

## **Questions and Answers for NPTEL-Phase 2 Video Course on 'Groundwater (GW) Hydrology'**

*Question 1. Elaborate on the importance of GW and its historical background.*

Answer 1: Water in general and freshwater in particular is required for human beings, all other animals and plants for sustaining life. Human dependence on freshwater starts with rainwater or else surface water or else groundwater or else desalinated sea water or else any other freshwater that is available. Rainwater is available generally during rainfall and surface water is available only where there are surface water bodies. So GW is the most common source of freshwater, which can provide spatio-temporal water security. GW use has been proved to be easy and feasible technically and economically.

Traditionally GW is being utilized for domestic purpose, irrigation, other municipal uses, industrial use etc. For example, there were at least 10 states in USA wherein the %age of GW use to total water use was more than 50%, way back in 1975. During that time, there were at least 9 other states where this percentage was between 40 and 50%. Likewise in India in 2004, in Punjab, Haryana, Rajasthan, Delhi, Daman & Diu as well as Pondicherry, the annual GW draft was more than the net annual GW availability. In that year, this ratio was between 50 and 100% for Gujarat, Karnataka, Tamil Nadu, Uttar Pradesh (UP) [inclusive of present Uttarakhand] and Lakshadweep. All these facts highlight the importance of GW.

Historically, GW has been in use since Indus Valley Civilization at least 5000 years ago, through open wells. The Old Testament contains a number of references to GW, springs and wells. During Mauryan period in 4<sup>th</sup> Century BC, GW wells were supporting irrigation. Nearly 3000 year old technology of horizontal wells (i.e., Qunats) in Iran is well known. In 1804, a 500m deep bore well was reported near Kolkata. In 1926, the Ganga Valley State Tubewell Irrigation Scheme was launched in UP to dig 1,500 deep tube wells. These are some instances describing the historical background on GW.

*Question 2. What is the role of GW in hydrologic cycle? Provide the water balance equation and highlight the GW related components in it.*

Answer 2. GW has an important role in hydrologic cycle. Volumetrically, the life sustaining freshwater is just 2.5% of global water [i.e., approx. 35 M-km<sup>3</sup>]. Within freshwater, GW forms 30% by volume. And unlike freshwater in the form of polar ice/ mountain ice caps and glaciers, GW is available everywhere. Wherever it is managed properly, GW is ensuring water availability over space and time.

Water Balance Equation can be given as follows [wherein all components are expressed as depths over an area over a certain time period]:

$$P + I_r = ET + E + Q_p + Q_g + Q_s \pm Q_g \pm Q_s \pm \Delta S_m \pm \Delta S_s \pm \Delta S_g \quad (1)$$

where, P = total precipitation over the area,  
I<sub>r</sub> = Irrigation supply,

ET = Evapotranspiration,  
E = Evaporation,  
Qp = GW pumping,  
Qg = GW outflow/ inflow,  
Qs = Direct surface runoff,  
 $\Delta S_m$  = Change in soil moisture storage,  
 $\Delta S_s$  = Change in surface water storage, and  
 $\Delta S_g$  = Change in GW storage.

Here, Qp, Qg,  $\Delta S_m$  and  $\Delta S_g$  are the groundwater related components which indirectly include infiltration/ artificial GW recharge also.

*Question 3. List some of the notable internet sources on GW. Enumerate the major reasons for GW level fluctuations.*

Answer 3. The notable internet sources on GW are as follows:

- online libraries/databases of journal publishing houses [e. g., Groundwater, Journal of Hydrology, etc.],
- online libraries/ databases of Govt. agencies [e. g., United States Geological Survey (USGS) real time data, National Water Data Storage & Retrieval System (WATSTORE) etc.]
- online libraries/ databases of United Nations (UN) agencies [e. g., Intergovernmental Panel on Climate Change (IPCC), World Water Forum (WWF), World Meteorological Organization (WMO) etc.]
- other online databases/ libraries [e. g., National Centre for Medium Range Weather Forecasting (NCMRWF), National Institute of Ocean Technology (NIOT), Centre for Science and Environment (CSE) Guidelines for Water Harvesting etc.].

Major reasons for GW level fluctuations are:

- Streamflow variations,
- Meteorological and tidal phenomena,
- Urbanization,
- Earthquakes, land subsidence,
- External loads, etc.

*Question 4. How can isotope hydrology help in the GW age determination?*

Answer 4. Tritium ( $H_1^3$ ) –an isotope of hydrogen [with a half life period of 12.3 years] and the Carbon-14 Isotope ( $C_6^{14}$ ) [with a half life period of 5,730 years] are the two major isotopes used for estimating GW age. While tritium is used for estimating GW residence time upto 50 years, Carbon-14 isotope is used for estimating GW residence times ranging from 100 to 50,000 years.

*Question 5. With a sketch or a figure, show the various types of aquifers, confining units, wells and interfaces in them [along with their equivalent terminology(ies) –if any].*

Answer 5. The following Figure 1 shows the different types of aquifers [i.e., water bearing strata], confining units, wells and interfaces.

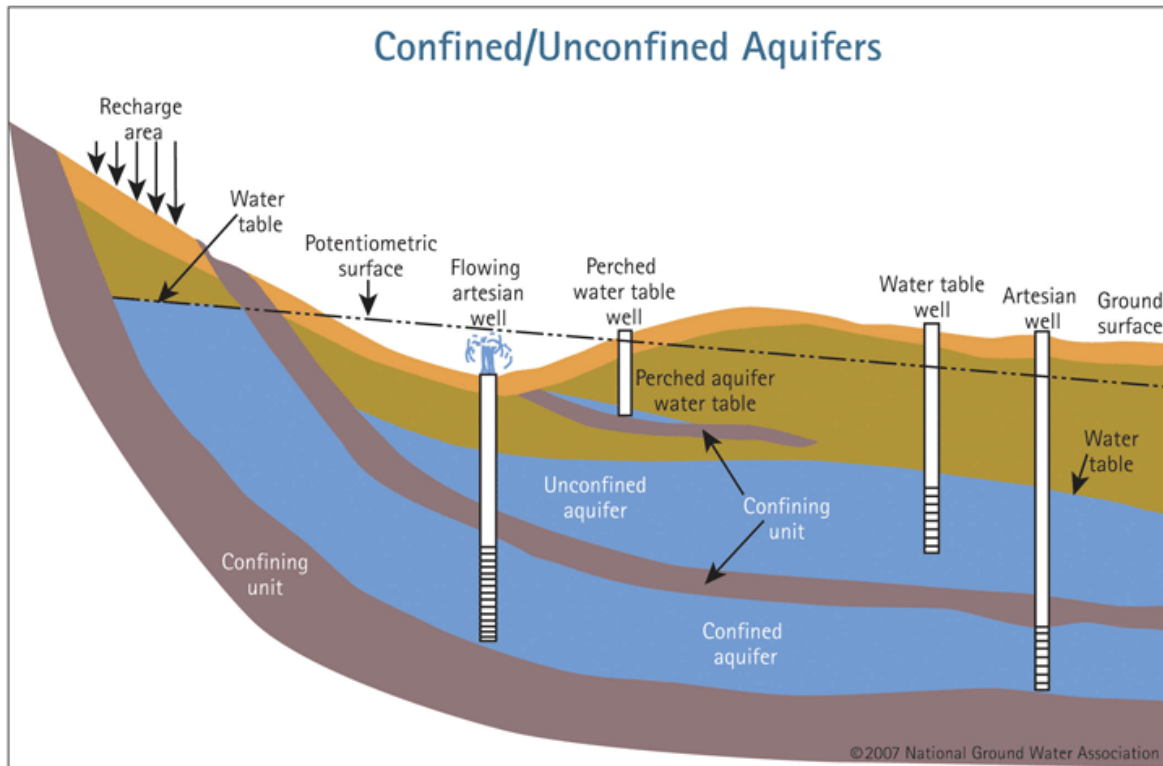


Figure 1. Various types of aquifers, confining units, wells and interfaces; [Source: National Ground Water Association (NGWA), USA; 2007].

Refer to the following Table for various types of aquifers/ confining units/ their equivalent terminologies [if any]

S. No.	Item Name	Item Type	Equivalent Terminology(ies)/ <u>Meaning</u>
1.	Unconfined aquifer	Aquifer	Water table aquifer, phreatic aquifer.
2.	Confined aquifer	Aquifer	Artesian aquifer, pressure aquifer.
3.	Leaky aquifer	Aquifer	Semi-confined aquifer.
4.	Perched aquifer	Aquifer	Locally raised aquifer.
5.	Aquitard	Confining unit	Semi-pervious stratum with some GW storage and flow.
6.	Aquiclude	Confining unit	Impervious soil stratum not yielding any GW.
7.	Aquifuge	Confining unit	Impervious rocky stratum not yielding any GW.
8.	Flowing Artesian well	Well	Flowing well.
9.	Water table	Interface	Interface between saturated and partially/ unsaturated zones.
10.	Potentiometric surface	Interface	Piezometric surface.

*Question 6. Briefly elaborate on the formation constants which characterize an aquifer.*

Answer 6. There are 3 formation constants [which characterize an aquifer] as follows:

i) Hydraulic conductivity (i.e., Coefficient of permeability or permeability -denoted as K), which is defined by the Darcy' Law as the proportionality constant between the apparent GW seepage velocity (v) and the hydraulic gradient (i);

As per Darcy's law, 'v' [commonly called the seepage velocity and it is the ratio of GW flow rate (Q) to its flow cross sectional area (A)] is directly proportional to 'i'.

i.e.,  $v = Q/A \propto i$

or  $Q \propto i \cdot A$

or  $Q = k \cdot i \cdot A = k \cdot \left[-\frac{dh}{dl}\right] A$ , (2)

where '-dh' is the incremental decrease in the hydraulic head in an incremental length of GW flow path of 'dl'.

ii) Transmissivity (i.e., Transmissibility –denoted as T) which is defined as the GW flow rate through a unit aquifer width under a unit hydraulic gradient;

We have,

$Q = k \cdot i \cdot A$ .

By Definition of 'T',  $Q = T$ , when  $i = 1$  and  $A = 1 \cdot B$

Therefore,  $T = K \cdot B$  (3)

where, B is the saturated aquifer thickness.

and

iii) Storativity (i.e., Storage coefficient –denoted as S) which is defined as the volume of GW that an aquifer releases or absorbs per unit surface area per unit change in piezometric head.

Generally for confined aquifers,  $0.00005 < S < 0.005$ .

*Question 7. What are the assumptions made in the steady GW flow through unconfined aquifers?*

Answer 7. There are two assumptions made in the steady GW flow through unconfined aquifers, called Dupuit's assumptions. They are as follows:

i) The curvature of the free surface is very small so that the streamlines are assumed to be horizontal at all sections;

ii) The slope of the hydraulic grade line (HGL) is equal to the free surface slope and it does not vary with the depth.

*Question 8. What is the Theis Equation for Unsteady flow into a well fully penetrating a confined aquifer? Elaborate on the Cooper-Jacob approximation for solving this equation and to estimate the transmissivity (T), storativity (S).*

Answer 8.

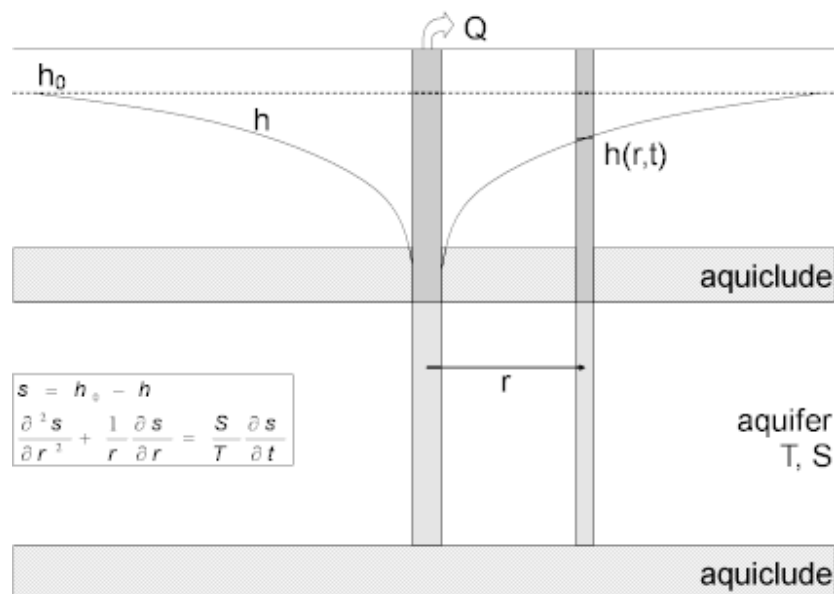


Figure 2. Unsteady flow into a well fully penetrating a confined aquifer [Source: <http://www.aqtesolv.com/cooper-jacob.htm>]

The Cooper - Jacob solution [proposed in 1946] (i. e., *Jacob's modified non-equilibrium method*) is useful for determining the hydraulic properties (transmissivity and storativity) of **non-leaky confined** aquifers. Analysis involves matching a straight line to drawdown data plotted as a function of the logarithm of time since the start of pumping.

The Cooper - Jacob solution is an approximation of the Theis non-equilibrium method which is given in compact notation as follows:

$$s = \frac{Q}{4\pi T} \cdot w(u) \quad (4)$$

$$u = \frac{r^2 S}{4Tt} \quad (5)$$

where  $s$  is drawdown [L],  $Q$  is pumping rate [ $L^3/T$ ],  $T$  is transmissivity [ $L^2/T$ ],  $r$  is radial distance from pumping well to observation well [L],  $S$  is storativity [-] and  $t$  is elapsed time since start of pumping [T].

The Theis well function,  $w(u)$ , in Equation(4) may be evaluated using the following infinite series expression:

$$w(u) = 0.5772 - \ln(u) + u - \frac{u^2}{[2 \cdot (2!)]} + \frac{u^3}{[3 \cdot (3!)]} - \frac{u^4}{[4 \cdot (4!)]} + \dots \quad (6)$$

where  $u$  is given by Equation (5). For small values of  $u$  (i.e., large values of time and small values of  $r$ ), Cooper and Jacob found that the Theis' well function may be approximated using only the first two terms in Equation (6):

$$w(u) \cong -0.5772 - \ln(u) \quad (7)$$

The critical value of  $u$  for the Cooper - Jacob approximation is given as  $u \leq 0.01$ . A smaller value for the critical value of  $u$  leads to a more accurate approximation.

Combining Equation (4) and Equation (7), Cooper - Jacob approximated the drawdown in a nonleaky confined aquifer with the following linear equation:

$$s = Q/(4\pi T) \cdot [-0.5772 - \ln(r^2 S / \{4Tt\})] \quad (8)$$

$$s = Q/(4\pi T) \cdot \ln\{2.25Tt/(r^2 S)\} \quad (9)$$

which is an equation for a st. line.

To apply the Cooper -Jacob solution, plot  $s$  as a function of  $\log(t)$  on a semi-logarithmic plot and draw a straight line through the data.

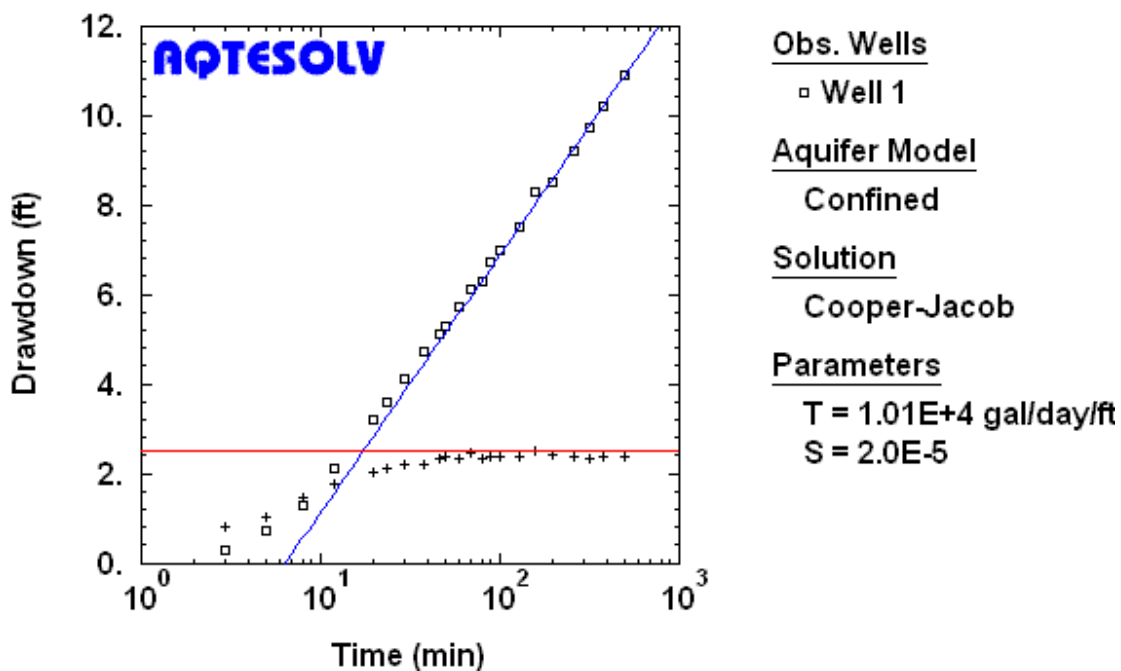


Figure 3. Semi-log plot of drawdown vs. time for Cooper – Jacob Approximation [Source: <http://www.aqtesolv.com/cooper-jacob.htm>]

Using the slope,  $\Delta s = s_2 - s_1$ , of the fitted line, determine  $T$  from the following Equation (10):

$$T = Q / (4\pi \Delta s) \quad (10)$$

With the estimate of  $T$  from Equation (10), calculate  $S$  as follows:

$$S=2.25Tt_0/r^2 \quad (11)$$

where  $t_0$  is the intercept of the line on the horizontal time axis.

The following assumptions apply to the use of the Cooper - Jacob solution:

- aquifer has infinite areal extent and is homogeneous, isotropic and of uniform thickness
- control well is fully penetrating and the flow to control well is horizontal
- aquifer is confined and the flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the control well can be neglected
- values of  $u$  are small (i.e.,  $r$  is small and  $t$  is large)

*Question 9. Describe the well flow near aquifer boundaries.*

Answer 9.

Mathematical solutions for pumping test analysis (e.g., Theis [1935]) typically assume *aquifers of infinite lateral extent*. In practice, the extent of an aquifer may be limited by one or more boundaries. Aquifer boundaries may not impact the results of short-term pumping tests, but the effects of distant boundaries become more evident as the duration of pumping increases.

The following two types of boundaries generally exist in aquifers:

- no-flow boundaries (i. e., barrier boundaries)
- constant-head boundaries

### **No-Flow (i. e., Barrier) Boundary**

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When an aquifer composed of permeable materials abuts impermeable or confining materials, it is possible to simulate the contact by a *no-flow (barrier or negative) boundary*. Lithologic changes (e.g., glacial outwash deposited in a low-permeability bedrock valley) or impermeable vertical faults can result in no-flow boundaries that limit the lateral extent of the aquifers.

A discharging well located near a no-flow boundary exhibits more drawdown than the same well pumping from an infinitely extensive aquifer. One may use the *method of images* to represent the bounded aquifer in mathematical terms by placing a discharging image well on the opposite side of the boundary from the real well (Figure 4). The image well has the same discharge rate and distance to the boundary as the real well. Thus, the drawdown at the no-flow boundary is exactly twice the drawdown observed an infinite aquifer.

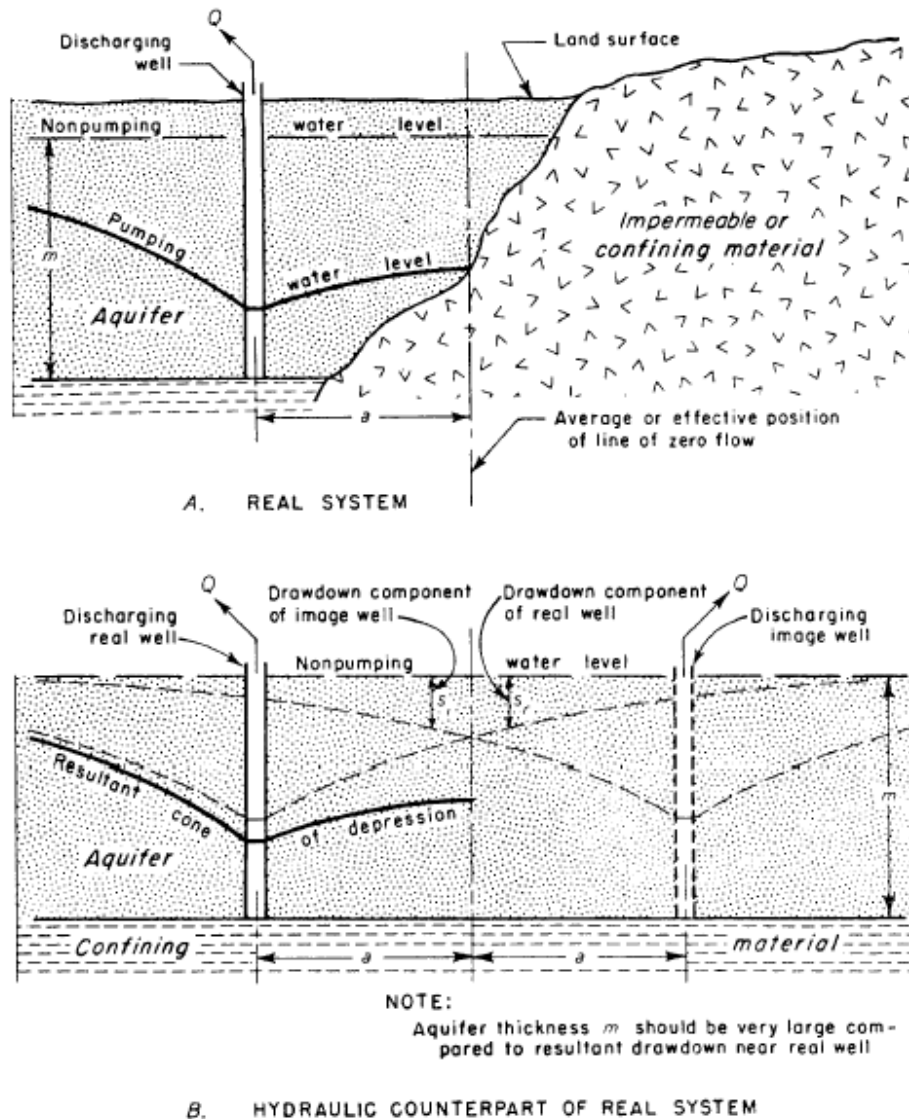


Figure 4. Representation of a single no-flow boundary with a discharging image well  
 [Source: <http://www.aqtesolv.com/pumping-tests/pumping-tests-in-bounded-aquifers.htm>]

### Constant-Head (Recharge) Boundary

When a surface water body is hydraulically connected to an aquifer, one may represent the feature by a *constant-head (recharge or positive) boundary*. Lakes, streams and rivers are examples of constant-head boundaries encountered in pumping test analyses.

A discharging well located near a constant-head boundary experiences less drawdown than the same well pumping from an extensive aquifer. One may use the *image wells* to represent the bounded aquifer in mathematical terms by placing a recharging image well on the opposite side of the boundary from the real well (Figure 5). The image well has the same pumping rate and



distance to the boundary as the real discharging well except that the image well recharges the aquifer. Thus, drawdown in the aquifer is exactly zero at the constant-head boundary.

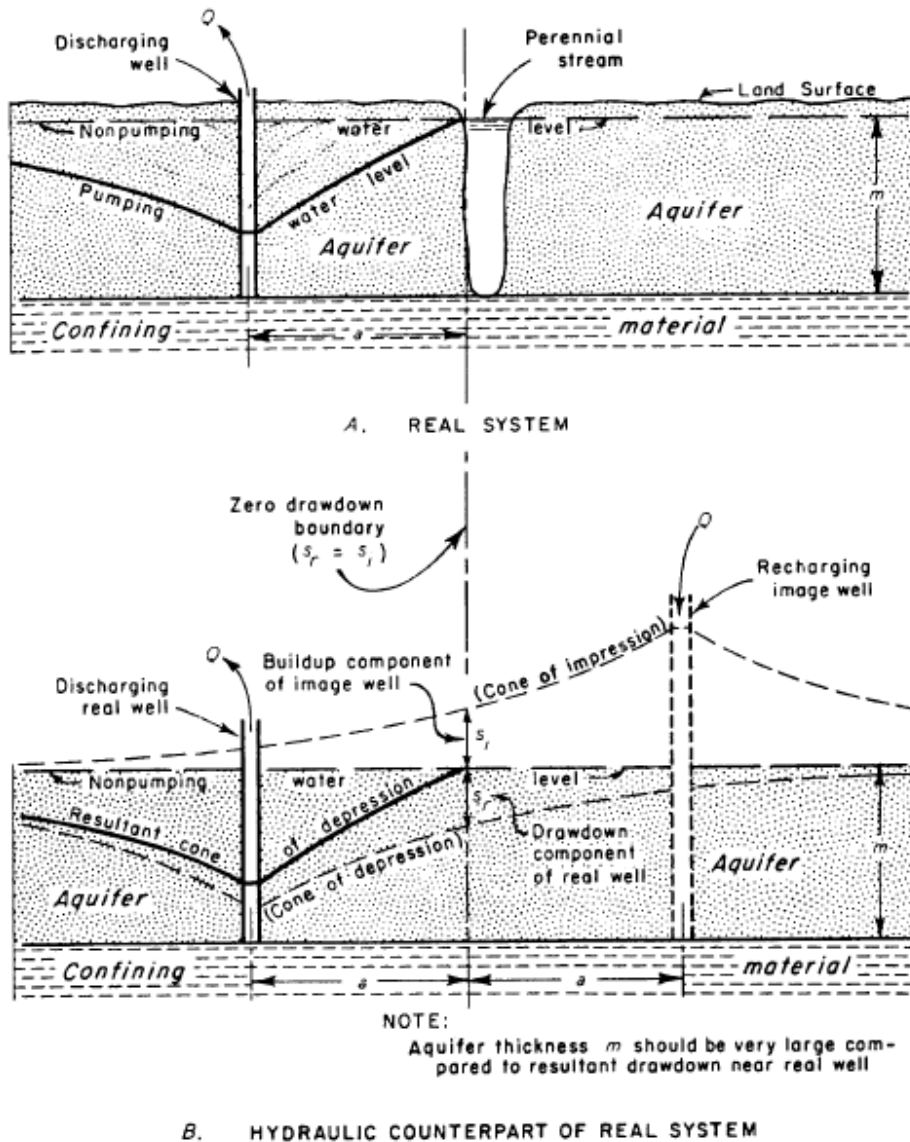


Figure 5. Representation of a single constant-head boundary with a recharging image well [Source: <http://www.aqtesolv.com/pumping-tests/pumping-tests-in-bounded-aquifers.htm>].

Question 10. What is well development and what are the methods employed in it?

Answer 10. Well development is the process of increasing the specific capacity (i. e., discharge per unit drawdown), preventing sand accumulation, obtaining maximum economic benefit through the well for its extended service life. The common methods employed in well development are:

- a) Pumping, b) Surging, c) Surging with air, d) Backwashing with air, e) Hydraulic jetting,
- f) Use of appropriate chemicals, g) hydraulic fracturing and h) Use of explosives.

*Question 11. What are purposes of and methods for artificial GW recharge (AGWR)?*

The main objective of AGWR is to supplement the natural GW recharge (NGWR) to improve water security/availability in general and GW security/availability in particular. Additionally, AGWR has the following purposes:

- a) To coordinate the operation of surface/subsurface reservoirs;
- b) To overcome adverse conditions like progressive lowering of GW levels, unfavourable salt/ salinity balance in water;
- c) To reduce/ stop land subsidence significantly;
- d) To provide localized subsurface water distribution system through established/ newly constructed wells;
- e) To provide treatment/ storage for reclaimed wastewater for subsequent partial/ total reuse;
- f) To conserve/ extract energy in the form of hot/ cold water.

The generally adopted methods of AGWR are as follows:

- i) Basin Method; ii) Stream channel method; iii) Ditch and furrow method; iv) Flooding method;
- v) Irrigation method; vi) Pit method and vii) Recharge well method.

*Question 12. What are the causes of sewer leakages?*

Answer 12. The following are the general causes of sewer leakages:

- a) Poor workmanship;
- b) Defective sewer pipe;
- c) Damage by tree roots;
- d) Damage due to earthquake;
- e) Damage due to heavy loads/ soil slippage/ landslides;
- f) Loss of foundation supports;
- g) Shearing caused by differential settlement in/ near manholes;
- h) Infiltration of sewage into abandoned sewer laterals.

*Question 13. Tabulate of drinking water quality standards as per Bureau of Indian standards (BIS).*

Answer 13. As per BIS 10500-1991, the following Table provides the drinking water quality standards [Source: [www.yourarticlelibrary.com](http://www.yourarticlelibrary.com)] :

<b>Sl. No.</b>	<b>Substance of Characteristic</b>	<b>Requirement (Desirable Limit)</b>	<b>Permissible Limit in the absence of Alternate source</b>
	<b>Essential characteristics</b>		
1.	Colour, (Hazen units, Max.)	5	25
2.	Odour	Unobjectionable	Unobjectionable
3.	Taste	Agreeable	Agreeable
4.	Turbidity (NTU, Max.)	5	10
5.	pH Value	6.5 to 8.5	No Relaxation
6.	Total Hardness (as CaCO <sub>3</sub> ) mg/lit., Max.	300	600
7.	Iron (as Fe) mg/lit, Max.	0.3	1.0
8.	Chlorides (as Cl) mg/lit, Max.	250	1000
9.	Residual, free chlorine, mg/lit, Min.	0.2	—
	<b>Desirable Characteristics</b>		
10.	Dissolved solids mg/lit, Max.	500	2000
11.	Calcium (as Ca) mg/lit, Max.	75	200
12.	Copper (as Cu) mg/lit, Max.	0.05	1.5
13.	Manganese (as Mn) mg/lit, Max.	0.10	0.3
14.	Sulfate (as SO <sub>4</sub> ) mg/lit, Max.	200	400
15.	Nitrate (as NO <sub>3</sub> ) mg/lit, Max.	45	100
16.	Fluoride (as F) mg/lit, Max.	1.9	1.5
17.	Phenolic Compounds (as C <sub>5</sub> H <sub>5</sub> OH) mg/lit, Max.	0.001	0.002
18.	Mercury (as Hg) mg/lit, Max.	0.001	No relaxation
19.	Cadmium (as Cd) mg/lit, Max.	0.01	No relaxation
20.	Selenium (as Se) mg/lit, Max.	0.01	No relaxation
21.	Arsenic (as As) mg/lit, Max.	0.05	No relaxation
22.	Cyanide (as CN) mg/lit, Max.	0.05	No relaxation
23.	Lead (as Pb) mg/lit, Max.	0.05	No relaxation
24.	Zinc (as Zn) mg/lit, Max.	5	15
25.	Anionic detergents (as MBAS) mg/lit, Max.	0.2	1.0
26.	Chromium (as Cr <sup>6+</sup> ) mg/lit, Max.	0.05	No relaxation
27.	Polynuclear aromatic hydrocarbons (as PAH) g/lit, Max.	—	—
28.	Mineral Oil mg/lit, Max.	0.01	0.03
29.	Pesticides mg/l, Max.	Absent	0.001
30.	Radioactive Materials (i) Alpha emitters Bq/l, Max. (ii) Beta emitters pci/l, Max.	— —	1.0 1.0
31.	Alkalinity mg/lit, Max.	200	600
32.	Aluminium (as Al) mg/lit, Max.	0.03	0.2
33.	Boron mg/lit., Max.	1	5

Question 14. What are the commonly used methods for graphical representation of GW quality?

Answer 14: The following are the commonly used methods for graphical representation of GW quality:

- a) Vertical bar graphs; b) Trilinear diagrams; c) Radiating vector diagrams; d) Circular diagrams; e) Semi-logarithmic diagrams; f) Pattern diagrams.

*Question 15. List the surface features identified by aerial photographs which assist in GW condition evaluation.*

Answer 15. The following are the surface features which are identified by aerial photographs:

- i) Topography, ii) Phreatophytes and aquatic plants, iii) Geological land forms expected to contain relatively permeable strata, iv) Lakes and streams, v) Moist depressions and seepages, vi) Springs, vii) Artificial water bodies.

*Question 16. Enumerate the different methods used in surface and subsurface investigation of GW.*

Answer 16. Different methods used in surface investigation of GW are as under:

- a) Electrical resistivity method, b) Seismic refraction method, c) Gravity method, and d) Magnetic method.

Different methods used in subsurface investigation of GW are as under:

- i) Resistivity logging method,  
 ii) Spontaneous potential logging method,  
 iii) Radiation logging method [including Natural gamma logging, gamma-gamma logging and Neutron logging method],  
 iv) Temperature logging method,  
 v) Caliper logging method,  
 vi) Fluid conductivity logging method,  
 vii) Fluid velocity logging method, and  
 viii) Miscellaneous logging methods.

*Question 17. Briefly elaborate on the Wenner and Schlumberger arrangements for electrode spacing to determine electrical resistivity.*

Answer 17. The Wenner arrangement and Schlumberger arrangements for electrode spacing to determine electrical resistivity are shown in the Following Figure 6:

The measurements of current (I) and voltage ( $V_m$ ) are used to calculate the apparent resistivity, ( $\rho_a$ ) which is the resistivity for the equivalent homogeneous earth that produces the same I and  $V_m$ . For the Wenner electrode configuration the apparent resistivity is given as:

$$\rho_a = 2\pi a \frac{V_m}{I} \quad (12)$$

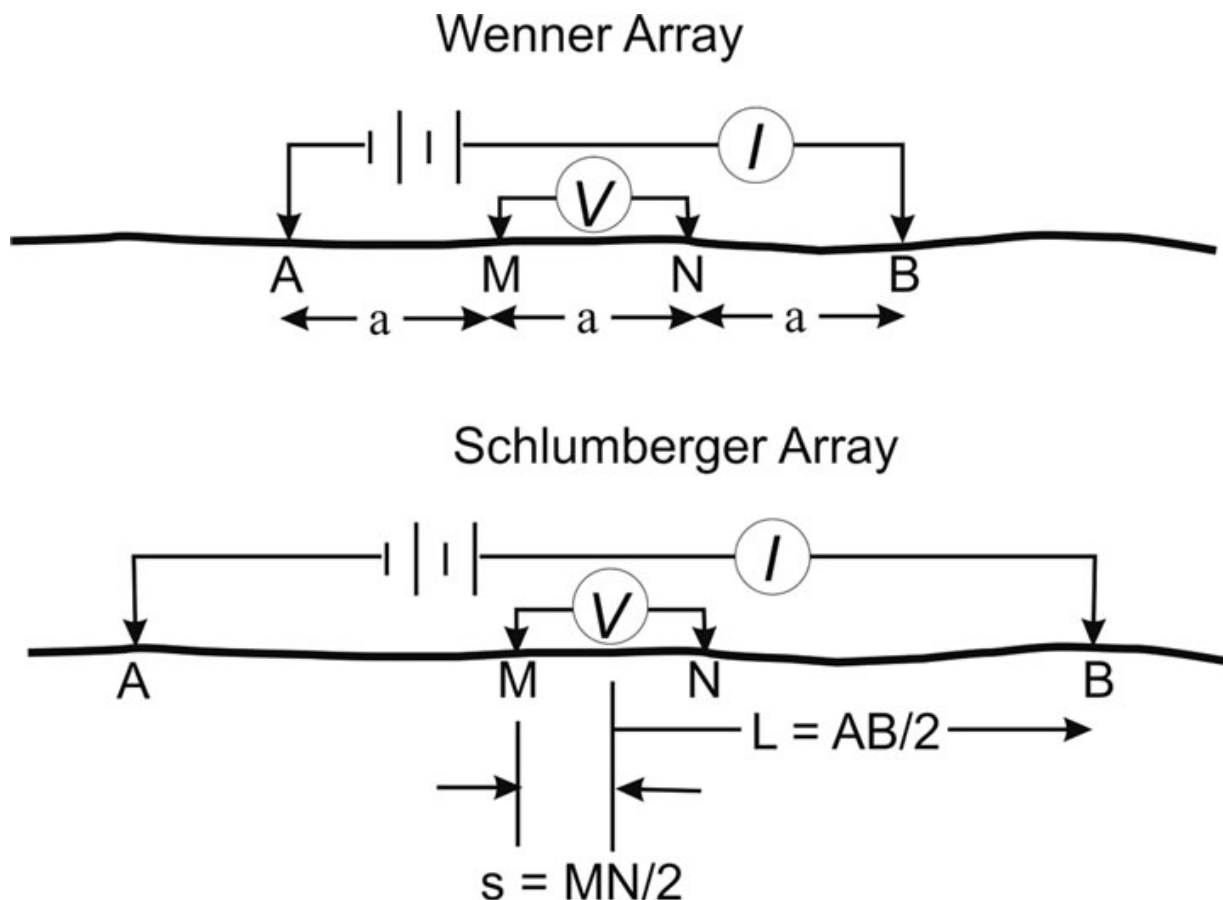


Figure 6. Wenner and Schlumberger arrangements for electrode spacing to determine electrical resistivity [Source: [http://file.scirp.org/Html/8-9401345\\_8137.htm](http://file.scirp.org/Html/8-9401345_8137.htm)]

For the Schlumberger arrangement the relationship is:

$$\rho_a = \frac{\pi V_m (L^2 - s^2)}{2sI} \tag{13}$$

with the L and s being the distances as defined in Figure 6. For a homogeneous earth structure, as the current electrodes are spread farther apart the apparent resistivity will not change. If the actual earth resistivity decreases with depth, the calculated apparent resistivity will decrease as the electrode spread increases. This occurs because at large spread a greater proportion of current is flowing in the lower resistivity region at depth, and that is reflected in the measured current and voltage at the surface. It is this relationship, coupled with theory of current flow in layered materials, that allow inference of resistivity properties at depth.

Two problems can arise in that 1) the earth may have a natural voltage or “self potential” that is unrelated to earth resistivity at depth, and 2) the DC current source itself can gradually induce an electrical potential around the electrodes from polarization. Both the self potential and the

induced polarization effects can be minimized by periodically reversing the current at a rate of about 1 Hertz. A slowly alternating current reduces polarization because a charge concentration cannot accumulate.

*Question 18: Elaborate on the neutron logging method for subsurface investigation of GW.*

Answer 18. In neutron logging, the formation is bombarded with high energy neutrons that scatter due to the presence of hydrogen atoms. This scattering reduces the energy of the neutrons or gamma rays, so gamma ray count back to the tool will decrease. Therefore, formations with high hydrogen concentration will result in low gamma ray detection. In reality, there are other elements that affect the attenuation. These errors are minimized by calibrating the tool to pure limestone. The results are not porosities of the formation, but the porosity that would occur if the formation tested was a limestone. The porosity is then corrected for the appropriate type of rock. Figure 7 shows various neutron porosities for differing rock types.

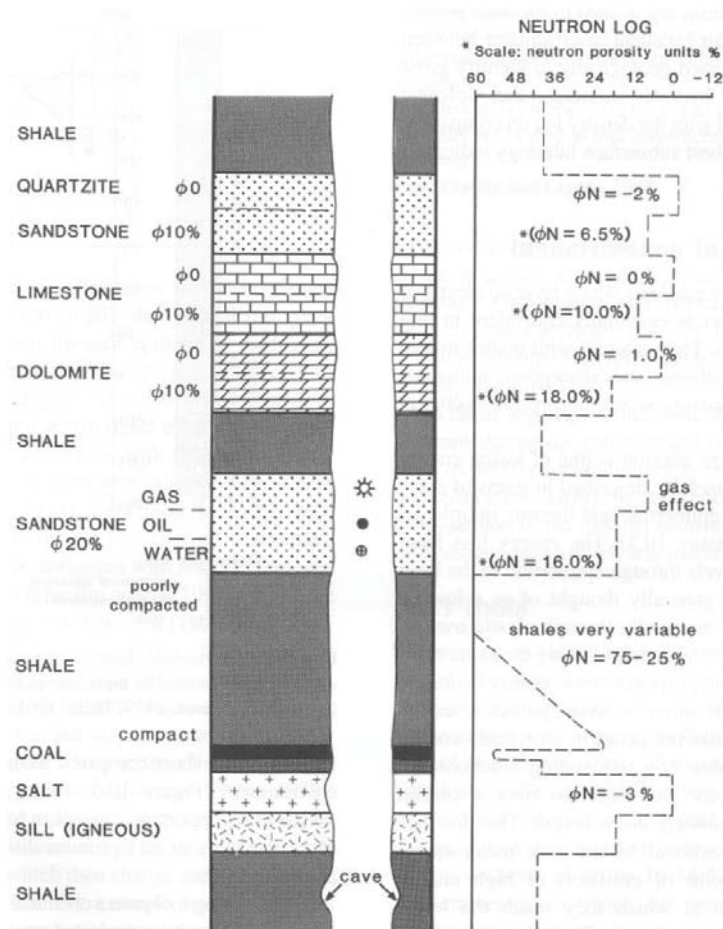


Figure 7. Neutron log of various rock types showing neutron porosity changes with lithology. [Source: [http://www.colorado.edu/geolsci/Resources/WUSTectonics/Salt\\_Tectonics/method.htm](http://www.colorado.edu/geolsci/Resources/WUSTectonics/Salt_Tectonics/method.htm).

Various lithologies are identified based on which rock type contains hydrogen atoms (e.g., hydrated minerals are present in metamorphic rocks and bound water is present in shale). Hydrated evaporites (i.e., gypsum, kainite, carnalite, and polyhalite) are detected using waters of crystallization, which give limestone porosities specific to the rock type. Limestone porosities for evaporites that contain no water are low since they lack hydrogen.