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Hydrology and Water Resources

Groundwater resources

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swarm

Co-funded by the Erasmus+ Programme of the European Union

Water Resources Modelling: Part2 - Reservoir operation

Groundwater Management

Teresa Melo
Instituto Superior Técnico – Universidade de Lisboa

7th – 11th February 2022

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University of Nis

www.swarm.ni.ac.rs

Strengthening of master curricula in water resources management for the Western Balkans HEIs and stakeholders

Project number: 597888-EPP-1-2018-1-RS-EPPKA2-CBHE-JP

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Hydrogeology (definition): occurrence, distribution, movement and geological interaction of water in the Earth's crust

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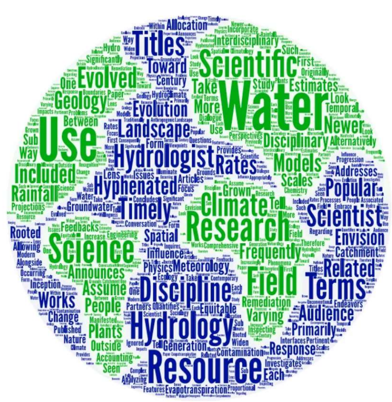
Hydro(geo)logy is a truly interdisciplinary subject

Involving

- Earth sciences
- Hydrology
- Physics
- Engineering
- Agriculture
- Chemistry
- Biology
- Mathematics
- Statistics
- Climatology

- Ecology
- Computer science
- Sociology
- Economics
- Law
- Policy
- History
- Art
- Music
- Arquitecture



DOI: (10.1002/2016WR019835)

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One of hydrology's first disciplinary partners is geology, which manifested as a sub-discipline: hydrogeology.

Involving

- Earth sciences
- **Hydrology**
- Physics
- Engineering
- Agriculture
- Chemistry
- Biology
- Mathematics
- Statistics
- Climatology

- Ecology
- Computer science
- Sociology
- Economics
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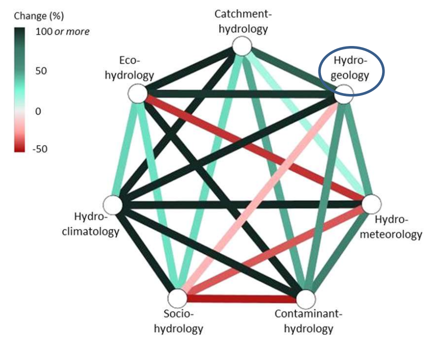
- Policy
- History
- Art
- Music
- Arquitecture



DOI: (10.1002/2016WR019835)

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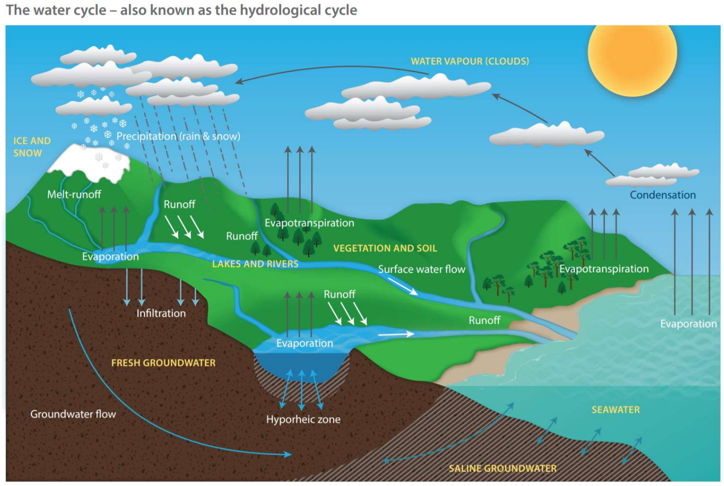
Groundwater in the water cycle

A useful start in promoting a holistic approach to linking ground and surface waters is to adopt **the hydrological cycle** as a basic framework.

The hydrological cycle, as depicted in this Figure, can be thought of as the continuous circulation of water near the surface of the Earth from the ocean to the atmosphere and then via precipitation, surface runoff and groundwater flow back to the ocean.

The water cycle – also known as the hydrological cycle



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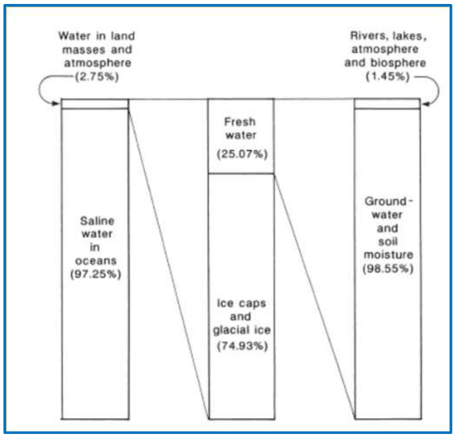
Groundwater resources



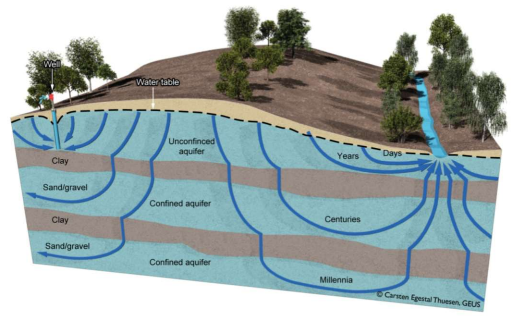


Illustration of groundwater flow and retention times as a function of distance between recharge and discharge area and depth of aquifer.

- About 22% of the world's freshwater reserves (8'300'000 km^3) is groundwater;
- The inflow and outflow of these reserves is about 5000 km^3/year.
- The average residence time of water in underground reservoirs is 1700 years.

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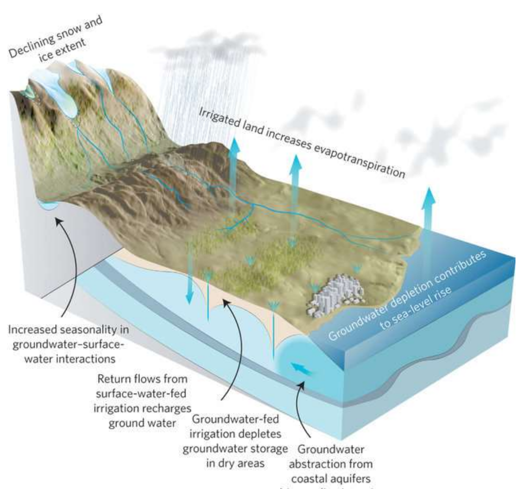
Conceptual representation of key interactions between ground water and climate.



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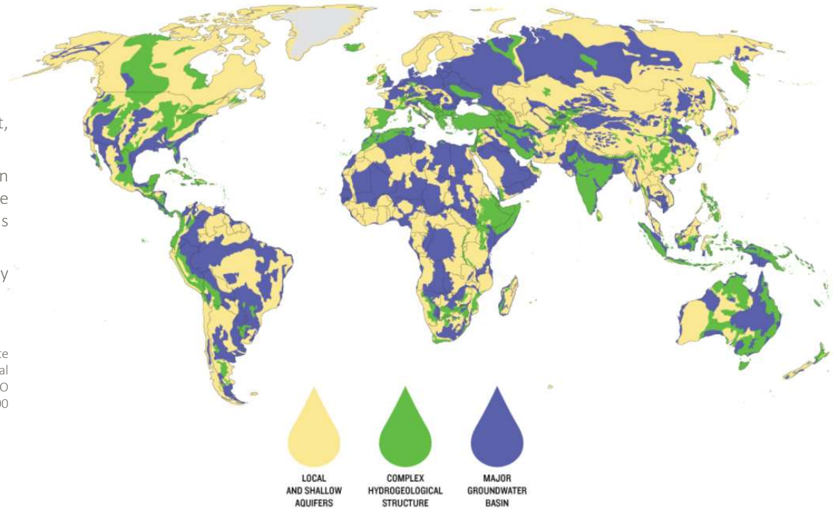
Global groundwater resources

Major basins (purple) hold abundant, relatively easily extracted groundwater.

More complex basins (green) might contain multiple aquifers separated by impermeable rock or have layers of saltwater as well as fresh.

Local and shallow aquifers provide only limited quantities of water.

Source: Map created by Peder Engstrom and Kate Brauman of the Institute on the Environment's Global Landscape Initiative. Data provided by BGR & UNESCO (2008): Groundwater Resources of the World 1 : 25 000 000. Hannover, Paris.



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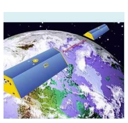
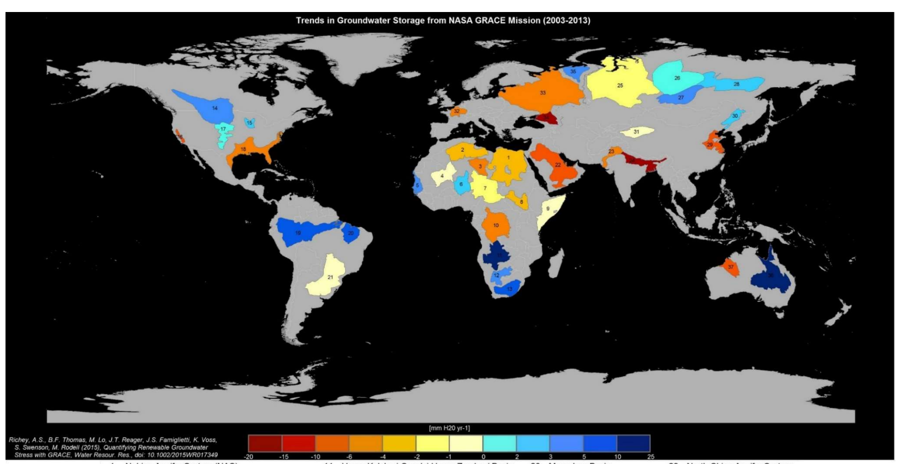
Quantifying renewable groundwater



More than half of Earth's 37 largest aquifers are being depleted, according to gravitational data from Grace satellite system.



1 Nubian Aquifer System (NAS)
2 Northwestern Sahara Aquifer System (NWSAS)
3 Murzuk-Djado Basin
4 Taoudeni-Tanezrouft Basin
5 Senegalo-Mauritanian Basin
6 Iullemeden-Irhazer Aquifer System
7 Lake Chad Basin
8 Sudd Basin (Umm Ruwaba Aquifer)
9 Ogaden-Juba Basin
10 Congo Basin
11 Upper Kalahari-Cuvelai-Upper Zambezi Basin
12 Lower Kalahari-Stampriet Basin
13 Karoo Basin
14 Northern Great Plains Aquifer
15 Cambro-Ordovician Aquifer System
16 Californian Central Valley Aquifer System
17 Ogallala Aquifer (High Plains)
18 Atlantic and Gulf Coastal Plains Aquifer
19 Amazon Basin
20 Maranhao Basin
21 Guarani Aquifer System
22 Arabian Aquifer System
23 Indus Basin
24 Ganges-Brahmaputra Basin
25 West Siberian Basin
26 Tunguss Basin
27 Angara-Lena Basin
28 Yakut Basin
29 North China Aquifer System
30 Song-Liao Basin
31 Tarim Basin
32 Paris Basin
33 Russian Platform Basins
34 North Caucasus Basin
35 Pechora Basin
36 Great Artesian Basin
37 Canning Basin

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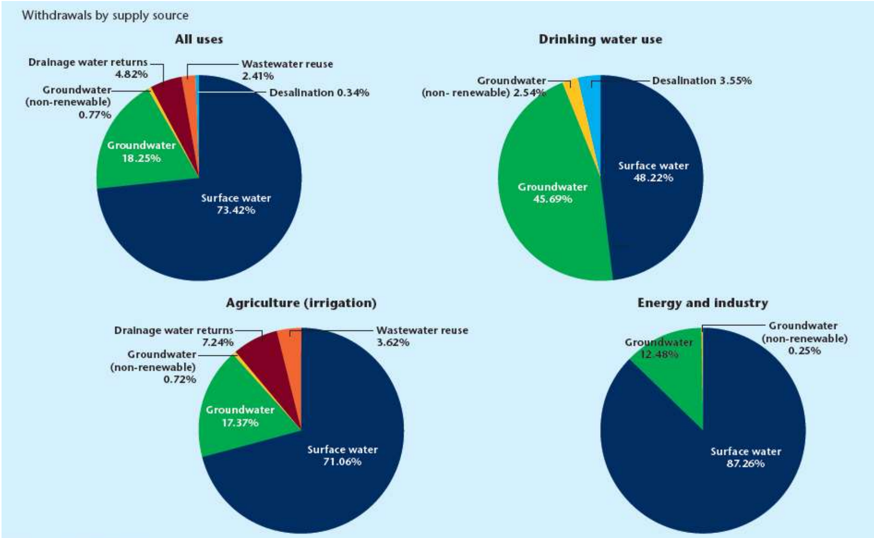
Water withdrawals by supply source



Source: FAO-AQUASTAT.

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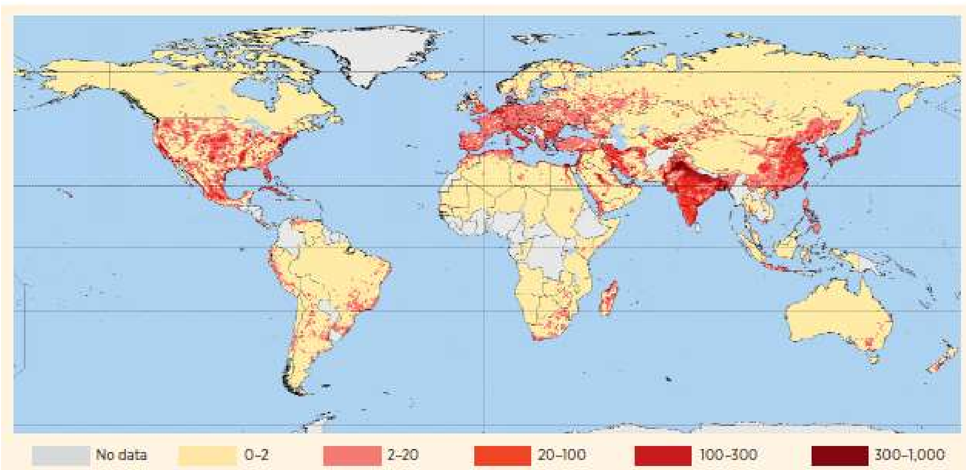
Intensity of groundwater abstraction in 2000 (mm/year)



Source: Wada et al. (2010, p. 2, © American Geophysical Union, reproduced by permission).

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Key estimates on global groundwater abstraction

Key estimates on global groundwater abstraction (reference year 2010)

Continent	Groundwater abstraction[1]					Compared to total water abstraction	
	Irrigation	Domestic	Industrial	Total		Total water abstraction[2]	Share of groundwater
	km³/year	km³/year	km³/year	km³/year	%	km³/year	%
North America	99	26	18	143	15	524	27
Central America and the Caribbean	5	7	2	14	1	149	9
South America	12	8	6	26	3	182	14
Europe (including Russian Federation)	23	37	16	76	8	497	15
Africa	27	15	2	44	4	196	23
Asia	497	116	63	676	68	2257	30
Oceania	4	2	1	7	1	26	25
World	666	212	108	986	100	3831	26

1 Estimated on the basis of IGRAC (2010), AQUASTAT (2011), EUROSTAT (2011), Margat (2008) and Siebert et al. (2010).
2 Average of the 1995 and 2025 'business as usual scenario' estimates presented by Alcamo et al. (2003).

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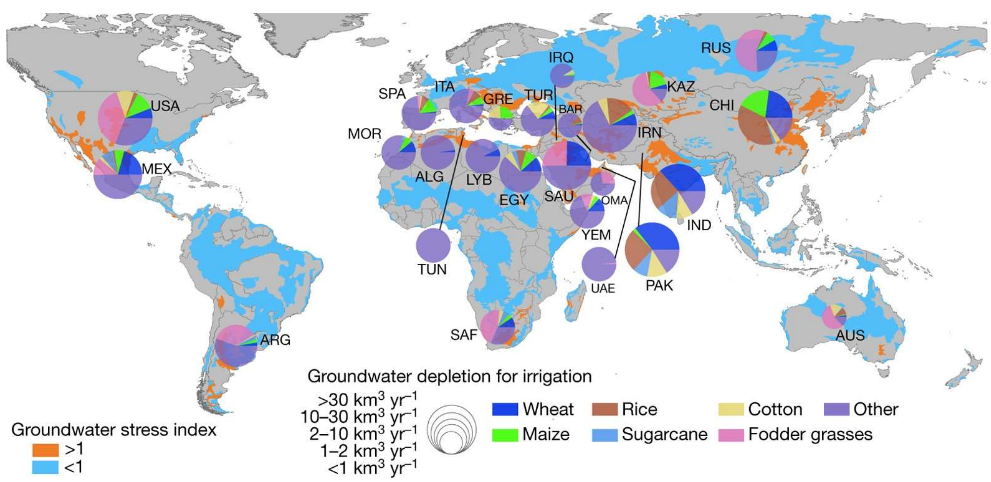
Global groundwater for irrigation



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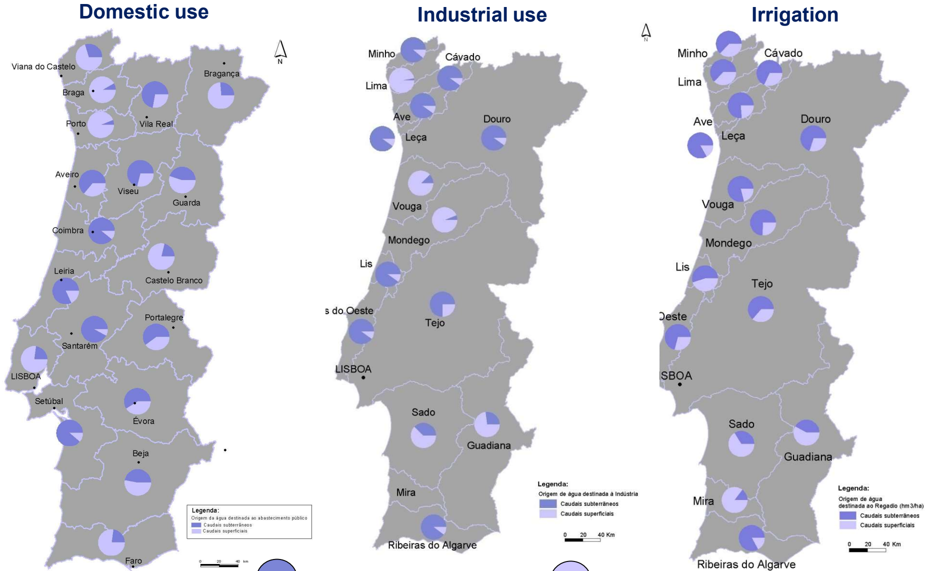
Water use in Portugal by source

Domestic use | **Industrial use** | **Irrigation**



Groundwater   Surface water

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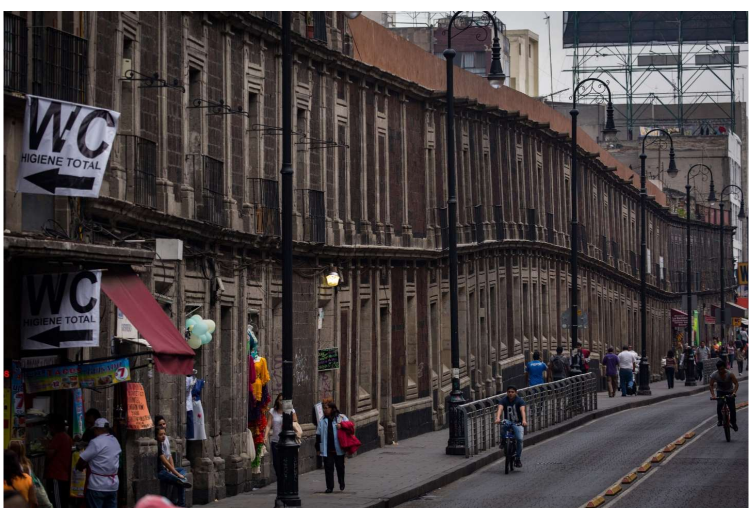
Subsidence due to excessive groundwater withdrawals.



México city

São Joaquin Valley, CA

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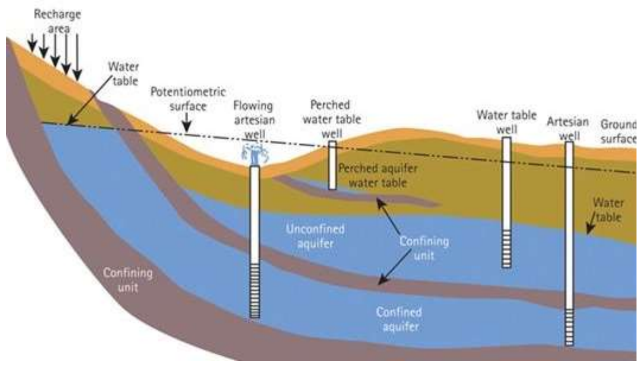
Types of aquifers

Aquifer – A porous and permeable geologic unit with the ability to store and yield water.
Classification according to their confinement:

Unconfined aquifer – aquifer top at atmospheric pressure;

Confined aquifer - overlain and underlain by impervious units; pressure at the top is greater than atmospheric pressure.



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Types of geologic units: according to water storage and yield

- **Aquifer:** a porous and permeable geologic unit with the **ability to store and yield water**. Unconsolidated deposits of sand and gravel (alluvial deposits) are examples of an aquifer.
- **Aquitard**: a leaky confining bed that **transmits water at a very slow rate** to or from an adjacent aquifer; Sandy clay is a perfect example of an aquitard as the clay particles block the voids present in the sand and make it partly permeable.
- **Aquiclude:** a body of relatively impermeable rock that is **capable of absorbing water slowly but does not transmit it rapidly enough** to supply a well or spring; it contains a large amount of water in it, but it does not permit water through it and also does not yield water. It is because of its high porosity. Clay is an example of aquiclude.
- **Aquifuge:** an impermeable geological formation which is **neither porous nor permeable**, which means it **cannot store water and cannot permit water through**. Compact rock is an example of aquifuge.

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Types of aquifers: Classification according to porosity

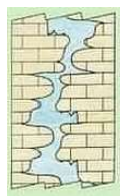
Intergranular – sedimentary rocks or sandy soils with uniformly distributed voids (pores) where water is stored and moves.

Considered as one of the most important types of aquifers, as it stores larger volumes of water that are more easily exploitable.

Fractured – igneous, metamorphic rocks with fractures which allow the water movement.

The amount of water in these aquifers is directly related to the number of fractures. The flow of water only occurs through fractures. As a rule, they are not very productive, but they can be important locally.

Karst – carbonate rocks with large fractures or caves resulting from the dissolution of soluble rocks (e.g. calcium carbonate) in water



These aquifers can give rise to large cavities (algares). Karst fissures can have kilometers forming the so-called underground rivers.

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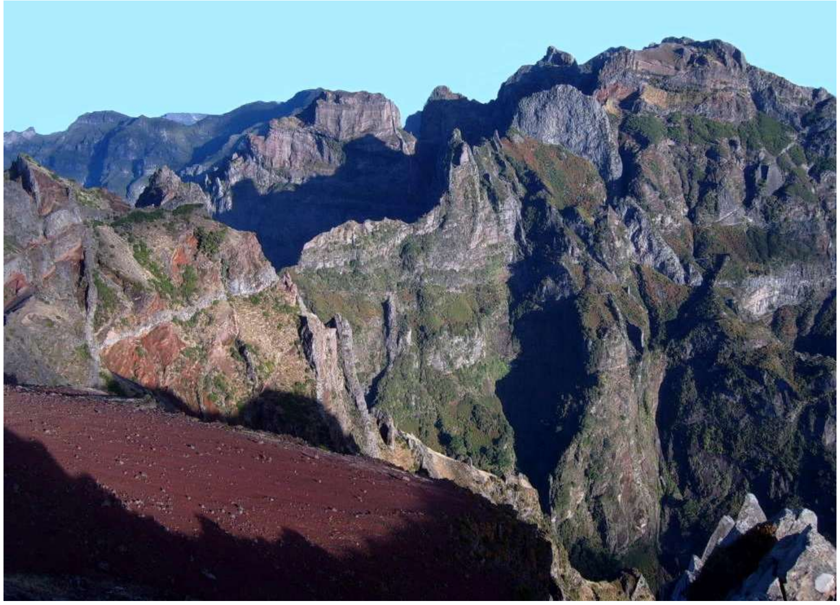
Geology

- **Alluvial deposits** offer the best conditions for aquifers with intergranular porosity; best performing aquifers occur in these deposits.
- **Volcanic rock (e.g. basalts)** may offer good conditions for storing water in interstitial spaces, between lava beds, tubes or cracks.
- **Limestone** (calcário) offer conditions for karst aquifers
- **Sandstone** (arenito) offer limited conditions for storing water, as their porosity is decreased by the cement; some cracks may store small amounts of water.
- **Igneous (plutonic) and metamorphic rocks** serve as poor aquifers as these rocks are relatively impermeable; some cracks may store small amounts of water.
- **Clay** (argila) serve as poor aquifers as their pores (voids) are very small.

Volcanic land scape (basalt rocks)



Madeira Island, Portugal

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Karst landscape

The caves of a karst landscape, Minerve, Hérault, France.*(Credits: Hugo Soria)*

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Karst caves

Mira de Aire caves, Portugal

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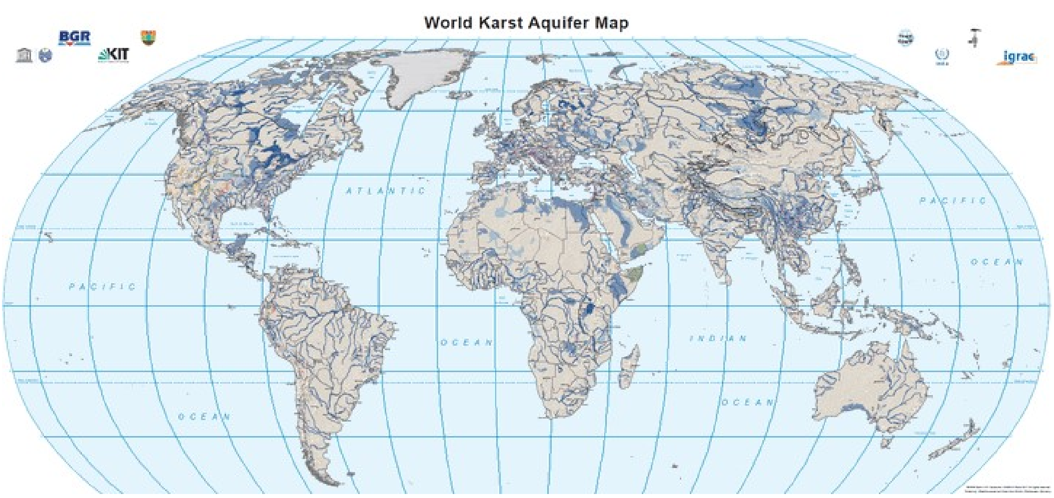
Karst regions of the world



World Karst Aquifer Map 1 : 40 000 000, published in 2017 and presented at the 44th Congress of the International Association of Hydrogeologists (IAH), Dubrovnik/CroatiaSource: *BGR, IAH, KIT & UNESCO*

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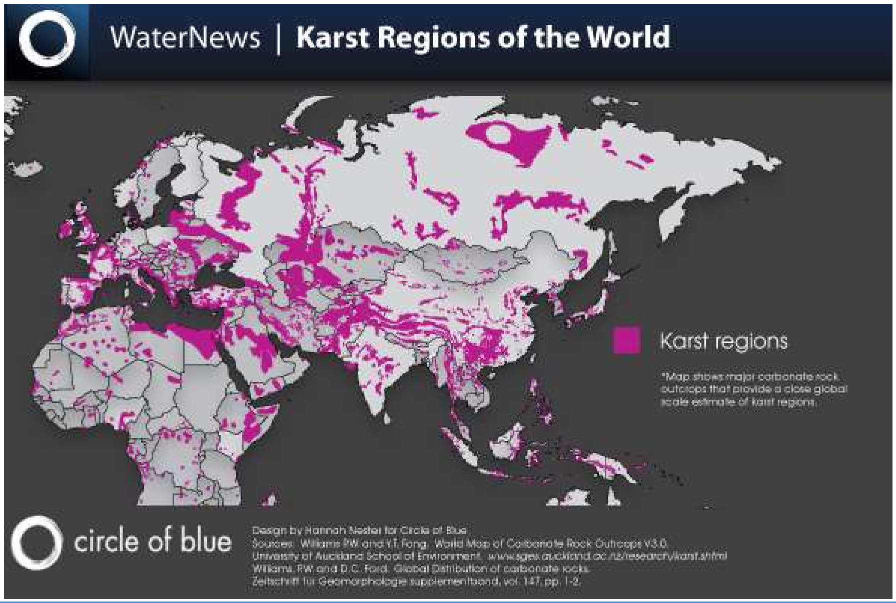
Karst regions of the world



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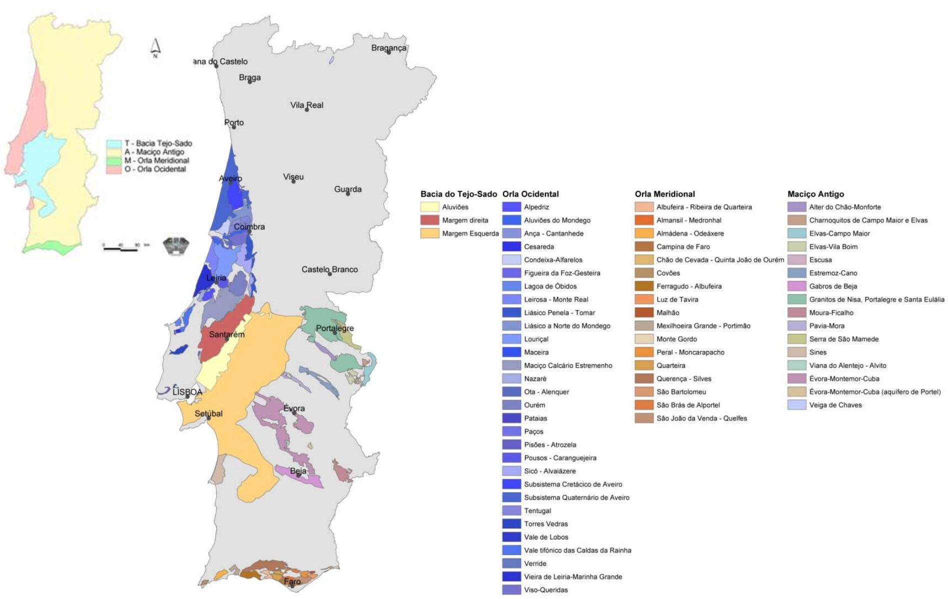
Main aquifers in Portugal



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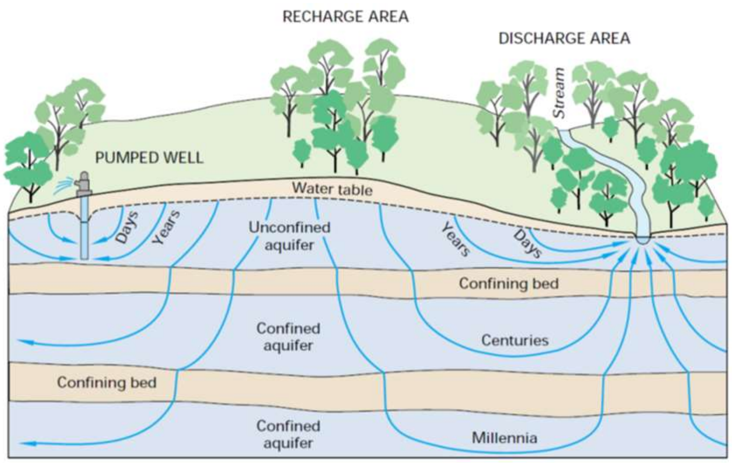
Residence times



Groundwater flow length and residence time vary significantly: from a few years, or less, to many thousands of years. On average, the residence time of groundwater is around 1700 years, but measurements have shown that water from deep wells in the desert of United Arab Republic and Saudi Arabia is 20,000-30,000 years old.

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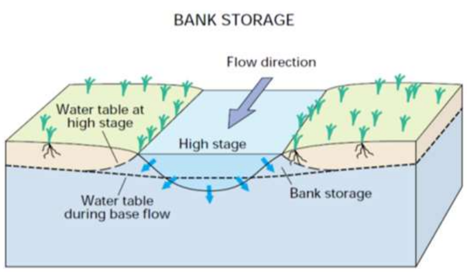
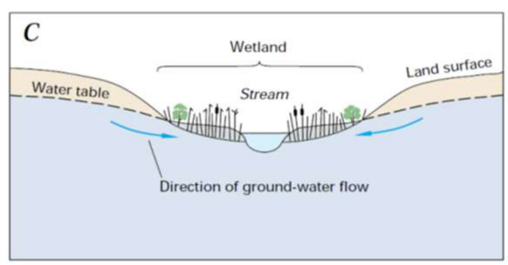
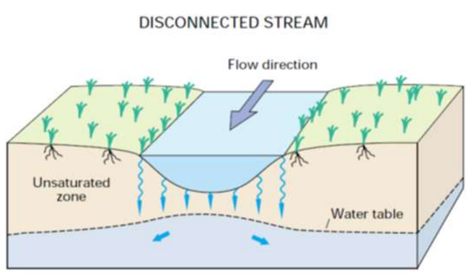
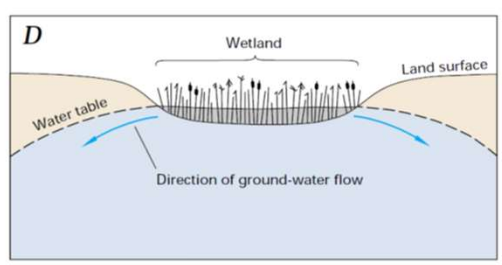
River- aquifer interactions









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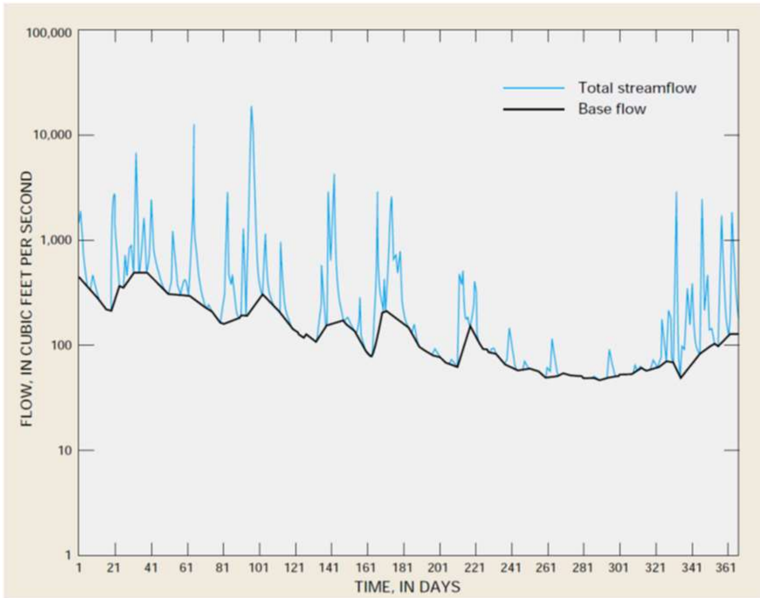
River baseflow



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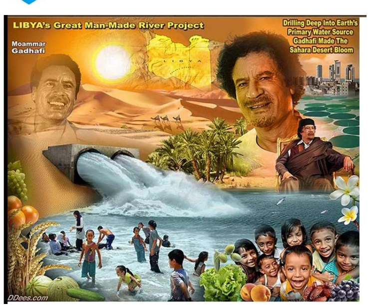
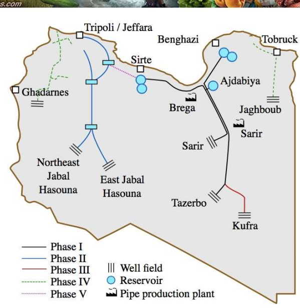
The Man-Made River, in Lybia





Nubian Sandstone Aquifer:

- Northeast of the Sahara desert
- Egypt, Libya, Chad and Sudan
- Area: $2x10^6$ km^2
- Precipitation: 5 mm/year
- Water age: 20,000 years
- Abstraction:
  - 3 km^3/year, before Man Made River
  - Egypt is also planning to explore the aquifer

Man-Made River project

- 1000 wells, 5000 km from the coast
- Abstraction: 6 km^3/year
- The water covers a distance of up to 1,600 kilometers and provides 70% of all freshwater used in Libya.

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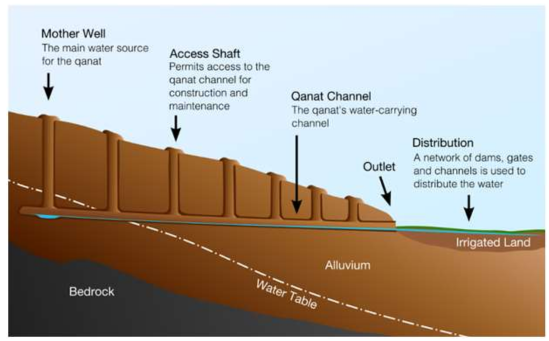
Groundwater development dates from ancient times

Qanat - An almost horizontal tunnel collecting water from an underground water source. The water is transported along underground tunnels, so-called koshkan, by gravity due to the gentle slope of the tunnel to the exit (mazhar), from where it is distributed by channels to the agricultural land of the shareholders. Well shafts are sunk at regular intervals along the route of the tunnel to enable removal of spoil and allow ventilation.

The Persian Qanat: Aerial View, Jupar, Bagh-e Shahzadeh (Mahan) © S.H. Rashedi



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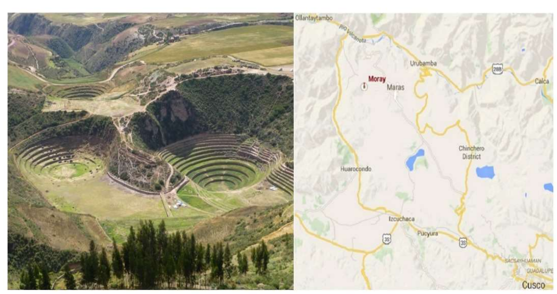
Groundwater development dates from ancient times

PUQUIOS

PUQUIOS are an old and extensive system of subterranean aqueducts, surface channels, reservoirs and spiraling holes that allowed the Nazca civilization to distribute water in one of the most arid places in the world..

PUQUIOS, QANATS Y MANANTIALES: GESTIÓN DEL AGUA EN EL PERÚ ANTIGUO



Muyus de la localidad de Moray, distrito de Maras, departamento de Cusco, Perú (www.hidraulicainca.com). A la derecha, ubicación de Moray (maps.google.com).
Muyus from the location of Moray, district of Maras, department of Cusco, Perú (www.hidraulicainca.com). To the right, location of Moray (maps.google.com).

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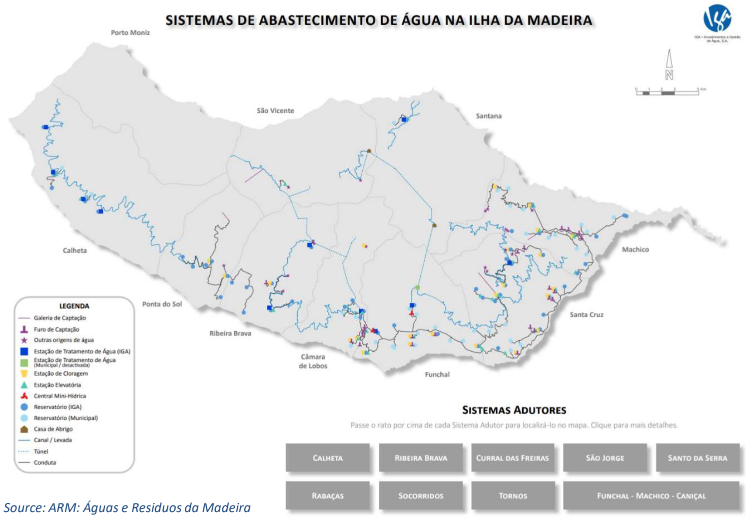
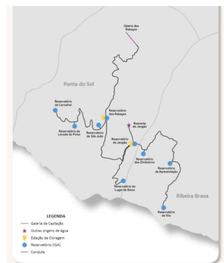
Madeira island water supply system



Source: ARM: Águas e Residuos da Madeira

SISTEMA ADUTOR DAS RABAÇAS



Principais instalações:

2 Captações (1 galeria e 1 nascente)
2 Estações de Cloragem
9 Reservatórios de Armazenagem (IGA)

Galeria das Rabaças
Comprimento - 1.500 m
Caudal de exploração - 8.640 m³/dia

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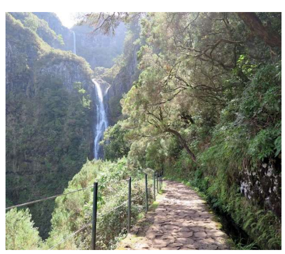
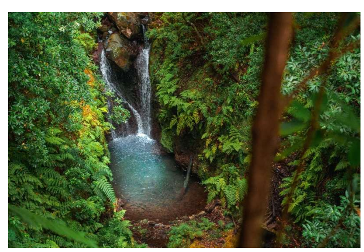
Groundwater development

LEVADAS
Madeira island
(Portugal)





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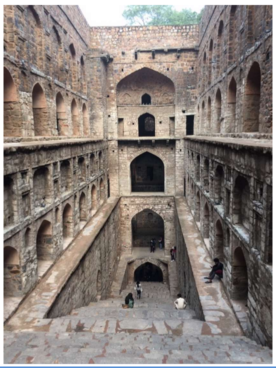
Groundwater development

Well

Horizontal well (galeria) / Qanat (Persia/Iran)



Well, New Delhi, India

Well, Jodphur, India

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Groundwater development

Drilled bore (furo) equipped with a wind generator

Drilling a bore (furo)

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Groundwater monitoring

Main variables:

- Groundwater or piezometric level
- Spring discharge
- Water quality parameters

KLL-Q-2

Water level sensor DS22

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Water sampling for water quality monitoring

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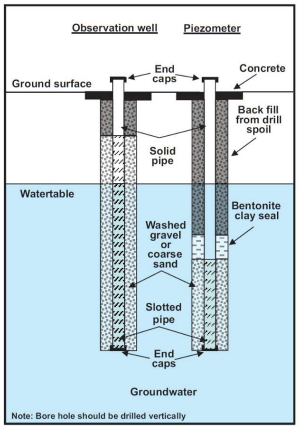
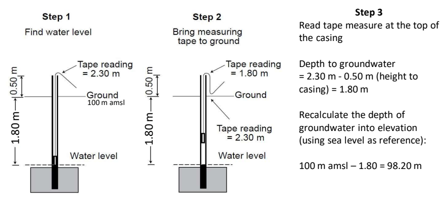
How and where do you measure hydraulic heads?





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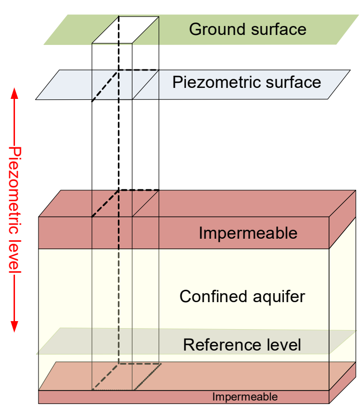
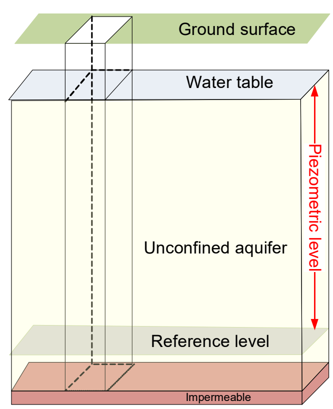
Piezometric level monitoring

The **piezometric level** measured in bore drilled in an unconfined aquifer represents the hydraulic head (or potential) at that location.





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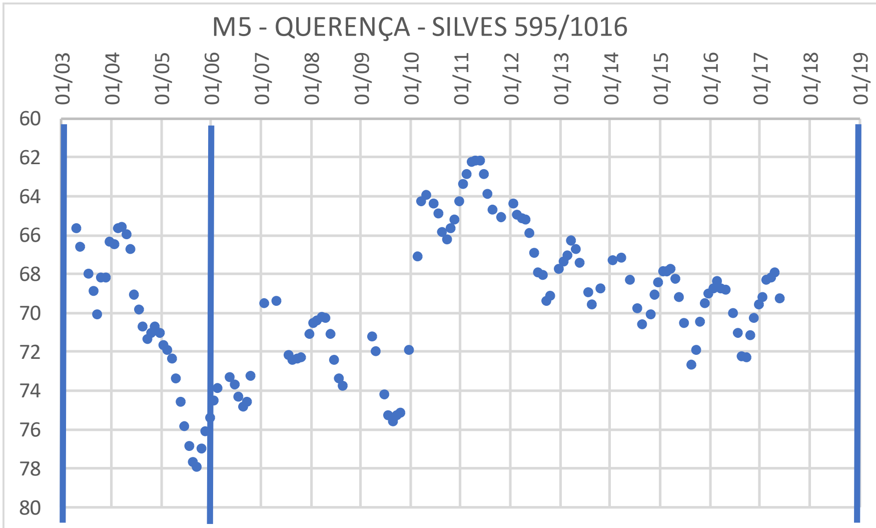
Piezometric records



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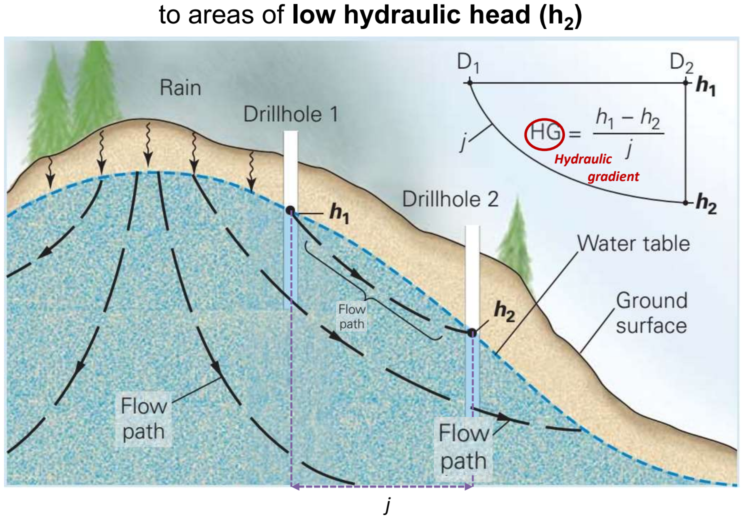
How does groundwater moves?

Groundwater moves from areas of **high hydraulic head (h_1)** to areas of **low hydraulic head (h_2)**



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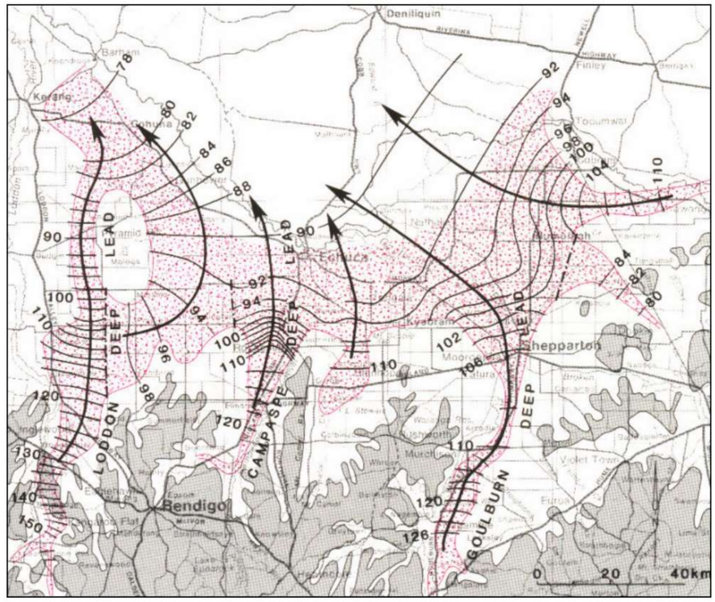
Potentiometric surface

A map of **equipotential lines** (i.e. contours of equal potential) provides indication of the flow direction.



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Specific storage

Specific storage, S_s – The volume of water an aquifer releases per unit surface of area per unit decline of hydraulic head (units: 1/m):

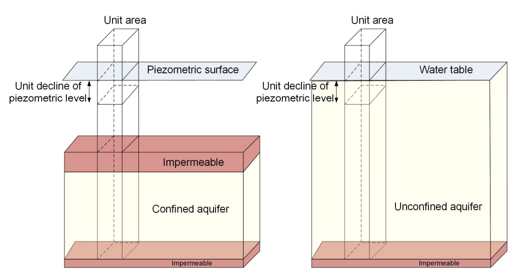
- Confined aquifers: pressure decrease leads to expansion of voids and water

$$S_S = \gamma_w(\beta_p + n \cdot \beta_w)$$

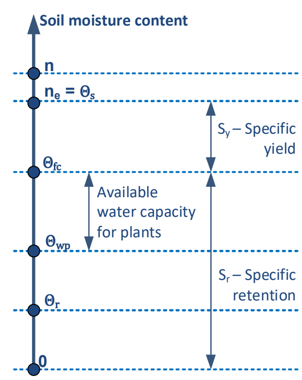
$$Storavity: S = S_S \cdot b$$

γ_w – specific weigth of water (N/m^3)
β_p - compressibility of the aquifer bulk material (m^2/N)
β_w - compressibility of water (m^2/N)
n – aquifer porosity (-)
b - aquifer thickness

- Unconfined aquifers: S_s = Specific yield (-)



Specific storage from confined aquifers are smaller than in unconfined aquifers.



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Vertical, drained compressibilities	
Material	**α (m^2/N or Pa^{-1})**
Plastic clay	$2\times10^{-6} – 2.6\times10^{-7}$
Stiff clay	$2.6\times10^{-7} – 1.3\times10^{-7}$
Medium-hard clay	$1.3\times10^{-7} – 6.9\times10^{-8}$
Loose sand	$1\times10^{-7} – 5.2\times10^{-8}$
Dense sand	$2\times10^{-8} – 1.3\times10^{-8}$
Dense, sandy gravel	$1\times10^{-8} – 5.2\times10^{-9}$
Ethyl alcohol	1.1×10^{-9}
Carbon disulfide	9.3×10^{-10}
Rock, fissured	$6.9\times10^{-10} – 3.3\times10^{-10}$
Water at 25 °C (undrained)	4.6×10^{-10}
Rock, sound	$< 3.3\times10^{-10}$
Glycerine	2.1×10^{-10}
Mercury	3.7×10^{-1}

Material	Compressibility, α (m^2/N or Pa^{-1})
Clay	10^{-8} to 10^{-6}
Sand	10^{-9} to 10^{-7}
Gravel	10^{-10} to 10^{-8}
Jointed rock	10^{-10} to 10^{-8}
Sound rock	10^{-11} to 10^{-9}

Material	S_s (ft^{-1})
Plastic clay	7.8×10^{-4} to 6.2×10^{-3}
Stiff clay	3.9×10^{-4} to 7.8×10^{-4}
Medium hard clay	2.8×10^{-4} to 3.9×10^{-4}
Loose sand	1.5×10^{-4} to 3.1×10^{-4}
Dense sand	3.9×10^{-5} to 6.2×10^{-5}
Dense sandy gravel	1.5×10^{-5} to 3.1×10^{-5}
Rock, fissured	1×10^{-6} to 2.1×10^{-5}
Rock, sound	$< 1\times10^{-6}$

To Convert	Divide By	To Obtain
ft^{-1}	0.3048	m^{-1}

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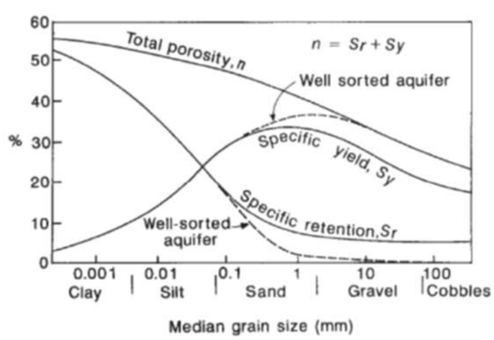
Effective porosity, specific yield or drainable porosity of unconfined aquifers

Due to capillarity forces, not all water stored in voids and in interstitial spaces can be extractable.

- For unconfined aquifers, effective porosity, specific yield or drainable porosity represents the part of total porosity that yields water.
- $n = S_r + S_y$ S_r - specific retention
  S_y - specific yield or effective drainable porosity



Material	Porosity (%)	Specific Yield (%)	Specific Retention (%)
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (unconsolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (young)	11	8	3

Heath, R.C., 1983. Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220

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Exercise

Estimate the storativity of a 10 m thick confined sand aquifer with n = 0.3.

Using specific storage data:

$$S = S_c \cdot b = \gamma_w(\beta_p + n \cdot \beta_w) \cdot b = 9800 \cdot (10^{-8} + 0.3 \cdot 4.4 \cdot 10^{-10}) \cdot 10 = 1 \cdot 10^{-3}$$

γ_w – *specific weigth of water (N/m³)*
β_p - *compressibility of the aquifer bulk material (m²/N)*
β_w - *compressibility of water (m²/N)*
n – *aquifer porosity (-)*
b - *aquifer thickness*

Using specific storage data:

$$S = S_S \cdot b = 15 \cdot 10^{-5} \cdot 10 = 1.5 \cdot 10^{-3}$$

A 10 m thick confined sand aquifer releases 1.5x10^{-3} m^3/m^2 (1.5 L/m^2) when the pressures decrease 1 m.

A 10 m thick unconfined sand aquifer would release 220 L/m^2, given that the specific yield of sand is 22%. Note that the thickness of the aquifer is irrelevant.

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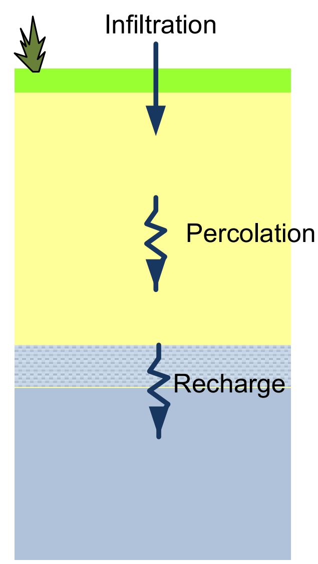
Groundwater availability

- **Infiltration**: The entry of water in the soil through the soil surface;
- **Percolation**: Water movement through the soil;
- **Recharge**: Water that reaches the saturated part of the lithologic column (aquifer).
- Most estimates of natural recharge rates range between about 5% and 25% of rainfall but vary widely locally.
- The exploitable water from an aquifer should not exceed the average annual recharge; for security reasons, the exploited amount should be 80%-90% of the average annual recharge.
- Each year, the volume raised may be greater than the recharge in that year.
- More risky approaches can be adopted if detailed studies on the aquifer behavior are completed.



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Groundwater recharge

Natural recharge

- **Non-point source**
- **Point**

Artificial recharge

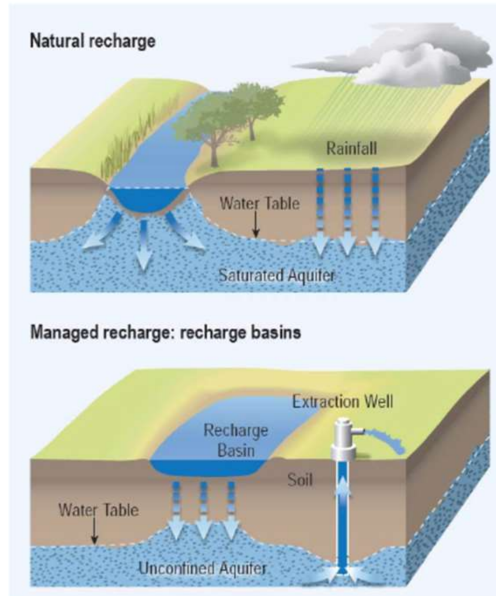
Factors affecting recharge:

Non-point source:

- Precipitation / Climate
- Land use and vegetation cover
- Topography and orography
- Soil type
- Geology / Depth of the water table

Point (e.g. from a river):

- Water source area
- Flow rate and flow rate
- Drainage height of watercourse
- Hydraulic conductivity
- Geology / Depth of the water table



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Methods to estimate recharge

Physical methods

- Analysis of piezometric levels fluctuations
- Analysis of river base flows

Geochemical methods

- Groundwater dating
- Tracers (e.g. chlorides)

Mathematical models

- Water balance

  P = AET + H + ΔS

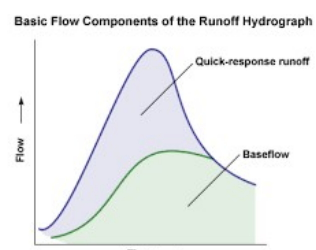
  P = AET + H + R

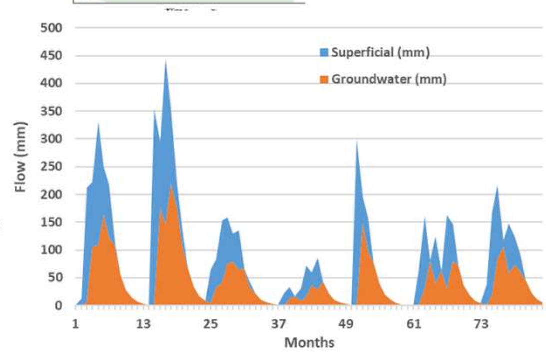
  R = P – AET - H

- Hydrologic modelling

  Using models to relate recharge and records of piezometric levels

Analysis of river base flows





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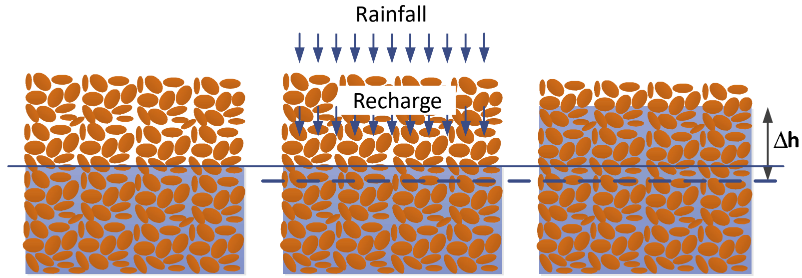
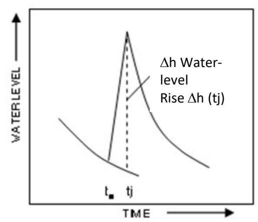
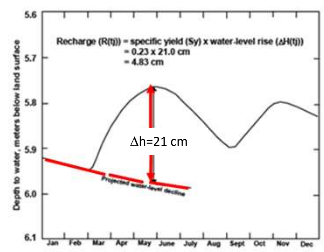
Analysis of piezometric levels of unconfined aquifers







$$Recharge = S_y \cdot \frac{\Delta h}{\Delta t}$$ (specific yield, S_y)

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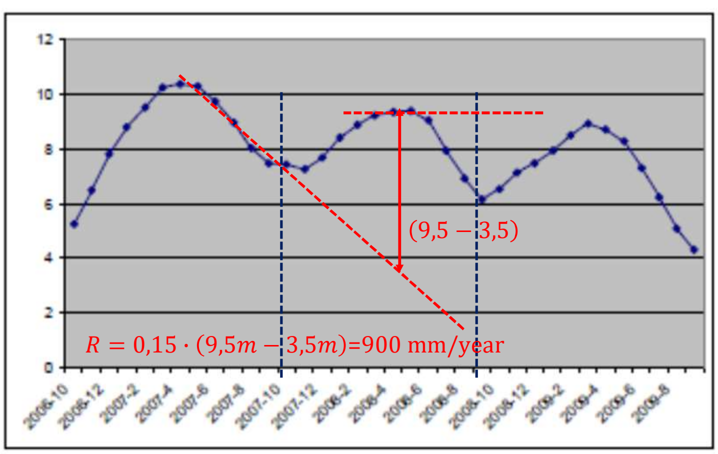
Exercise

The figure shows a piezometric record (values in meters) observed in a monitoring well of Querença-Silves aquifer, in Algarve. Using the piezometric level method, determine the recharge in 2007/08, assuming a specific yield equal to the effective porosity (0.15).



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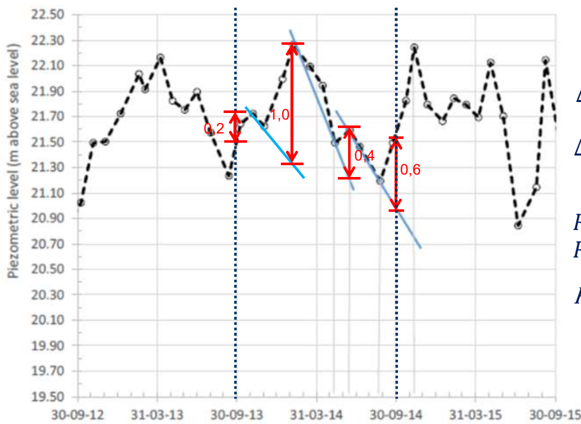
Exercise

Considering a representative figure of the annual fluctuation of the piezometric level in a free aquifer in a region with an average annual precipitation equal to 850 mm, calculate the recharge ratio in the year 2013/14. Assume a specific yield value of 0.15.



$$\Delta h = \Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4$$

$$\Delta h = 0{,}2 + 1{,}0 + 0{,}4 + 0{,}6 = 2{,}2\ m$$

$$R = Sy \cdot \Delta h / \Delta t$$

$$R = 0.15 \cdot 2.2/1 year = 330\ mm/year$$

$$R = 39\%\ \text{of precipitation}$$

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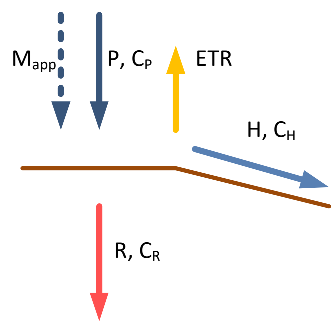
Chloride method

By measuring the concentration of chlorides in the various components of the water balance, it is possible to estimate the recharge.

Chloride balance:

- C_P – Chloride concentration in rainwater
- C_H - Chloride concentration in runoff
- M_{app} – Dry deposition
- C_R - Chloride concentration in recharge
- C_{GW} - Chloride concentration in groundwater
- P – Average annual precipitation
- H – Average annual runoff
- R – Average annual recharge



$$P \cdot C_p + M_{app} = H \cdot C_H + R \cdot C_R$$

$$R = \frac{P \cdot C_p + M_{app} - H \cdot C_H}{C_H}$$

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Exercise

Consider the region surrounding Beja in Alentejo (interior of Portugal), with an average annual precipitation equal to 578 mm/year and very low runoff. The chloride concentration in precipitation and groundwater has been monitored for some years and is estimated to be 4.2 mg/L and 48.2 mg/L, respectively. Using the Chloride method, estimate the average annual recharge.

$$R = \frac{C_P \cdot P + M_{app}}{C_{GW}}$$

$$P = 578\ mm$$

$$C_p = 4.2\ mg/L$$

$$C_{GW} = 48.2\ mg/L$$

$$R = \frac{C_P \cdot P + M_{app}}{C_{GW}} = \frac{4.2 \cdot 578 + 0}{48.2} = 50.4\ \text{mm/year}$$