KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 2001-46

The Design and Analysis of Pumping Tests
for Aquifer Evaluation
Workshop Notebook

Training Workshop for Division of Water Resources
Kansas Department of Agriculture
Topeka, Kansas
October 16, 2001

by

James Butler

Disclaimer

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Workshop Notebook

The Design and Analysis of Pumping Tests for Aquifer Evaluation

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PRESENTATION OUTLINE

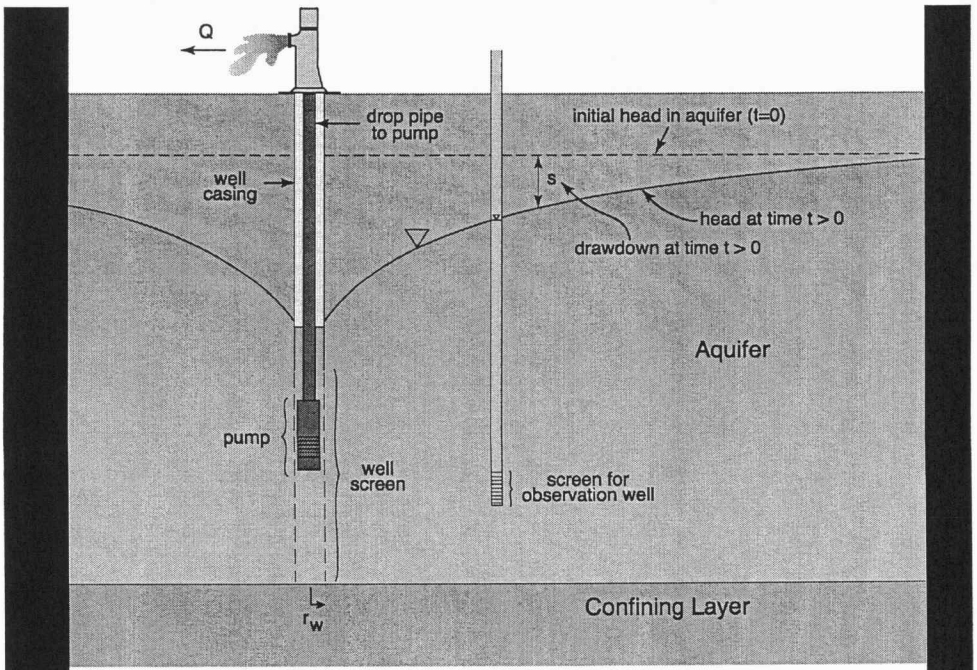
- **Introduction**
- General Design Guidelines
- Direct Push Applications
- Major Methods for Data Analysis
- Data Analysis Strategies
- Conclusions

Well Tests - An Introduction

- What?
  - in-situ estimation of the transmissive and storage properties of a formation
- When?
  - water quantity/quality investigations
- Why?
  - quantitative assessments of groundwater flow and transport
- How?
  - introduce stress and measure response

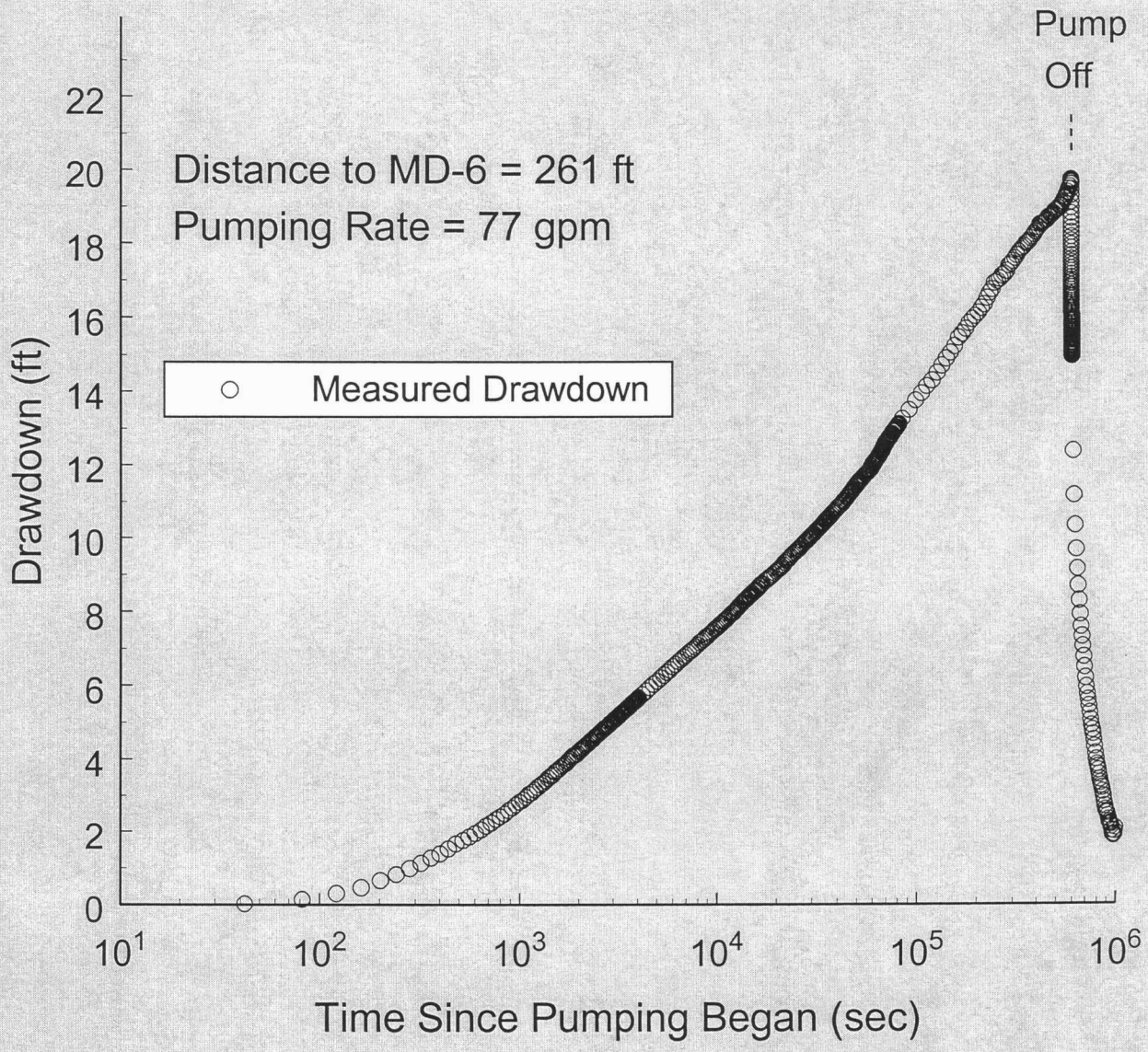
The Pumping Test

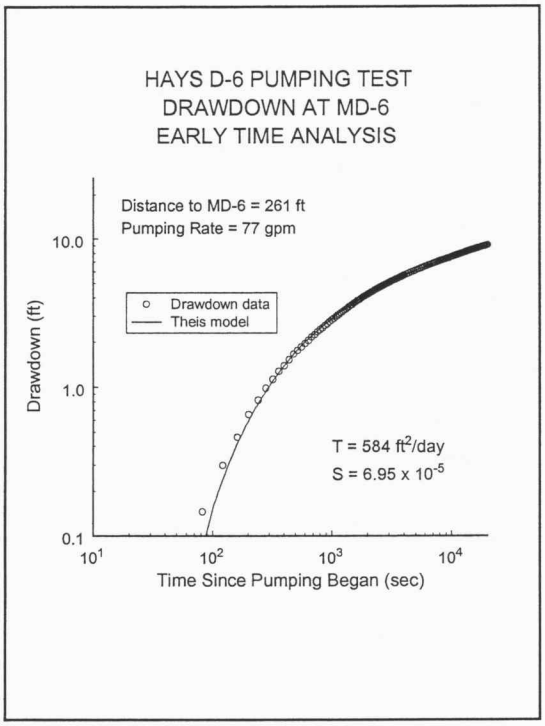
- Purpose
  - in-situ estimation of large-scale hydraulic properties
    - transmissivity (T) and storativity (S)
  - hydraulic boundaries
    - laterally bounded?
    - tight confining unit?
  - conditions at pumping well
    - pumping efficiency
- Mechanics
  - pump well to produce change in water level (or head) in formation
  - measure change (drawdown) at pumped and nearby wells
  - analyze drawdown measurements

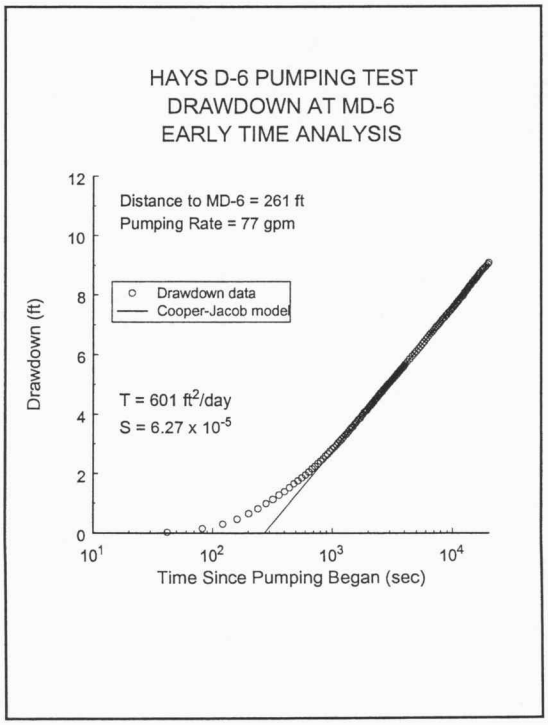


Pumping Test in an Unconfined Aquifer

HAYS D-6 PUMPING TEST
DRAWDOWN FROM MD-6
7/7/97 - 7/19/97




HAYS D-6 PUMPING TEST
DRAWDOWN AT MD-6
EARLY TIME ANALYSIS
Distance to MD-6 = 261 ft
Pumping Rate = 77 gpm
Drawdown data
Theis model
T = 584 ft²/day
S = 6.95 x 10⁻⁵
Drawdown (ft)
10.0
1.0
0.1
10¹
10²
10³
10⁴
Time Since Pumping Began (sec)


HAYS D-6 PUMPING TEST
DRAWDOWN AT MD-6
EARLY TIME ANALYSIS
Distance to MD-6 = 261 ft
Pumping Rate = 77 gpm
Drawdown data
Cooper-Jacob model
T = 601 ft²/day
S = 6.27 x 10⁻⁵
Drawdown (ft)
12
10
8
6
4
2
0
10¹
10²
10³
10⁴
Time Since Pumping Began (sec)

PRESENTATION OUTLINE

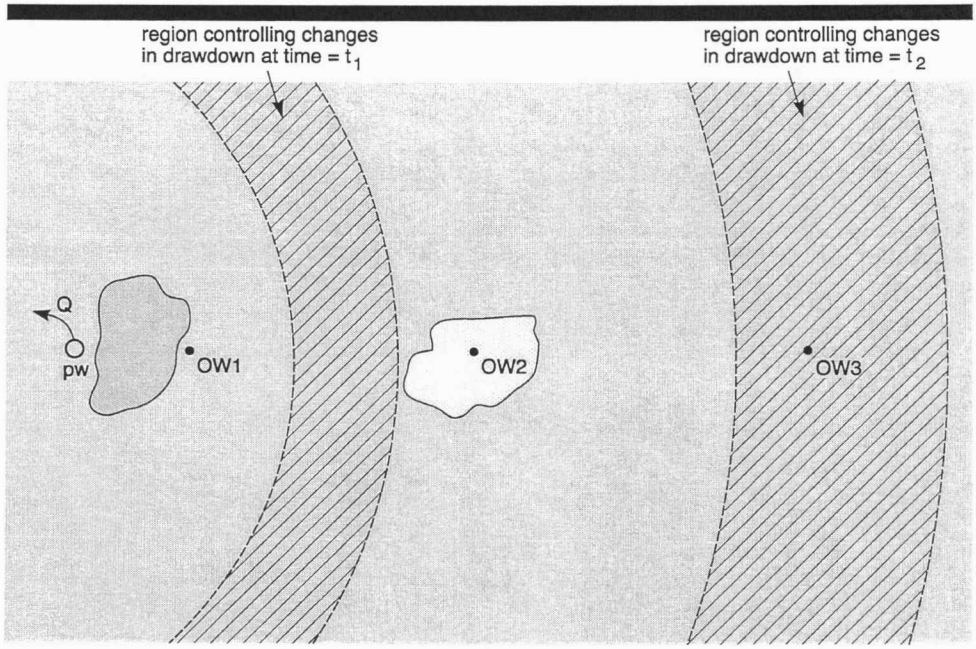
- Introduction
- **General Design Guidelines**
- Direct Push Applications
- Major Methods for Data Analysis
- Data Analysis Strategies
- Conclusions

General Design Guidelines for Pumping Tests

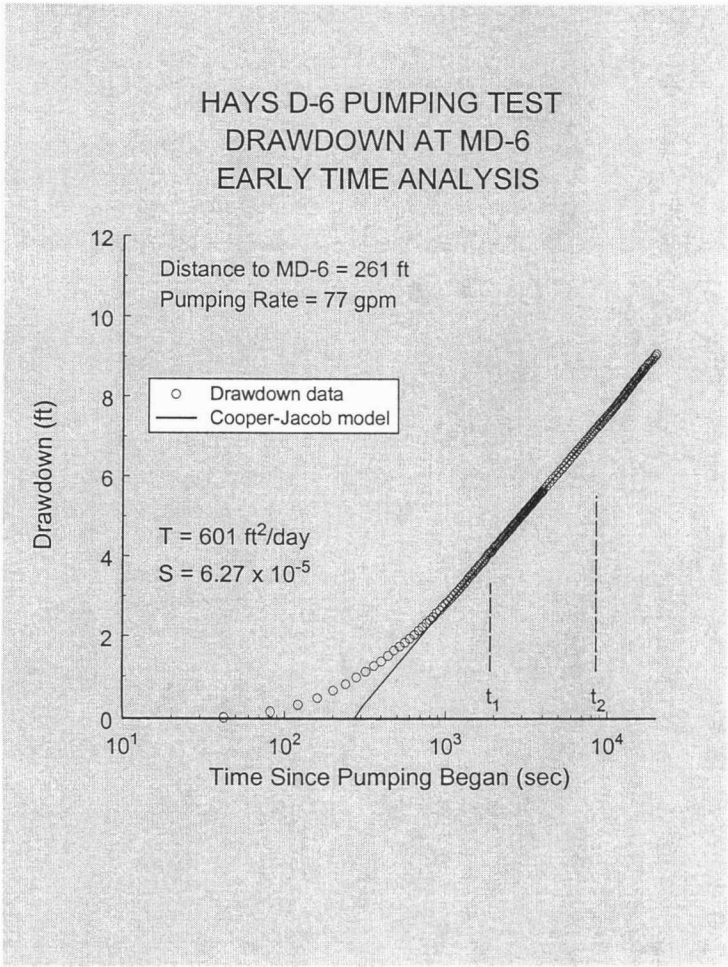
- Overall Goal
  - Justify model selection
  - Confidence in T and S estimates
- Key Elements
  - Location of observation wells
  - Pumping rate and duration
  - Preparation for problems

Location of Observation Wells

- **Purpose of Test**
  - **Bulk properties and boundaries**
    - **close to pumping well**
  - **Discrete regions**
    - **pairs of observation wells**
    - **slug tests**
  - **Hydraulic connection**
    - **region of interest**
- Geologic Framework
  - Place within same aquifer
    - geologic and geophysical logs

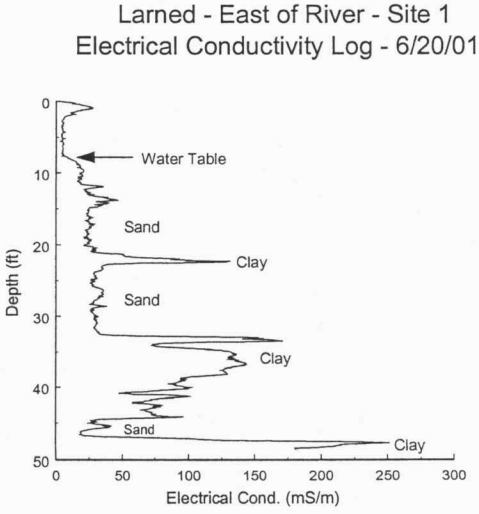


Areal View (not to scale)



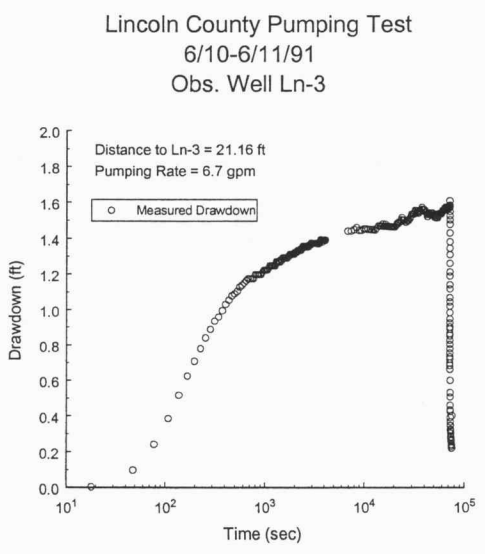
Location of Observation Wells

- Purpose of Test
  - Bulk properties and boundaries
    - close to pumping well
  - Discrete regions
    - pairs of observation wells
    - slug tests
  - Hydraulic connection
    - region of interest
- **Geologic Framework**
  - **Place within same aquifer**
    - **geologic and geophysical logs**



Pumping Rate and Duration

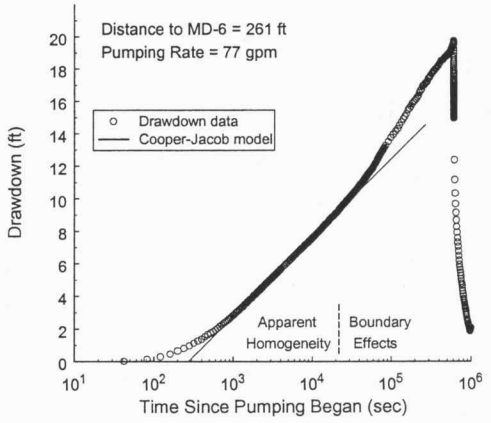
- **Pumping Rate**
  - **affects signal to noise ratio**
  - **no effect on test scale**
    - **relative contribution does not change**
- Pumping Duration
  - scale increases with duration
    - early homogeneous aquifer behavior followed by boundary effects



Pumping Rate and Duration

- Pumping Rate
  - affects signal to noise ratio
  - no effect on test scale
    - relative contribution does not change
- **Pumping Duration**
  - **scale increases with duration**
    - **early homogeneous aquifer behavior followed by boundary effects**

HAYS D-6 PUMPING TEST
DRAWDOWN AT MD-6
EARLY TIME ANALYSIS



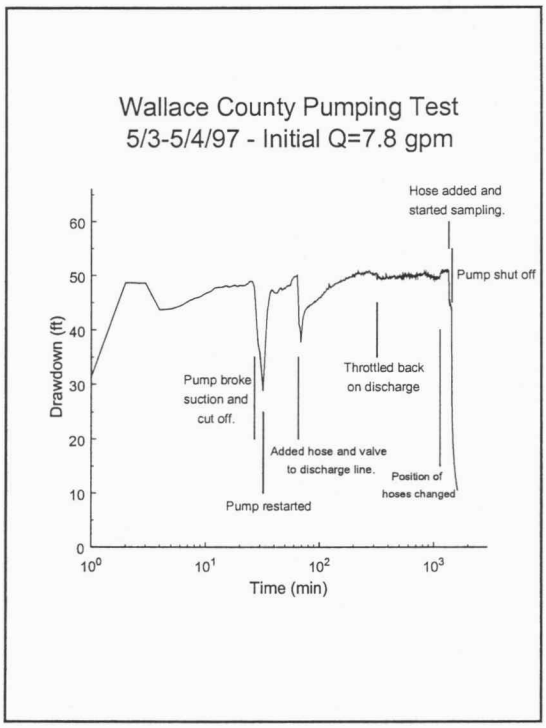
Common Problems in Pumping Tests

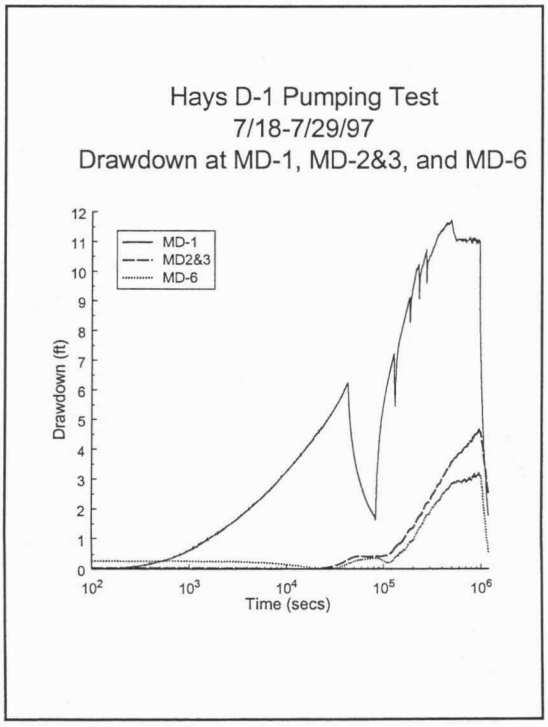
- Variable Pumping Rate
- Drawdown at Pumping Well
- Nearby Pumping Wells
- Barometric Pressure and Precipitation

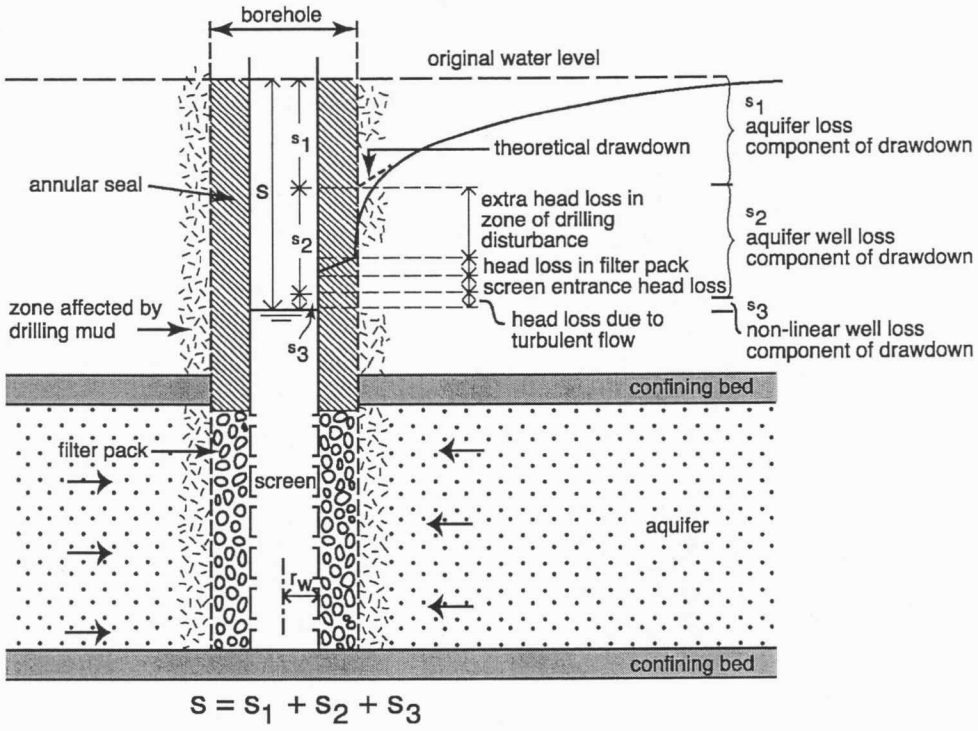
Common Problems in Pumping Tests

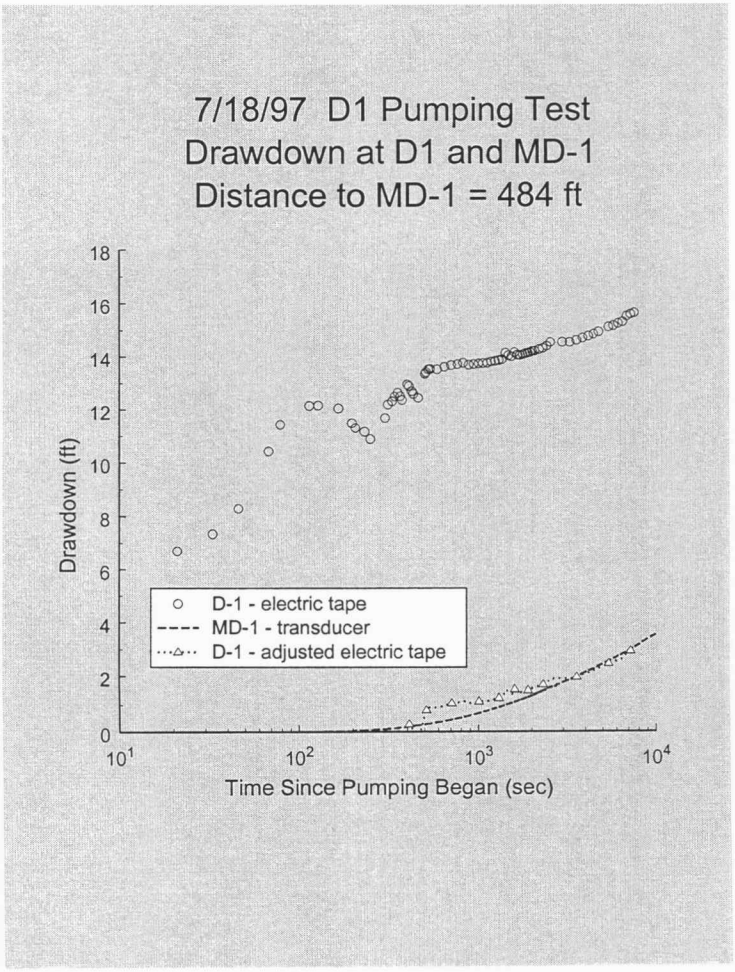
- **Variable Pumping Rate**
- **Drawdown at Pumping Well**
- Nearby Pumping Activity
- Barometric Pressure and Precipitation

- **General Strategy**
  - measure and incorporate
  - analyze unaffected intervals
  - use recovery data


Wallace County Pumping Test
5/3-5/4/97 - Initial Q=7.8 gpm
Hose added and started sampling.
Pump shut off
Throttled back on discharge
Pump broke suction and cut off.
Added hose and valve to discharge line.
Position of hoses changed
Pump restarted
Drawdown (ft)
Time (min)


Hays D-1 Pumping Test
7/18-7/29/97
Drawdown at MD-1, MD-2&3, and MD-6
MD-1
MD2&3
MD-6
Drawdown (ft)
Time (secs)

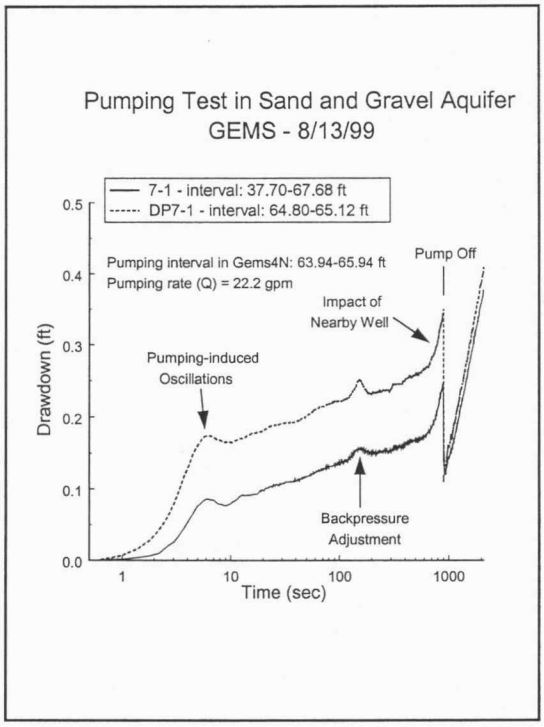

borehole
original water level
s_1
aquifer loss
component of drawdown
theoretical drawdown
annular seal
s
extra head loss in
zone of drilling
disturbance
s_2
aquifer well loss
component of drawdown
head loss in filter pack
screen entrance head loss
zone affected by
drilling mud
head loss due to
turbulent flow
s_3
non-linear well loss
component of drawdown
confining bed
filter pack
screen
aquifer
r_w
confining bed
$s = s_1 + s_2 + s_3$

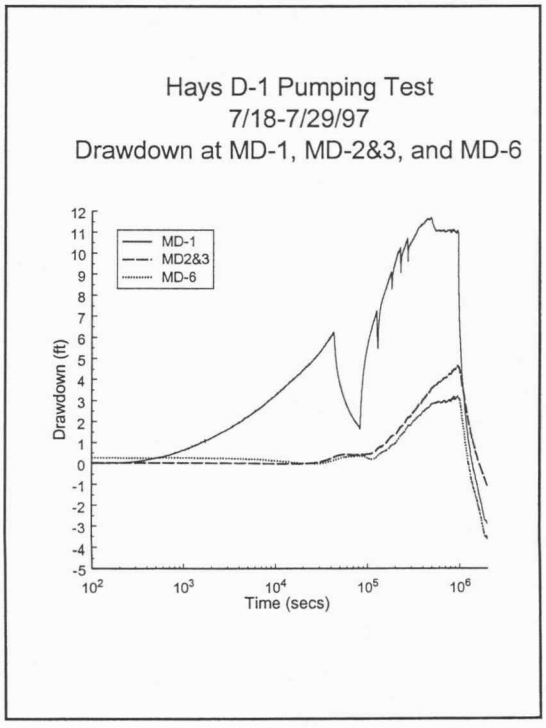

7/18/97 D1 Pumping Test
Drawdown at D1 and MD-1
Distance to MD-1 = 484 ft
Drawdown (ft)
Time Since Pumping Began (sec)
D-1 - electric tape
MD-1 - transducer
D-1 - adjusted electric tape

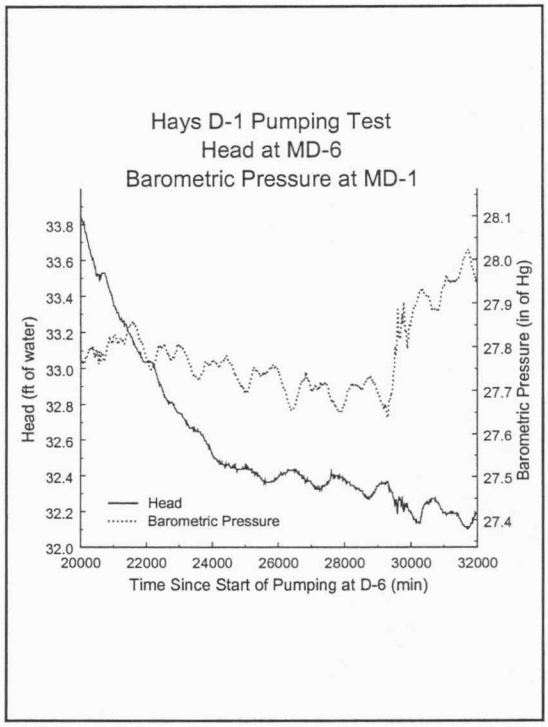
Common Problems in Pumping Tests

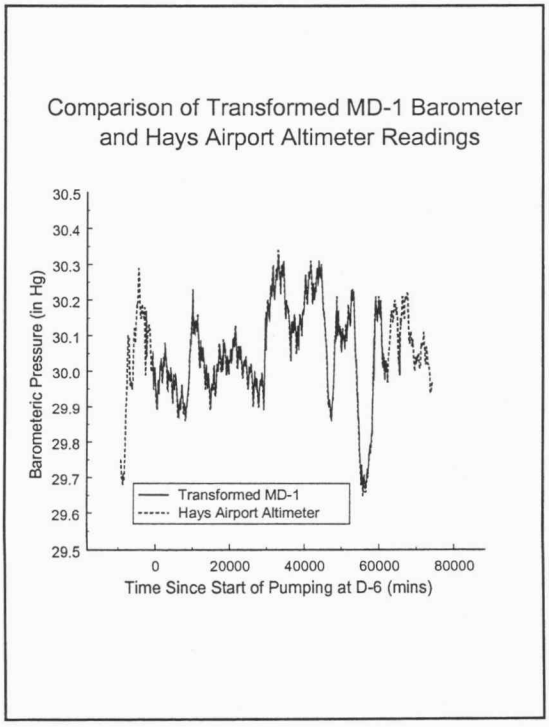
- Variable Pumping Rate
- Drawdown at Pumping Well
- **Nearby Pumping Activity**
- **Barometric Pressure and Precipitation**

- **General Strategy**
  - measure and incorporate
  - analyze unaffected intervals
  - schedule carefully
  - observation well close to pumping well


Pumping Test in Sand and Gravel Aquifer
GEMS - 8/13/99
7-1 - interval: 37.70-67.68 ft
DP7-1 - interval: 64.80-65.12 ft
Pumping interval in Gems4N: 63.94-65.94 ft
Pumping rate (Q) = 22.2 gpm
Pump Off
Impact of
Nearby Well
Pumping-induced
Oscillations
Backpressure
Adjustment
Drawdown (ft)
Time (sec)
0.0
0.1
0.2
0.3
0.4
0.5
1
10
100
1000


Hays D-1 Pumping Test
7/18-7/29/97
Drawdown at MD-1, MD-2&3, and MD-6
MD-1
MD2&3
MD-6
Drawdown (ft)
Time (secs)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
10^2
10^3
10^4
10^5
10^6


Hays D-1 Pumping Test
Head at MD-6
Barometric Pressure at MD-1
Head (ft of water)
Barometric Pressure (in of Hg)
33.8
33.6
33.4
33.2
33.0
32.8
32.6
32.4
32.2
32.0
28.1
28.0
27.9
27.8
27.7
27.6
27.5
27.4
Head
Barometric Pressure
20000
22000
24000
26000
28000
30000
32000
Time Since Start of Pumping at D-6 (min)

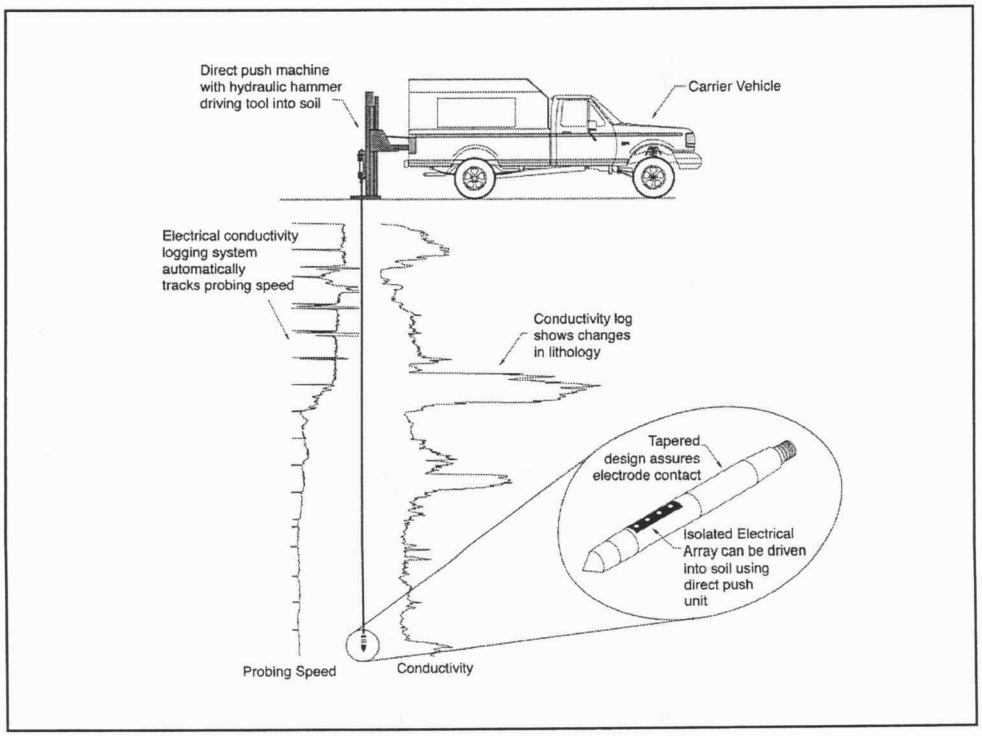

Comparison of Transformed MD-1 Barometer
and Hays Airport Altimeter Readings
Barometeric Pressure (in Hg)
30.5
30.4
30.3
30.2
30.1
30.0
29.9
29.8
29.7
29.6
29.5
Transformed MD-1
Hays Airport Altimeter
0
20000
40000
60000
80000
Time Since Start of Pumping at D-6 (mins)

PRESENTATION OUTLINE

- Introduction
- General Design Guidelines
- **Direct Push Applications**
- Major Methods for Data Analysis
- Data Analysis Strategies
- Conclusions

Overview of Well Tests with Direct Push Tools

- Direct Push Methods
  - rapid installation of temporary observation wells
  - reduce nonuniqueness
  - improve stratigraphic control
- Equipment
  - Electrical conductivity log
  - Shrouded screen tool
  - Head measurement
  - Well development
- Important Considerations
  - Degree of compaction
  - Well development

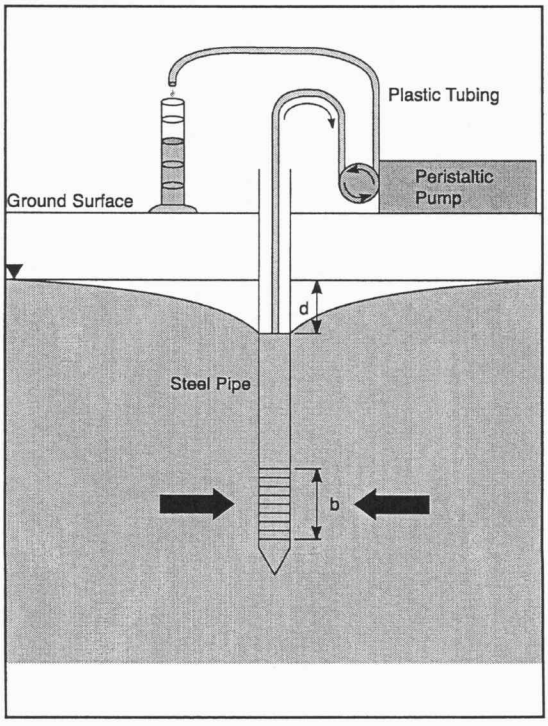

Direct push machine with hydraulic hammer driving tool into soil
Carrier Vehicle
Electrical conductivity logging system automatically tracks probing speed
Conductivity log shows changes in lithology
Tapered design assures electrode contact
Isolated Electrical Array can be driven into soil using direct push unit
Probing Speed
Conductivity


0 CM 5 10 15


0 CM 5 10 15

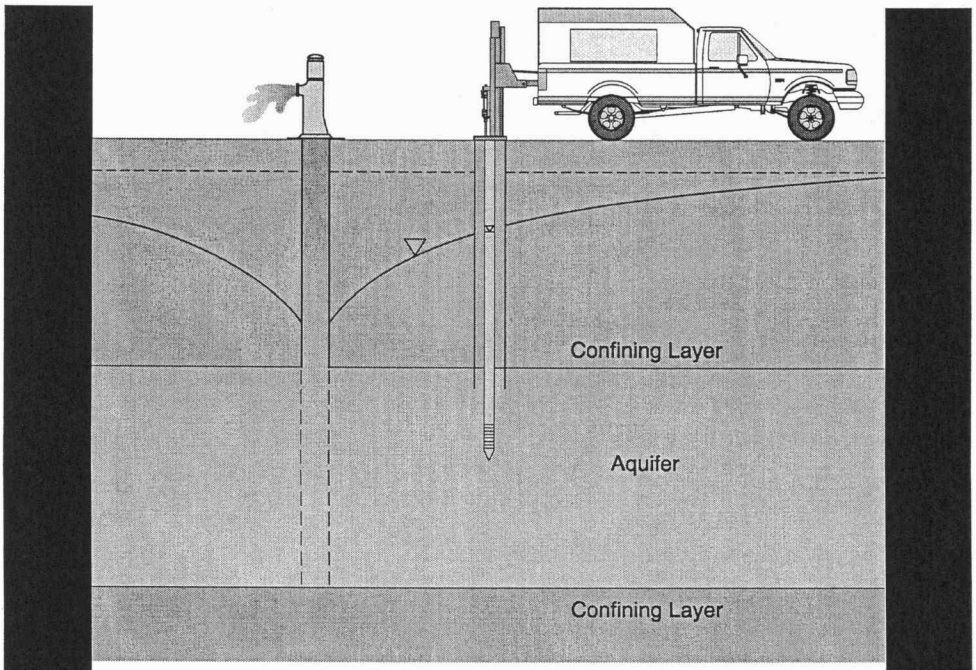
Well Tests with Direct Push Tools

- Pumping Tests
  - **Pumping well**
    - **constant-head tests**
  - Observation well
    - shrouded screen
    - electrical conductivity log



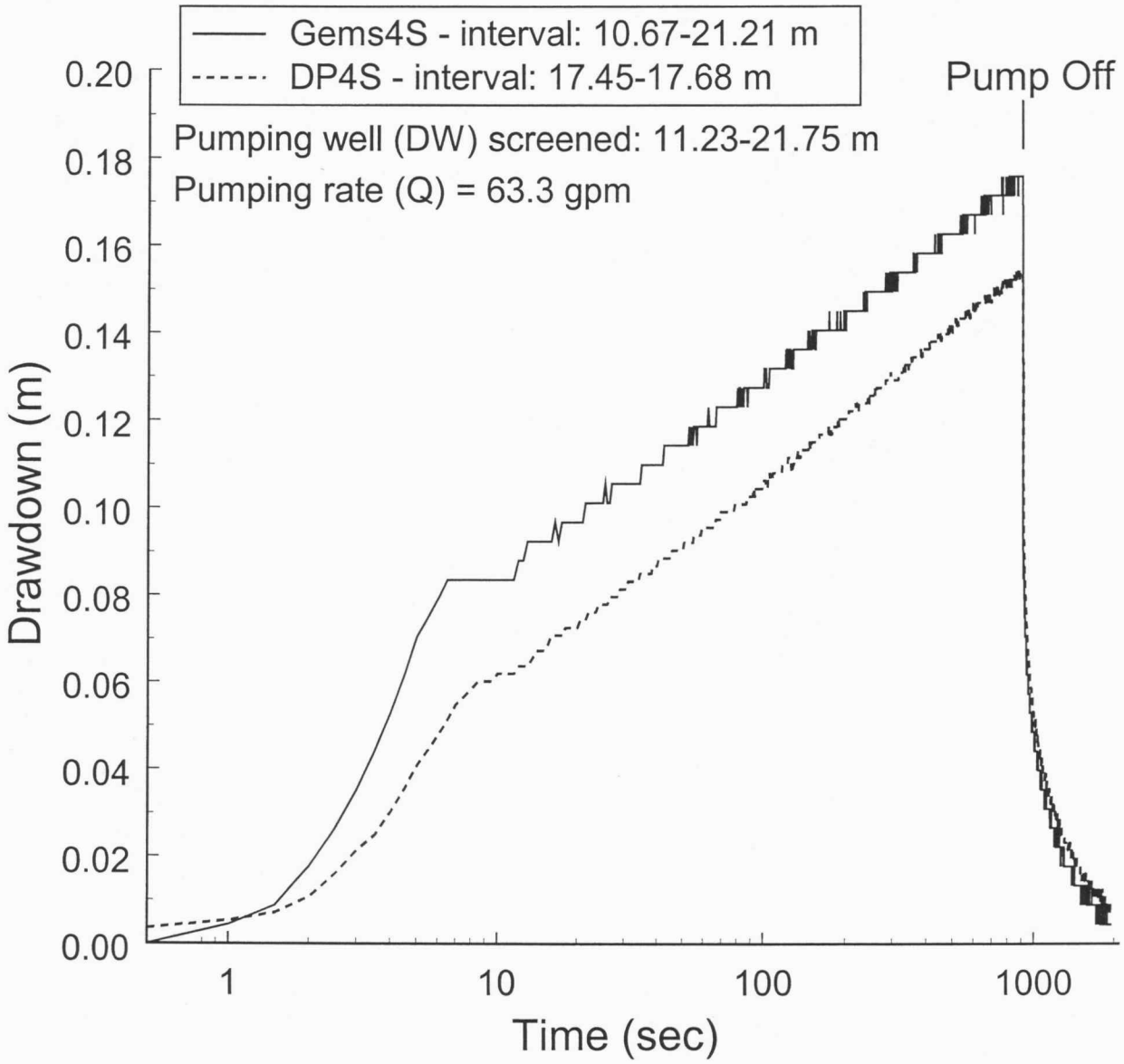
Well Tests with Direct Push Tools

- Pumping Tests
  - Pumping well
    - constant-head tests
  - **Observation well**
    - **shrouded screen**
    - **electrical conductivity log**



Pumping Test in a Confined Aquifer

GEMS - 3/16/99 Pumping Test
Direct-push and conventional well

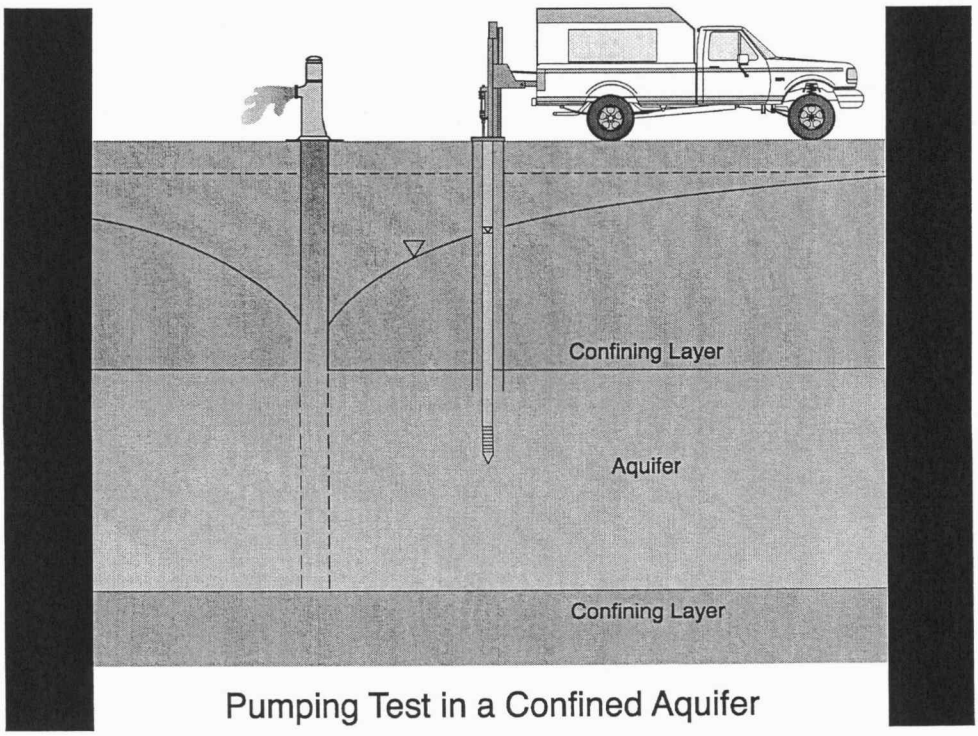


PRESENTATION OUTLINE

- Introduction
- General Design Guidelines
- Direct Push Applications
- **Major Methods for Data Analysis**
- Data Analysis Strategies
- Conclusions

Pumping Tests
Major Methods for Data Analysis

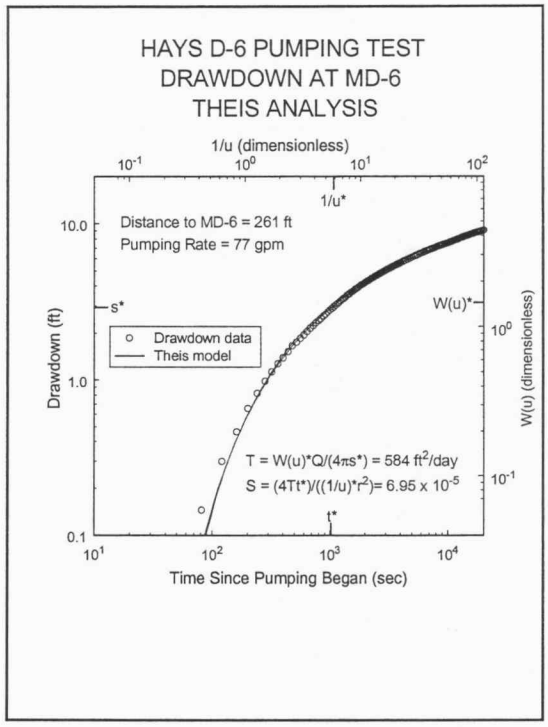
- **Confined Aquifers**
- Leaky Aquifers
- Unconfined Aquifers
- Recovery Methods
- Additional Mechanisms
- Less Common Settings/Tests

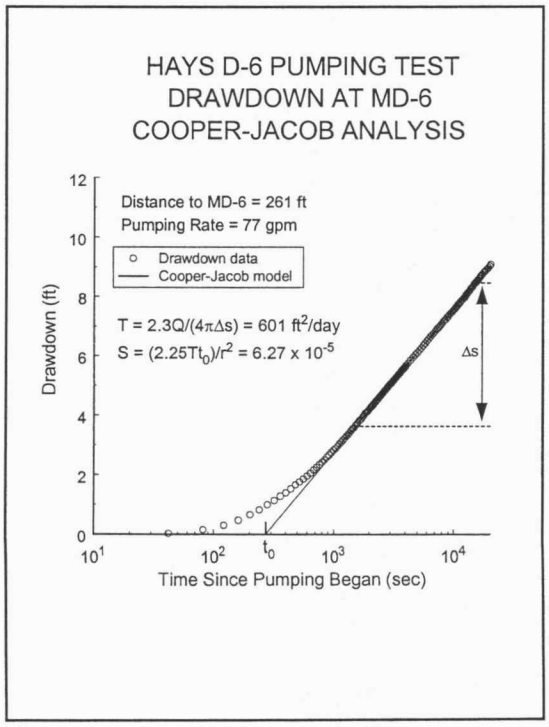


Pumping Test in a Confined Aquifer

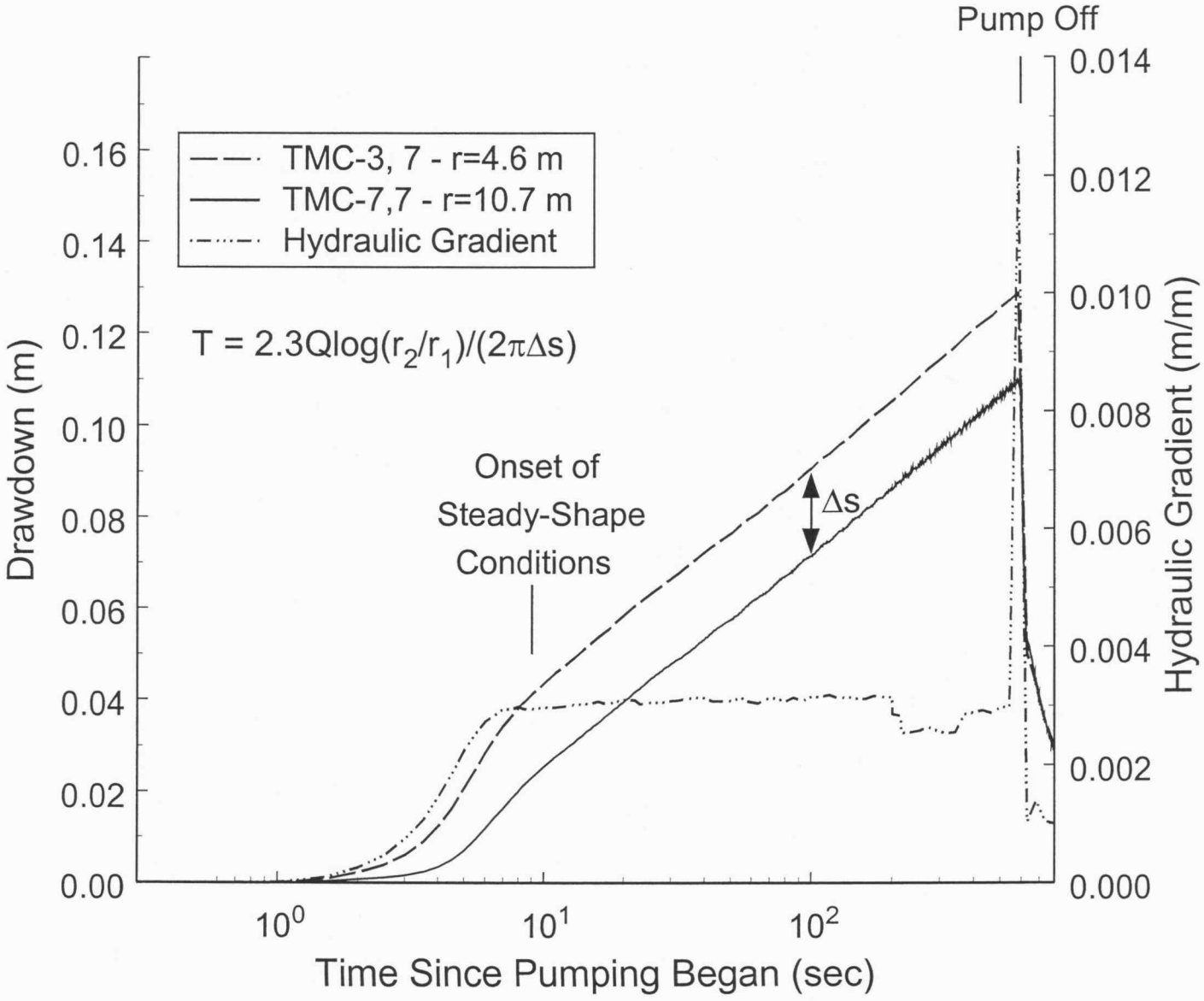
Pumping Tests
Major Methods for Data Analysis

- **Confined Aquifers**
  - Theis method
    - log-log plot
    - type curve matching
      - type curve = theoretical response
      - total drawdown
  - Cooper-Jacob method
    - semilog plot
      - straight line fit
    - changes in drawdown
  - Thiem method
    - quasi-steady-state conditions
      - steady shape
      - same as Cooper-Jacob for distance


HAYS D-6 PUMPING TEST
DRAWDOWN AT MD-6
THEIS ANALYSIS
1/u (dimensionless)
10^{-1}
10^{0}
10^{1}
10^{2}
1/u*
Distance to MD-6 = 261 ft
Pumping Rate = 77 gpm
10.0
s*
W(u)*
10^{0}
Drawdown data
Theis model
Drawdown (ft)
1.0
W(u) (dimensionless)
T = W(u)*Q/(4πs*) = 584 ft²/day
S = (4Tt*)/((1/u)*r²)= 6.95 x 10^{-5}
10^{-1}
t*
0.1
10^{1}
10^{2}
10^{3}
10^{4}
Time Since Pumping Began (sec)

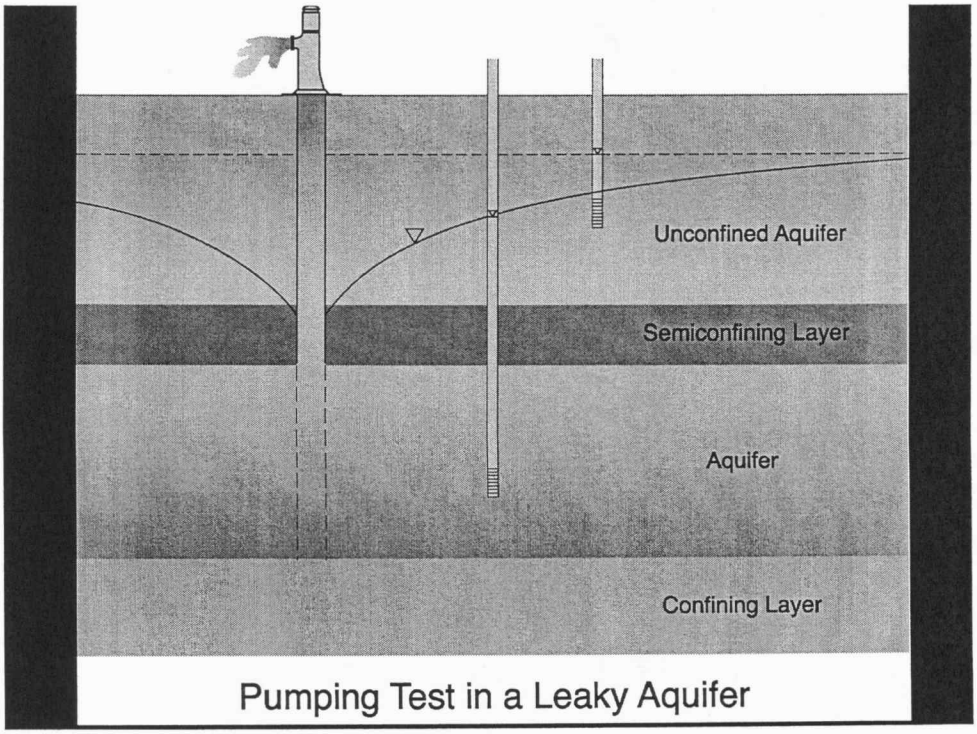

HAYS D-6 PUMPING TEST
DRAWDOWN AT MD-6
COOPER-JACOB ANALYSIS
12
10
Distance to MD-6 = 261 ft
Pumping Rate = 77 gpm
Drawdown data
Cooper-Jacob model
8
Drawdown (ft)
T = 2.3Q/(4πΔs) = 601 ft²/day
S = (2.25Tt0)/r² = 6.27 x 10^{-5}
6
Δs
4
2
0
10^{1}
10^{2}
t_0
10^{3}
10^{4}
Time Since Pumping Began (sec)

GEMS - 8/12/97 Pumping Test #1



Pumping Tests
Major Methods for Data Analysis

- Confined Aquifers
- **Leaky Aquifers**
- Unconfined Aquifers
- Recovery Methods
- Additional Mechanisms
- Less Common Settings/Tests



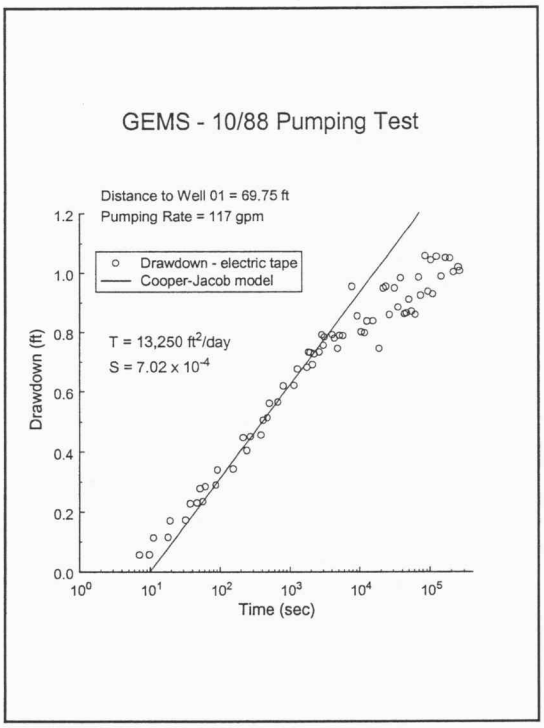
Pumping Test in a Leaky Aquifer

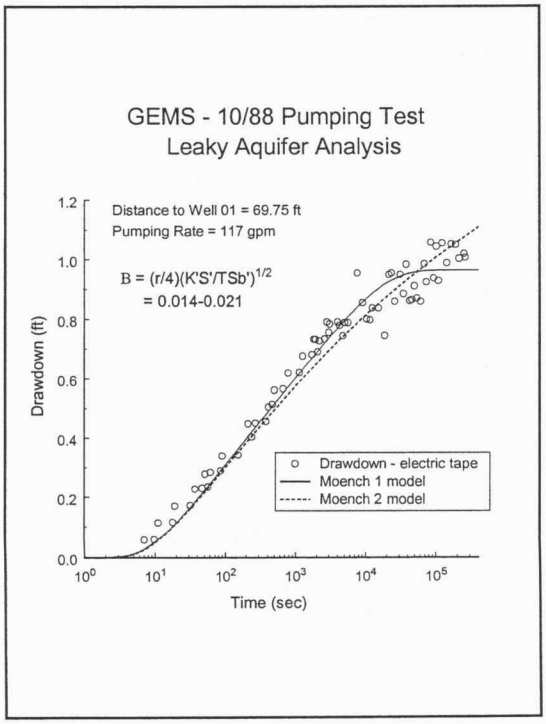
Pumping Tests Major Methods for Data Analysis

- **Leaky Aquifers**
  - log-log type curve methods
    - Hantush-Jacob/Walton
    - Hantush
    - Neuman and Witherspoon
    - Moench
  - significant issues
    - representation of aquitard
      - aquitard storage
    - nature of vertical boundaries
    - appropriate driving force

Analysis of Pumping Tests in Leaky Aquifers

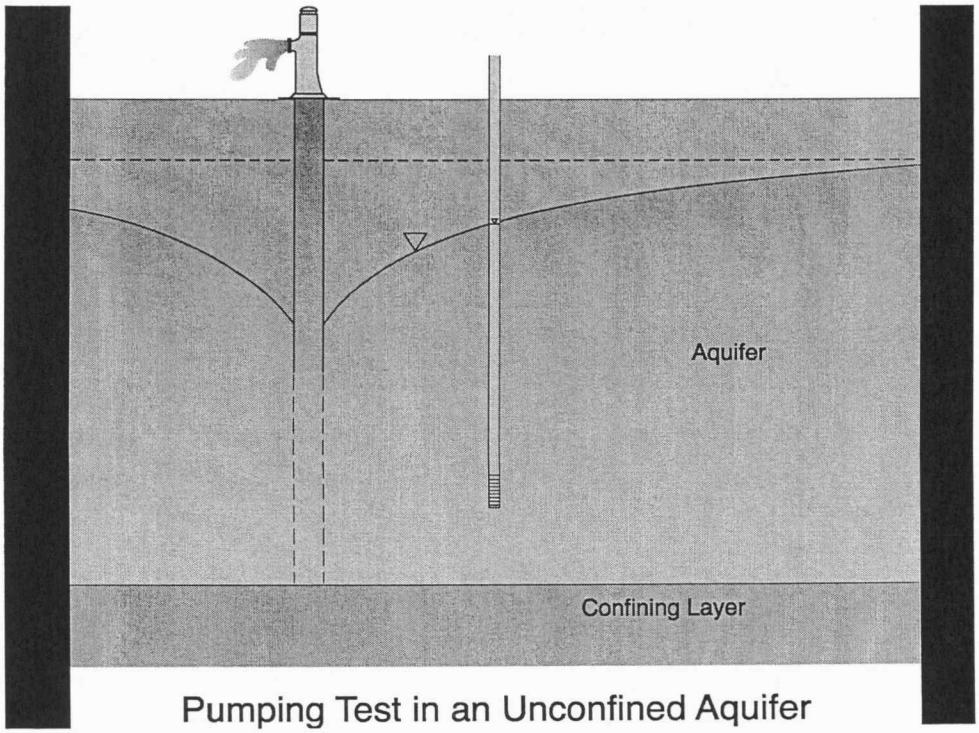
- Hantush-Jacob
  - aquitard storage ignored
  - overlying constant-head aquifer
- Hantush
  - includes aquitard storage
  - two aquitards
  - three configurations
- Neuman and Witherspoon
  - Hantush except overlying aquifer not at constant head
- Moench
  - Hantush with well-bore storage
  - appropriate at all times


GEMS - 10/88 Pumping Test
Distance to Well 01 = 69.75 ft
Pumping Rate = 117 gpm
Drawdown - electric tape
Cooper-Jacob model
T = 13,250 ft²/day
S = 7.02 x 10⁻⁴
Drawdown (ft)
Time (sec)

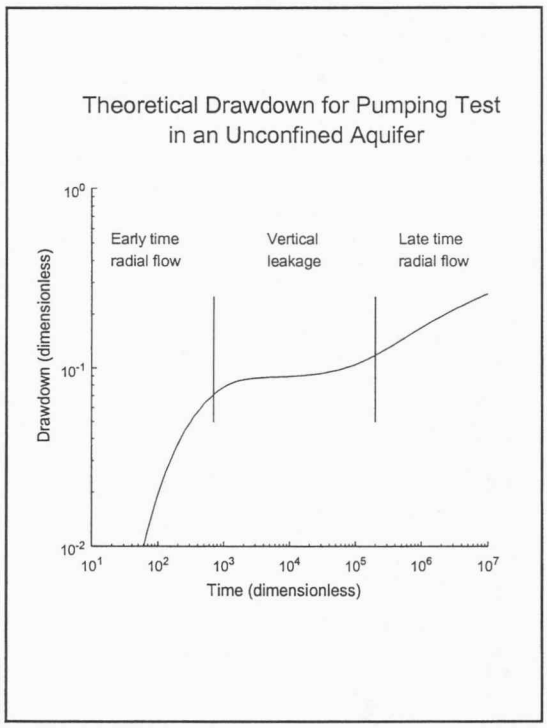

GEMS - 10/88 Pumping Test
Leaky Aquifer Analysis
Distance to Well 01 = 69.75 ft
Pumping Rate = 117 gpm
B = (r/4)(K'S'/TSb')^1/2
= 0.014-0.021
Drawdown - electric tape
Moench 1 model
Moench 2 model
Drawdown (ft)
Time (sec)

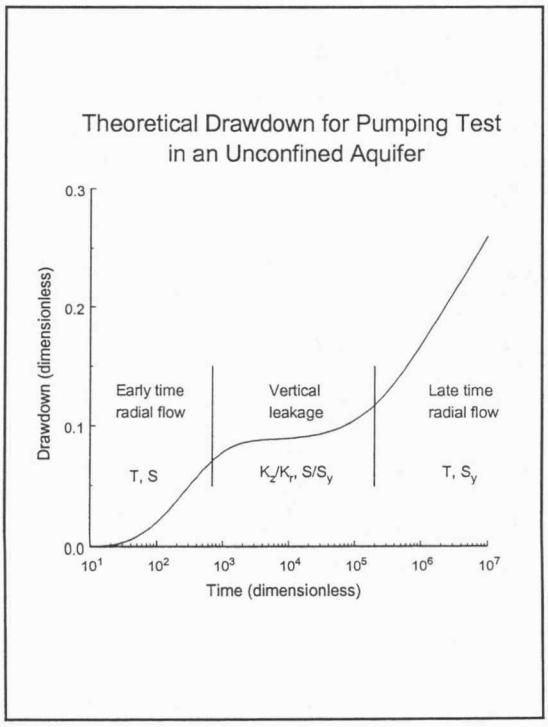
Pumping Tests Major Methods for Data Analysis

- Confined Aquifers
- Leaky Aquifers
- **Unconfined Aquifers**
- Recovery Methods
- Additional Mechanisms
- Less Common Settings/Tests



Pumping Test in an Unconfined Aquifer


Theoretical Drawdown for Pumping Test
in an Unconfined Aquifer
Early time
radial flow
Vertical
leakage
Late time
radial flow
Drawdown (dimensionless)
Time (dimensionless)

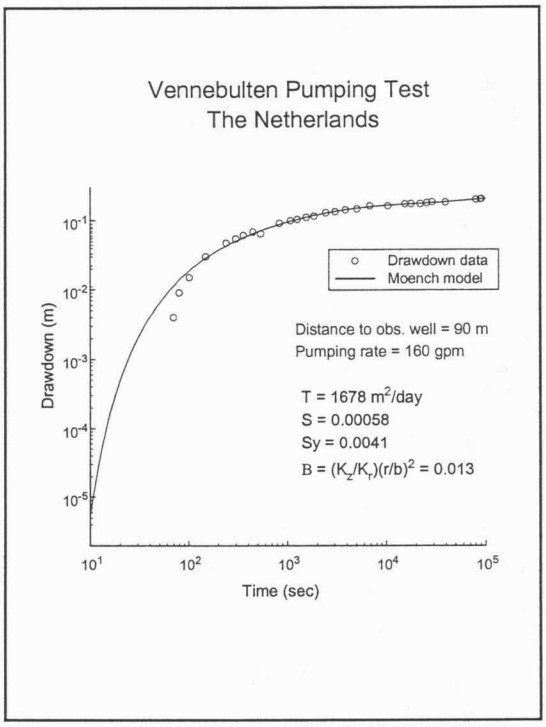

Theoretical Drawdown for Pumping Test
in an Unconfined Aquifer
Early time
radial flow
Vertical
leakage
Late time
radial flow
T, S
Kz/Kr, S/Sy
T, Sy
Drawdown (dimensionless)
Time (dimensionless)

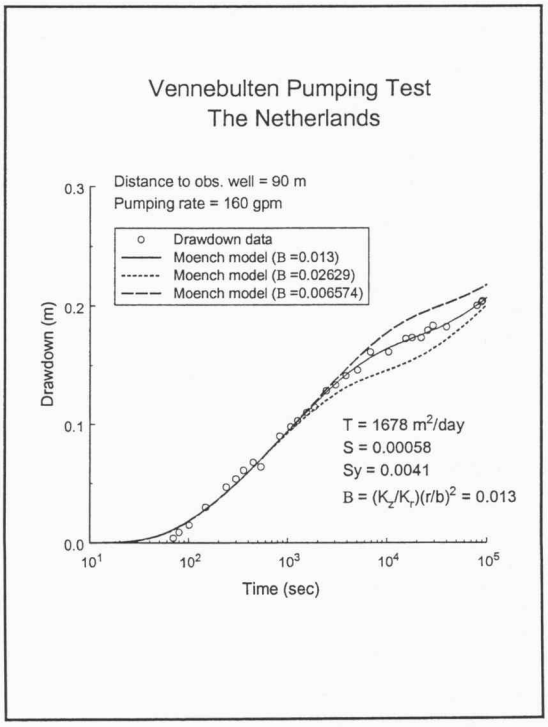
Pumping Tests Major Methods for Data Analysis

- **Unconfined Aquifers**
  - log-log type curve methods
    - Theis with Jacob correction
    - Neuman
    - Moench
  - significant issues
    - vertical drainage
    - drawdown relative to aquifer thickness

Analysis of Pumping Tests in Unconfined Aquifers

- Theis with Jacob correction
  - no vertical leakage
    - use for analysis of late-time radial flow
  - good when drawdown is large relative to thickness of aquifer
- Neuman
  - vertical leakage
    - instantaneous release of water from unsaturated zone
  - drawdown is small relative to thickness of aquifer
- Moench
  - Neuman with additions
    - well-bore storage
    - non-instantaneous release of water from unsaturated zone
    - computationally efficient


Vennebulten Pumping Test
The Netherlands
Drawdown data
Moench model
Distance to obs. well = 90 m
Pumping rate = 160 gpm
T = 1678 m²/day
S = 0.00058
Sy = 0.0041
B = (Kz/Kr)(r/b)² = 0.013
Drawdown (m)
Time (sec)

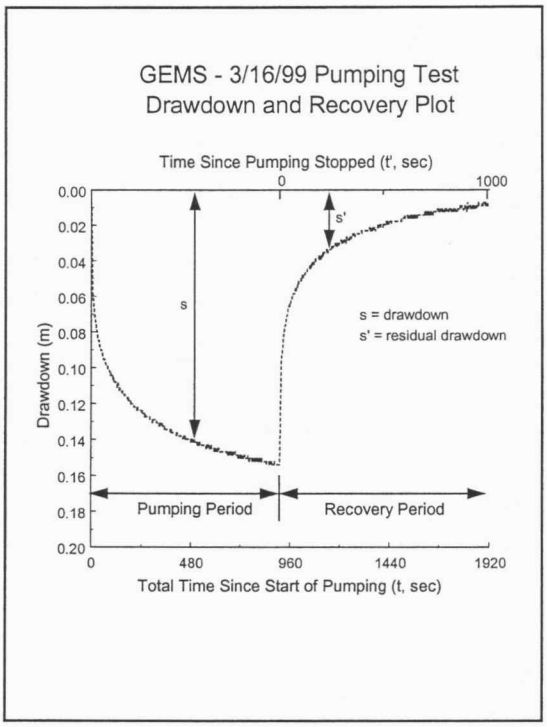

Vennebulten Pumping Test
The Netherlands
Distance to obs. well = 90 m
Pumping rate = 160 gpm
Drawdown data
Moench model (B =0.013)
Moench model (B =0.02629)
Moench model (B =0.006574)
T = 1678 m²/day
S = 0.00058
Sy = 0.0041
B = (Kz/Kr)(r/b)² = 0.013
Drawdown (m)
Time (sec)

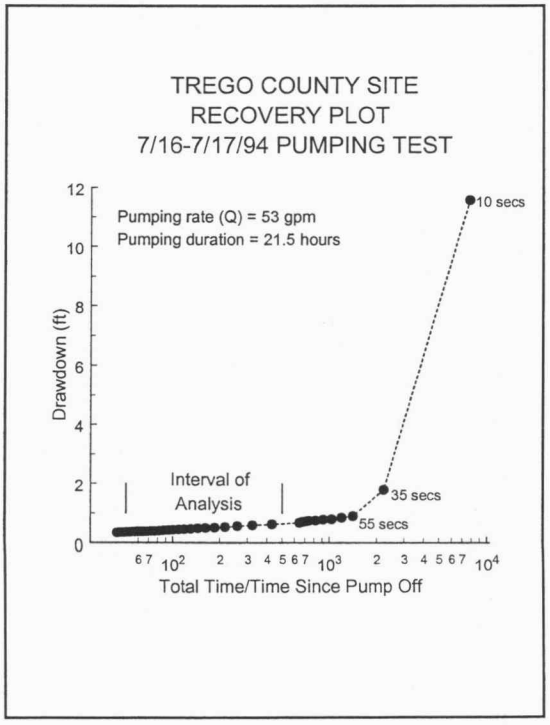
Pumping Tests
Major Methods for Data Analysis

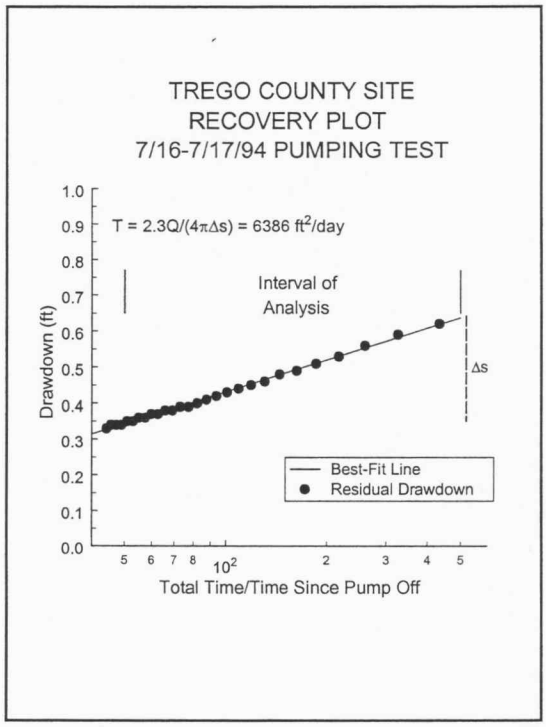
- Confined Aquifers
- Leaky Aquifers
- Unconfined Aquifers
- **Recovery Methods**
- Additional Mechanisms
- Less Common Settings/Tests

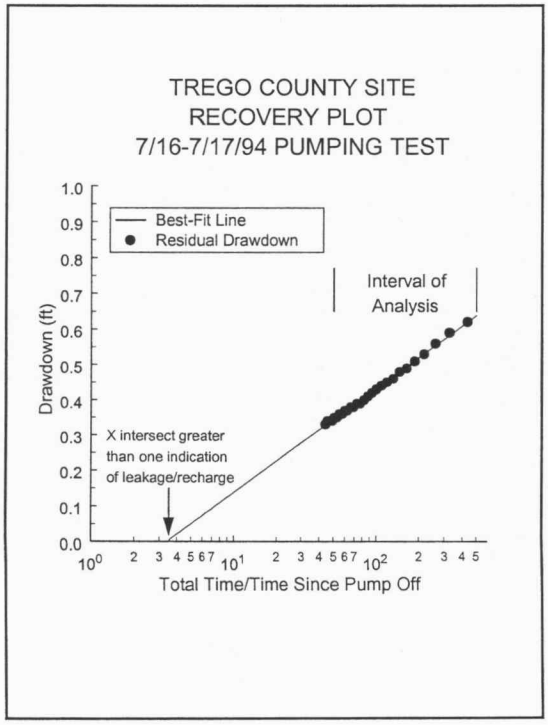
Pumping Tests
Major Methods for Data Analysis

- **Recovery Analyses**
  - analysis of drawdown after cessation of pumping
  - Theis recovery method
    - semilog plot
      - straight-line fit
      - changes in drawdown
  - advantages
    - useful at pumping well
      - no pumping-induced noise
      - negligible well losses
    - relatively insensitive to rate variations


GEMS - 3/16/99 Pumping Test
Drawdown and Recovery Plot
Time Since Pumping Stopped (t', sec)
0
1000
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
Drawdown (m)
s
s'
s = drawdown
s' = residual drawdown
Pumping Period
Recovery Period
0
480
960
1440
1920
Total Time Since Start of Pumping (t, sec)


TREGO COUNTY SITE
RECOVERY PLOT
7/16-7/17/94 PUMPING TEST
Pumping rate (Q) = 53 gpm
Pumping duration = 21.5 hours
10 secs
35 secs
55 secs
Interval of
Analysis
12
10
8
6
4
2
0
Drawdown (ft)
6 7 10^2 2 3 4 5 6 7 10^3 2 3 4 5 6 7 10^4
Total Time/Time Since Pump Off


TREGO COUNTY SITE
RECOVERY PLOT
7/16-7/17/94 PUMPING TEST
T = 2.3Q/(4πΔs) = 6386 ft²/day
Interval of Analysis
Δs
Best-Fit Line
Residual Drawdown
Drawdown (ft)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
5 6 7 8 10² 2 3 4 5
Total Time/Time Since Pump Off


TREGO COUNTY SITE
RECOVERY PLOT
7/16-7/17/94 PUMPING TEST
Best-Fit Line
Residual Drawdown
Interval of Analysis
X intersect greater than one indication of leakage/recharge
Drawdown (ft)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10⁰ 2 3 4 5 6 7 10¹ 2 3 4 5 6 7 10² 2 3 4 5
Total Time/Time Since Pump Off

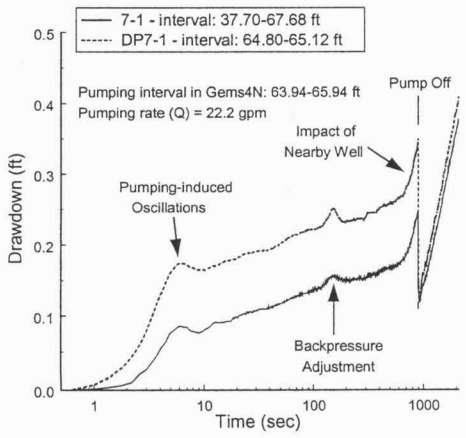
Pumping Tests
Major Methods for Data Analysis

- Confined Aquifers
- Leaky Aquifers
- Unconfined Aquifers
- Recovery Methods
- **Additional Mechanisms**
- Less Common Settings/Tests

Pumping Tests
Major Methods for Data Analysis

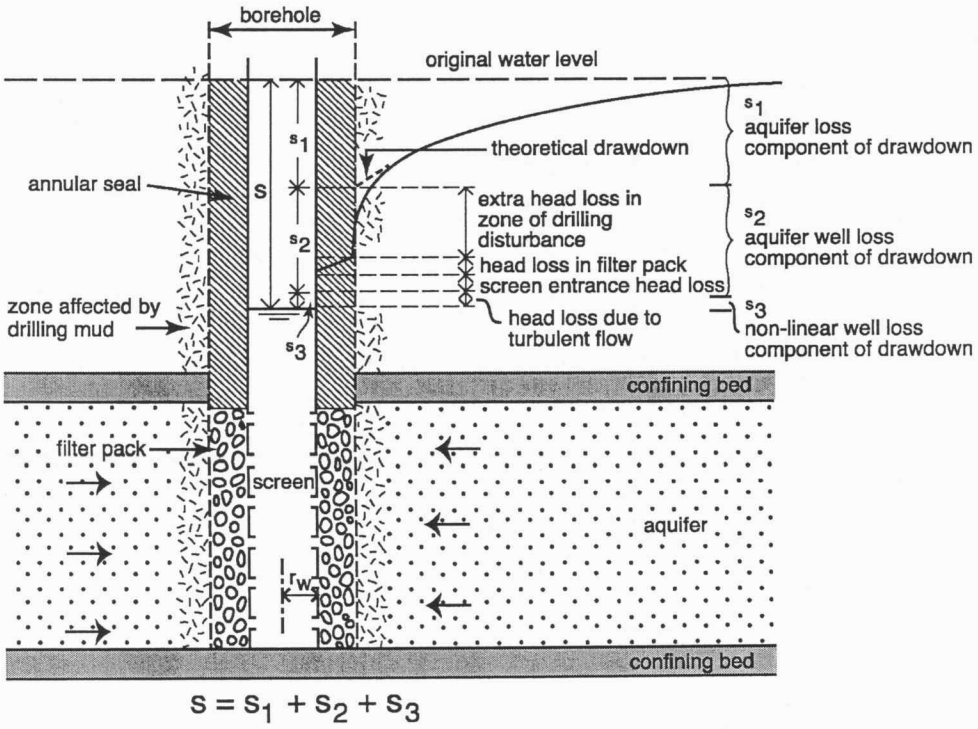
- **Additional Mechanisms**
  - wellbore storage
    - important at and near pumping well
    - only influences early-time drawdown
  - oscillating water levels
    - important at and near pumping well
    - only influences early-time drawdown

Pumping Test in Sand and Gravel Aquifer
GEMS - 8/13/99 Pumping Test #1



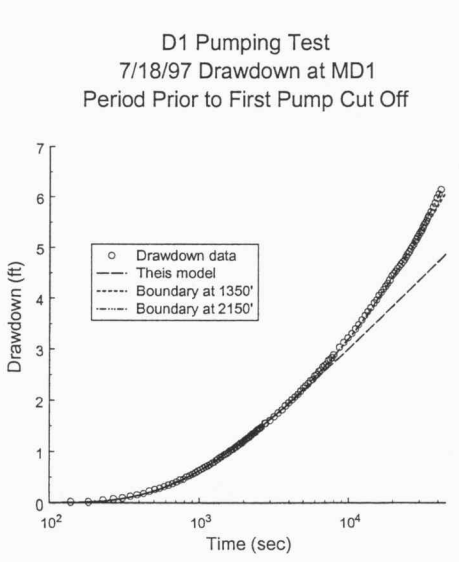
Pumping Tests Major Methods for Data Analysis

- **Additional Mechanisms**
  - well losses
    - only important at pumping well
    - influence drawdown at all times
      - constant factor added to drawdown
  - partial penetration
    - important at and near the pumping well
    - influences drawdown at all times
      - constant factor at later times



Pumping Tests
Major Methods for Data Analysis

- **Additional Mechanisms**
  - lateral boundaries
    - important at all well locations
    - influence drawdown at later times



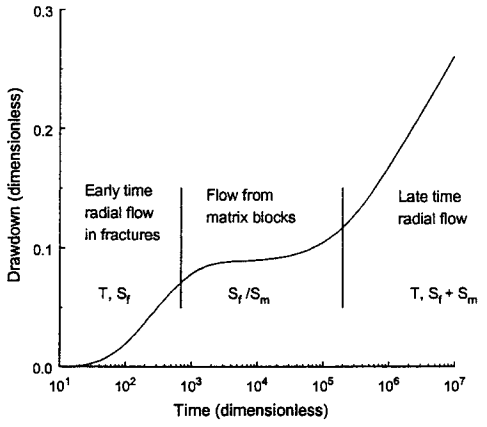
Pumping Tests
Major Methods for Data Analysis

- Confined Aquifers
- Leaky Aquifers
- Unconfined Aquifers
- Recovery Methods
- Additional Mechanisms
- **Less Common Settings/Tests**

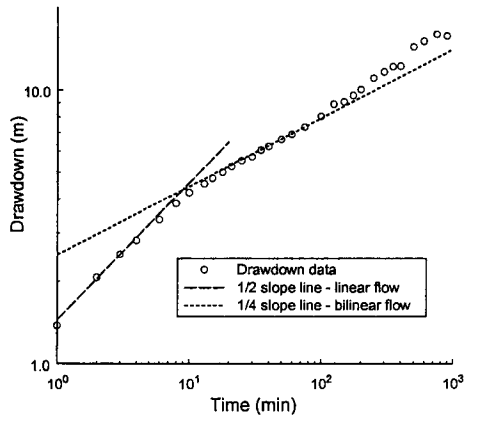
Pumping Tests
Major Methods for Data Analysis

- **Less Common Settings/Tests**
  - fractured aquifers
    - double-porosity models
      - Moench
    - discrete-fracture models
    - fracture zone in less permeable matrix
      - Butler and Liu
        - KGS web site

Theoretical Drawdown for Pumping Test in a Highly Fractured Aquifer

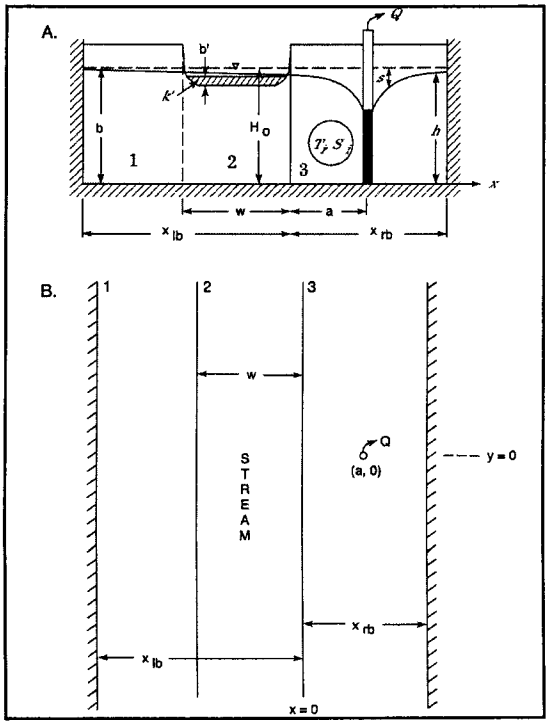


Brandwag Tweeling Dike Pumping Test



Pumping Tests
Major Methods for Data Analysis

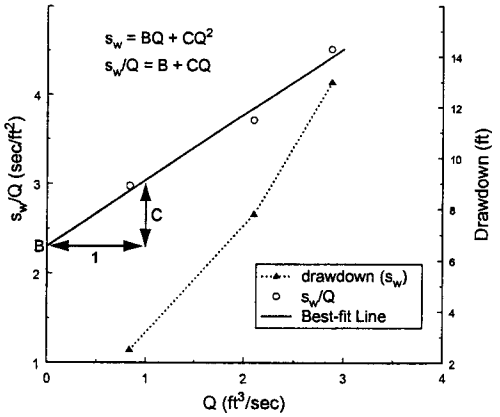
- **Less Common Settings/Tests**
  - stream-aquifer interactions
    - fully penetrating stream
      - Glover-Balmer, Jenkins
    - partially penetrating stream
      - Butler et al.
      - KGS web site



Pumping Tests
Major Methods for Data Analysis

- **Less Common Settings/Tests**
  - step-drawdown tests
    - well performance
    - multiple short-term pumping periods

Step-Drawdown Test Example

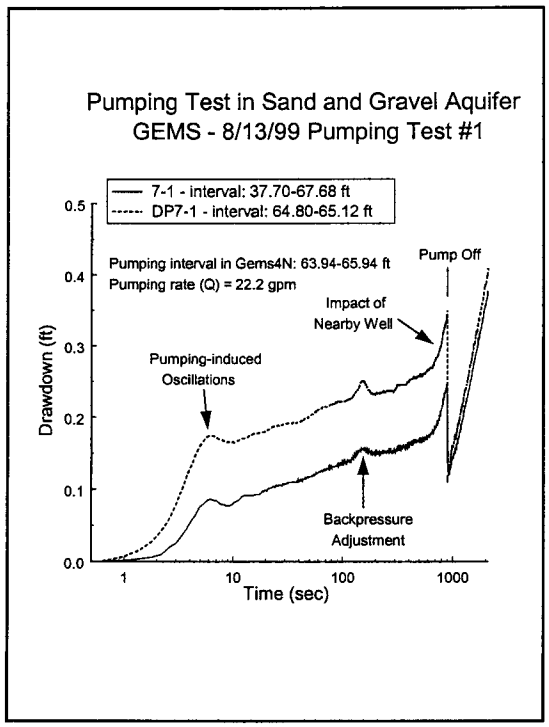


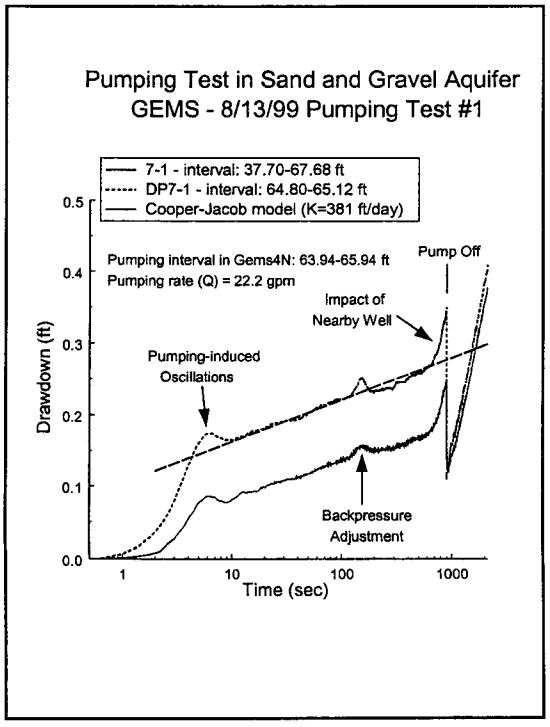
PRESENTATION OUTLINE

- Introduction
- General Design Guidelines
- Direct Push Applications
- Major Methods for Data Analysis
- **Data Analysis Strategies**
- Conclusions

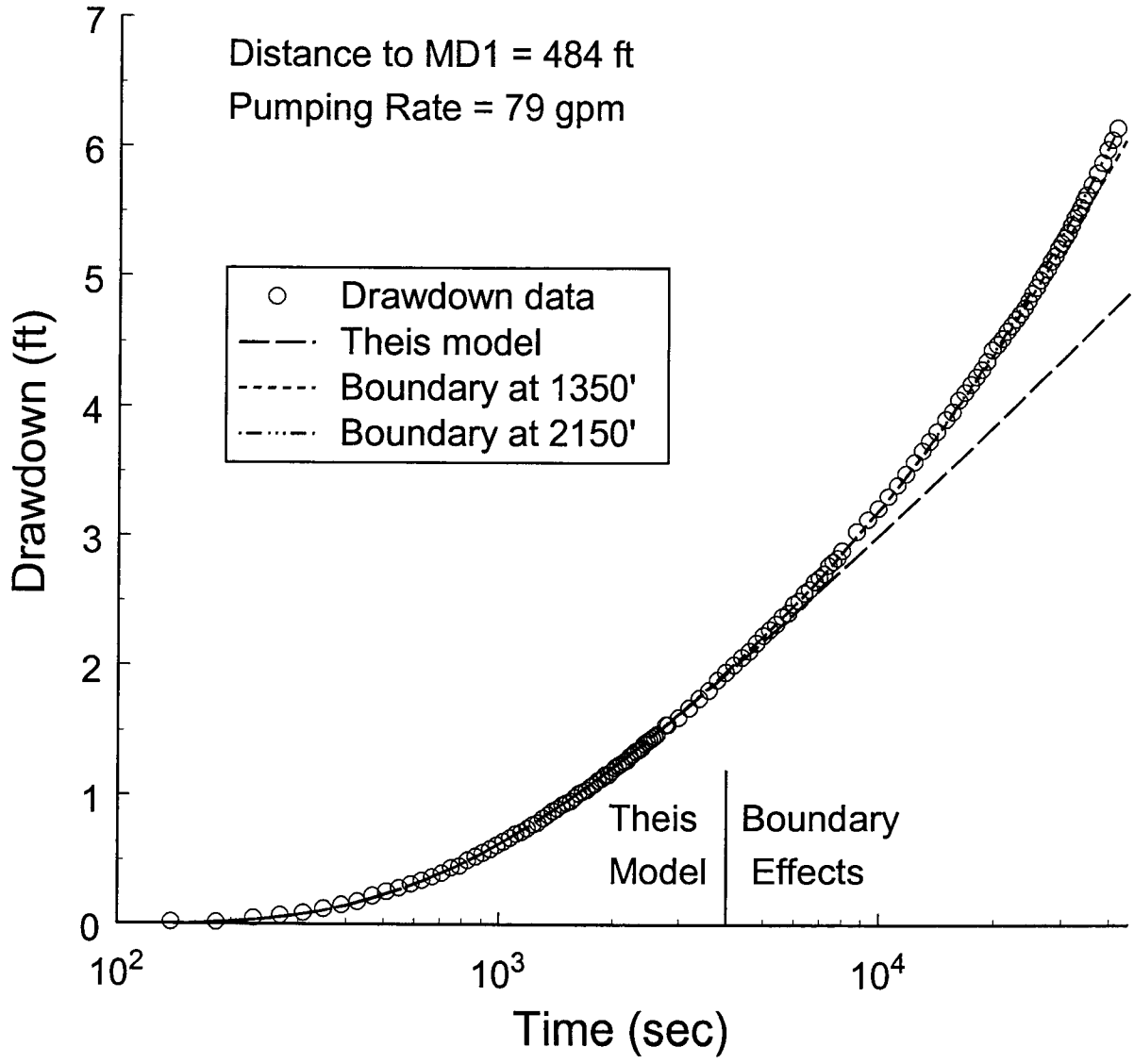
Data Analysis Strategies Pumping Tests

- Select Appropriate Model
  - test design
    - consistent with target parameters
    - consistent with geologic framework
    - attempt to minimize complexities
  - specialized plots
    - assist in the identification of flow regimes
      - radial, linear, bilinear, etc.
- Principle of Parsimony
  - identify radial flow regime
    - analyze with Theis or Cooper-Jacob model
  - analyze remainder of record
    - consistent with objectives of test


Pumping Test in Sand and Gravel Aquifer
GEMS - 8/13/99 Pumping Test #1
7-1 - interval: 37.70-67.68 ft
DP7-1 - interval: 64.80-65.12 ft
Pumping interval in Gems4N: 63.94-65.94 ft
Pumping rate (Q) = 22.2 gpm
Pump Off
Impact of
Nearby Well
Pumping-induced
Oscillations
Backpressure
Adjustment
Drawdown (ft)
0.0
0.1
0.2
0.3
0.4
0.5
1
10
100
1000
Time (sec)


Pumping Test in Sand and Gravel Aquifer
GEMS - 8/13/99 Pumping Test #1
7-1 - interval: 37.70-67.68 ft
DP7-1 - interval: 64.80-65.12 ft
Cooper-Jacob model (K=381 ft/day)
Pumping interval in Gems4N: 63.94-65.94 ft
Pumping rate (Q) = 22.2 gpm
Pump Off
Impact of
Nearby Well
Pumping-induced
Oscillations
Backpressure
Adjustment
Drawdown (ft)
0.0
0.1
0.2
0.3
0.4
0.5
1
10
100
1000
Time (sec)

D1 Pumping Test
7/18/97 Drawdown at MD1
Period Prior to First Pump Cut Off



PRESENTATION OUTLINE

- Introduction
- General Design Guidelines
- Direct Push Applications
- Major Methods for Data Analysis
- Data Analysis Strategies
- **Conclusions**

Pumping Tests

- The Need for Care
  - Design
    - Justify model selection
    - Confidence in parameter estimates
    - Minimize complexities
  - Performance
    - Rate - appropriate signal to noise ratio
    - Duration - consistent with objectives
  - Analysis
    - Principle of parsimony
      - Cooper-Jacob model or recovery variant
      - consistent with objectives
- Large Scale Hydraulic Properties
  - Extrapolate to larger times with caution
    - Additional boundaries

LIST OF NOTATION

B = linear loss coefficient in step-drawdown equation, $[T/L^2]$;

b = aquifer thickness, [L];

b' = thickness of aquitard, [L];

C = quadratic loss coefficient in step-drawdown equation, $[T^2/L^5]$;

K' = hydraulic conductivity of aquitard, [L];

K_r, K_h = radial (horizontal) component of the hydraulic conductivity of the formation, [L/T];

K_z = vertical component of the hydraulic conductivity of the formation, [L/T];

Q = pumping rate, $[L^3/T]$;

r = distance to observation well, [L];

r_c = effective radius of well casing, [L];

r_w = effective radius of well screen, [L];

S = storativity of formation, [dimensionless];

S' = storativity of aquitard, [dimensionless];

S_f = storativity of fractures, [dimensionless];

S_m = storativity of matrix, [dimensionless];

S_s = specific storage of formation, [1/L];

S_y = specific yield of formation, [dimensionless];

s = drawdown, [L];

s' = residual drawdown, [L];

s_w = drawdown at pumping well, [L];

Δs = change in drawdown in time or space used in Cooper-Jacob and Thiem methods, respectively, [L];

T = transmissivity of formation, [L^2/T];

t = total time since the start of the test, [T];

t_0 = time at which Cooper-Jacob straight line intersects x axis, [T];

$u = r^2S/4Tt$, dimensionless term used in Theis equation;

z = vertical direction, [L];

$B = (K_z/K_r)(r/b)^2$, dimensionless parameter for pumping tests in unconfined aquifers;

$B = (r/4)(K'S'/TSb')^{1/2}$, dimensionless parameter for pumping tests in leaky aquifers;

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General

Batu, *Aquifer Hydraulics*, Wiley, 727 pp., 1998 – good theoretical treatment of mostly pre-1980 methods – place to go for derivations of classic methods but not for practical aspects.

Kruseman and de Ridder, Analysis and Evaluation of Pumping Test Data, *ILRI Publication 47* (2nd edition), 377 pp., 1990 - henceforth, KdeR – most complete coverage currently available – stresses practical side.

General Design Guidelines

KdeR – Chapter 2.

Butler, The role of pumping tests in site characterization: Some theoretical considerations, *Ground Water*, 28(3), 394, 1990 – discussion of observation-well placement.

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Design of Tests in Low-K Media

Cho, Wilson, and Beck, Measuring vertical profiles of hydraulic conductivity with in-situ direct push methods, *Jour. of Environmental Engineering*, 126(8), 775, 2001 – constant drawdown pumping test performed in direct-push pipe using a suction pump – although approach is applied to test in an aquifer, it would work best in a low-K formation.

Design of Tests in High-K Media

Zhan and Butler, Hydraulic tests in highly permeable aquifers: A new analytical solution and insight for hydraulic tomography (abstract), *Eos*, 82(20), S160 (2001 Spring AGU Conference) – most complete analysis to date - article to follow shortly.

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Direct Push Applications

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Butler, J.J., Jr., J.M. Healey, L. Zheng, W. McCall, and M.K. Schulmeister. 1999a. Hydrostratigraphic characterization of unconsolidated alluvium with direct-push sensor technology (abstract). *GSA 1999 Annual Meeting Abstracts with Program*. v. 31, no. 7: A350 (full report (*Kansas Geological Survey Open-File Rept. 99-40*) available at www.kgs.ukans.edu/Hydro/Publications/OFR99_40/index.html) – covers direct-push electrical conductivity logging.

Cho, Wilson, and Beck, Measuring vertical profiles of hydraulic conductivity with in-situ direct push methods, *Jour. of Environmental Engineering*, 126(8), 775, 2001 – constant drawdown pumping test performed in direct-push pipe using a suction pump.

Major Methods for Data Analysis

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KdeR – Chapters 3-15, 17-19.

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