Groundwater is the water that occurs in a saturated zone of variable thickness and depth below the earth's surface

The field of science that is concerned with the study of the occurrence, distribution and movement of water below the surface of the earth is called Groundwater Hydrology. Geohydrology and Hydrogeology have similar connotations;

although hydrogeology differs only with its emphasis on geology.

The job of a groundwater hydrologist is the management of groundwater system. His investigation area of interest may be

local, regional or even across countries. Example of areas in which groundwater studies are carried out include

- evaluation and exploitation of groundwater resources
- dewatering for construction
- inflow into a mine shaft or pit
- seepage beneath or through a dam
- subsurface return flow from irrigation
- seepage from canals and reservoirs
- recharge from rainfall.

AQUIFERS

Aquifer is a word produced from two Latin words: Aqua, which means water and ferre, which means to bear. Therefore, the term Aquifer can literally be understood as Waterbearing formation.

Aquifer can formally be defined as a saturated permeable geological unit that is permeable enough to yield economic quantities of water to wells. In other words, it is defined as a saturated geological unit that can transmit significant quantities of water under hydraulic head. The most important underground water-bearing materials are unconsolidated sand and gravels. But, permeable sedimentary rocks such as sandstone and limestone, and heavily fractured or weathered volcanic and crystalline rocks can also be taken as aquifer (water-bearing) materials.

Aquitard is a geological unit that is permeable enough to transmit water in significant quantities for large area and long period. However, its permeability is not sufficient to justify the construction of production wells to be place in it. In other words, Aquitard *is a geologic* *formation that can transmit water at a relatively lower rate compared to aquifer*. Example includes formations that are predominantly clays, loams and shales.

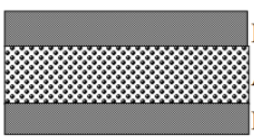
Aquiclude is an impermeable geological unit, which does not transmit water at all. Although this formation is capable of absorbing water slowly. It means that this geological formation *can store water, but cannot transmit it easily*. In other words, Aquiclude is a saturated geological unit that is incapable of transmitting significant quantities of water under ordinary hydraulic head. Example: metamorphic rocks.

Aquifuge is a geological formation that can neither absorbs nor transmits water (as granite)

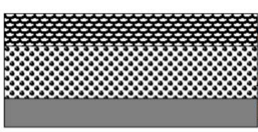
AQUIFER CLASSIFICATION

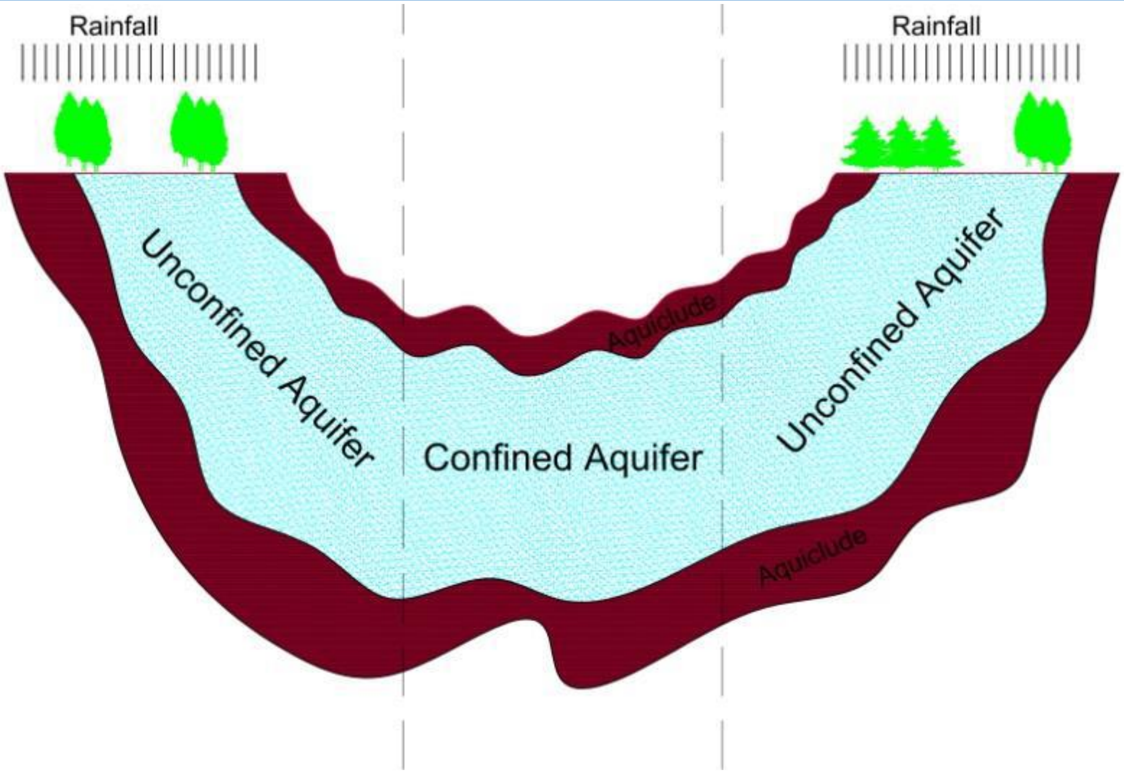
Aquifers may be classed as **confined**, **unconfined**

A confined aquifer is confined above and below by an impervious (may contain water but can't transmit it) layer under pressure greater than the atmospheric. Therefore, in a well penetrating such an aquifer, the water level rises above the bottom of the top confining bed. The water in a confined aquifer is called confined or artesian water. Artesian water flows freely without pumping and the well producing such water is called an artesian or a free flowing well.


Impervious K'=0
Aquifer K>K'
Impervious K'=0

Unconfined Aquifer (Phreatic, Water table) An unconfined aquifer is one in which a water table (phreatic surface) serves as its upper boundary. A phreatic aquifer is directly recharged from the ground surface above it.


Water table K'
Aquifer K=K'
Impervious K"=0



Leaky aquifer A leaky aquifer is also known as ***semi-confined aquifer*** as either both the upper and the lower boundaries are aquitards or one of them is aquiclude and the remaining is aquitard. The water is free to move through aquitards either upward or downward.

Recharge and Discharge

Groundwater recharge represents the portion of rainfall which reaches an aquifer. Groundwater therefore owes its existence directly or indirectly to precipitation. Artificial recharge occurs from excess irrigation seepage from canals and water purposely applied to augment groundwater supplies. Seawater can enter underground along the coasts where the hydraulic gradients slope in an inland direction.

Discharge of groundwater occurs when water emerges from underground. Most natural discharge occurs as flows into the surface water bodies e.g. streams, lakes and oceans. Discharge to the ground surface appears as springs. Groundwater discharge also occurs by evaporation from within the soil and by transpiration from vegetation, that has access to the water table. However, pumpage from wells constitutes the major artificial discharge of groundwater.

Basic Concepts and Definitions

I- Physical Properties of Aquifers

الخواص الفيزيائية للتكاوين المائية

1- Porosity (n): The porosity of a rock is its property of containing pores or voids. It is defined as the ratio of volume of voids Vv to total volume of medium (rock) VT; i.e.:

n = (Vv/VT) 100

2- Specific Yield (Sy): It is defined as the ratio of total drainable water volume (Vw) to the bulk volume of medium (VT); i.e.:

Sy =(Vw / VT) *100

3- Specific Retention (Sr): It is defined as the ratio of total retained water volume (Vr) to the bulk volume of medium (VT); i.e.:

Sr = (Vr / VT)*100

4- Storage Coefficient (S): The ability of an aquifer to store groundwater. It is defined as the volume of water that an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head, i.e.:

S= Vw/(dh *A)

Where Vw=volume of water released or taken into storage by the aquifer, dh= change in the piezometric surface and A= cross sectional area.

It can also be defined as the ratio of abstracted volume of water from the aquifer (Vw) to the dewatered volume of aquifer (Va):

S = (Vw/Va)*100

Values of S ranges between $10^{-6} – 10^{-2}$ for confined aquifers.

For unconfined aquifers it ranges between 0.3-0.01, which is considered equal to the specific yield Sy.

5- Hydraulic Conductivity (K): It expresses the ability of rocks to let the water through under any hydraulic gradient. It can be defined as rate of flow of water that can passes through a unit cross section of the aquifer under unit hydraulic gradient. It has the unit of velocity (L/t) for example m/day.

6- Transmissivity (T) معامل النقولية

Transmissivity (T) is the product of the average hydraulic conductivity K and the saturated thickness of the aquifer (D) i.e.

T=KD

It is defined also as the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the aquifer:

T = Q/wi

Where Q= Discharge rate,

w= width of the aquifer

i= hydraulic gradient.

Transmissivity has the dimensions of Length^2/Time and is, for example, expressed in m^2/d or cm^2/s.

2-Basic Definitions

1*- *Static water level مستوى الماء الثابت

The level at which groundwater stands in the well during the pump shut down. It is explained by the distance from the surface to the water level in the well (m)

2*- *Dynamic water level مستوى الماء المتحرك

The level at which groundwater stands during the pump operation (m).

3-Drawdown الهبوط (s)

The drop in the groundwater level, it equals the difference between the static and dynamic water levels measured at any time after pumping start (m).

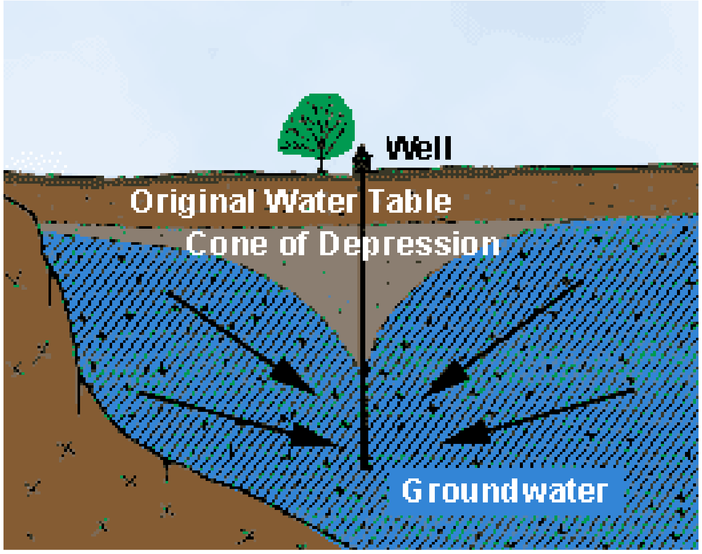
4-Rate of discharge معدل تصريف البئر (Q)

The volume of water abstracted during a unit of time. Q has a dimension of volume/ time i.e. m3/day or l/min.

5- Cone of depression مخروط الانخفاض

A cone of occurs in an aquifer when ground water is pumped from a well.

In an unconfined (water table) aquifer, this is an actual depression of the water levels. In confined (artesian) aquifers, the cone of depression is a reduction in the pressure head surrounding the pumped well.

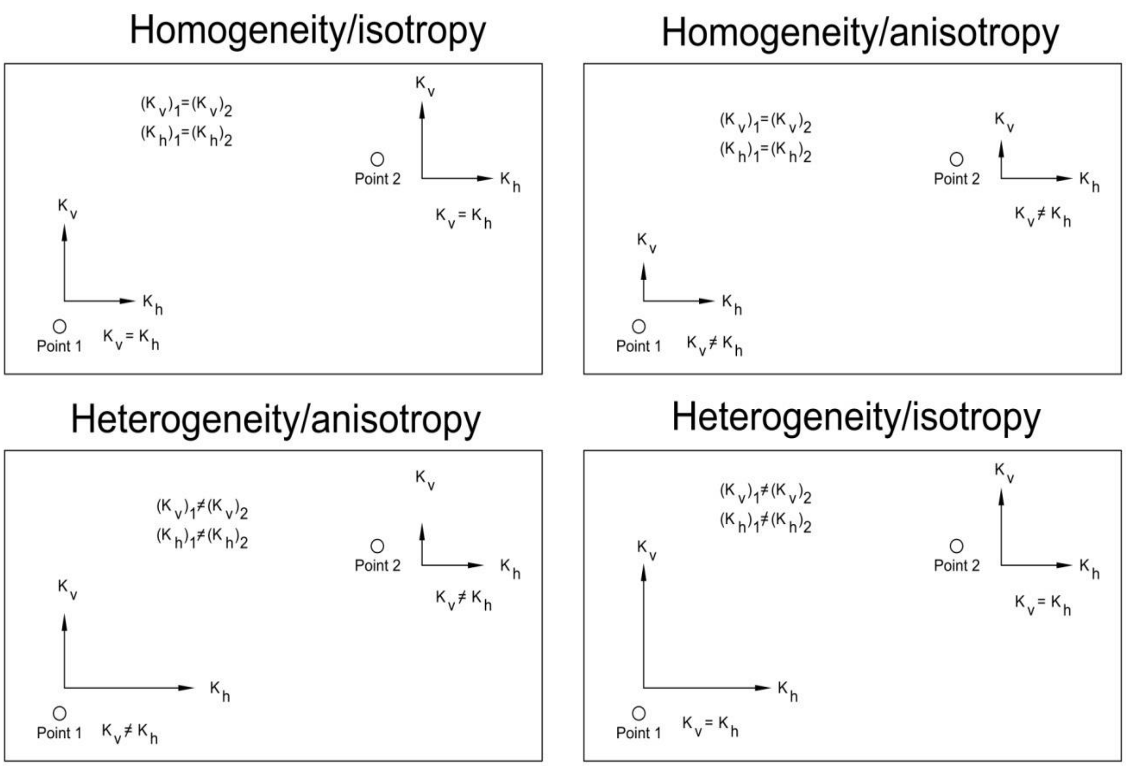


6- Radius of influence (R) التأثير قطر نصف

The radial distance from the center of a well to the point where there is no lowering of the water table or potentiometric surface (the edge of the cone of depression) (m).

Anisotropy and heterogeneity

Groundwater hydraulic equations are based on some assumptions. If the hydraulic conductivity, K, is independent of direction at any a point in a geologic formation, the formation is called isotropic at that point. If the hydraulic conductivity, K, is dependent on direction at a point in a geologic formation, the formation is anisotropic. Let, in any xyz coordinate system, Kx, Ky and Kz represent hydraulic conductivity values in the x, y and z directions, respectively. If $Kx = Ky = Kz$at any point, the formation is isotropic, whereas, for anisotropic condition to occur, $Kx \neq Ky \neq Kz$. In addition, if the hydraulic conductivity is independent of spatial variation (position) within a geologic formation, the formation is termed as homogeneous. And if the hydraulic conductivity is dependent on spatial variation within a geologic formation, the formation is heterogeneous formation. In homogeneous geologic formation, the hydraulic conductivity, K(x,y,z)=C=constant, whereas in heterogeneous geologic formation, the hydraulic conductivity, K(x,y,z)≠C. We can say that aquifers and aquitards are homogenies and isotropic if we assume that the hydraulic conductivity is same throughout a geologic formation and in all directions. If hydraulic conductivity in the horizontal direction Kh is greater than the hydraulic conductivity in the vertical direction Kv, this phenomenon is called anisotropy. In fact, lithology of geological formation varies significantly horizontally and vertically. For homogeneous, anisotropic formation,$x(x,y) = K1$ at every point and $Ky(x,y) = K2$ at every point, but $K1 \neq K2$.



Steady state and unsteady state flow

There are two types of well-hydraulic equations and these are steady state flow and unsteady state flow equations. The definitions of these flow conditions are given as follows.

Steady state is independent of time. In this flow state, the velocity may differ from point to point, but it will not change with time at any given point in the flow field. As a result, the steady state condition, water level does not change with time. For example, the water level in the pumping well and surrounding piezometers does not vary with time. The steady state flow takes place if pumping aquifer is recharged by outside water resource, rainfall (unconfined aquifer), leakage through the aquitard (Leaky aquifer) from upward or downward and directly from open water sources. As a result, we can say that steady state flow is attained if the changes in the water level in wells and piezometers are very small with time that they can be ignored.

Unsteady state occurs from the time of the star of pumping until steady state flow is reached. The flow can be assumed as unsteady state as long as water level changes in the well and piezometers are measurable and cannot ignored.

Hydraulic resistance (HR)

Hydraulic resistance measures the resistance of vertical flow (upward or downward) through aquitard. In other words, it characterizes the amount of leakage through aquitard.The hydraulic resistance can be defined as:

$$HR = DvKv$$

Here, Kv is hydraulic conductivity of aquitard in vertical direction, and Dv is thickness of aquitard. It is obvious that, for impervious medium, K=0. Therefore, HR goes to infinity. As a result, this parameter can measure the resistance of aquitard (semi-previous) formation to upward or downward leakage in leaky aquifers. Hydraulic resistance has dimension of time (Time).

Leakage factor

Leakage factor measures spatial variation of leakage through an aquitard in a leaky aquifer. It is defined as:

$$L = \sqrt{T}\ HR$$

Lower values of L show high leakage rate through the aquitard, whereas, high values of L show low leakage rate. Leakage factor has dimension of Length.

Compressibility (α and β)

It is required to define compressibility of water and porous media separately. Compressibility of porous media describes the change in volume caused in an aquifer under a given stress and is given as:

$$\alpha = -\frac{\frac{dV_T}{V_T}}{d\sigma_e}$$

Here, VT is the total volume of a given mass of material and dσe, is the change in effective stress.

The compressibility of water is defined as:

$$\beta = -\frac{\frac{dV_W}{V_W}}{dp}$$

The negative sign is required because of pressure, p, and to make βa positive number. An increase in pressure, dp, leads to a decrease in the volume Vw of a given mass of water. For incompressible water, since specific mass =ρ=ρ0= constant, then β=0.

Specific storage

Specific storage is defined as the volume of water that unit volume of aquifer release from storage under a unit decline in hydraulic head. It is well-known that decrease in hydraulic head, h, lead to decrease in fluid pressure and increase in effective stress σe. The decrease in hydraulic head causes two results: 1) increase in effective stress 2) decrease in pressure.
The first one is controlled by aquifer compressibility, α, and the second one is controlled by fluid compressibility, β. As a result, Specific storage is given as:

$Ss=\rho.g(\alpha+n\beta)$

And storage coefficient can be written as:

$S=Ss\ D$

Here, D is saturated thickness, and Ss is specific storage coefficient. Transmissivity, T, and storage coefficient, S, (storativity) were developed for the analysis of well hydraulics in confined aquifer.

Water table

Water table refers to the boundary between saturated zone and unsaturated zone. In other words, it is the upper surface of saturated zone. On this surface, the fluid pressure in pores of porous media is atmospheric (**p=0**). This implies that **ψ=0**, hence $h=\psi+z$, hydraulic head at any point on the water table must be equal to elevation of the water table. Therefore,

h=*z*

Negative pressure

Ψ=0 at any point on the water table (boundary)
Ψ>0 at any point under water table (saturated zone)
Ψ<0 at any point above water table (unsaturated zone)
Since water in the unsaturated zone is kept in the soil under surface-tension forces, the pressure head, ψ is taken as tension head or suction head when **ψ<0**. As mentioned before, hydraulic head is algebraic sum of elevation, z and *pressure head ψ.* Above the water table, where ψ is taken as tension head or suction head, it is not appropriate to measure hydraulic head with piezometers. But it can be measured with tensiometer (جهاز قياس الشد الرطوبى في التربه).

Saturated, Unsaturated, and Tension-Saturated Zone

Saturated zone:

1) The saturated zone occurs under water tables (**ψ>0**)
2) The soil pores are filled fully with water. The moisture content, θ is equal to porosity, n (**θ=n**)
3) The fluid pressure is greater than atmospheric pressure and the pressure head, **ψ is greater than zero (ψ>0).**

4) The hydraulic head must be measured with a piezometer.
5) The hydraulic conductivity is a constant. It is not a function of pressure head ψ.

Unsaturated zone

1) It occurs above the water table and above the capillary fringe.

2) The soil pores are only partially filled with water. The moisture content is less than the porosity, n.

3) The fluid pressure is less than atmospheric pressure. This implies that the pressure head is **less than zero.**

4) The hydraulic head, h must be measured with a tensiometer.

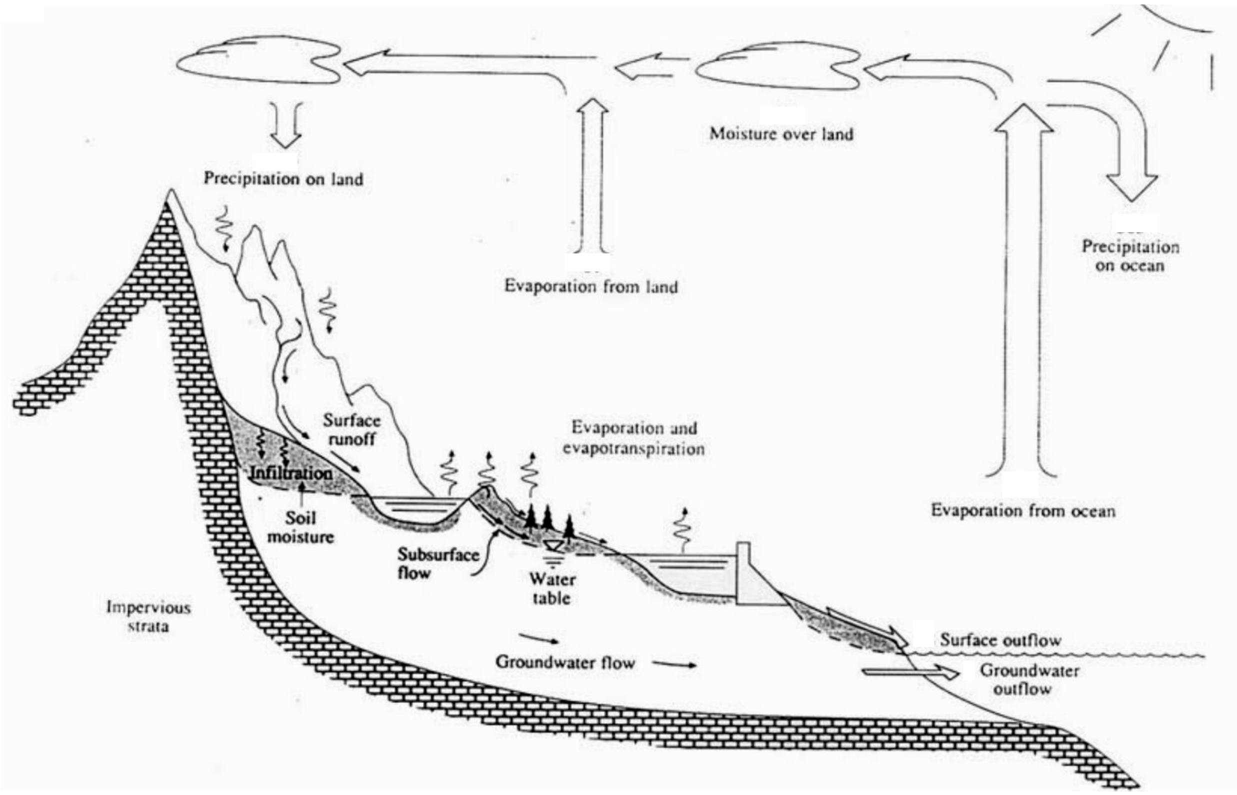
5) The hydraulic conductivity, K and moisture content, θ are both functions of the pressure head, ψ.

In Summary

For saturated flow: $\psi>0$, $\theta=n$, $K=K_0$
For unsaturated flow: $\psi<0$, $\theta=\theta(\psi)$, and $K=K(\psi)$.

Hydrologic budget

A) Processes in the hydrologic cycle: 1) Precipitation 2) Evaporation: a physical/chemical response 3) Transpiration: needs plants Plants act as pumps: remove water from the soil, release water vapor into the atmosphere. 4) Runoff: - Is commonly known as stream or channel flow - Has 3 components: overland flow, interflow and underflow (Doesn't just include surface flow).



a) **overland flow** = flow input from land surface drainage across the land surface (not channelized)

Side note: The terms “overland flow”, “depression storage” and “surface water” are all different. Don’t confuse them!

Overland flow is moving water

Depression storage is water that accumulates in low spots and is essentially stationary. A common name for depression storage? A puddle!

Surface water is water that is stored in ponds, lakes, rivers and streams. This is a broader term, that includes runoff.

b) **interflow:**
Quantity is usually minor
Describes lateral flow through the unsaturated (soil) zone (Note: unsaturated zone is also called the vadose zone)
The process by which surface water enters the subsurface is called **infiltration**; almost all of the water is the subsurface is placed there by infiltration. The only exception is **magmatic water**, which is added from depth due to de-gassing of magma.
c) **baseflow** = groundwater input
Describes lateral flow in the saturated zone (below the water table) that contributes to stream flow.
Note: **Underflow** is different. Underflow is deep groundwater flow, and is not directly connected to surface flow or surface conditions.
So: In summary, total stream flow (runoff) is the sum of 3 components:
Runoff = overland flow + interflow + baseflow
B) Water storage within the hydrologic cycle:
- Most water is stored as saline water in the oceans (97%)
- Freshwater: is < 3% of total
- Within the freshwater component:
- Glacial storage = 2.14%
- Groundwater storage = 0.61%
- Surface water storage = 0.009%
- Soil moisture = 0.005%
- Atmospheric moisture = 0.001%
- Other ways of looking at this:
- 98% of available freshwater is groundwater, <2% is surface water
- Groundwater is almost 68 times more abundant than surface water
- Explains the bias of this course toward groundwater.

C) The Hydrologic Equation:
- The general equation: Is essentially a problem of conservation of mass:
Inflow = outflow +/- storage OR: Inflow - Outflow = change in storage
Inflow = precipitation, surface inflow, loss from a body of surface water, subsurface inflow, overland flow, groundwater discharge into a body of surface water.
Outflow = evaporation, transpiration, surface outflow, soil evaporation, loss of water through a stream bed, loss of water to a body of surface water, loss to vegetation, percolation to the water table,pumpage, removal to a water supply.
Change in storage = increase or decrease in subsurface storage, increase or decrease in surface storage.
- Fetter has written a more specific equation to represent the hydrologic cycle from the perspective of an aquifer:
P = R + T + E +/- U +/- Storage terms
where: P = precipitation R = runoff
T = transpiration, E = evaporation & U = underflow

قوانين حركة المياه الجوفية

Groundwater Flow Laws

Darcy's Law

Darcy law states that the rate of flow through a porous medium is proportional to the loss of head and inversely proportional to the length of the flow path, or

v =Q/A or

v=- Ki= K (Δ h/ Δ L) =- K (h2-h1/L)

where:

v = Darcy velocity , Specific discharge , Filter velocity (L/T),

A= cross sectional area normal to flow direction (L3).

K= Hydraulic conductivity (Coefficient of permeability) (L/T),

Δ h= head loss (L),

L= distance between two points along the flow path (L),

i = dh/dl=h_2-h_1= H**ydraulic gradient** is simply the slope of the *water table* or *potentiometric surface*. It is the change in hydraulic head over the change in distance between the two monitoring wells.

Validity of Darcy's Law

Darcy law is valid only for laminar flow, but not for turbulent flow. In case of doubt, one can use the Reynold's number (NR) as a criterion to distinguish between laminar and turbulent flow. NR is expressed as:

NR = (ρ vD/ μ)

Where:

NR= Reynold's No.,

P = the fluid density,

v= the specific discharge,

D= the average length of the aquifer material, expressed usually as d10.

μ = the fluid viscosity.

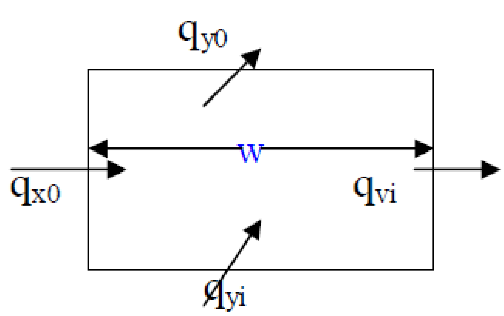
Darcy law is valid for NR=1- 10.

General Groundwater Flow Equations

A- Rectangular Coordinates:

1- Unsteady saturated flow

In unsteady state flow velocity and head change with time. This figure shows a unit volume of porous medium known as element control volume, rate of inflow into the unit equals:



$q_{xi} = - T_x w\ (\partial h/ \partial x\ )_i$ $\qquad$ $q_{x0} = - T_x w\ (\partial h/ \partial x\ )_I$

Tx Transmissivity in the x direction, (∂ h/ ∂ x)0 and (∂ h/ ∂ x)I hydraulic gradients in the inflow and outflow points.

The rate of flow through the square as found by the Continuity equation, as:

(qxi -qx0) + (qyi -qy0) = Sw (∂ h/ ∂ t)

$$\frac{T_x\,(\partial h/\partial x\,)_i - (\partial h/\partial x\,)_0 + T_y\,(\partial h/\partial y)_i\ - (\partial h/\partial y)_0}{w} = \frac{S\ \ (\partial h/\partial t)}{w}$$

if w is extremely small and the aquifer is isotropic, then the equation becomes:

(∂ x2/ ∂ 2h)+(∂ 2h/ ∂ y2) = S/T (∂ h/ ∂ t)

This equation is known as Laplace equation for unsteady two dimensional flow. *<u>For three dimensions it is written as</u>*:

$$(\partial^2 h/ \partial x^2)+(\partial^2 h/\partial y^2) + (\partial^2 h/\partial Z^2) = (S/T) \ (\partial h/\partial t)$$

2- Steady State Flow

In steady state flow head does not change with time i.e. $\partial h/ \partial t=0$, therefore the above equation becomes:

$$(\partial^2 h/ \partial x^2)+(\partial^2 h/\partial y^2) + (\partial^2 h/\partial Z^2) = 0$$

B- Radial Coordinates

Groundwater flow towards wells is radial. Assuming homogenous and isotropic aquifer Lapalce equation for unsteady state radial flow is:

$$(\partial^2 h/\partial r^2) + (1/r)(\partial h/\partial r) = (S/T)(\partial h/ \partial t)$$

Laplace equation for steady state radial flow is:

$$(\partial^2 h/\partial r^2)+ (1/r)(\partial h/\partial r) = 0$$