S.S. Papadopulos & Associates, Inc.
Environmental and Water Resource Consultants

Foundations of Pumping Test Interpretation

2. "Real" aquifers

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Outline

1. What is a real aquifer?
2. Proposed analysis approach with the composite plot
3. Assessment of the proposed approach for estimating the bulk-average transmissivity
4. Case study #1: Cambridge NDPW1-08
5. Case study #2: Elmira EW-3

Real aquifers are heterogeneous

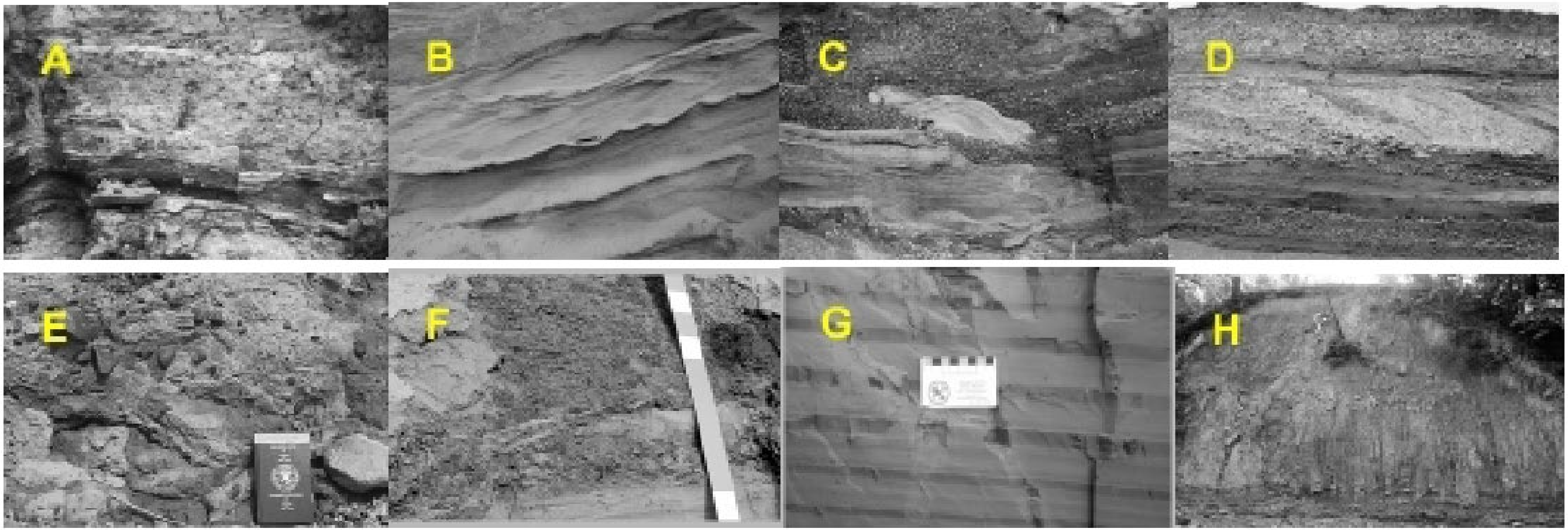
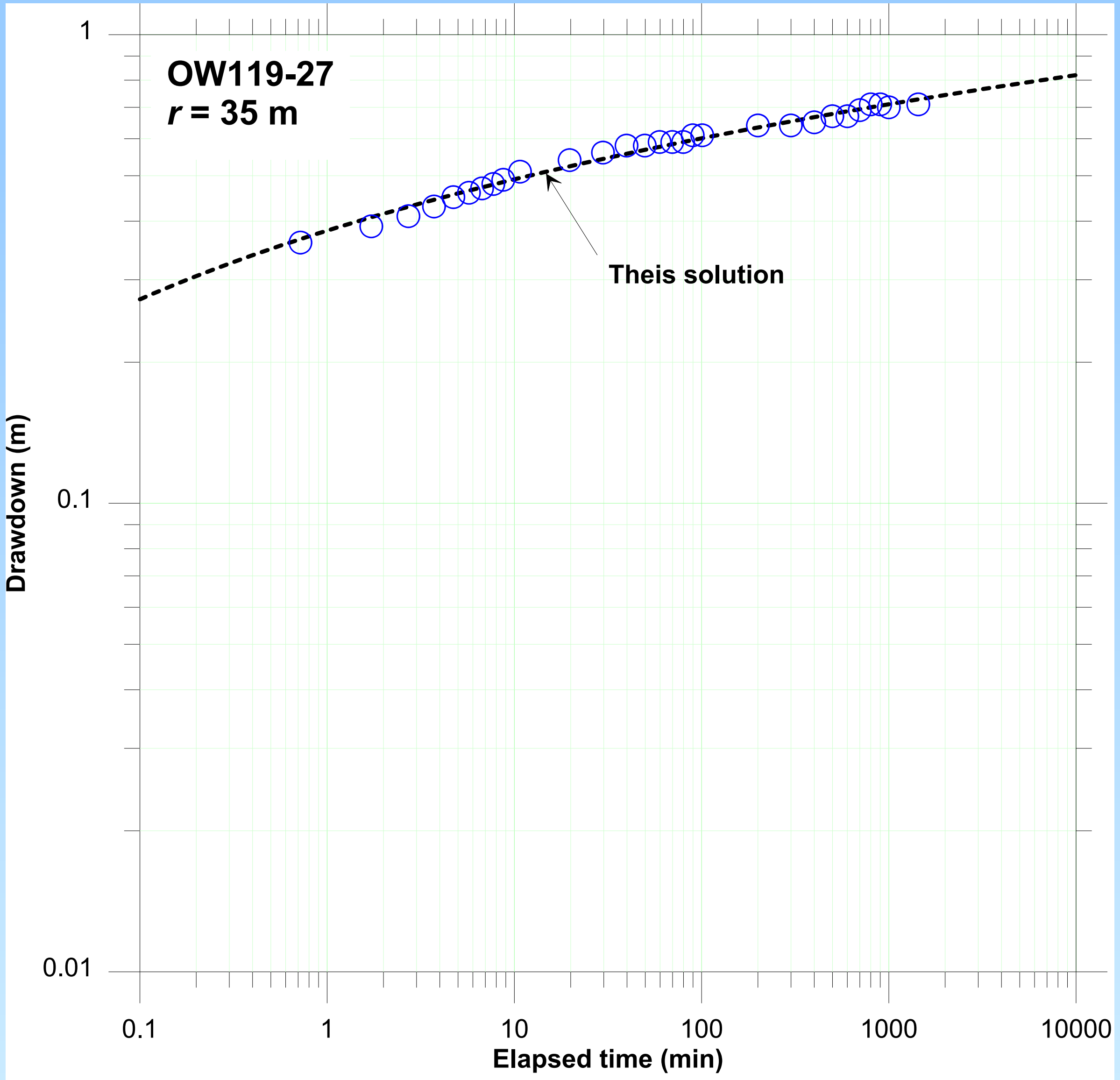


Figure 5. *Major types of sediment and rock in the ORM/GTA* ***a)*** *Halton interbedded sediments;* ***b)*** *ORM fine sand and silt;* ***c)*** *ORM gravel;* ***d)*** *channel gravel;* ***e)*** *Newmarket Till;* ***f)*** *lower sediments, Scarborough sand and organics;* ***g)*** *lower sediment, rhythmites;* ***h)*** *Shale-carbonate bedrock (below shovel) overlain by Newmarket and Halton Tills, Etobicoke Creek*

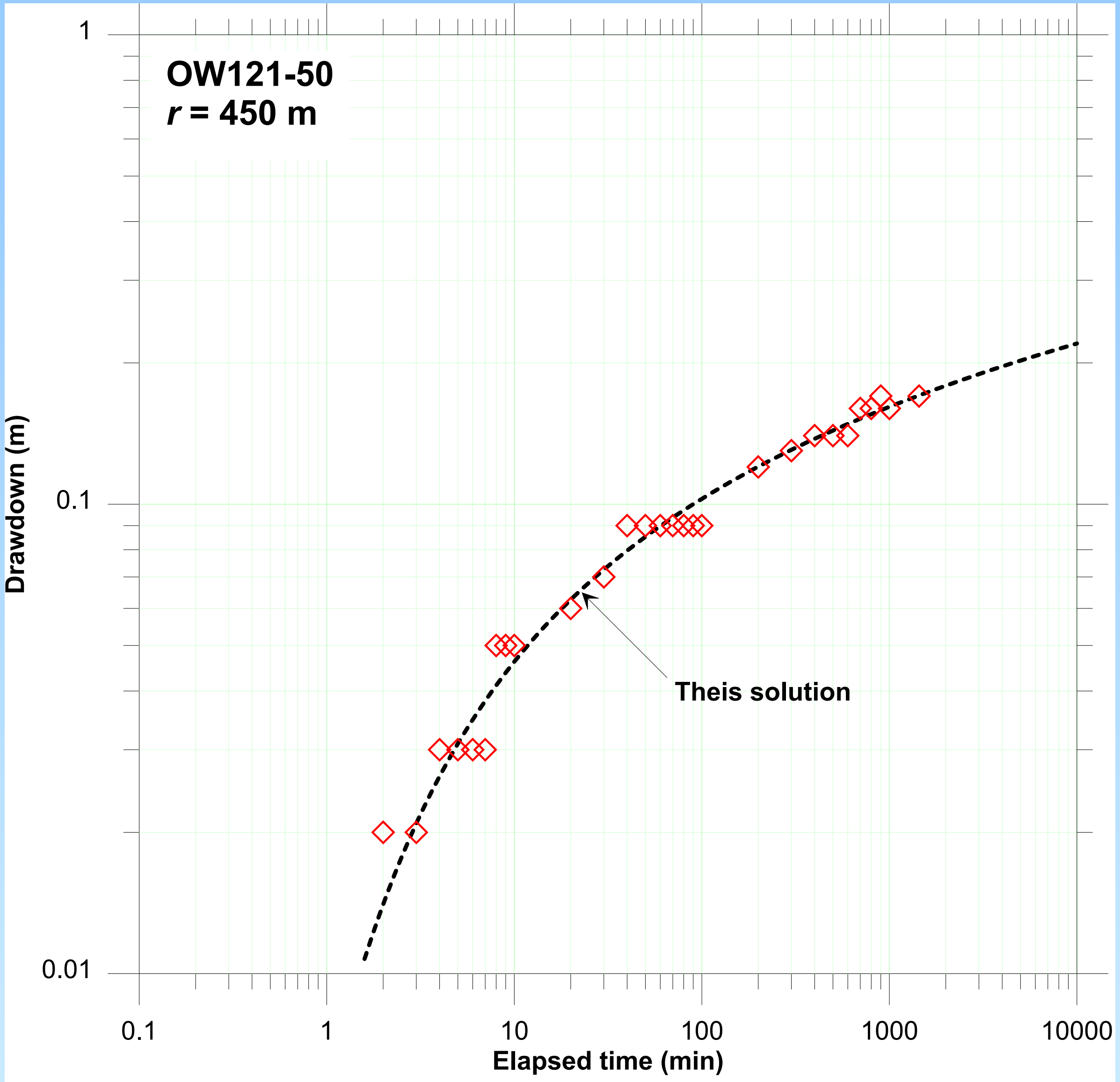
Sharpe et al. (1999) Current Research 1999-E; Geological Survey of Canada, p. 123–136.

Real aquifers are heterogeneous (2)

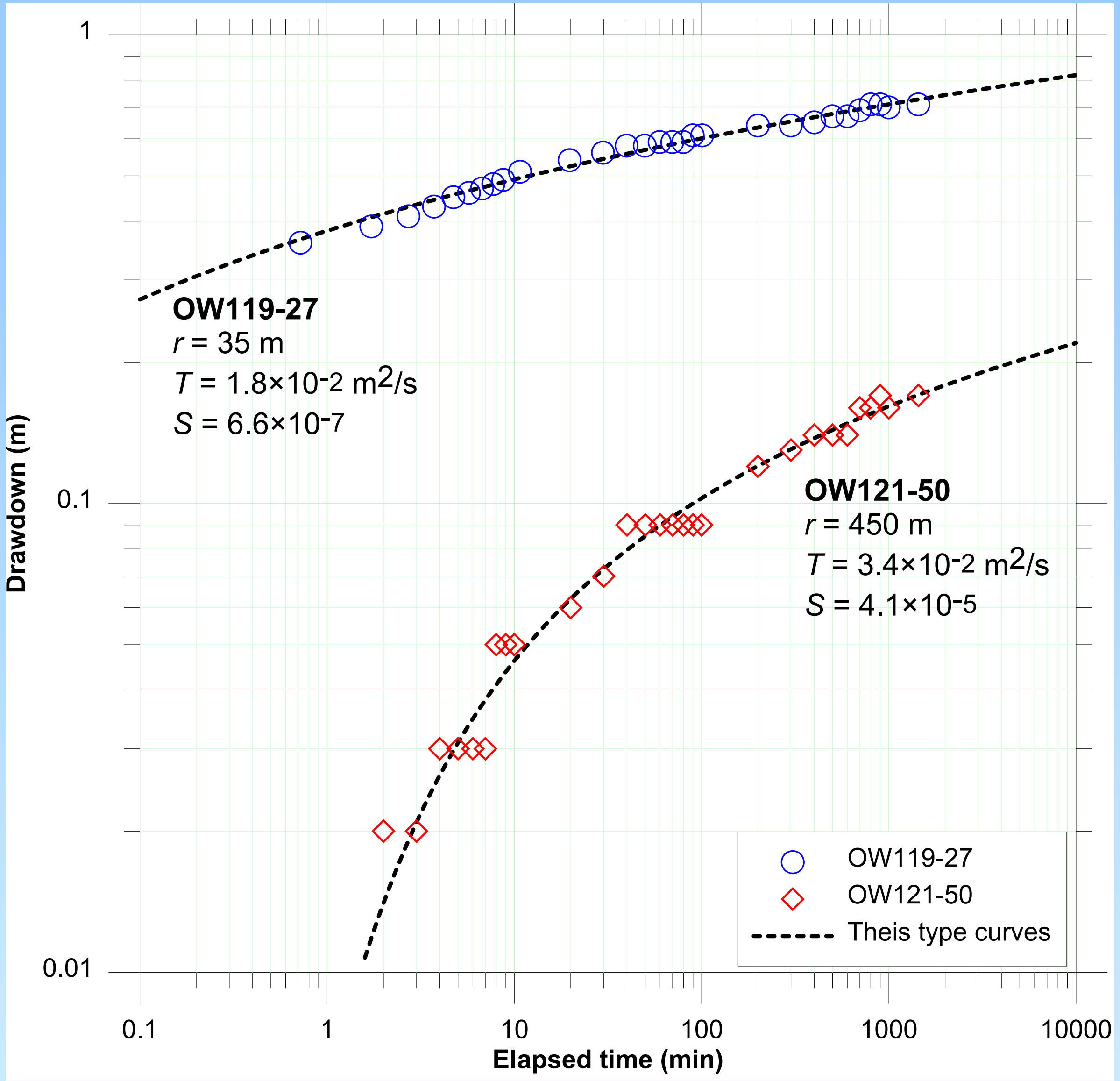
Case study



OW119-27
r = 35 m
Theis solution
Drawdown (m)
Elapsed time (min)
1
0.1
0.01
0.1
1
10
100
1000
10000

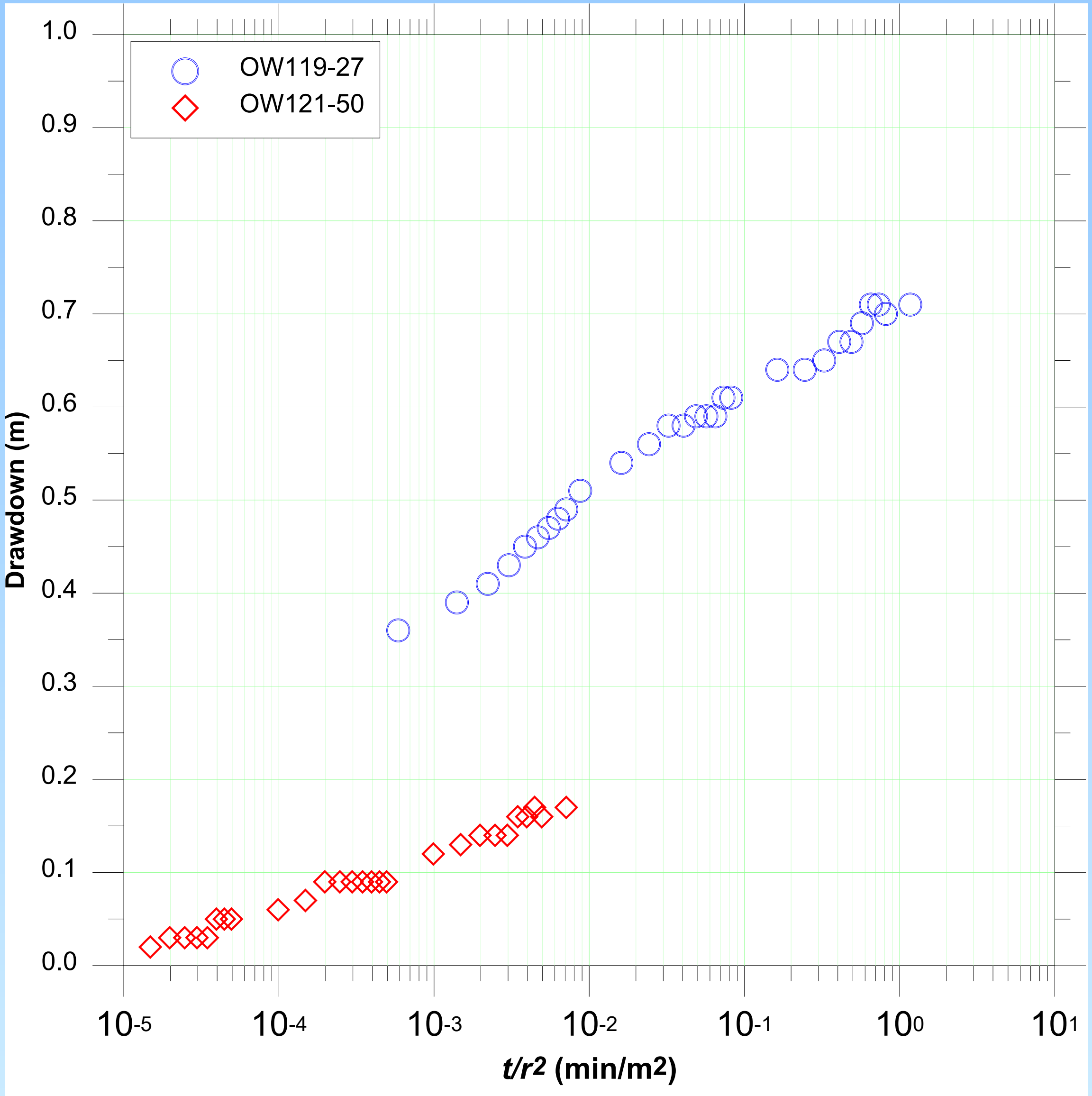


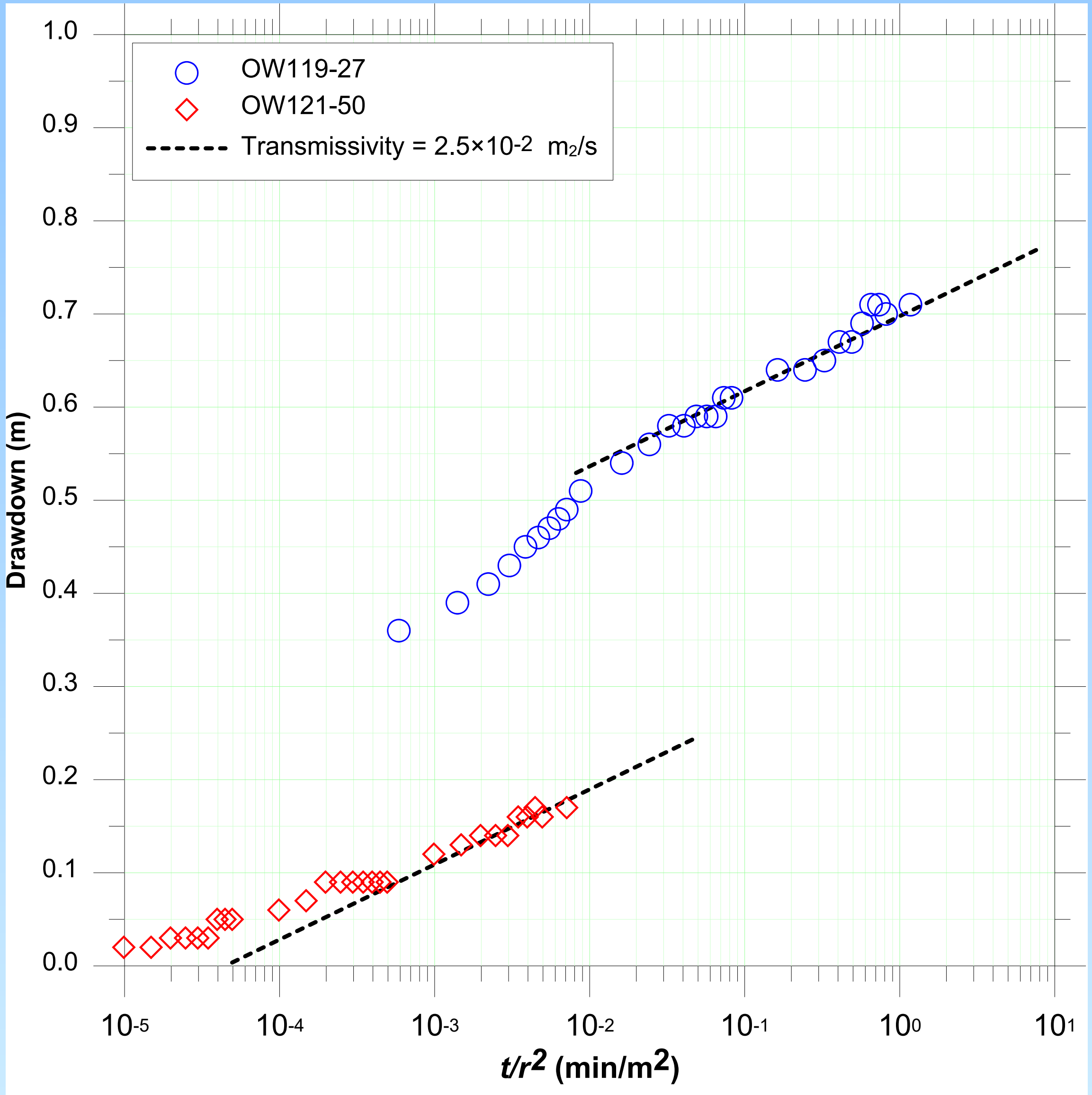
OW121-50
r = 450 m
Theis solution
Drawdown (m)
Elapsed time (min)
1
0.1
0.01
0.1
1
10
100
1000
10000



1
0.1
0.01
Drawdown (m)
0.1
1
10
100
1000
10000
Elapsed time (min)
OW119-27
r = 35 m
T = 1.8×10-2 m2/s
S = 6.6×10-7
OW121-50
r = 450 m
T = 3.4×10-2 m2/s
S = 4.1×10-5
OW119-27
OW121-50
Theis type curves

Proposed approach





OW119-27
OW121-50
Transmissivity = 2.5×10-2 m2/s
Drawdown (m)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10-5
10-4
10-3
10-2
10-1
100
101
t/r2 (min/m2)

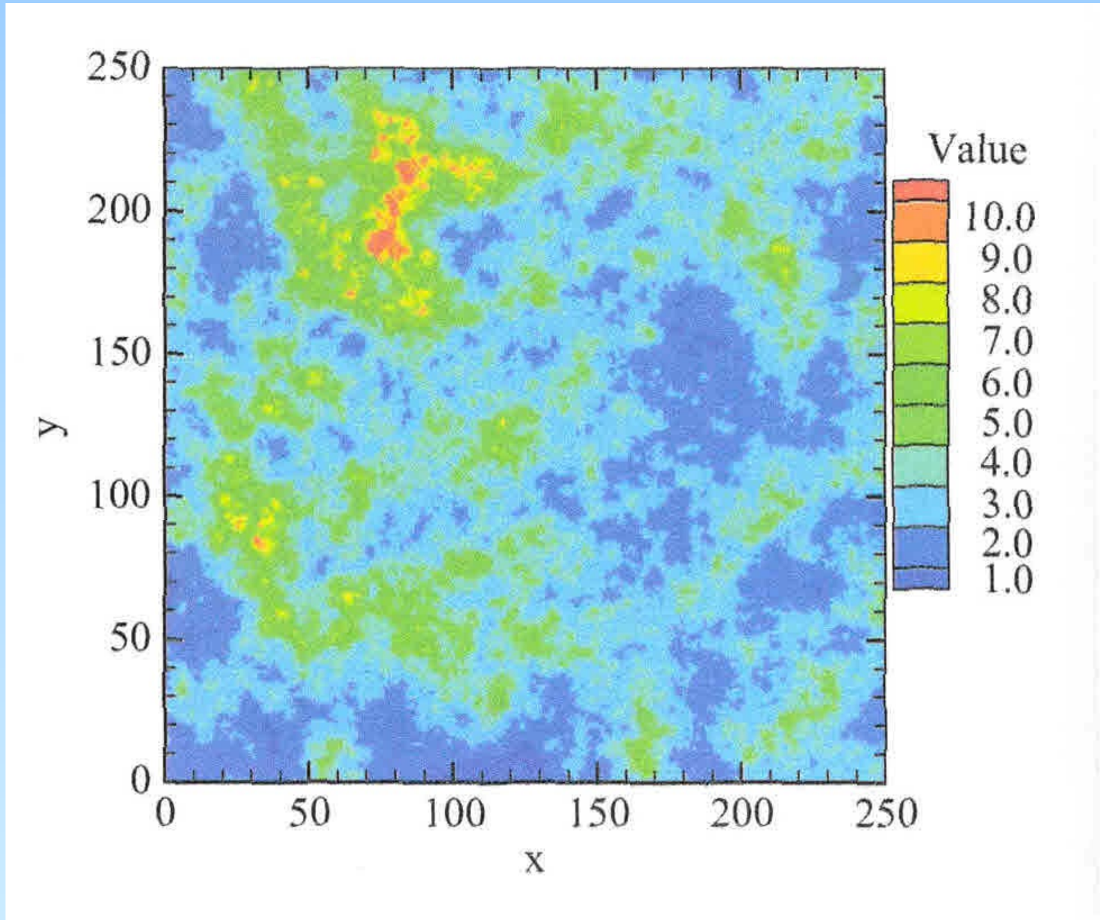
Assessment of the proposed approach

1. Pumping tests in homogeneously heterogeneous aquifers (random fields)

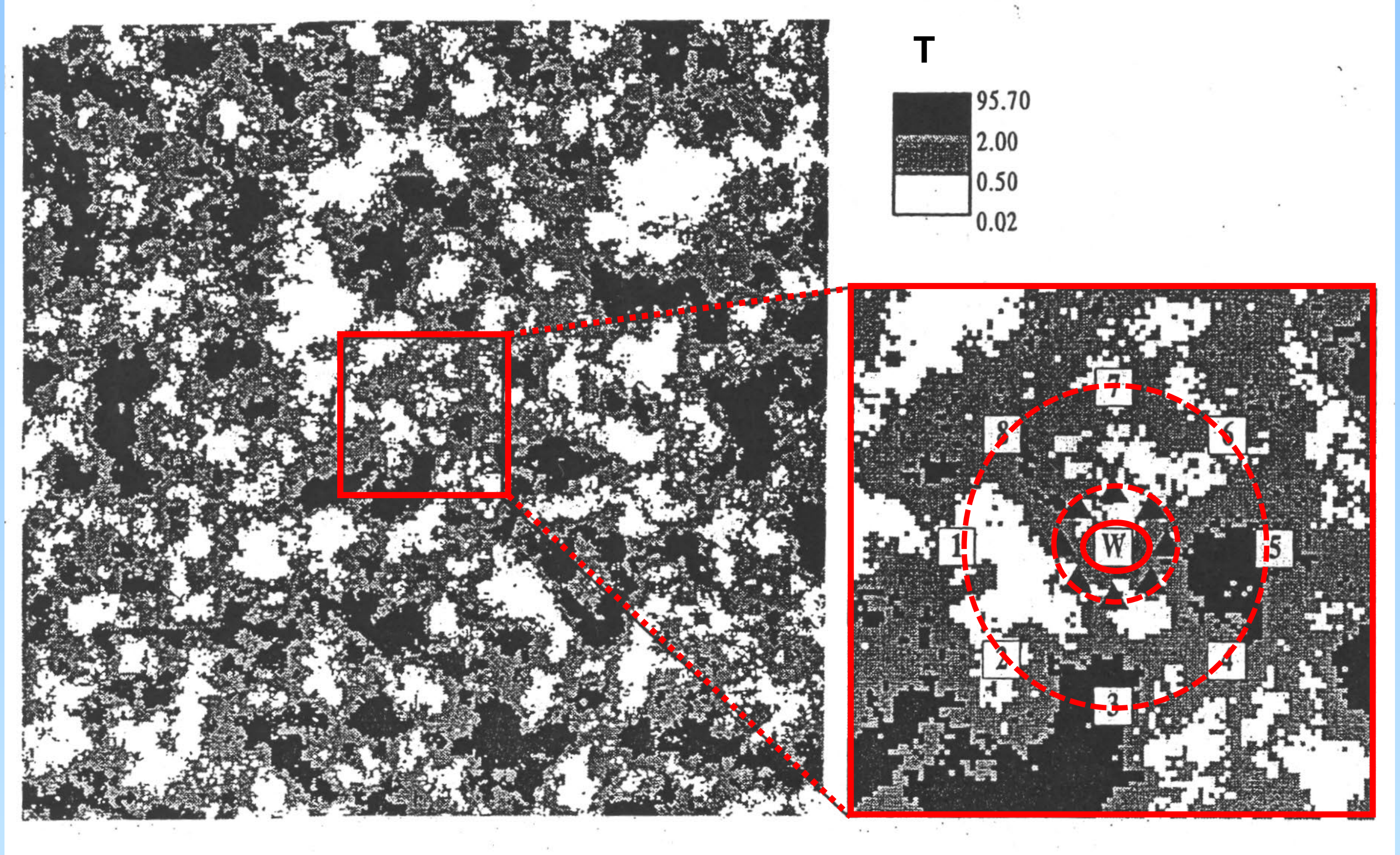
2. Pumping tests in aquifers with discrete zones

Conceptual model #1

Pumping tests in homogeneously heterogeneous aquifers (random fields)



Meier et al. (1998):
Numerical simulation of pumping tests in random-*T* fields



Lognormal transmissivity:

$\ln(T) = y = N(\ln\{T_G\}, \sigma_y)$

T_G = Geometric mean transmissivity

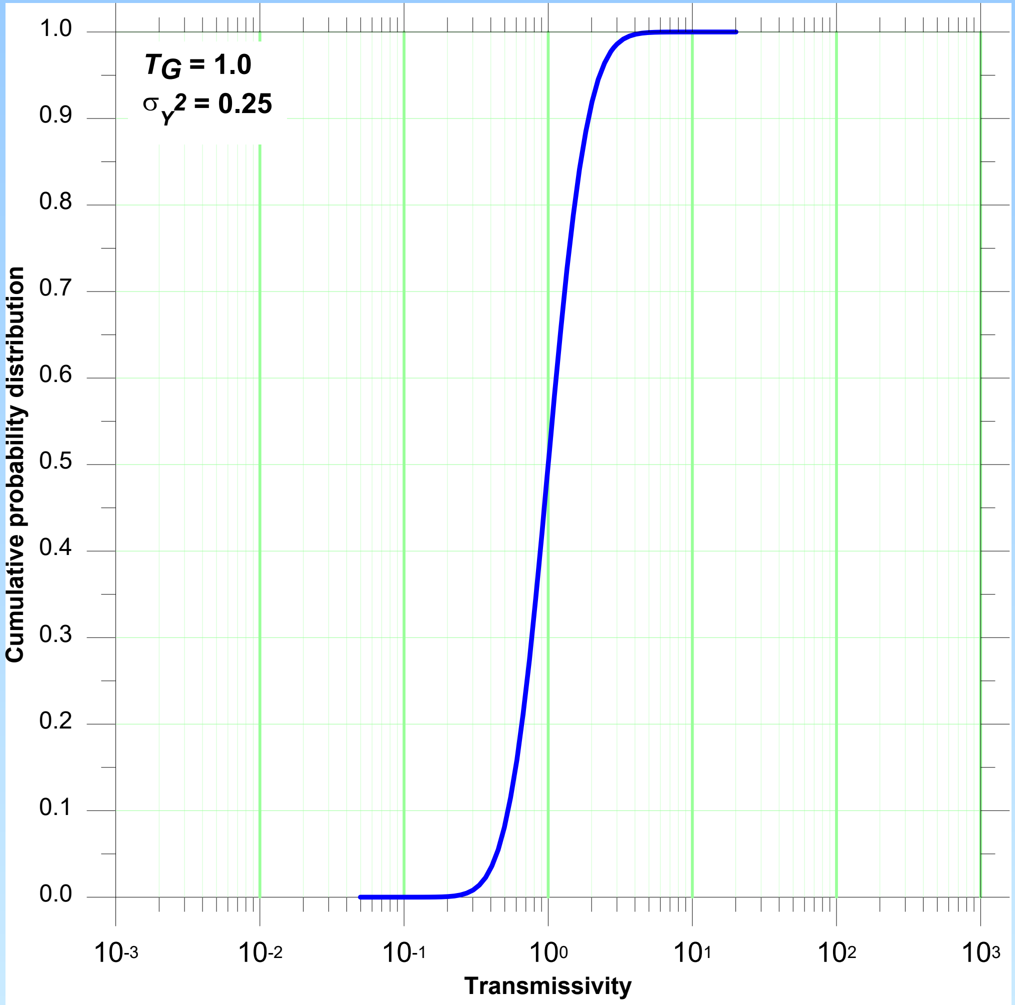
σ_y^2 = Variance of the log-transmissivity

Cumulative probability plot for transmissivity

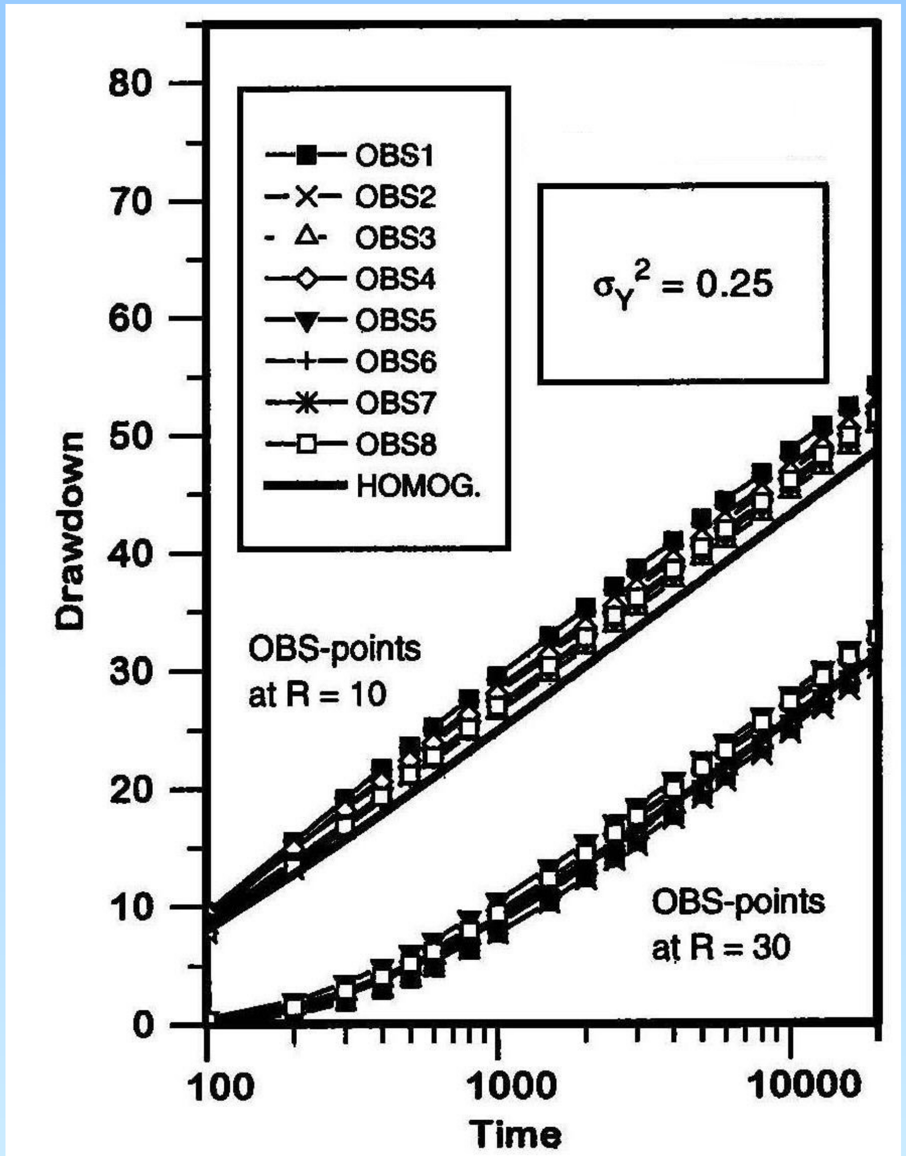
Case 1

$T_G = 1.0$

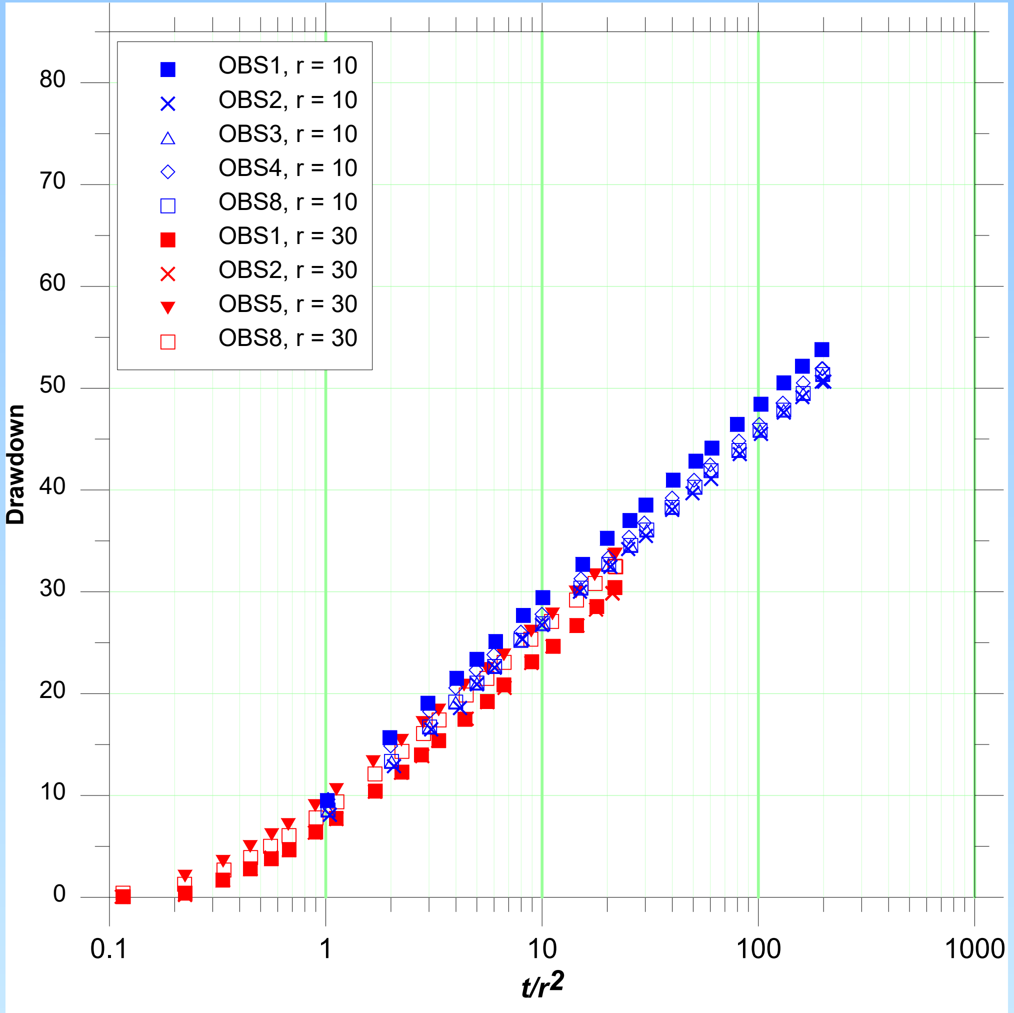
$\sigma_y^2 = 0.25$

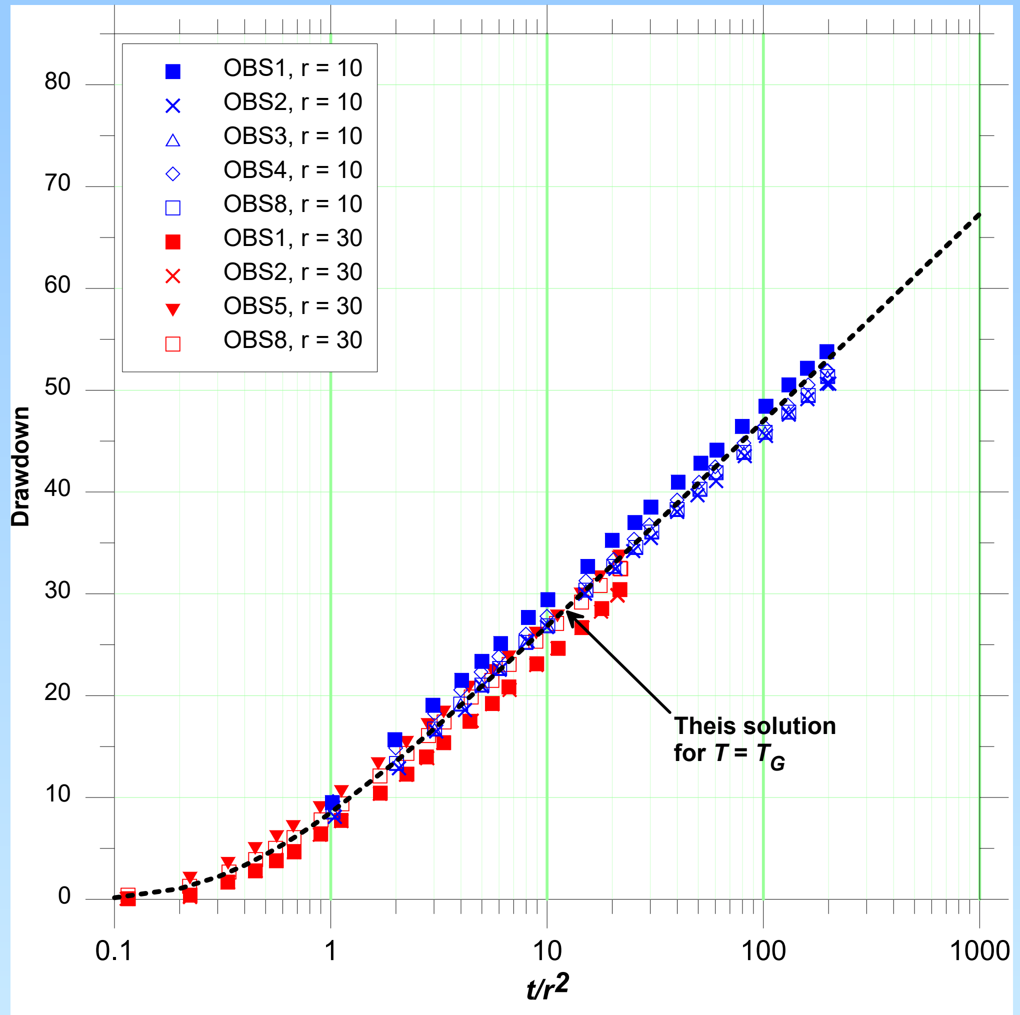


Simulated drawdowns



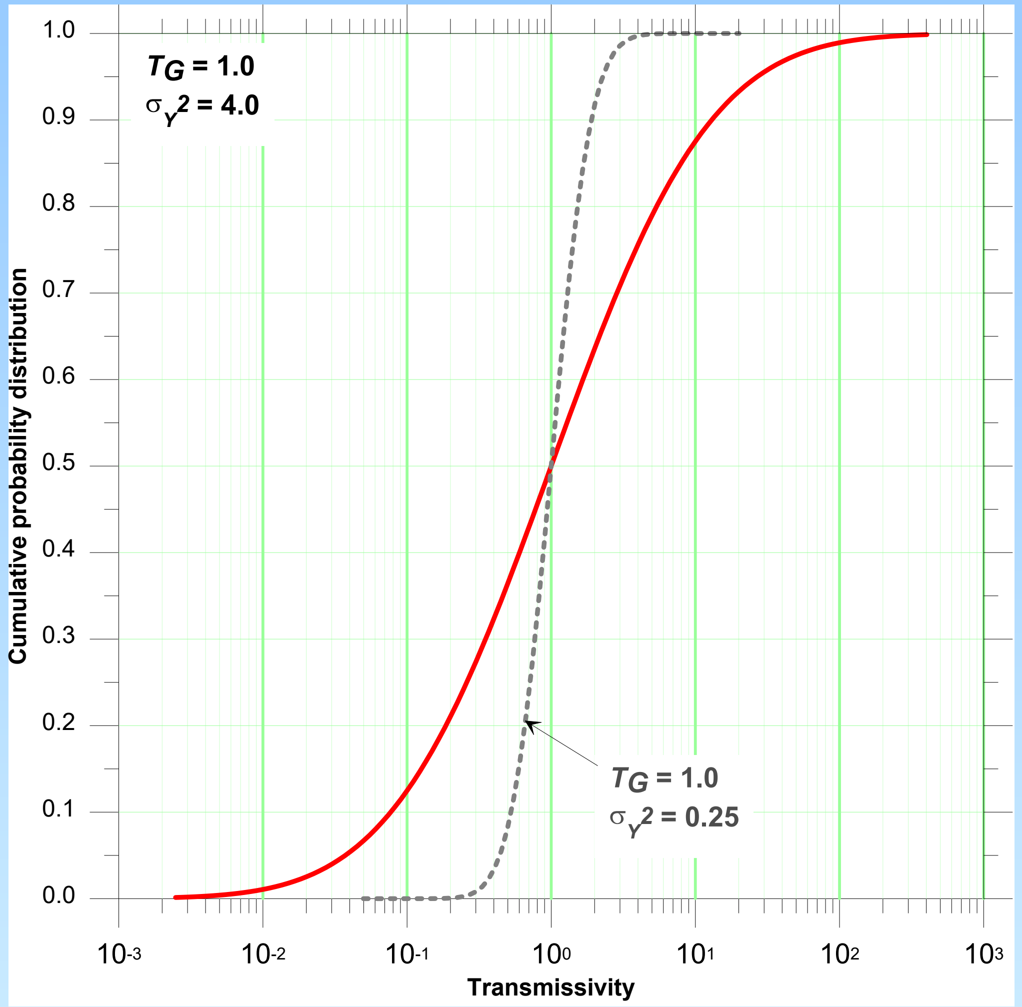
Simulated drawdowns on a composite plot



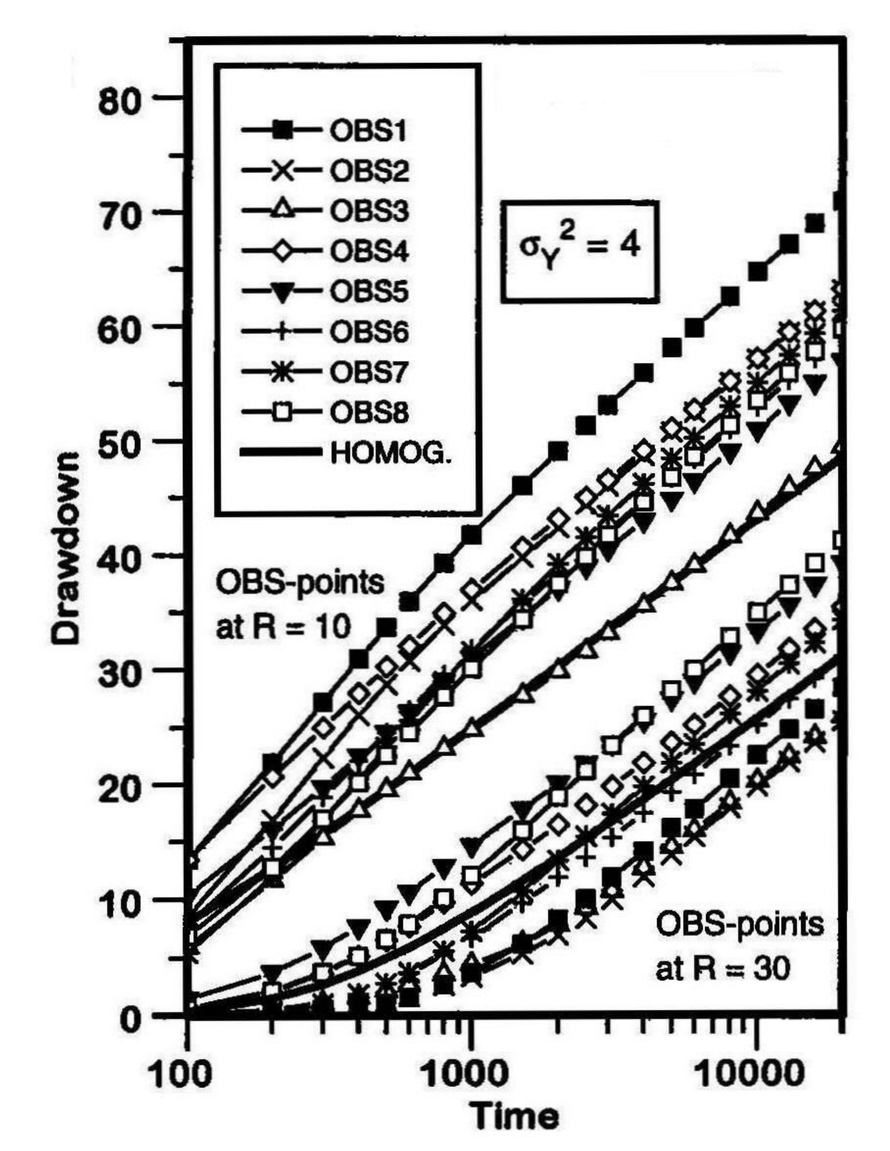

OBS1, r = 10
OBS2, r = 10
OBS3, r = 10
OBS4, r = 10
OBS8, r = 10
OBS1, r = 30
OBS2, r = 30
OBS5, r = 30
OBS8, r = 30
Drawdown
0
10
20
30
40
50
60
70
80
0.1
1
10
100
1000
t/r^2
Theis solution
for $T = T_G$

Cumulative probability plot for transmissivity

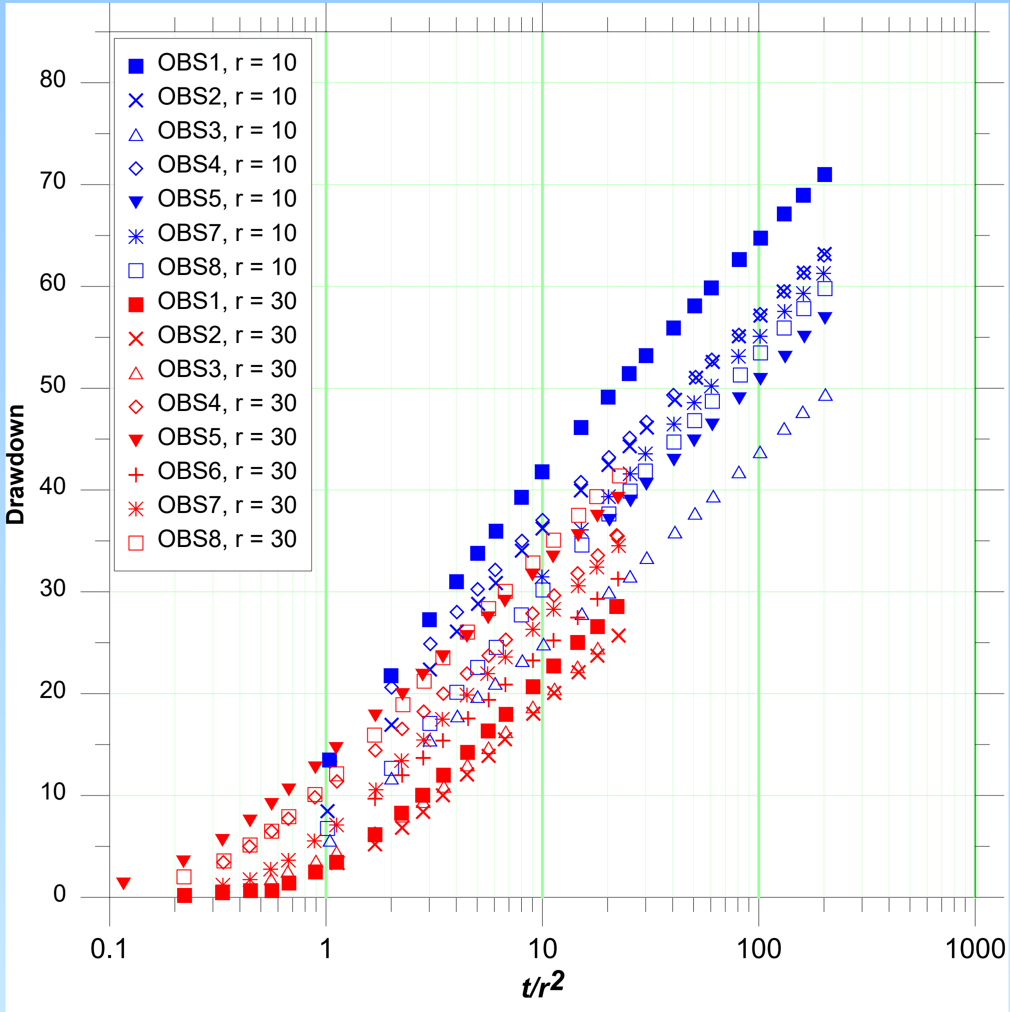
Case 2
$T_G = 1.0$
$\sigma_y^2 = 4.0$ [>> 0.25 of Case 1]

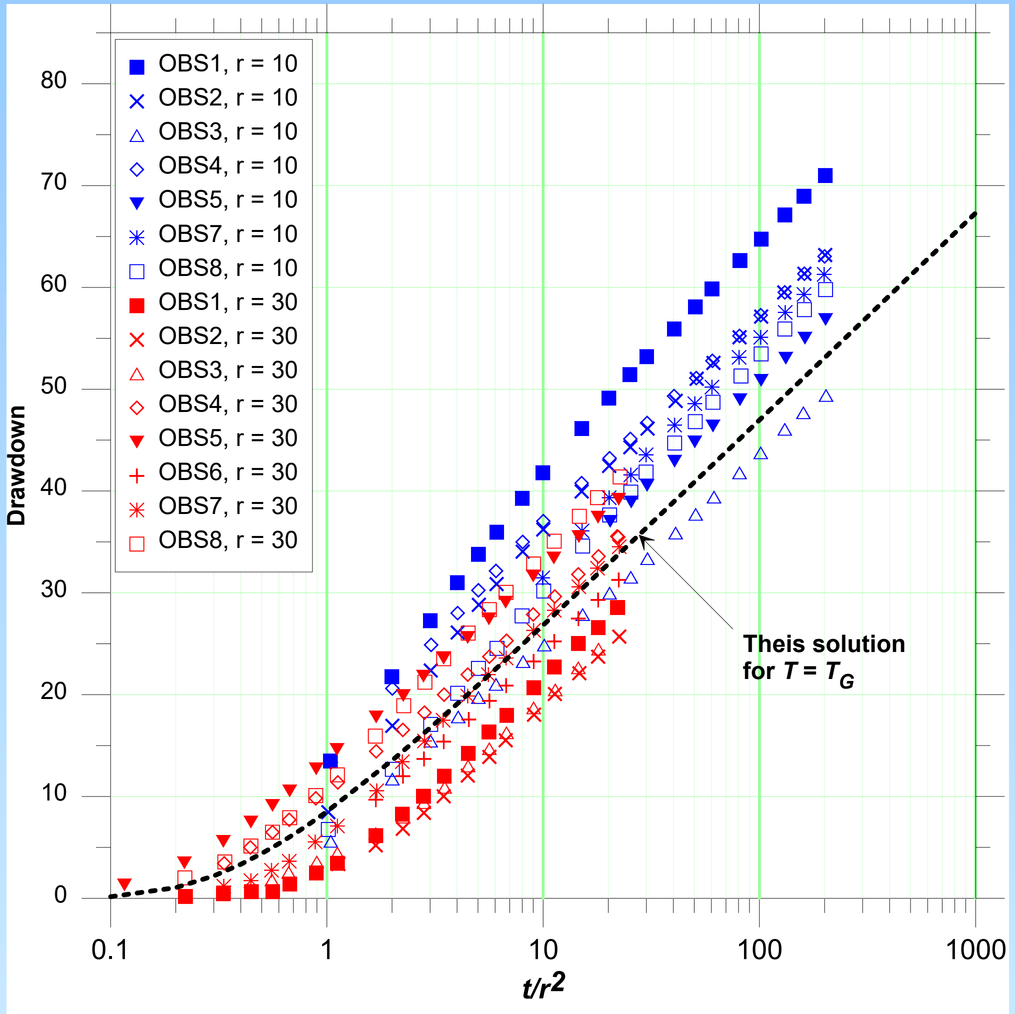


Simulated drawdowns



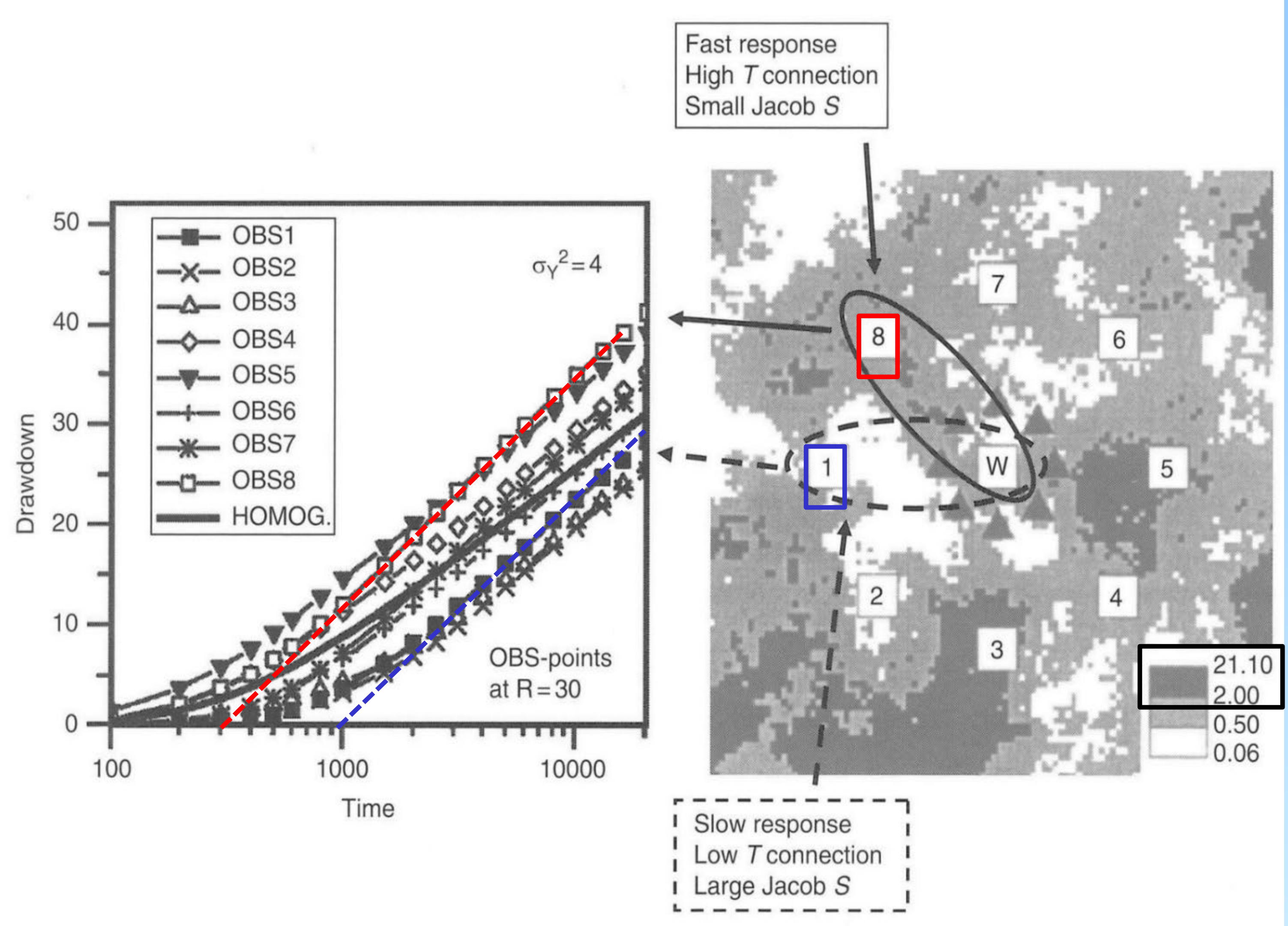
Simulated drawdowns on a composite plot





OBS1, r = 10
OBS2, r = 10
OBS3, r = 10
OBS4, r = 10
OBS5, r = 10
OBS7, r = 10
OBS8, r = 10
OBS1, r = 30
OBS2, r = 30
OBS3, r = 30
OBS4, r = 30
OBS5, r = 30
OBS6, r = 30
OBS7, r = 30
OBS8, r = 30
Drawdown
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
t/r2
Theis solution
for T = TG

Inference of hydraulic *connectivity*

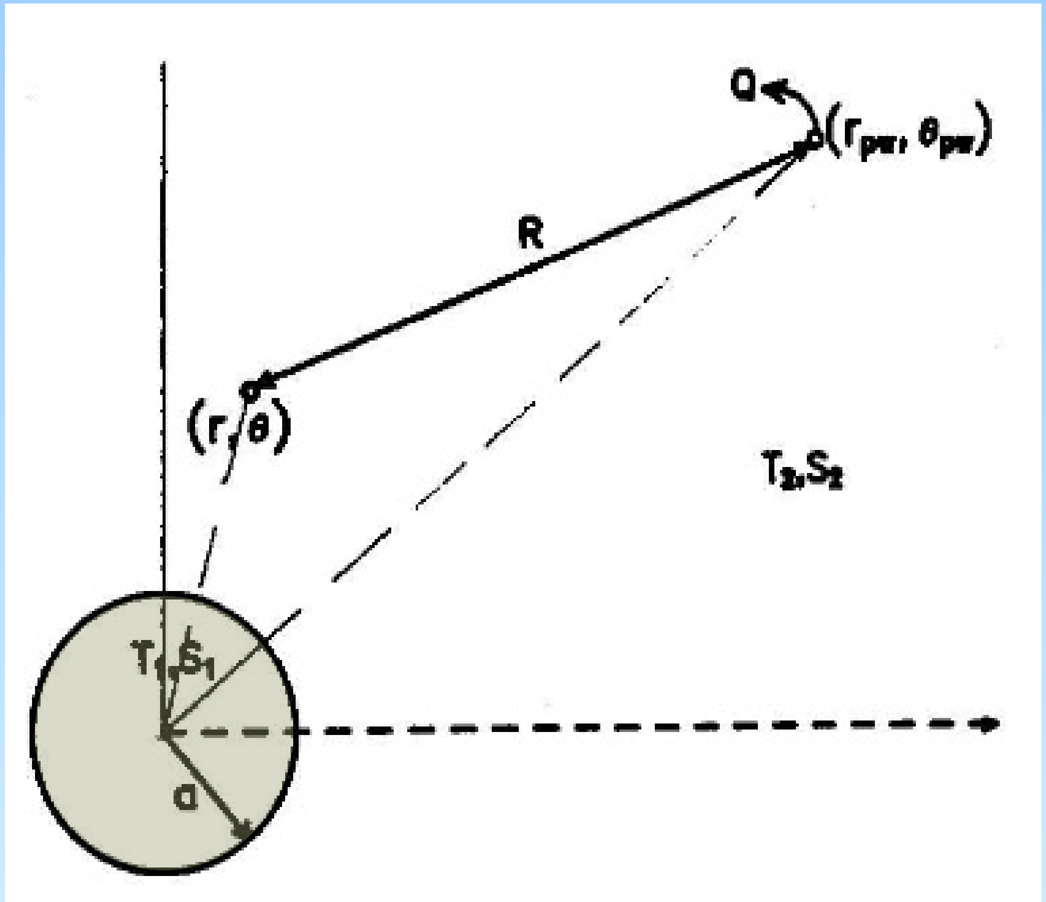


Conceptual model #1

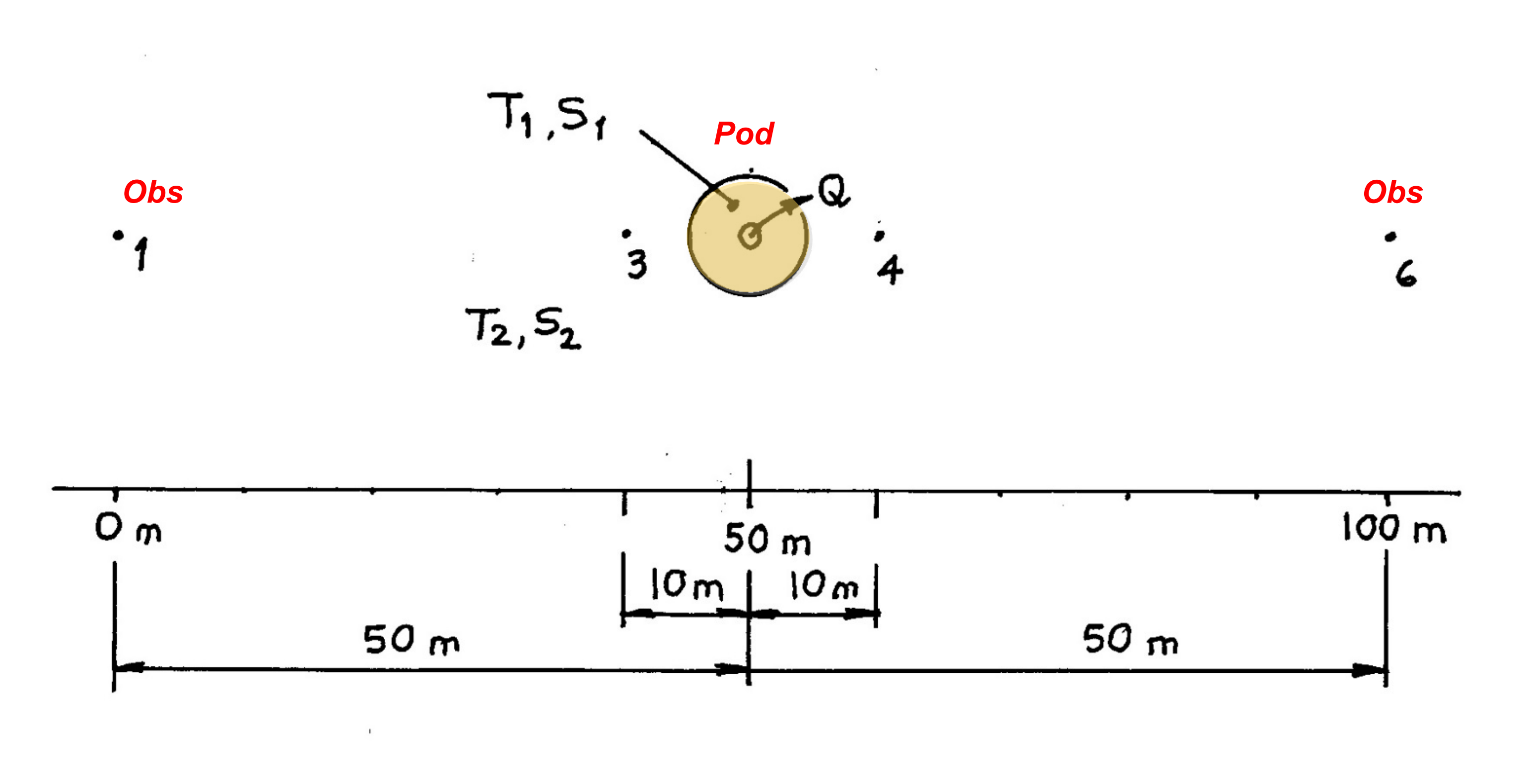
Tentative conclusion:

The results of the Meier and others (1998) simulations suggest that it may be possible to estimate an effective, *bulk-average*, transmissivity from a pumping test in a *homogeneously heterogeneous* aquifer, even for aquifers in which the degree of heterogeneity is relatively large.

Conceptual model #2: Zones of different transmissivity (*pods*) (Butler and Liu, 1993)



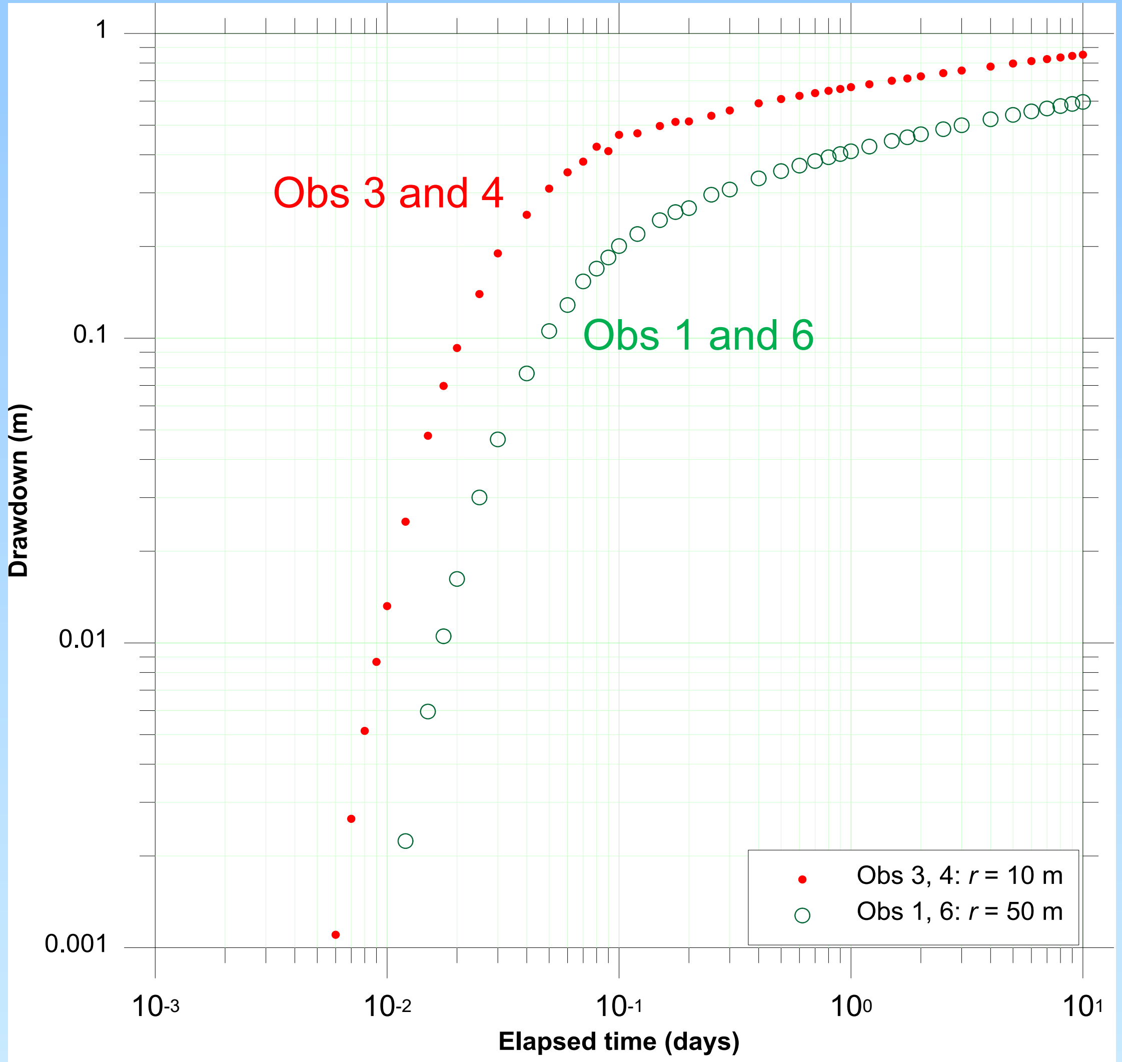
“Pod problem” #1



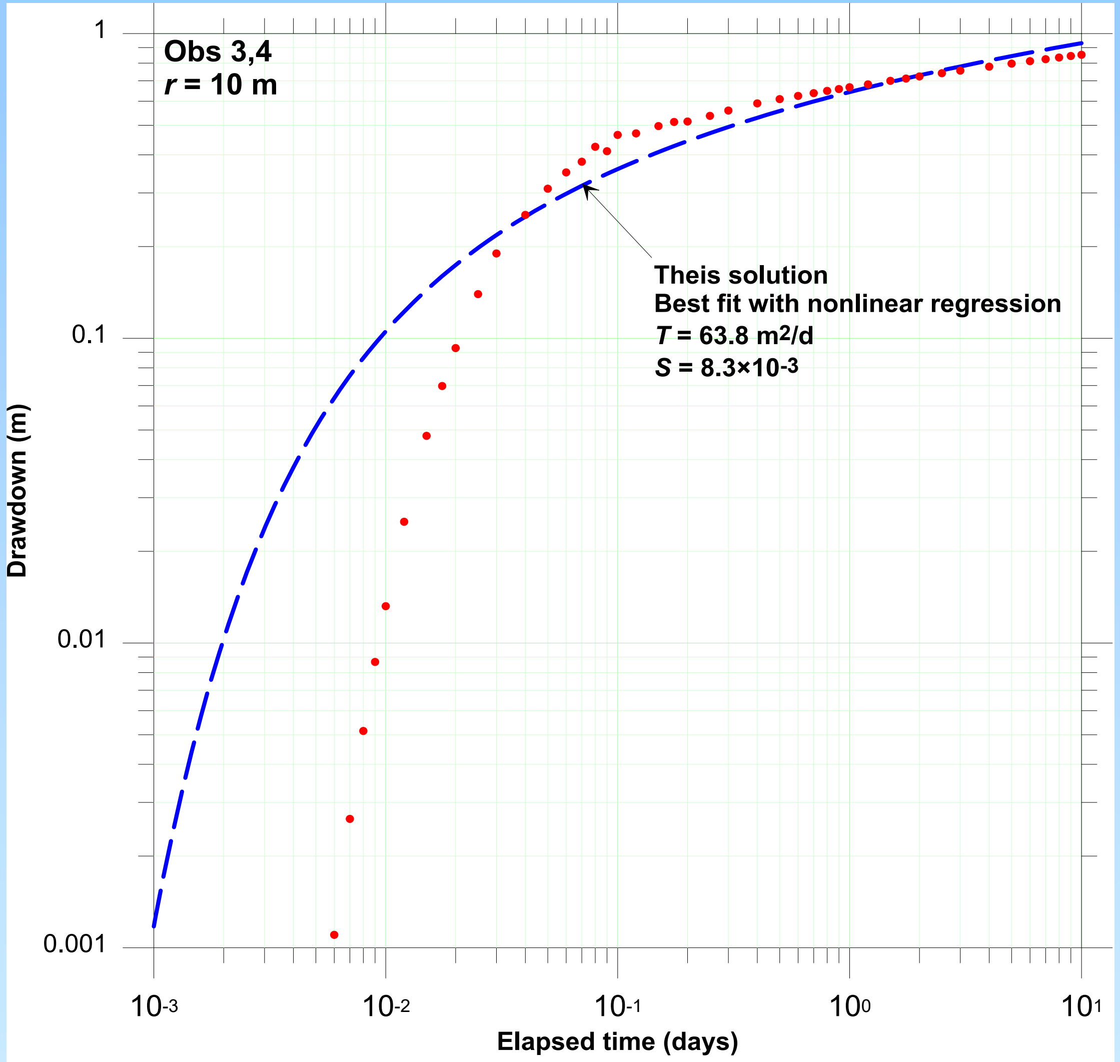
T_2 = 100 m^2/d [formation]

T_1 = 0.1 m^2/d [pod containing the pumping well]

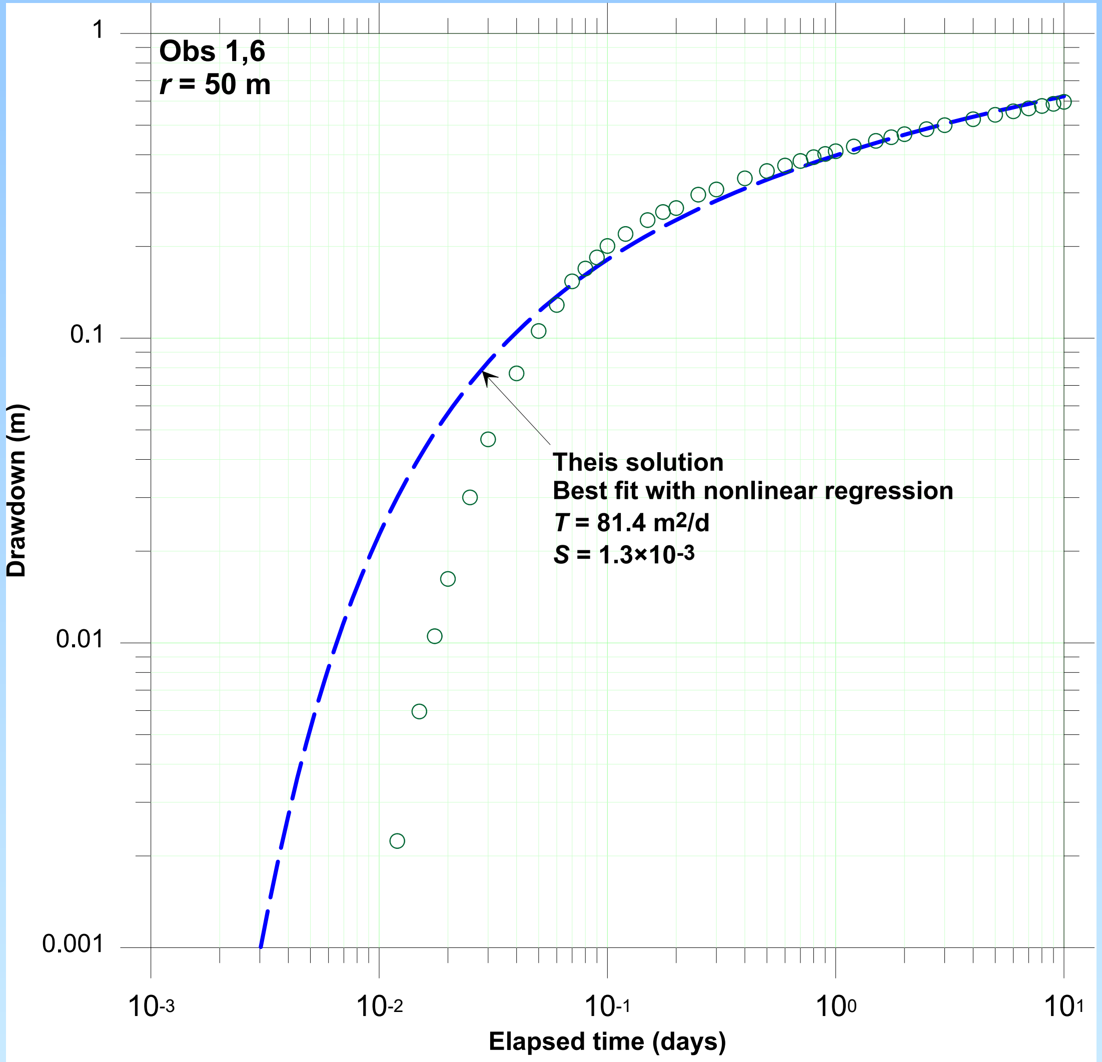
Individual time-drawdown plots



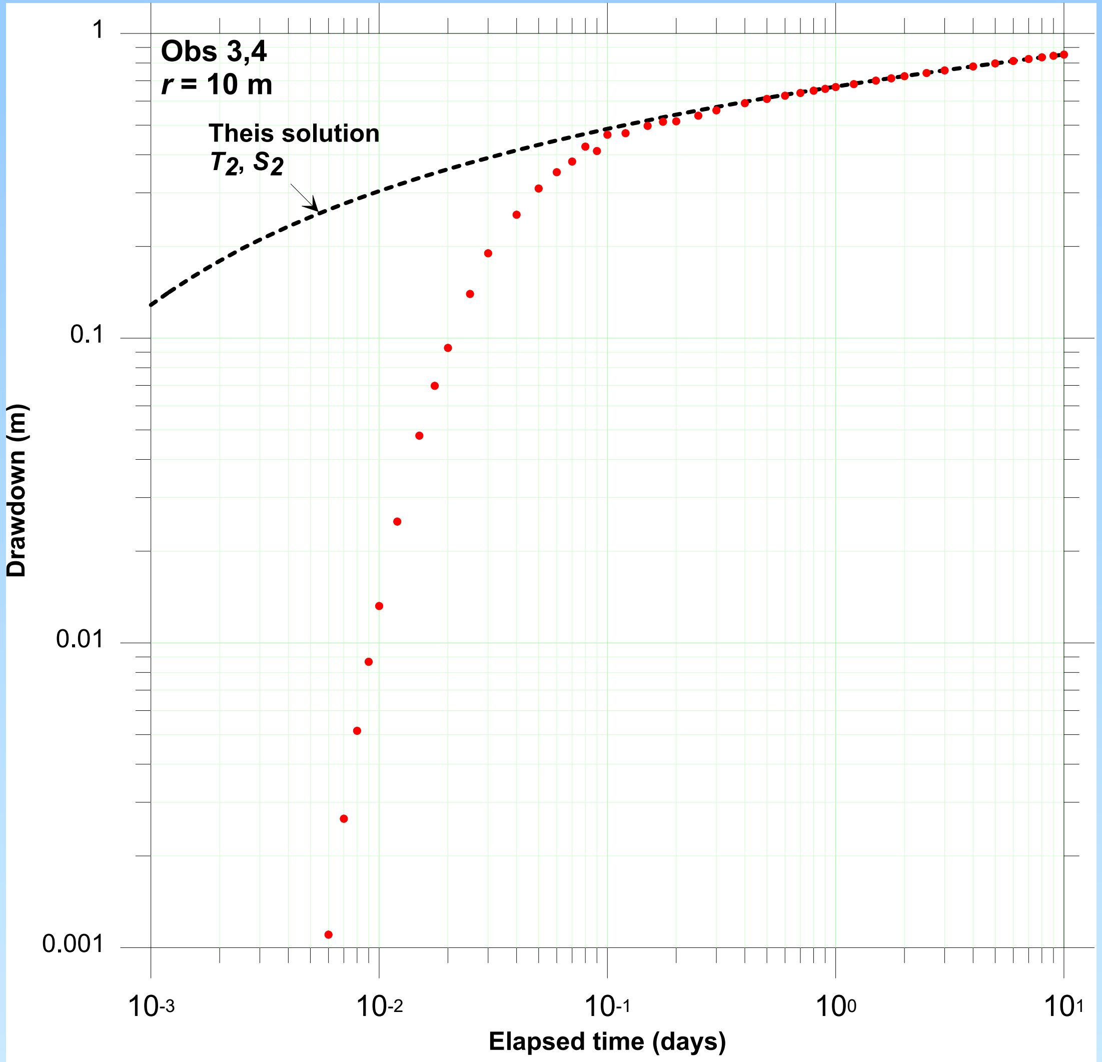
Theis analysis (Naïve approach, Part 1)



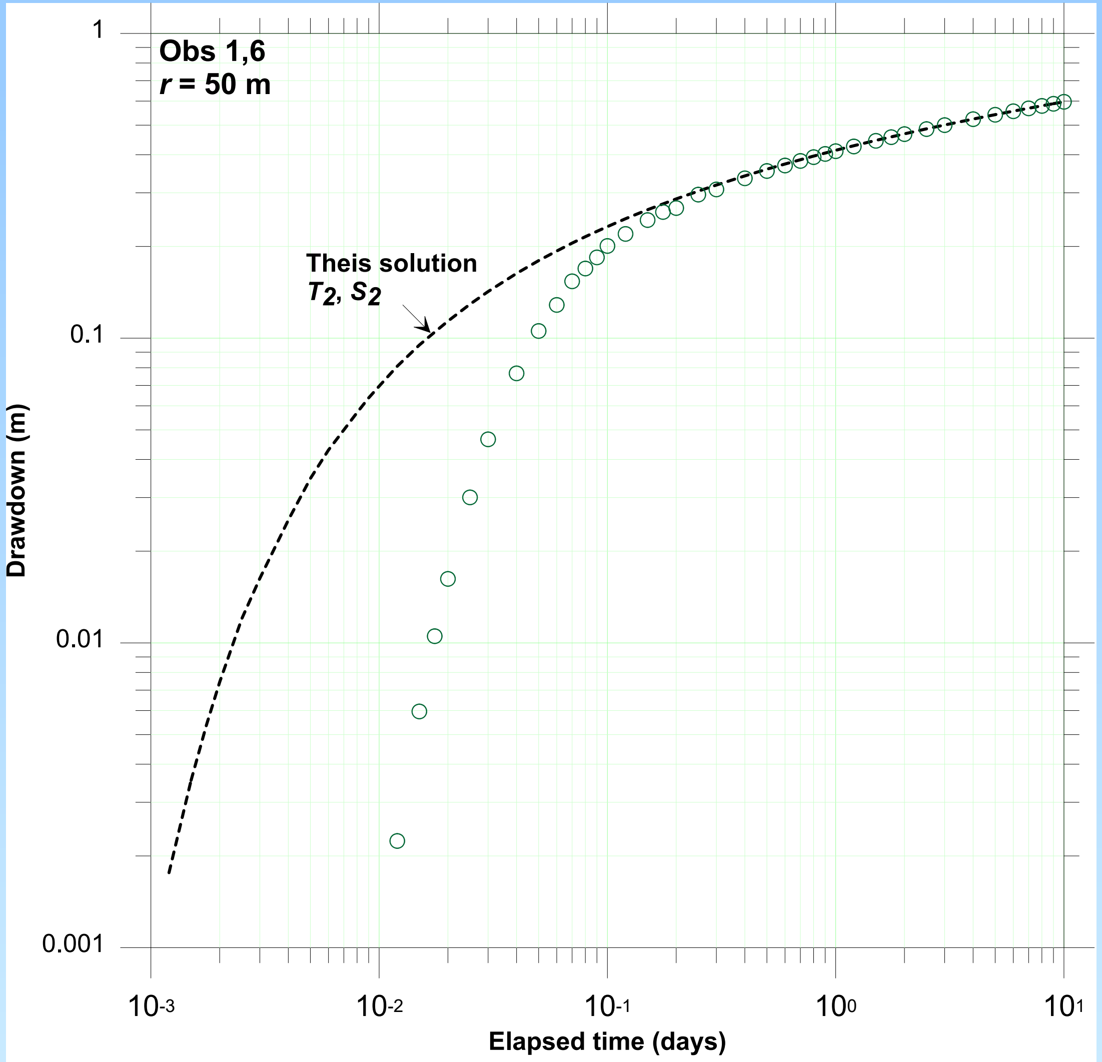
Theis analysis (Naïve approach, Part 2)



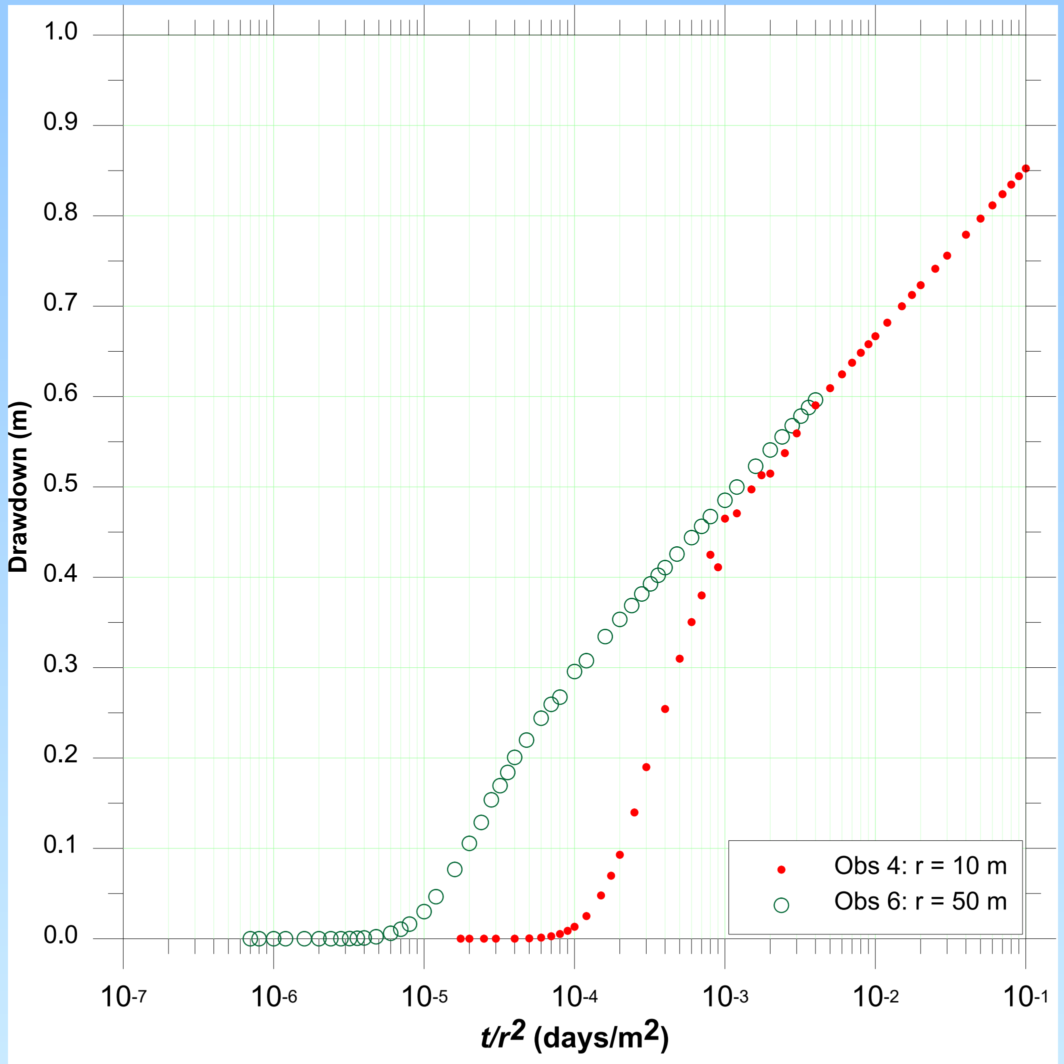
Theis analyses with formation properties (Answer at the back of the book)



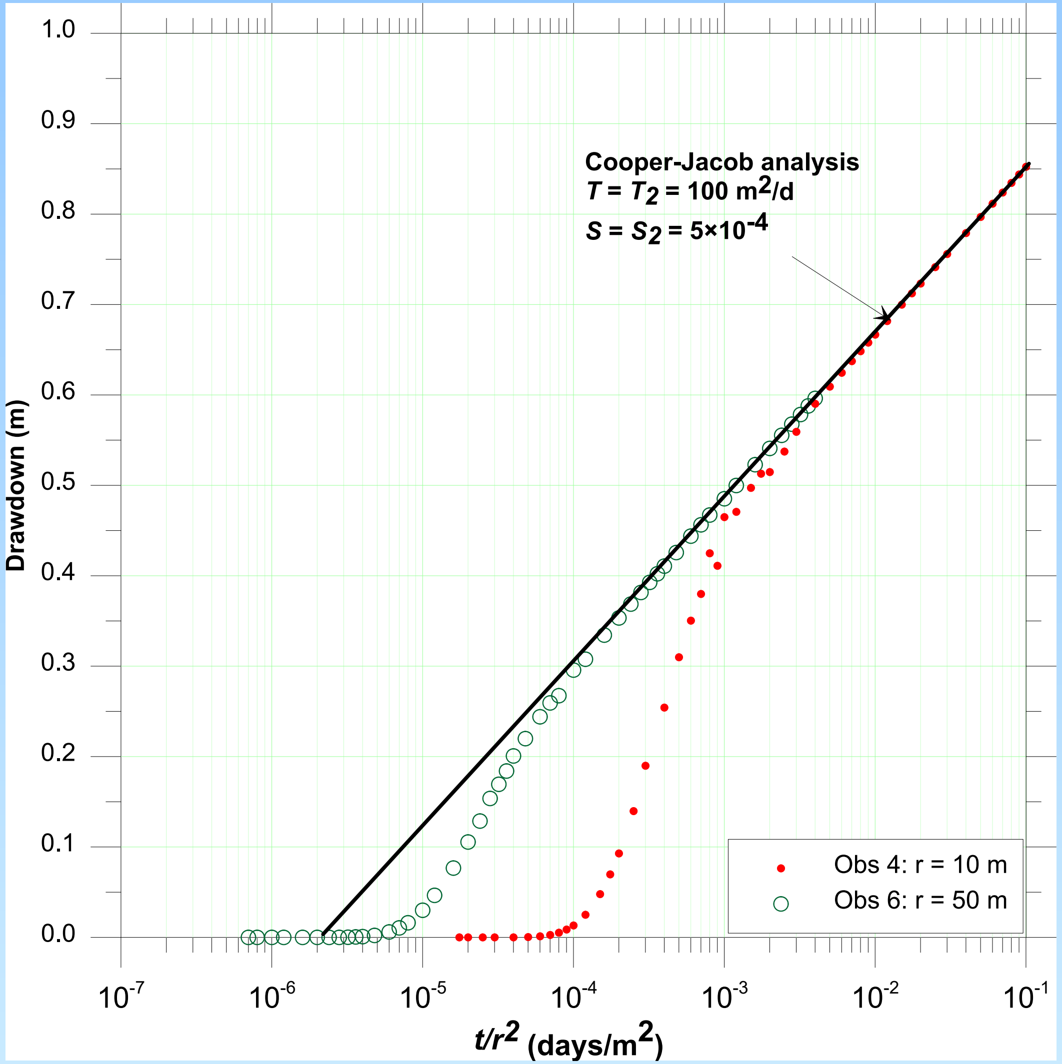
Theis analyses with formation properties (Answer at the back of the book, Part 2)



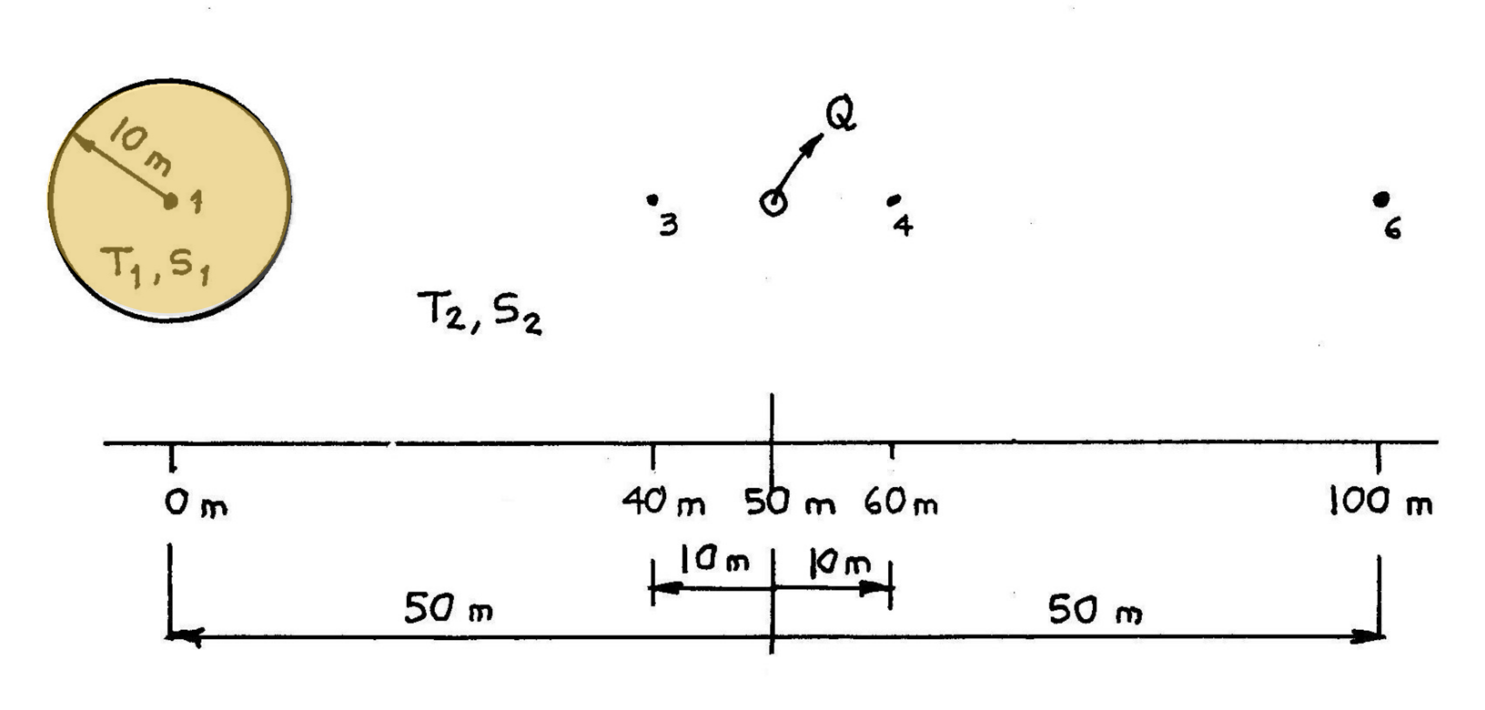
Semilog composite plot



Cooper-Jacob analysis



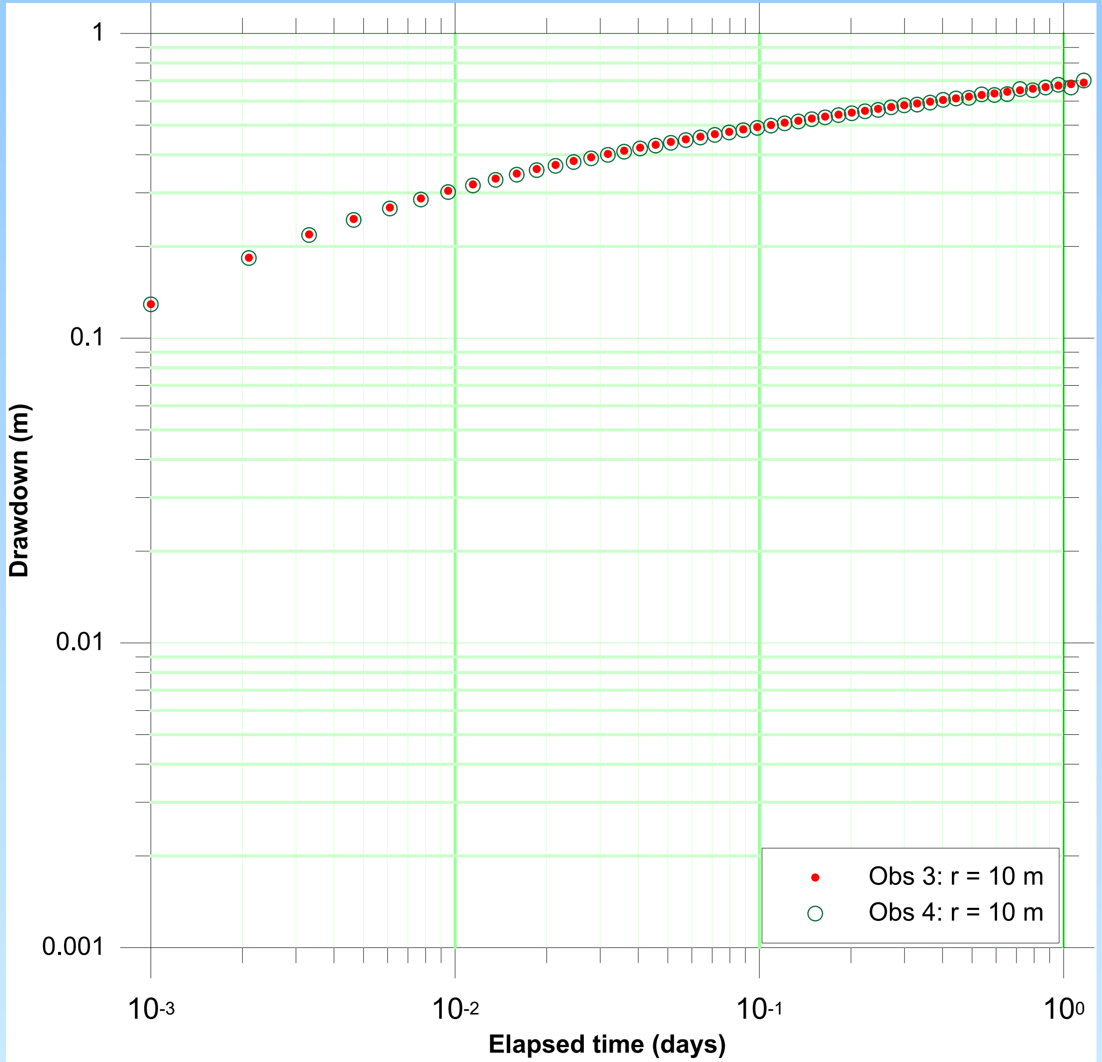
Pod problem #2



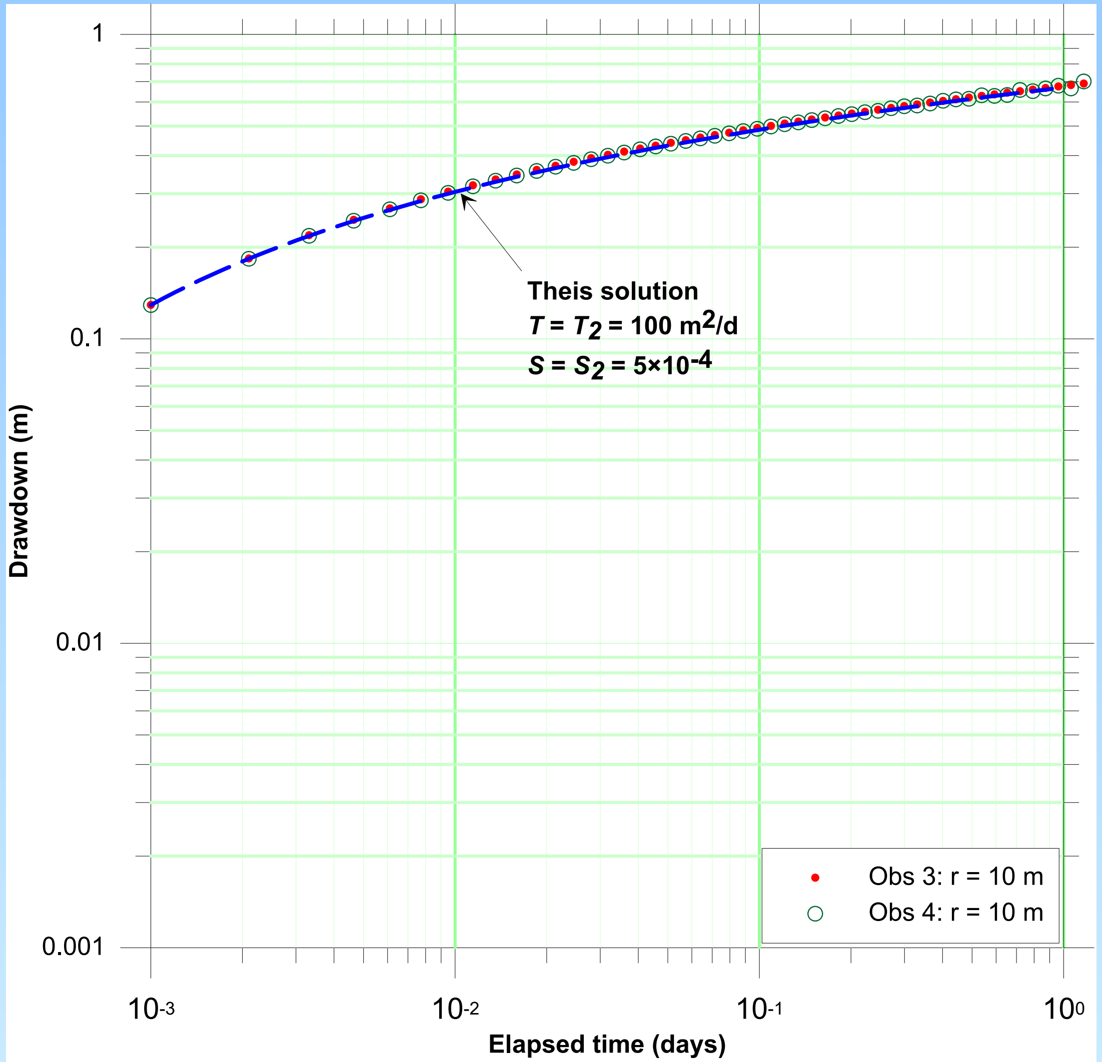
T_2 = 100 m^2/d [formation]

T_1 = 0.1 m^2/d [pod containing Obs. Well #1]

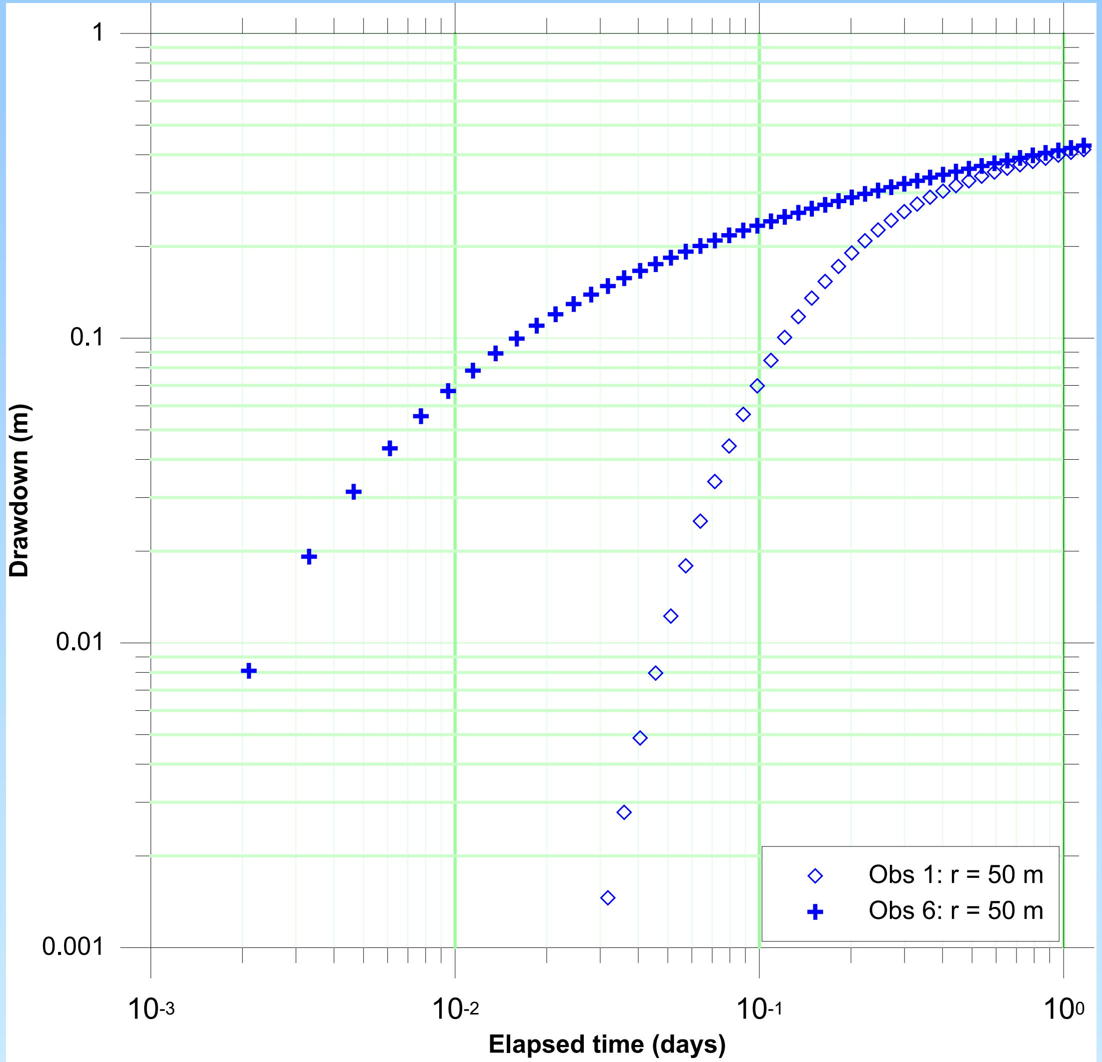
Observation wells at r = 10 m



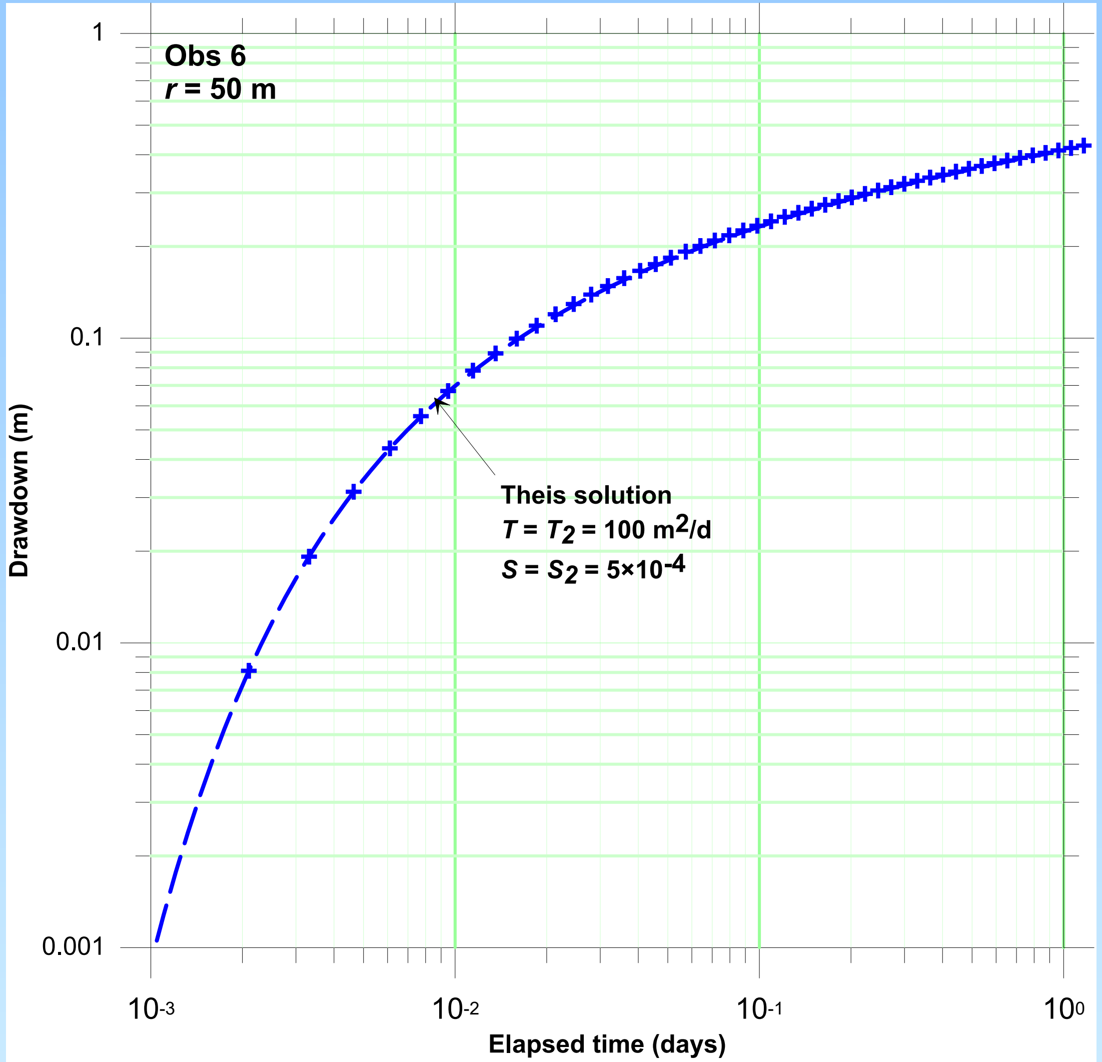
Match to observation wells at r = 10 m



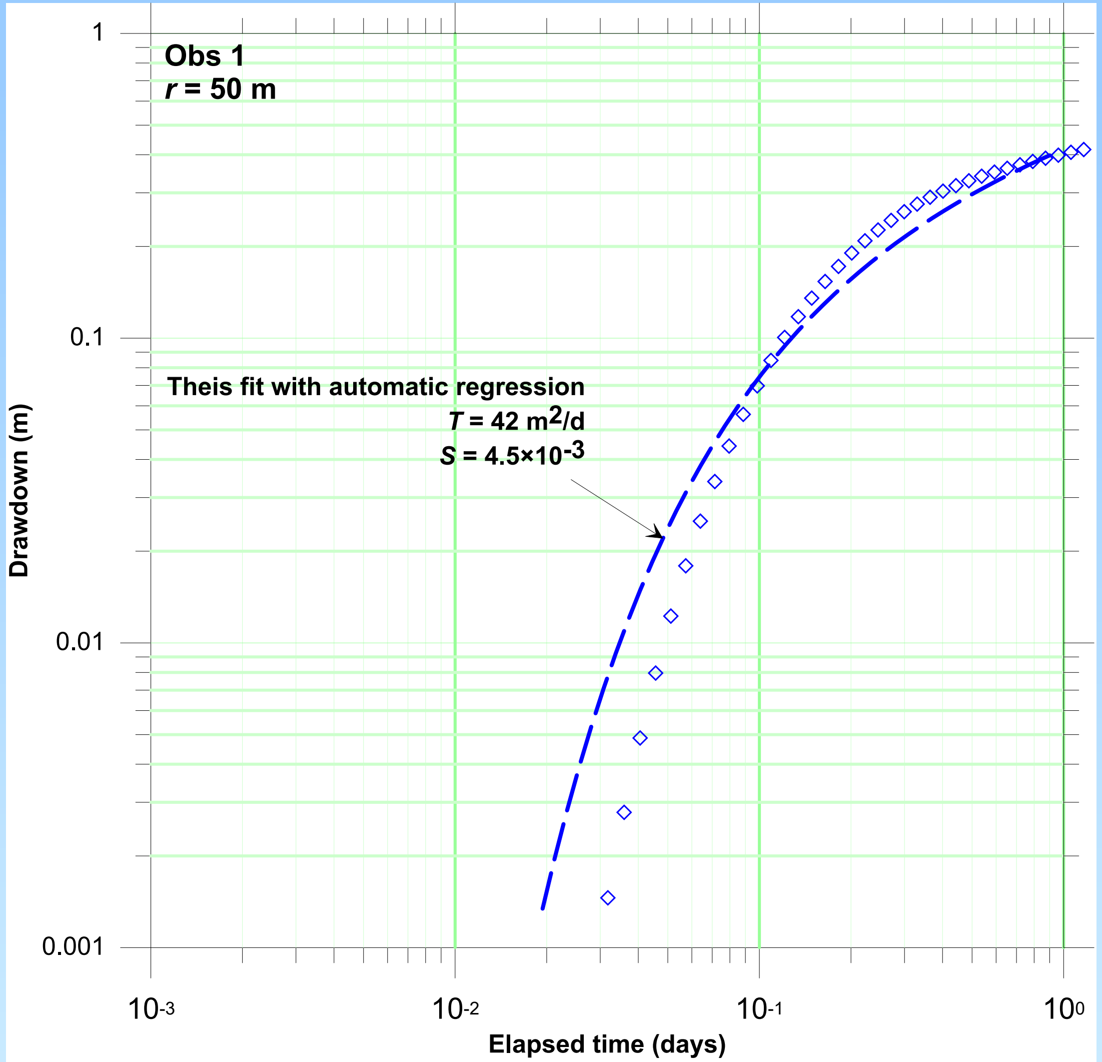
Observation wells at r = 50 m



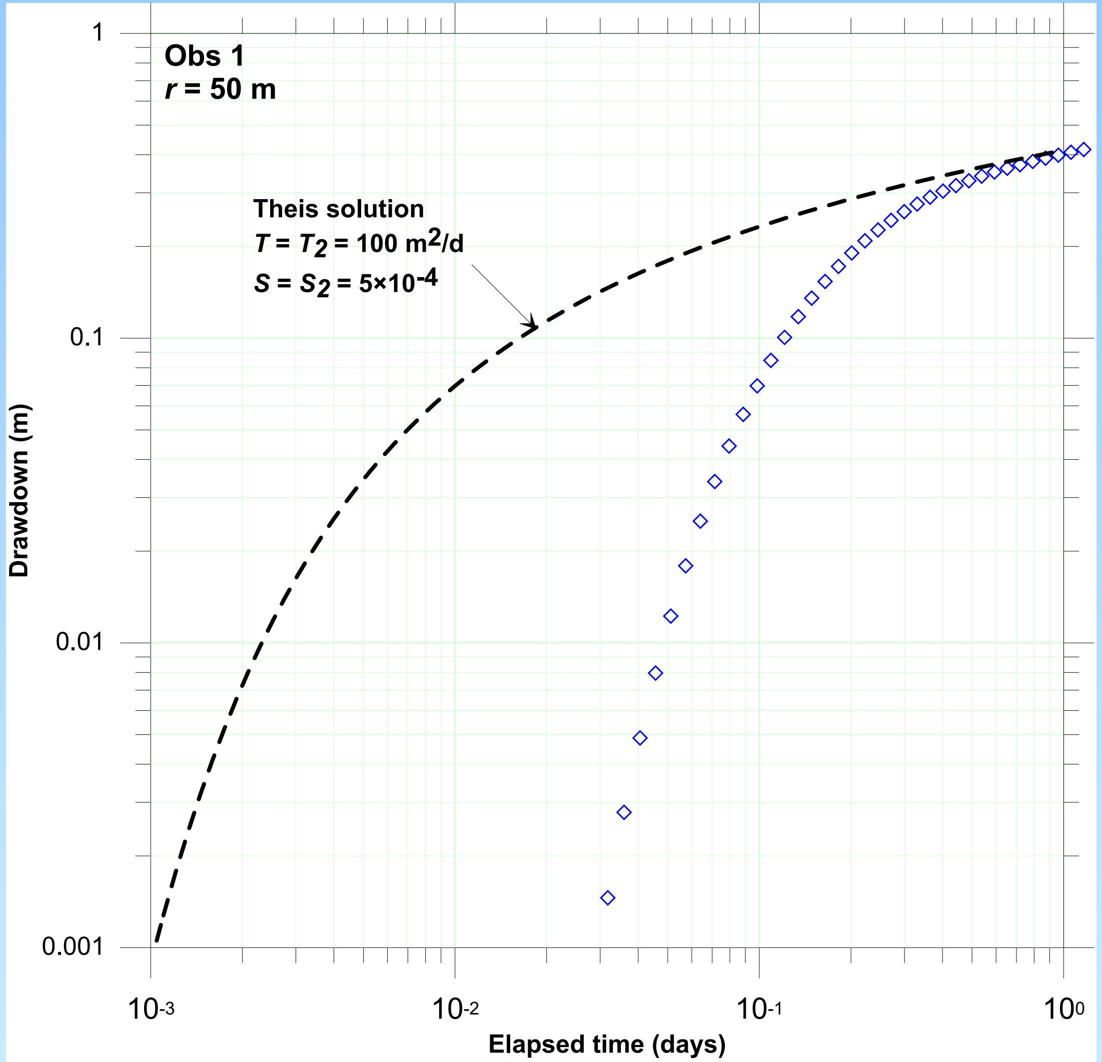
Match to observation well Obs 6



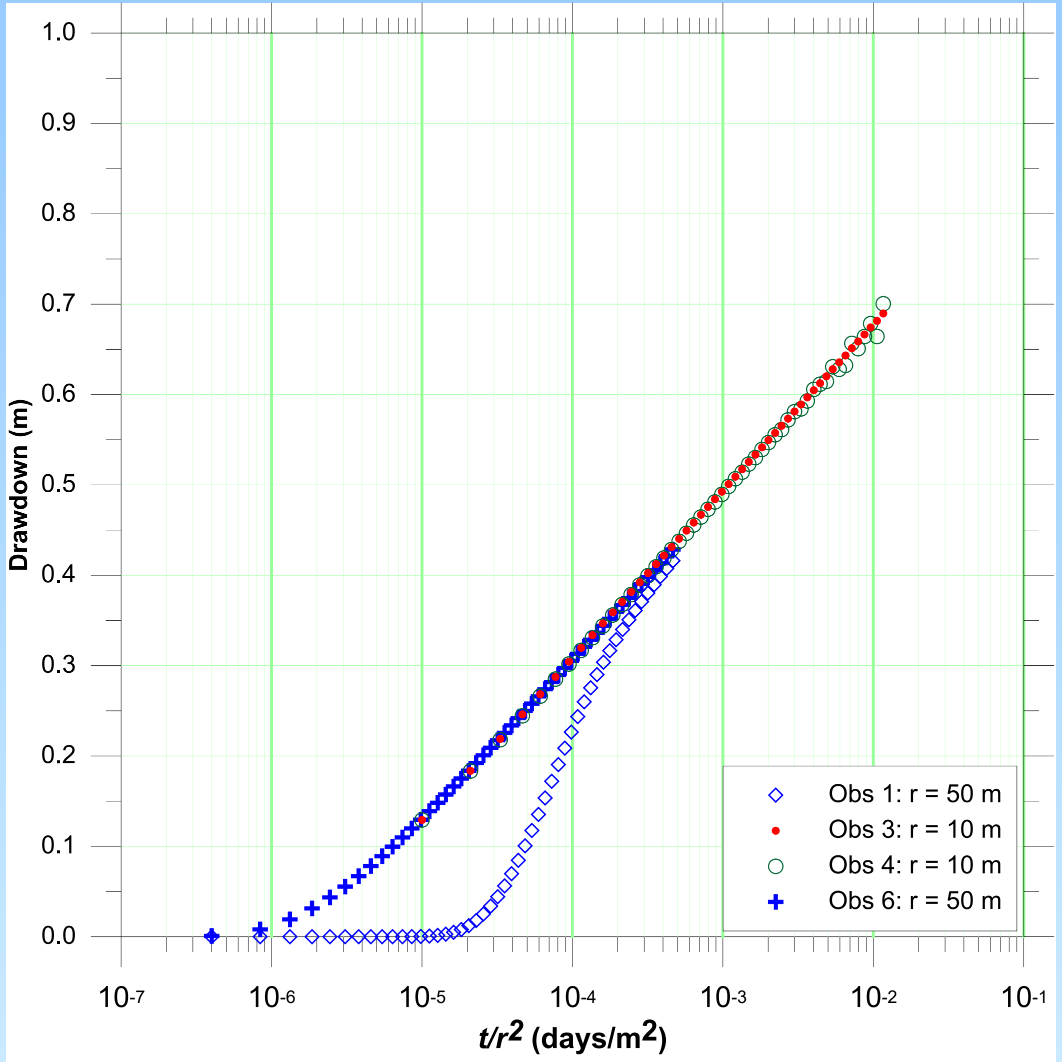
Match to observation well Obs 1



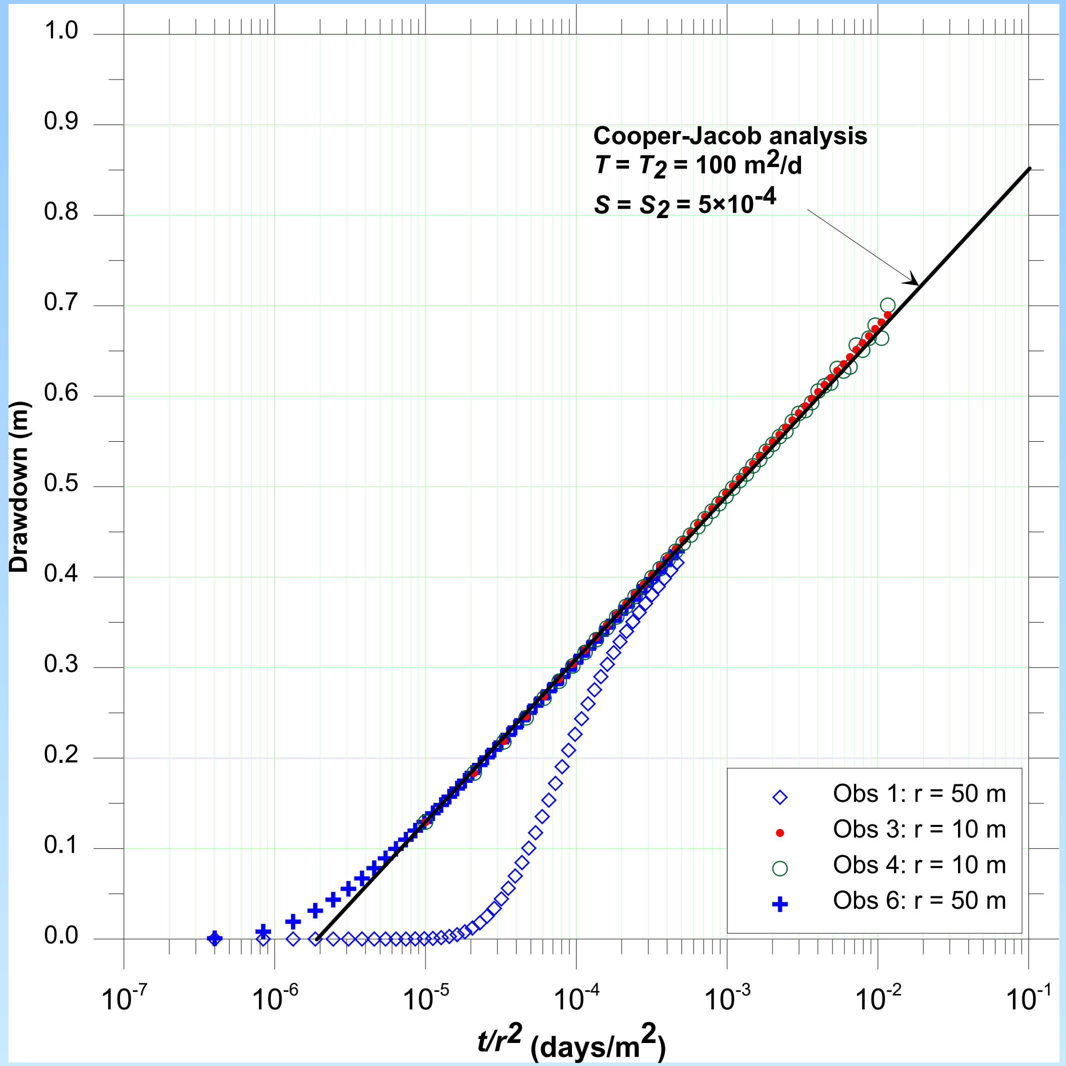
Obs 1: Theis model, formation properties



Semilog composite plot



Cooper-Jacob analysis



Conceptual model #2

Pumping tests in aquifers with discrete zones

<u>Tentative conclusion</u>

In aquifers that contain distinct zones it may be possible to take advantage of the strengths of the Cooper-Jacob composite analysis to identify the portion of the response that is representative of bulk-average radial flow, and to estimate a representative transmissivity from that portion of the data.

Take home points (1)

1. Real aquifers are heterogeneous, but models of pumping tests are generally founded on the assumption of *homogeneity*.

2. The composite plot is the appropriate starting point for the interpretation of pumping tests with multiple observation wells in heterogeneous aquifers.

3. The composite plotting approach directs analysts to the recognition of the effects of heterogeneity <u>and</u> to the estimation of a bulk-average transmissivity.

Further reading

The Role of Pumping Tests in Site Characterization: Some Theoretical Considerations

by James J. Butler, Jr.[a]

Ground Water, vol. 28, no. 3, pp. 394-402 (1990)

Technical Commentary/

Pumping Tests for Aquifer Evaluation—Time for a Change?

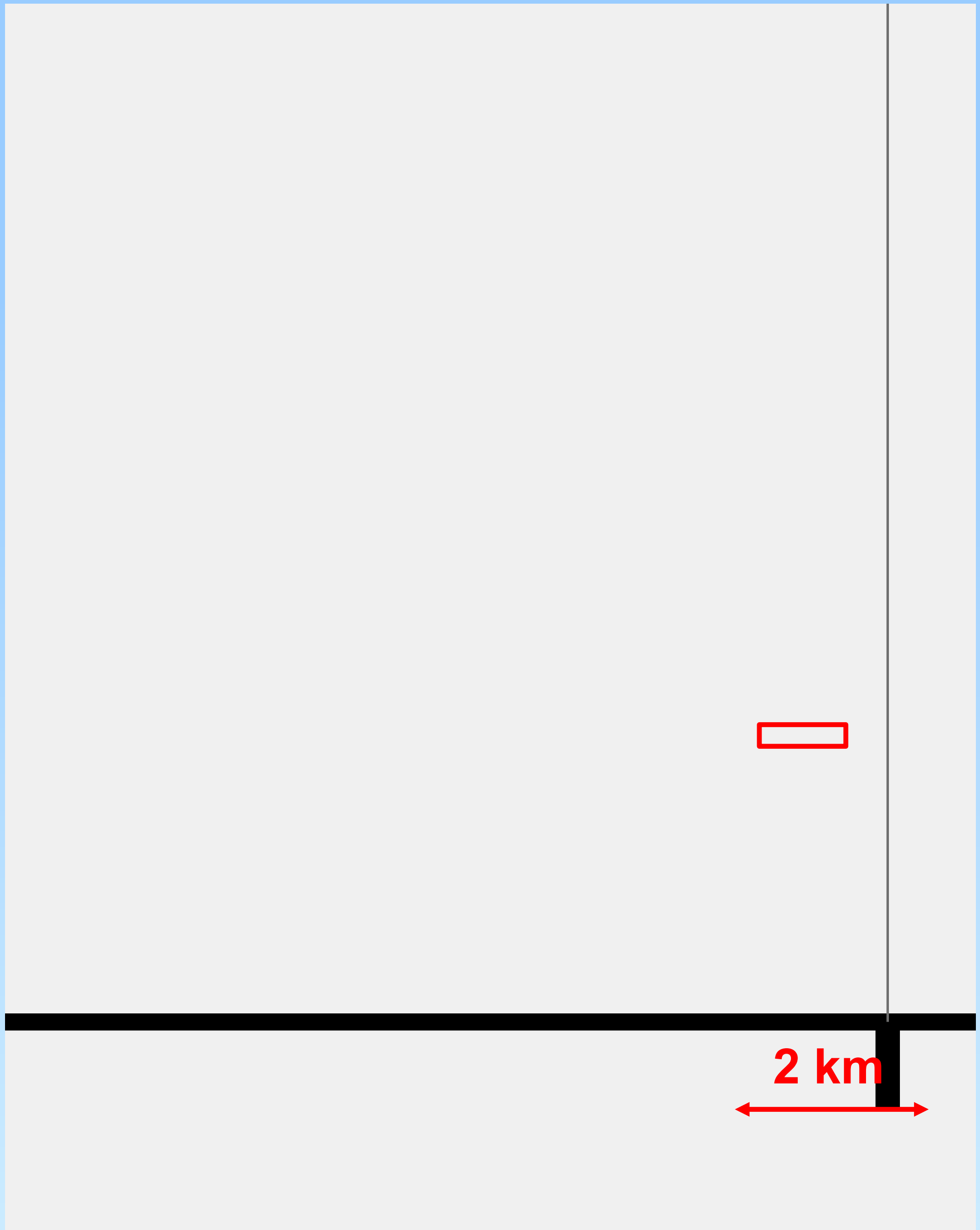
by James J. Butler Jr

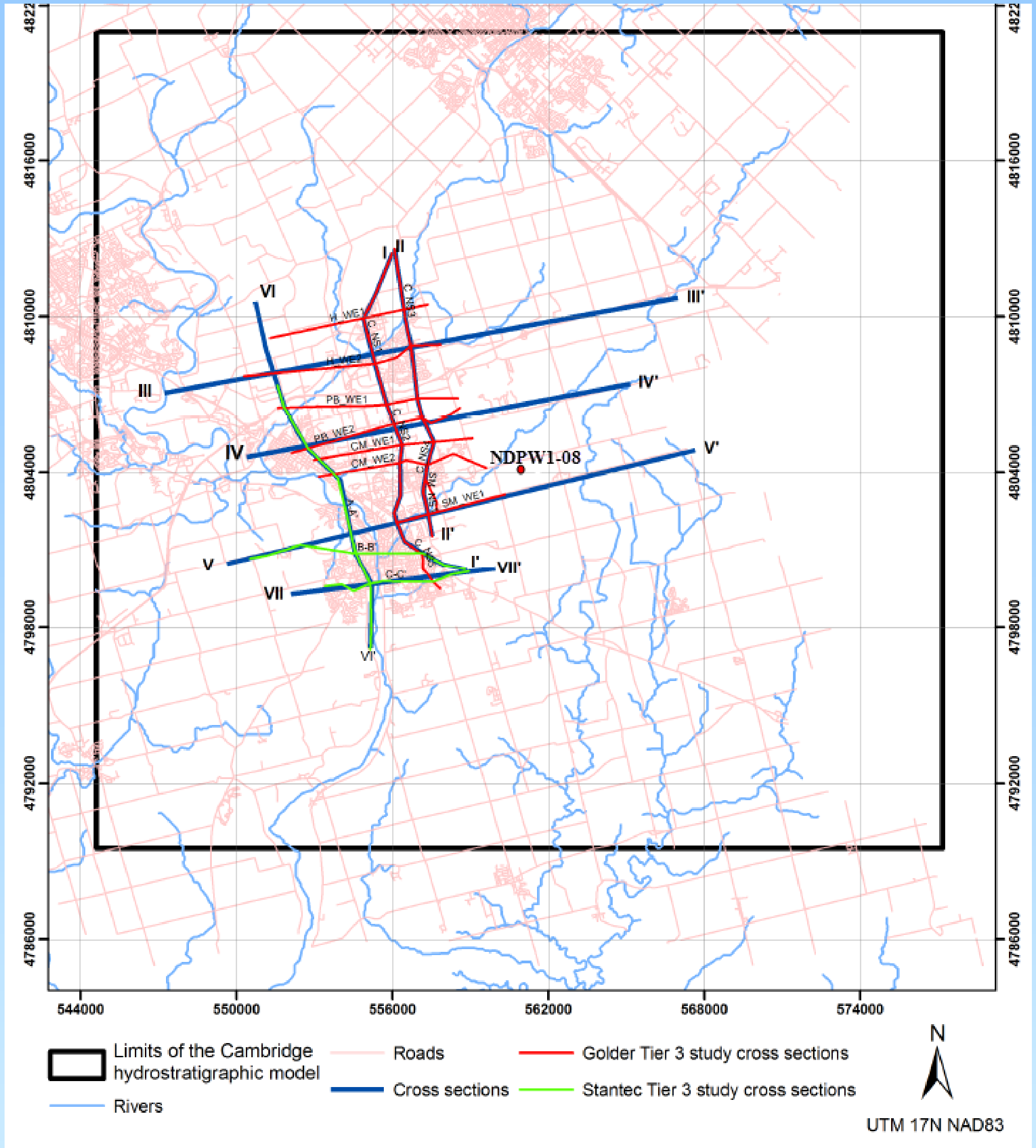
Ground Water, vol. 47, no. 5, pp. 615-617 (2009)

Case study: NDPW1-08

Testing of potential new municipal production well Cambridge, Ontario

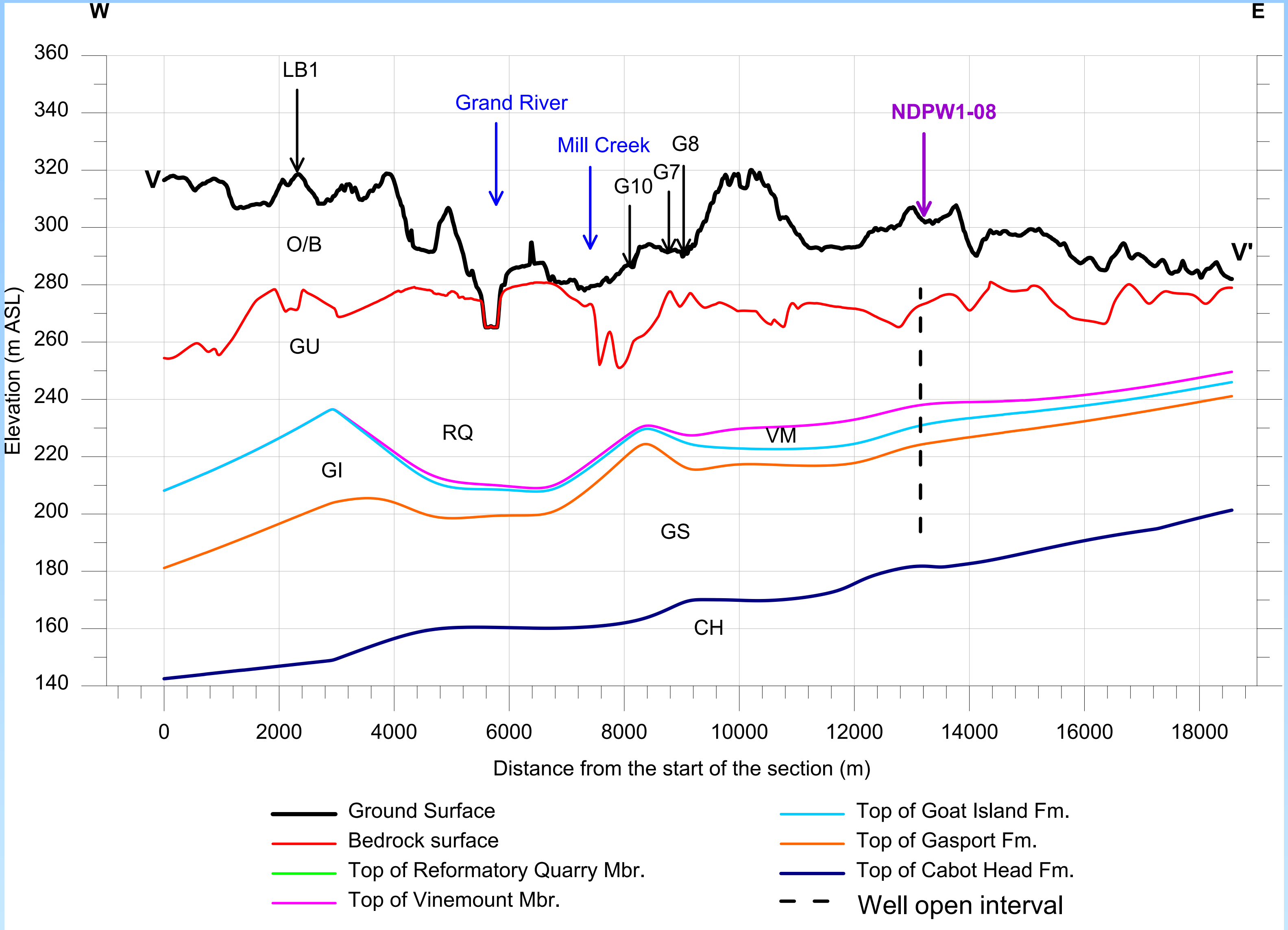

Lake Ontario
Acton Quarry
Proposed Flamborough Quarry
Cambridge East
Niagara Falls, NY
Coronation Blvd
Mohawk Rd
Wilson St W
Brant Ave
Colborne St E
Brant Rd
Victoria St N
Eramosa Rd
Tower St S
Gardiner Expy
Lakeshore Rd E
Lake Shore Blvd E
Allen Rd
Dundas St


2 km

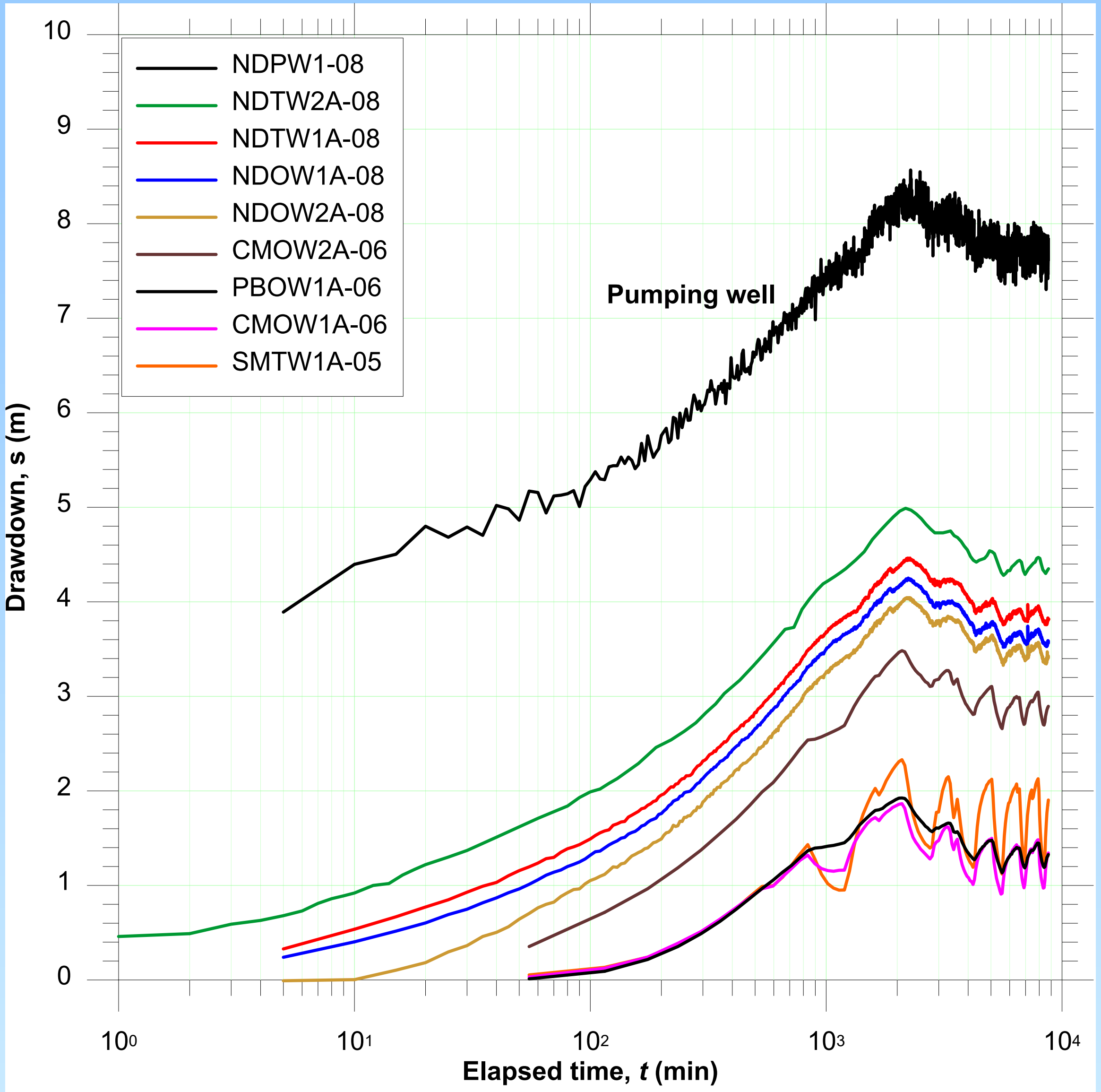


NDPW1-08
I
II
III
III'
IV
IV'
V
V'
VI
VI'
VII
VII'
I'
II'
544000
550000
556000
562000
568000
574000
4786000
4792000
4798000
4804000
4810000
4816000
Limits of the Cambridge hydrostratigraphic model
Rivers
Roads
Cross sections
Golder Tier 3 study cross sections
Stantec Tier 3 study cross sections
N
UTM 17N NAD83

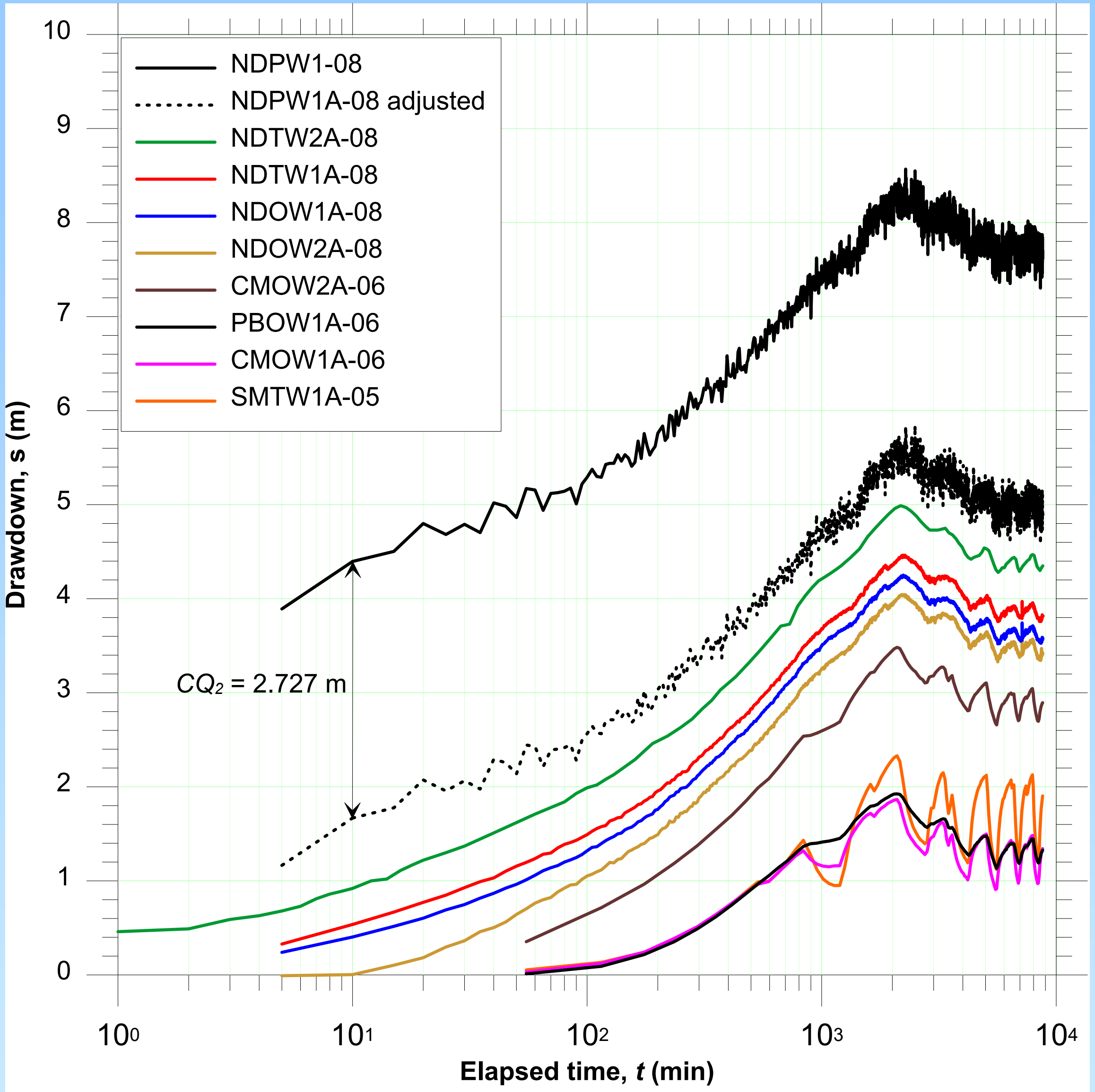
Stratigraphy



Time-drawdown plots

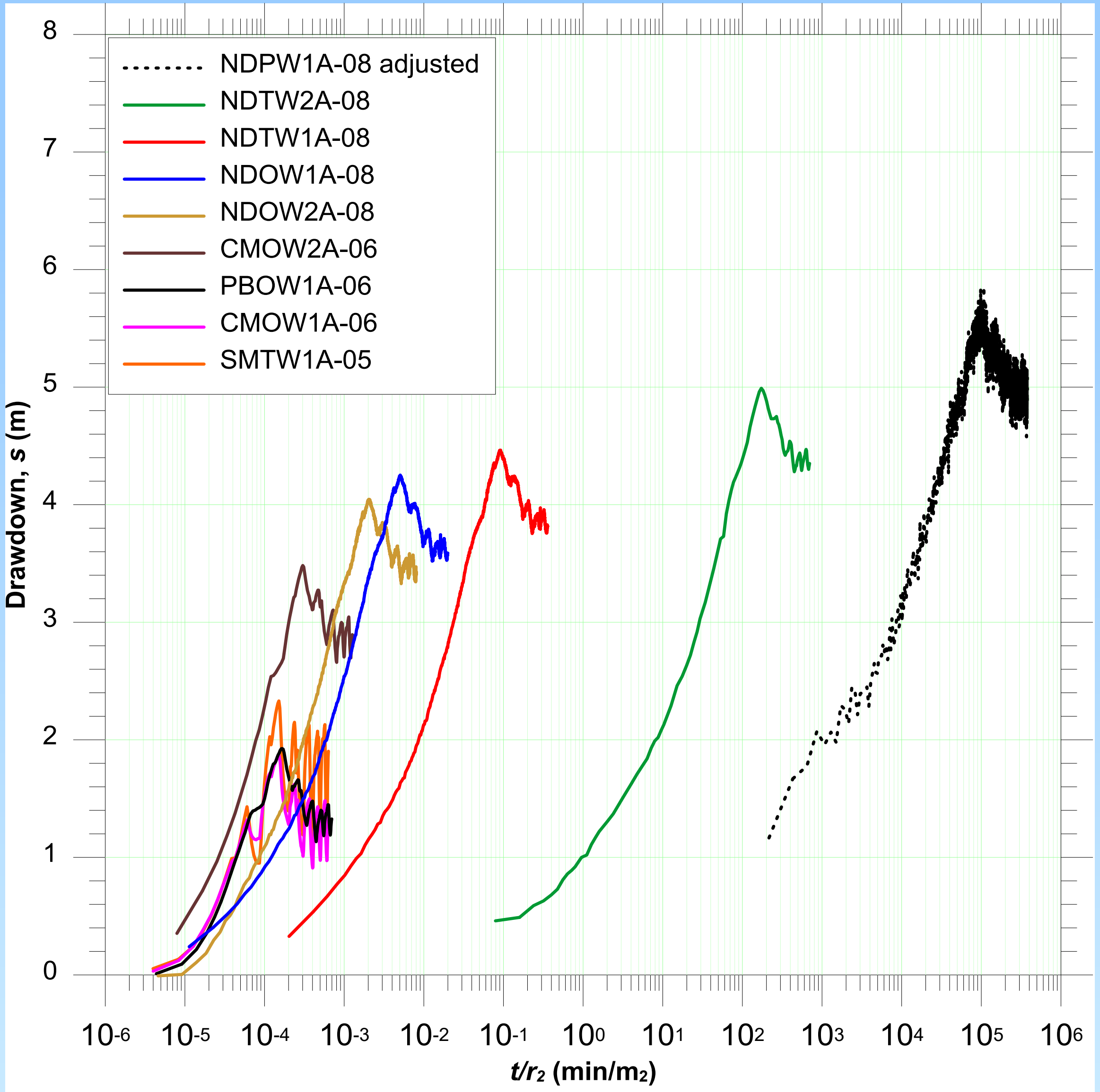


Time-drawdown plots

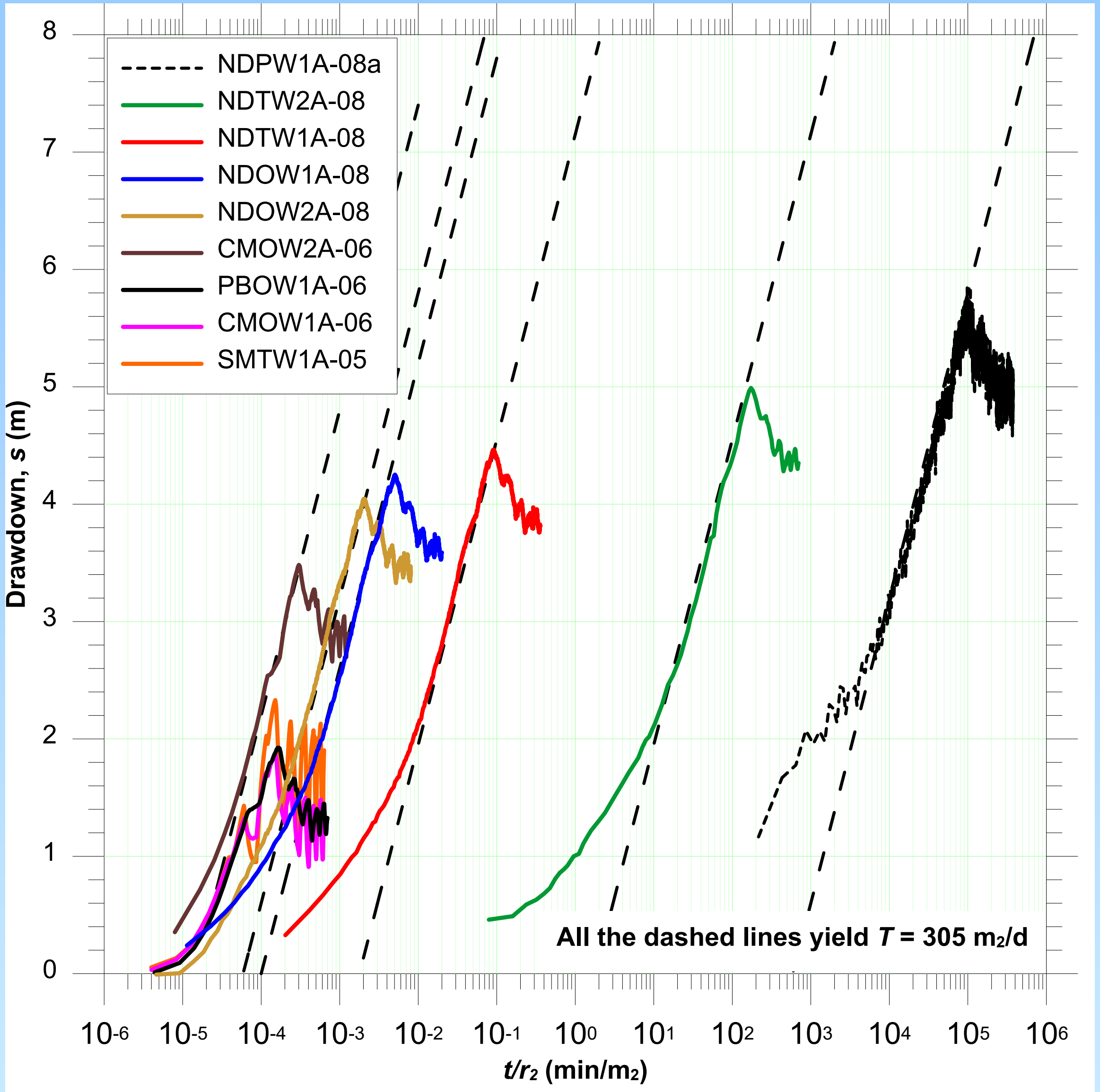


Pumping well drawdowns adjusted for nonlinear well losses with the results of a step test.

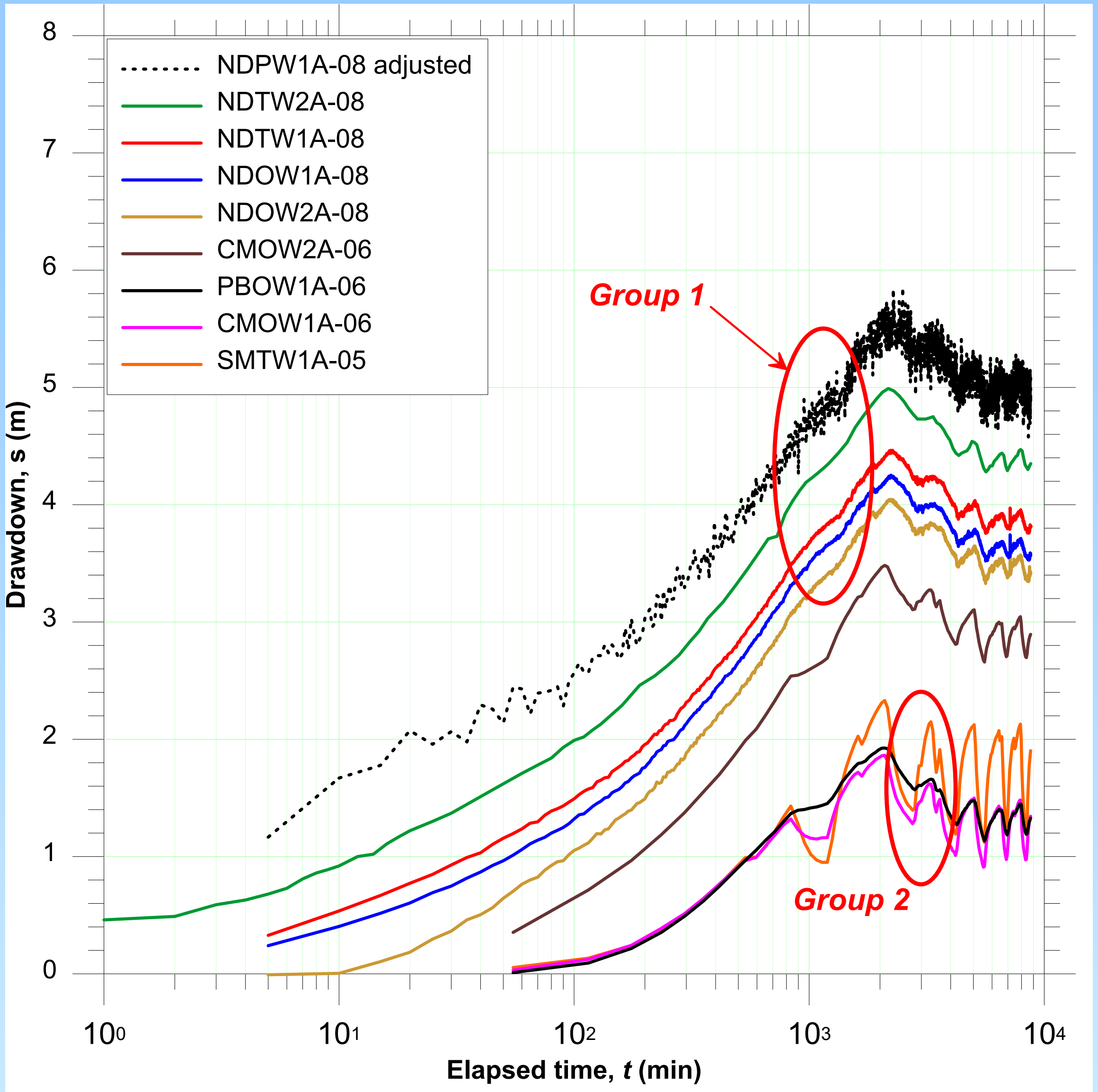
Composite plot



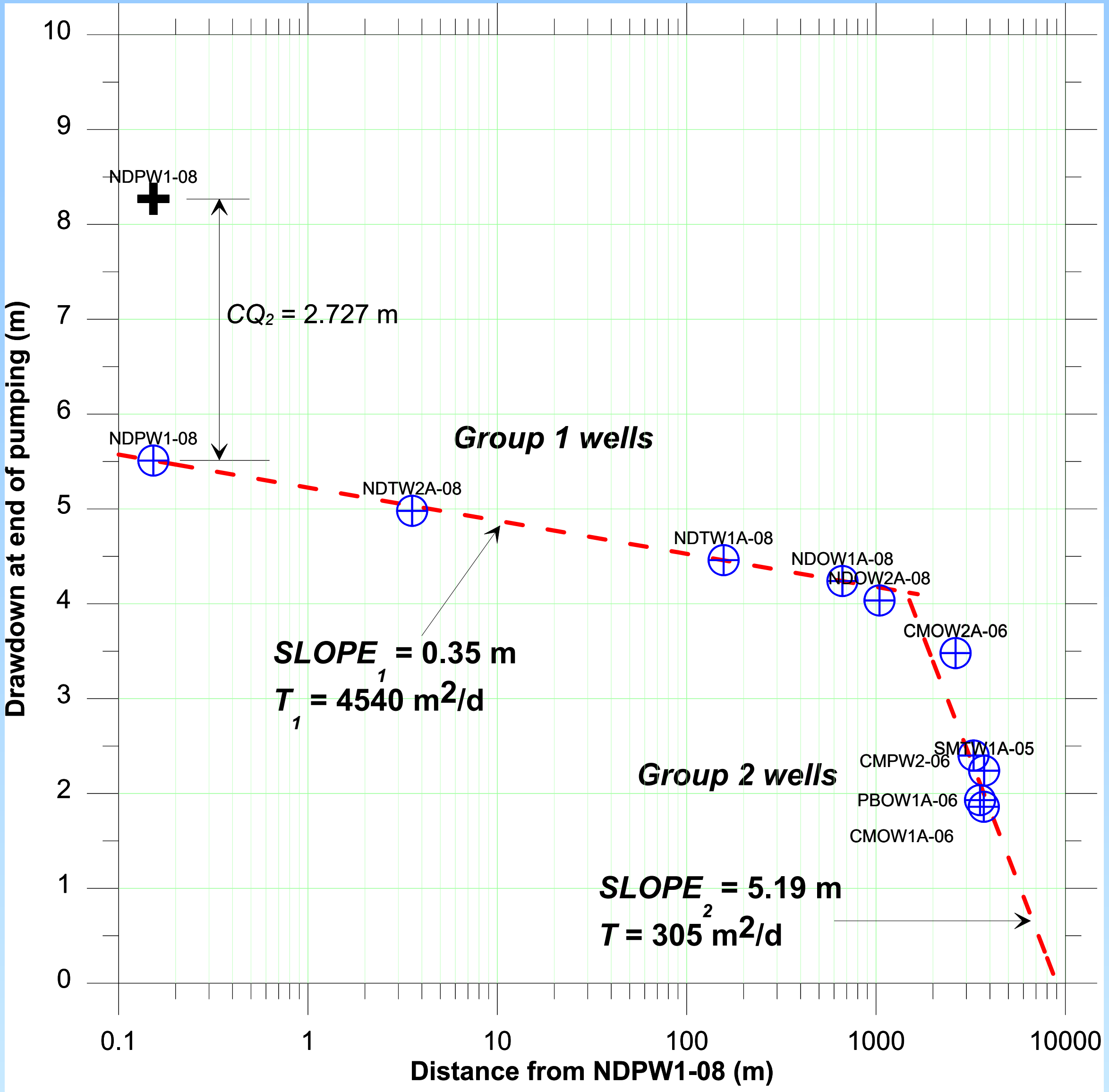
CJSL analysis on the composite plot



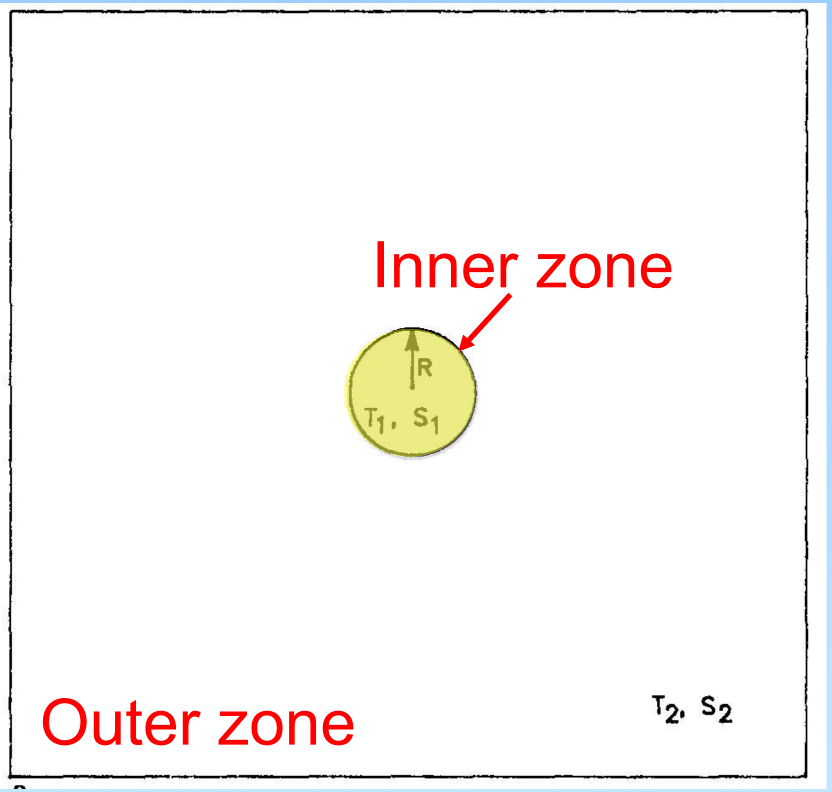
Further diagnosis…

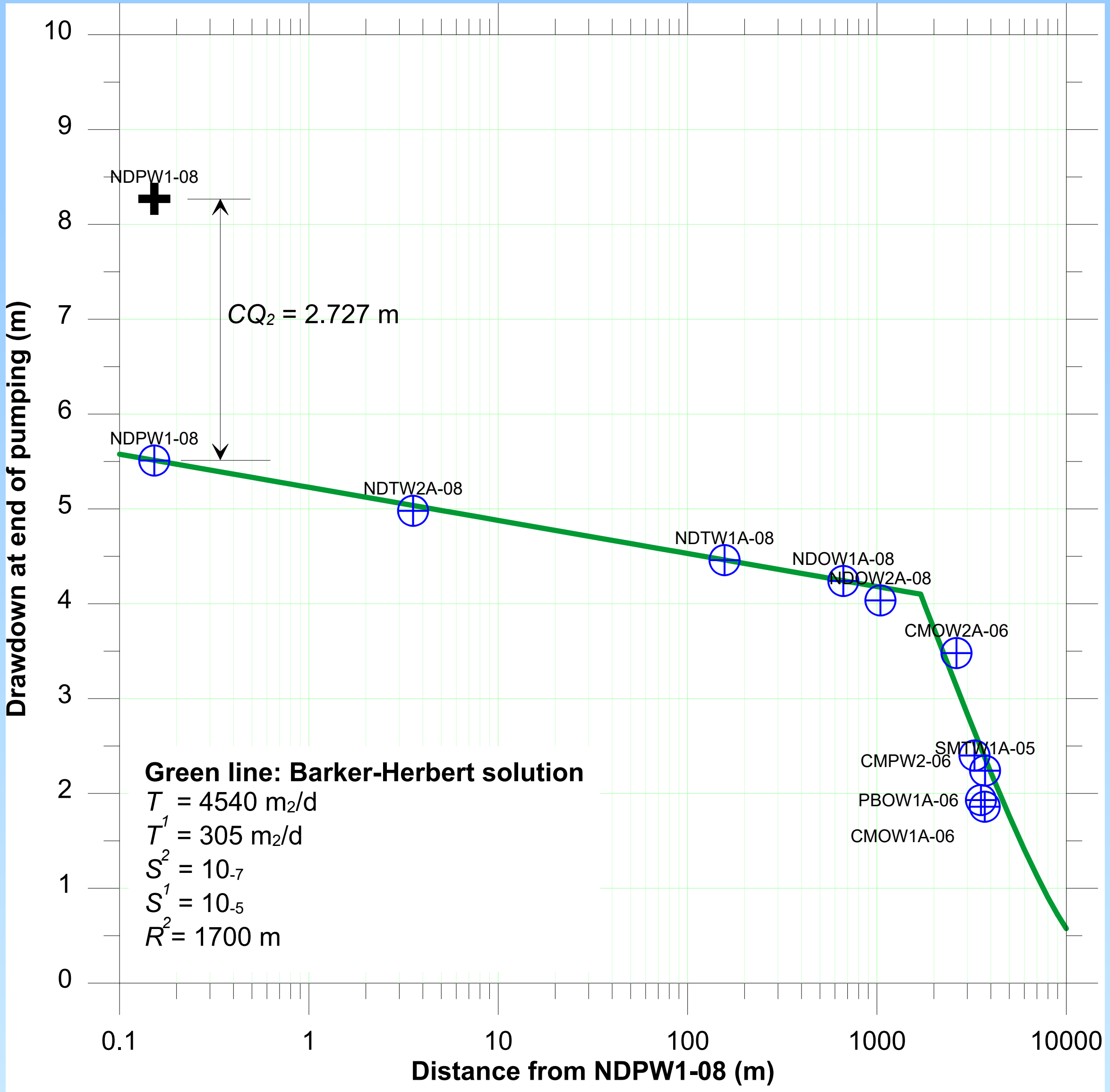


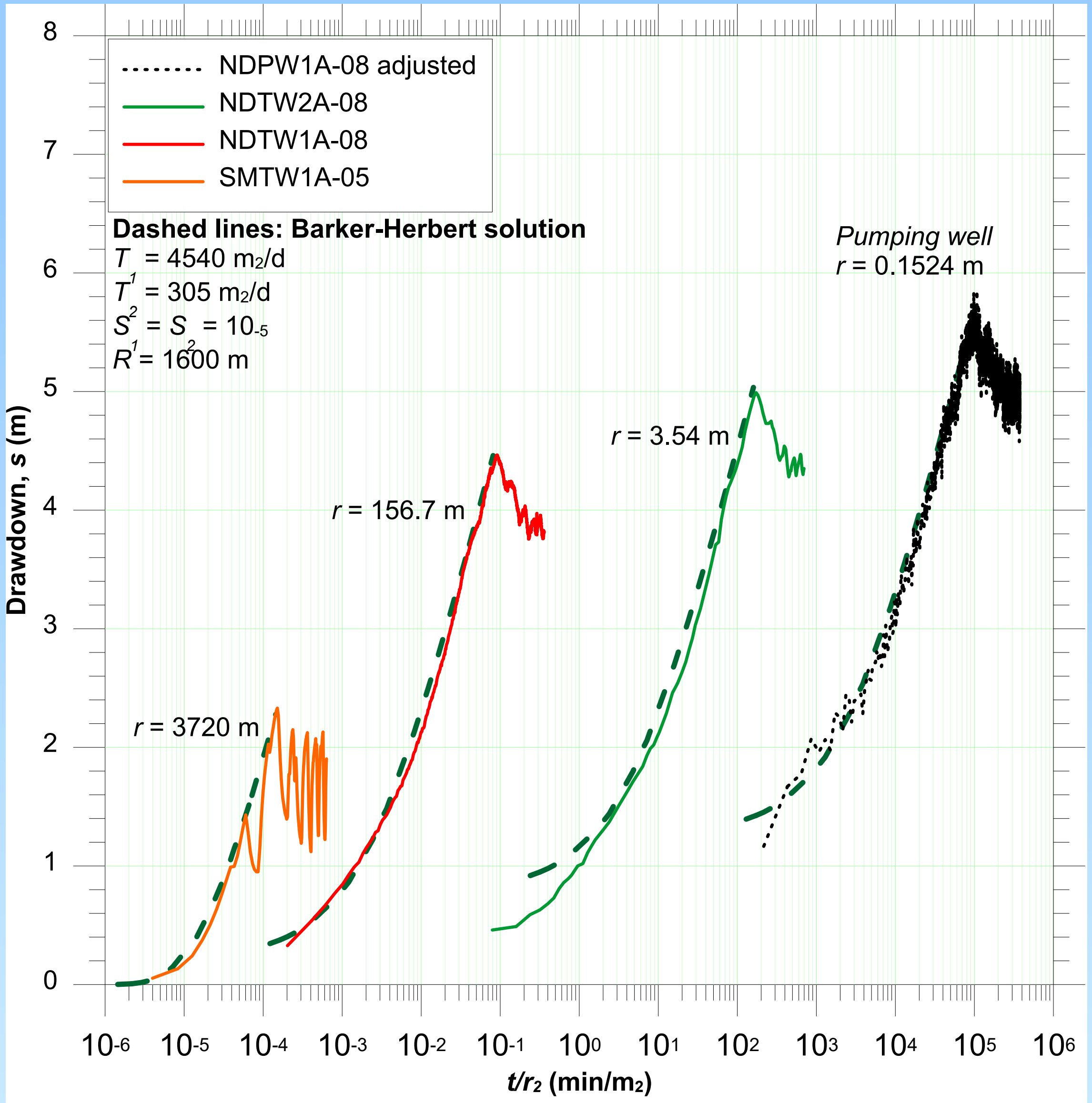
Distance-drawdown plot at maximum drawdowns



Barker and Herbert (1982) model
[Predecessor to the Butler and Liu (1993) pod model]

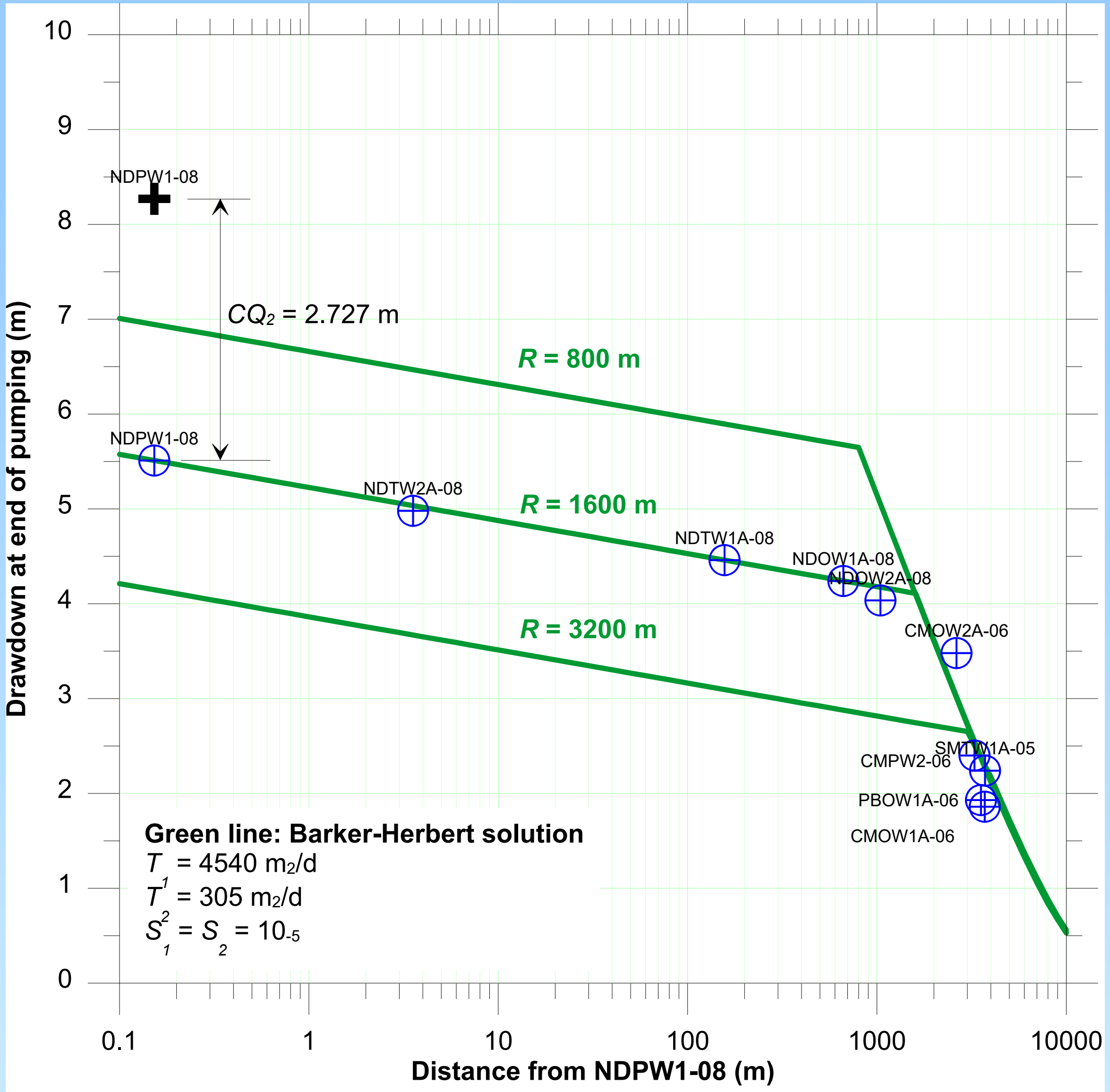



10
9
8
7
6
5
4
3
2
1
0
0.1
1
10
100
1000
10000
Drawdown at end of pumping (m)
Distance from NDPW1-08 (m)
NDPW1-08
CQ2 = 2.727 m
NDPW1-08
NDTW2A-08
NDTW1A-08
NDOW1A-08
NDOW2A-08
CMOW2A-06
SMTW1A-05
CMPW2-06
PBOW1A-06
CMOW1A-06
Green line: Barker-Herbert solution
T = 4540 m2/d
T = 305 m2/d
S = 10-7
S = 10-5
R = 1700 m

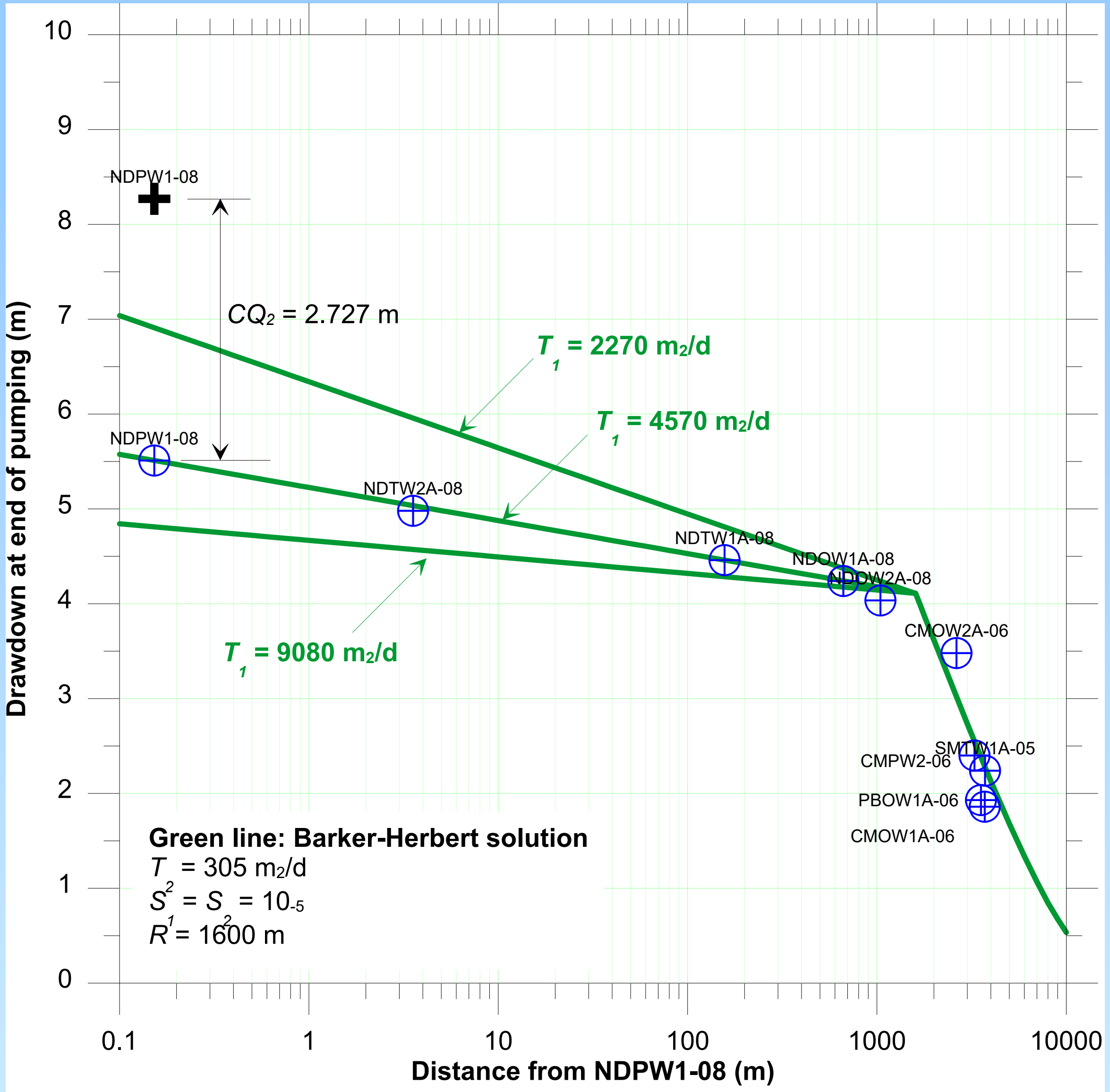


NDPW1A-08 adjusted
NDTW2A-08
NDTW1A-08
SMTW1A-05
Dashed lines: Barker-Herbert solution
T_1 = 4540 m²/d
T_2 = 305 m²/d
S_1 = S_2 = 10⁻⁵
R = 1600 m
Pumping well
r = 0.1524 m
r = 3.54 m
r = 156.7 m
r = 3720 m
Drawdown, s (m)
t/r² (min/m²)

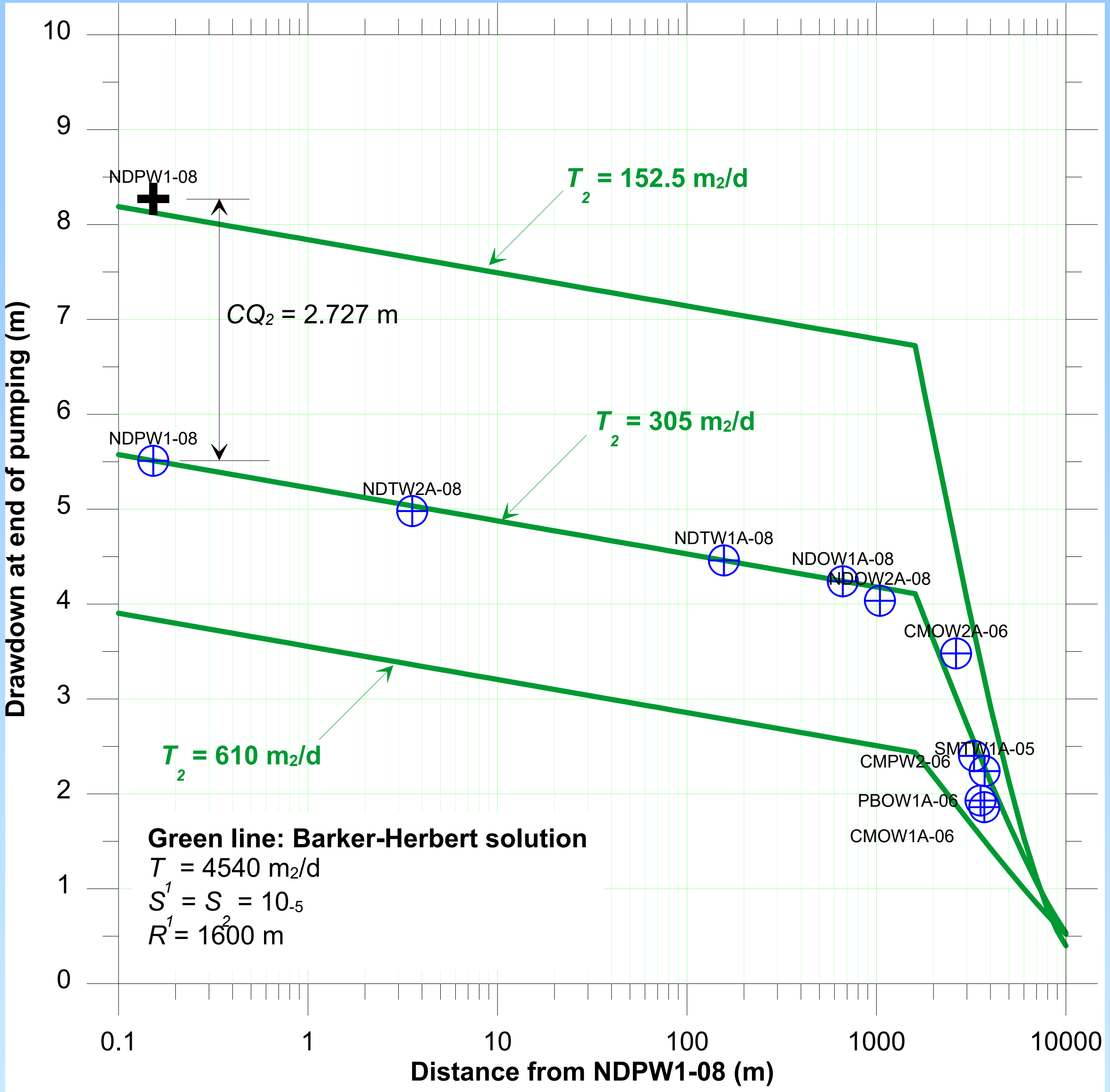
Sensitivity w.r.t. size of inner zone (R)



Sensitivity w.r.t. *T* of inner zone (T_1)



Sensitivity w.r.t. T of outer zone (T_2)



Take-home points (2)

4. My analysis is not <u>the</u> answer. *However*, the Barker-Herbert two-zone conception is the simplest possible model that matches all of the available data.

5. Distance-drawdown never lies.

$$Q = T \times 2\pi r \times \frac{\partial h}{\partial r} = T \times 2\pi \times \frac{1}{2.303} \frac{\partial h}{\partial(\log\{r\})}$$

Case Study:

W3 Pumping Test

Elmira, Ontario

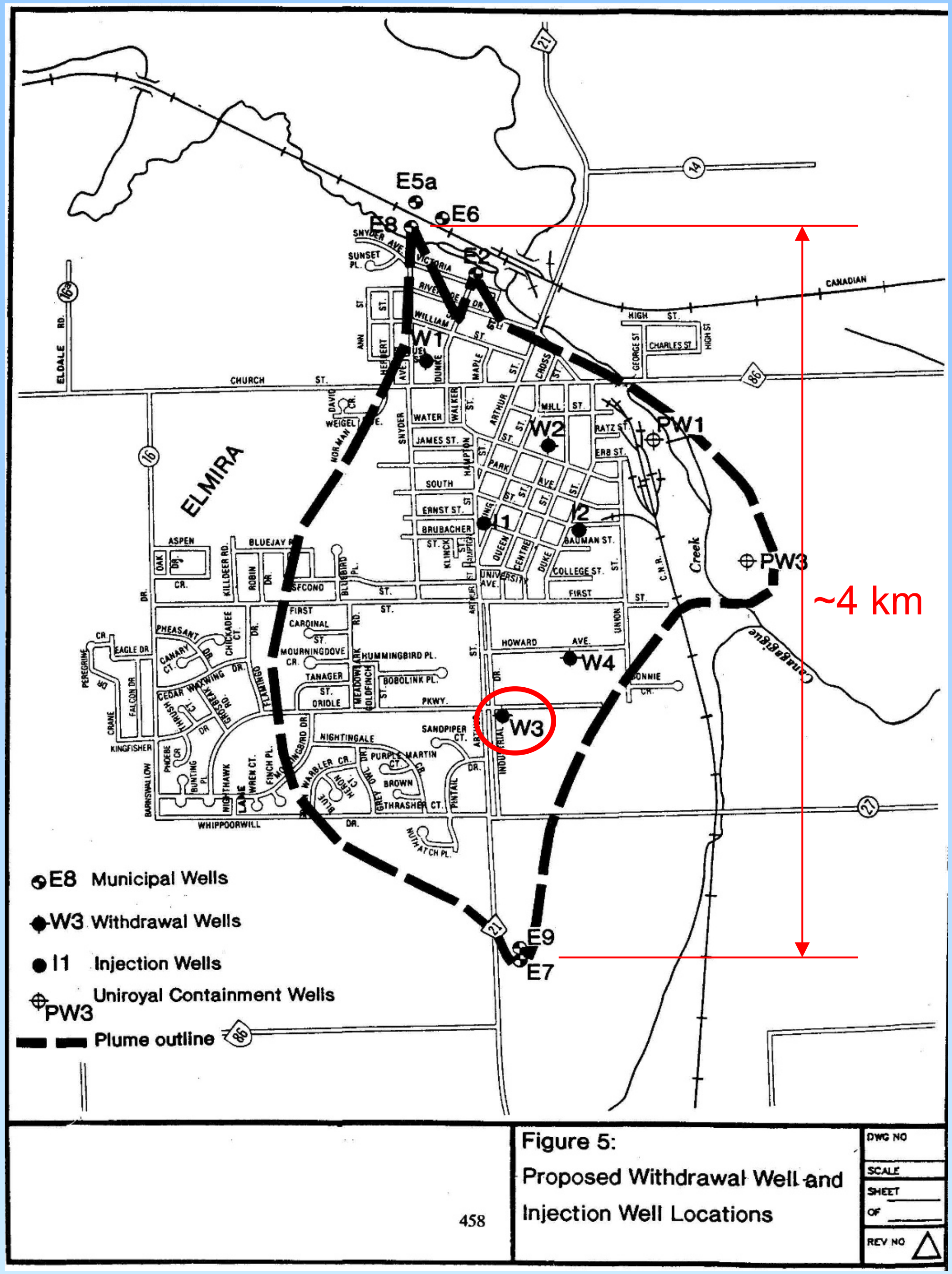
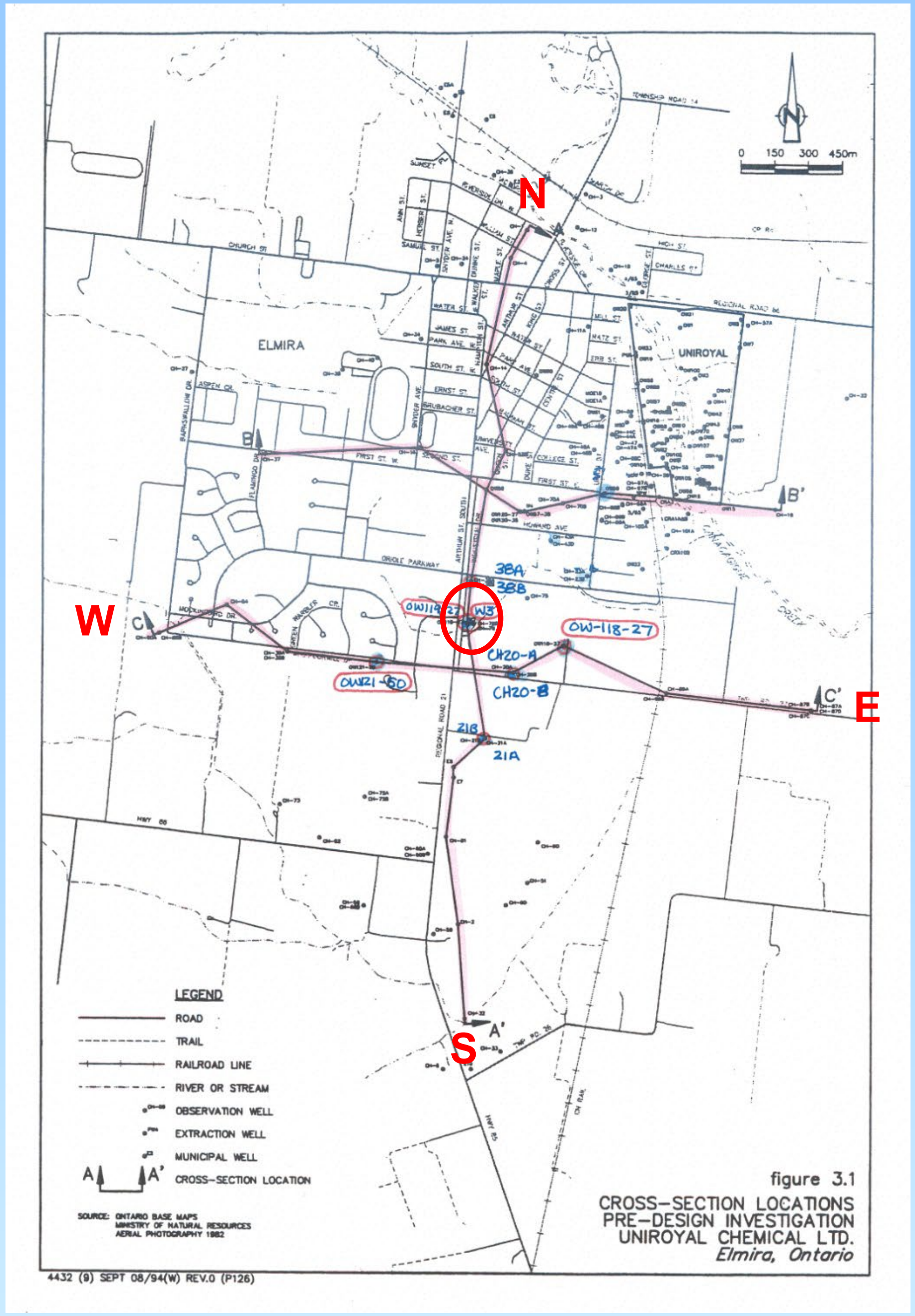
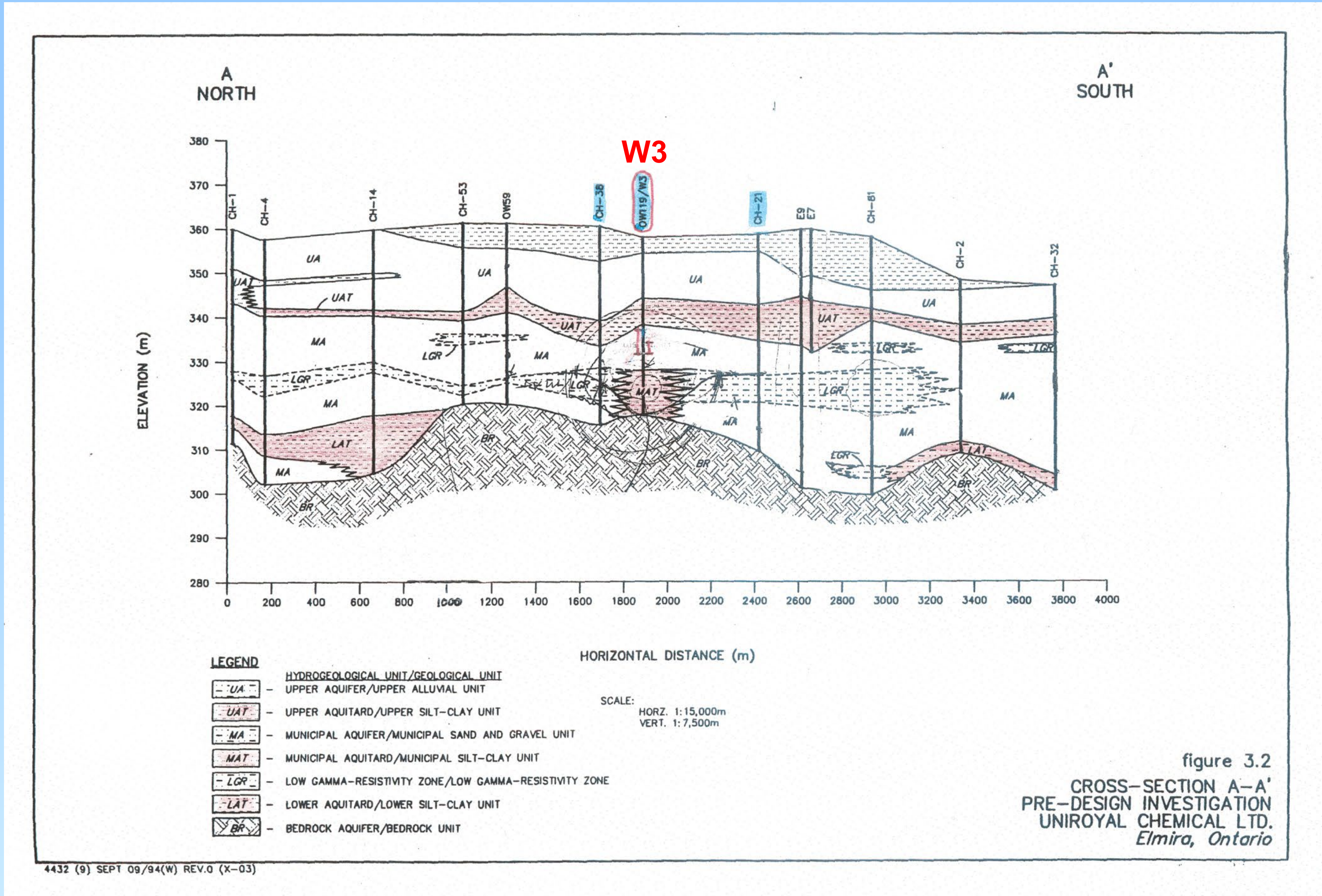
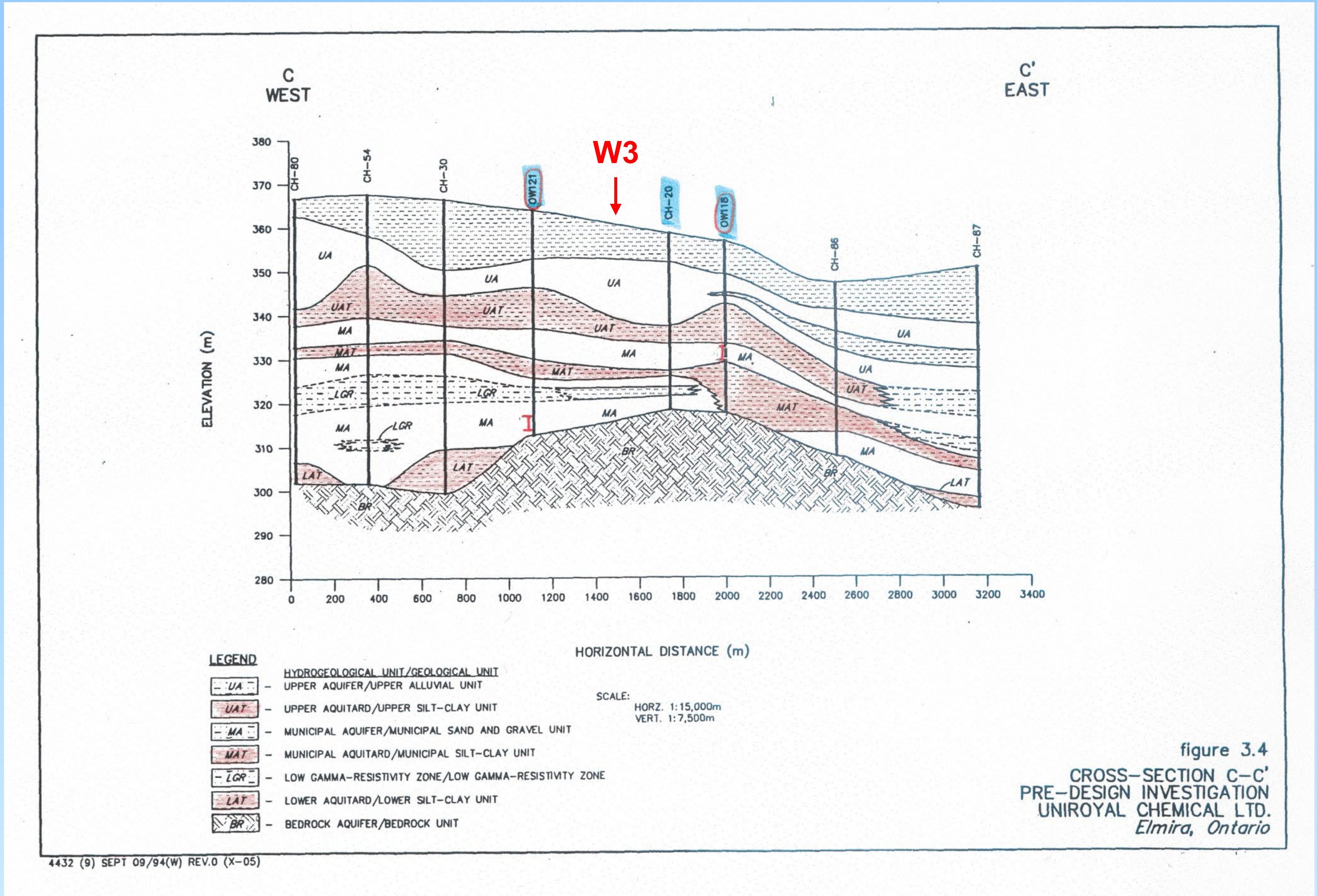


Figure 5:
Proposed Withdrawal Well and Injection Well Locations


N
W
E
S
ELMIRA
UNIROYAL
LEGEND
ROAD
TRAIL
RAILROAD LINE
RIVER OR STREAM
OBSERVATION WELL
EXTRACTION WELL
MUNICIPAL WELL
CROSS-SECTION LOCATION
SOURCE: ONTARIO BASE MAPS
MINISTRY OF NATURAL RESOURCES
AERIAL PHOTOGRAPHY 1982
0 150 300 450m
OW119-27
W3
OW-118-27
OW21-60
CH20-A
CH20-B
38A
38B
21B
21A
figure 3.1
CROSS-SECTION LOCATIONS
PRE-DESIGN INVESTIGATION
UNIROYAL CHEMICAL LTD.
Elmira, Ontario
4432 (9) SEPT 08/94(W) REV.0 (P126)


W3
A
NORTH
A'
SOUTH
ELEVATION (m)
380
370
360
350
340
330
320
310
300
290
280
CH-1
CH-4
CH-14
CH-53
OW59
CH-38
OW119/W3
CH-21
E9
E7
CH-61
CH-2
CH-32
UA
UAT
MA
LGR
MAT
LAT
BR
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
HORIZONTAL DISTANCE (m)
LEGEND
HYDROGEOLOGICAL UNIT/GEOLOGICAL UNIT
UA – UPPER AQUIFER/UPPER ALLUVIAL UNIT
UAT – UPPER AQUITARD/UPPER SILT-CLAY UNIT
MA – MUNICIPAL AQUIFER/MUNICIPAL SAND AND GRAVEL UNIT
MAT – MUNICIPAL AQUITARD/MUNICIPAL SILT-CLAY UNIT
LGR – LOW GAMMA-RESISTIVITY ZONE/LOW GAMMA-RESISTIVITY ZONE
LAT – LOWER AQUITARD/LOWER SILT-CLAY UNIT
BR – BEDROCK AQUIFER/BEDROCK UNIT
SCALE:
HORZ. 1:15,000m
VERT. 1:7,500m
figure 3.2
CROSS-SECTION A-A'
PRE-DESIGN INVESTIGATION
UNIROYAL CHEMICAL LTD.
Elmira, Ontario
4432 (9) SEPT 09/94(W) REV.0 (X-03)


C
WEST
C'
EAST
W3
CH-80
CH-54
CH-30
OW121
CH-20
OW118
CH-86
CH-87
UA
UAT
MA
MAT
LGR
LAT
BR
ELEVATION (m)
380
370
360
350
340
330
320
310
300
290
280
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400
HORIZONTAL DISTANCE (m)
LEGEND
HYDROGEOLOGICAL UNIT/GEOLOGICAL UNIT
UA – UPPER AQUIFER/UPPER ALLUVIAL UNIT
UAT – UPPER AQUITARD/UPPER SILT-CLAY UNIT
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BR – BEDROCK AQUIFER/BEDROCK UNIT
SCALE:
HORZ. 1:15,000m
VERT. 1:7,500m
figure 3.4
CROSS-SECTION C-C'
PRE-DESIGN INVESTIGATION
UNIROYAL CHEMICAL LTD.
Elmira, Ontario
4432 (9) SEPT 09/94(W) REV.0 (X-05)

Reporting

SUMMARY OF TRANSMISSIVITY RESULTS, W3 PUMPING TEST
PRE-DESIGN INVESTIGATION
UNIROYAL CHEMICAL LTD.
ELMIRA, ONTARIO

Location	Distance to Pumped Well (metres)	Drawdown at 23 Hours (metres)	Drawdown Results (m^2/min)	Drawdown Results (m^2/day)	Recovery Results (m^2/min)	Recovery Results (m^2/day)	Geometric Mean (m^2/min)
W3	0.127	1.26	0.5371	7.73E+02	1.0380	1.49E+03	7.47E-01
CH78B (1)	3	0.53	1.1360	1.64E+03	0.9562	1.38E+03	1.04E+00
OW119-27 (1)	35	0.71	0.9637	1.39E+03	0.9707	1.40E+03	9.67E-01
CH38A	210	0.36	0.9665	1.39E+03	0.9503	1.37E+03	9.58E-01
CH38B	210	0.24	1.7900	2.58E+03	1.7390	2.50E+03	1.76E+00
CH20B	240	0.07	3.8680	5.57E+03	6.4610	9.30E+03	5.00E+00
CH75A	290	0.37	0.6343	9.13E+02	0.5222	7.52E+02	5.76E-01
CH75B	290	0.43	0.7488	1.08E+03	0.6304	9.08E+02	6.87E-01
OW118-27	400	0.09	3.1000	4.46E+03	1.9540	2.81E+03	2.46E+00
OW121-50	450	0.17	2.0580	2.96E+03	1.9890	2.86E+03	2.02E+00
CH43A	490	0.25	0.9151	1.32E+03	0.8451	1.22E+03	8.79E-01
CH21A	545	0.06	4.5790	6.59E+03	2.3010	3.31E+03	3.25E+00
CH21B	545	0.05	11.1100	1.60E+04	7.6270	1.10E+04	9.21E+00
CH23B	575	0.30	1.1180	1.61E+03	0.9304	1.34E+03	1.02E+00
OW56-26	900	0.34	2.0380	2.93E+03	0.4996	7.19E+02	1.01E+00
						Geometric Average of all Results:	1.47E+00

Notes:

(1) The transmissivity value calculated from drawdown results has been corrected for partial penetration of the aquifer by the observation and pumping wells.

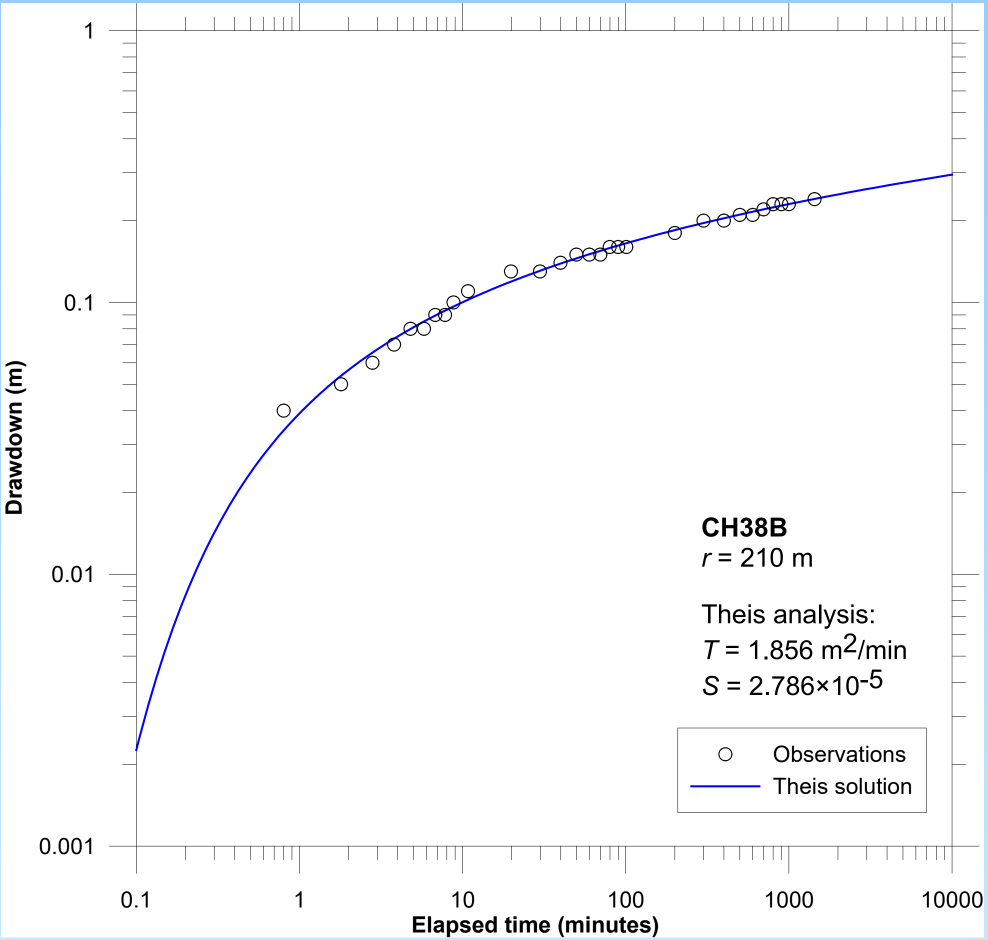
The pumping test was conducted at 150 Igpm (0.66 m^3/min) on July 20-21, 1994.

All transmissivities were obtained using the Theis method in AQTESOLV except the drawdown test for W3 which was analysed with the Cooper- Jacob method in AQTESOLV.

m^2/min metres squared per minute

m^2/day metres squared per day

Analysis approach:
Example individual analysis



- 15 observation wells
- 15 matches with the Theis solution

Q1. Is the reporting appropriate?

TABLE 3.2

SUMMARY OF TRANSMISSIVITY RESULTS, W3 PUMPING TEST
PRE-DESIGN INVESTIGATION
UNIROYAL CHEMICAL LTD.
ELMIRA, ONTARIO

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					Geometric Average of all Results:		1.47E+00

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m^2/min metres squared per minute
m^2/day metres squared per day

Q2. Are the analyses conceptually sound?

TABLE 3.2

SUMMARY OF TRANSMISSIVITY RESULTS, W3 PUMPING TEST
PRE-DESIGN INVESTIGATION
UNIROYAL CHEMICAL LTD.
ELMIRA, ONTARIO

Location	*Distance to Pumped Well (metres)*	*Drawdown at 23 Hours (metres)*	*Drawdown Results* (m^2/min)	(m^2/day)	*Recovery Results* (m^2/min)	(m^2/day)	*Geometric Mean (m^2/min)*
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OW56-26	900	0.34	2.0380	2.93E+03	0.4996	7.19E+02	1.01E+00
						Geometric Average of all Results:	1.47E+00

Notes:

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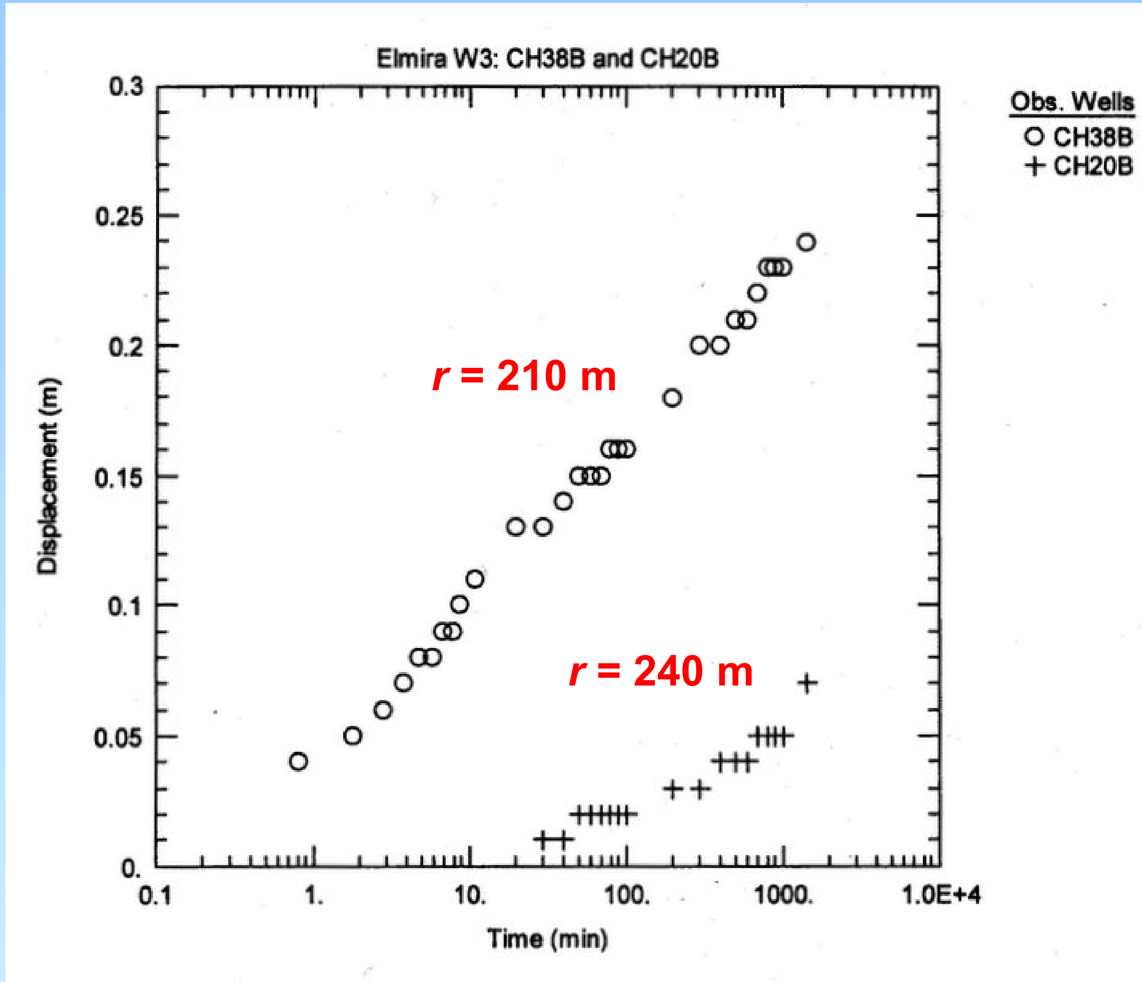
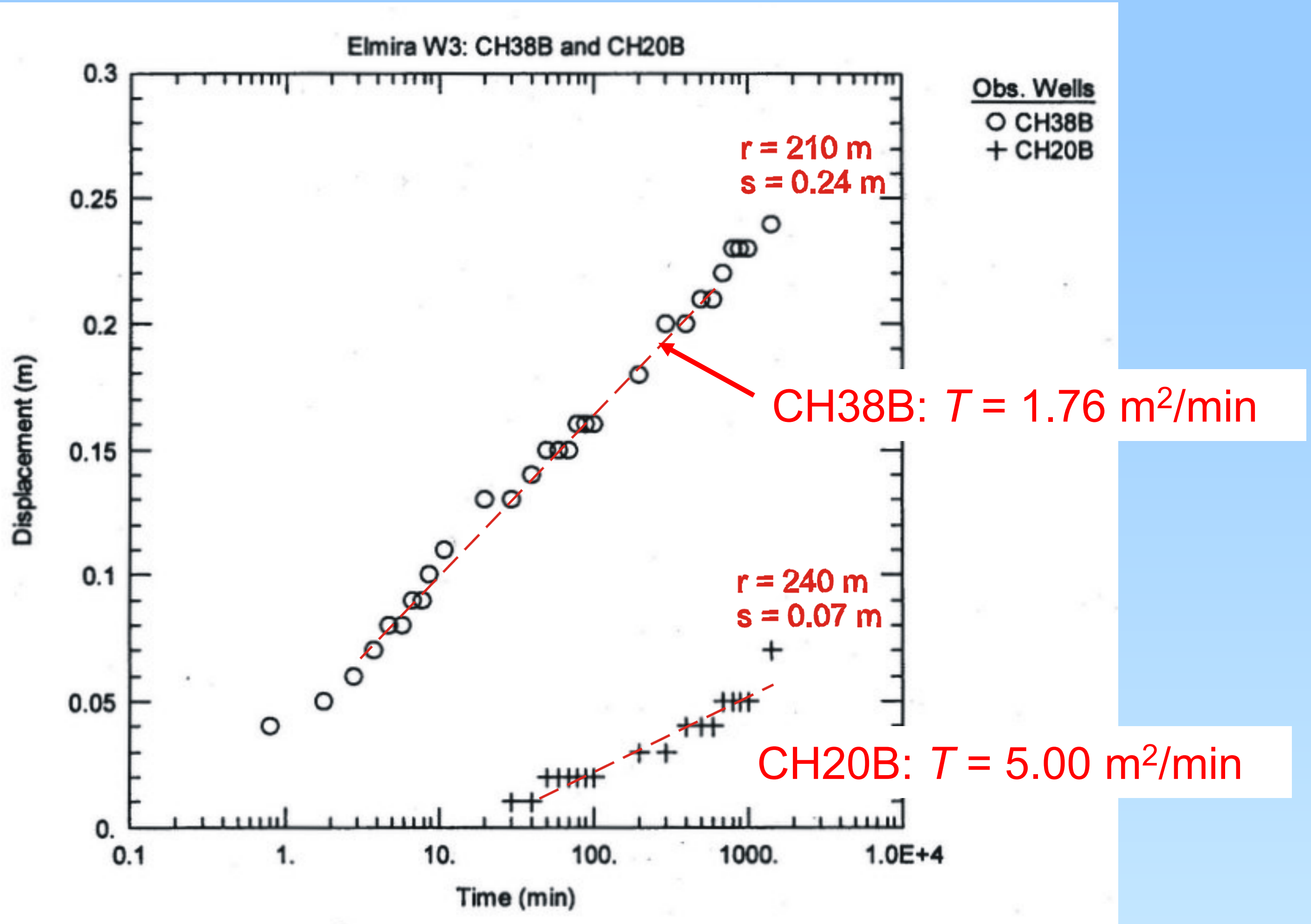
m^2/min metres squared per minute

m^2/day metres squared per day

Q3. Are the interpretations reliable?

Might the interpretations of individual drawdown records provide reliable (perhaps not general, but local) transmissivity estimates?

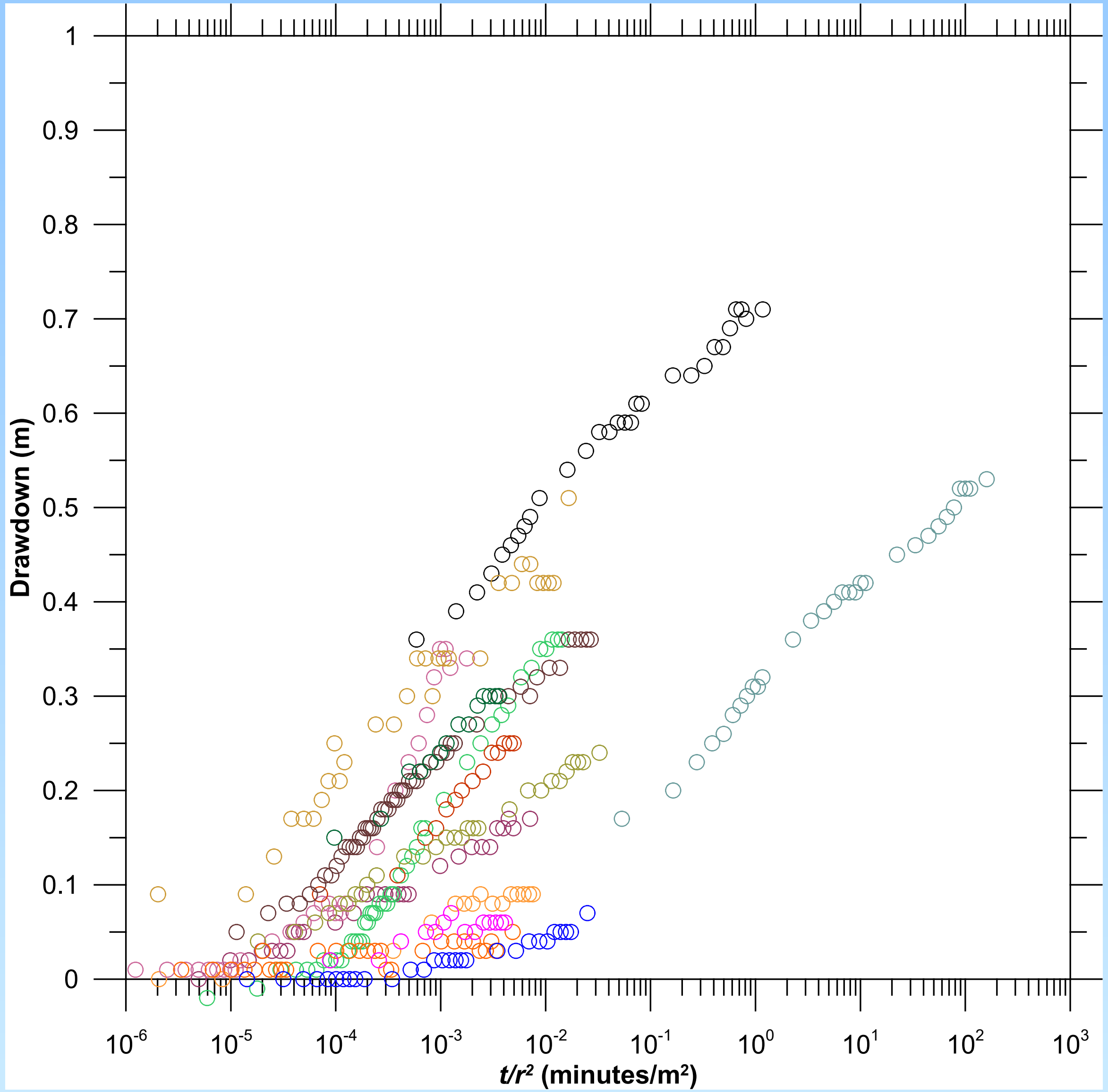



Elmira W3: CH38B and CH20B
Obs. Wells
CH38B
CH20B
r = 210 m
s = 0.24 m
r = 240 m
s = 0.07 m
Displacement (m)
0.3
0.25
0.2
0.15
0.1
0.05
0.
0.1
1.
10.
100.
1000.
1.0E+4
Time (min)
CH38B: T = 1.76 m2/min
CH20B: T = 5.00 m2/min

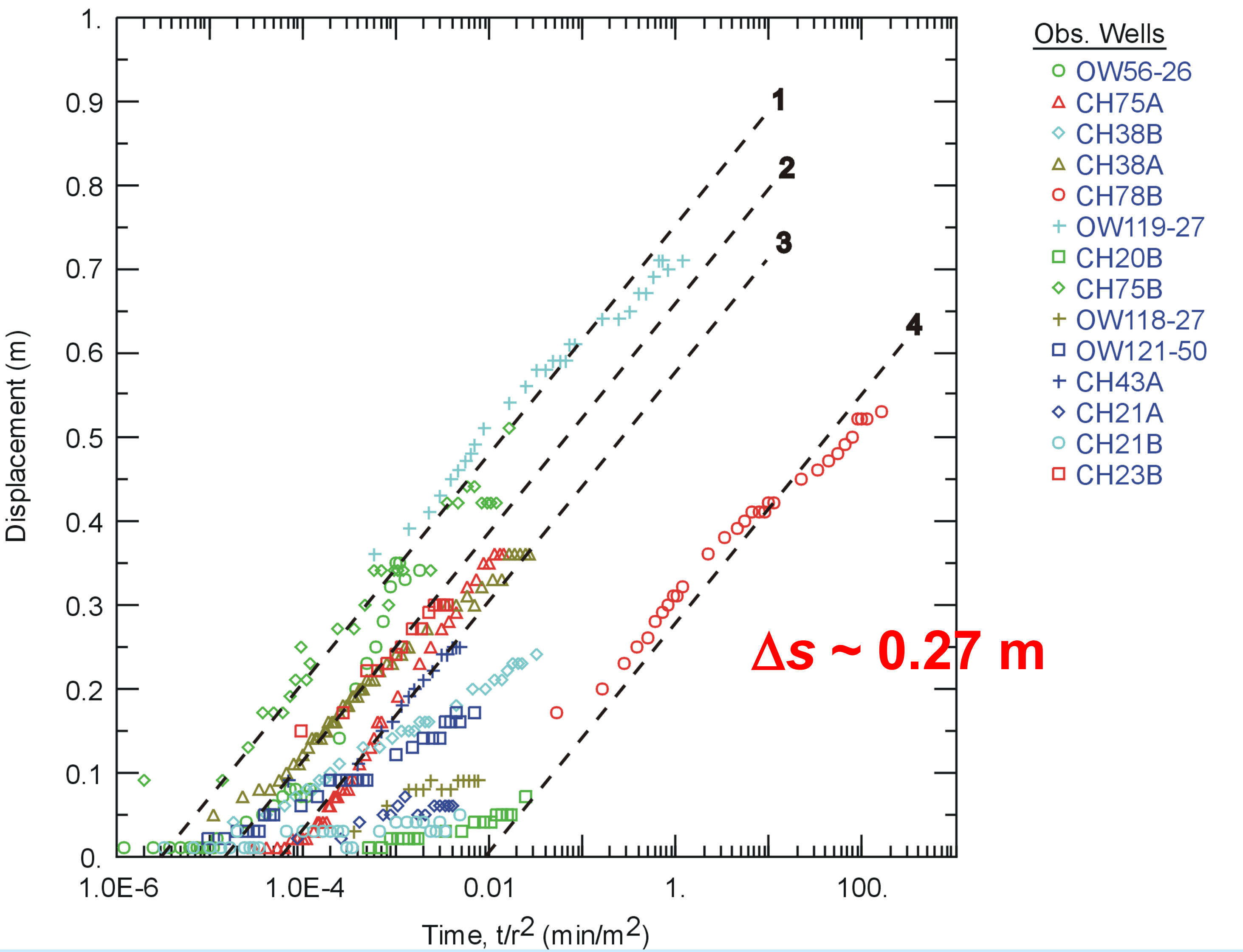
Q4. Do the analyses have any diagnostic value?

- Does the table of reported values shed any light on the subsurface structure?
- Does the table of reported values provide any insight into the representative large-scale transmissivity?
- Does the table of reported values help identify outliers?

Alternative Interpretation: Composite plot



Interpretation: CJSL Analysis



Estimation of transmissivity

SLOPE 1, 2, 3 and 4 ≅ 0.27 m/log cycle t/r^2

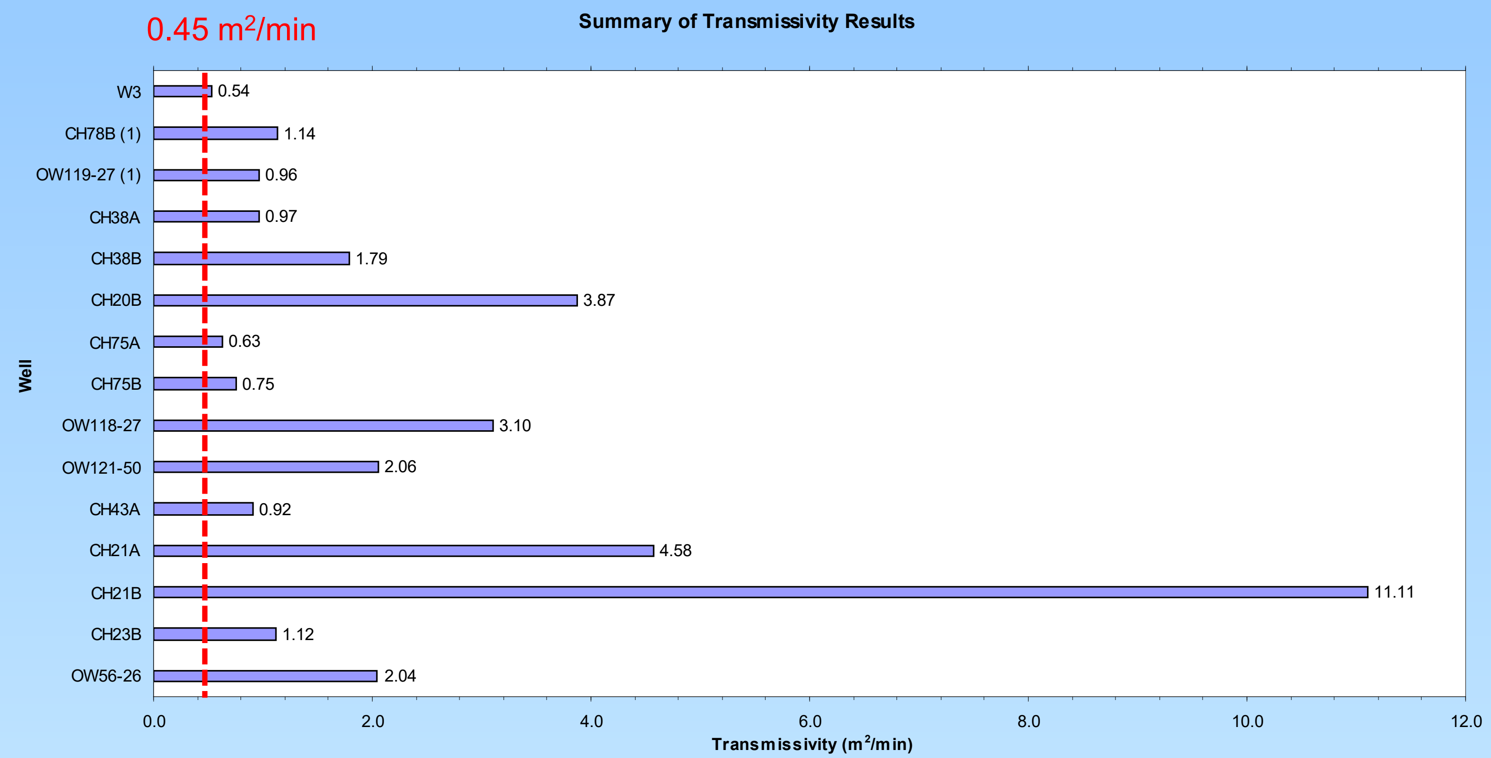
Average pumping rate: Q = 150 gpm (= 0.66 m^3/min)

$$T = 2.303\frac{Q}{4\pi}\frac{1}{\Delta s}$$

$$\cong 2.303\frac{(0.66\ \mathrm{m}^3/\mathrm{min})}{4\pi}\frac{1}{(0.27\ \mathrm{m})}$$

$$= 0.45\ \mathrm{m}^2/\mathrm{min}$$

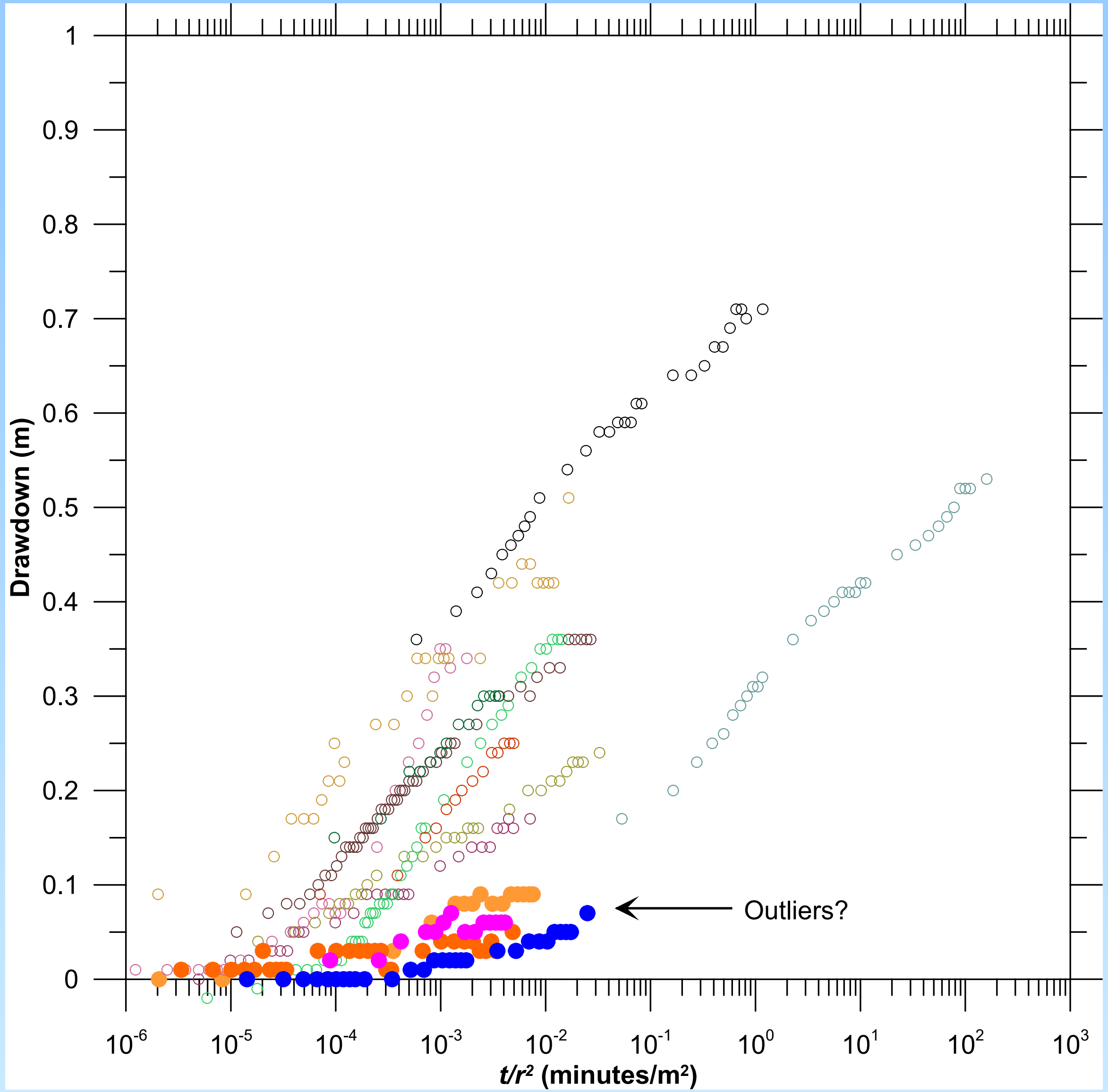
Original analysis: T = 0.5 to 11.1 m²/min



Cooper-Jacob composite analysis: T = 0.45 m²/min

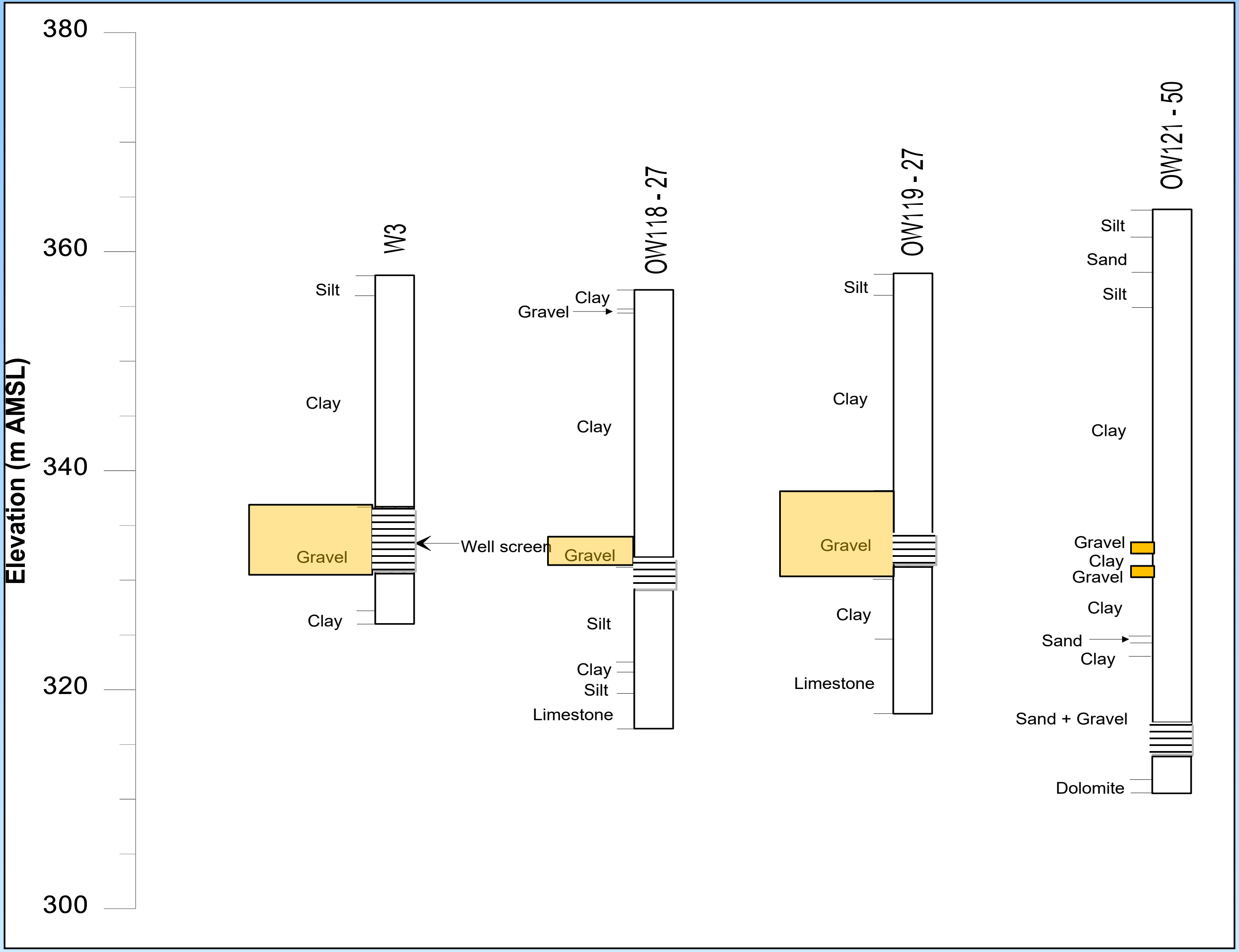
Outliers?

Outliers?



Drawdown (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Outliers?
10-6
10-5
10-4
10-3
10-2
10-1
100
101
102
103
t/r² (minutes/m²)

Further analysis?



Take-home points (3)

6. Careful how you report your results.

7. Assembling a table with a wide range of transmissivity estimates obtained from matching the data with a solution that assumes aquifer homogeneity is <u>not</u> helpful to anyone.