What You Need to Know from Previous Lecture

- Hydrologic Cycle
- Vadose Zone
  - Specific Yield
  - Capillary pressure
- Groundwater Flow Systems
  - Confined versus Unconfined Flow
  - Perched water
  - Artesian Flow
- Hydrologic Units
  - Aquifer, Aquitard, Aquiclude
- Properties
  - Hydraulic Conductivity (K) versus Permeability (k)
  - General ranges for geologic materials
  - Specific capacity (Q/h)
- Porous versus Fracture Flow
Hydrogeologic Characterization

- Hydraulic Head and Pressure
  - Hydraulic Gradient

- Confined and Unconfined Flow to a Well
  - Definition of Storage and Storativity
  - Difference between De-pressuring and Dewatering

- Steady flow and its applications
  - Theim equation
    - Specific Capacity
  - Falling Head Test
  - Packer test
    - Wire line packer
  - Lugeon Test
  - Flow Log

- Transient Flow and its Applications
  - Pump Test
  - Slug Test

- Principles of Groundwater Monitoring
  - Piezometer types
  - Piezometer Design
Pressure and Hydraulic Head

- **Energy that drives water**
  - Gravity
  - Chemistry (mainly in clays)
  - Electricity (mainly in clays)

- **Pressure is a measure of total energy**

- **Head is a measure of potential energy** – it is what drives flow
  - Elevation Head
  - Pressure Head
  - It is expressed
Outline

- Basic Properties and Parameters
- Steady flow to a well
- Transient flow to a well
- Groundwater monitoring
Flow Velocity

Compare Fracture Velocity to Porous Medium Velocity

1-m cube
T=1-e5
Fracture Aperture = .0005 m
Sand porosity = 10%
Gradient = 1
Steady Flow Methods

- Packer Testing
  - Falling Head Test
  - Constant Pressure/Lugeon Test

- Flow Logging
  - Heat pulse
  - Spinner
  - Hydrophysical
Useful Definitions and Concepts

- **Transmissivity** -- Properties of a conductor (aquifer, reservoir, single fracture, fracture zone) \( (L^2/T) \)

- **Permeability, Hydraulic Conductivity** -- Property of material inside conductor \( (L/T) \)
Steady Radial Flow

- Pressure and flow constant
- Only exists with constant pressure boundary
- Generally underestimates due to skin

\[
T = \frac{\ln(R/r_w)Q}{2\pi\Delta h} \approx \frac{Q}{\Delta h}
\]
Steady Flow Applications

- **Specific Capacity**
  - Driller’s term – Flow rate divided by a drawdown

- **Packer Test**
  - Test usually run with inflatable well seals – common engineering test

- **Lugeon Test**
  - Packer test usually for grouting
Flow Log

- **Both**
  - Indicate locations of flow features and relative strengths

- **Ambient Flow**
  - Indicates up or downward flow due to natural gradients

- **Pumped Flow**
  - Indicates transmissivity of flowing feature
Hydrophysical Log

(1) Replace fluid with deionized water
(2) Log fluid resistivity while pumping
Heat Pulse Log

Posiva (Finland) Heat Pulse Flow Log (Åspö)
FLOW LOGS FOR BOREHOLES P1-20 AND P1-21
MAWS/Campo Landfill Stage 1 WMRP/CA
Image Logging (Correlate Flow to Feature)

Borehole TV (BIPS)  

FMI (micro-resistivity)

Structure #20

KI0025F03  
L = 73.2 m (326/64)

KI0025F02  
L = 74.7 m (134/89)
Wireline Packer

Tigre Tierra® zone packers are available for 5-feet and 10-feet test zones.
Packer Test (Fixed Interval Length)

- Used in Civil Engineering
- Testing at fixed interval lengths
- Some zones have no fractures; some zones have multiple fractures
- Efficient testing has some no flows but not too many
Lugeon Test

- Packer Test usually for grouting
- 1 Lugeon unit = 1 litre of water taken per metre of test length, per minute, at 10 bars pressure (150 psi approx)
- Typically done in steps
- Implications
  - 1 Lugeon Unit – no sweat
  - 10 Lugeon Units – fire up the grout mixer
  - >100 Lugeion Units – file for a change order
Stepped Lugeon Test

- Linear Laminar Flow
- Turbulent Flow
- Hydrojacking, Washout
Hvorslev Falling Head

- Fill hole and watch level decline
- Steady Flow
- High Perm (constant pressure) boundary
- Variant on Steady Flow Solution

\[ K = \frac{r_w^2 \ln \frac{R}{r_w} 1}{2b} \ln \frac{h_1}{h_2} \]

http://www.aqtesolv.com/
Composite Transmissivity

- Determine head at composite boundary and solve steady flow from that R (outer radius)
- c is composite boundary, w is well radius

\[ h_c = \frac{h_R}{\left[ \frac{K_i}{K_o} \ln \frac{R}{r} \right] + 1} \]

Almost all head lost in inner region! Inner region K controls flow!
Transient Testing

- **Pump Test**
  - Maintain a constant flow and observe transient pressure
  - Maintain constant pressure and observe transient flow

- **Slug Test**
  - Look at pressure decay after instant charge of water

- **Interference Tests**
  - Analyze connectivity, storage, diffusivity
Storage and Transient Behavior

- Storage is in diffusivity the equivalent of electrical capacitance and heat capacity
- Storage means flow in response to a pressure change is transient until/unless a very large water source takes over influence

- Unconfined Aquifers
  - Basically Storage is porosity (big number)

- Confined Aquifers
  - Specific Storage – property of material
  - Storativity – $S_s \times$ thickness – property of aquifer
Radial Diffusion Equation
(Radial Cylindrical Flow)

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \eta}{\partial r} \right) = \frac{1}{\eta} \frac{\partial \eta}{\partial t}
\]
Exponential Integral (aka Theis equation):

\[
\Delta p(r, t) = \frac{q}{4\pi T} \int_{r^2/(4\eta t)}^{\infty} \frac{e^{-x}}{x} \, dx = \frac{q}{4\pi T} \left[ -\text{Ei}\left( -\frac{r^2}{4\eta t}\right) \right]
\]
Exponential Integral and Derivative

\[ \log p_D \]

\[ \log t_D \]
Semilog Approximation of the Exponential Integral

\[-\text{Ei}(-u) = -05772 - \ln u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} + \ldots \]

\[\Delta p(r,t) = 2.3026 \frac{q}{4\pi T} \log \frac{2.246\eta t}{r^2}\]
Semi-log Line (Jacob-Cooper) Method

\[ T = \frac{2.3Q}{4\pi m} \]

\( m = \text{semi-log slope} \)
Derivative Methods

- Plots $\Delta P/\Delta \log(t)$
- Intent to make semi-line unambiguous
- Effect is a very powerful tool to interpret geometry from tests
- Derivative is a map of transmissivity versus distance from the well
- Shape of derivative constrains network geometry
Well Test Function (Exponential Integral) and (Semilog) Derivative
Slug Test

- Transient Flow
- Infinite Aquifer
- Variations for Boundaries
- Variations for “closed” (water-filled) or “open” (open hole with air water interface) systems

http://www.aqtesolv.com/
Comments on Interference Tests

- Radius of Investigation (very handy !!!)
- Estimate diffusivity from response time

- Independent of dimension

\[ r = 2\sqrt{\eta t} \]
Interference Demo

Derivative plot, drawdown

Well 2

Well 3
Groundwater Piezometer Systems

Key Point: Isolate different parts of flow system

- Water Sampling
- Pressure monitoring (eg determine flow, seasonal changes, pore pressure)
- Avoid cross contamination

http://www.claire.co.uk/
Bure : Westbay System

Multipacker system – technical cross section of borehole EST207
Anomalous Osmotic Pressure
(chemically induced)