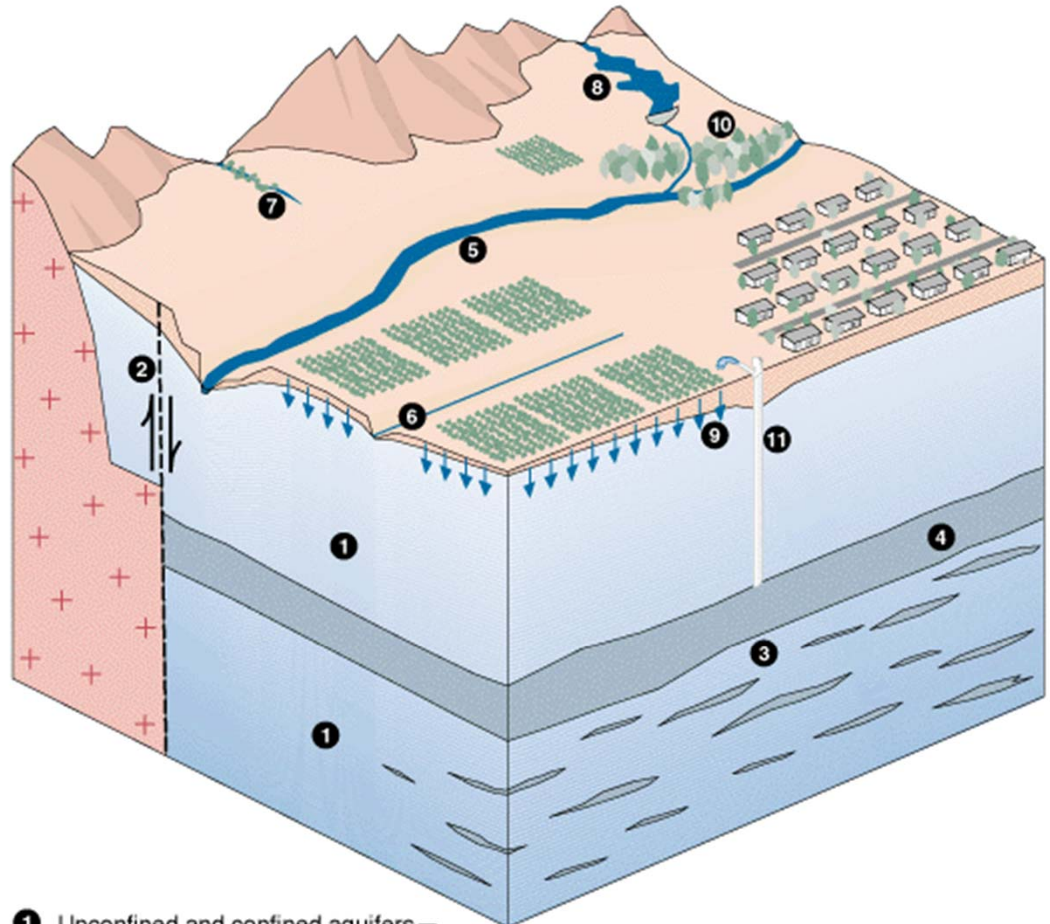
CE EN 547 – BRIGHAM YOUNG UNIVERSITY

MODFLOW – Introduction Organization & Main Packages

- Developed by McDonald & Harbaugh of the USGS, 1983
- Public Domain
- Most widely used groundwater model
- Steady state or transient saturated flow
- Latest version is MODFLOW 2005
- GMS uses MODFLOW 2000 version

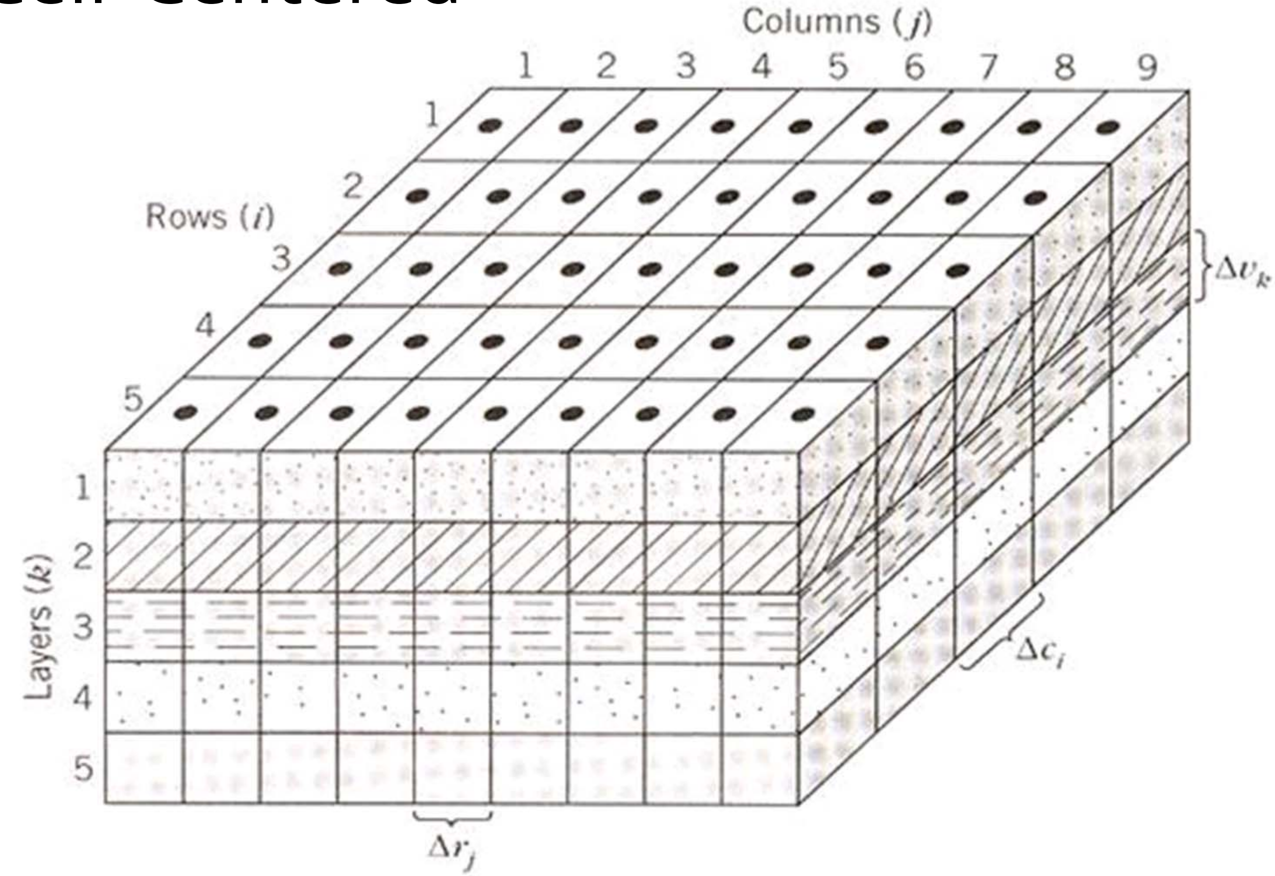


1. Unconfined and confined aquifers—Ground-water flow and storage changes
2. Faults and other barriers—Resistance to horizontal ground-water flow
3. Fine-grained confining units and interbeds
4. Confining units—Ground-water flow and storage changes
5. Rivers—Exchange of water with aquifers
6. Drains and springs—Discharge of water from aquifers
7. Ephemeral streams—Exchange of water with aquifers
8. Reservoirs—Exchange of water with aquifers
9. Recharge from precipitation and irrigation
10. Evapotranspiration
11. Wells—Withdrawal or recharge at specified rates

Figure 1. Features of an aquifer system that can be simulated by MODFLOW.

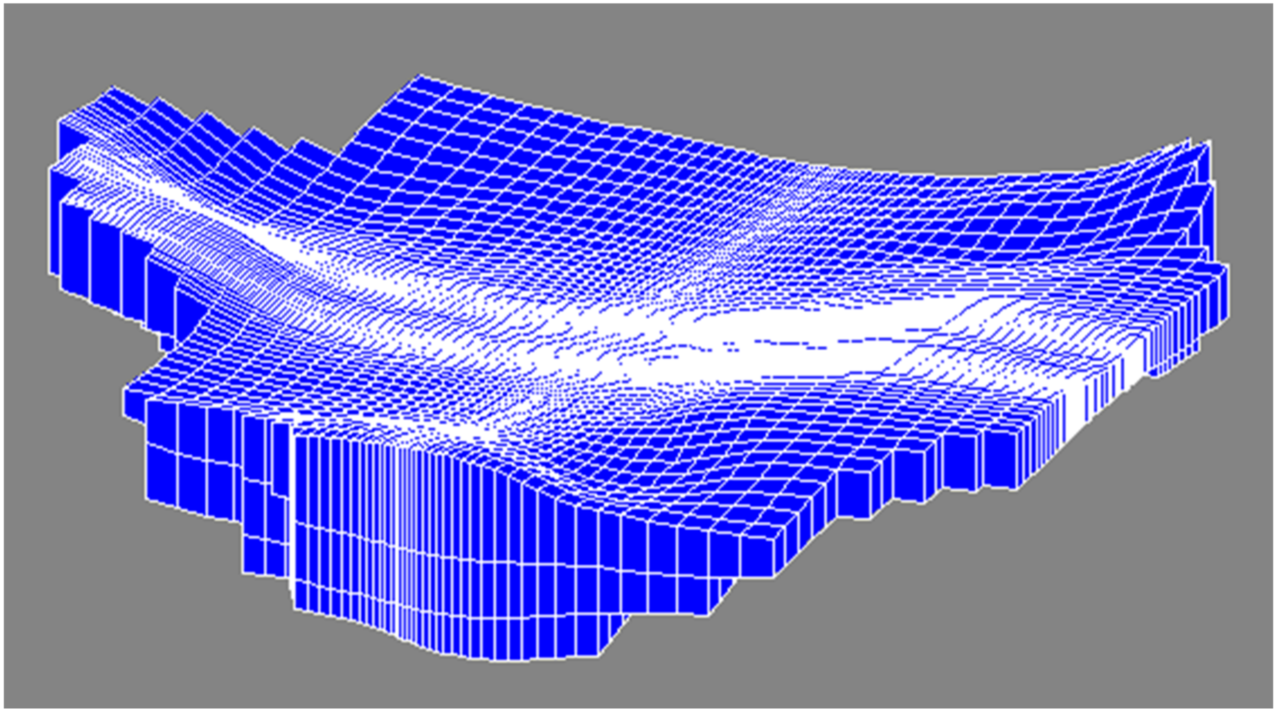
Finite Difference Model

- 3D Cartesian Grid
- Cell-Centered



Grid Geometry

- Orthogonal in xy
- Thickness varies in z



Governing Equation

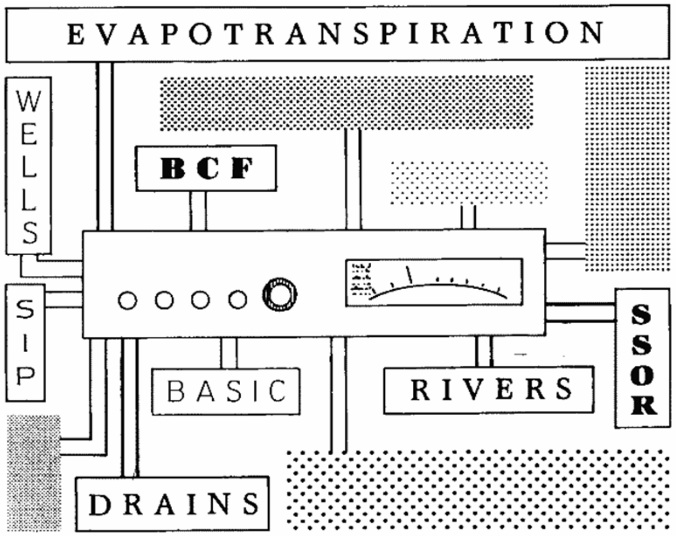
$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

where:

K_{xx}, K_{yy}, K_{zz}	= values of hyd. cond. along xyz axes
h	= total head
W	= Sources and sinks
S_s	= Specific storage
t	= time

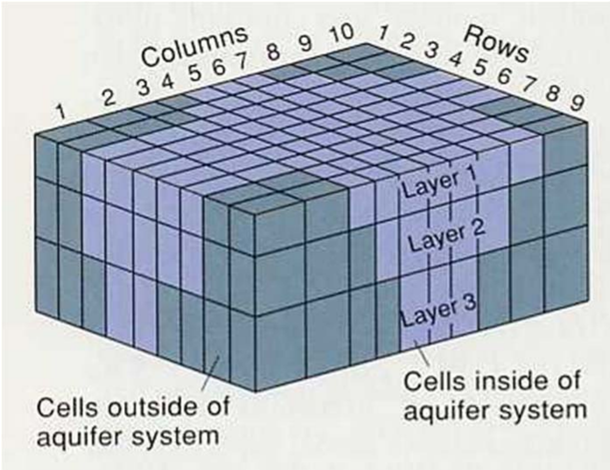
Processes & Packages

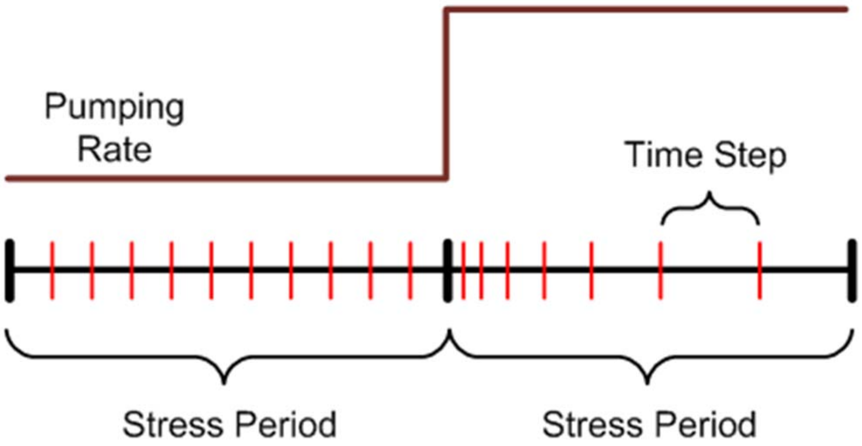
- MODFLOW is divided into a series of processes & packages.
- Major tasks are organized as processes
- More specific tasks are performed by packages
- Each process may use one or more packages



Global Process

- Spatial discretization
  - # rows, cols, layers
  - Top/bottom elevations
- Temporal discretization
  - Stress periods
  - Time steps
- Units
- Package Selection





Ground Water Flow Process

- Formulation and solution of the ground water flow equation by the FD method
- Main part of MODFLOW code
- Includes
  - Flow package (BCF, LPF, or HUF)
  - Source/sink packages
  - Solvers

Other Processes

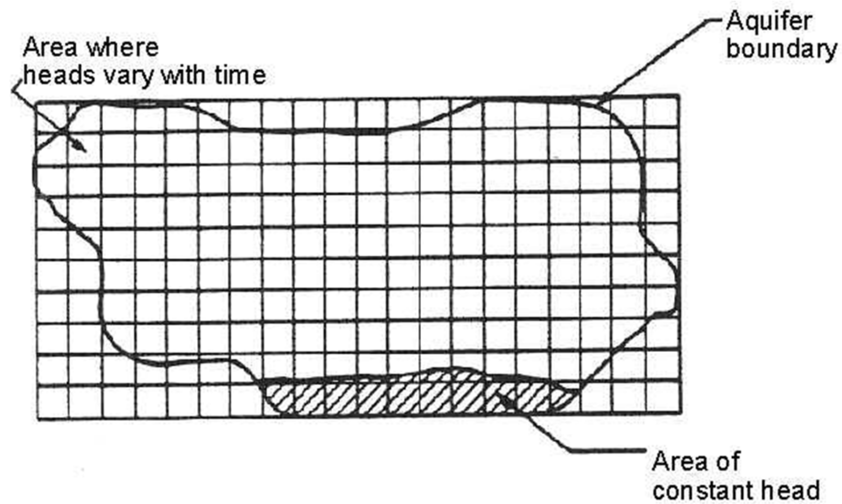
- Observation Process
  - Observed heads and flows
  - Used for calibration
- SEN Process
  - Sensitivity analysis
  - Calibration
- PES Process
  - Automated parameter estimation (calibration)

Packages

- Required Packages
  - Basic
  - Global
  - Output Control
  - Flow Package (BCF, LPF, HUF)
  - Solver (SIP, SSOR, PCG, GMG, etc.)
- List-Based Stress Packages
  - River
  - Stream-Aquifer Interaction
  - Drain
  - General Head
  - Well
  - Lake
  - Changing Head Boundary
- Array-Based Stress Packages
  - Recharge
  - Evapotranspiration
- Other
  - Horizontal Flow Barrier

Basic Package

- Starting Heads Array
  - Provides initial set of heads for iterative solver.
  - Defines head values at specified head cells
- IBOUND Array
  - Array of integers
  - Three possible values
    - zero = inactive
    - negative = specified head
    - positive = variable head



0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0

IBOUND Codes

< 0 Constant head

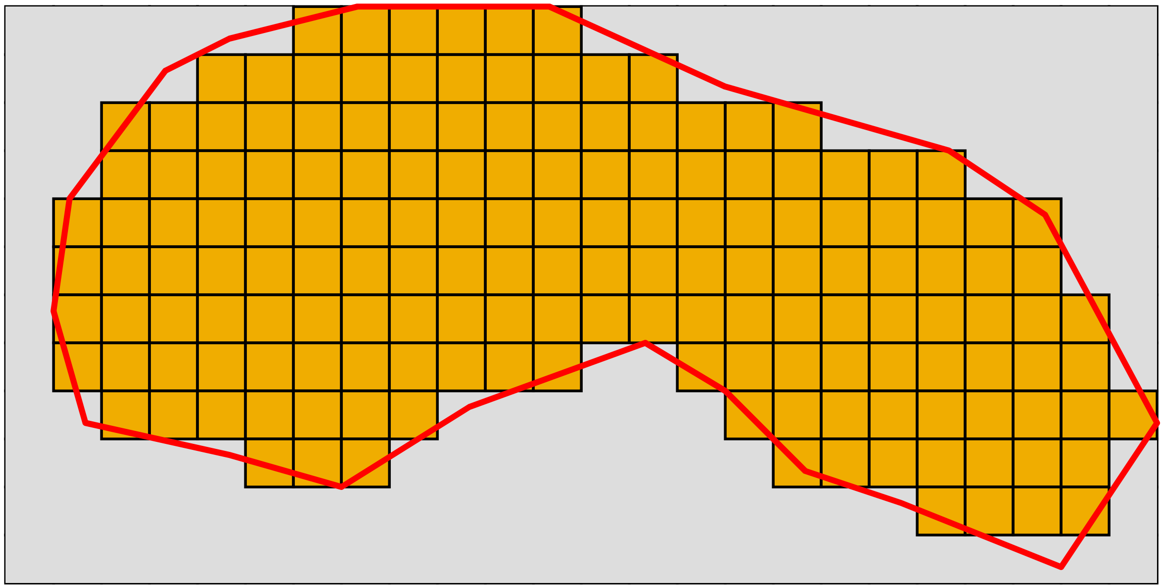
= 0 No flow

> 0 Variable head

Figure 19-1 (figure 19, McDonald and Harbaugh, 1988).
Example of the boundary array (IBOUND) for a singe layer.

Active/Inactive Zones

Cells outside problem domain are marked as inactive



Virginia Coastal Plain Model

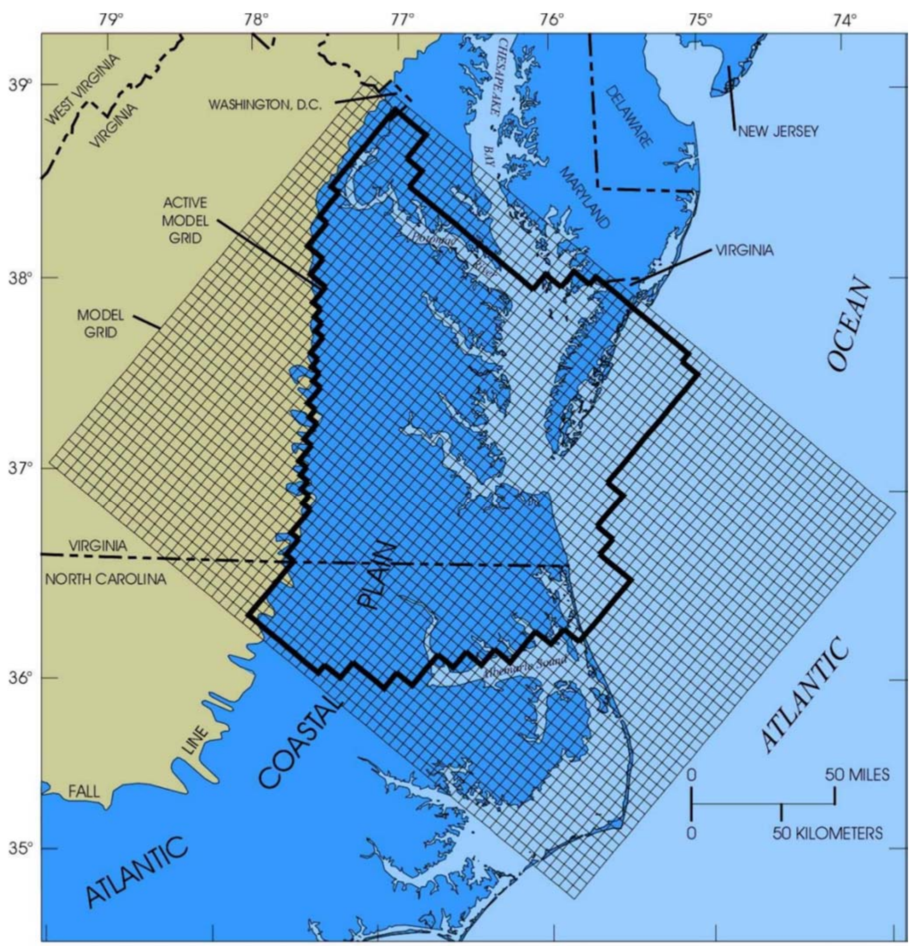


Figure 3. **Ground-water-flow model grid in the Virginia Coastal Plain.**

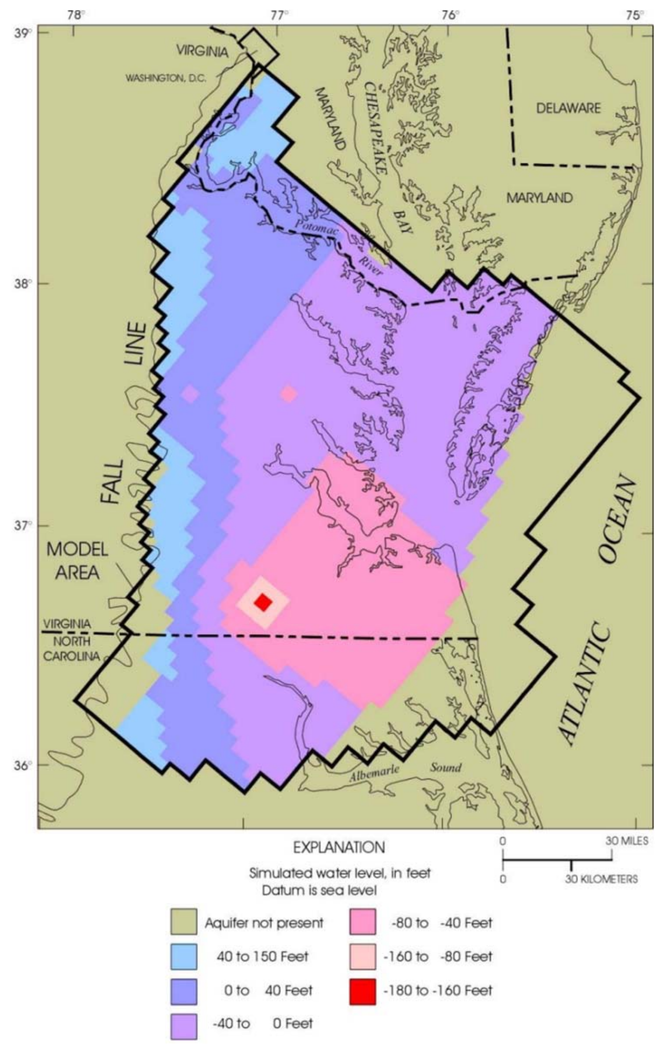


Figure 31. **Simulated water levels for 1978-80 in the middle Potomac aquifer.**

Flow Packages

- Three options
  - Block-Centered Flow (BCF)
  - Layer Property Flow (LPF)
  - Hydrogeologic Unit Flow (HUF)
- One of the three packages must be used

BCF Package

- Original flow package
- Each layer is assigned a layer type
- Layer data are entered (depending on type)
  - Horizontal K
  - Bottom elevation
  - Transmissivity
  - Leakance
  - etc.

Layer Property Flow (LPF) Package

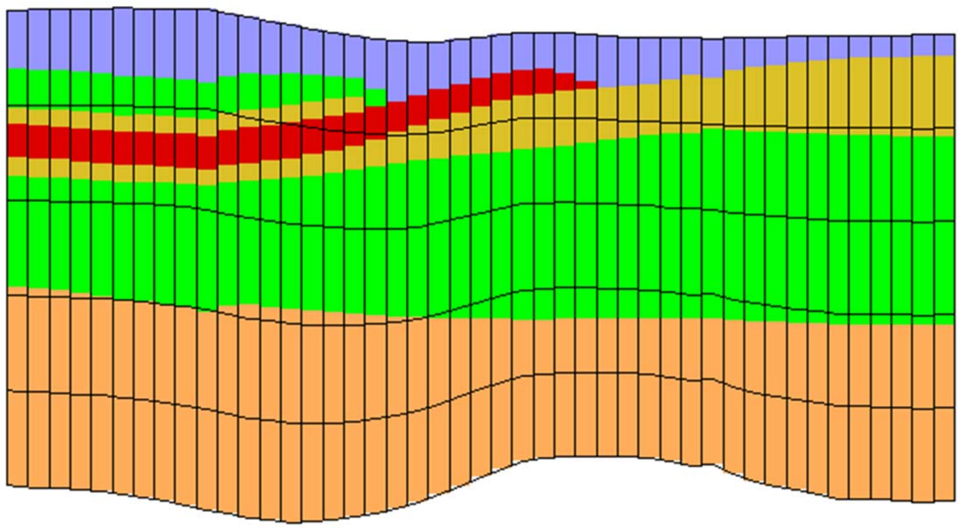
- User enters K_h, K_v and storage terms for all layers, regardless of type
- K_v can be entered as directly or in terms of vertical anisotropy
- Horizontal anisotropy entered on a cell-by-cell basis
- Two layer types
  - Confined
  - Convertible

LPF Property Input

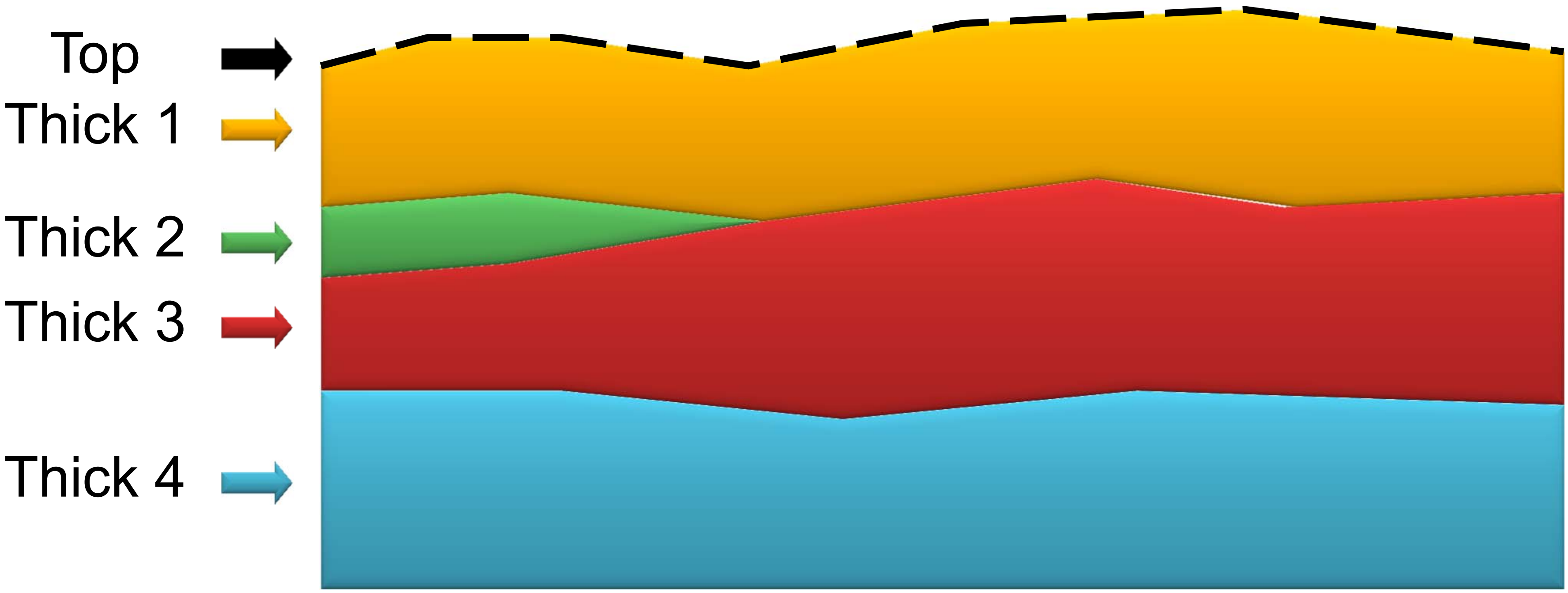
- Two options for inputting hydraulic properties:
  - Array input
    - one value per cell
  - Material id approach
    - Each cell is assigned a material id
    - Properties are inherited from material

Hydrogeologic Unit Flow (HUF) Package

- Aquifer stratigraphy represented in a grid-independent fashion
- Equivalent K_h, K_v computed at runtime

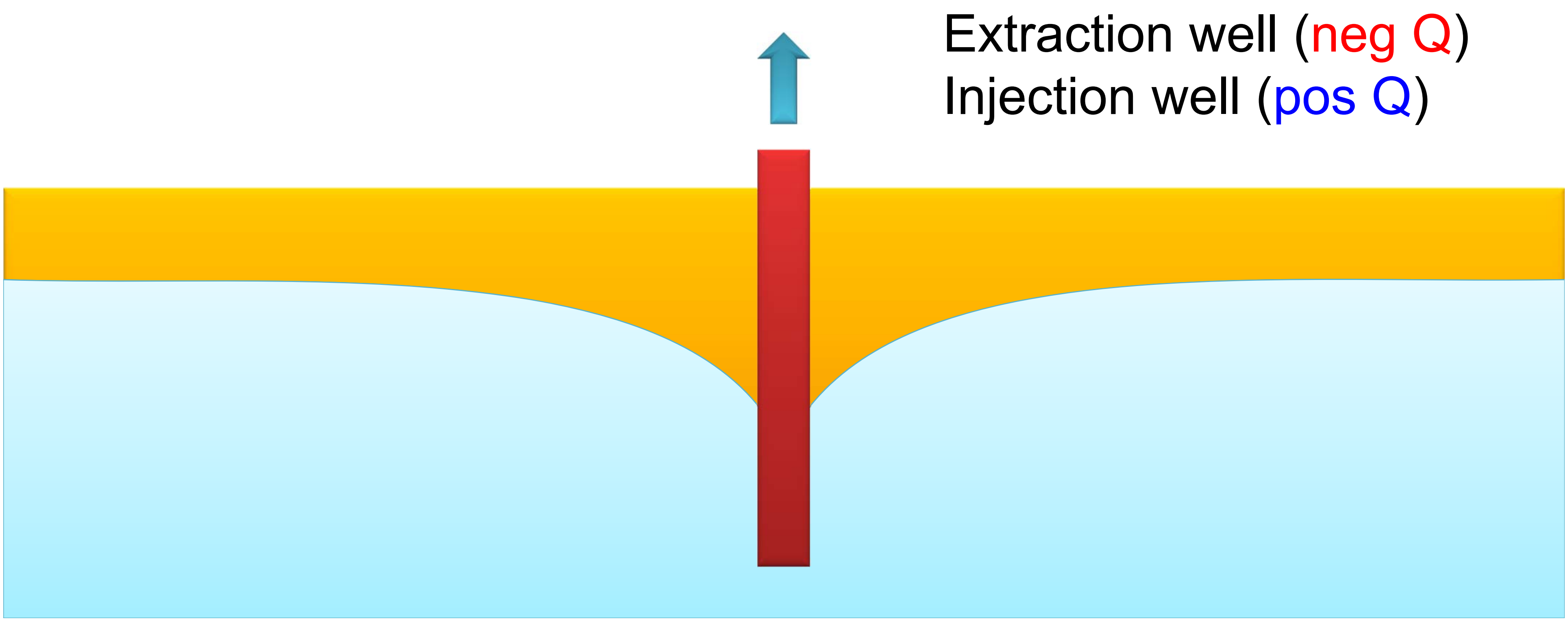


HUF Arrays



Well Package

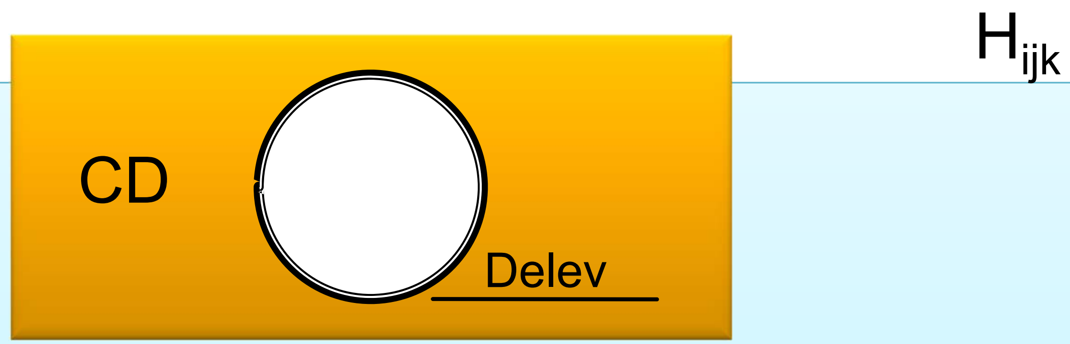
- Assigned to individual cells
- Q can be steady state or transient



Drain Package

- Assigned to individual cells
- Used to simulate
  - Agricultural drains
  - Springs
  - Creek beds
- Required parameters
  - Elevation
  - Conductance

Drains

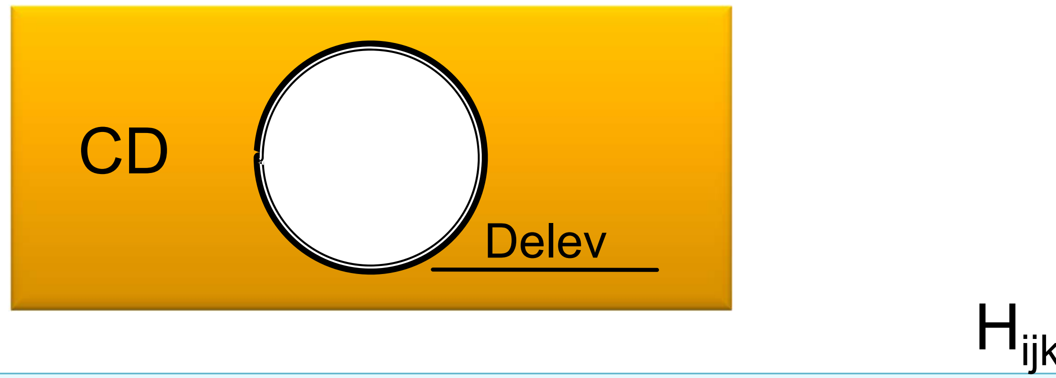


When the head is above the drain elevation:

$Q = CD\ (H_{ijk} - Delev)$ or

$Q = CD\ (Delev - H_{ijk})$ for proper sign on Q

Drains



When the head is below the drain elevation:

$Q = 0$

Conductance

Darcy's Law:

$$q = k \frac{\Delta h}{L} A$$

where

q = flow rate
k = hydraulic conductivity
Δh = head difference
L = flow length
A = gross cross-sectional area

Conductance, Cont.

Darcy's law can be rewritten as:

$$q = C \cdot \Delta h$$

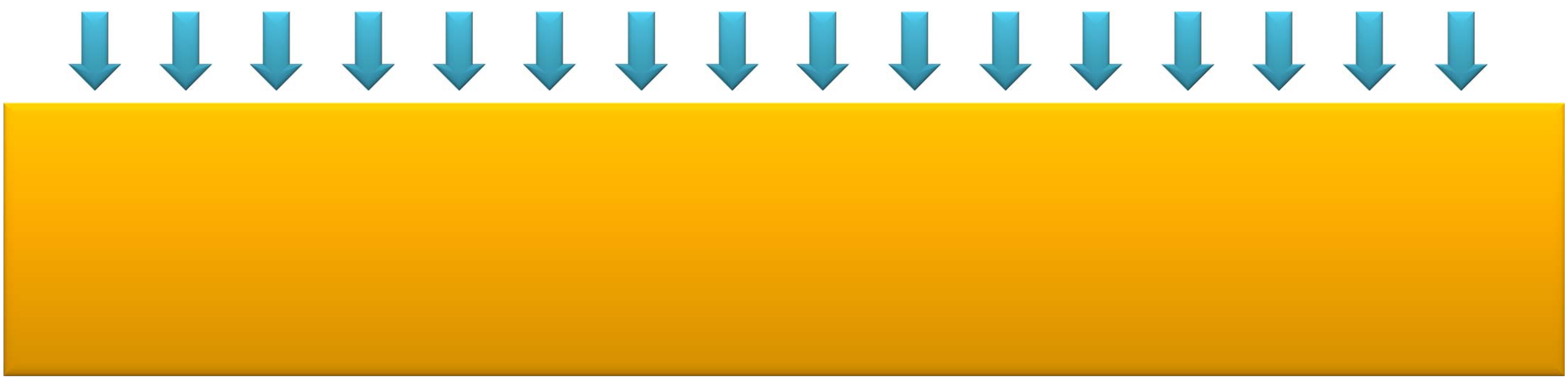
where

$$C = \frac{kA}{L}$$

The appropriate values for k, A, and L must be determined on a case-by-case basis

Recharge Package

- One value assigned to each vertical column
- Represents recharge due to precipitation
- Can be steady state or transient
- Infiltration rate must be assigned in correct units [L/T]



Factors Affecting Recharge Rate

- Rainfall
- Runoff
  - Slope
  - Soil type
  - Land use
- Evapotranspiration
  - Soil type
  - Vegetation