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.
**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.

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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.

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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.

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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

### Diagram
- Unsaturated
- Surface water
- Water table
- Groundwater (saturated flow)
## 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.

### Hydrologic processes

- Precipitation
- Evaporation
- Flow towards Ocean
- River
- Land Hydrology

### Land Hydrology

- Groundwater

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**WATERSHED MANAGEMENT**
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
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.
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: \( v = -K \frac{dh}{dl} \)
Where \( v \) is Darcy velocity or specific discharge; \( K \) is hydraulic conductivity; \( \frac{dh}{dl} \) 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.

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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.

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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.

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Groundwater Contamination Sources

- 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 into 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.

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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

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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. \( \text{OUT} - \text{IN} = -\Delta\text{Storage} \)
3. Combine with: \( q = -K \text{grad } h \)

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Derivation of Groundwater Flow Equation


\[ \text{div } q = - S_s \left( \frac{\partial h}{\partial t} \right) \quad (\text{Law of Mass Balance}) \]

\[ q = - \mathbf{K} \text{ grad } h \quad \text{(Darcy’s Law)} \]

\[ \text{div } (\mathbf{K} \text{ grad } h) = S_s \left( \frac{\partial h}{\partial t} \right) \quad (S_s = S / \Delta z) \]
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 (-, +).

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Ground Water Transport Modeling

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

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

- \( D_{ij} \) is the hydrodynamic dispersion coefficient tensor (L² 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)

\[ v_x = -K_x \frac{\partial h}{\partial x} \]
\[ v_y = -K_y \frac{\partial h}{\partial y} \]
\[ V_x = \frac{v_x}{n_e} \]
\[ V_y = \frac{v_y}{n_e} \]

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)**

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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

\[
\frac{dh}{dx} = -\frac{q}{K} \quad \Rightarrow \quad \int_{h_0}^{h} dh = -\frac{q}{K} \int_{0}^{x} dx \quad \Rightarrow \quad h - h_0 = -\frac{q x}{K}
\]

\[
h(x) = h_0 - \frac{q x}{K}
\]

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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.

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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 $\Delta x$ and $\Delta y$

\[
\frac{h_{I+1,J}^n - 2h_{I,J}^n + h_{I-1,J}^n}{(\Delta x)^2} + \frac{h_{I,J+1}^n - 2h_{I,J}^n + h_{I,J+1}^n}{(\Delta y)^2} = \left( \frac{S}{T} \right) \frac{h_{I,J}^{n+1} - h_{I,J}^n}{(\Delta t)} - \frac{R_{I,J}^n}{T}
\]
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
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 800 mm.
- 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 environment consists of 55 rows and 65 columns (small rectangles, \(250 \text{ m} \times 250 \text{ m}\)) and two layers covering an area of 16000 m \(\times\) 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 ($\infty$) 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
References

- J.V.S Murthy (1991), Watershed Management, New Age international Publications

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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.

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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.

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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.

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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.

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