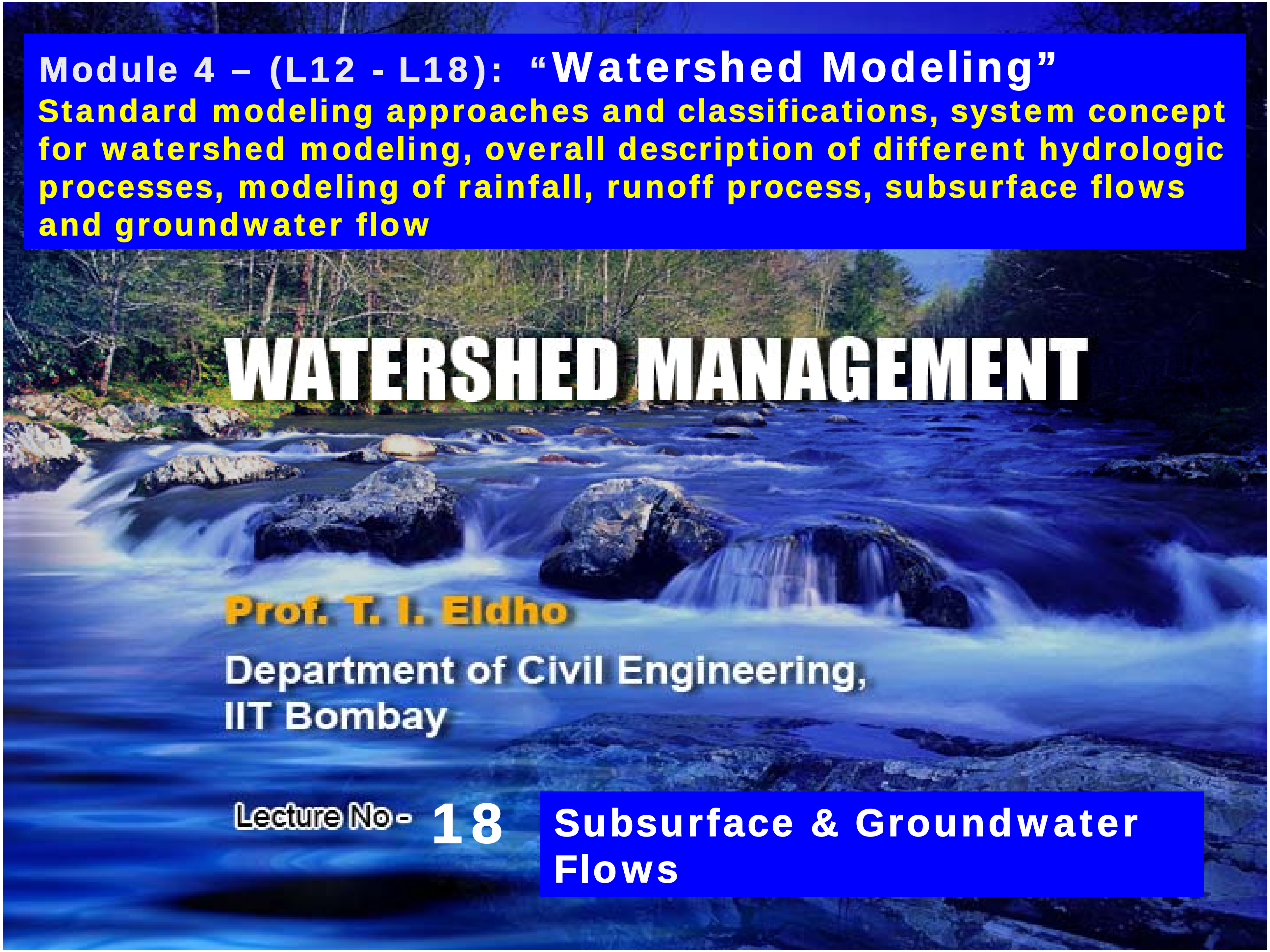

Module 4 – (L12 - L18): “Watershed Modeling”

Standard modeling approaches and classifications, system concept for watershed modeling, overall description of different hydrologic processes, modeling of rainfall, runoff process, subsurface flows and groundwater flow

WATERSHED MANAGEMENT

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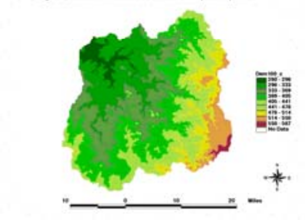
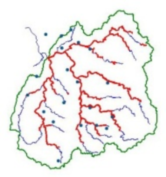
Lecture No - 18

Subsurface & Groundwater Flows

L18–Subsurface & Groundwater Flows

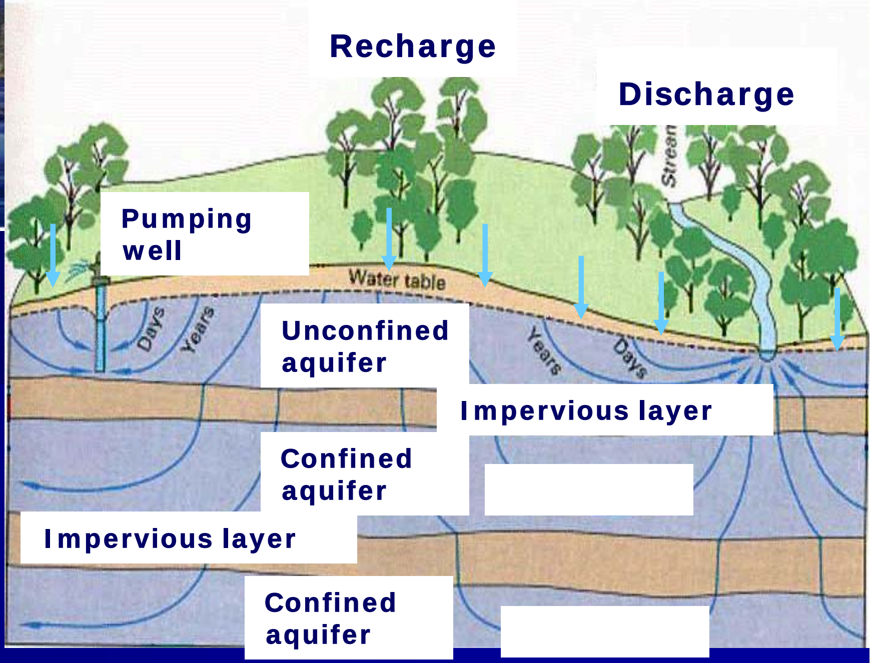
- **Topics Covered**
- Subsurface flow, Infiltration, Aquifers Groundwater flow, Groundwater flow modeling, Numerical modeling, Groundwater quality
- Keywords: Subsurface flow, Infiltration, Aquifer, Groundwater flow, Groundwater flow modeling, Numerical modeling, Groundwater quality.

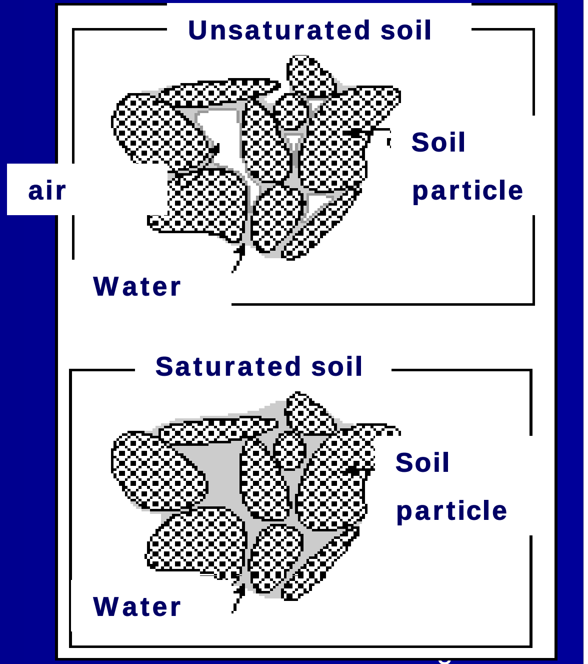




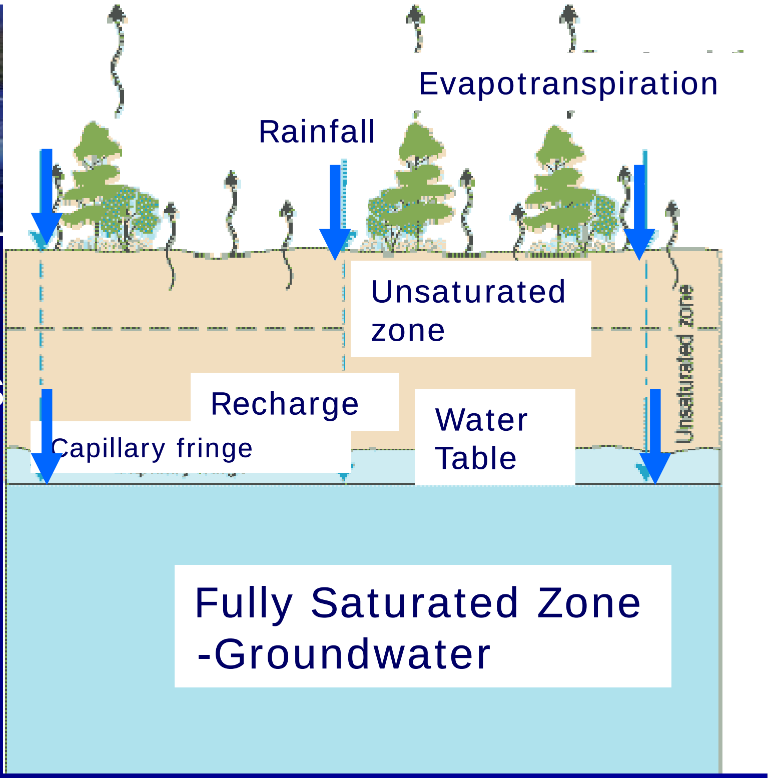
Subsurface Flow

- Subsurface water – all water beneath the Earth’s surface
- Recharged by infiltration either directly on the land surface or in the beds of streams, lakes & oceans.
- Discharged through - evaporation, transpiration, from springs, seeps on land surface or beds of surface water bodies, pumping wells, gravity drains etc.
- Subsurface environment –some arrangement of porous materials – water moves within the pores of these materials.
- Most terrestrial hydrologic activities takes place within root zone.





Subsurface Water

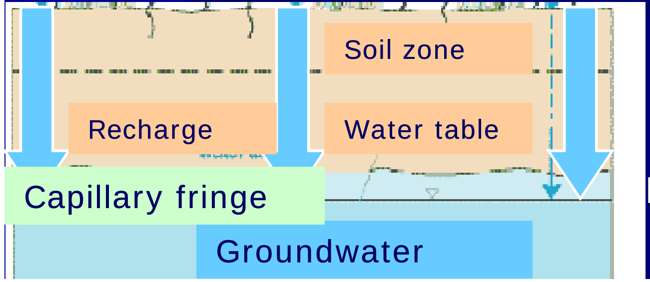


- Soil water - divided into 3 parts
- Drainable water – that readily drains from soil under the influence of gravity – water occupying pores larger than capillary size.
- Plant available water – volume of water released from soil between a soil water pressure head of about -1/3 bar (field capacity) and about -15 bars (wilting point) – water detained in storage by capillary forces.
- Unavailable water – hygroscopic water – water held tightly in films around individual soil particles.

Infiltration

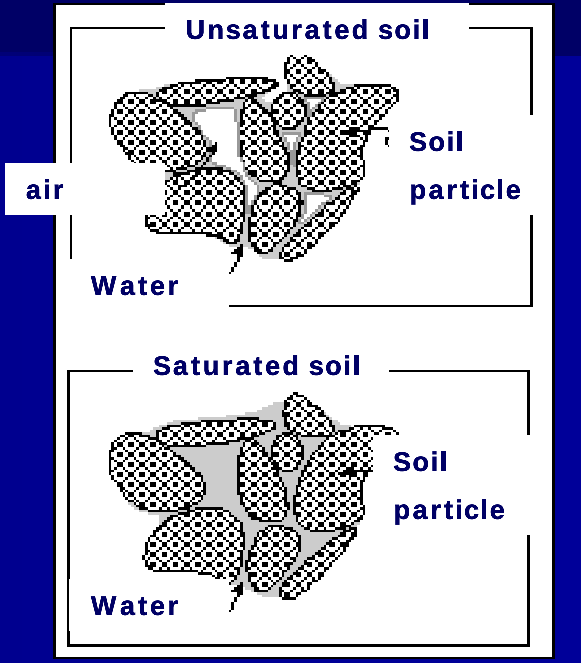
Infiltration: process by which water on the ground surface enters the soil.

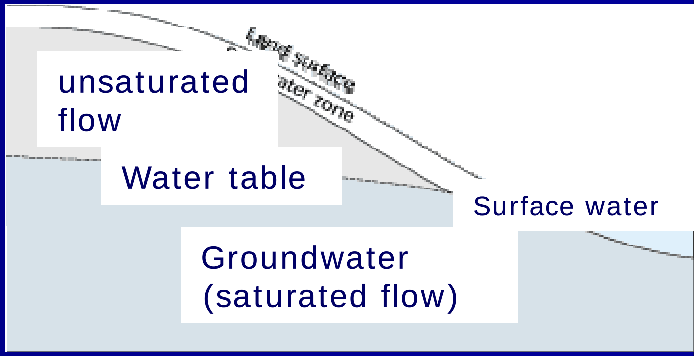
- **Infiltration capacity** of soil determines – amount & time distribution of rainfall excess for runoff from a storm.
- **Important for estimation** of surface runoff, subsurface flow & storage of water within watershed.
- **Controlling factors:** Soil type (size of particles, degree of aggregation between particles, arrangement of particles); vegetative cover; surface crusting; season of the year; antecedent moisture; rainfall hyetograph; subsurface moisture conditions etc.



Unsaturated & Saturated Flows

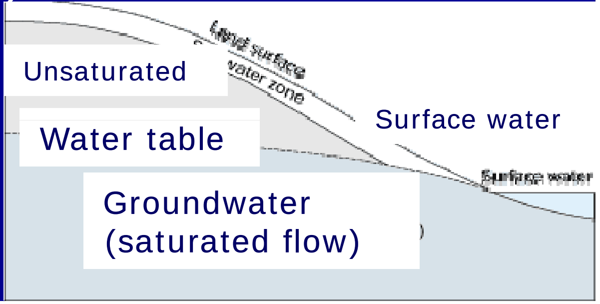
- Unsaturated soils: water moves primarily in small pores & through films located around and between solid particles. As water content decreases, cross sectional area of the films decreases & flow paths become more limited. Result is a hydraulic conductivity function that decreases rapidly with water content.
- Saturated soils: Soil pores are considered full with water (may not be completely full due to air entrapment); Hydraulic conductivity is constant with respect to head h.





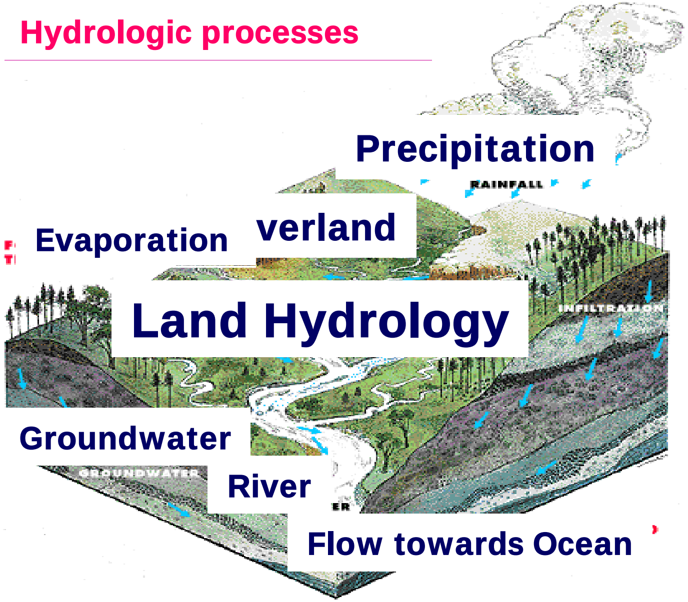
Unsaturated & Saturated Flows..

- Soil Water Movement: response to a gradient
- Wet soil to Dry Soil - low soil moisture tension to high SMT; high soil water potential to low soil potential
- Saturated conditions: water moving mainly in the macropores, all of the pores are filled.
- Unsaturated conditions: macropores full of air micropores filled with water & air - moisture tension gradient creates unsaturated flow.
- Saturated flow (gravitational flow) occurs under saturated conditions when the force of gravity is greater than forces holding water in the soil. Capillary flow occurs in unsaturated soil (also called unsaturated flow).
- Measuring Soil Moisture: Gravimetric method Tensiometer, Electrical resistance method



Groundwater

- Infiltrated water – some replenishes soil moisture deficiency – if soil is not saturated
- When saturated – shallow groundwater system
- Water then percolates down until it reaches the saturated zone – called Aquifer or deep groundwater system
- Upper water surface of saturated zone – groundwater – is called water table.
- Soil above water table – not saturated vadose or unsaturated zone
- Groundwater – important source of fresh water–part of hydrologic cycle
- Constitutes more than 80 times amount of fresh water in rivers & lakes combined.

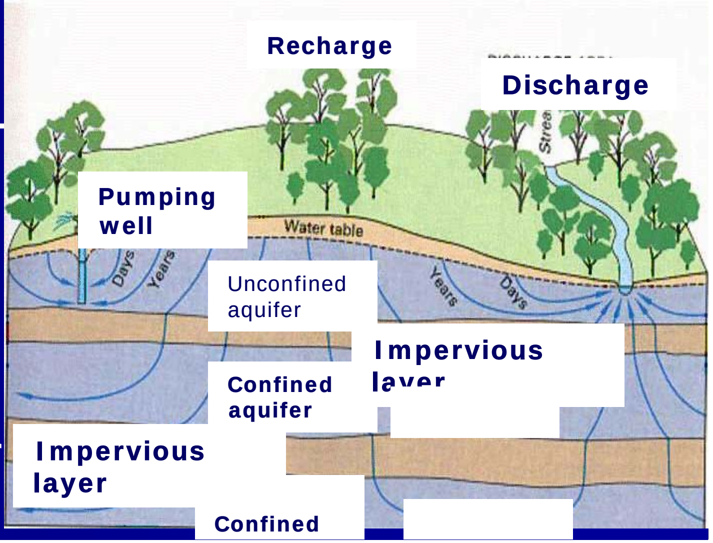


Groundwater - Aquifers

- Aquifer- formation that contains sufficient saturated permeable material to yield significant quantity of water to wells/ springs e.g. Sand.
- Aquiclude: saturated but relatively impermeable material – does not yield appreciable quantities of water; e.g. Clay.
- Aquifuge: relatively impermeable formation – neither contain nor transmit water; e.g.: granite.
- Aquitard: saturated but poorly permeable stratum; e.g.: sandy clay.

Aquifers: Confined or unconfined


Unsaturated soil



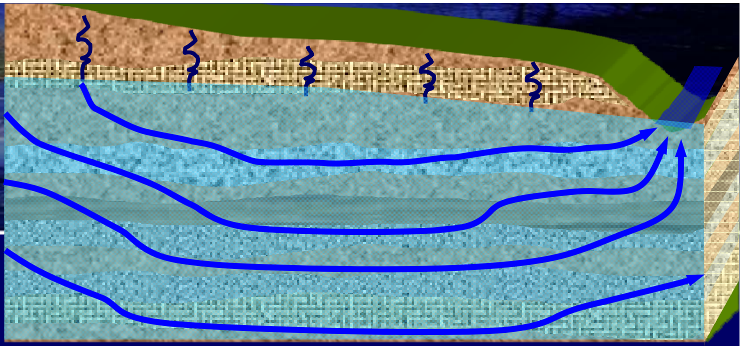
Aquifer Characteristics

- Porosity (n): Those portions of soil, not occupied by solids; Ratio of volume of pores or interstices to total volume.
- Percolation – rate at which water moves downward through soil; Permeability – an expression of movement of water in any direction.
- Specific yield (S_y): ratio of volume of water that, after saturation, can be drained by gravity.
- Storage coefficient (S- storativity): volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in head normal to that surface.

Hydraulic conductivity (K): constant that serves as a measure of the permeability of the porous medium.

Transmissivity (T): Rate at which water is transmitted though a unit width of aquifer under unit hydraulic gradient; T = Kb; b is saturated thickness of aquifer.

Soil media



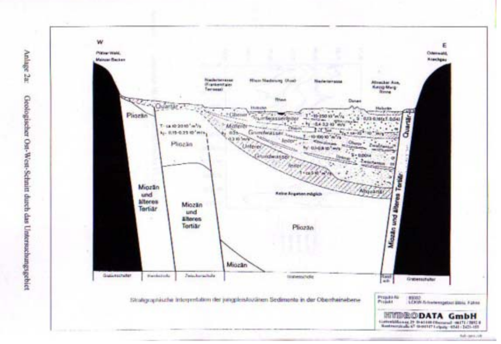
Groundwater Flow

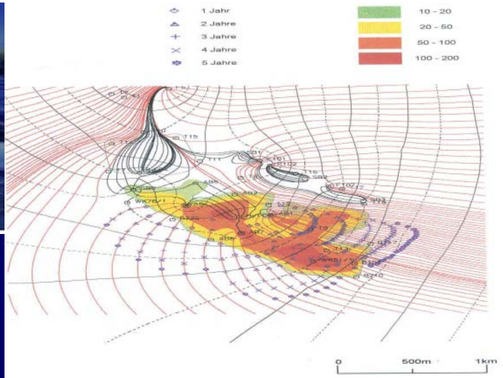
- Darcy's Law: Darcy defined how water moves through a saturated porous medium with analogy of a cylinder fitted with inflow and outflow pipes. He showed that velocity was a function of difference in head 'h' over a finite distance 'l'
- Darcy's law: Velocity of flow: $v = -K\ (dh/dl)$

  Where v is Darcy velocity or specific discharge; K is hydraulic conductivity; dh/dl is hydraulic gradient; '-' sign – flow water in the direction of decreasing head; actual velocity $= v/n$.
- Darcy's law valid: when Re (Reynolds number -> Inertia force/ viscous force) < 1
- Hydraulic conductivity K: found by pumping tests, tracer tests, formulas, laboratory methods etc.

Groundwater Flow in Porous Media

- Porous media – heterogeneous & anisotropic
- Geologic formation as aquifers: Alluvial deposits, limestone, volcanic rock, sandstone, igneous & metamorphic rocks – accordingly porous media characteristics changes.
- Hydraulic conductivity varies from one location to another (heterogeneous) and varies with respect to direction.
- Accordingly groundwater movement varies.
- Groundwater flow analysis – very complex due to complexity of aquifer media and various other parameter.
- Complex hydrogeological systems
- Field investigations - Limitations
- Importance of groundwater flow modeling.

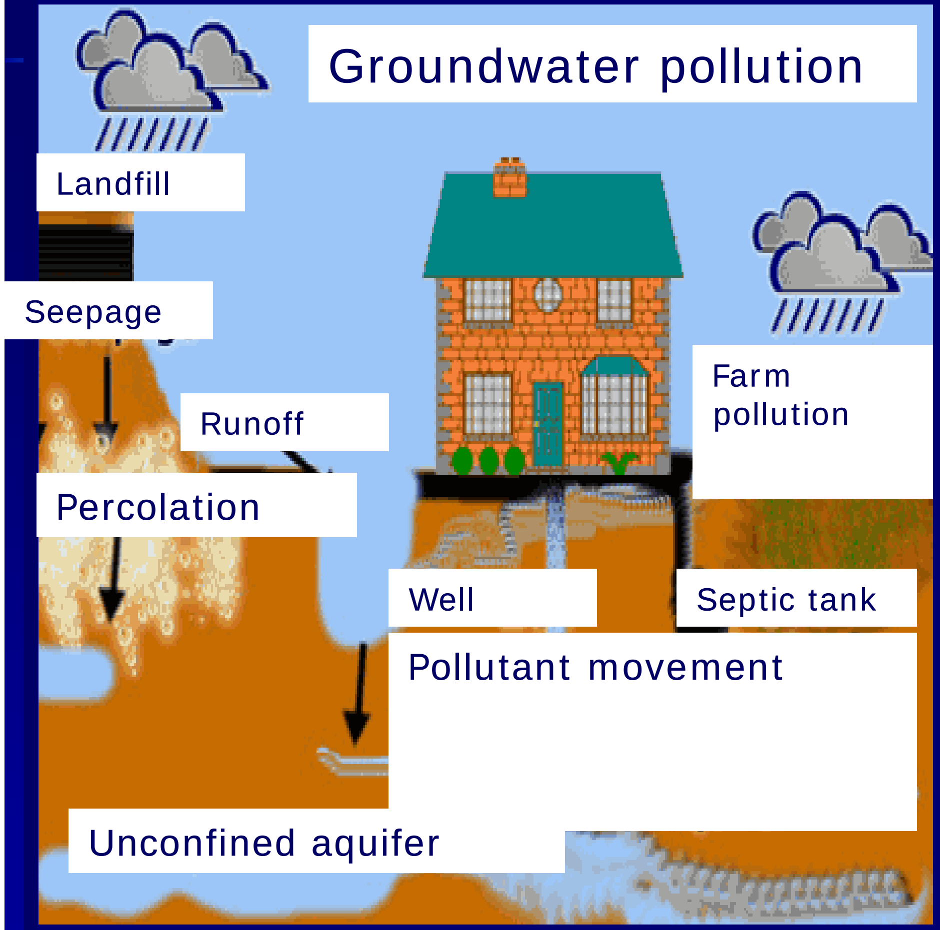




Groundwater Quality Problems

- Groundwater Pollution- a major problem in many countries.
- Indiscriminate disposal of industrial wastes, extensive use of chemicals in agriculture (fertilizers & pesticides) and a host of other human interventions have been causing pollution.
- Effluents in water bodies after affecting soils, extends to the groundwater system through downward gravitational movement, lateral dispersion & advective migration.
- Fractures, Fissures, Joints etc., provide additional preferred pathways for fast migration of pollutants
- With increase in industrialization & increasing use & reliance on groundwater, it is imperative to assess the water quality & study the movement of contaminants in an aquifer system to predict the migration.

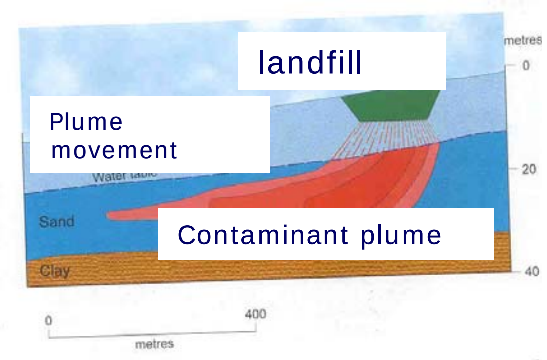
Groundwater Contamination Sources



http://www.filterwater.com/asp/cs/images/gwcont.gif

- Natural contamination
- Agricultural contamination
- Industrial contamination
- Underground storage tanks
- Land application and mining
- Septic tanks
- Waste disposal injection wells
- Landfills

Groundwater Contamination Mechanism



- **Changes in chemical concentration occurs in groundwater system by four distinct processes**

  1. Advective transport

  Dissolved chemicals are moving with the groundwater flow.

  2. Hydrodynamic dispersion

  Mechanical , hydraulic, molecular and ionic diffusion

  3. Fluid sources

  Water of one composition is introduced in to and mixed with water of different composition.

  4. Reactions

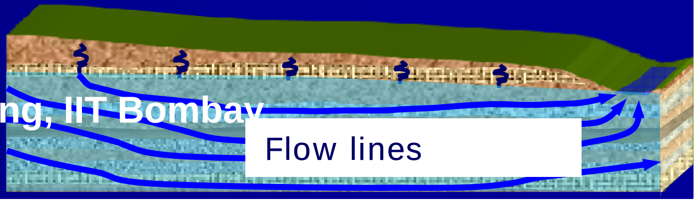
  Some amount of a particular dissolved chemical species may be added or removed from groundwater as a result of chemical, biological and physical reactions in the water or between the water and the solid aquifer materials.

Work Elements for Groundwater Investigations

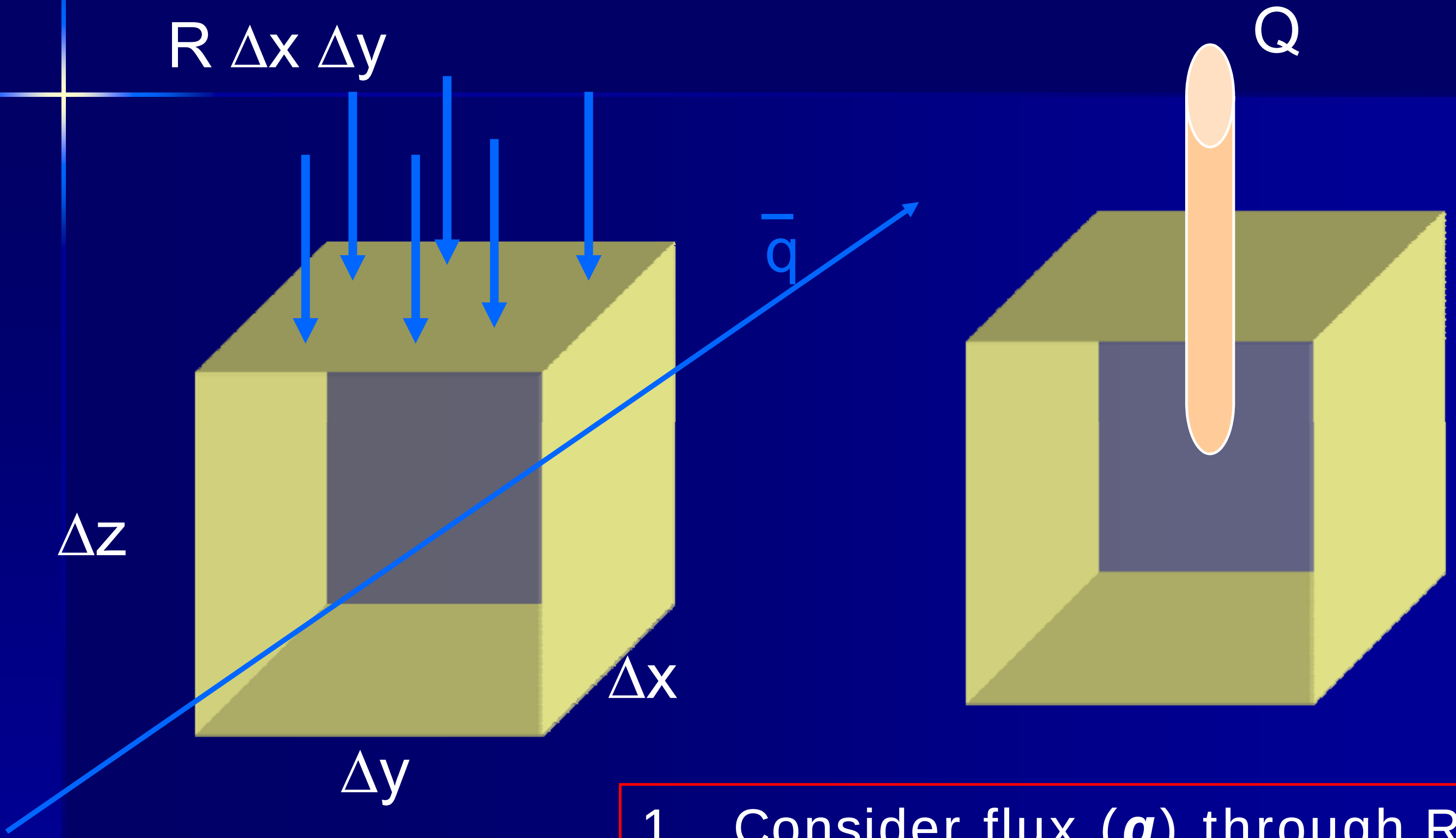
- Well inventory and selection of observation wells
- Preparation of groundwater level map
- Geophysical investigations to decipher the subsurface layers and their characteristics
- Identification of hydrogeological features of interest which are likely to control groundwater flow & transport.
- Understanding of aquifer geometry
- Detailed and periodical water quality analysis
- Periodical monitoring of water levels in observation wells

Groundwater – Mathematical Model

- A Model is a representation of a system - only effective way to test effects of groundwater management strategies
- Mathematical model: simulates ground-water flow and/or solute fate and transport indirectly by means of a set of governing equations thought to represent the physical processes that occur in the system.
- Governing Equation
- (Darcy’s law + water balance equation) with head (h) as the dependent variable
- Boundary Conditions
- Initial conditions (for transient problems)



Derivation of Groundwater Flow Equation



1. Consider flux (***q***) through REV
2. OUT – IN = - ΔStorage
3. Combine with: ***q*** = -K ***grad*** h

Derivation of Groundwater Flow Equation

Law of Mass Balance + Darcy's Law =
Governing Equation for Groundwater Flow

$div\ q = -S_s\,(\partial h/\partial t)$ ***(Law of Mass Balance)***

$q = -\underline{\mathbf{K}}\ \overline{grad}\ h$ ***(Darcy's Law)***

$$div\,(\underline{\mathbf{K}}\ \overline{grad}\ h) = S_s\,(\partial h/\partial t)$$

$$(S_s = S\,/\,\Delta z)$$

Ground Water Flow Modeling

General 3D equation

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

2D confined:

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

2D unconfined:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) = S_s \frac{\partial h}{\partial t} - R$$

Storage coefficient (S) is either storativity or specific yield.
$S = S_s b$ & $T = K b$; R is recharge or pumping (-,+).

Ground Water Transport Modeling

The advective-dispersive solute transport equation in groundwater can be written as

$$\frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_i}\right]-\frac{\partial}{\partial x_i}(CV_i)+\frac{W(x,y,z,t)}{n}C^{'}=\frac{\partial C}{\partial t},i,j=1,2,3$$

- D $_{ij}$ is the hydrodynamic dispersion coefficient tensor ($L^2 T^{-1}$),
- C is the concentration of solute in source or sinks fluid (ML^{-3}),
- n is the porosity dimensionless,
- x_i, x_j are the Cartesian co ordinates, (L),
- V_i is the seepage velocity ($L\ T^{-1}$)
- W(x,y,z,t) is the volume of flux per unit volume (T^{-1})
- C’ is the sorbed concentration

Velocity computations (Darcy's law)

$$v_x = -K_x \frac{\partial h}{\partial x} \qquad v_y = -K_y \frac{\partial h}{\partial y} \qquad V_x = v_x / n_e \qquad V_y = v_y / n_e$$

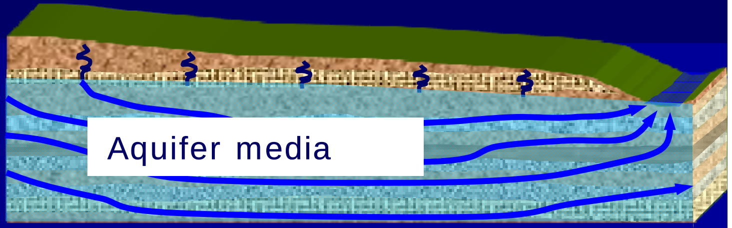
Initial & Boundary conditions

Types of Solutions of Mathematical Models

- Analytical Solutions: h= f(x,y,z,t)
  (example: Theis equation)
- Numerical Solutions
  - Finite difference method (FDM)
  - Finite element method (FEM), FVM, BEM etc.
- Analytic Element Methods (AEM)

Ground Water Flow Modeling

A powerful tool for furthering our understanding of hydrogeological systems & groundwater flow

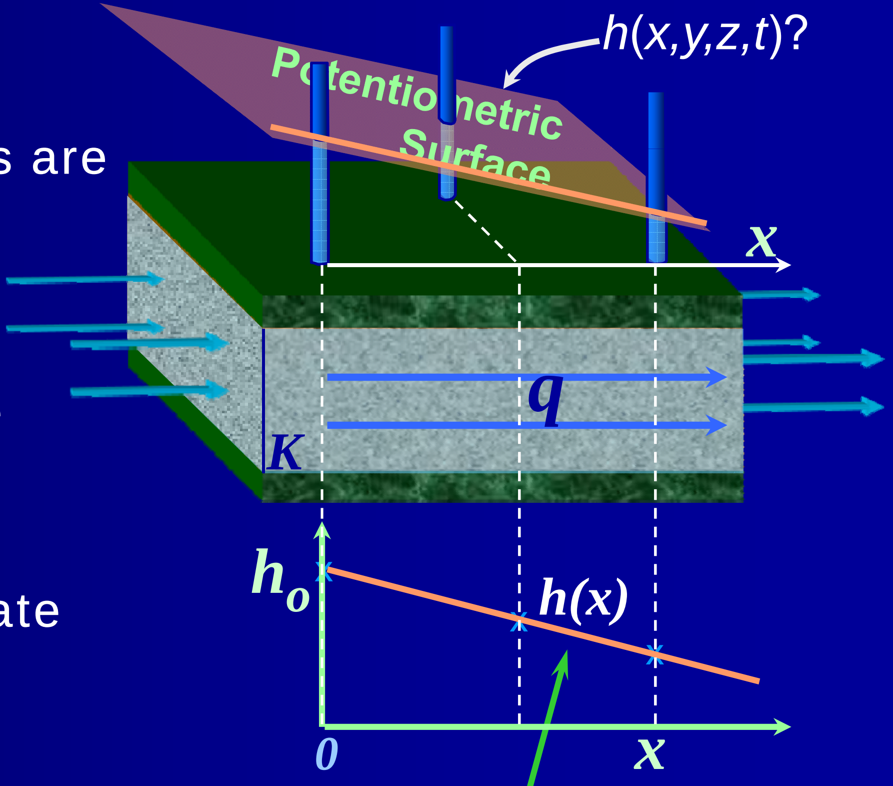


- Importance of ground water flow modeling
  - Construct accurate representations of hydrogeological systems
  - Understand interrelationships between elements of systems
  - Efficiently develop a sound mathematical representation
  - Make reasonable assumptions and simplifications
  - Understand the limitations of the mathematical representation
  - Understand limitations of the interpretation of the results

Ground Water Flow Modeling

Predicting heads (and flows) **and Approximating parameters**

- Solutions to the flow equations
  - Most ground water flow models are solutions of some form of the ground water flow equation
  - Partial differential equation needs to be solved to calculate head as a function of position and time, i.e., h=f(x,y,z,t)
  - “e.g., unidirectional, steady-state flow within a confined aquifer



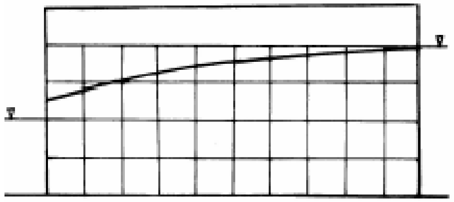
Darcy’s Law Integrated

$$\frac{dh}{dx} = -\frac{q}{K} \Rightarrow \int_{h_0}^{h} dh = -\frac{q}{K}\int_{0}^{x} dx \Rightarrow h - h_0 = -\frac{q\,x}{K}$$

$$h(x) = h_0 - \frac{q\,x}{K}$$

Finite Difference Method

- Continuous variation of the function concerned by a set of values at points on a grid of intersecting lines.
- The gradient of the function are then represented by differences in the values at neighboring points and a finite difference version of the equation is formed.
- At points in the interior of the grid, this equation is used to form a set of simultaneous equations giving the value of the function at a point in terms of values at nearby points.
- At the edges of the grid, the value of the function is fixed, or a special form of finite difference equation is used to give the required gradient of the function.



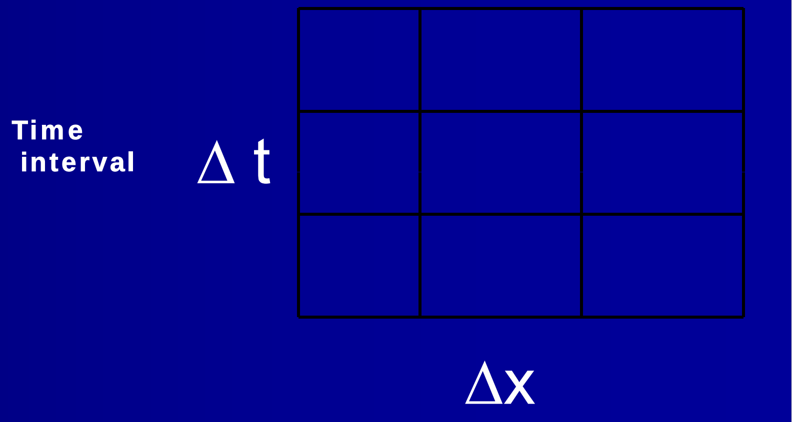
(A) - FDM - DISCRETIZATION

FDM for Groundwater Flow Eqn.

- **Eg. Explicit scheme:** Consider a groundwater flow equation for homogeneous isotropic aquifer
- Using the finite difference scheme, for a node I,J & for a specific time n
- Using forward discretization in time and central difference discretization in space
  - FTCS in spatial and temporal domain
  - choosing constant mesh intervals Δx and Δy

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S}{T}\frac{\partial h}{\partial t}-\frac{R(x,y,t)}{T}$$

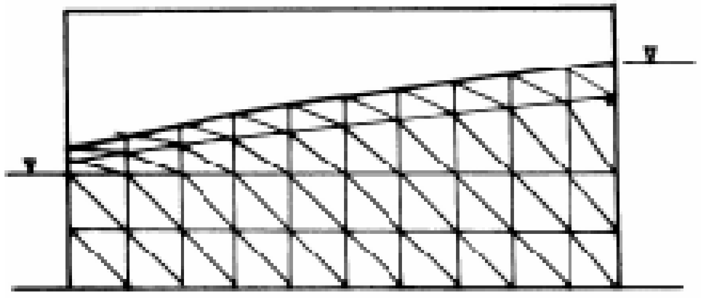
$$\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S}{T}\frac{\partial h}{\partial t}-\frac{R(x,y,t)}{T}\right)^{n}_{I,J}$$



$$\frac{h^{n}_{I+1,J}-2h^{n}_{I,J}+h^{n}_{I-1,J}}{(\Delta x)^2}+\frac{h^{n}_{I,J+1}-2h^{n}_{I,J}+h^{n}_{I,J+1}}{(\Delta y)^2}=\left(\frac{S}{T}\right)\frac{h^{n+1}_{I,J}-h^{n}_{I,J}}{(\Delta t)}-\frac{R^{n}_{I,J}}{T}$$

Finite Element Method

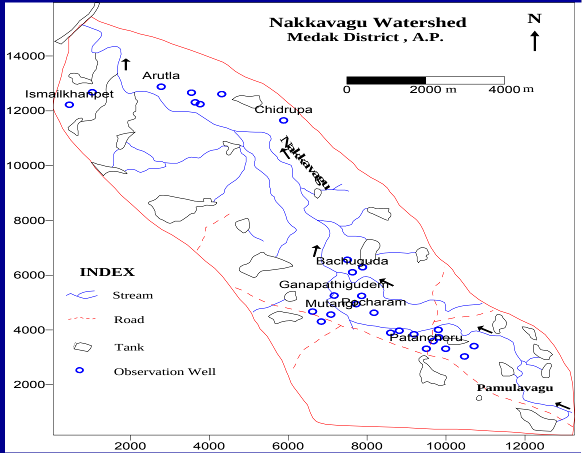
- The region of interest is divided in a much more flexible way
- The nodes at which the value of the function is found have to lie on a grid system or on a flexible mesh
- The boundary conditions are handled in a more convenient manner.
- Direct approach, variational principle or weighted residual method is used to approximate the governing differential equation



(B)- FEM DISCRETIZATION

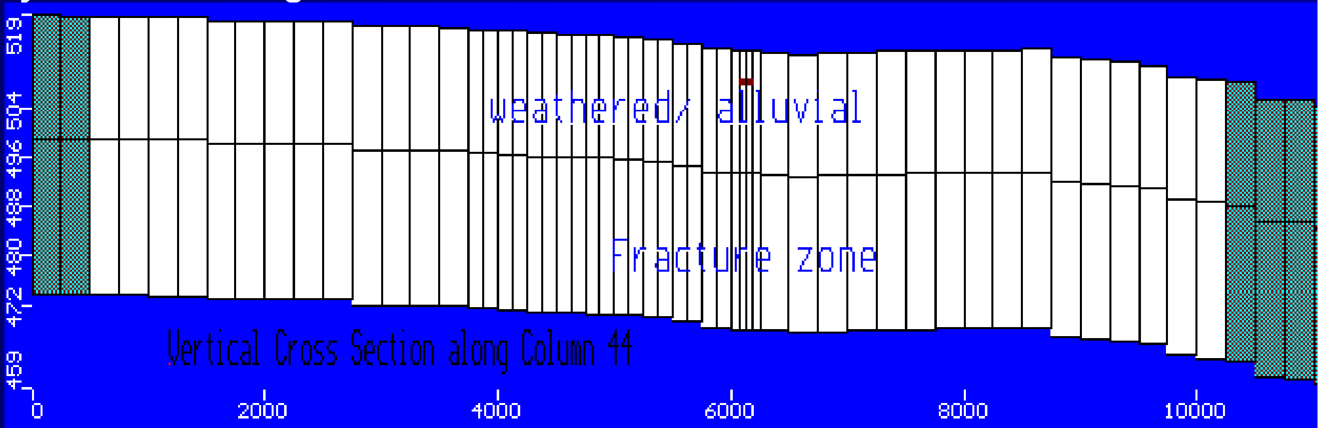
Case study: IDA Patancheru

- Industrial Development Areas of Patancheru near Hyderabad in A.P , part of the stream catchments of Naka vagu, a tributary of Manjira River.
- The area is in Medak district covering about 500 sq km spread over in three mandals Patancheru, Jinnaram and Sangareddy;
- More than 600 industries in this area dealing with pharmaceuticals, paints and pigments, metal treatment & steel rolling, cotton & synthetic yarn & engineering goods were established since 1977
- As part of contaminant transport study, a flow model using an FDM package Visual MODFLOW is developed



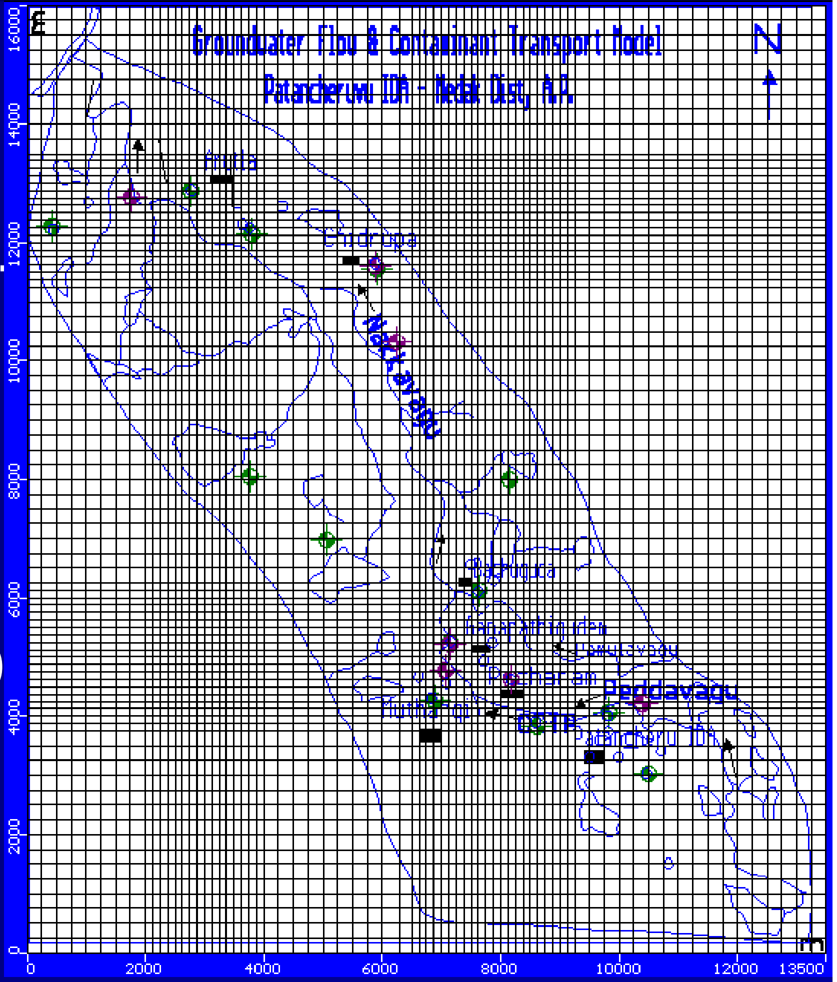
Case study: IDA Patancheru

- The groundwater recharge varies from 100-110 mm yr^{-1} for an annual rainfall of 800mm.
- Permeability values as high as 50-80 m/day were found in the alluvium around Arutla village
- Transmissivity is found to vary from 140 m^2 / day in granites to 1300 m^2/day in alluvium.
- Observed site data shows that the top weathered aquifer is having 10-15 m thick is underlain by fractured layer.
- The simulated model domain of Patancheru IDA and it's environ consists of 55 rows and 65 columns (small rectangles,**250 m x 250 m)** and two layers covering an area of 16000 m x 13500 m.



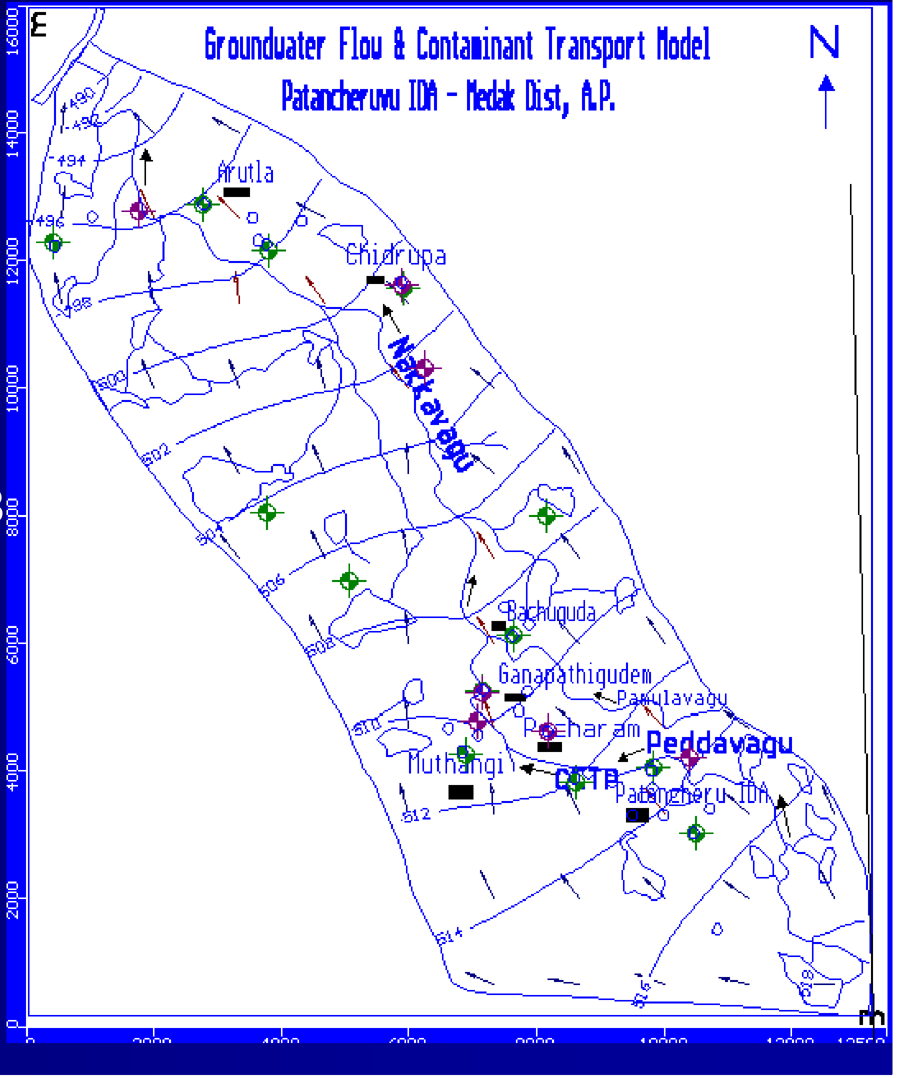
Case study: IDA Patancheru

- Top layer consists of 10-25 m thick alluvium along Nakka vagu or weathered zone in granites and is underlain by 10-20 m fractured zone.
- Vertical section simulated in model is having the total thickness of 45 m.
- Water table in the area has an elevation difference of 75 m with southern boundary near Beramguda having a water table of 570 m (amsl) and lowest water table elevation of 495 m elevation fixed as a constant head @ Manjira river confluence.
- Flow is assumed to be steady state.



Case study: IDA Patancheru

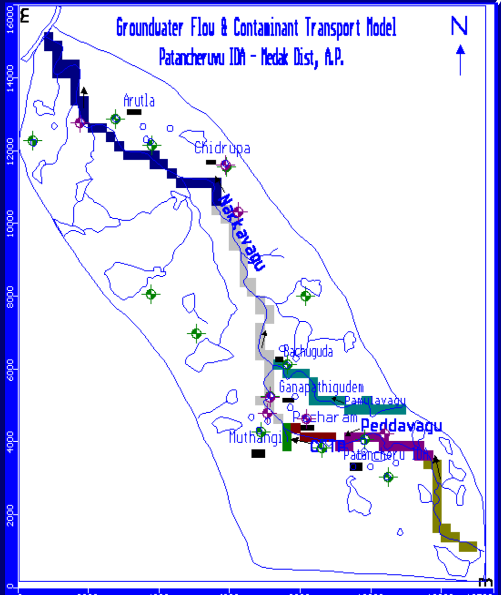
- By using the visual MODFLOW software (Guiger and Franz, 1996) the aquifer model simulation is carried out.
- Model is calibrated between observed data & simulated results. Water table configuration of November 2003 was adopted for this purpose. Computed & observed water level for the steady state condition is shown in Fig.
- Good agreement is observed between computed & observed water levels.

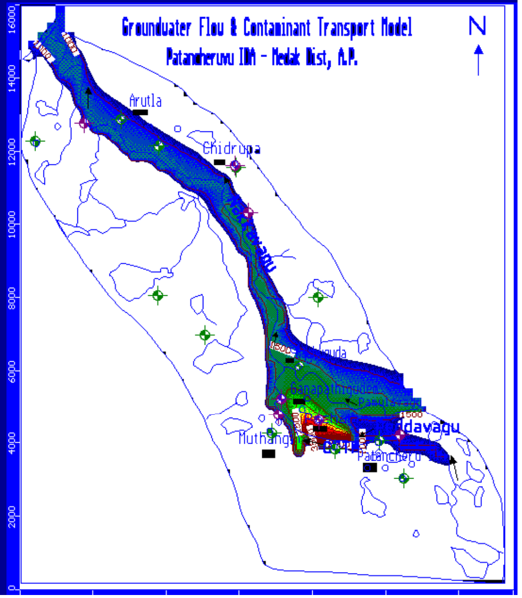


Case study: IDA Patancheru

- Using MT3D: Values for dispersivities (∝) are assumed as 100m, 1m, 0.01- based on field observation.
- A constant TDS concentration at different nodes of Nakka vagu was assigned varying from 4500 mg/L at CETP Patancheru to 1500 mg/L down stream near Ismailkhanpet.
- Downstream concentration of the order of 1500 mg/L is observed all along Nakka vagu right up to confluence with Manjira river – based on 2003 measurements.
- The time step used in this model is one day.
- Contaminant prediction is done for the year 2007

▪1500 mg/L
▪1800 mg/L
▪2000 mg/L
▪4500 mg/L
▪1000 mg/L





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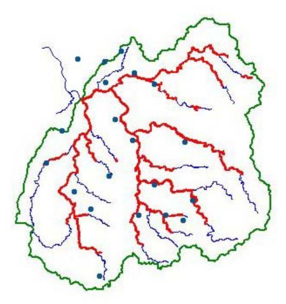
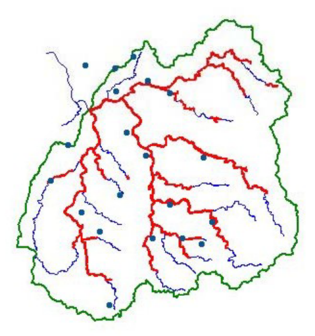


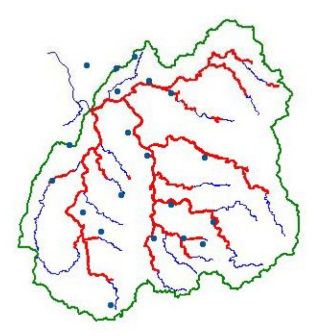
Tutorials - Question!.?.

- How groundwater condition can be improved in a watershed.?.
- Discuss the importance of groundwater in watershed management plans.
- Discuss groundwater resources improvement by rainwater harvesting & artificial recharge.



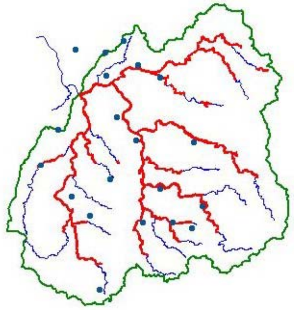
Self Evaluation - Questions!.

- Why groundwater is very important in watershed management?.
- Describe different types of soil water.
- Differentiate between unsaturated flows and saturated flows.
- What are the important work elements in groundwater investigations?.
- Discuss groundwater quality issues.



Assignment- Questions?.

- Explain how to assess groundwater potential?.
- Describe different types of aquifers & classify aquifers according to characteristics.
- Discuss fundamental laws governing groundwater in a watershed.
- How to model groundwater flow?.
- Explain major modeling techniques for groundwater flow?.



Unsolved Problem!.

- Study the groundwater potential of your watershed area.
- Collect data related to aquifer, soil, land use/ land cover etc.
- Obtain hydrogeological maps & top sheets of the watershed.
- Assess the groundwater potential based on available data.
- Get the data related to number of wells in the watershed and study the head variations within the wells.
- Discuss how you can improve the groundwater availability in the area.

THANK YOU

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