967)
Water Res. Research

Topography-driven flow and conductivity

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- Slow vertical flow through layers with a low hydraulic conductivity, fast horizontal flow through layers with a high conductivity:

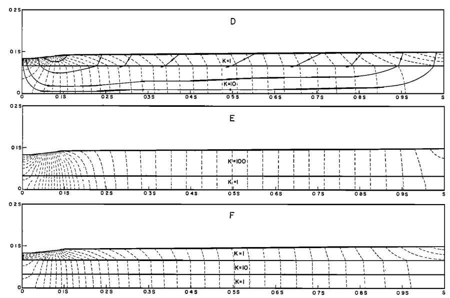
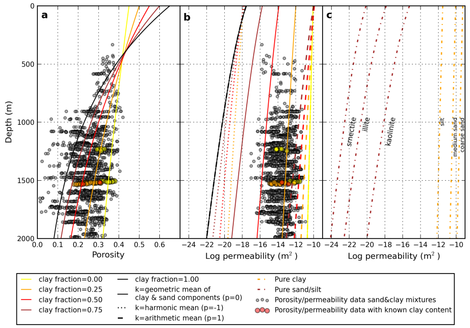


Fig. 2. Regional groundwater flow through layered mediums with a simple water-table configuration.

 Freeze & Witherspoon (1967) Water Res. Research

Topography-driven flow and conductivity

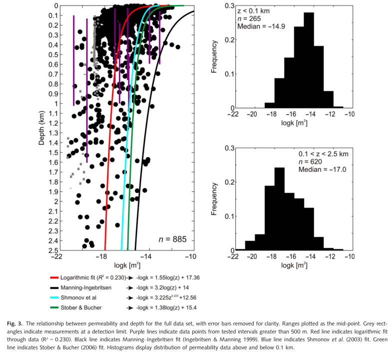
- Permeability & hydraulic conductivity tend to decrease with depth
- -> flow decreases with depth, most groundwater flow is relatively shallow, and local
- True for sedimentary rocks:



Permeability decrease with depth for siliciclastic sediments, Luijendijk & Gleeson (2015) Geofluids

Topography-driven flow and conductivity

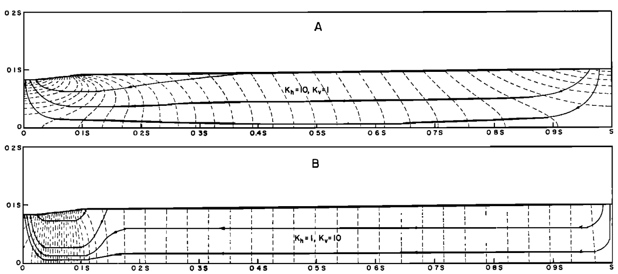
- Permeability & hydraulic conductivity tend to decrease with depth
- -> flow decreases with depth, most groundwater flow is relatively shallow, and local
- And for crystalline rocks:



Permeability decrease with depth for crystalline rocks, Ranjram et al. (2015) Geofluids

Topography-driven flow and anisotropy

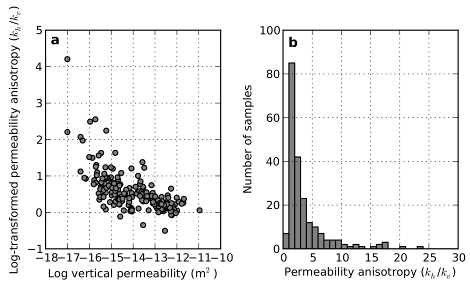
- Effects of anisotropic hydraulic conductivity: higher horizontal / bedding-parallel permeability keeps flow shallower and more local



 Freeze & Witherspoon (1967) Water Res. Research

Topography-driven flow and anisotropy

- Most sedimentary rocks are strongly anisotropic
- Small scale: Kh/Kv = 1 to 10
- At larger scales Kh/Kv increases to >100
- Consequence: stronger horizontal than vertical flow
- This keeps groundwater flow systems relatively shallow and local



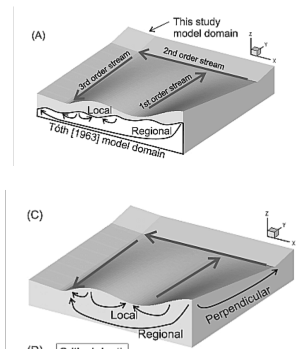
Permeability anisotropy of ~10 cm size samples of sedimentary rocks Luijendijk & Gleeson (2015) Geofluids

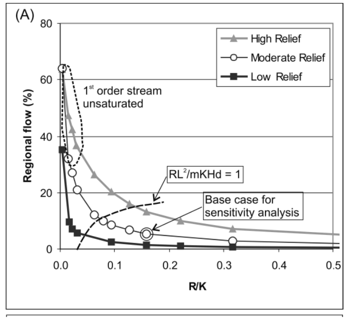
Local vs regional flow

- How important is regional groundwater flow?
- In Toth's models: up to ~20% is regional flow, the remainder is local. This may be an overestimate, because in permeability was constant in these models
- The ratio of local and regional flow depends on watertable gradient, which (in general) is a subdued version of the topographic gradient
- More recent models with realistic topography and permeability: up to 50% regional flow in mountainous settings, much less in most cases

Local vs regional flow

- More recent models with realistic topography and permeability: up to 50% regional flow in mountainous settings, much less in most cases

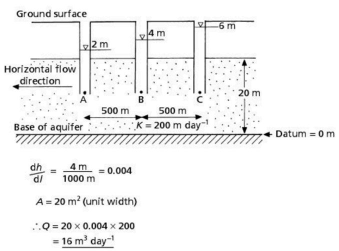




Gleeson & Manning (2008) WRR

Mapping groundwater flow

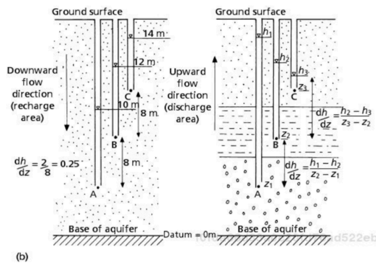
- Data on groundwater levels & hydraulic head can be used to quantify flow direction and rates
- In this case flow can be calculated using the depth integrated version of Darcy's law: Q = K b dh/dx (units of Q = m2/s)
- Or if we assume we know the width of the aquifer too: Q = K A dh/dx (units of Q = m3/s)



Hiscock and Bense (2014)

Mapping groundwater flow

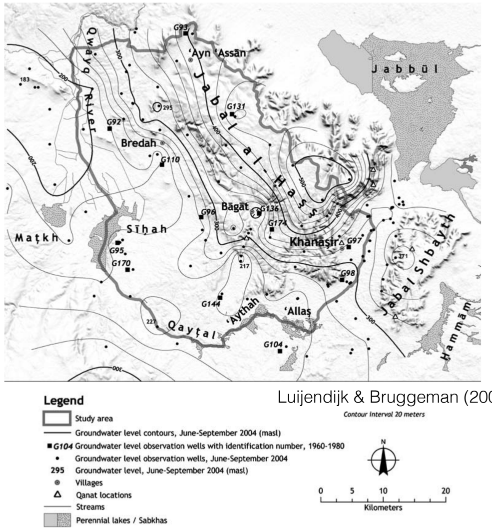
- One can also map vertical groundwater flow directions in single locations by measuring hydraulic head at different depths
- This can provide important information on the locations of recharge and discharge areas and recharge and discharge rates



Hiscock and Bense (2014)

Mapping groundwater flow

- Map of hydraulic head in a shallow aquifer in semi-arid syria
- Try to locate groundwater flow directions, recharge and discharge areas
- Note that groundwater flow always follows the steepest hydraulic gradient -> perpendicular to the lines of equal hydraulic head



Luijendijk & Bruggeman (2008) HGJ

Summary

- Fluid flow in the subsurface is the result of gravitational force and fluid pressure
- Energy potential of a fluid: $$E_t = gz + \frac{p}{\rho}$$
- Hydraulic head (potential per unit weight): $$h = z + \frac{p}{\rho g}$$
- Topography-driven flow: the result of recharge and groundwater discharge to rivers, lakes, oceans or direct evapotranspiration
- Relief segments flow into local and regional flow systems
- Theoretical depth of topography-driven flow = equal to average length scale of watersheds (~10 km)
- However, flow decreases with depth due to layered permeability structure, permeability anisotropy and permeability decrease with depth.
- Hydraulic head measured in boreholes can be used to map flow directions, recharge and discharge areas, and to quantify groundwater flow rates in combination with depth-integrated versions of Darcy's law

Next week (18 Dec):

- Examples of basin-scale flow systems
- More driving forces: Convection, flow driven by density gradients
- Reading material: Garven (1995)