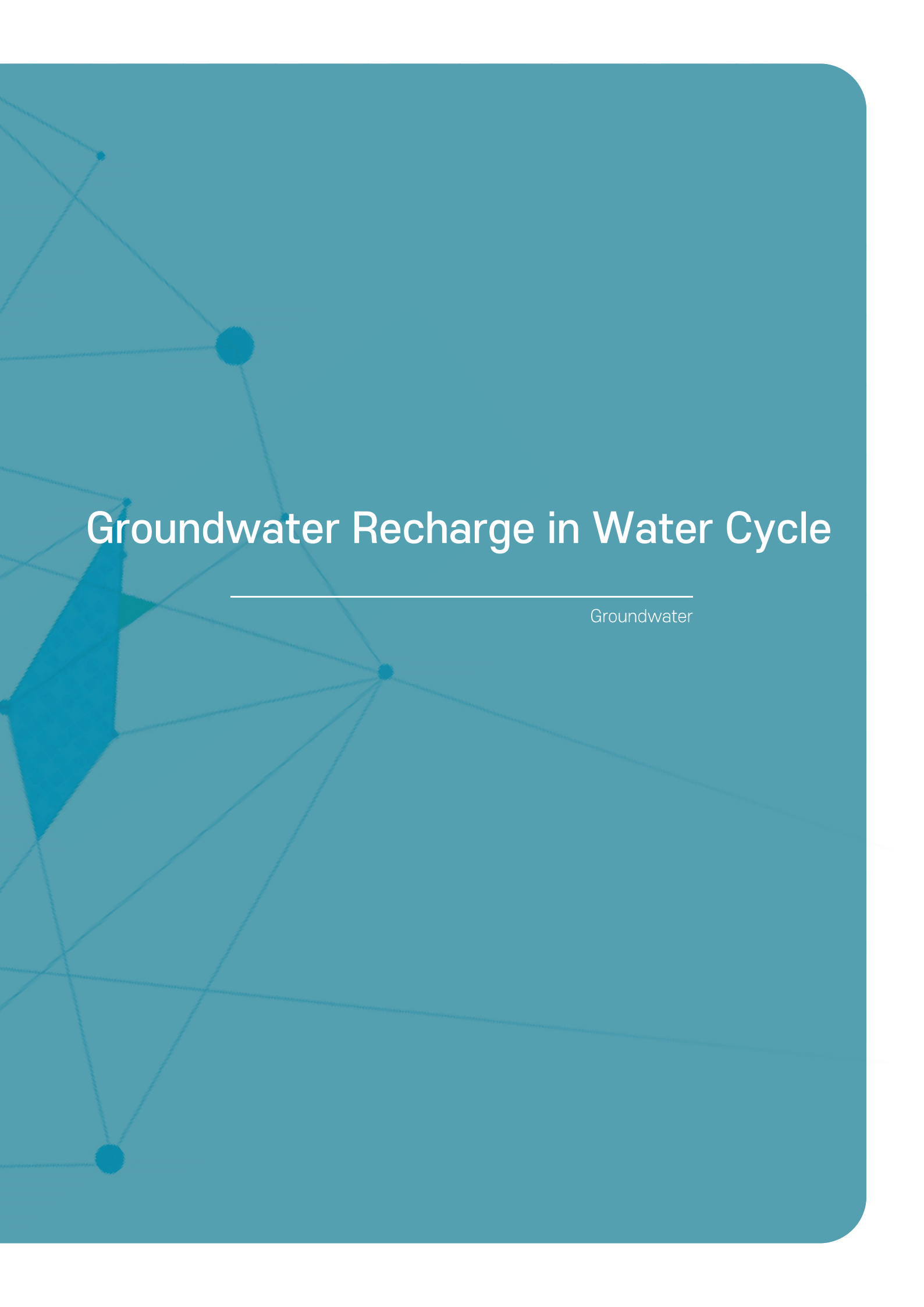
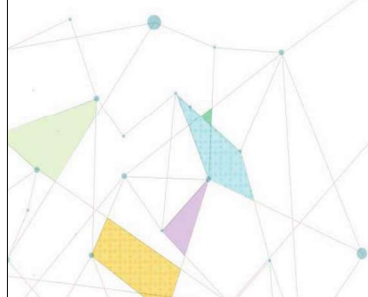


The background is a solid teal color. Overlaid on this are several thin white lines that intersect at various points, creating a network-like pattern. Some of these intersection points are marked with small white dots. On the left side, there is a larger, more complex geometric shape composed of several triangles, some of which are filled with a darker teal color, while others are white with teal outlines.

Groundwater Recharge in Water Cycle

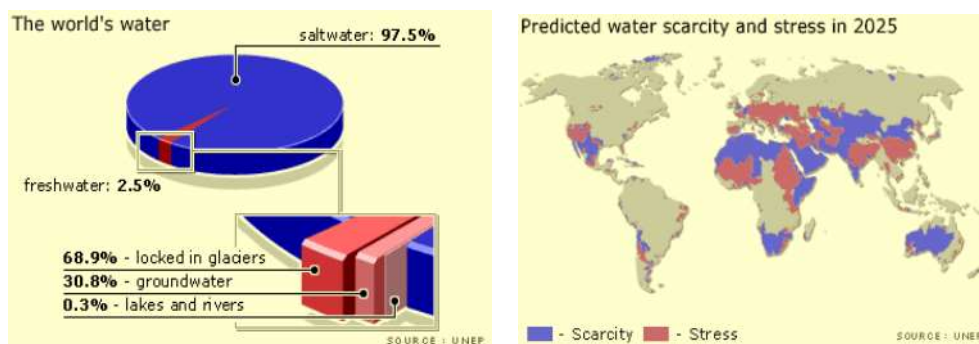
Groundwater

Groundwater Recharge in Water Cycle



Backgrounds

The world's water



- The amount of water on Earth is fixed. Less than 0.01% of the planet's 1.4 billion cubic kilometres is easily accessible freshwater in lakes and rivers.
- Africa and Asia are already hard-hit by water stress. Increasing populations will create more pressure in the coming decades.

3

Water Distribution on Earth

Table 1. Estimated global water supply (from Nace, 1967).

[km³, cubic kilometers]

Water storage	Volume, in thousands of km ³	Percentage of total water
Ocean water	1,320,000	97.1
Atmosphere	13	0.001
Water in land areas	37,800	2.8
Freshwater lakes	125	0.009
Saline lakes and inland seas	104	0.008
Rivers	1.25	0.0001
Icecaps and glaciers	29,200	2.14
Soil root zone	67	0.005
Ground water (to depth of 4,000 meters)	8,350	0.61

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets: Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308, 90 p.

Table 11.1 Estimate of global water distribution (source: Shiklomanov 1993)

Water source	Water volume (10 ³ km ³)	Percent of freshwater	Percent of total water
Oceans, seas, and bays	1,338,000	—	96.5
Ice caps, glaciers, and permanent snow	24,064	68.7	1.74
Ground water	23,400	—	1.7
Fresh groundwater	10,530	30.1	—
Saline/brackish groundwater	12,870	—	—
Soil moisture	16.5	0.05	0.001
Ground ice and permafrost	300	0.86	0.022
Lakes	176.4	—	0.013
Fresh	91.0	0.26	—
Saline	85.4	—	—
Atmosphere	12.9	0.04	0.001
Swamp water	11.47	0.03	0.0008
Rivers	2.12	0.006	0.0002
Biological water	1.12	0.003	0.0001
Total water	1,385,984	—	100
Total freshwater	35,029	100	2.53

A. Fares (ed.), Emerging Issues in Groundwater Resources, Advances in Water Security, DOI 10.1007/978-3-319-32008-3_11

Modern groundwater (<50 yrs old)

- Less than 6% of the groundwater in the uppermost portion of earth's landmass is modern (<50 yrs)
- The total gw volume in the upper 2 km of continental crust is approx. 22.6 M km³
- 0.1-5.0 M km³ is less than 50 yrs old

nature
geoscience

ARTICLES

PUBLISHED ONLINE: 16 NOVEMBER 2015 | DOI: 10.1038/NPGEO2590

The global volume and distribution of modern groundwater

Tom Gleeson^{1,2*}, Kevin M. Befus³, Scott Jasechko⁴, Elco Luijendijk^{2,5} and M. Bayani Cardenas³

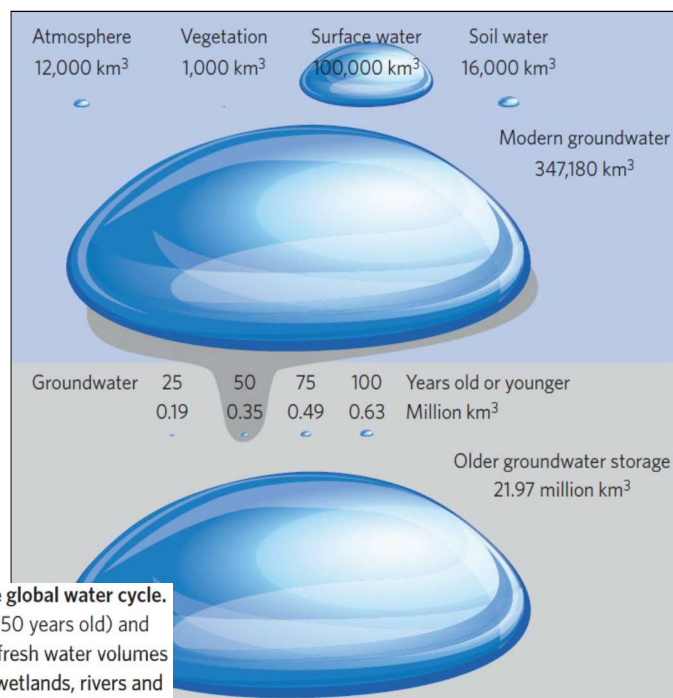
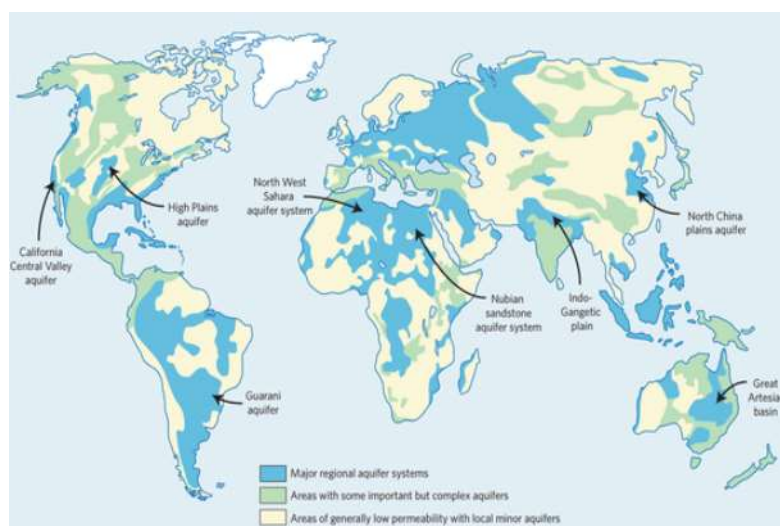


Figure 5 | The different volumes of water stored in the global water cycle. Global volumes of young (<100 years old), modern (<50 years old) and total groundwater to 2 km depth compared with other fresh water volumes stored in the atmosphere³³, in surface waters (that is, wetlands, rivers and lakes)³³, within plants or in soils³³.

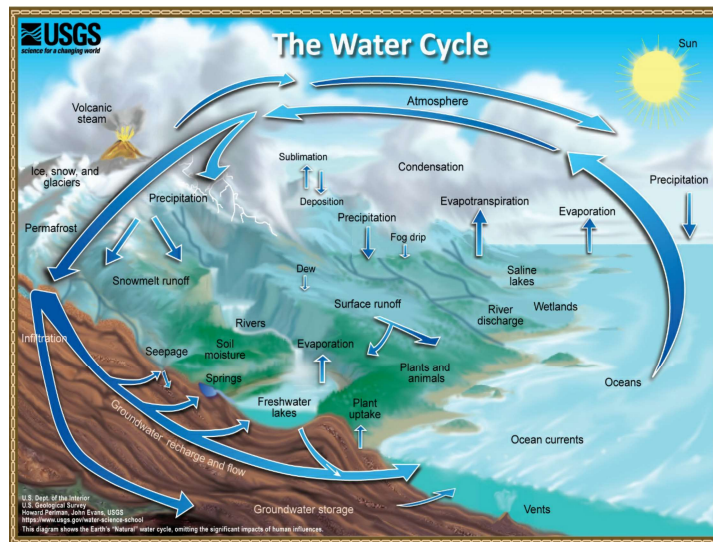
Global Aquifer System



A. Fares (ed.), Emerging Issues in Groundwater Resources, Advances in Water Security, DOI 10.1007/978-3-319-32008-3_11

Water Cycle (hydrologic Cycle)

- (Definition) cycle that involves the continuous circulation of water in the Earth-atmosphere system
- Endless, global scale, process linking water in atmosphere, on continents, and in oceans

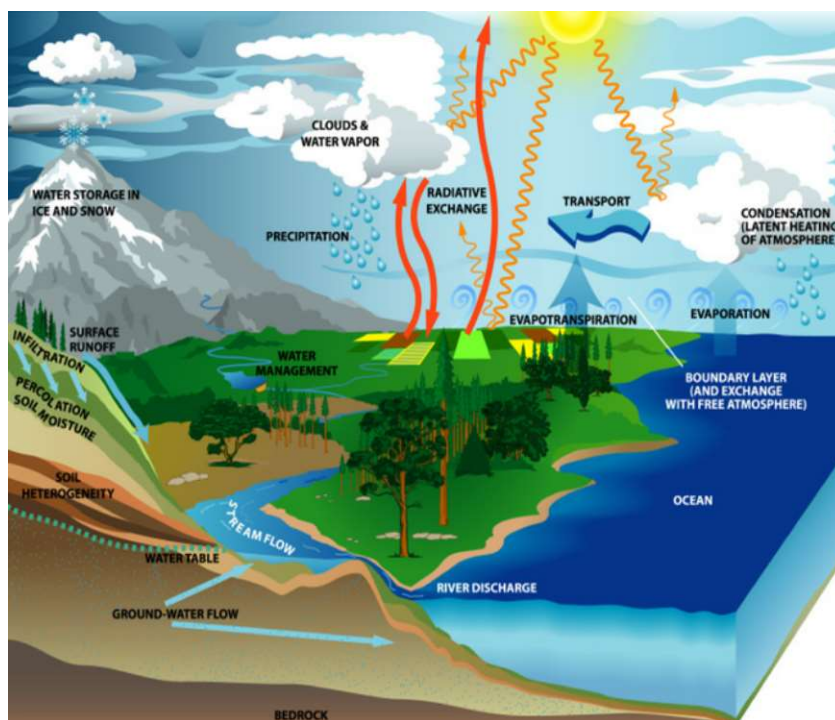


Source : USGS

Processes in Hydrologic Cycle

Processes in the cycle of water

- Precipitation
 - Rain
 - Snow
- Runoff
 - Surface & Subsurface
- Evaporation
 - Evapotranspiration
- Recharge
 - Infiltration
 - percolation
- Stream flow
 - Baseflow
- Storage
 - Glaciers
 - aquifers
 - Lakes, etc

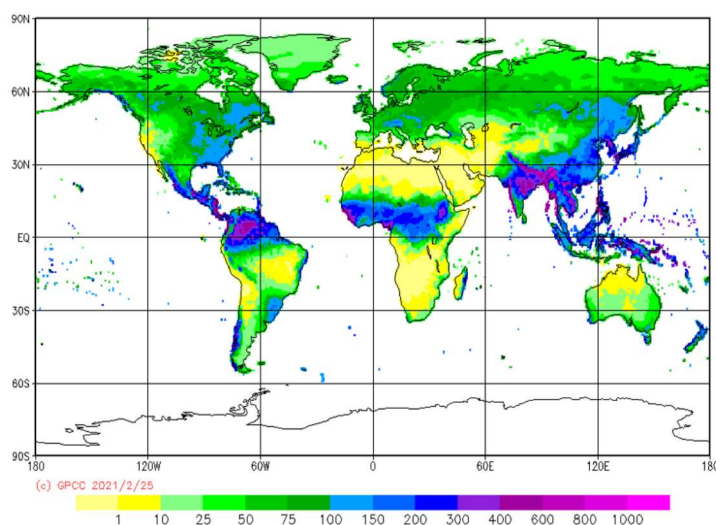


9

Precipitation [P]

- Water in atmosphere returning to Earth as liquid or solid (rain, snow, sleet)
- Most precipitation result of evaporation over oceans
- Extreme variability around world

GPCC Precipitation Climatology Version 2020 0.5 degree precipitation for July in mm/month



Source: GPCC (Global Precipitation Climatology Centre) version 2020, 0.5 degree precipitation for July in mm/month

Runoff / Evaporation / Evapotranspiration / Water storage (ΔS) / Water budget

- Surface Runoff:
 - Water flowing across land surface as streams, rivers, and drains after rain storm or melting snow
- Subsurface (Groundwater) Runoff [Q_{gw}]:
 - Water flowing beneath land surface through sediments and rock
- Evaporation
 - Process converting water to water vapor
- Evapotranspiration [ET]
 - Evaporation from soil surface and transpiration from plants
- Water Storage (ΔS)
 - Water collected in naturally occurring or manmade bodies along hydrologic cycle
 - Storage bodies include: lakes, reservoirs, wetlands, aquifer, ice caps
- Water Budget
 - Volume of water transferred in hydrologic cycle
 - Water budget developed for a hydrologic system e.g., watershed or where water stored e.g., surface or groundwater
 - Calculation involves a direct accounting for the inflows and outflows of water

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Estimating Evapotranspiration

- Lysimeter – Container holding soil and plants

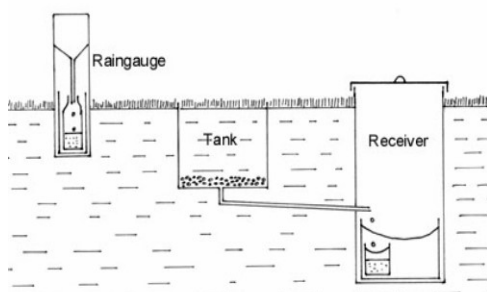


Fig 2. Lysimeter apparatus for measuring evapotranspiration

From <http://www.llansadwrn-wx.co.uk>

$$E_T = S_i + P + I - S_f - D$$

S_i = Volume of initial soil moisture

S_f = Volume of final soil moisture

P = Precipitation

I = Irrigation water added

D = Excess moisture drained from the soil



Estimating precipitation

- Precipitation
 - Water in atmosphere returning to Earth as liquid or solid (rain, snow, sleet)
 - Most precipitation result of evaporation over oceans
 - Extreme variability around world
- Effective depth of precipitation = Effective Uniform Depth(EUD)
- "average" rainfall value over watershed
- Estimating EUD
 - Generally uniform rain density = arithmetic average
 - Non uniform rain density
 - 1. Thiessen polygon method: based on a weighting factor for each rain gage
 - 2. Isohyetal method (lines of equal rainfall): based on relative size of each isohyets area

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Estimating precipitation

Arithmetic Mean Method

- Simplest method for determining areal average

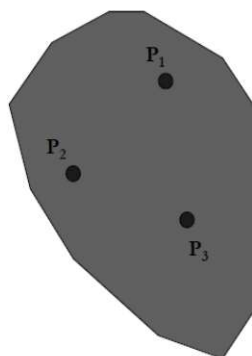
$$P_1 = 10 \text{ mm}$$

$$P_2 = 20 \text{ mm}$$

$$P_3 = 30 \text{ mm}$$

$$\bar{P} = \frac{1}{N} \sum_{i=1}^N P_i$$

$$\bar{P} = \frac{10+20+30}{3} = 20 \text{ mm}$$



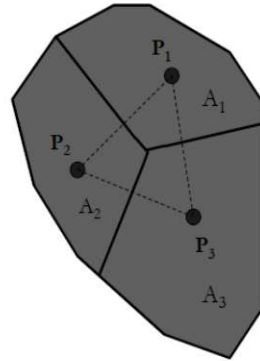
- Gages must be uniformly distributed
- Gage measurements should not vary greatly about the mean

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Estimating precipitation

Thiessen polygon method

- Steps
 1. Draw lines joining adjacent gages
 2. Draw perpendicular bisectors to the lines created in step 1
 3. Extend the lines created in step 2 in both directions to form representative areas for gages
 4. Compute representative area for each gage
 5. Compute the areal average using the following formula



$$\bar{P} = \frac{1}{A} \sum_{i=1}^N A_i P_i$$

$$\bar{P} = \frac{12 \times 10 + 15 \times 20 + 20 \times 30}{47} = 20.7 \text{ mm}$$

$$P_1 = 10 \text{ mm}, A_1 = 12 \text{ Km}^2$$

$$P_2 = 20 \text{ mm}, A_2 = 15 \text{ Km}^2$$

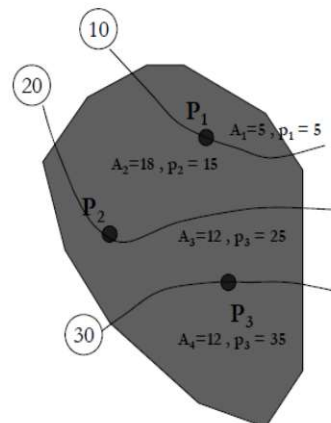
$$P_3 = 30 \text{ mm}, A_3 = 20 \text{ km}^2$$

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Estimating precipitation

Isohyetal method

- Steps
 - Construct isohyets (rainfall contours)
 - Compute area between each pair of adjacent isohyets (A_i)
 - Compute average precipitation for each pair of adjacent isohyets (p_i)
 - Compute areal average using the following formula



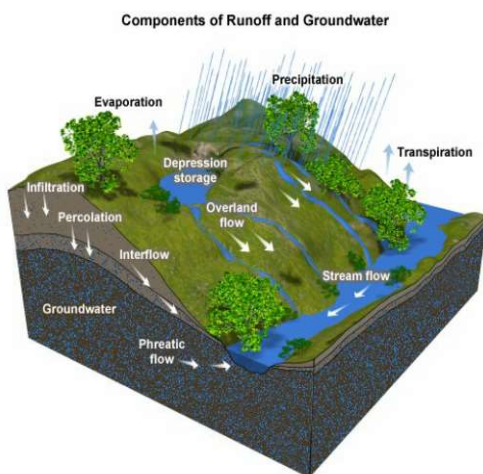
$$\bar{P} = \frac{1}{A} \sum_{i=1}^N A_i P_i$$

$$\bar{P} = \frac{5 \times 5 + 18 \times 15 + 12 \times 25 + 12 \times 35}{47} = 21.6 \text{ mm}$$

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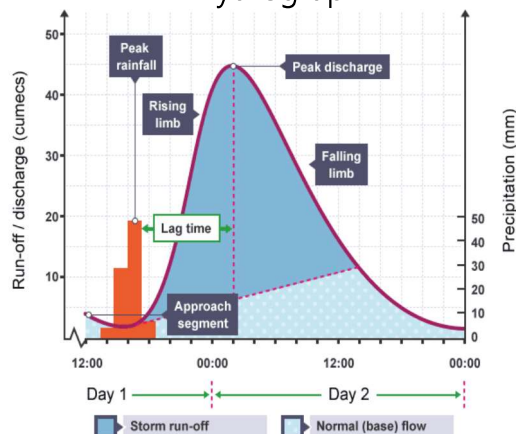
Estimating Stream flow (= overland flow + base flow)

- Events during precipitation
- 1. Interception: 8-35%
- 2. Stem flow
- 3. Infiltration (-> recharge)
- 4. Depression storage (puddle)
- 5. Overland flow (Runoff)



<https://kejian1.cmatc.cn> 17
©The COMET Program

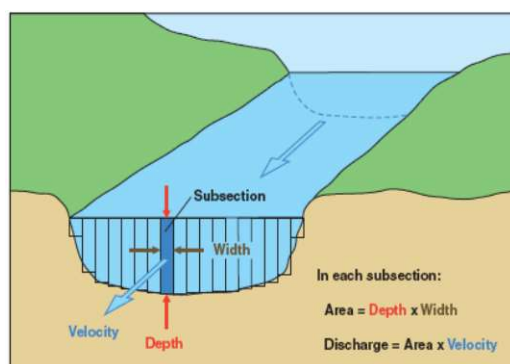
Hydrograph



<https://geographyaslevelaqa.wordpress.com>

Measurement of Stream flow (= overland flow + base flow)

- Stream flow (Q) = avg. velocity (V) x cross sectional area (A)

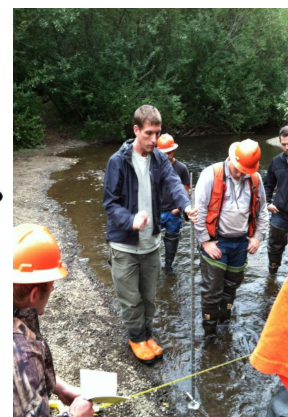


Current-meter discharge measurements are made by determining the discharge in each subsection of a channel cross section and summing the subsection discharges to obtain a total discharge.

<https://water.usgs.gov>



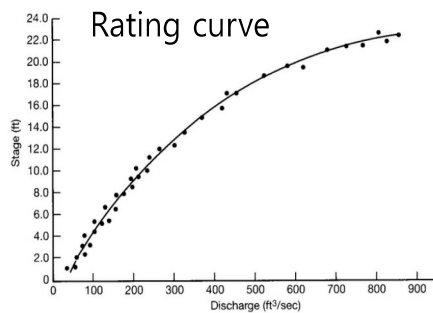
Propeller current meter



Measurement of Stream flow

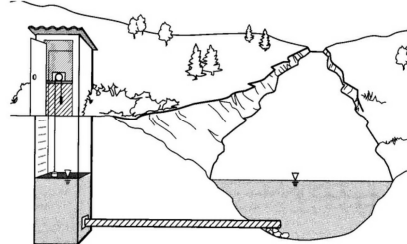
How to measure this in real time

- Rating curve is a graph of discharge versus stream water level (stage) for a given point on a stream
- Rating curve enables us to convert the water level to discharge rate in real time



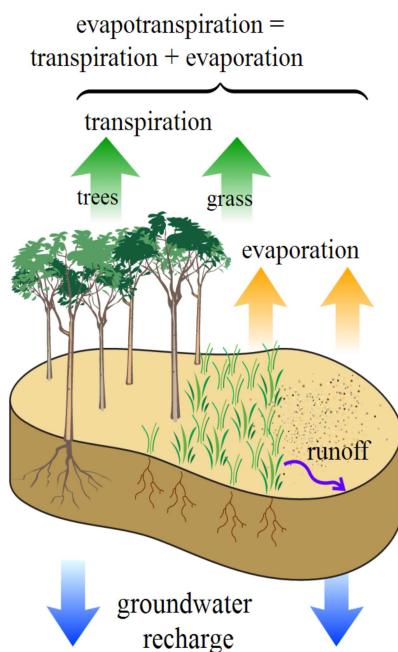
<https://www.utdallas.edu>

Stream water level monitoring station



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Estimating Groundwater Recharge



Groundwater Recharge

||

Precipitation

|

Streamflow

|

Evapotranspiration & Evaporation

*Stream flow = runoff + base flow

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Water Budget Equation (Hydrologic Eqn.)

For a given control volume (e.g., watershed) in a time interval Δt

$$\text{Input} - \text{Output} = \Delta \text{Storage} \quad (\text{Continuity equation})$$

IN (Precipitation, Surface water inflow, Groundwater inflow, Imported water)

OUT (Evapotranspiration, Reservoir evaporation, Surface water outflow, Groundwater outflow, Exported water)

Δ (Storage change in a watershed (groundwater, surface water))

$$P + Q_{in} = ET + Q_{out} + \Delta S$$

Written for a control volume such as watershed or catchment

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets: Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308, 90 p.

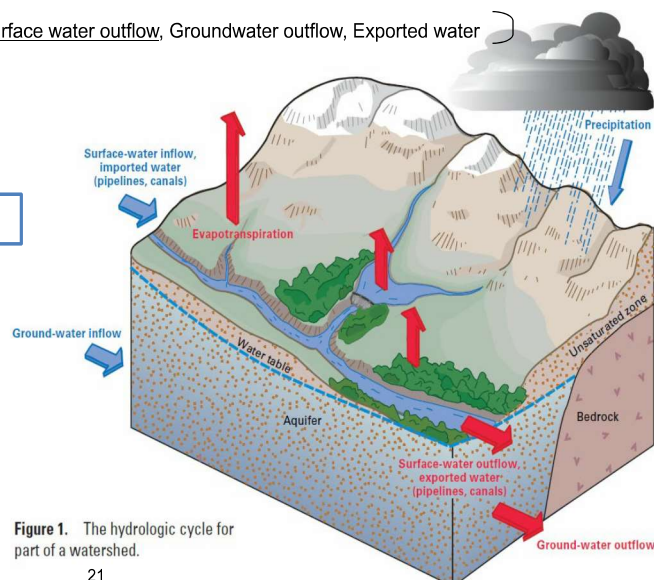


Figure 1. The hydrologic cycle for part of a watershed.

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Examples: Water budget analysis

Write a hydrologic budget equation for the scenarios below.

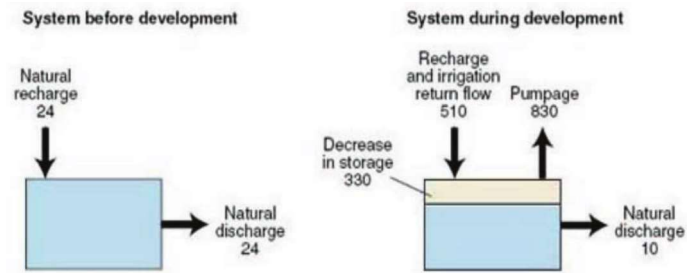
Calculate the change in storage.

Write whether the hydrologic budget is at a loss, a gain, or at steady state.

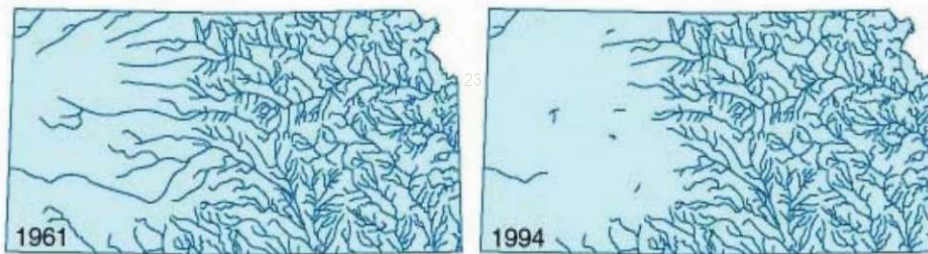
- a. Groundwater pumping [Q_{pump}] = 10 mm/yr.
- b. Surface water Runoff [Q_{runoff}] = 96 mm/yr.
- c. Evapotranspiration [ET] = 550 mm/yr.
- d. Precipitation [P] = 600 mm/yr.
- e. Groundwater inflow [$Q_{\text{in, gw}}$] = 80 mm/yr.



Examples: Water budget analysis (Southern High Plain Aquifer, USA)



Write hydrologic budget equations for the aquifer system before/after development.



Source: V.M. Ponce, 2007; USGS; Alley et al., 1999

Sustainability in the context of water cycle

Safe Yield

- Historical concerns on quantity of water that could be pumped from watershed
- Concept of 'Safe Yield'
 - "The limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve" [Lee, 1915]
- Definition expand through the years
 - Meinzer (1923): economic aspect
 - Conkling (1946): conditions for safe yield
 - Banks (1953): protection water rights
- 'Safe Yield' is not a unique or constant value
 - Idea good but implementation difficult

Moving from Safe Yield to Sustainability

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Sustainability

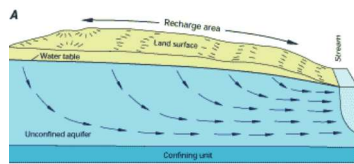
- Limit groundwater use to levels that can be sustained over longer time
 - ... development and use ... that can be maintained for indefinite time without unacceptable environmental, social, economic consequences.
- 'Sustainability' is also ambiguous, difficult to define
- Broader than safe yield concepts
 - Considers role of groundwater in streams, rivers, wetlands

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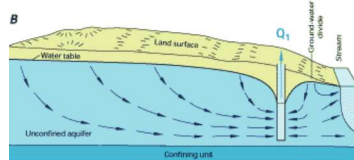
Groundwater-surface water connections

- Concept of safe yield obsolete because groundwater and surface water connected
- groundwater depletion causes depletion of surface water

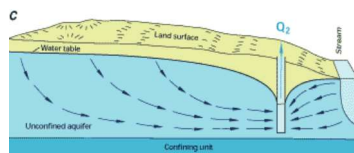
A. Natural system with groundwater discharge to stream (Natural recharge = natural discharge)



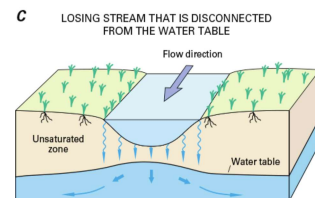
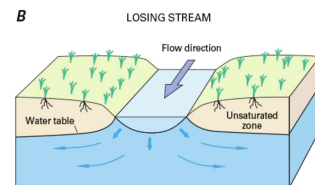
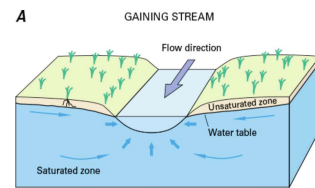
B. Moderate pumping causes reduced inflow to stream (pumping=captured recharge + captured discharge)



C. Heavy pumping induces flow from stream (pumping = CR+CD + captured storage)



Source: USGS

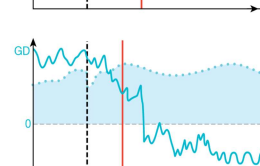
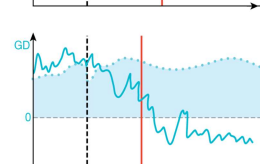
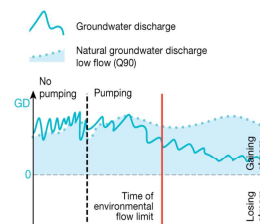
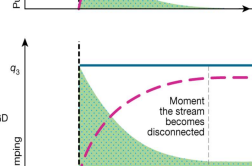
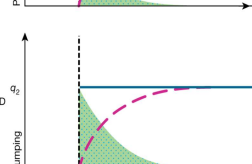
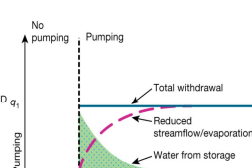
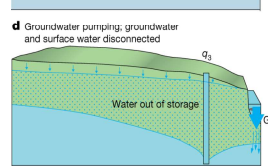
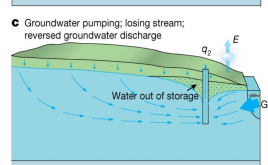
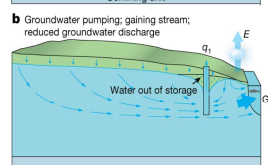
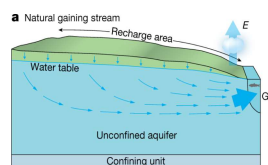
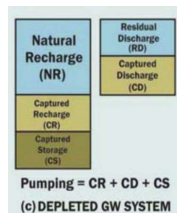
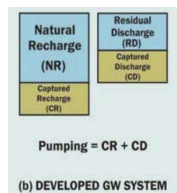
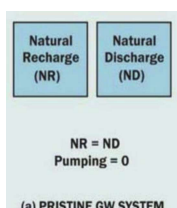


Source : Winter TC, Harvey JW, Franke OL, Alley WM (1998) Ground water and surface water: a single resource. U.S. Geological Survey Circular 1139:79

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Environmental flow limits to groundwater pumping

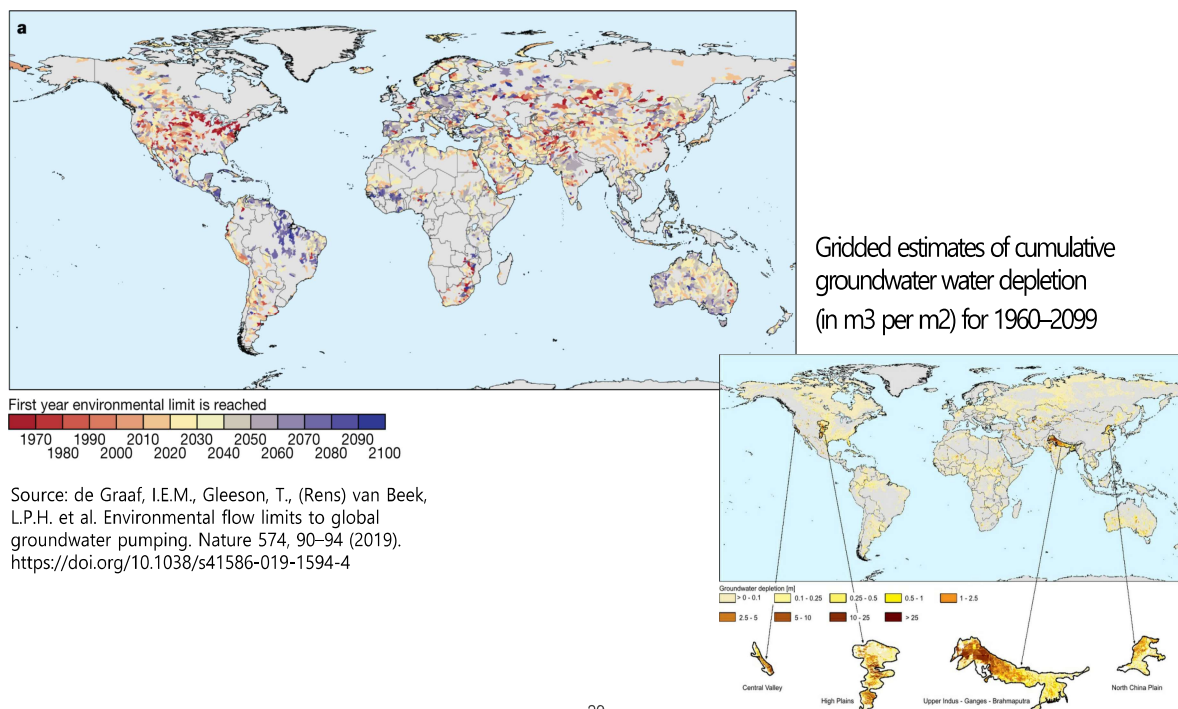
- Declines in groundwater level resulting from pumping decrease streamflow, affecting aquatic ecosystems.
- Pumping when environmentally critical streamflows will no longer be sustained.



Source: de Graaf, I.E.M., Gleeson, T., (Rens) van Beek, L.P.H. et al. Environmental flow limits to global groundwater pumping. Nature 574, 90–94 (2019). <https://doi.org/10.1038/s41586-019-1594-4>

Groundwater crisis caused by unsustainable pumping

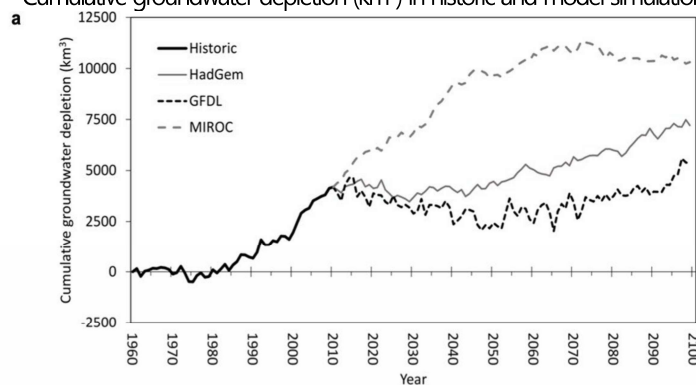
The first time at which environmental flow limits have been, or will be, reached



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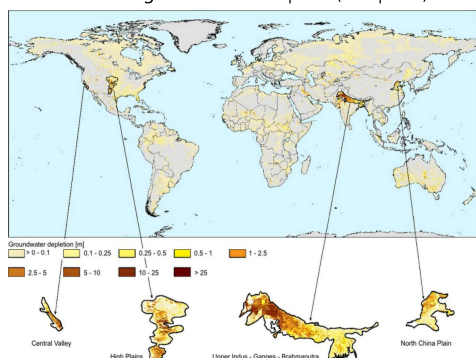
Groundwater crisis caused by unsustainable pumping

Cumulative groundwater depletion (km^3) in historic and model simulation



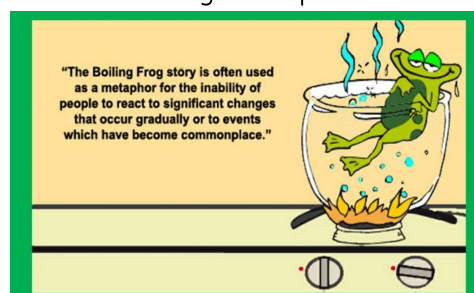
Source: de Graaf, I.E.M., Gleeson, T., (Rens) van Beek, L.P.H. et al. Environmental flow limits to global groundwater pumping. Nature 574, 90–94 (2019). <https://doi.org/10.1038/s41586-019-1594-4>

Gridded estimates of cumulative groundwater water depletion (in m^3 per m^2) for 1960–2099



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"the frog in the pot"



Source: <https://www.linkedin.com/pulse/frog-pot-how-correlates-stress-management-stefan-trappitsch>

Thank you very much

