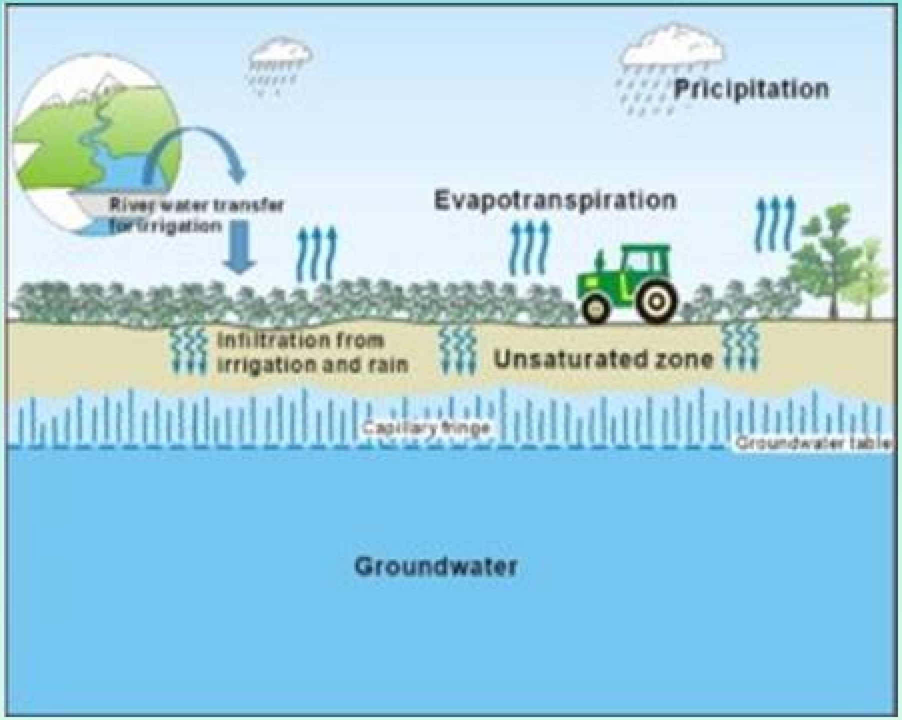
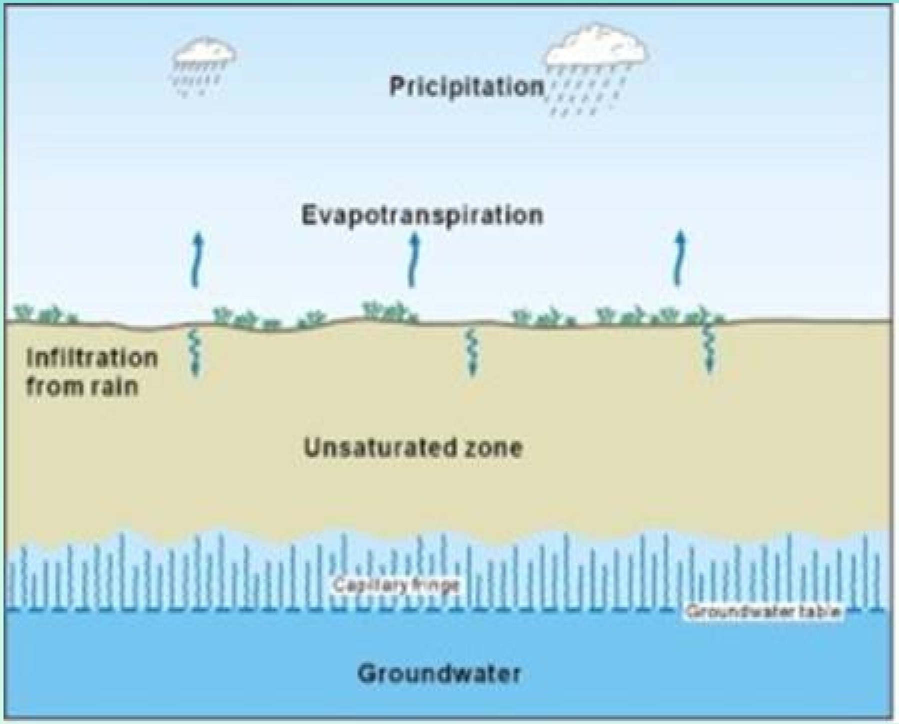
Basics of Groundwater Hydrology – Utilization, Flow & Transport

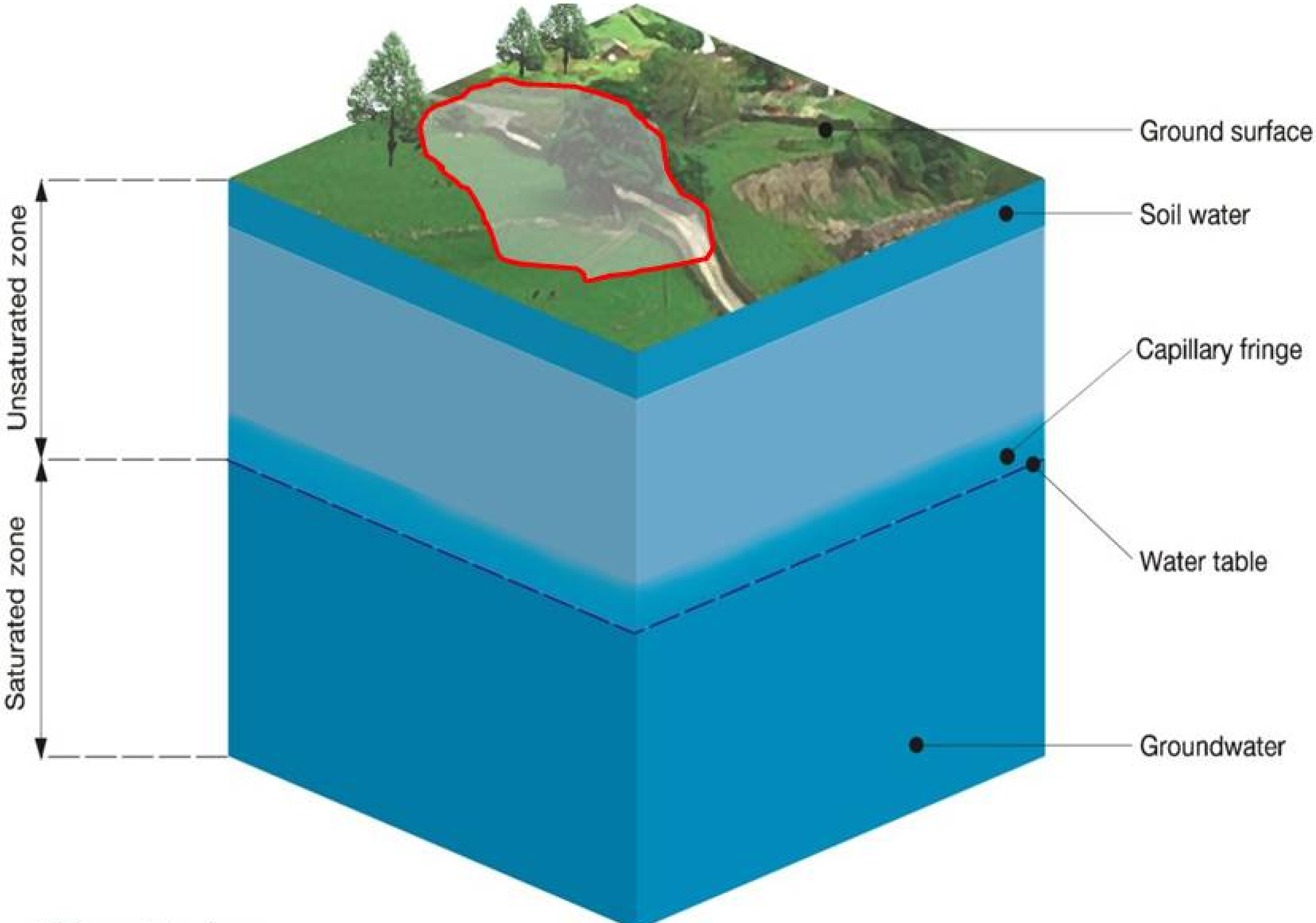




Outline of Presentation

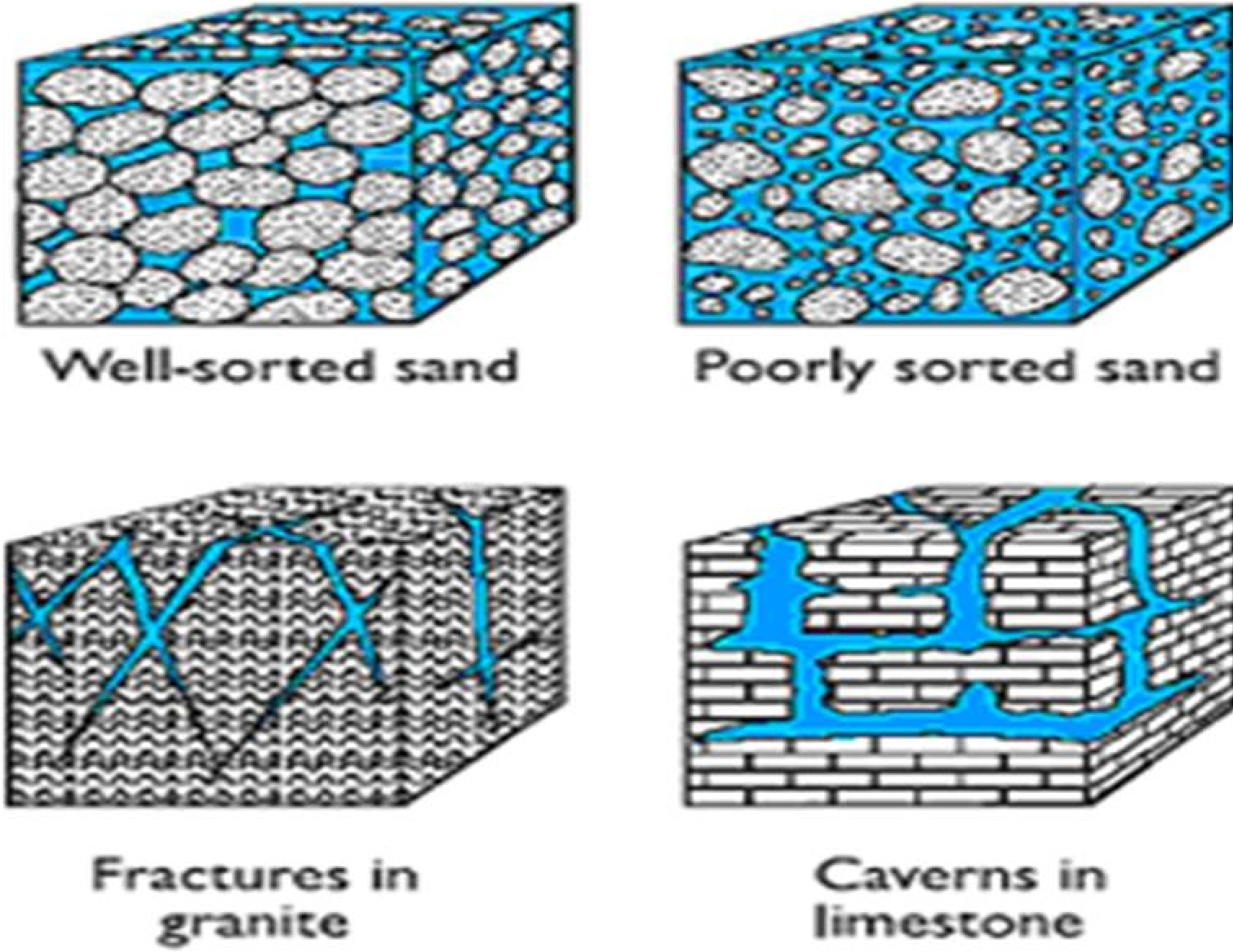
- Groundwater Basics
- Occurrence
- Utilization
- Properties & Data
- Groundwater Flow & Transport

Groundwater System Input



UK Groundwater Forum

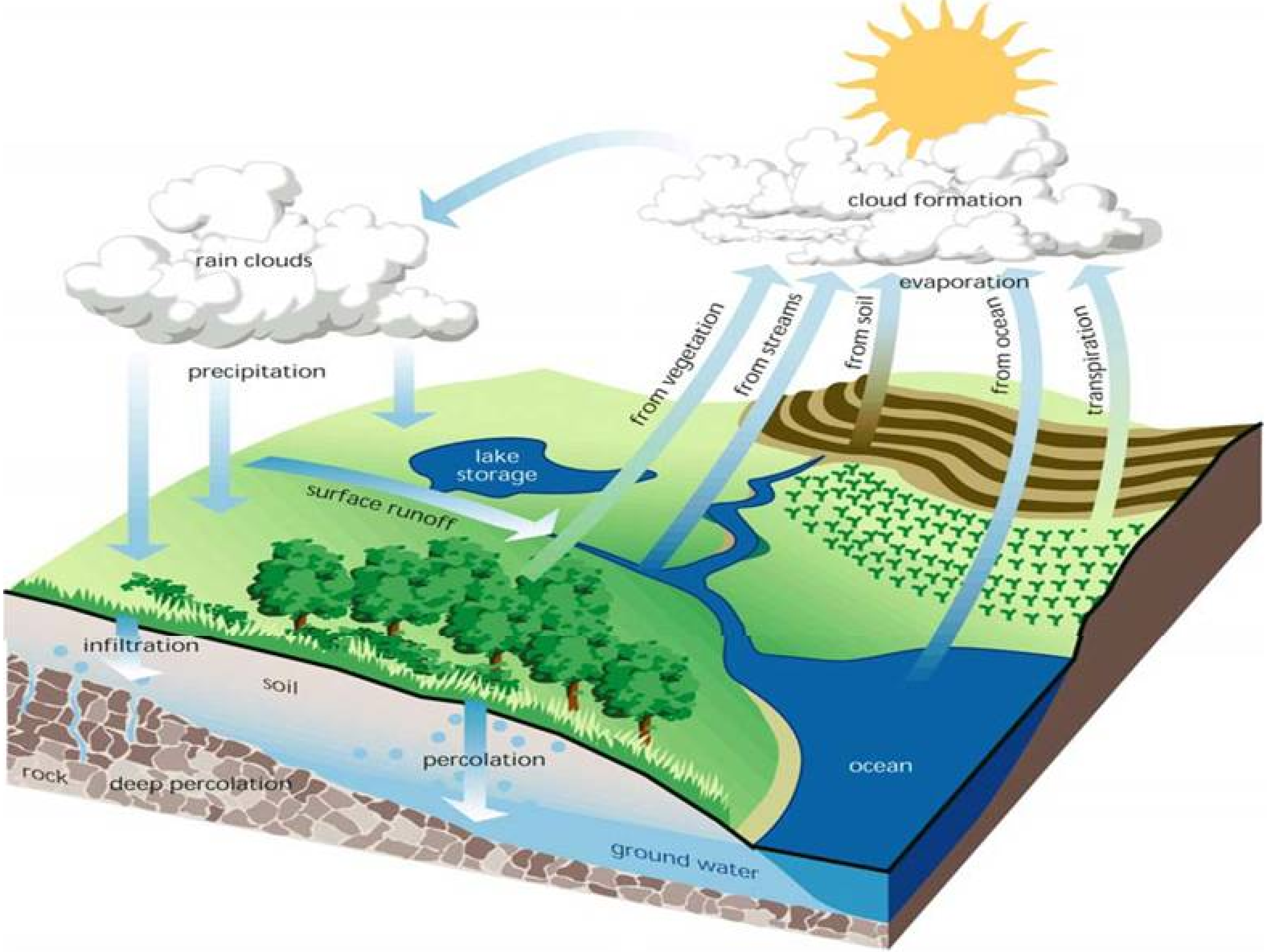
Groundwater



Hydrological Cycle & Groundwater

- **Hydrological cycle** is the most fundamental principle of groundwater hydrology.
- **Radiant energy** from the sun is the driving force for the circulation of atmospheric water.
- Water **evaporates** and travels into the air and becomes part of a cloud. It falls down to earth as precipitation. Then it evaporates again. This happens repeatedly in a never-ending cycle. Water keeps moving and changing from a solid to a liquid to a gas, repeatedly. This **hydrologic cycle** never stops.
- **Precipitation** creates **runoff** that travels over the ground surface and helps to fill lakes and rivers.
- It also **percolates** or moves downward through openings in the soil & rock to replenish **aquifers** under the ground called **groundwater**.
- Some places receive more **precipitation** than others do. These areas are usually close to oceans or large bodies of water that allow more water to **evaporate** and form clouds. Other areas receive less. Often these areas are far from seawater or near mountains.
- As clouds move up and over mountains, the water vapor condenses to form precipitation and freezes and thus **snow falls** on the peaks of mountains.

Groundwater System: Part of Hydrologic Cycle



Groundwater

- **Water that exists in the pore spaces and fractures in sediments and rocks below the ground surface is called groundwater.**

- **It originates as rainfall or snow, and then moves through the soil and rock into the groundwater system, where it eventually makes its way back to the surface streams, lakes, or oceans.**

- **Water table is the surface of water level in an unconfined aquifer at which the pressure is atmospheric.** ***It is the level at which the water will stand in a well drilled in an unconfined aquifer.***

- **A dependable source during droughts & floods.**

Groundwater

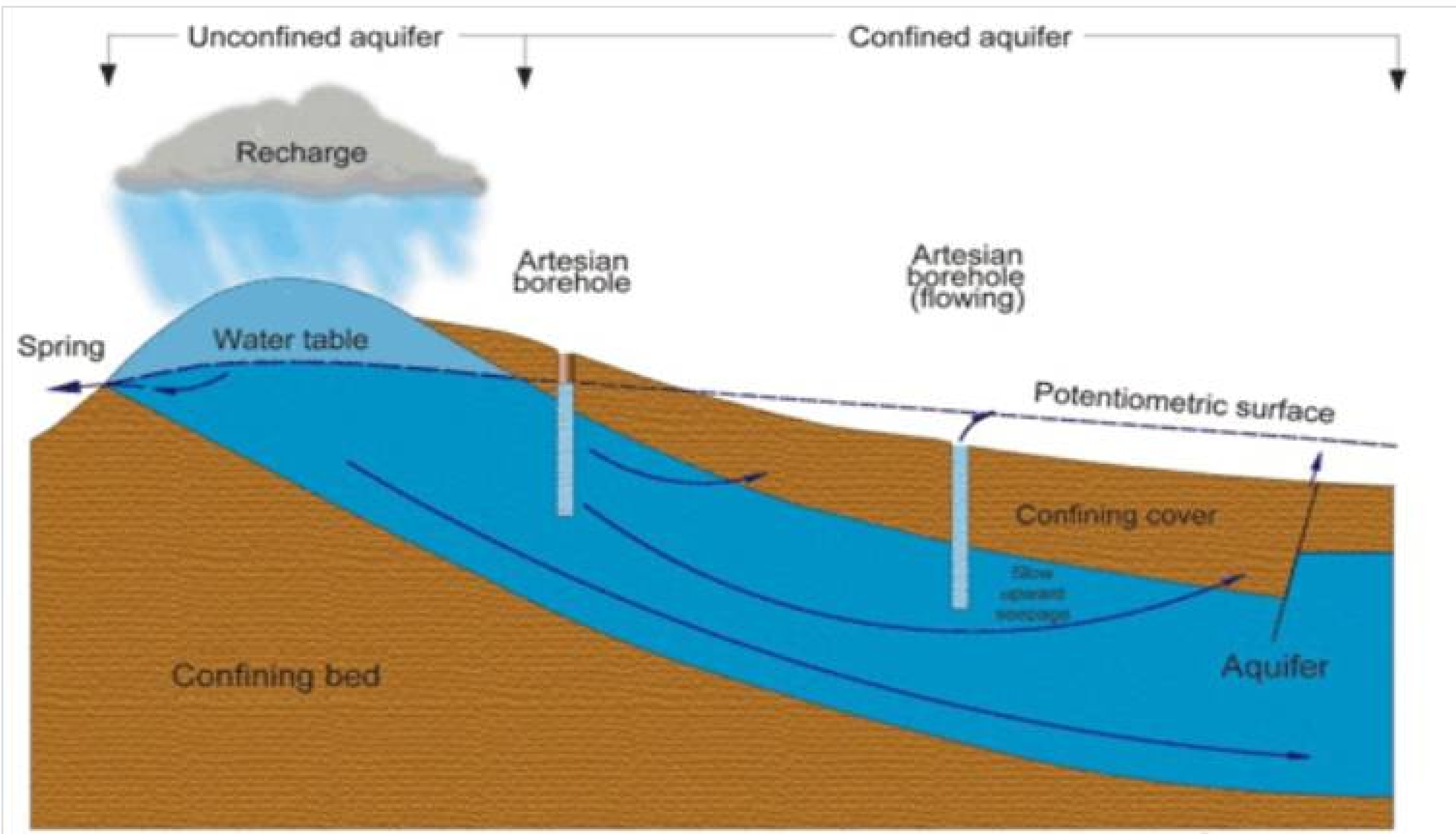
A hidden & common pool resource	Can be drawn as much as required	Has specific characteristics, like: - Large storage volume - Slow moving - Relatively risk free from pollution than SW - No evaporation

Groundwater Table

- Water Table is the surface of water level in an unconfined aquifer at which the pressure is atmospheric. It is the same level in an unconfined aquifer at which the water will stand in an observation well drilled.
- Water table is the surface of water level in an unconfined aquifer at which the pressure is atmospheric.
- It is the level at which the water will stand in a well drilled in an unconfined aquifer. The water table fluctuates whenever there is a recharge or an outflow from the aquifer. In fact, the water table is constantly in motion adjusting its surface to achieve a balance between the recharge and the outflow.
- Generally, the water table follows the topographic features and is high below ridges and low below valleys. However, sometimes the topographic ridge and the water table ridge may not coincide and there may be flow from one aquifer to the other aquifer, called **watershed leakage.**
- Wherever the water table intersects the ground surface, a seepage surface or a **spring** is formed.

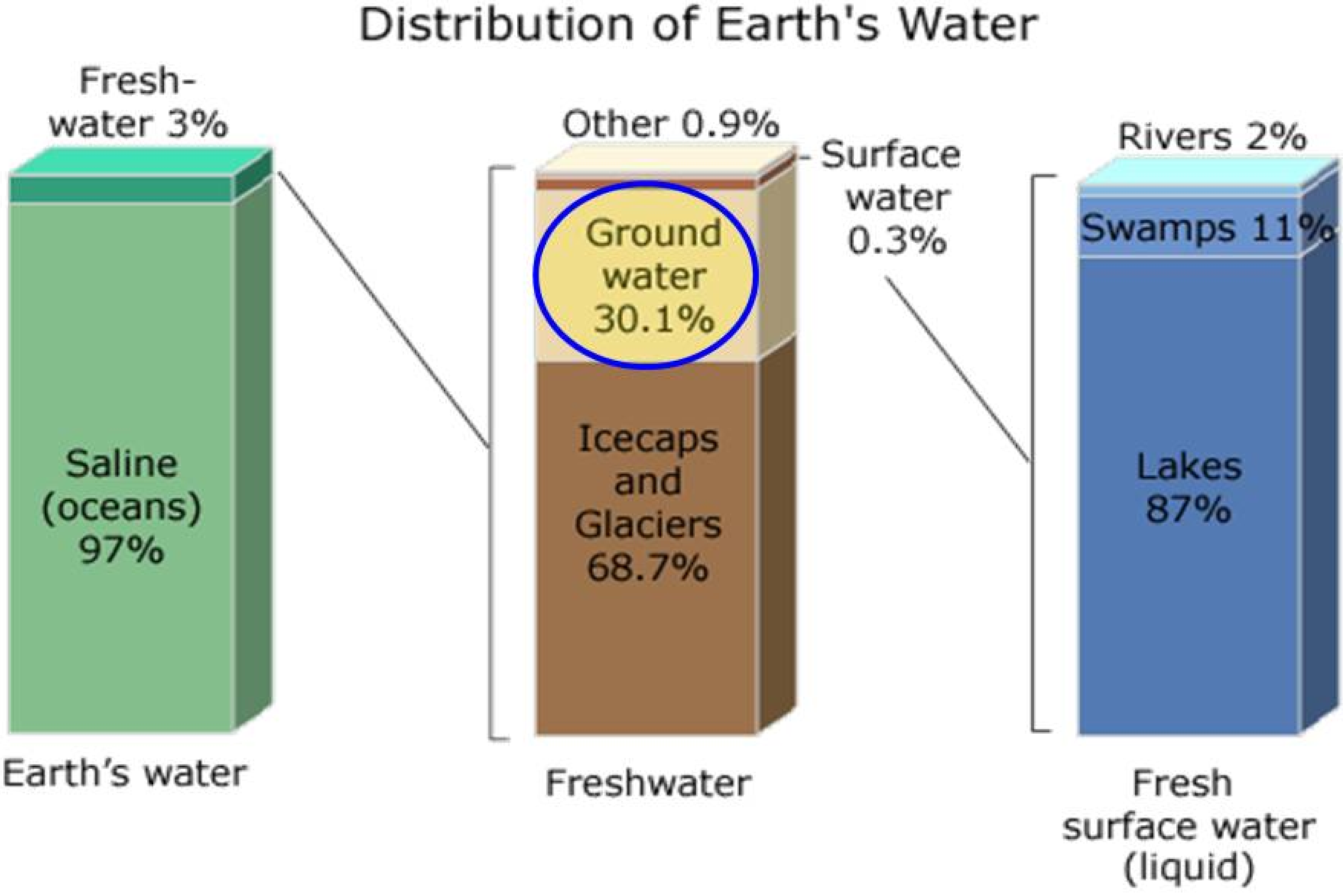
Piezometric surface

The water in a confined aquifer is under pressure. When a well is drilled in a confined aquifer, the water level in it will rise above the top of aquifer. **The piezometric surface is an imaginary surface to which the water level would rise if a piezometer was inserted in the aquifer.** Thus, it indicates the pressure of the water in the aquifer. Hence, a piezometric surface is the water table equivalent of the confined aquifer.



Groundwater Utilization

Global Groundwater Resource



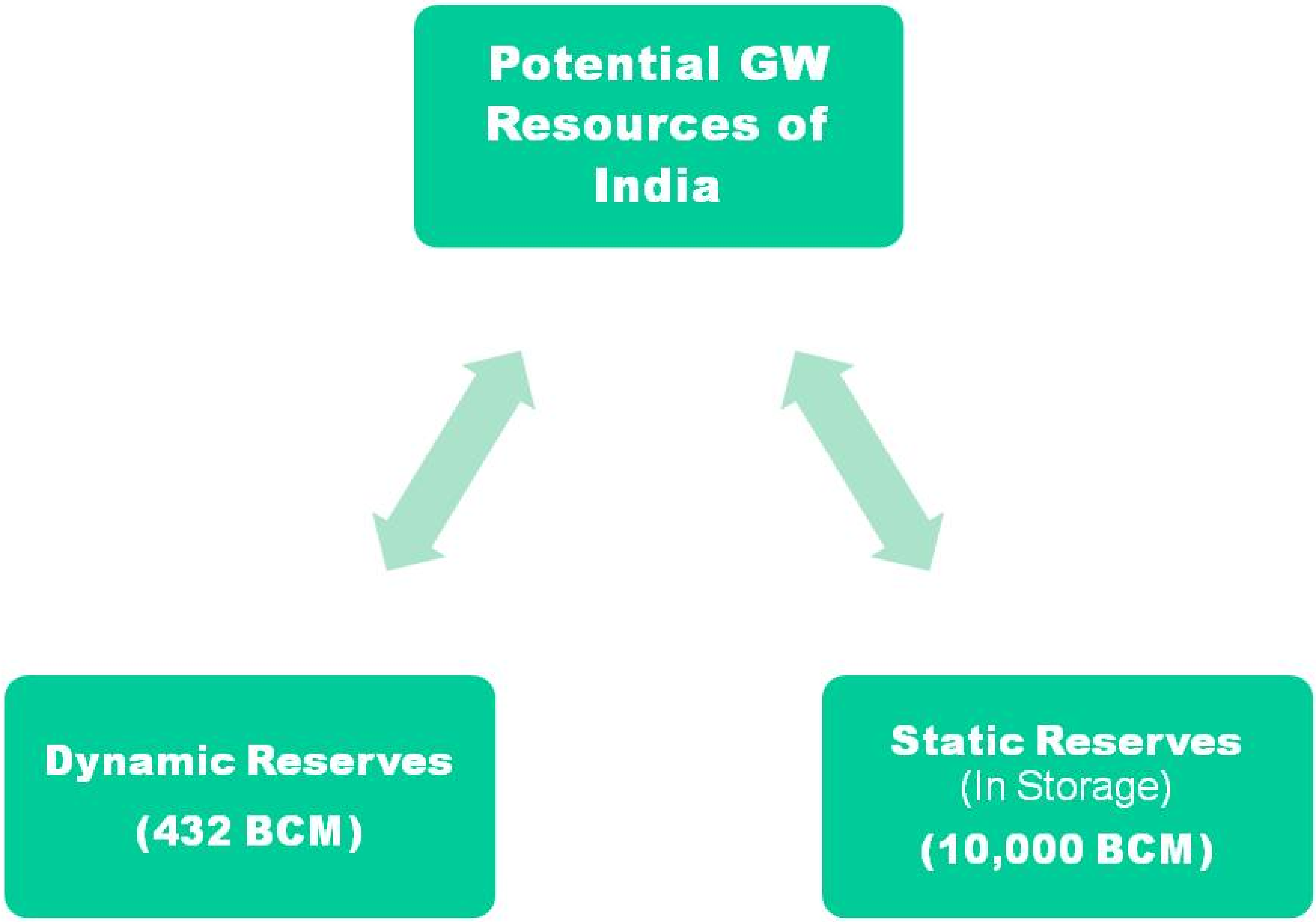
Indian Scenario for GW Use

Groundwater serves:

— **80 % Rural Population**

— **50 % Urban Population**

— **More than 50 % Irrigated Agriculture**


Potential GW Resources of India
Dynamic Reserves
(432 BCM)
Static Reserves
(In Storage)
(10,000 BCM)

Indian Scenario for GW Use

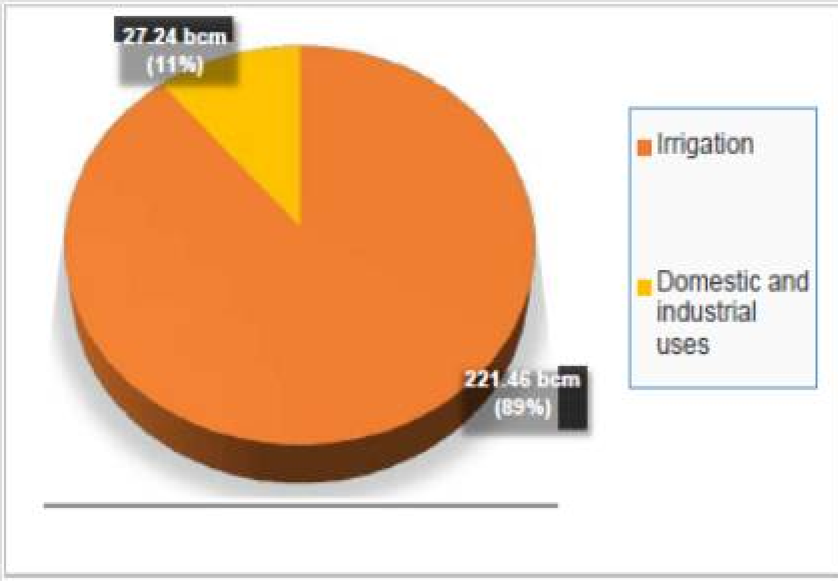
Groundwater serves:

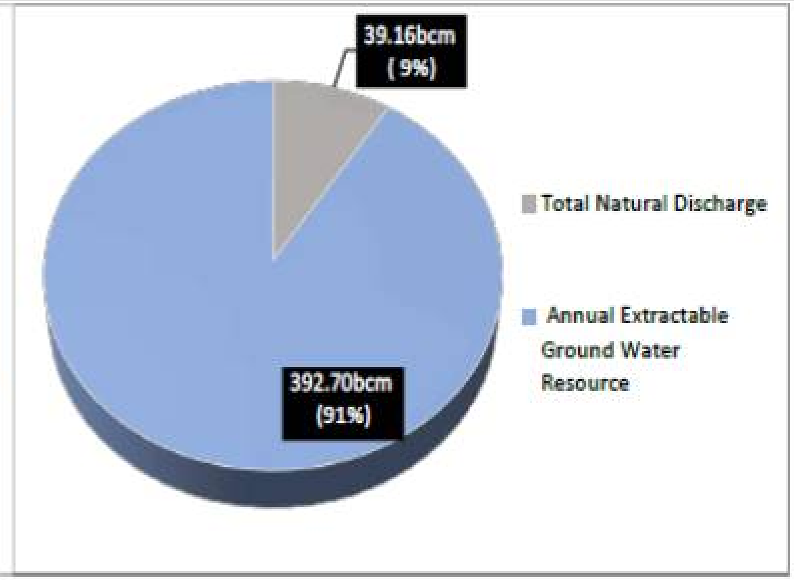
— 80 % Rural Population

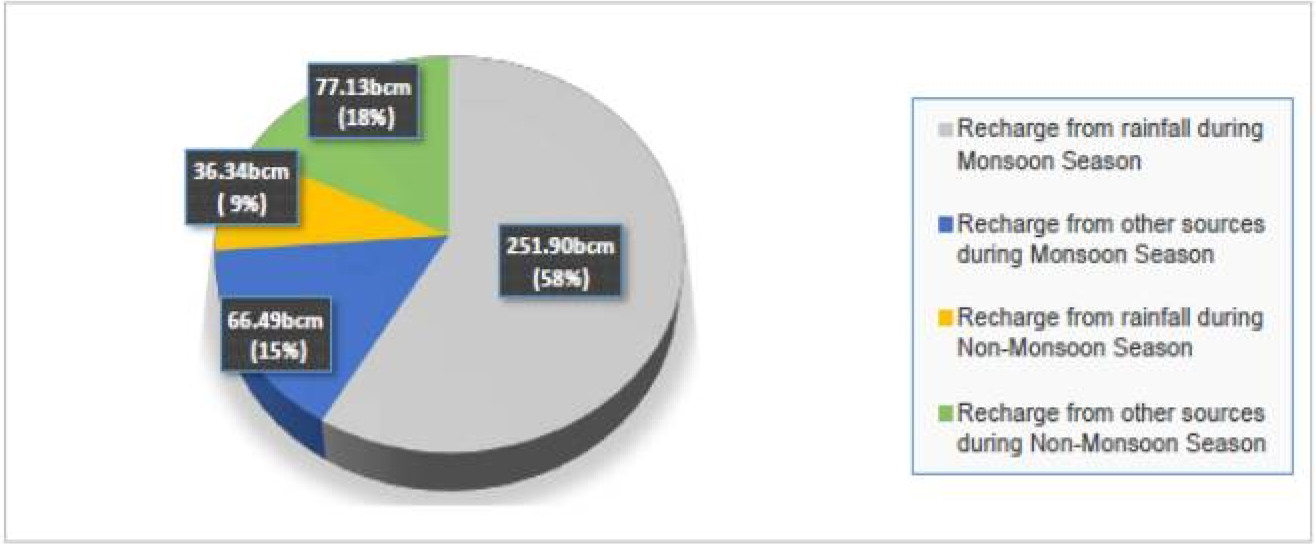
— 50 % Urban Population

— More than 50 % Irrigated Agriculture

Groundwater Utilization – Indian Scenario







Groundwater Utilization – Indian Scenario

Groundwater Resource Assessment: 2004 to 2017

S. No.	Ground Water Resources Assessment	2004	2009	2011	2013	2017
1	Annual Replenishable Ground Water Resources	433 bcm	431 bcm	433 bcm	447 bcm	432 bcm
2	Net Annual Ground Water Availability	399 bcm	396 bcm	398 bcm	411 bcm	393 bcm
3	Annual Ground Water Draft for Irrigation, Domestic & Industrial uses	231 bcm	243 bcm	245 bcm	253 bcm	249 bcm
4	Stage of Ground Water Development	58%	61%	62%	62 %	63%

Categorization of Assessment Units: 2004 to 2017

S. No.	Categorization of Blocks/ Mandals/ Talukas	2004	2009	2011	2013	2017
1	Total Assessed units	5723	5842	6607	6584	6881
2	Safe	4078	4277	4503	4519	4310
3	Semi-critical	550	523	697	681	972
4	Critical	226	169	217	253	313
5	Over-Exploited	839	802	1071	1034	1186
6	Saline	30	71	92	96	100

Groundwater Utilization - States

STATE-WISE GROUND WATER RESOURCES OF INDIA, 2017

(in bcm)

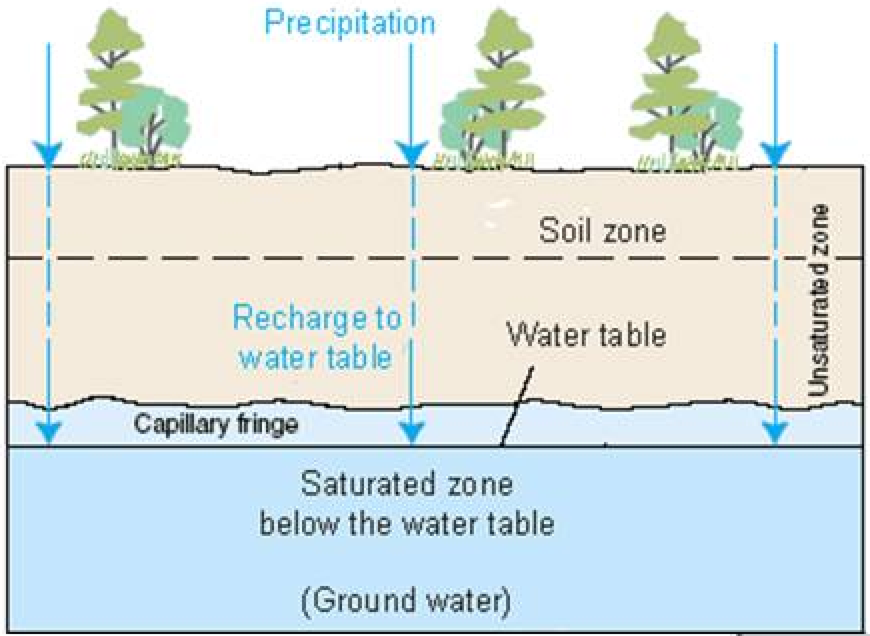
S. No.	States / Union Territories	Ground Water Recharge: Monsoon Season: Recharge from rainfall	Ground Water Recharge: Monsoon Season: Recharge from other sources	Ground Water Recharge: Non-monsoon Season: Recharge from rainfall	Ground Water Recharge: Non-monsoon Season: Recharge from other sources	Total Annual Ground Water Recharge	Total Natural Discharges	Annual Extractable Ground Water Resource	Current Annual Ground Water Extraction: Irrigation	Current Annual Ground Water Extraction: Industrial	Current Annual Ground Water Extraction: Domestic	Current Annual Ground Water Extraction: Total	Annual GW Allocation for for Domestic Use as on 2025	Net Ground Water Availability for future use	Stage of Ground Water Extraction (%)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	States														
1	Andhra Pradesh	9.96	5.62	1.21	4.42	21.22	1.07	20.15	7.85	0.14	0.90	8.90	1.48	12.31	44.15
2	Arunachal Pradesh	1.89	0.18	0.95	0.01	3.02	0.36	2.67	0.00	0.00	0.01	0.01	0.03	2.64	0.28
3	Assam	20.22	0.43	7.28	0.74	28.67	4.42	24.26	1.97	0.06	0.69	2.73	0.79	21.43	11.25
4	Bihar	19.83	3.95	3.14	4.50	31.41	2.43	28.99	10.78	0.66	1.83	13.26	1.83	15.78	45.76
5	Chhattisgarh	7.82	1.36	0.76	1.64	11.57	1.00	10.57	3.98	0.05	0.67	4.70	0.79	5.76	44.43
6	Delhi	0.13	0.06	0.03	0.11	0.32	0.02	0.30	0.09	0.02	0.24	0.36	0.29	0.02	119.61
7	Goa	0.19	0.03	0.01	0.05	0.27	0.11	0.16	0.02	*	0.03	0.05	0.04	0.07	33.50
8	Gujarat	15.95	3.40	0.00	3.02	22.37	1.12	21.25	12.84	0.11	0.63	13.58	0.90	7.98	63.89
9	Haryana	3.56	2.55	1.03	3.00	10.15	1.01	9.13	11.53	0.34	0.63	12.50	0.72	0.87	136.91
10	Himachal Pradesh	0.34	0.02	0.11	0.04	0.51	0.05	0.46	0.20	0.00	0.19	0.39	0.34	0.16	86.37
11	Jammu & Kashmir	1.00	0.50	0.88	0.51	2.89	0.29	2.60	0.20	0.07	0.50	0.76	0.50	1.84	29.47
12	Jharkhand	5.25	0.13	0.41	0.42	6.21	0.52	5.69	0.80	0.22	0.56	1.58	0.56	4.13	27.73
13	Karnataka	6.59	4.36	2.67	3.22	16.84	2.05	14.79	9.39	*	0.95	10.34	1.14	5.41	69.87
14	Kerala	3.91	0.04	0.68	1.13	5.77	0.56	5.21	1.22	0.01	1.44	2.67	1.57	2.41	51.27
15	Madhya Pradesh	27.10	1.51	0.82	6.99	36.42	1.95	34.47	17.43	0.22	1.24	18.88	1.72	15.84	54.76
16	Maharashtra	20.59	2.29	0.53	8.23	31.64	1.74	29.90	15.10	0.003	1.22	16.33	2.28	12.91	54.62
17	Manipur	0.23	0.01	0.17	0.02	0.43	0.04	0.39	0.00	0.00	0.00	0.01	0.04	0.34	1.44
18	Meghalaya	1.37	0.01	0.43	0.02	1.83	0.19	1.64	0.03	0.00	0.01	0.04	0.02	1.59	2.28
19	Mizoram	0.16	0.00	0.05	0.00	0.21	0.02	0.19	0.00	0.00	0.01	0.01	0.01	0.18	3.82
20	Nagaland	1.65	0.03	0.52	0.00	2.20	0.22	1.98	0.00	0.00	0.02	0.02	0.02	1.96	0.99
21	Odisha	10.53	2.34	1.50	2.37	16.74	1.17	15.57	5.28	0.14	1.15	6.57	1.30	8.85	42.18
22	Punjab	5.54	11.83	1.31	5.25	23.93	2.35	21.58	34.56	0.20	1.01	35.78	1.41	1.09	165.77
23	Rajasthan	9.74	0.78	0.24	2.44	13.21	1.22	11.99	14.85	0.00	1.92	16.77	2.67	0.88	139.88
24	Sikkim	5.20	0.00	0.43	0.00	5.63	4.11	1.52	0.00	0.00	0.00	0.00	0.01	1.51	0.06
25	Tamil Nadu	6.67	9.41	1.89	2.26	20.22	2.02	18.20	13.06	0.00	1.67	14.73	1.85	5.66	80.94
26	Telangana	7.56	1.42	1.88	2.76	13.62	1.25	12.37	7.09	*	1.00	8.09	1.39	4.26	65.45
27	Tripura	0.80	0.06	0.40	0.26	1.53	0.29	1.24	0.02	0.00	0.08	0.10	0.11	1.11	7.88
28	Uttar Pradesh	37.73	11.67	1.59	18.93	69.92	4.60	65.32	40.89	*	4.95	45.84	5.96	20.36	70.18
29	Uttarakhand	1.15	0.93	0.09	0.87	3.04	0.15	2.89	1.30	0.13	0.22	1.64	0.22	1.25	56.83
30	West Bengal**	18.71	1.51	5.26	3.85	29.33	2.77	26.56	10.84	*	1.00	11.84	1.53	14.19	44.60
	Total States	**261.36**	**66.41**	**36.30**	**77.06**	**431.13**	**39.09**	**392.04**	**221.33**	**2.38**	**24.77**	**248.47**	**31.62**	**172.82**	**63.38**
	Union Territories														
1	Andaman & Nicobar	0.35	0.00	0.02	0.00	0.37	0.04	0.33	0.00	0.00	0.01	0.01	0.01	0.32	2.74
2	Chandigarh	0.02	0.01	0.00	0.01	0.04	0.00	0.04	0.00	*	0.03	0.03	0.03	0.00	89.00
3	Dadra & Nagar Haveli	0.06	0.00	0.00	0.01	0.07	0.00	0.07	0.01	*	0.01	0.02	0.01	0.04	31.34
4	Daman & Diu	0.02	0.00	0.00	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.01	0.00	0.00	61.40
5	Lakshdweep	0.01	0.00	0.00	0.00	0.01	0.01	0.004	0.00	0.00	0.002	0.002	0.00	0.00	65.99
6	Puducherry	0.09	0.07	0.02	0.05	0.23	0.02	0.20	0.11	*	0.04	0.15	0.04	0.05	74.33
	Total UTs	**0.54**	**0.08**	**0.06**	**0.07**	**0.73**	**0.08**	**0.66**	**0.13**	**0.00**	**0.10**	**0.23**	**0.10**	**0.40**	**34.61**
	Grand Total	**261.90**	**66.49**	**36.34**	**77.13**	**431.86**	**39.16**	**392.70**	**221.46**	**2.38**	**24.87**	**248.69**	**31.82**	**173.26**	**63.33**

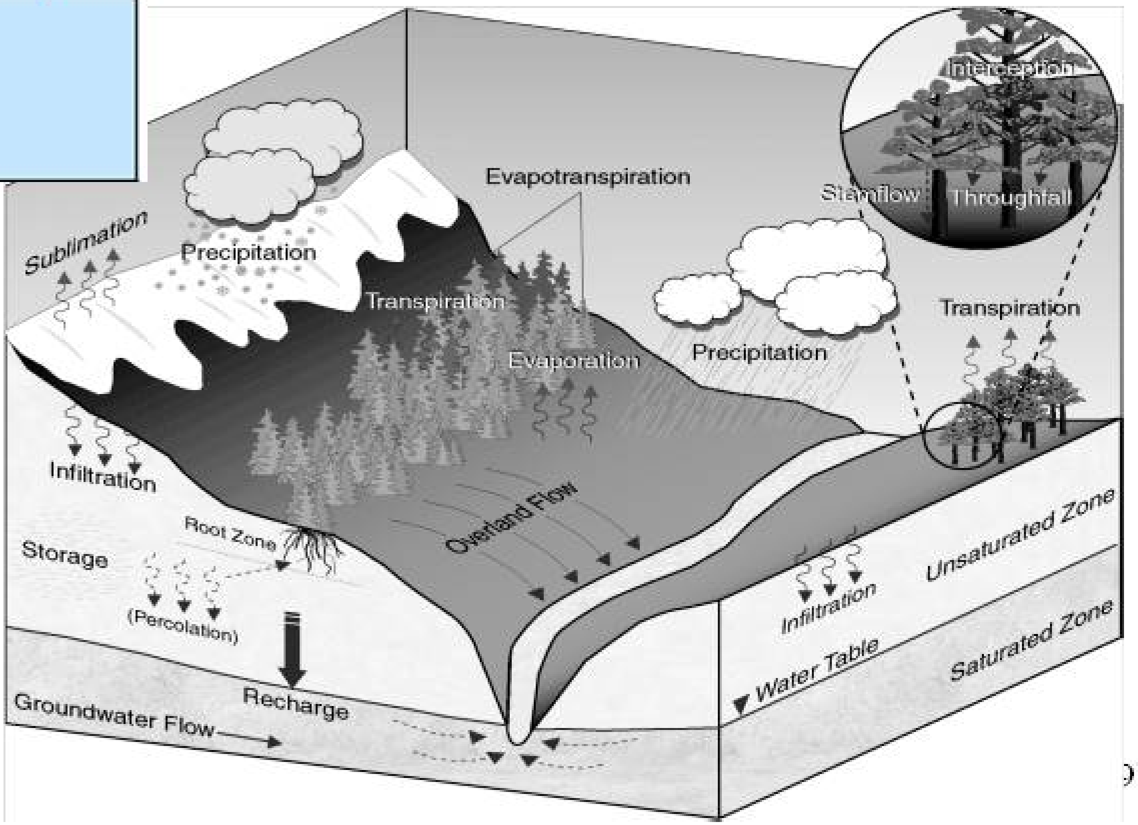
Note:

*Industrial and domestic draft has not been estimated separately in Goa, Himachal Pradesh, Karnataka, Rajasthan, Tamil Nadu, Uttar Pradesh, Chandigarh, Dadra & Nagar Haveli and Puducherry

**The Ground Water resources assessment as on 2013 has been considered for the state of West Bengal

Movement of Groundwater





Formation of Aquifers

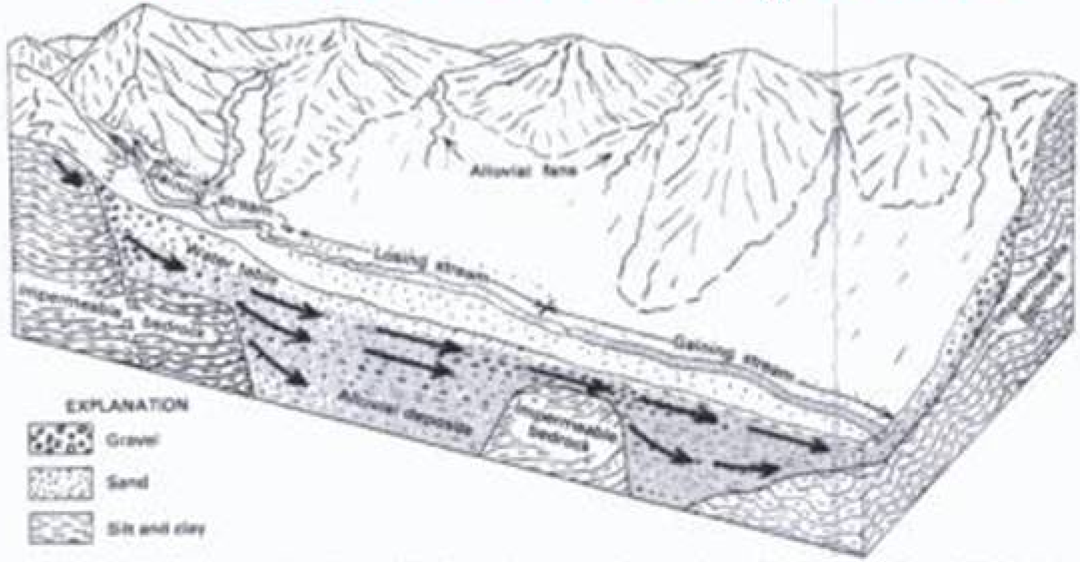


Figure 3.9. Unconfined aquifer development in an alluvial basin (Heath, 1984).

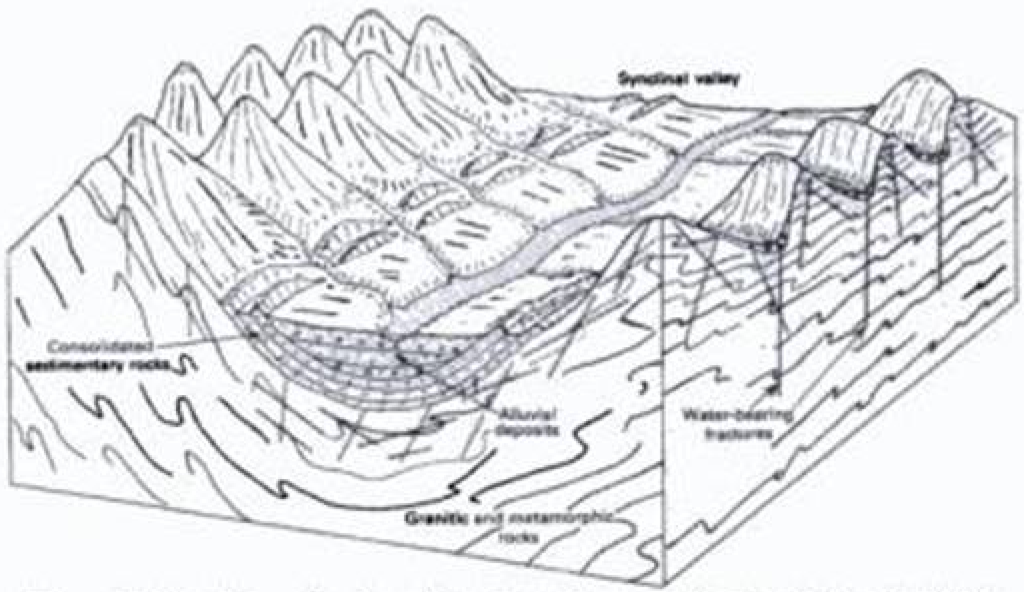
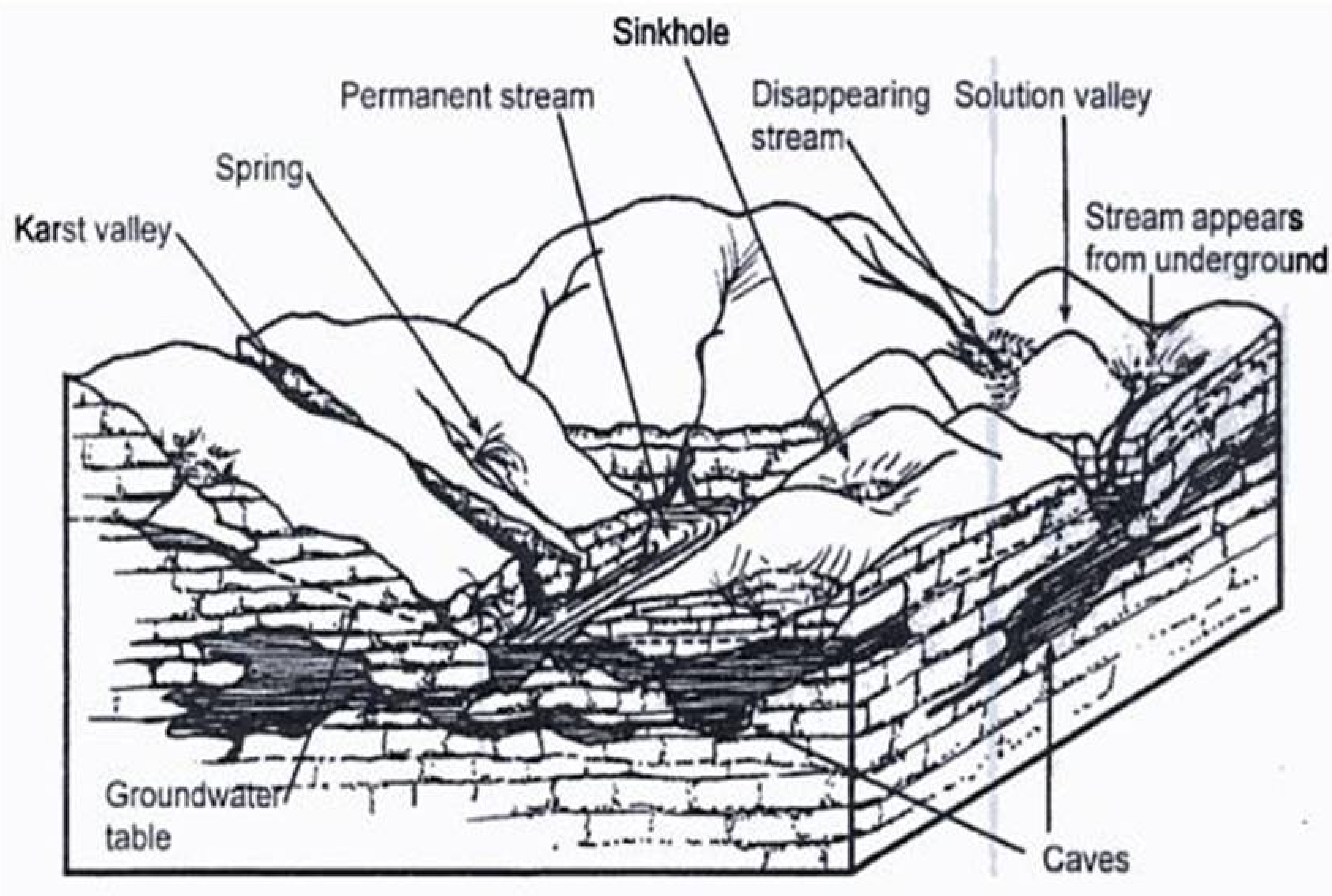


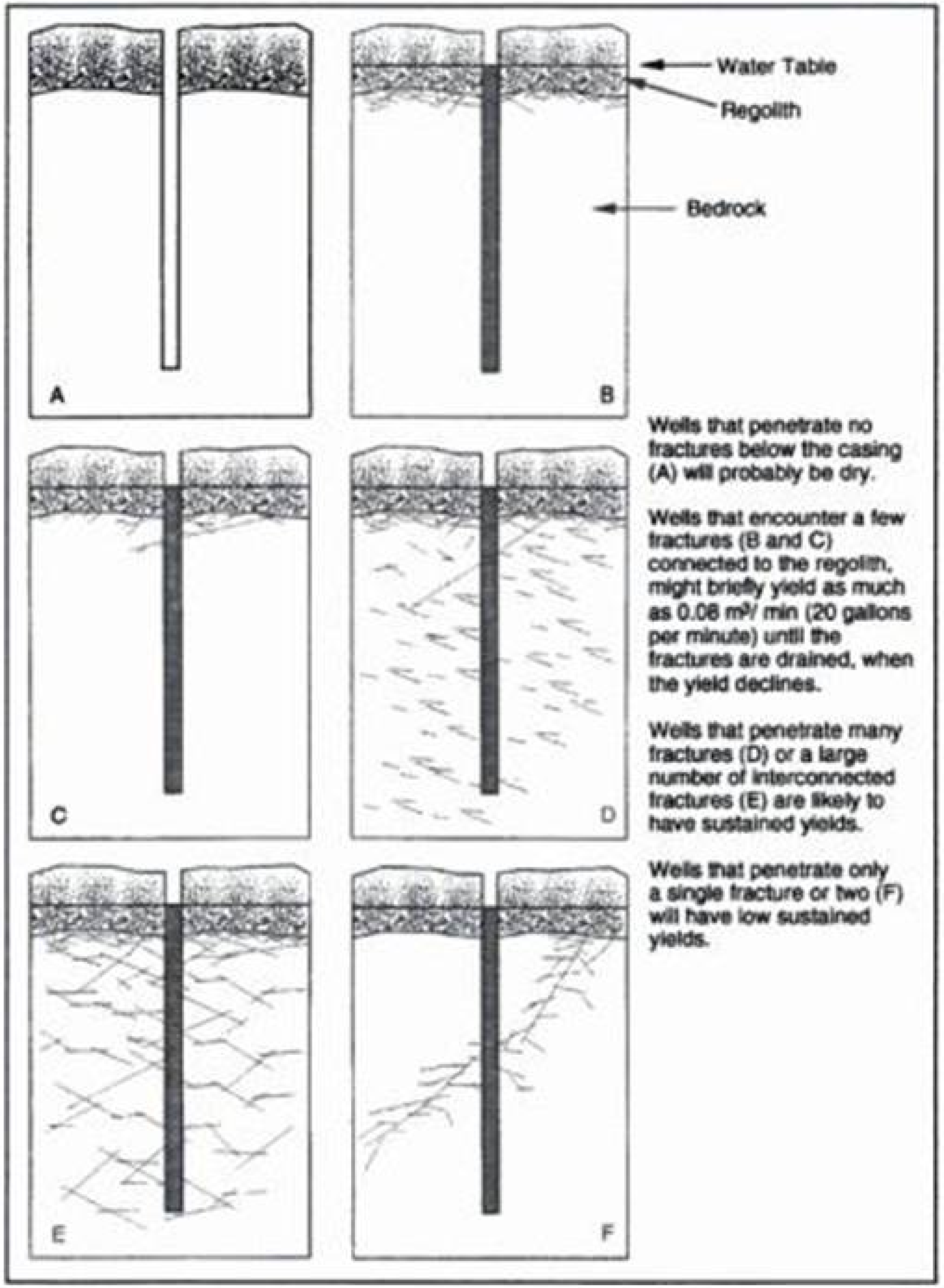
Figure 3.10. Unconfined aquifer above fractured bedrock (Heath, 1984).

Karst Aquifer System



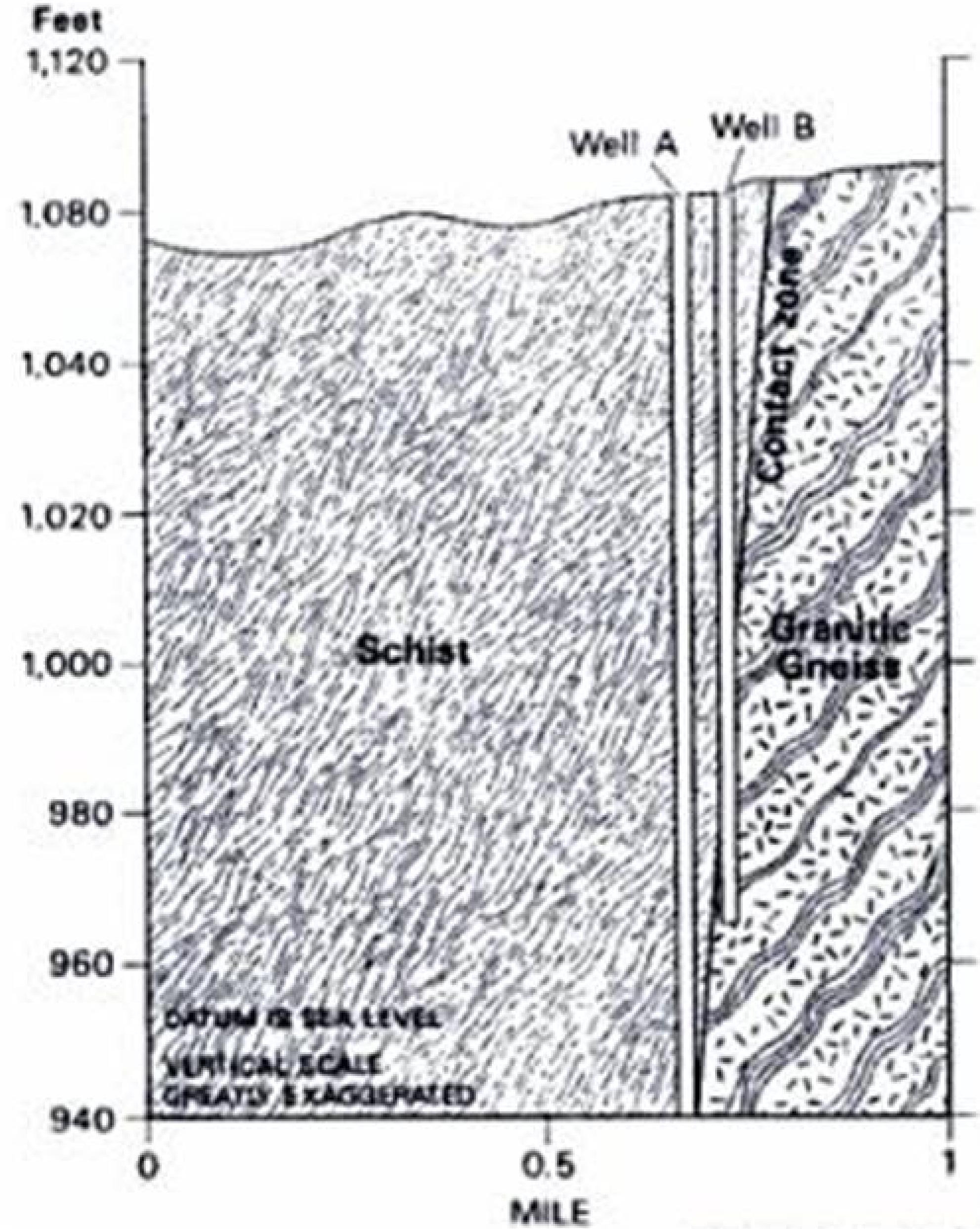
Fractured Rock System

In crystalline rocks, wells will have greater yield if they penetrate many fractures or interconnected fractures.



Water Yield

Wells screened in granitic gneiss and contact zones may provide higher yields.



Aquifer Properties

The following properties of the aquifer are required for study of groundwater hydrology:

1. Porosity
2. Specific Yield
3. Specific Retention
4. Coefficient of Permeability
5. Transmissibility
6. Specific Storage
7. Storage Coefficient

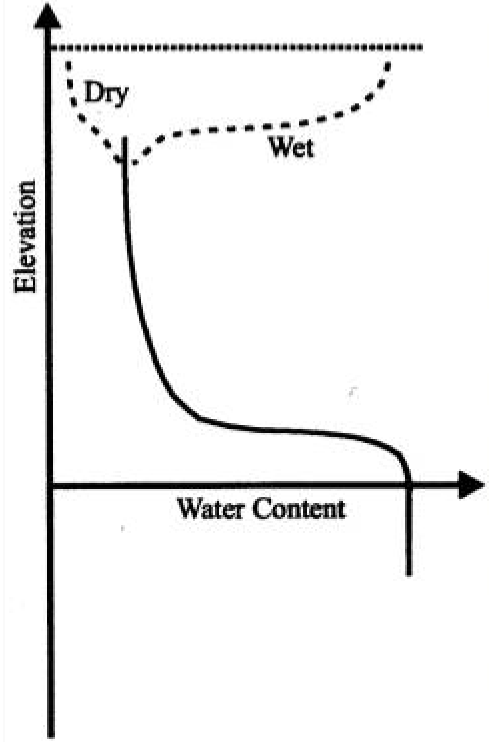
Distribution of Water in Subsurface

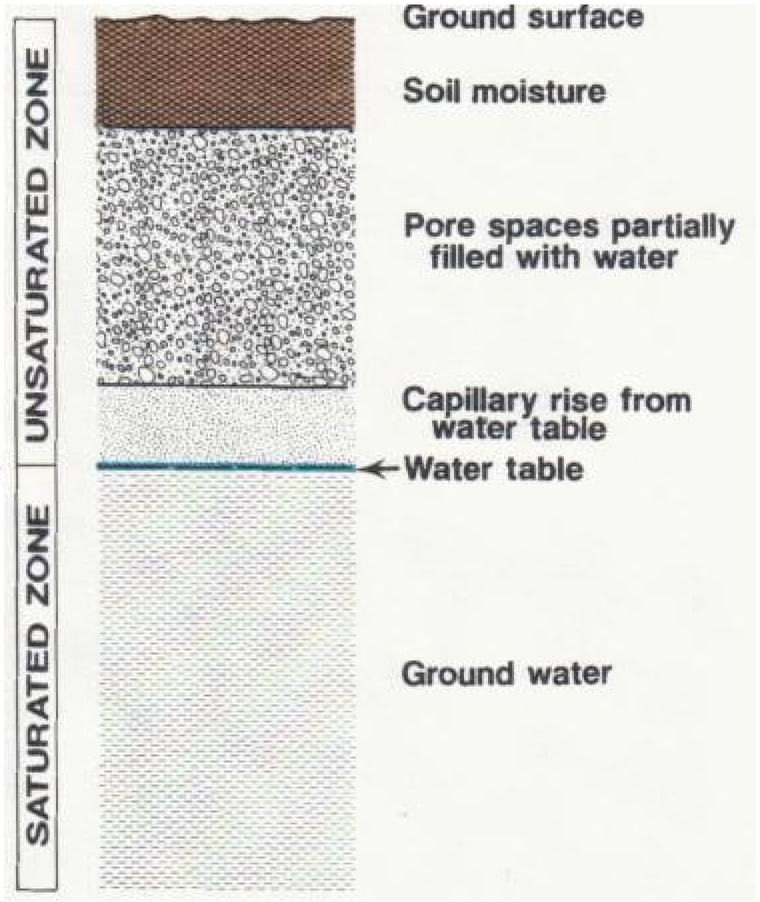
Moisture Profile Description

Different zones

- depend on % of pore space filled with water.

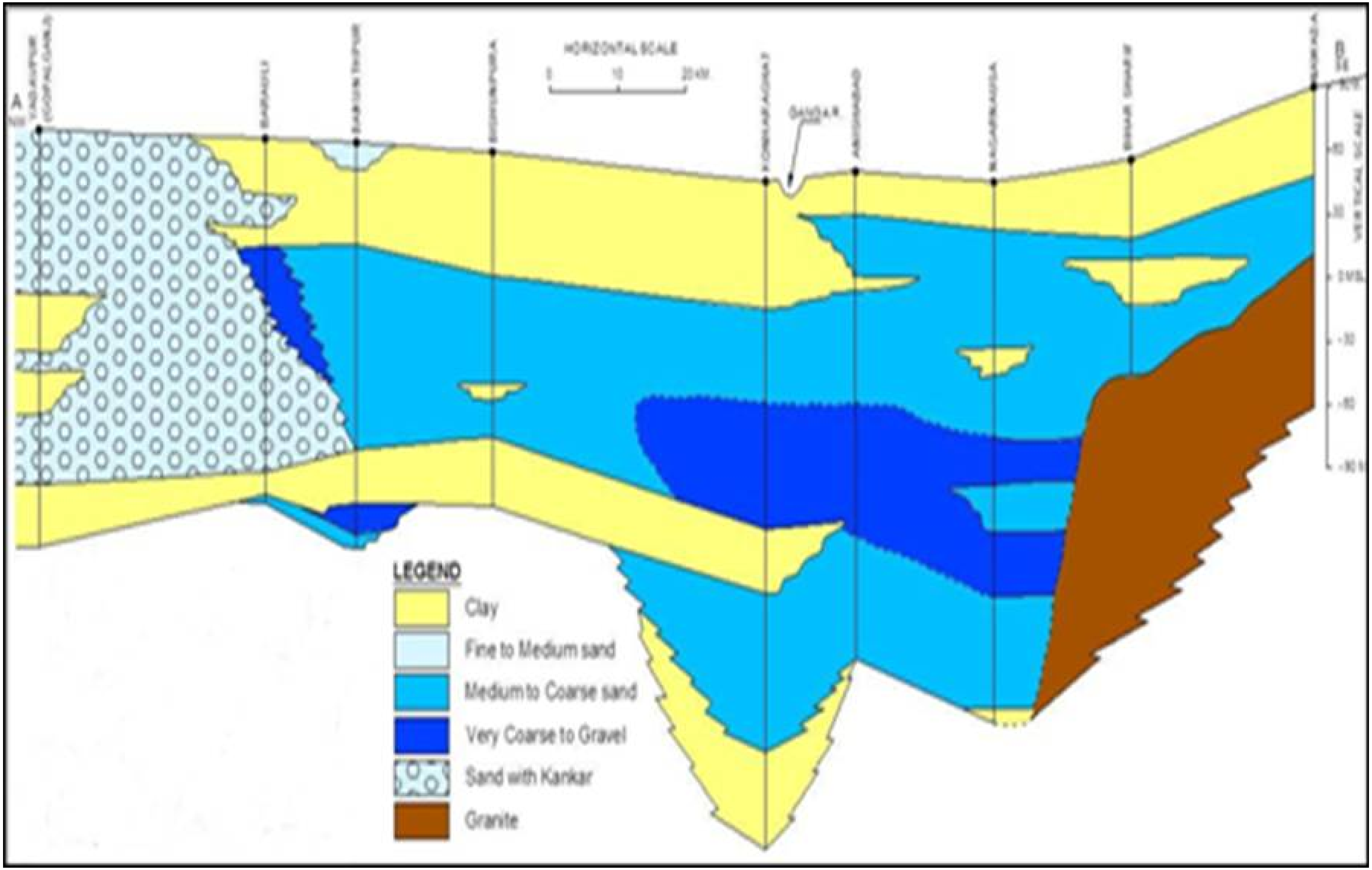
- **Unsaturated Zone**
  - Water held by capillary forces, water content near field capacity except during infiltration.
  - **Soil zone**
    - Water moves down (up) during infiltration (evaporation).
  - **Capillary fringe**
    - Saturated at base.
    - Field capacity at top.
- **Saturated Zone**
  - Fully saturated pores.





Field capacity - Water remaining after gravity drainage.
Wilting point - Water remaining after gravity drainage & evapotranspiration.

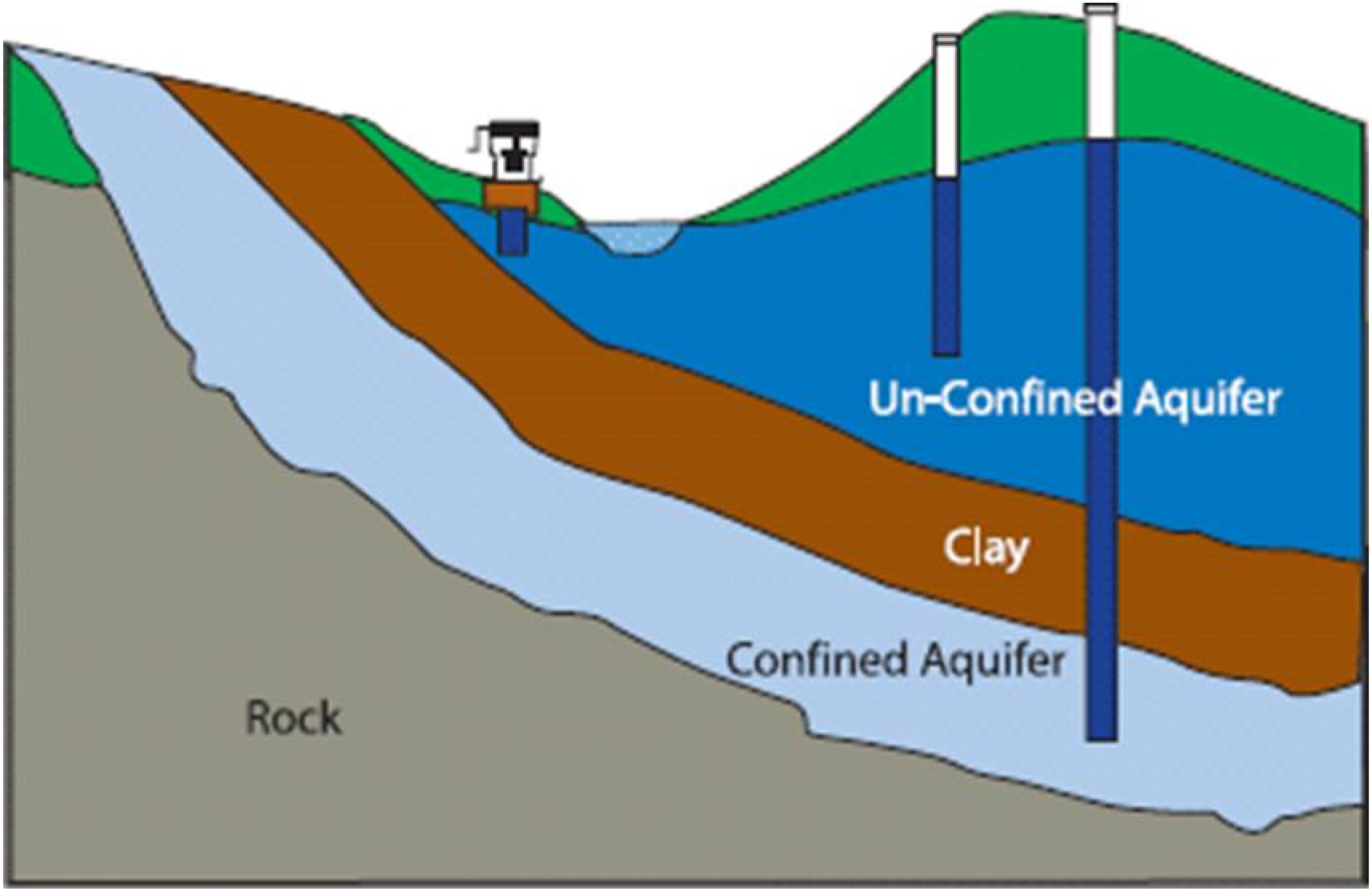
Aquifer Characterization



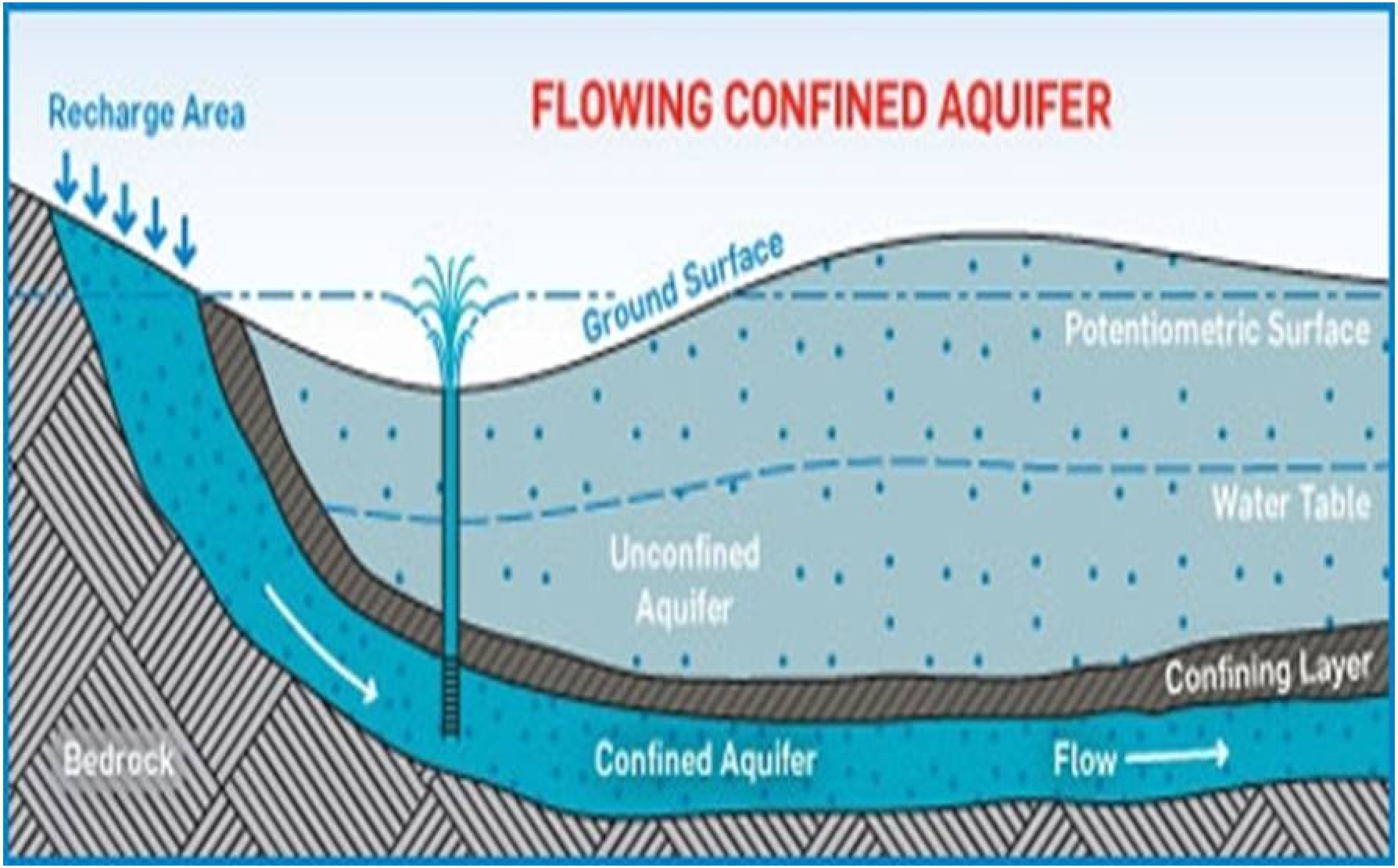
Underground Formations

GW in Hard Rock Areas

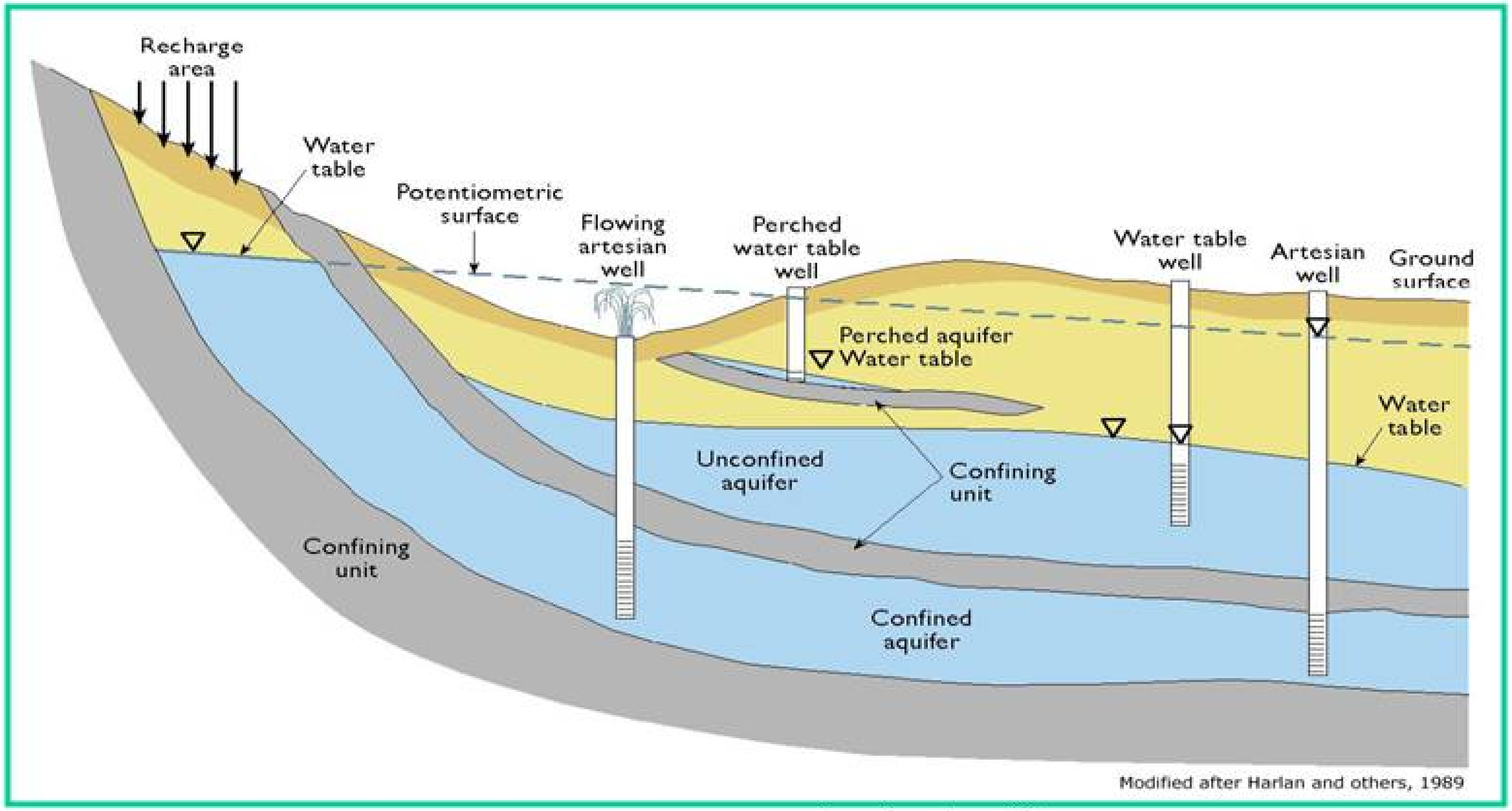
Investigations for Proper placing of Screens



Artesian Well



Types of Aquifer



Unconfined Aquifer

- Shallow aquifer confined at bottom only.
- Water table is under atmospheric condition.

Confined Aquifer

- Aquifer is confined both at top and bottom by impermeable layers.
- Water is under pressurized condition and more than the atmospheric pressure.

Leaky Aquifer

- Permeable stratum overlain or underlain by a semi-pervious aquitard or semiconfining layer.

Perched Aquifer (Special Case of Unconfined Aquifer)

- A formation separated from the main groundwater by a relatively impermeable stratum of small areal extent.
- Small aquifer formed above clay lenses in sedimentary deposits.

Groundwater Flow

How Groundwater Decline?

Net Recharge to GW < GW Withdrawal

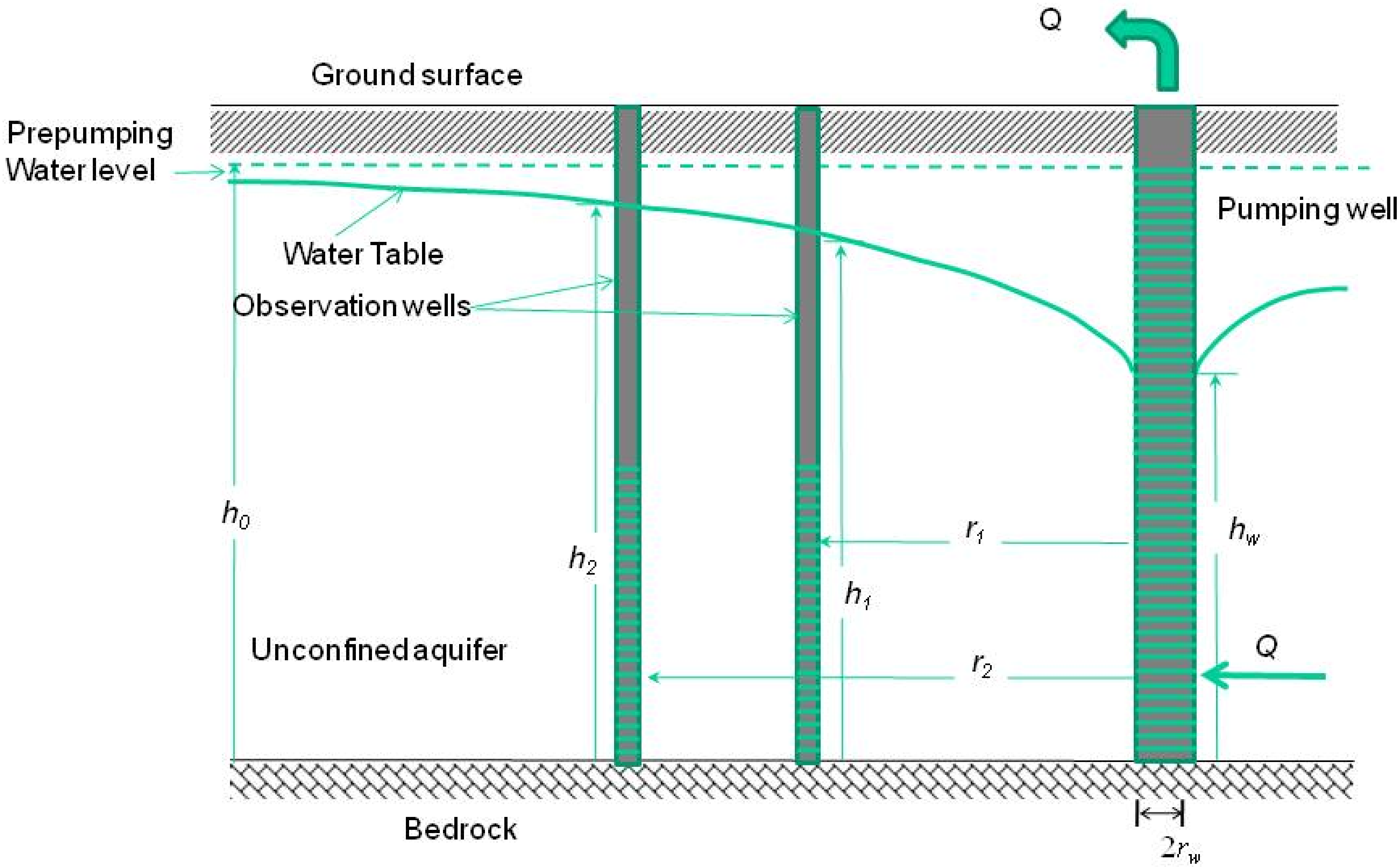
↓

Reduction in GW Storage

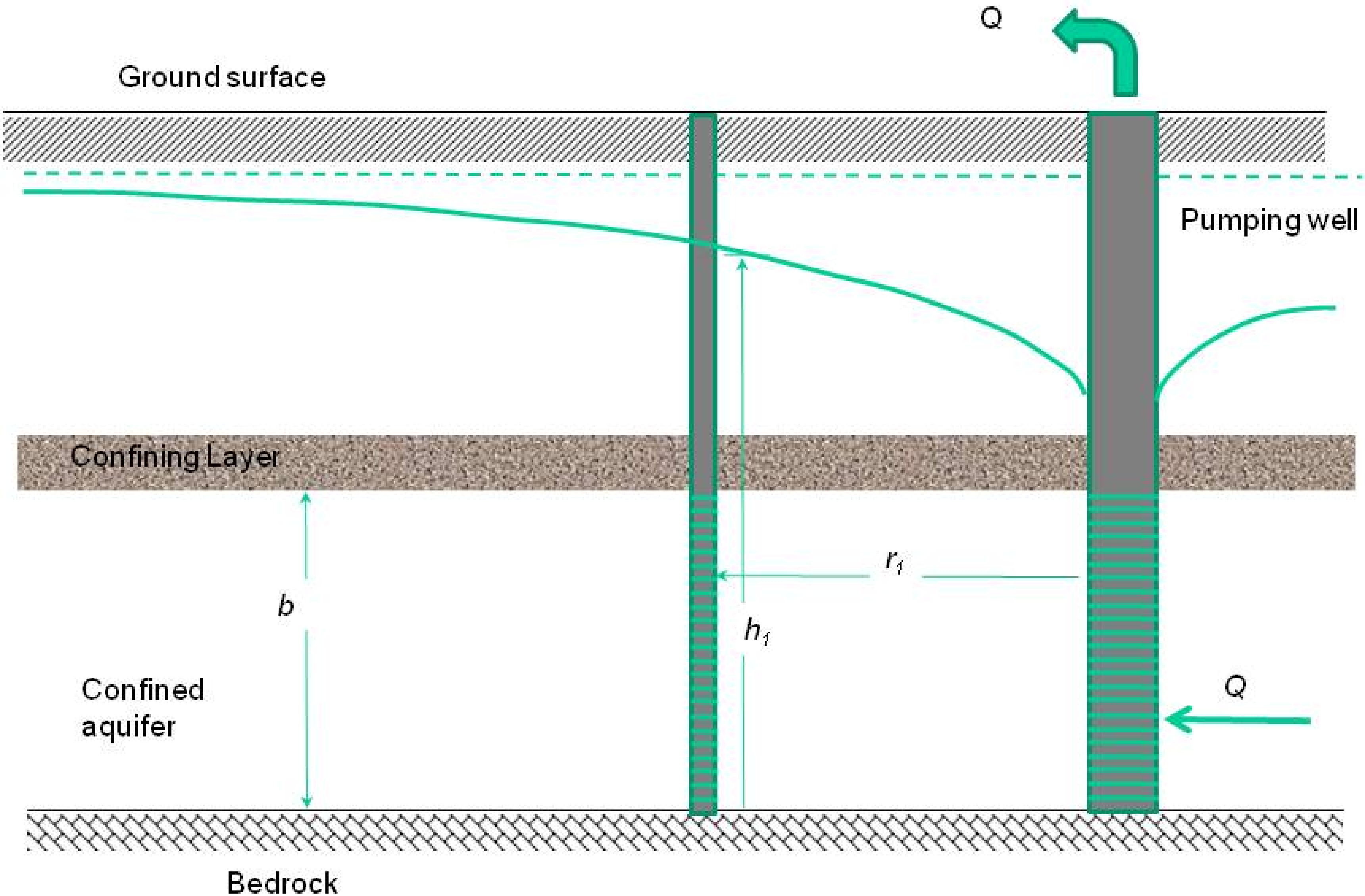
↓

Decline in Groundwater Table

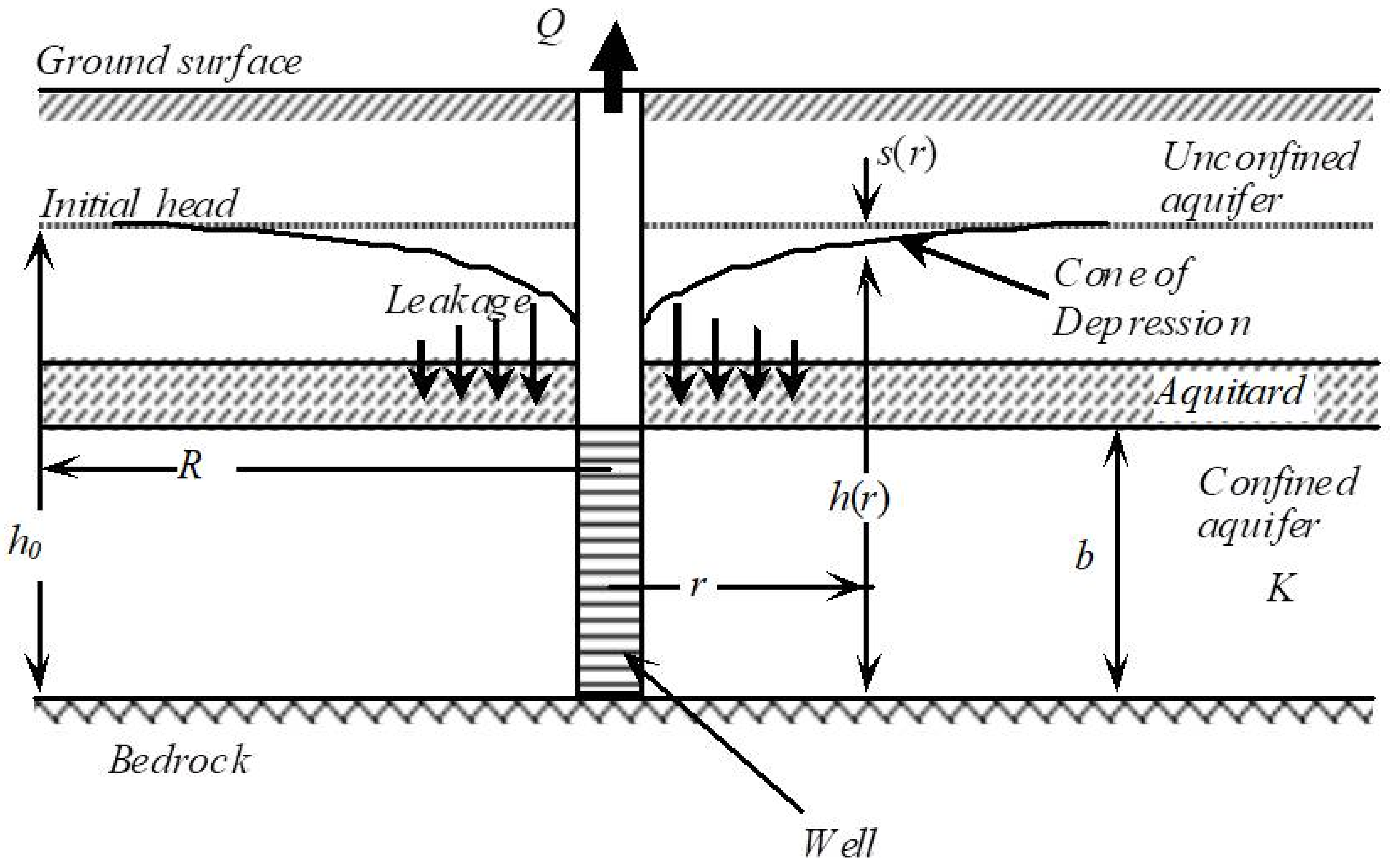
Groundwater Pumping from Unconfined Aquifer



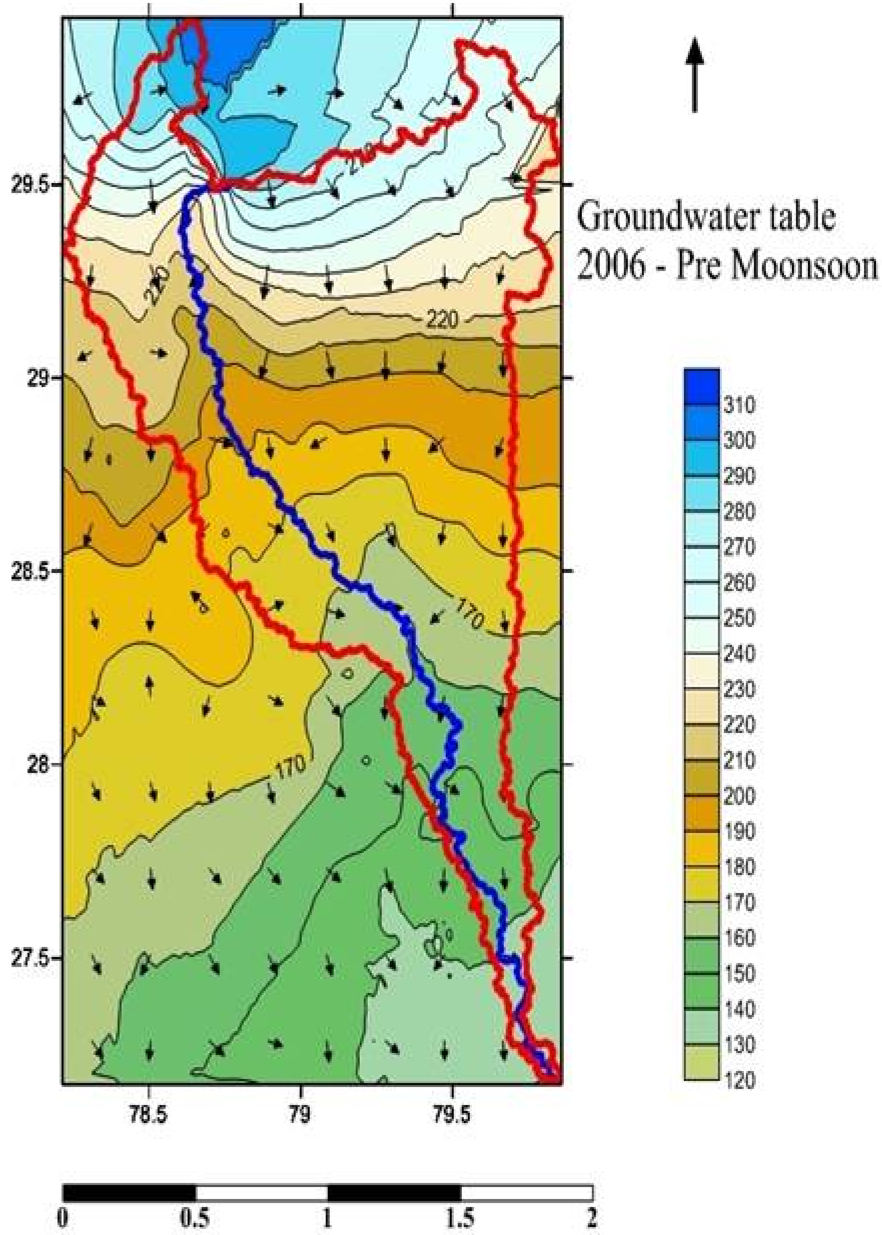
Pumping from Confined Aquifer

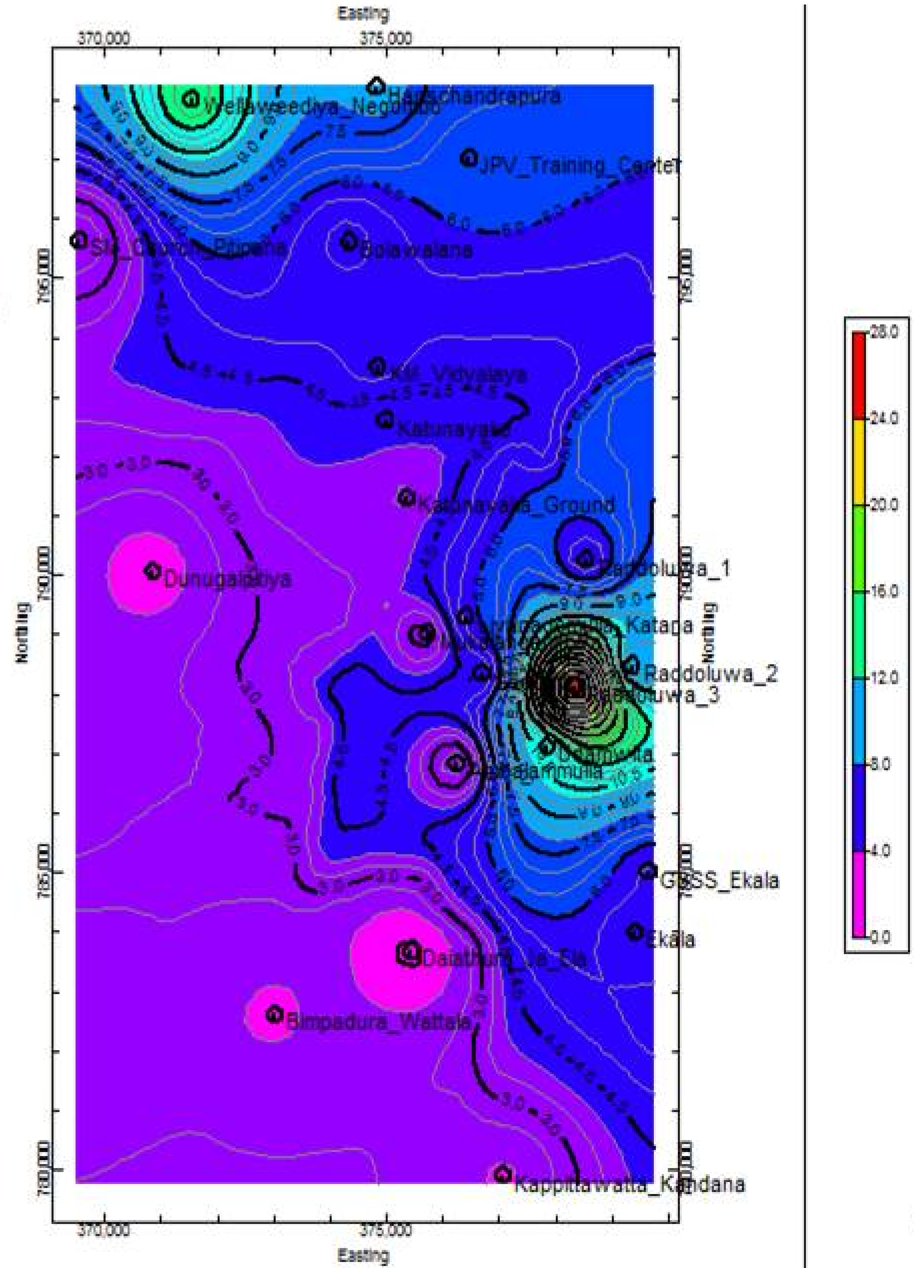


Pumping in a Leaky Aquifer

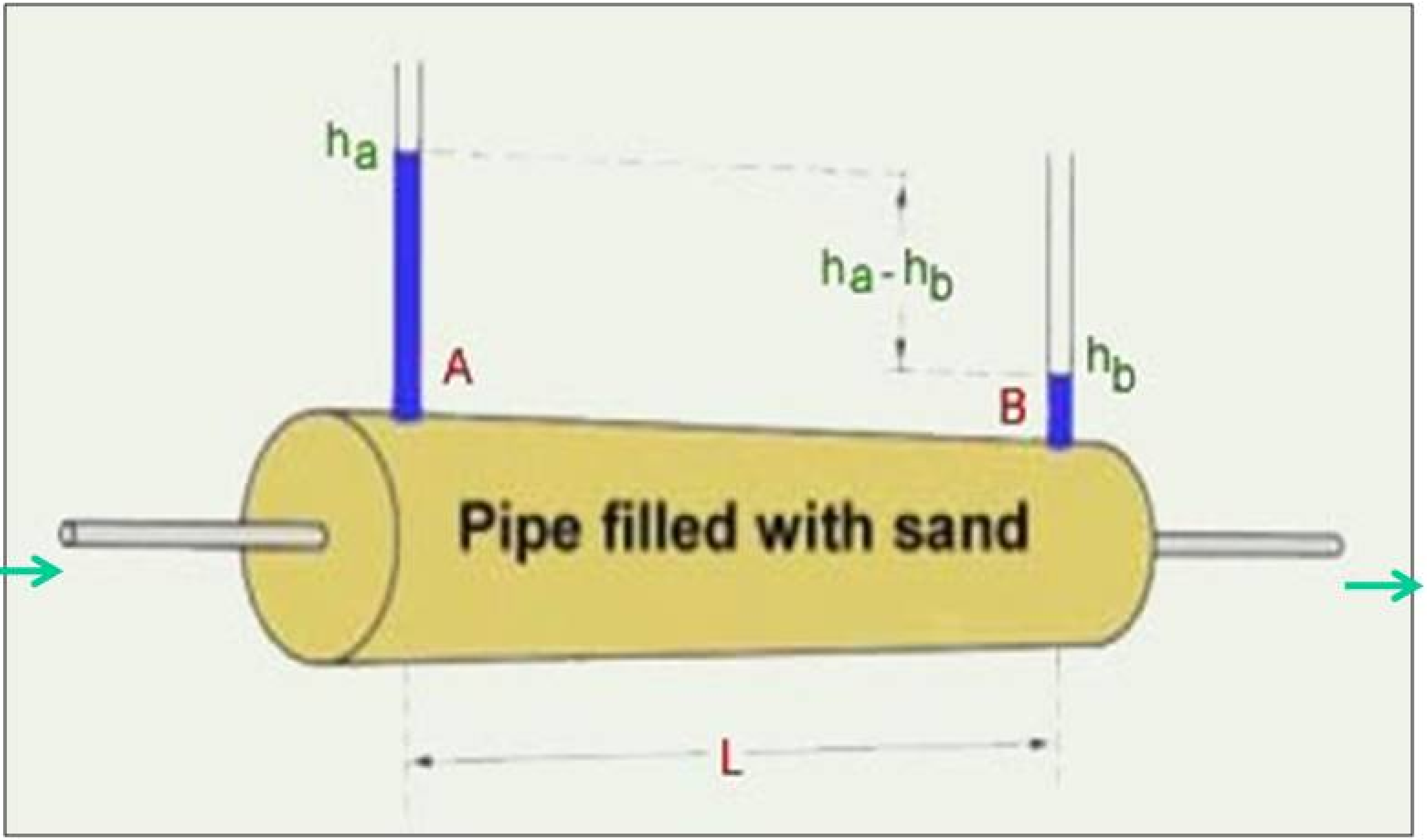


GW Flow Direction & Spatial variation





Groundwater Flow



Groundwater flows slowly through the voids between grains or the cracks in solid rock. Here, is an experiment to measure head loss in an aquifer.

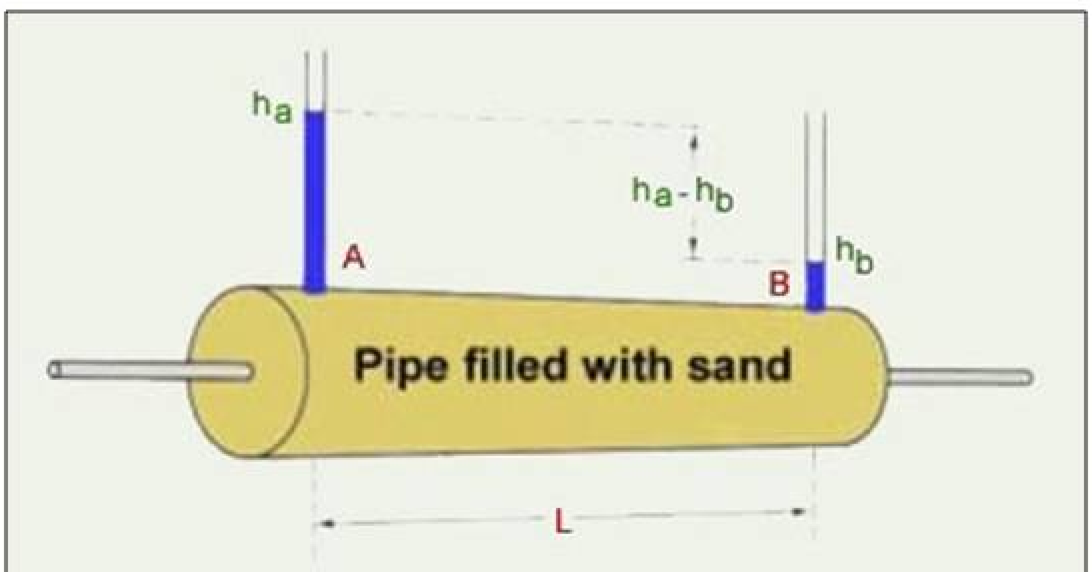
Darcy's Law

- Henri Darcy established empirically that the energy lost Δh $(h_a - h_b)$ in water flowing through a permeable formation **is proportional** to the length of the sediment column ΔL (for $1.0 < Re < 10$).
- The constant of proportionality (K) is called the **hydraulic conductivity**. The **Darcy Velocity, V_D:**

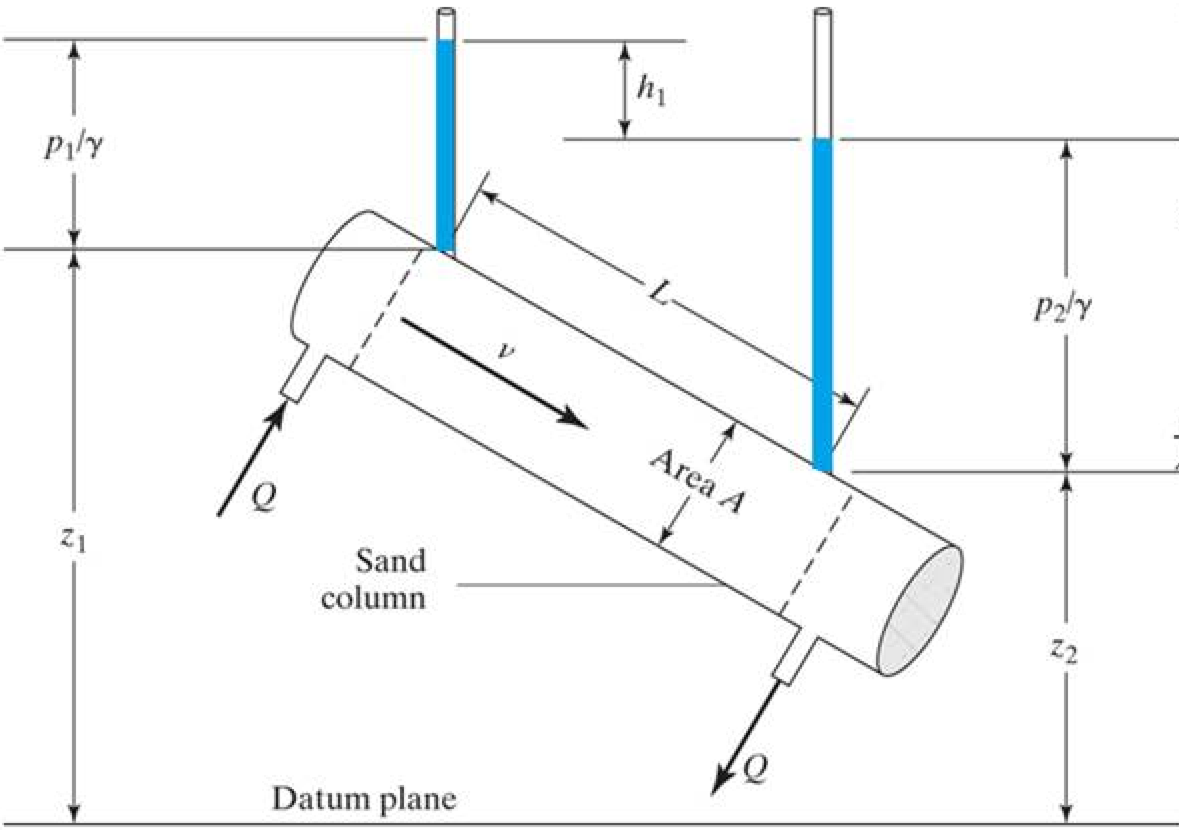
$$V_D = -K\,(\Delta h/\Delta L)$$

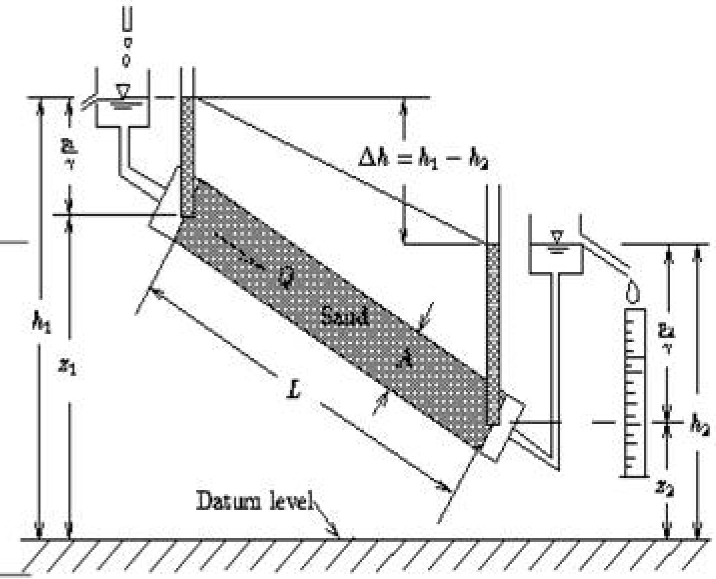
and since $Q = V_D A$ (where A = CS area)

$$Q = -KA\,(dh/dL)$$



Darcy's Experiment





Piezometers before and after sand. Pipe is full, so flow rate is constant

1. Velocities are small, V ~ 0, so: $\frac{P_1}{\gamma} + Z_1 = \frac{P_2}{\gamma} + Z_2 + h_L$

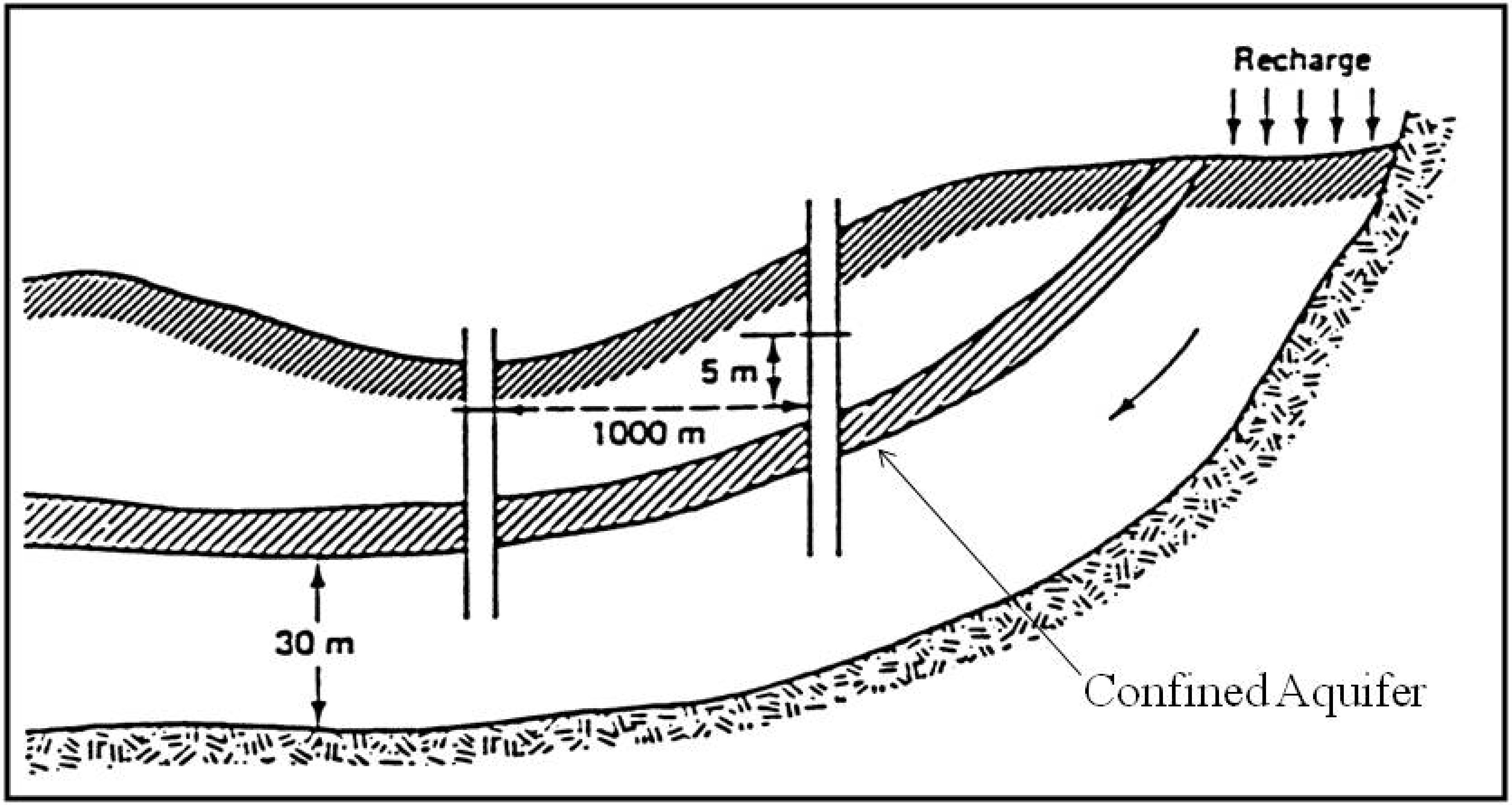
2. **Head difference doesn't change with the inclination of sand filter.**

3. Again, Darcy related reduced flow rate to head loss and length of column through a constant of proportionality (K)

$$V = Q/A = -K\, dh / dL$$

Darcy's Law helps in estimating:

- velocity or flow rate moving within the aquifer.
- average time of travel from the head of the aquifer to a point located downstream.
- prediction of contaminant plume arrival.

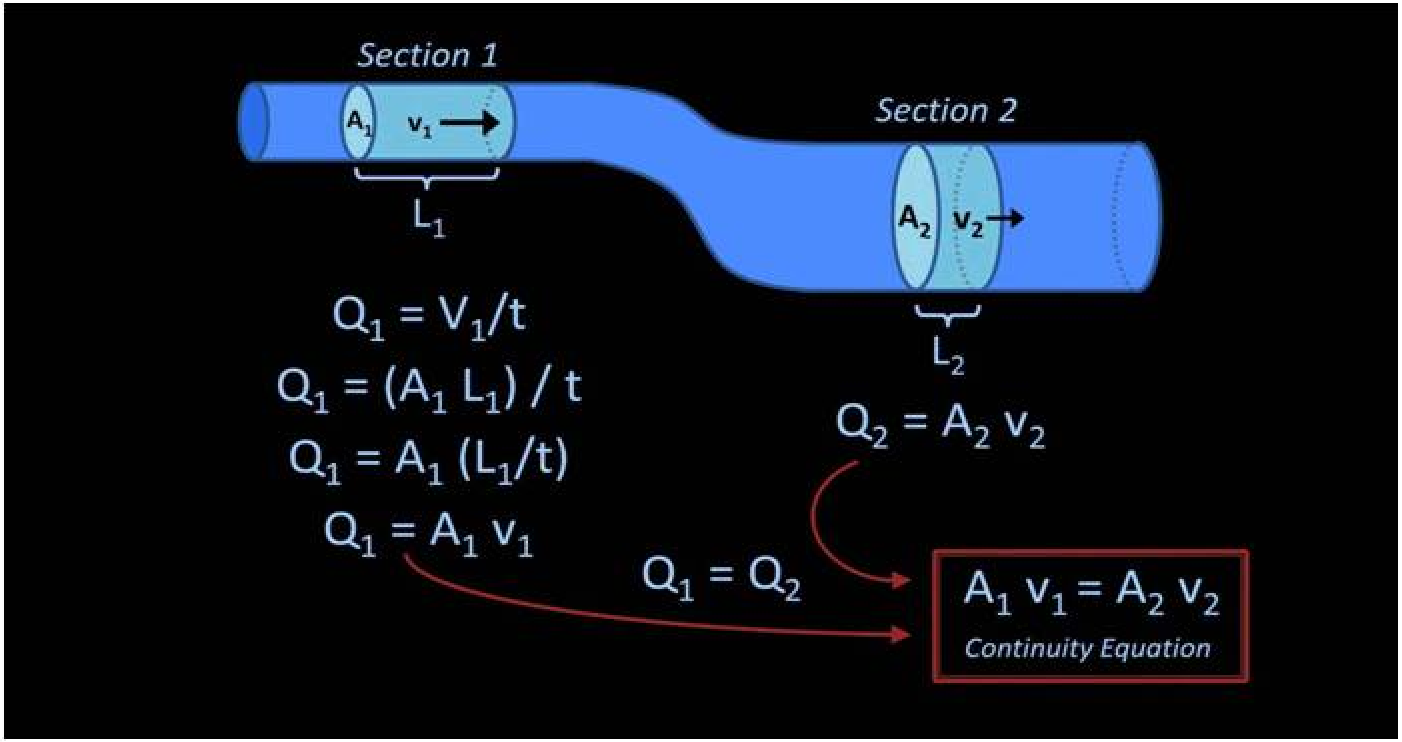


Dupuit's Assumptions

For **unconfined groundwater flow**, Dupuit developed a theory that allows for a simple solution based on the following assumptions:

1. The water table or free surface is slightly inclined.
2. Streamlines may be considered horizontal and thus equipotential lines are vertical.
3. Slope of the free surface is equal to the hydraulic gradient.

Continuity Equation

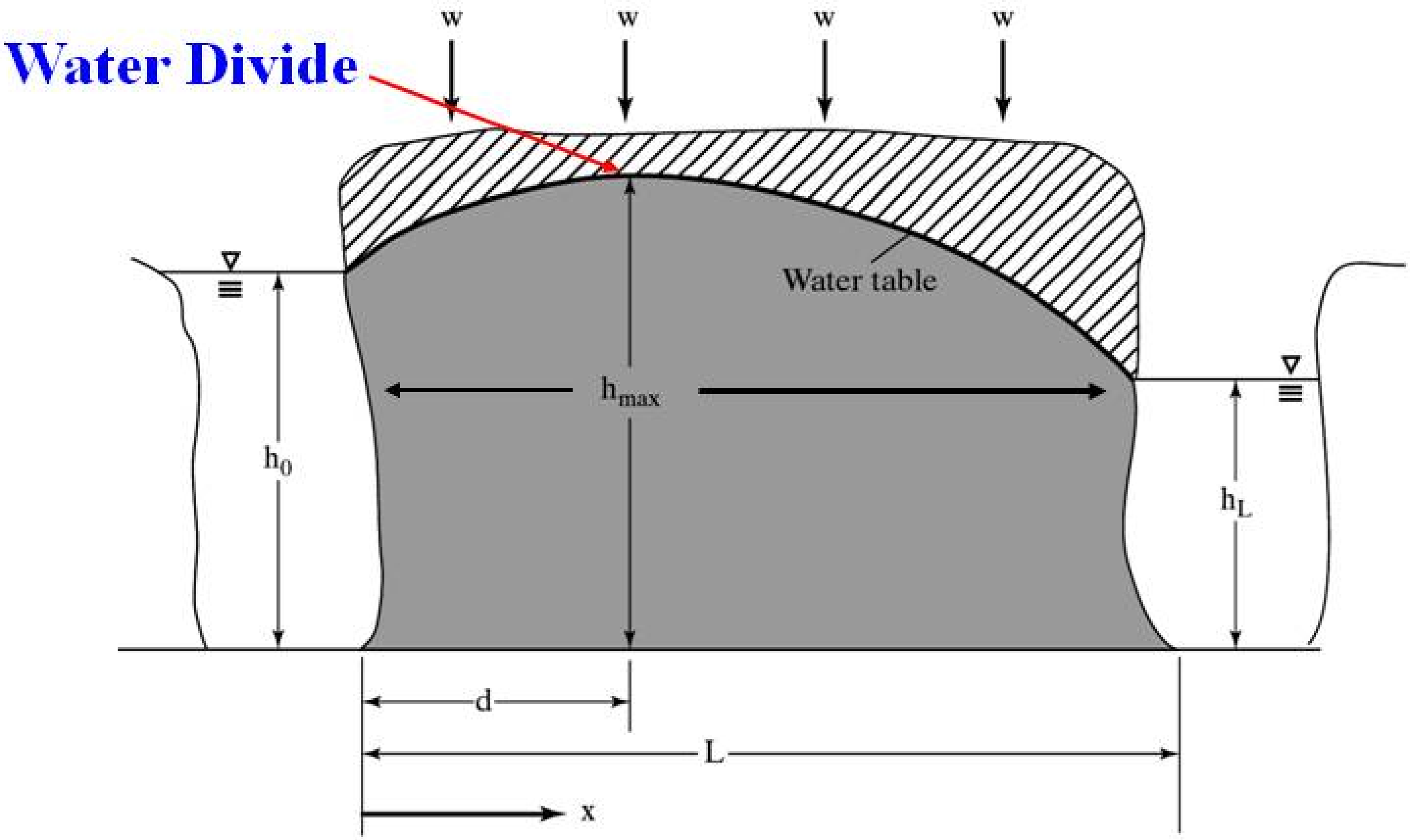


Based on Conservation of Mass:

Discharge through Section A1 = Discharge through Section A2

$$A_1 \, . \, V_1 = A_2 \, . \, V_2$$

Recharge Mound Formation



[redacted]

Dupuit parabola with recharge.

General 3D GW Flow Equation

For heterogeneous, anisotropic & transient flow with source/sink:

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = S_s \frac{\partial h}{\partial t} - W$$

For 2D Confined System:

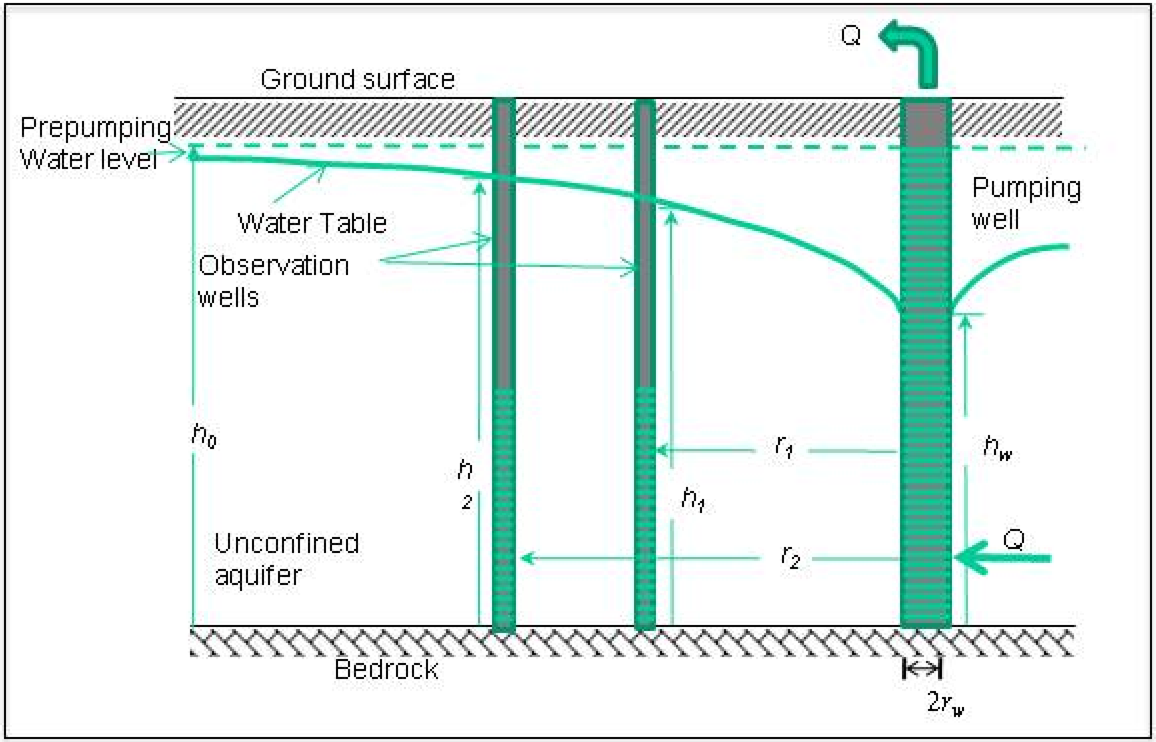
$$\frac{\partial}{\partial x}(T_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_y \frac{\partial h}{\partial y}) = S \frac{\partial h}{\partial t} - R$$

For 2D Unconfined System:

$$\frac{\partial}{\partial x}(hK_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(hK_y \frac{\partial h}{\partial y}) = S_y \frac{\partial h}{\partial t} - R$$

Groundwater Flow in an Unconfined Aquifer

- **Given:**
  - $Q = 300\ m^3/hr$
  - Unconfined aquifer
  - 2 observation wells,
    - $r_1 = 50$ m, $h = 40$ m
    - $r_2 = 100$ m, $h = 43$ m
- **Find: K**



$$K = \frac{Q}{\pi\left(h_2^2 - h_1^2\right)}\ln\left(\frac{r_2}{r_1}\right) = \frac{300\,m^3/hr/3600\,s/hr}{\pi\left[(43\,m)^2 - (40\,m)^2\right]}\ln\left(\frac{100\,m}{50\,m}\right) = 7.3x10^{-5}\ m/\sec$$

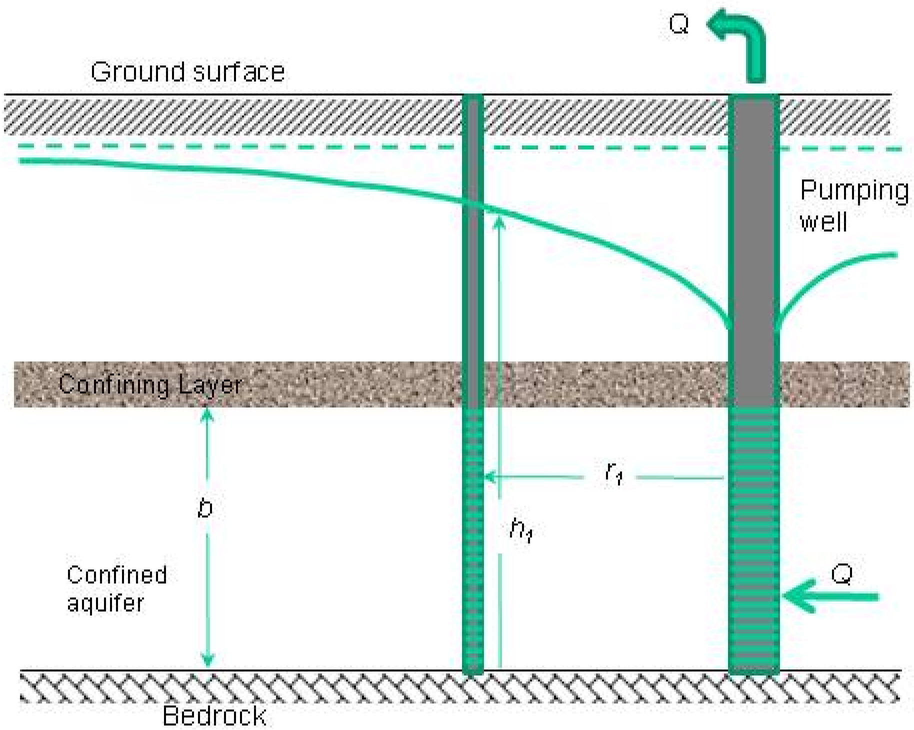
Groundwater Flow in a Confined Aquifer

Given

$Q = 1500 \text{ m}^3/\text{day}$

$T = 600 \text{ m}^2/\text{day}$

$S = 4 x 10^{-4}$



Find: Drawdown 1 km away from well.

$u = 4.6x10^{-4}$

$W(u) = 7.12$

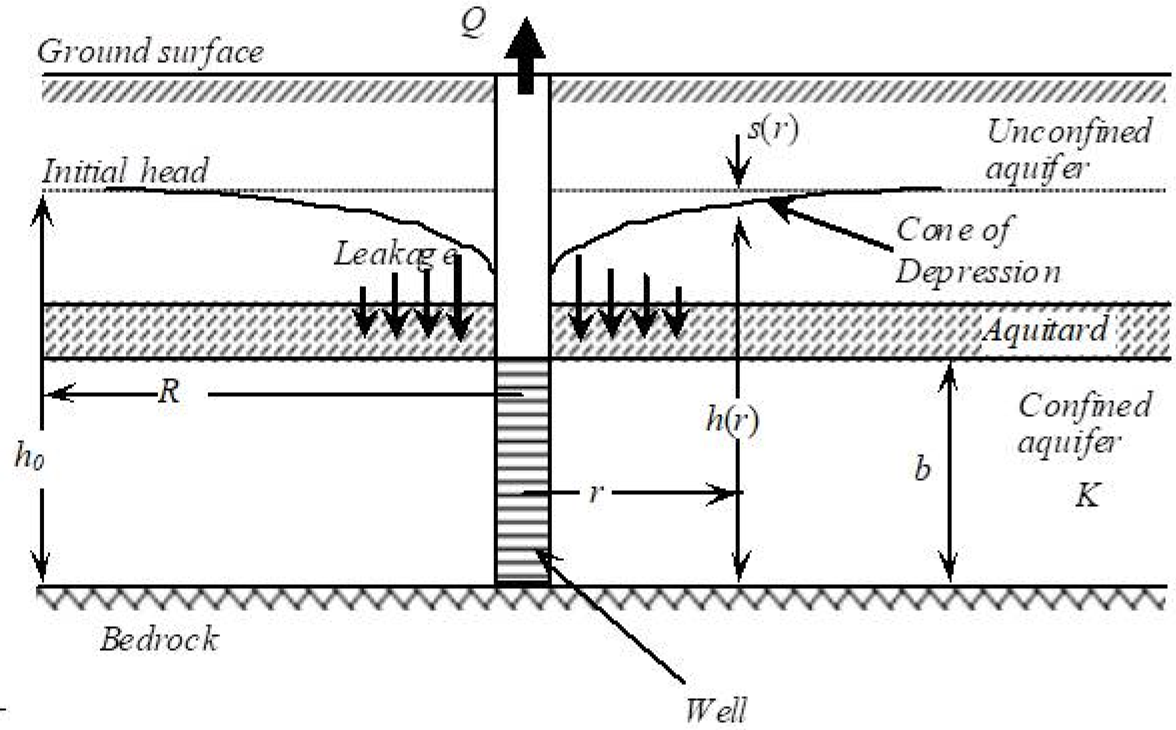
$$s = \frac{Q}{4\pi T} W(u) = \frac{1500\, m^3/d}{4\pi(600\, m^2/d)} * 7.12 = 1.42\, m$$

Groundwater Flow in a Leaky Aquifer

$$s = \frac{Q}{4\pi T} W\left(u, \frac{r}{B}\right)$$

$$\frac{r}{B} = \frac{r}{\frac{T}{K'/b'}}$$

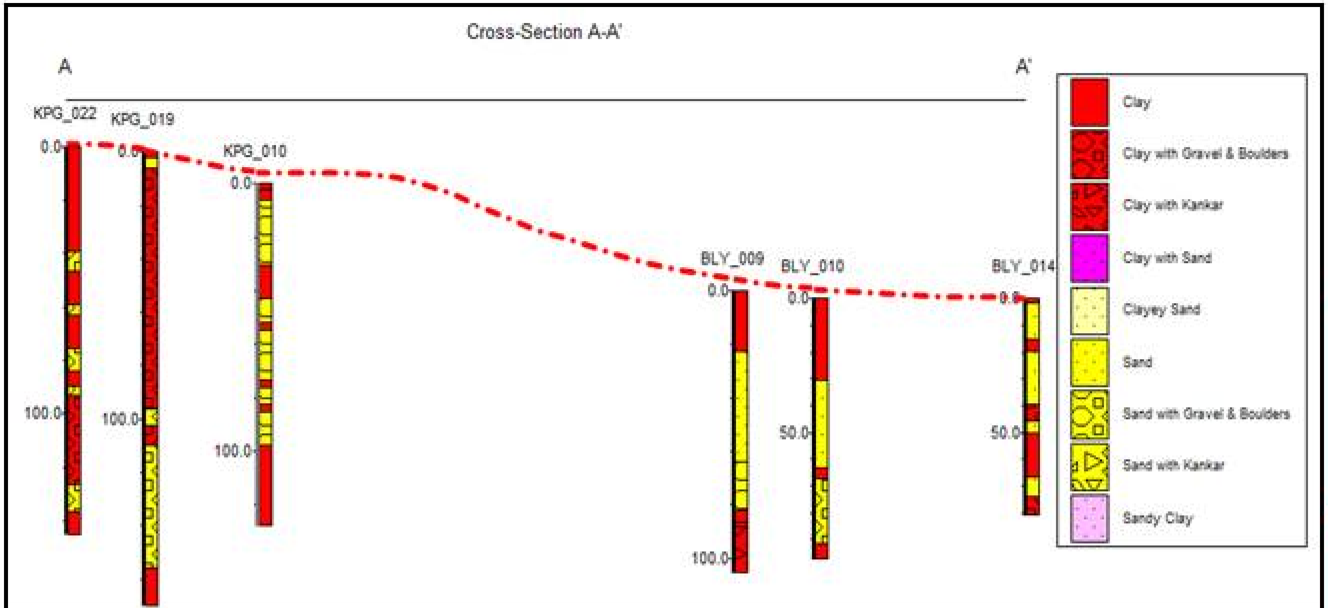
$$W\left(u, \frac{r}{B}\right) = \int_u^\infty \frac{e^{-z-\frac{r^2}{4B^2 z}}}{z} dz$$

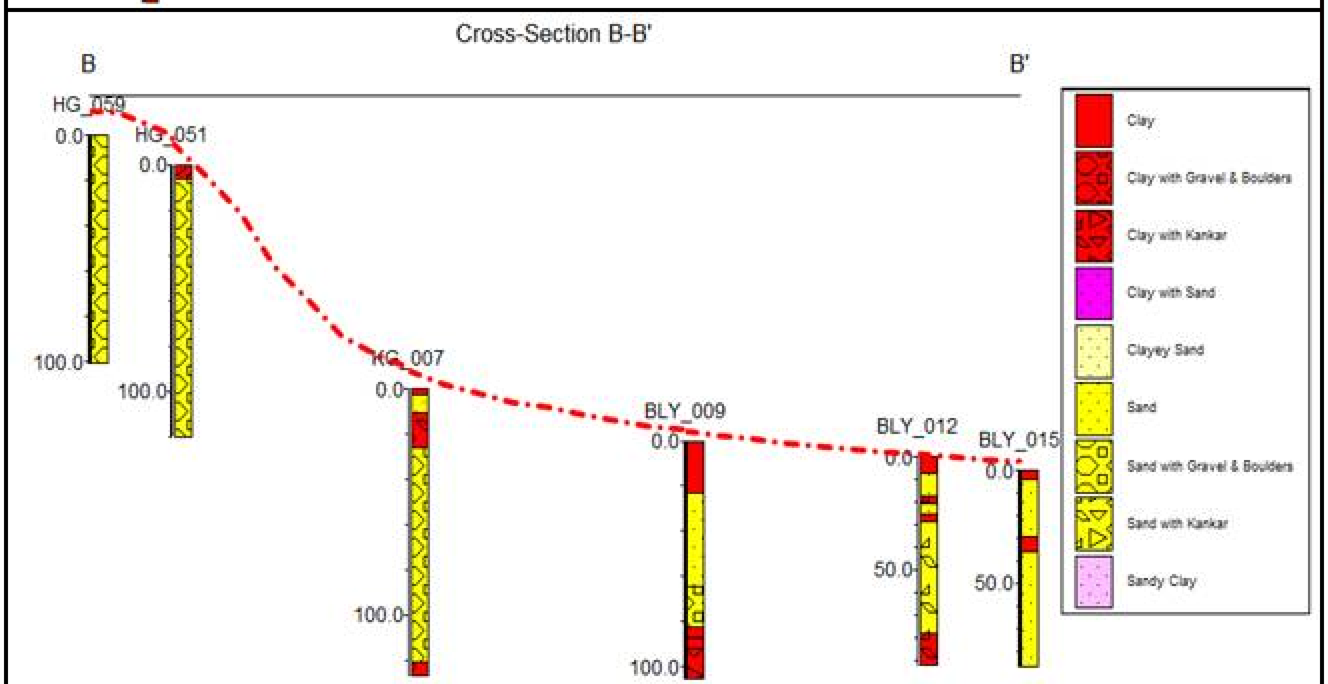


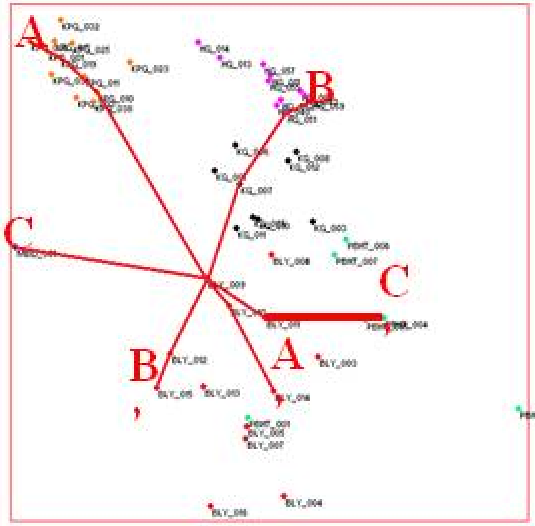
When there is leakage from other layers, the drawdown from a pumping test will be less than the fully confined case.

Underground Formations

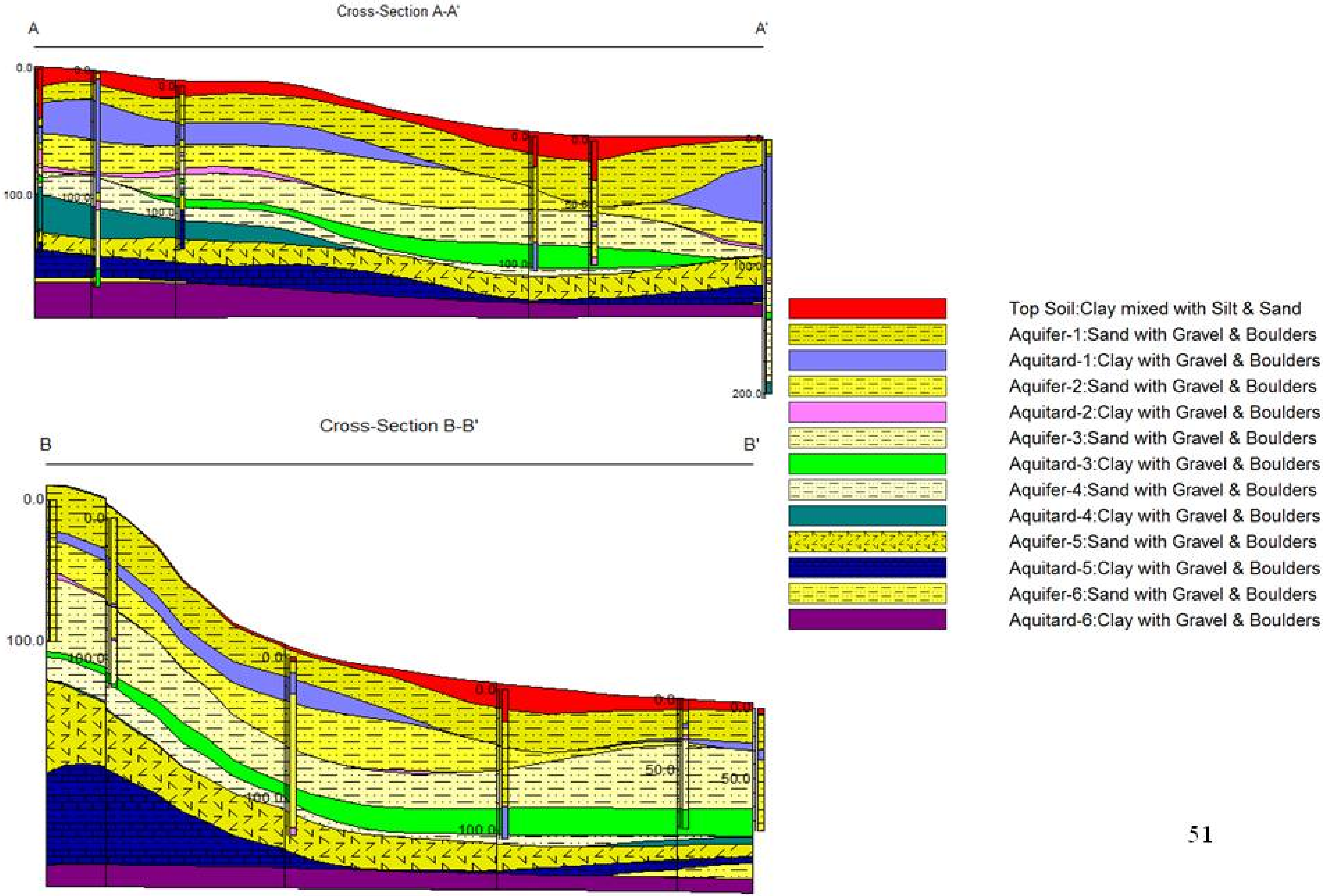
Litholog Sections



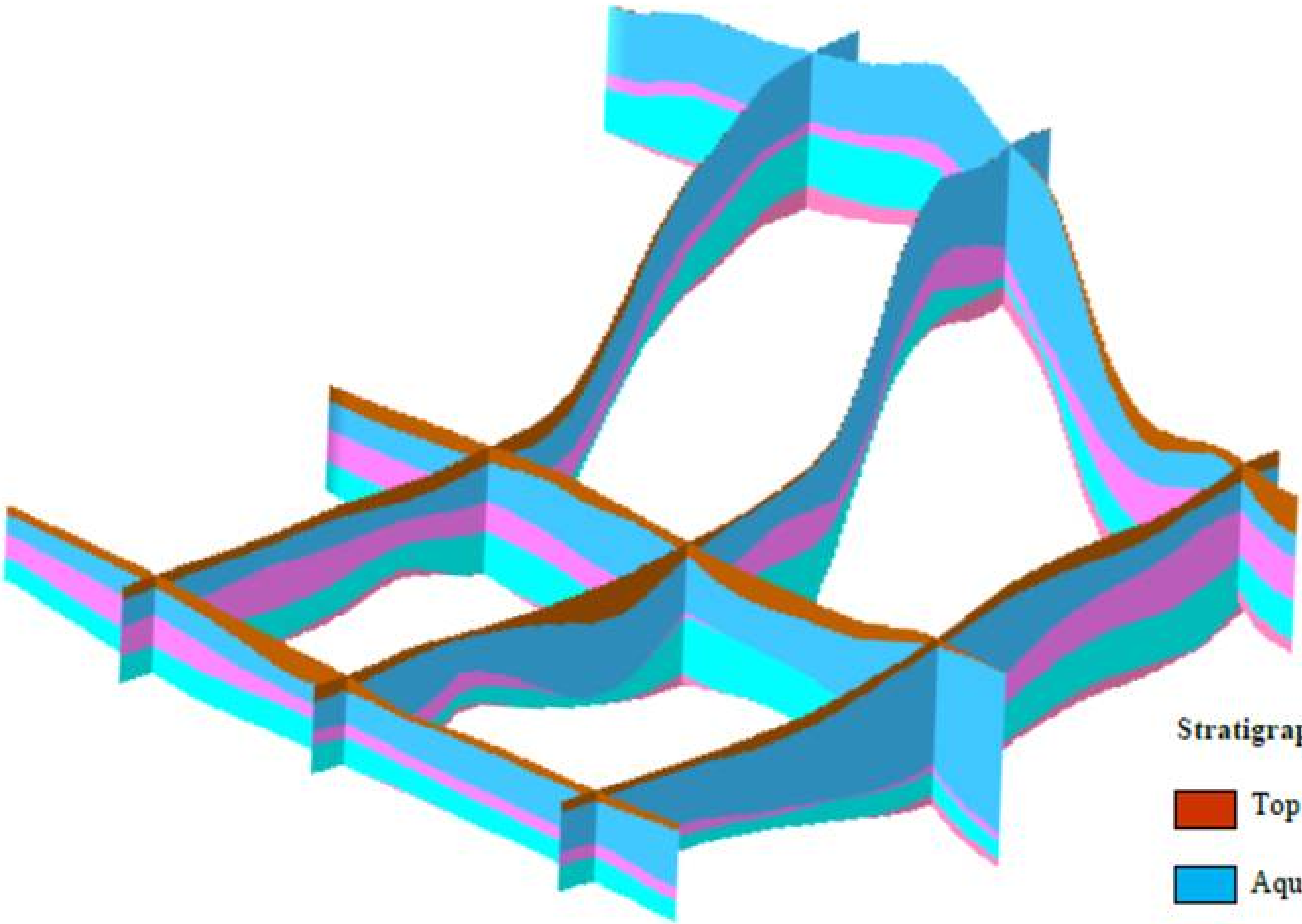


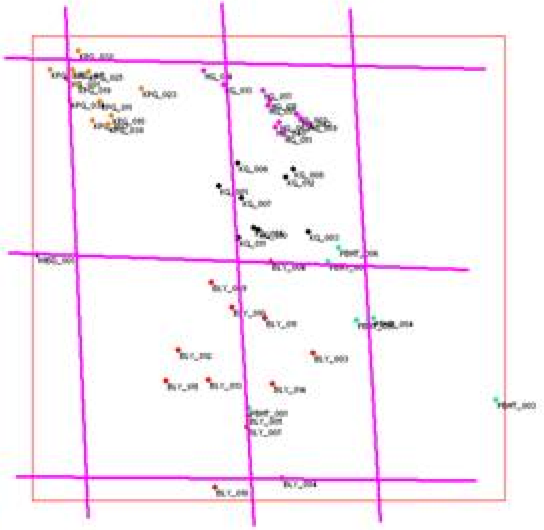


Modeled into Stratigraphy Sections



Underground Formations: Fence Diagram



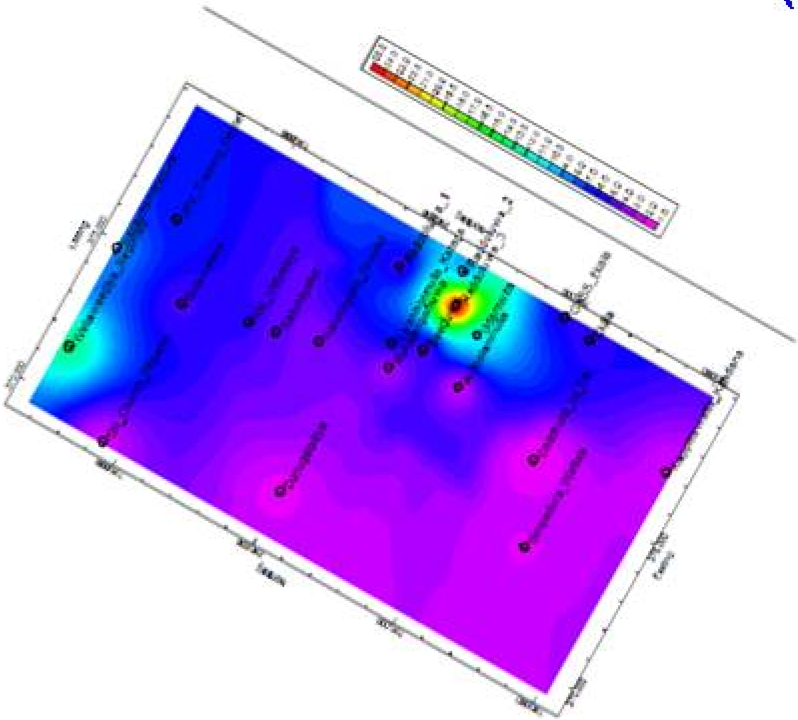


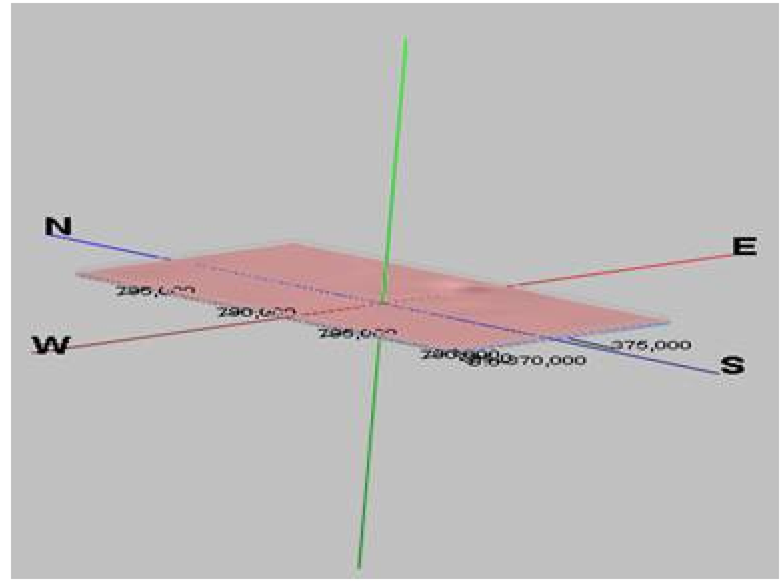
Stratigraphy

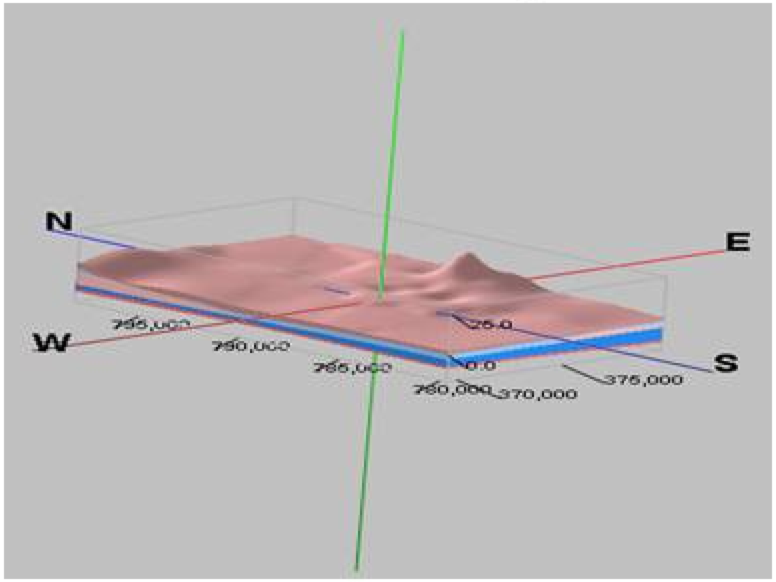
- Top Soil: Clay mixed with Silt & Sand
- Aquifer-1: Sand with Gravel & Boulders
- Aquitard-1: Clay with with Gravel & Boulders
- Aquifer-2: Sand with Gravel & Boulders
- Aquitard-2: Clay with with Gravel & Boulders

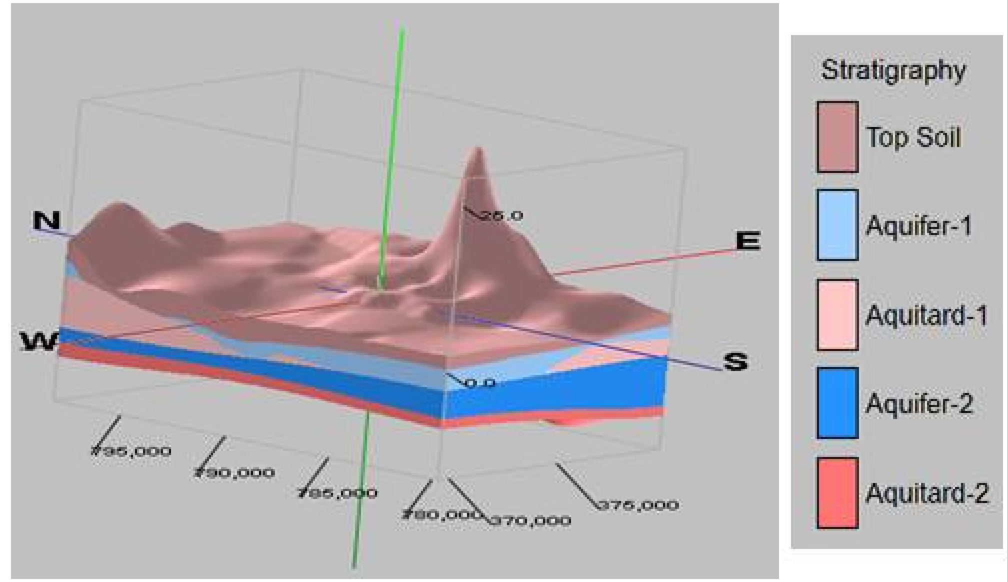
3D Model of Underground Formations

(VE=10, 100, 400)

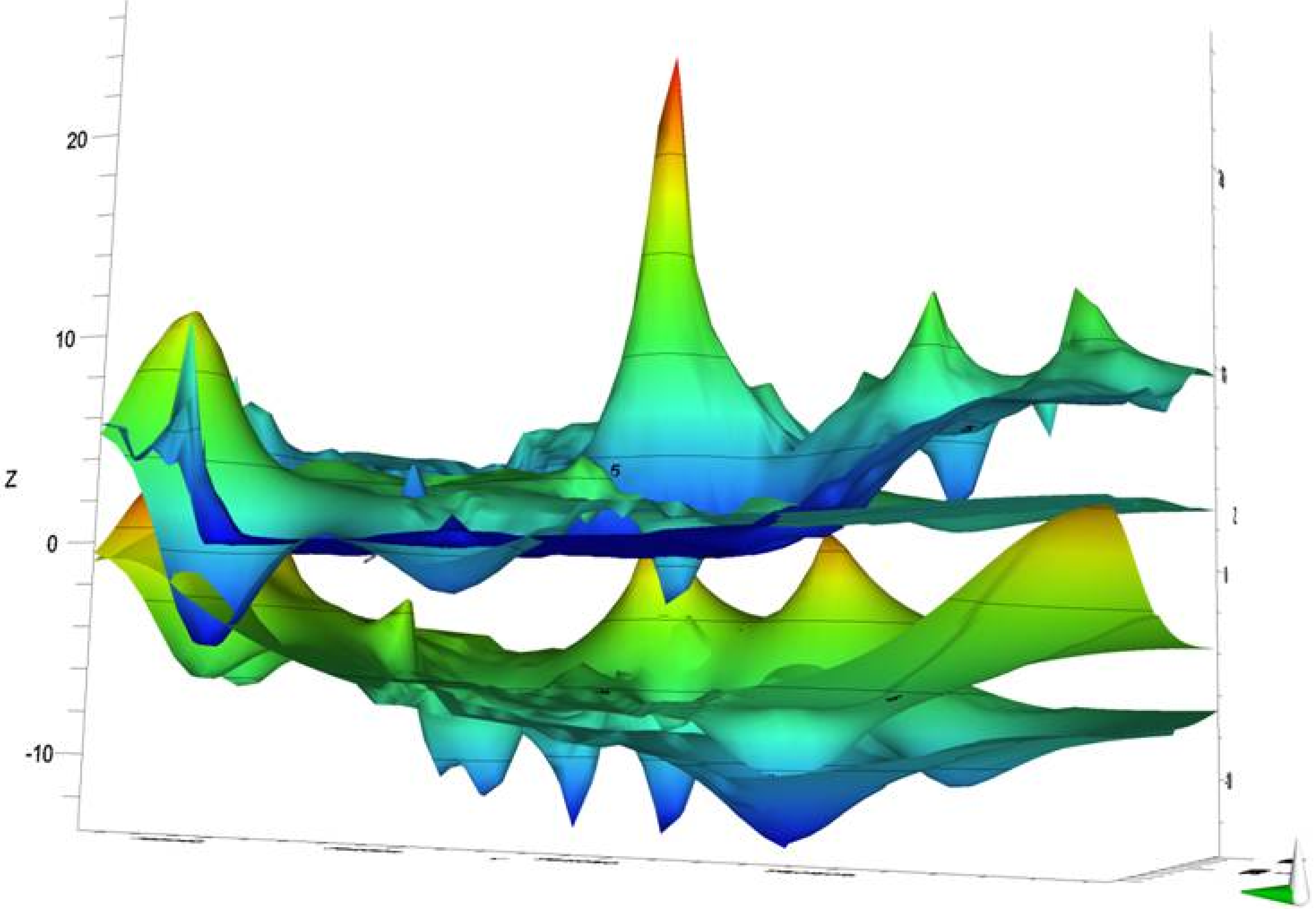




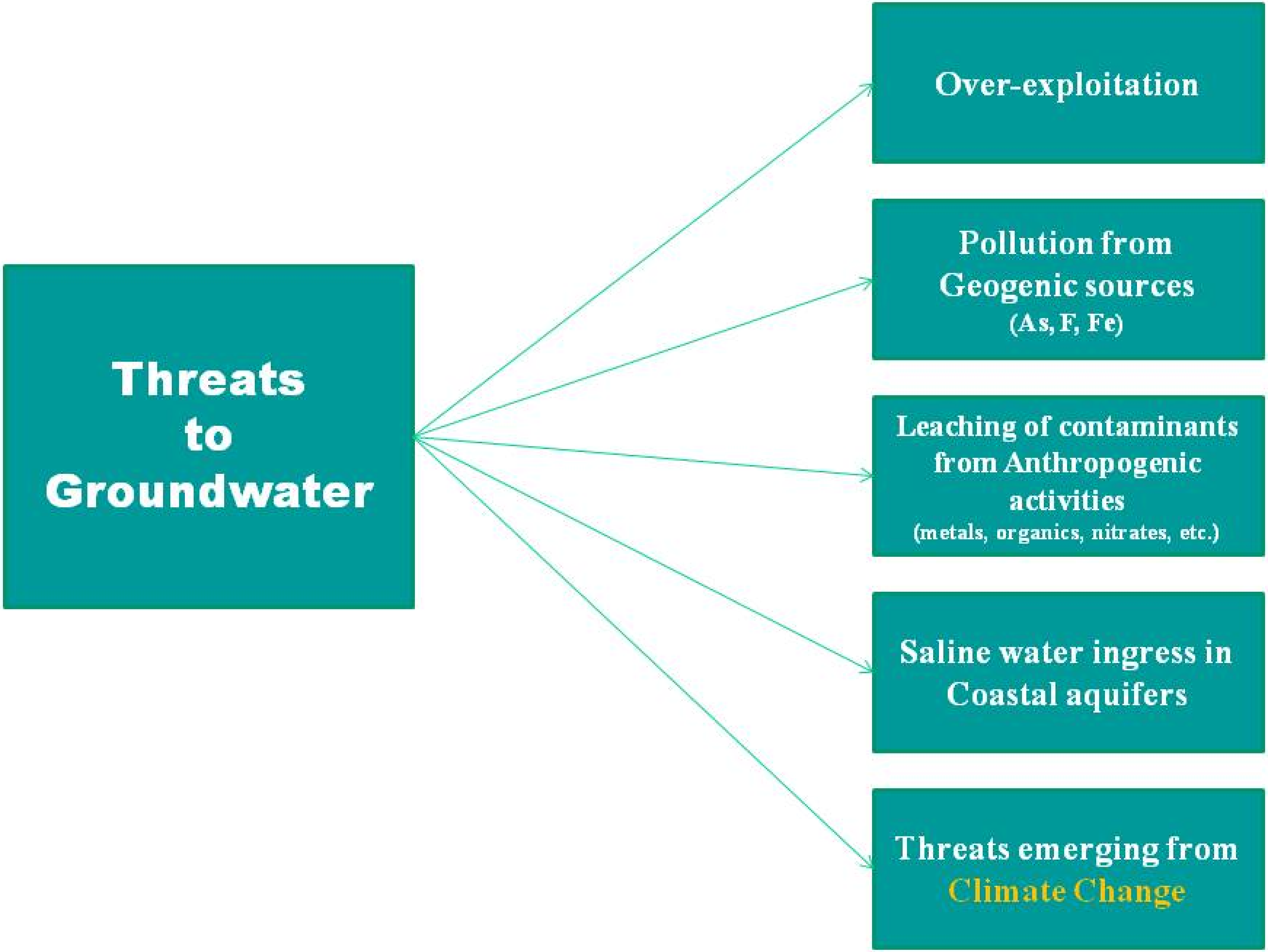




3D Layers



Problems related to Groundwater

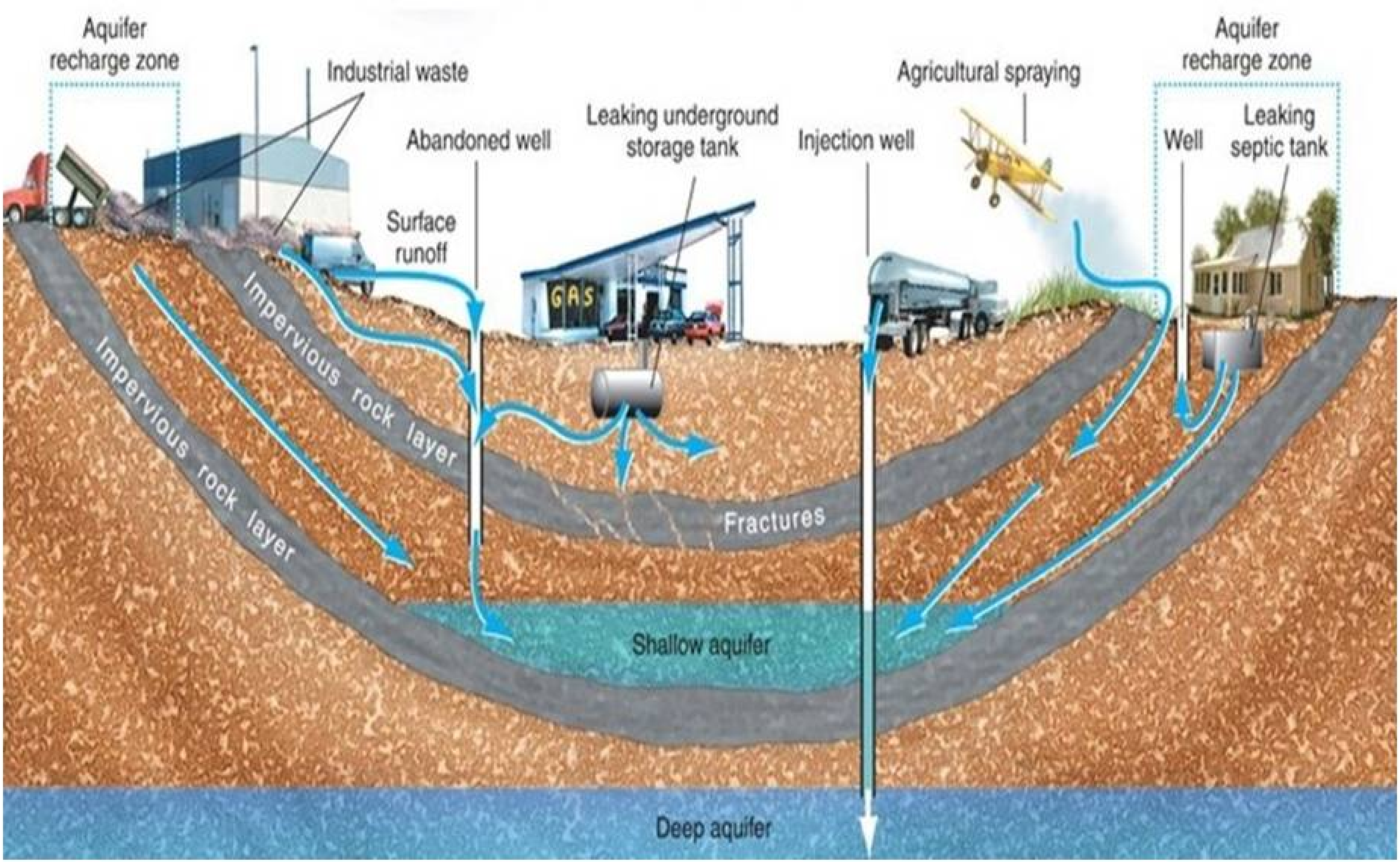

Threats to Groundwater
Over-exploitation
Pollution from Geogenic sources (As, F, Fe)
Leaching of contaminants from Anthropogenic activities (metals, organics, nitrates, etc.)
Saline water ingress in Coastal aquifers
Threats emerging from Climate Change

Pollution Transport in GW

Ground Water Contaminants

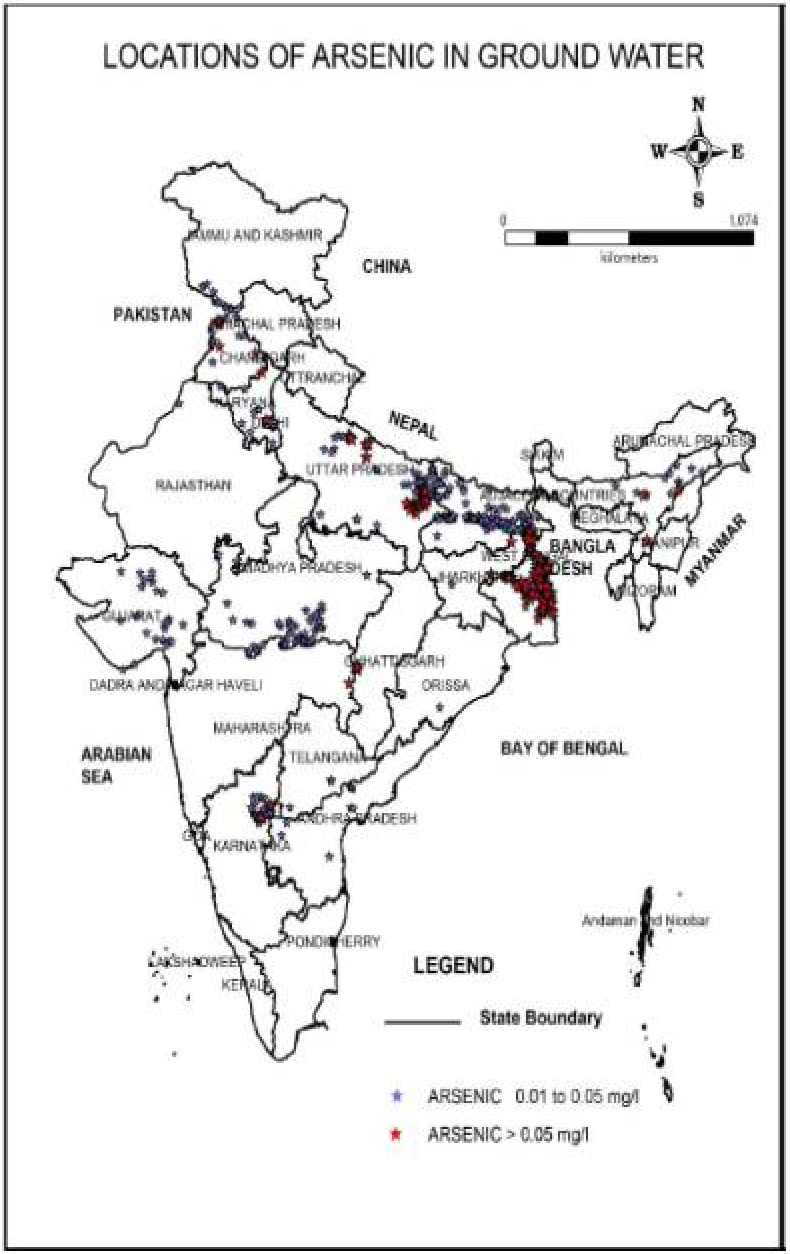
- **Nitrate** – Blue baby disease.
- **Pathogens** – Bacteria and virus causes water borne diseases such as typhoid, cholera, dysentery, polio and hepatitis.
- **Toxic Metals** – Arsenic, selenium, lead, mercury, cadmium, copper, chromium, nickel, etc.
- **Organic Compounds** – Pesticides, Phenols, Hydrocarbons, etc.

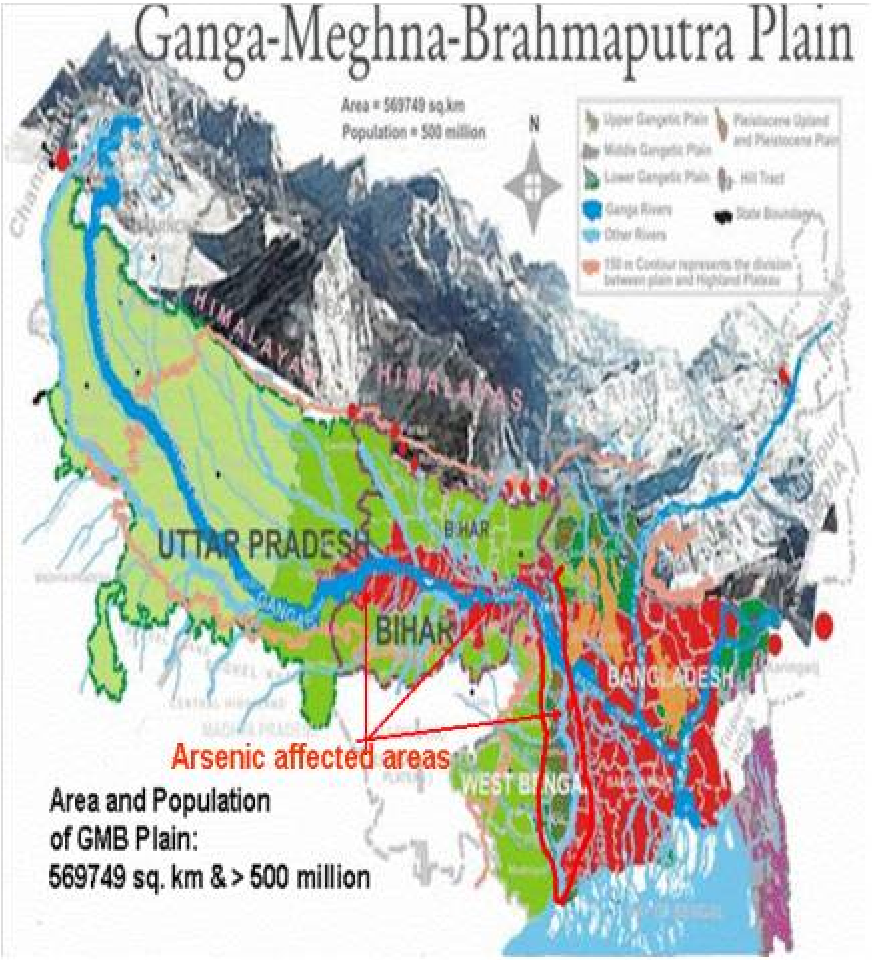
Transport of Pollutants



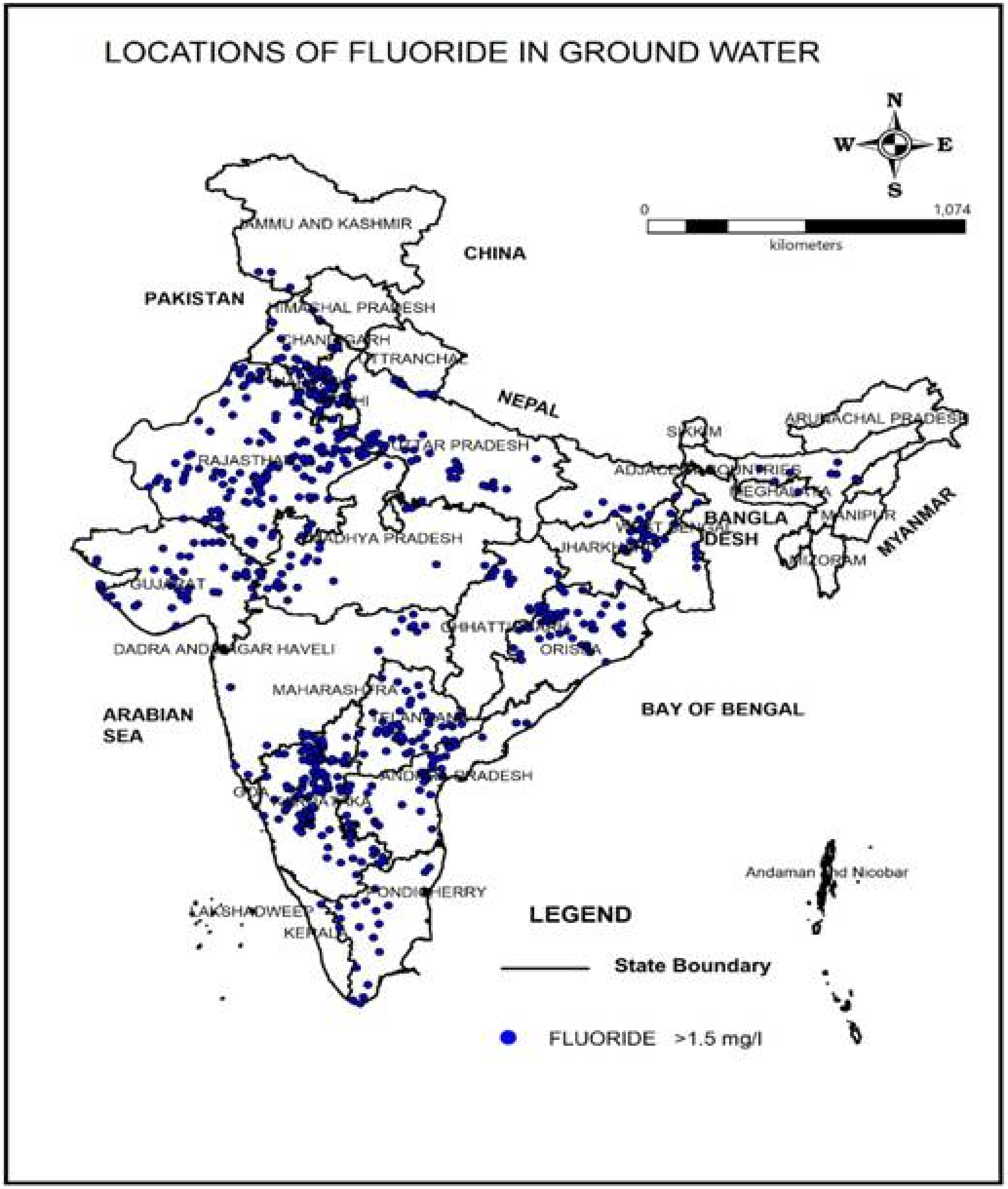
GW Pollution

GW Contamination due to Arsenic (CGWB)

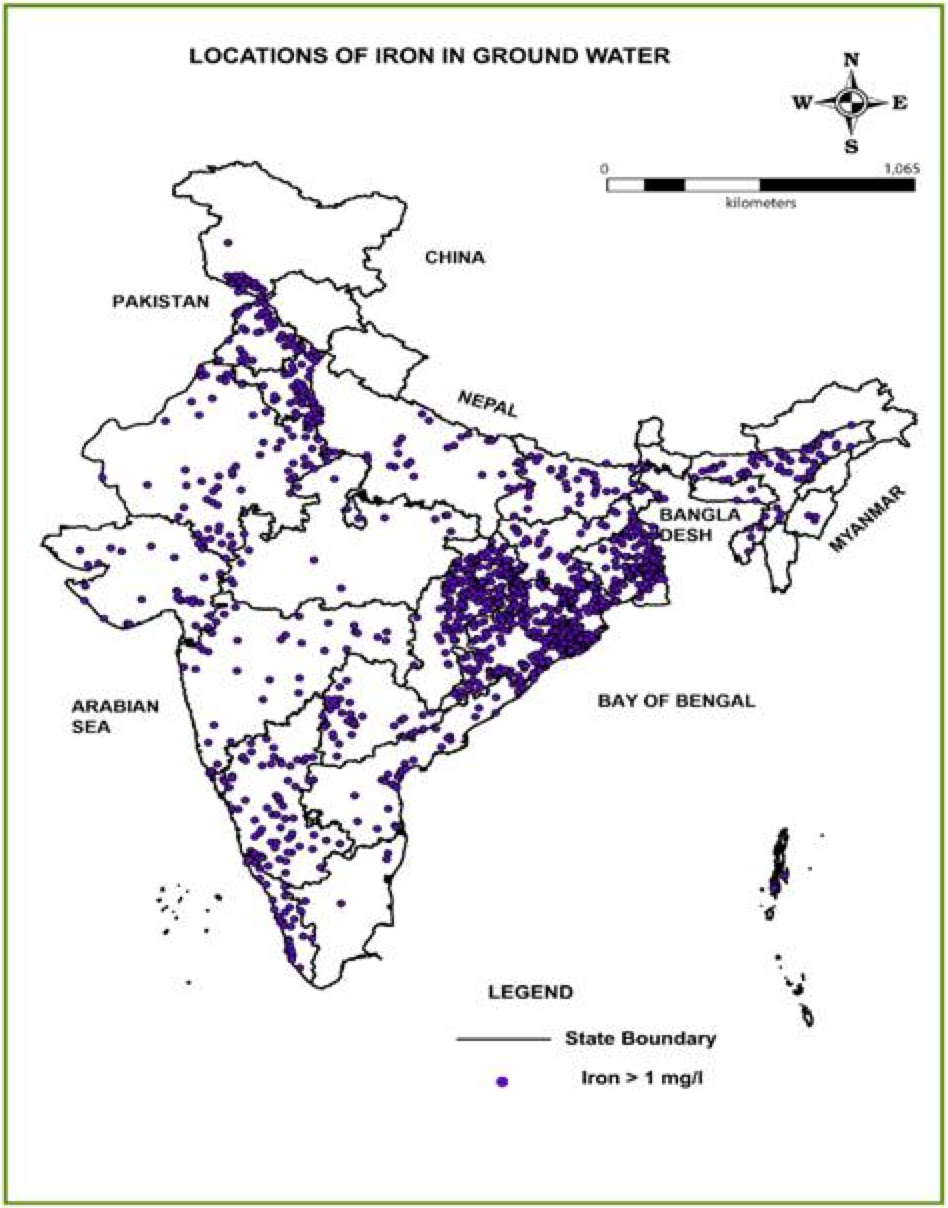




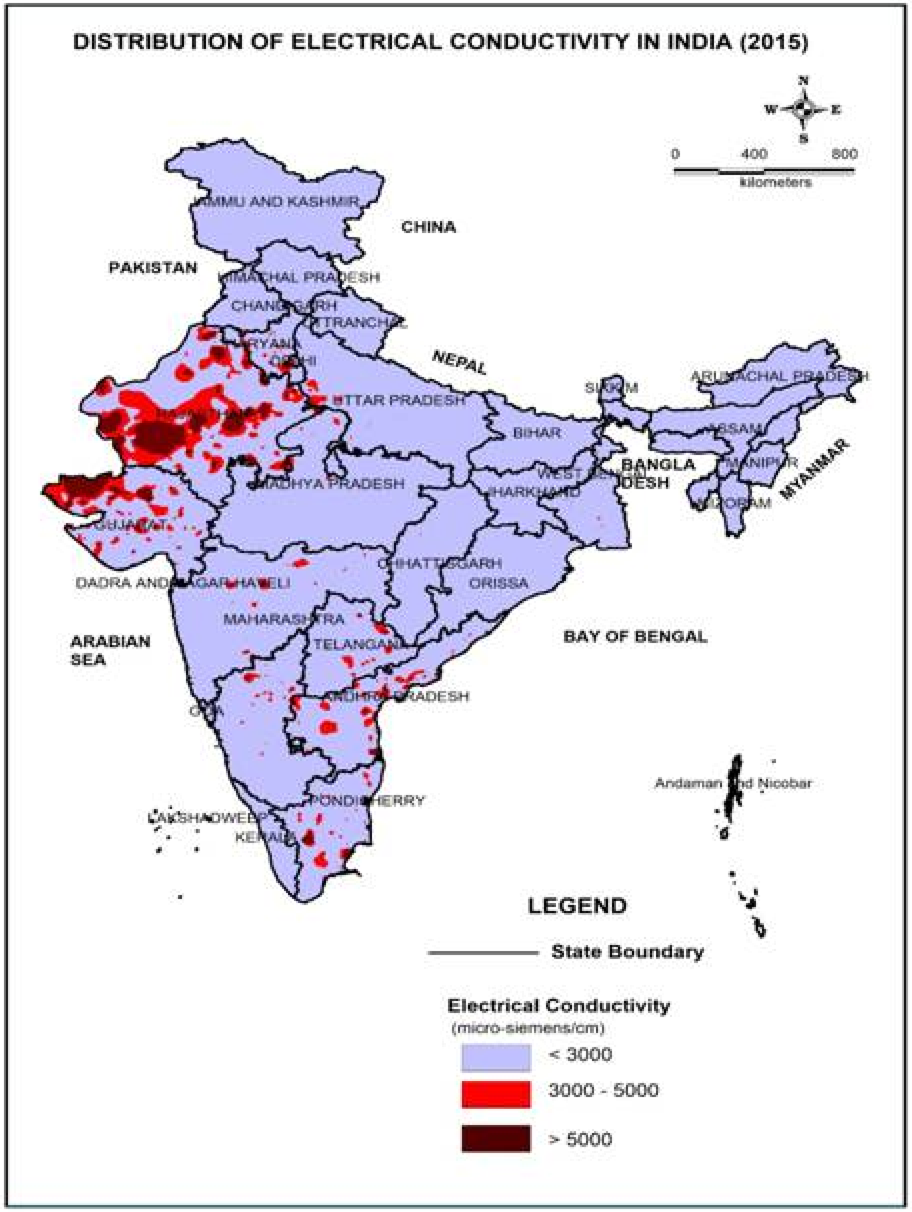
GW Contamination due to Fluoride (CGWB)



GW Contamination due to Iron (CGWB)

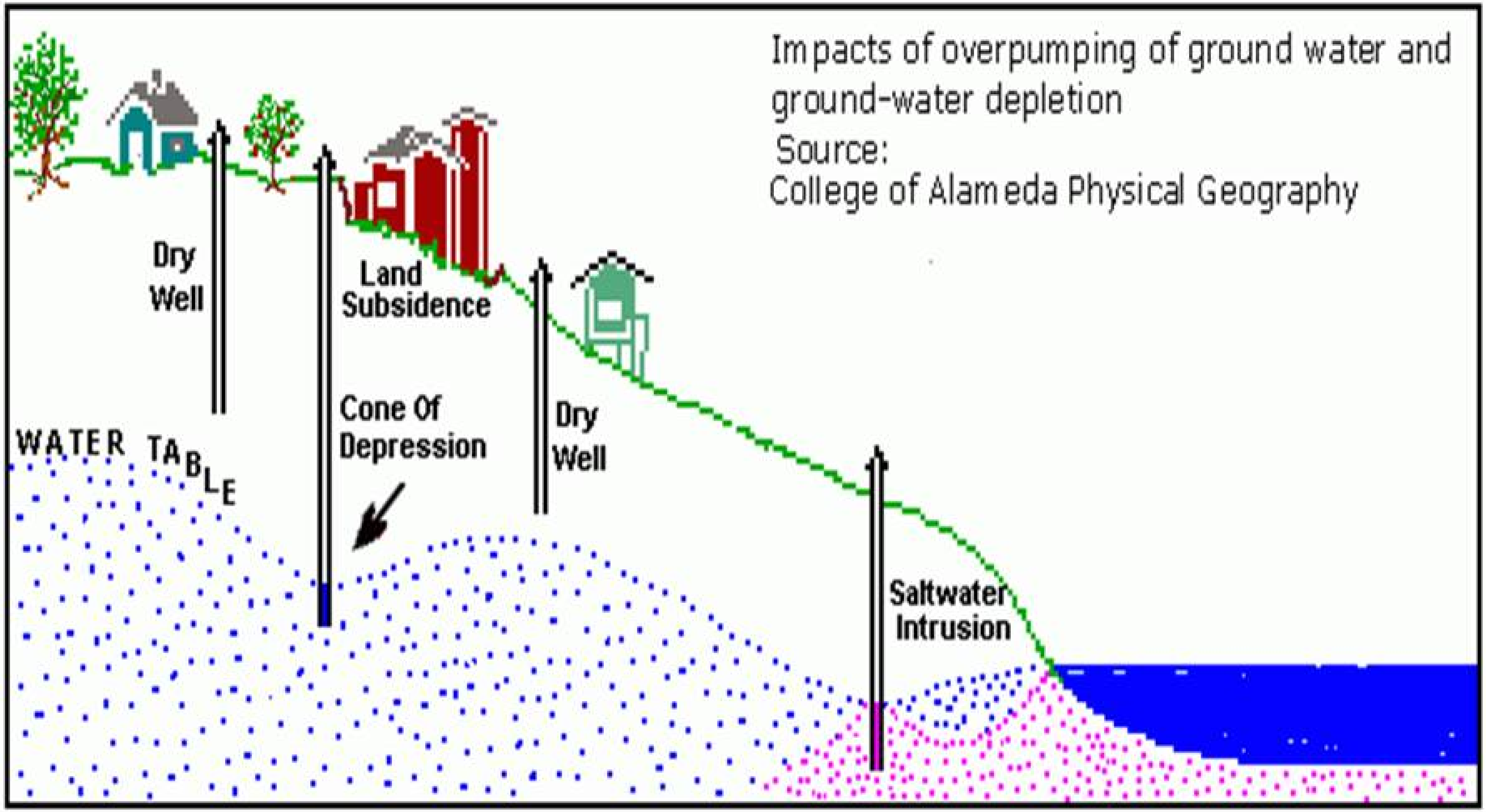


GW Contamination due to EC (CGWB)

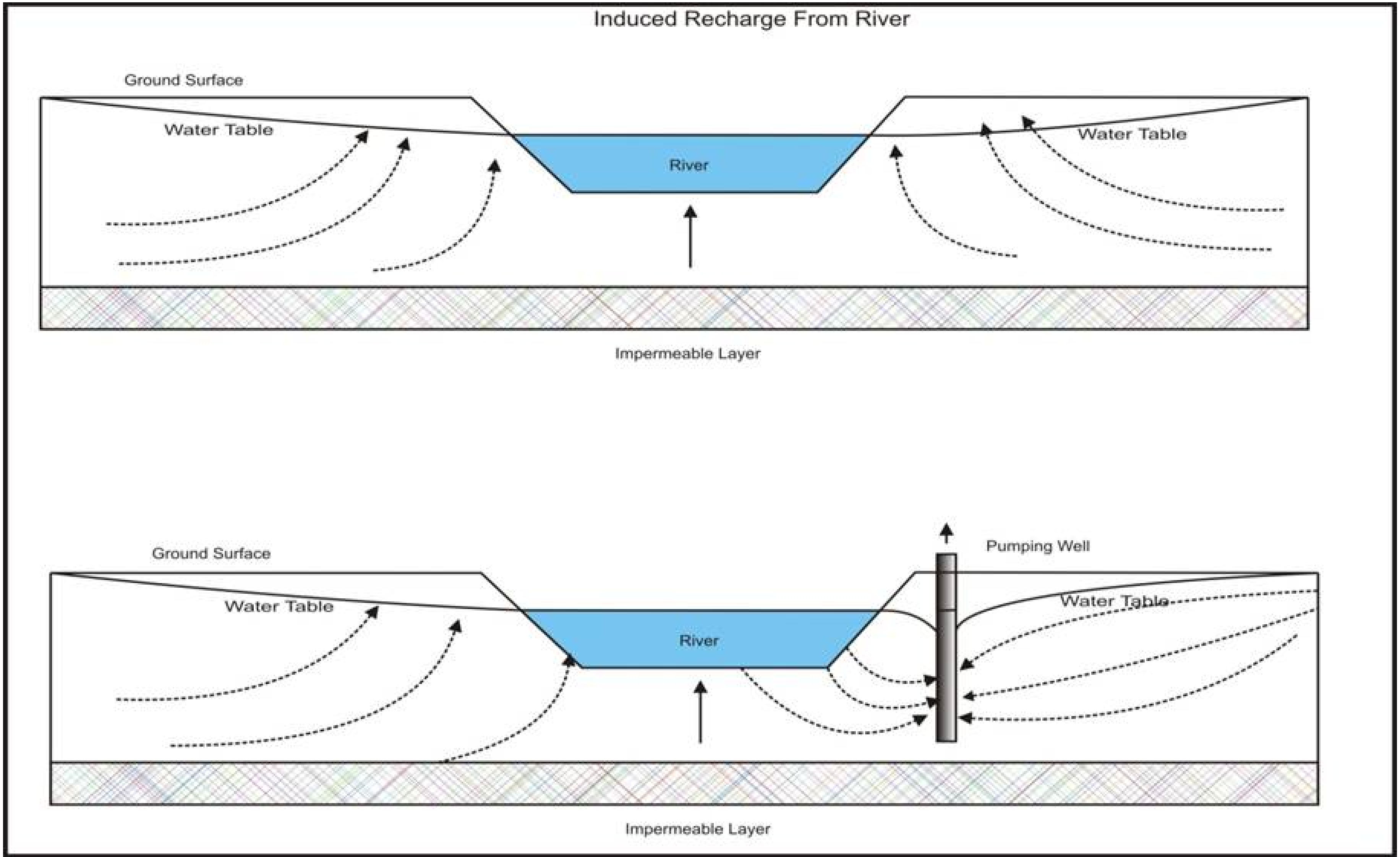


Salinization & Water Logging

Upconing of Saline Water

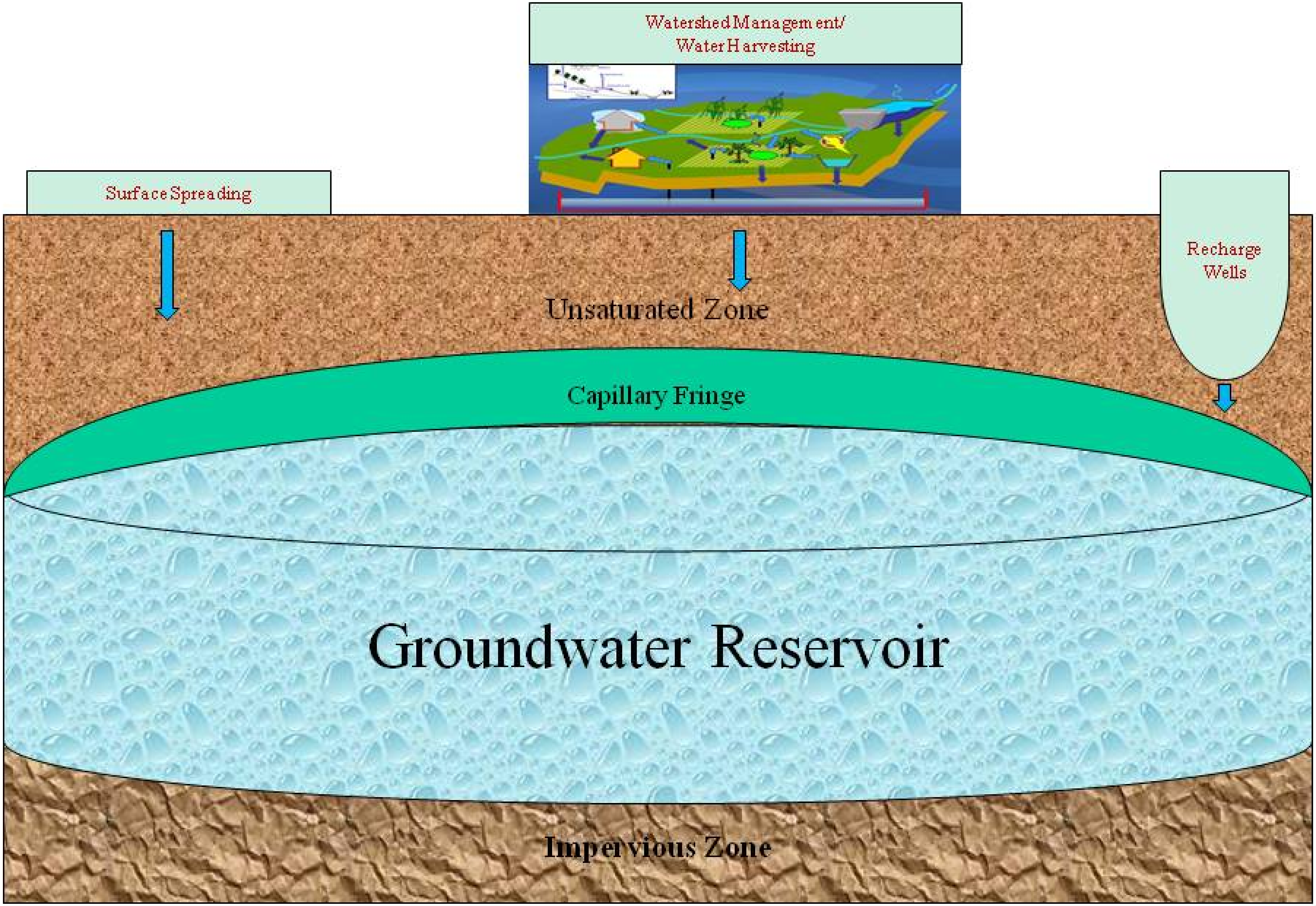


Induced Recharge to Groundwater

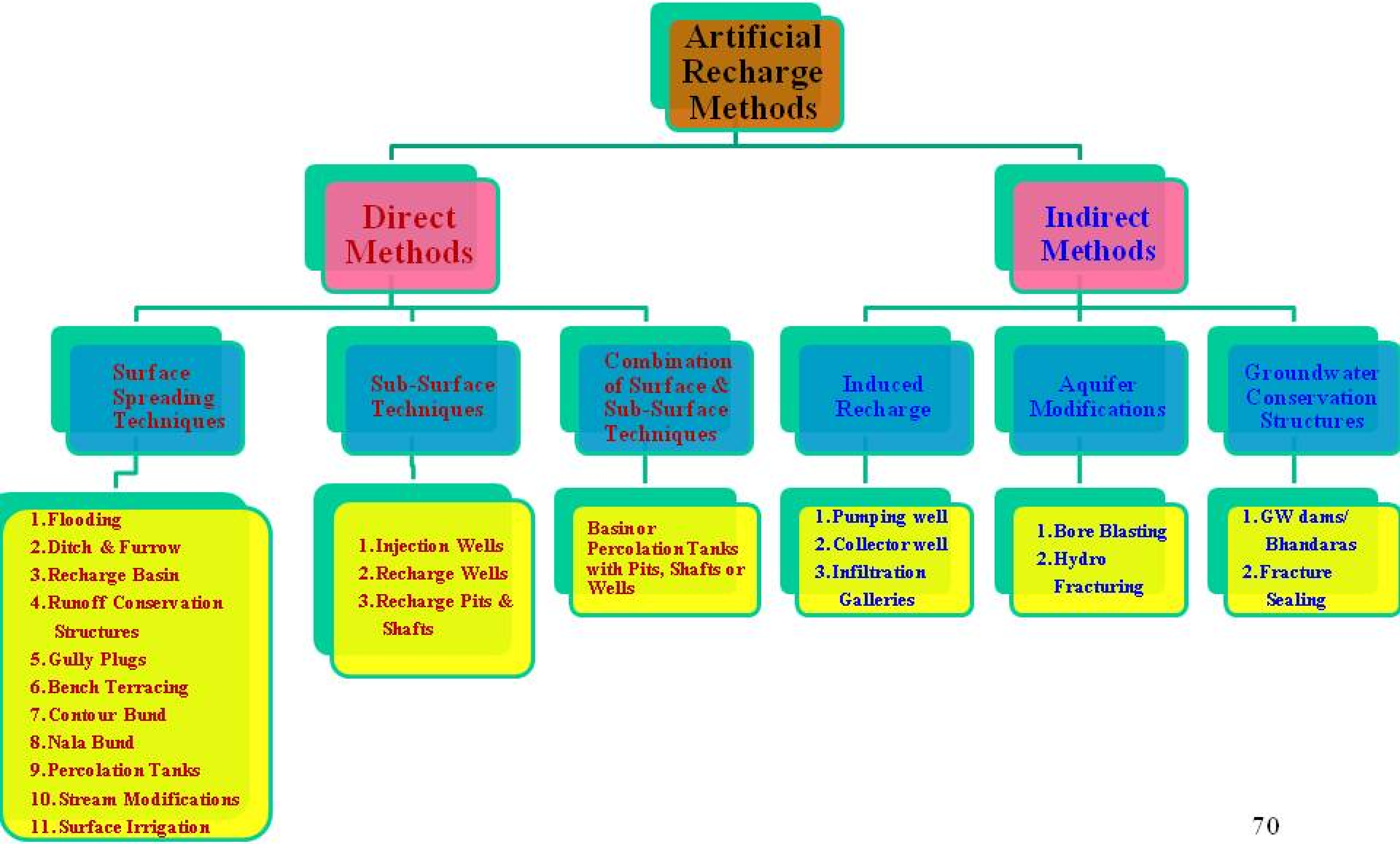


Solutions & Options

Artificial Recharge to Groundwater

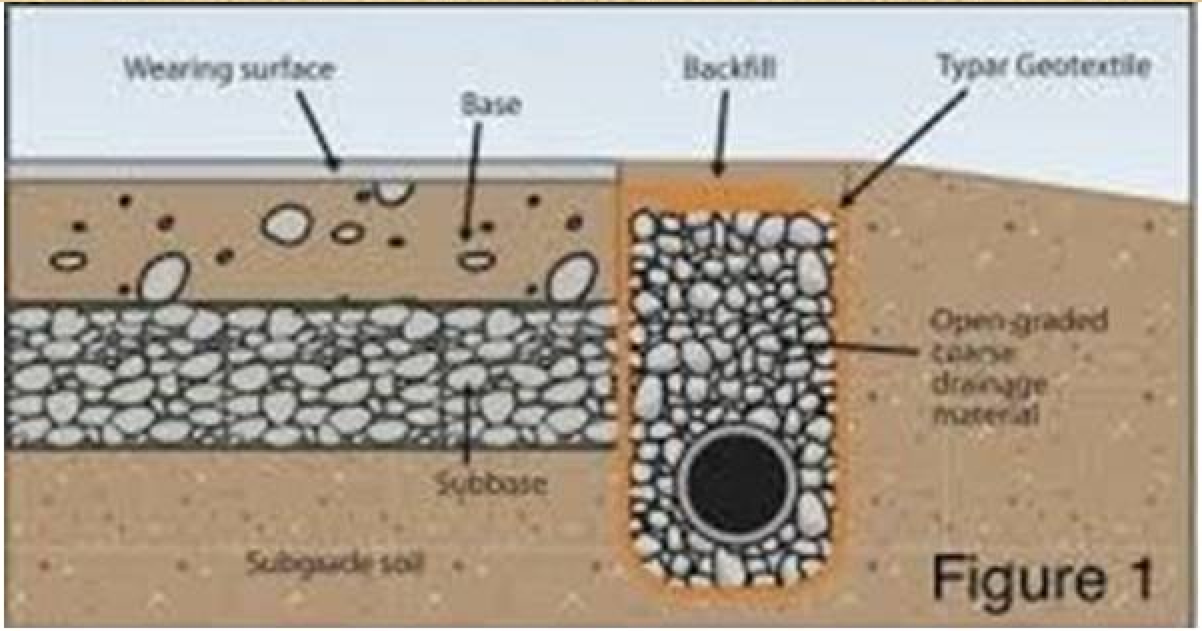


Artificial GW Recharge Techniques



Artificial GW Recharge for Declining GW Areas

Subsurface Drainage for Waterlogged & Saline Areas



Sea Water Intrusion Control Structures in Coastal Areas

Project : Checking of Salinity Ingress in Coastal Area under RKVY

ACTIVITY : WATER HARVESTING STRUCTURE

VILLAGE : DRON
TALUKA : UNA DIST. : JUNAGADH

THANK YOU