Leakage is for ‘Lumpers’ Lessons Learned from Aquifer Tests in Layered Till

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DEPARTMENT OF HEALTH

Presentation Topics

- Scope of Overall Project & Contribution by MDH
- Practical Physics of Layered Flow Systems
  - Conceptual models (analysis methods)
  - What is this ‘Leakage Factor’?
  - Inherent limitations of pumping tests
- Test Descriptions & Results from Four Sites
- Comparison of Test Results
- Conclusions

Study of Flow Through Till

- Data collection at four sites by USGS & U. Iowa
  - Rotosonic core
  - Obwells: water table, aquitard, and aquifer
  - Slug tests
  - Water chemistry: tritium, stable isotopes, chloride
  - Long-term (~ one year) water level monitoring
  - Three sites, limited collection of pumping records from public water supply (PWS) systems
- MODFLOW models

MDH Participation - Aquifer Tests

- Testing, analysis, and report for PWS
  - Cromwell – May, 2017
  - Litchfield – June, 2017
- Analysis of USGS & MGS data
  - UM Hydrogeology Field Camp - July, 2017 & July, 2018
- Preliminary evaluation of USGS data
  - Olivia – July, 2018

Aquifer vs. Aquitard Response

- Given:
  - Till is heterogeneous
  - Methods to estimate quantity of vertical flow / unit area (leakage) are scale-dependent
  - Traditional aquifer testing (obwells in aquifer) may provide a bulk estimate of leakage
- How do estimates of leakage compare?
  - obwells in aquifer
  - obwells in till

Why Leakage Matters in Layered Systems

- “All layered systems are leaky”
- Ultimate source of water in the system
- Theis conceptual model assumes no leakage; this is a problem
- Understanding requires conceptual model that includes leakage

Conceptual Model, Assumed Source of Water

Reference	Source of Water
• Theis (1935) - Transient	change in (Δ) storage **only** | no leakage constant head boundary: $r \longrightarrow \infty$
• de Glee (1930) - Steady-state	no Δ storage | leakage **only** constant head boundary: water table
• Composite (Transient & Steady-state)	Δ storage **+** leakage, const. head boundaries
• Hantush-Jacob (1955)	Δ storage in aquifer, no Δ storage in aquitard
• Neuman-Witherspoon (1969)	Δ storage in both: aquifer & aquitard

Composite Model of Leakage Solves For

Aquifer Property	Dimension
• Transmissivity	$length^2$ / time
• Storativity	dimensionless
• Characteristic Leakage Factor	length

Where does the Characteristic Leakage Factor (Leakage Factor) appear in the equations, how is it used? …

Theis (1935) → Hantush-Jacob (1955)
Two → Three Aquifer Properties

Transmissivity

$$T = \frac{Q}{4 \cdot \pi \cdot s} W(u, r/L)$$

Theis (1935) Well function, W(u)
& dimensionless parameter: r/L

Storativity

$$S = \left(\frac{4 \cdot \mathrm{T} \cdot \mathrm{t} \cdot \mathrm{u}}{r^2} \right)$$

Theis (1935) Storativity
unchanged

Leakage Factor

$$L = \sqrt{\frac{T}{k'/b'}}$$

Aquitard
k’ - vertical conductivity
b’ - thickness

Solve for Aquitard Vertical Conductivity, k'

Known quantities: b', T, & L

Published equation for Leakage Factor: $$L = \sqrt{\frac{T}{k'/b'}}$$

Aquitard hydraulic resistance, c = $\frac{k'}{b'}$ = ${L^2}/{T}$ time^{-1}

<u>Bulk</u> Aquitard Vertical Conductivity, $k' = {b'}/{(L^2/T)}$

Hantush-Jacob (1955)
Three Interdependent Aquifer Properties

Transmissivity

$$T = \frac{Q}{4 \cdot \pi \cdot s} W(u, r/L)$$

Storativity

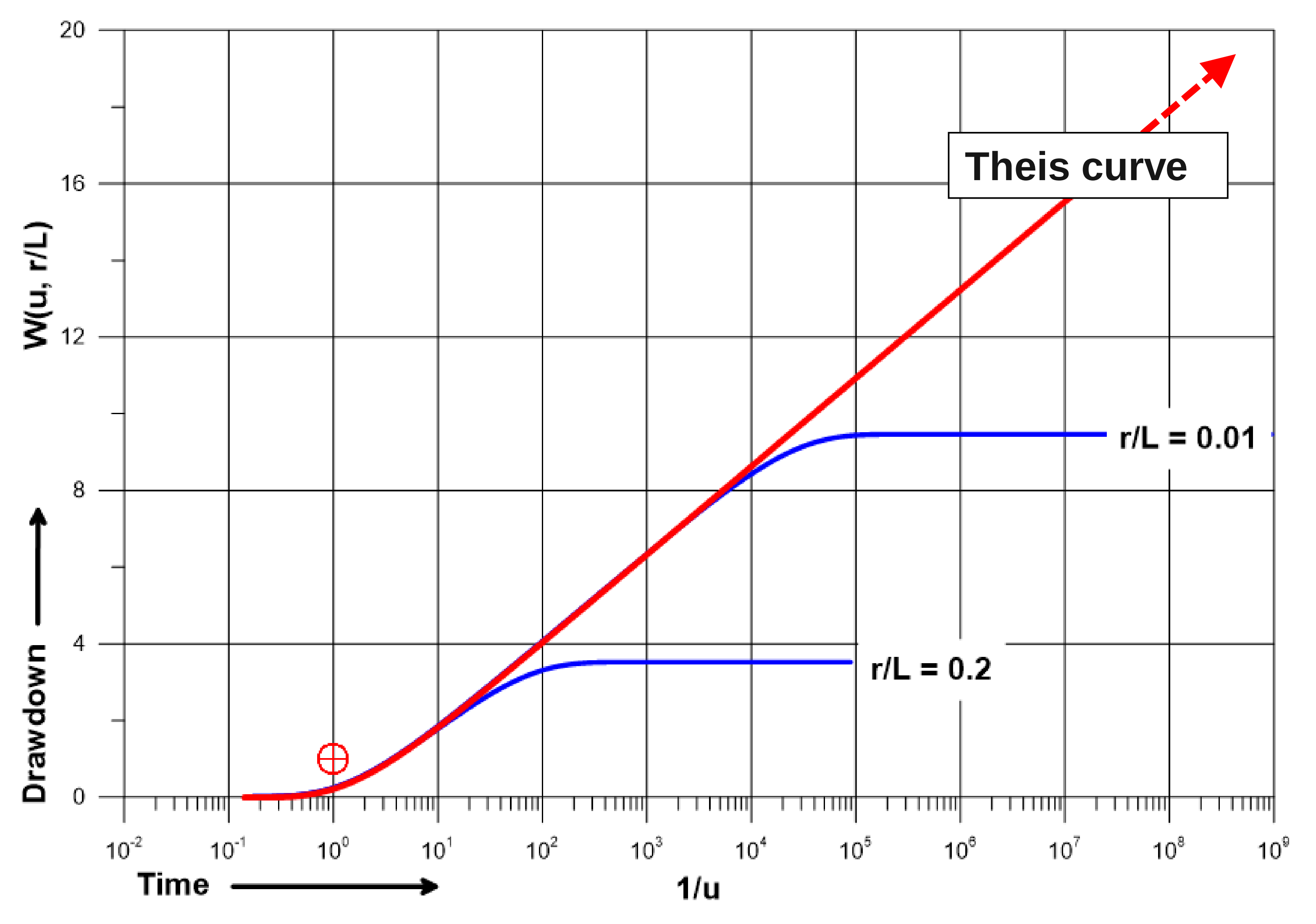
$$S = \left(\frac{4 \cdot T \cdot t \cdot u}{r^2} \right)$$

Leakage Factor

$$L = \sqrt{\frac{T}{k'/b'}}$$

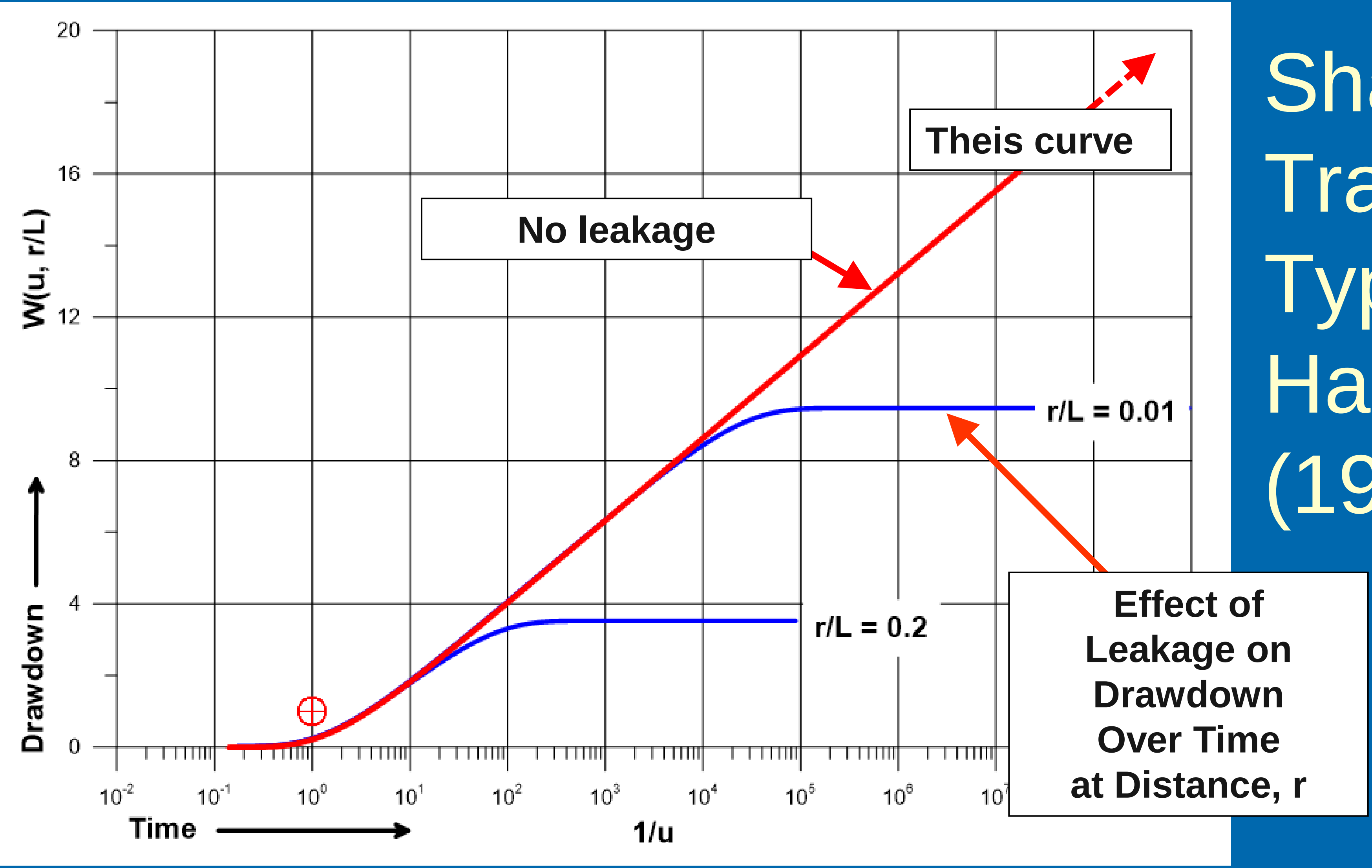
Interdependence:
Transmissivity appears in the equations for S and L, as parameters (u, and r/L) are also inputs to leaky Well function: W(u, r/L)

Aquitard
k' - vertical conductivity
b' - thickness

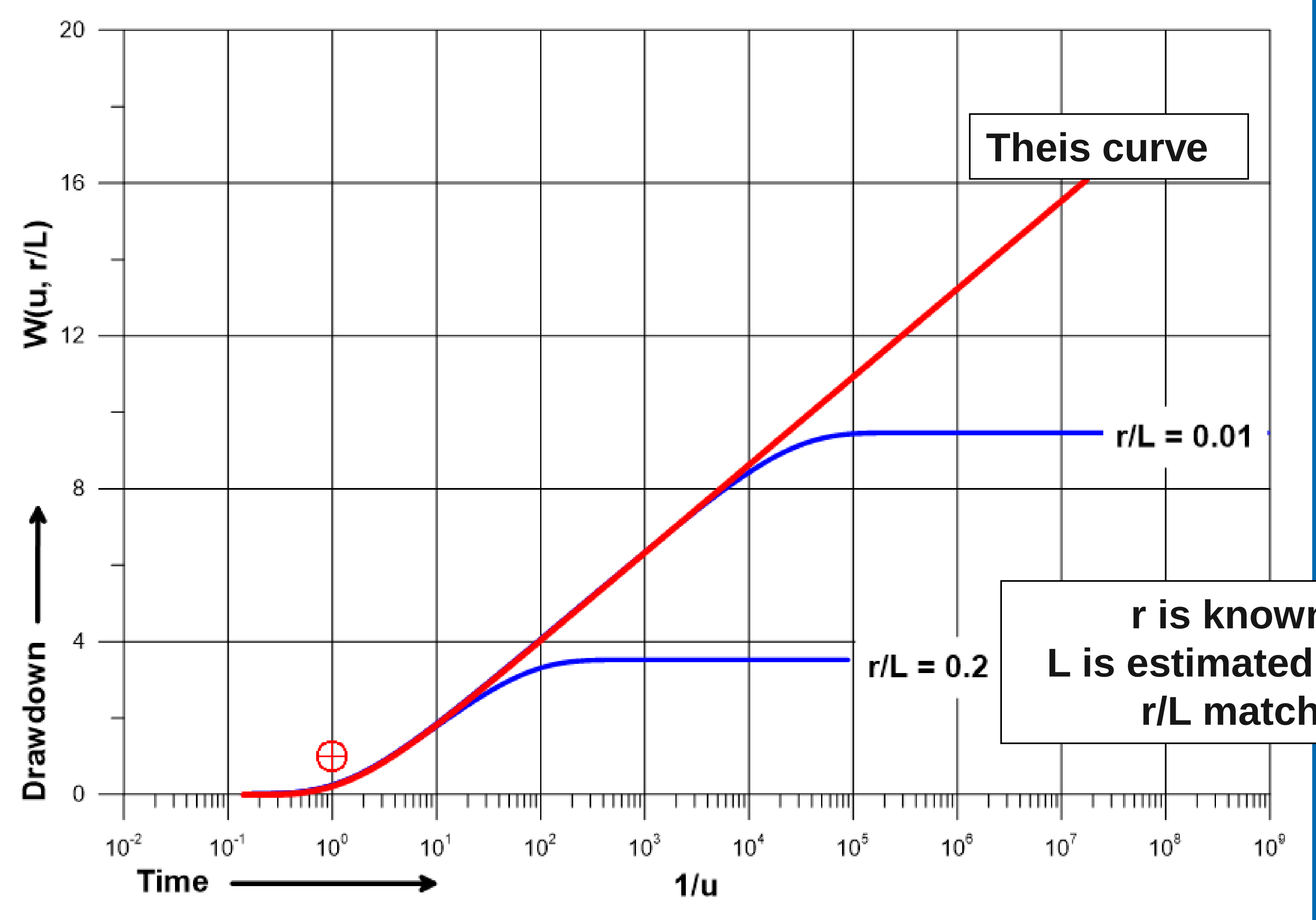


Shape of Transient Type-curves Hantush-Jacob (1955 a)

Δ Storage in Aquifer only,
No Δ Storage in Aquitard

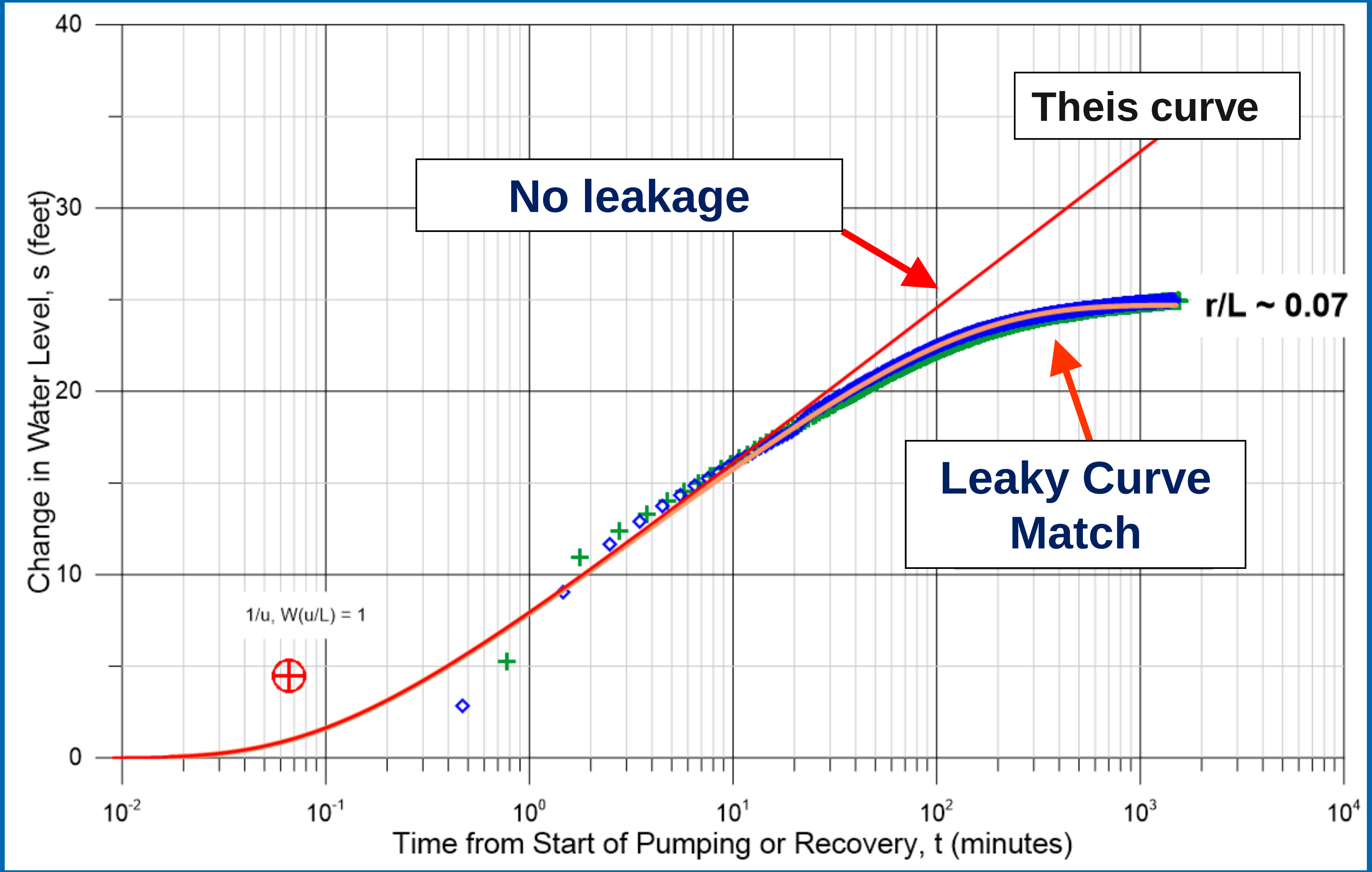


Shape of Transient Type-curves Hantush-Jacob (1955 a)



Shape of Transient Type-curves Hantush-Jacob (1955 a)

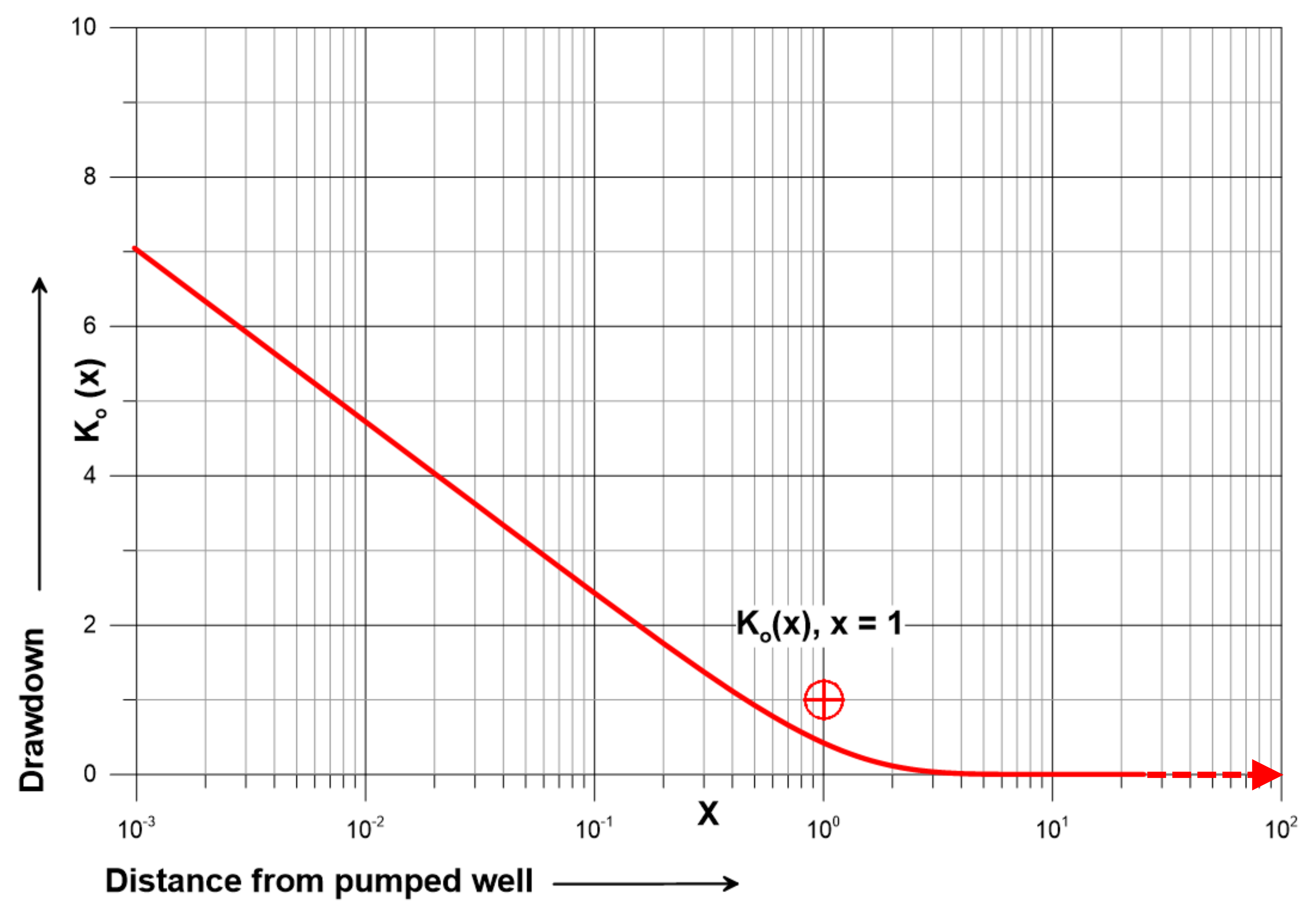
r is known
L is estimated from r/L match



Transient Analysis Shape

T = 2,420 ft²/day
S = 5.0e-5

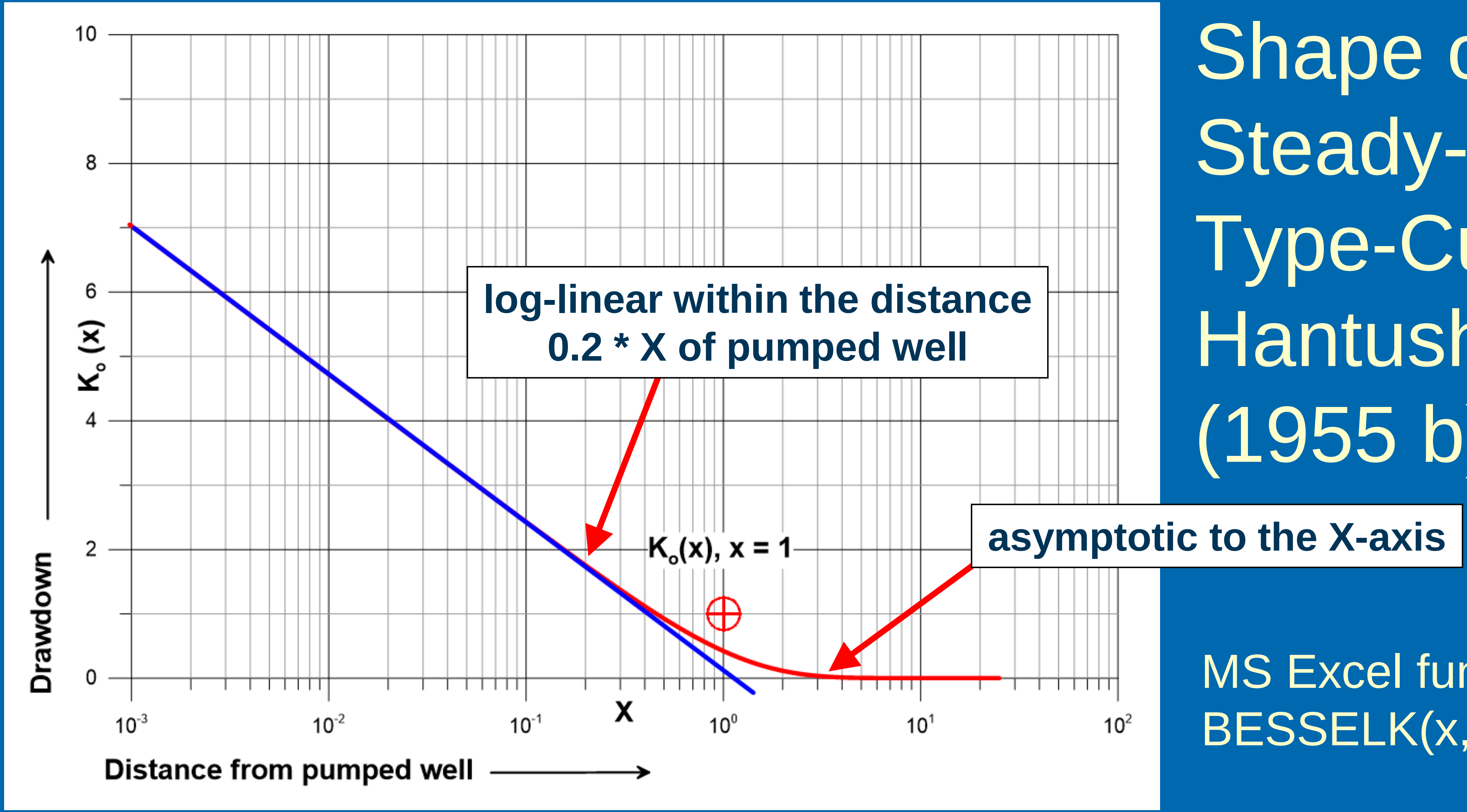
r = 100 ft.
L = r / (r/L)
L = 1,430 feet



Shape of Steady-state Type-Curve Hantush-Jacob (1955 b)

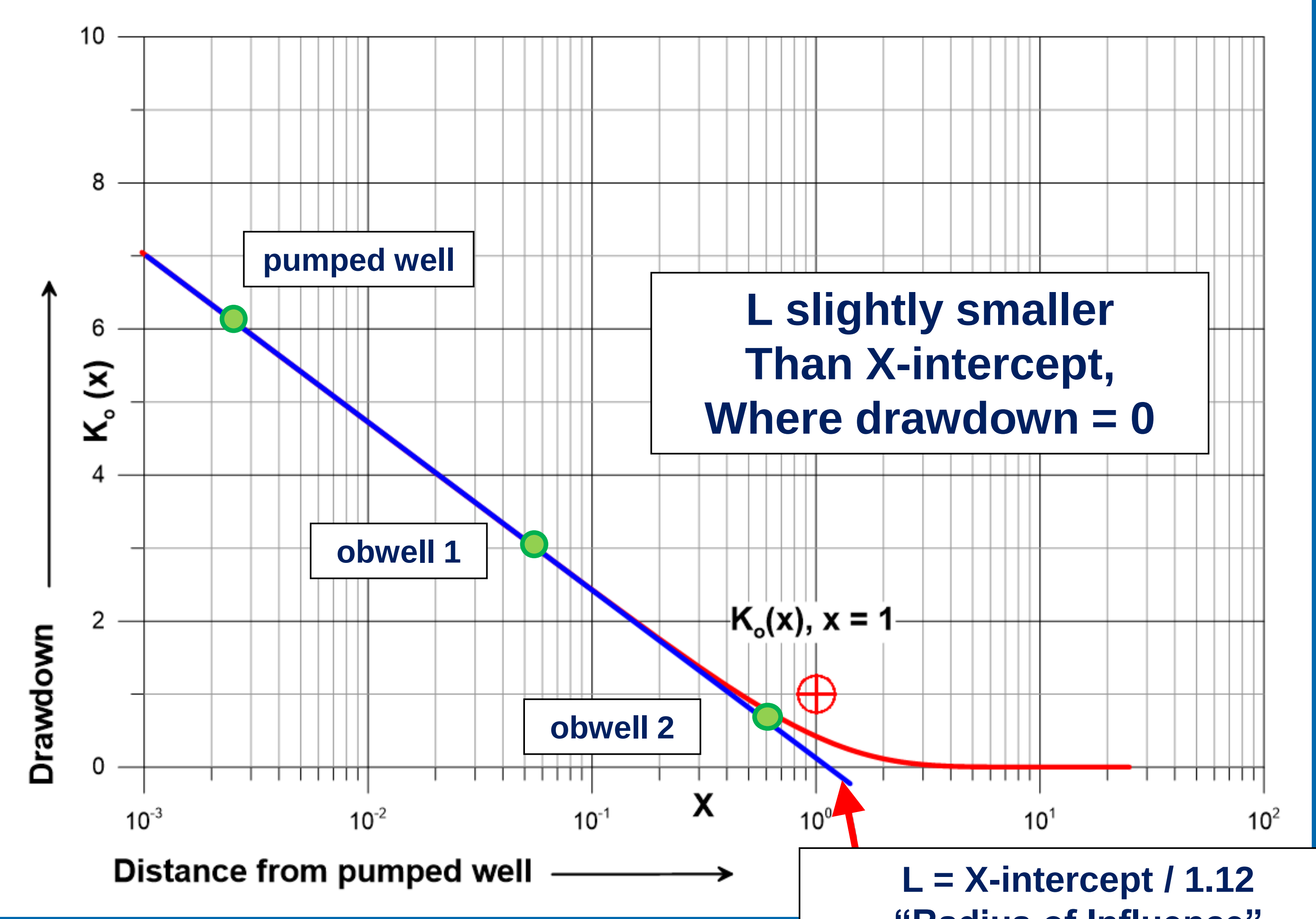
Bessel function of the second kind zero order, $K_o(x)$

Shape of Steady-state Type-Curve Hantush-Jacob (1955 b)



MS Excel function:
BESSELK(x,0)

Steady-state Analysis Shape

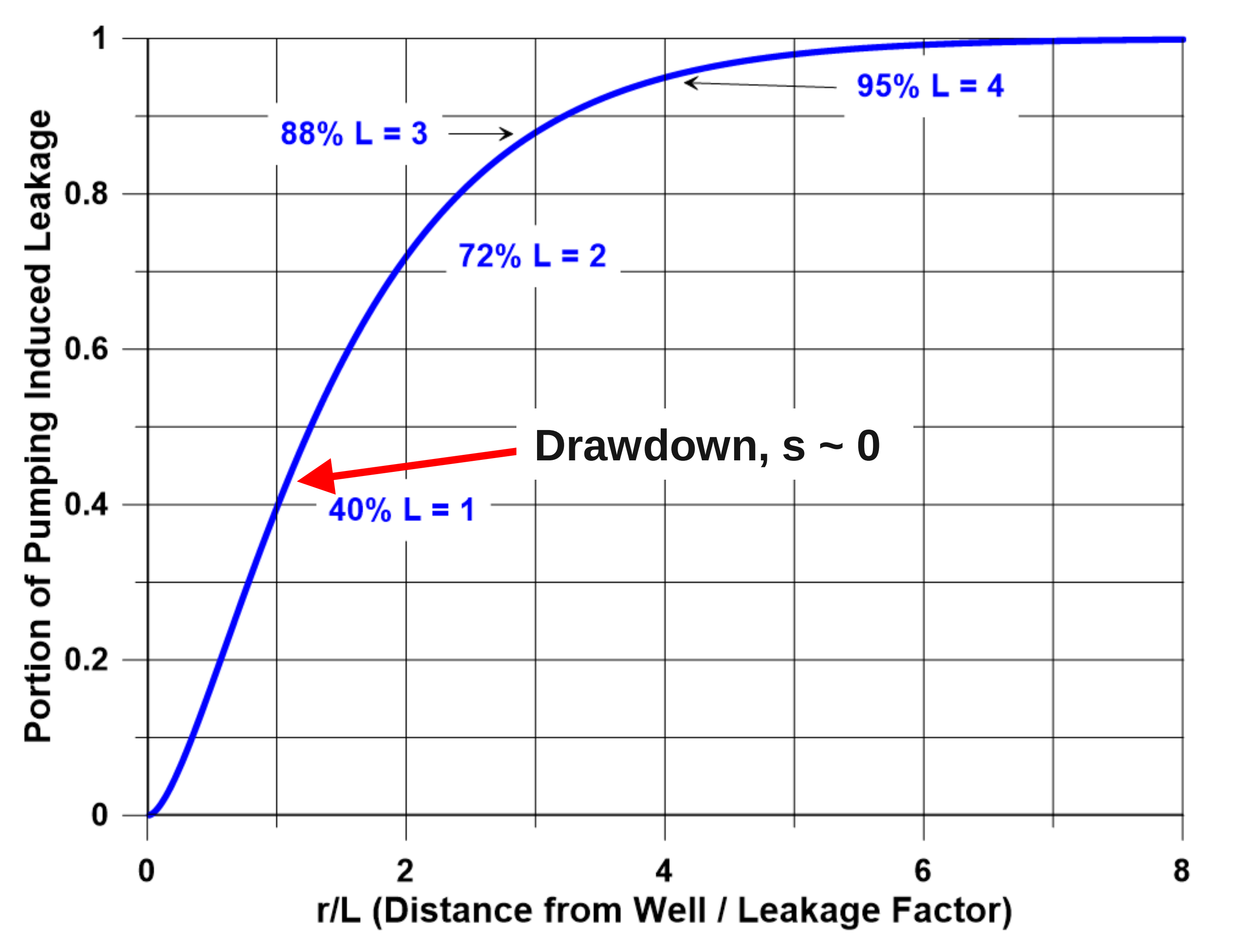


L = X-intercept / 1.12
"Radius of Influence"

T = 2,330 ft²/day
S = 9.6e-4

$X_{(s=0)}$ = 2,340 feet
L = 2,340 / 1.12
L = 2,090 feet

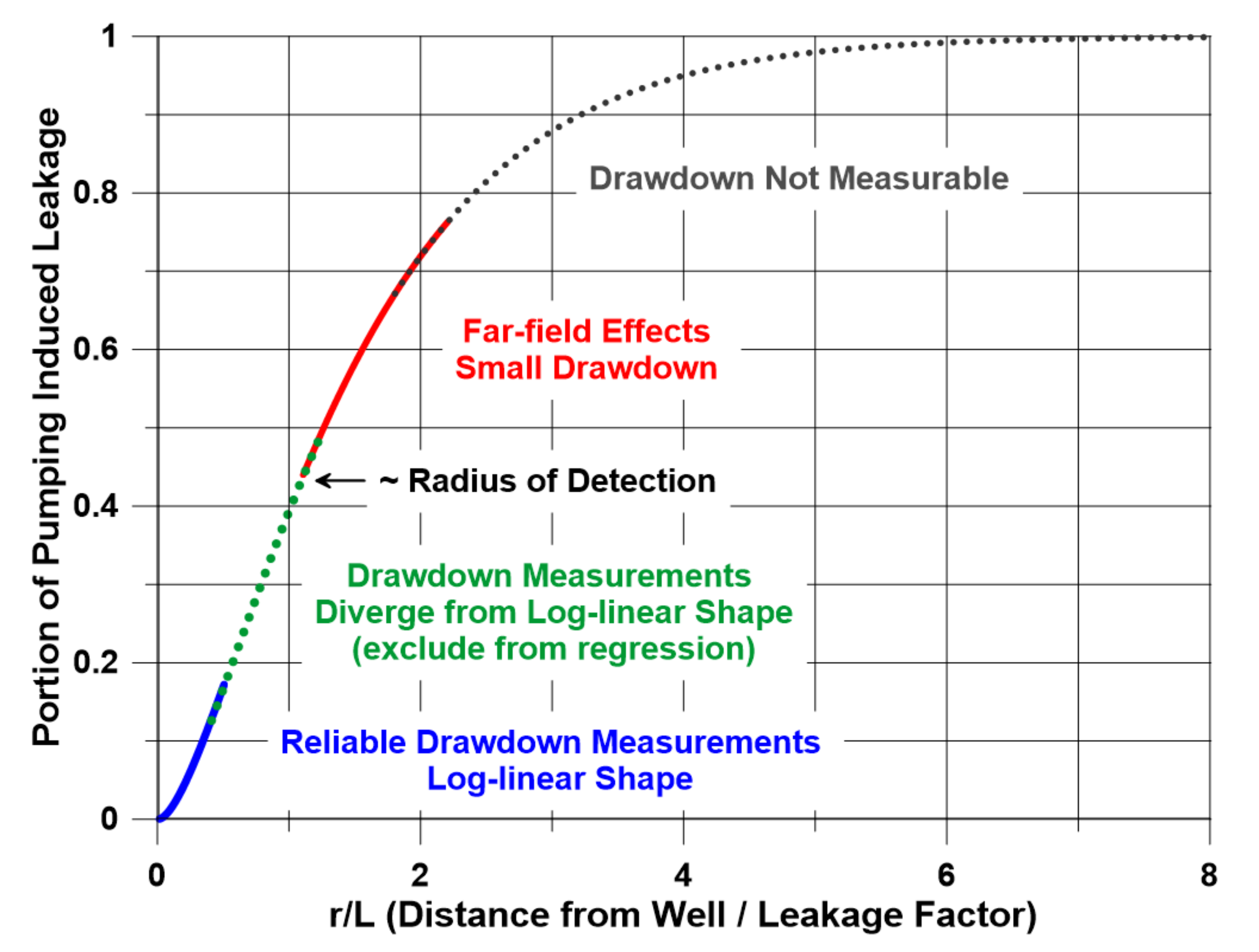
Leakage Factor vs. % of Pumped Volume



“Radius of Influence” Has a Problem

Zhou (2011) Sources of water, travel times and protection areas for wells in semi-confined aquifers. Hydrogeology Journal 19, 1285–1291.
DOI: 10.1007/s10040-011-0762-x

Leakage Factor vs. “Radius of Detection”



Working definition:

s ~ 0 at 1.12 * L

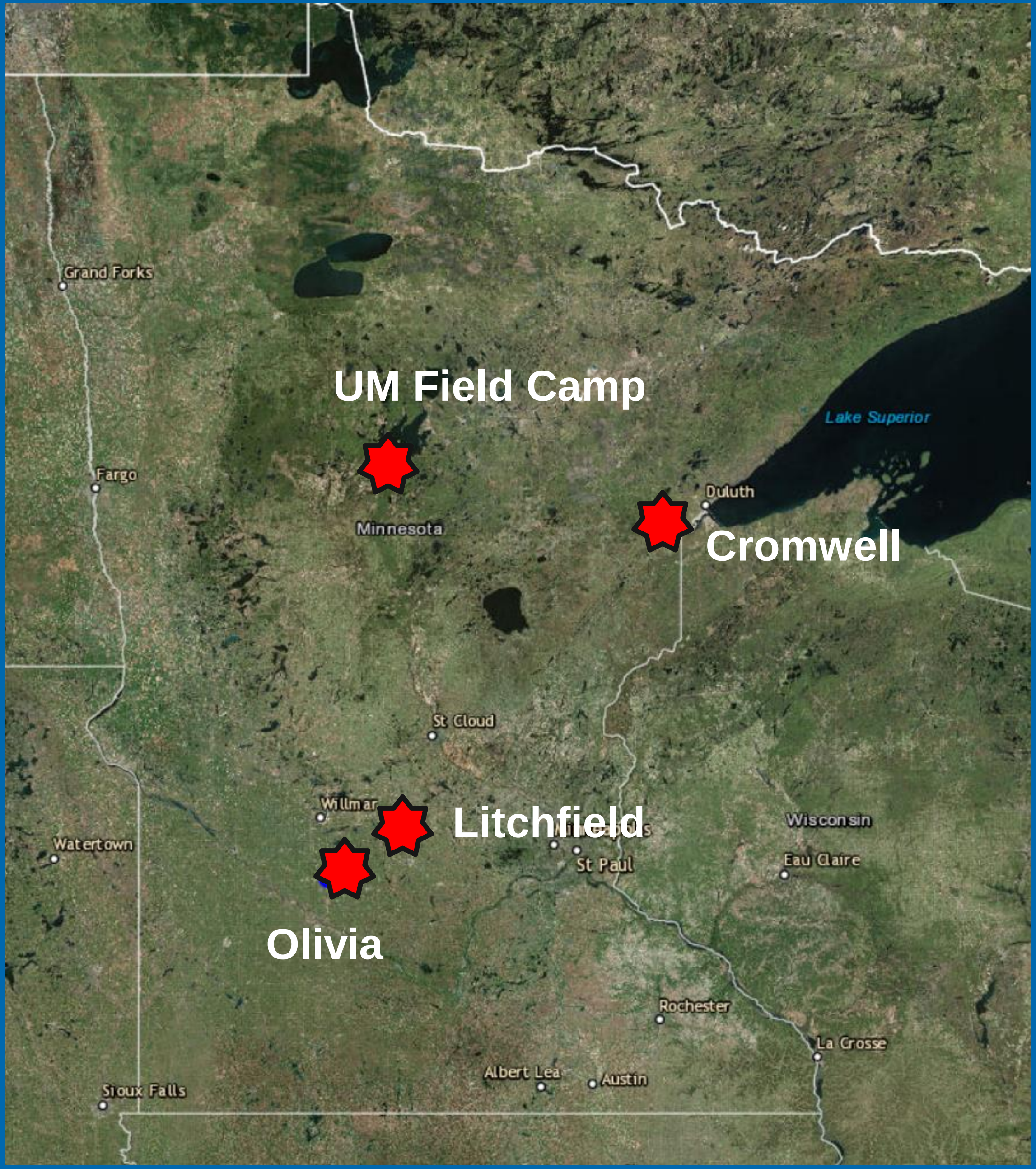
Radius of Detection

~ 30 to 50 % of pumping induced leakage occurs farther than the distance at which there is measurable drawdown

What is this ‘Leakage Factor’?

- 1 of 3 properties, together describe aquifer & leaky setting
- (aquifer transmissivity / aquitard hydraulic resistance) $^{0.5}$
- Required to estimate of vertical conductivity of aquitard, k’
- A distance that is slightly shorter than the X-axis intercept on the semi-log distance-drawdown plot, where s = 0
- Useful scaling factor for a given hydrogeologic setting
  - Estimate of radial limit of observable drawdown, ~radius of detection
  - The radius from the well over which a given portion of pumping volume recharges the aquifer – the distance does not change, regardless of pumping rate

Has Leakage Given You Brain Cramp?



Description of Four Aquifer Tests

Practical Concerns: Water Levels in Till

- Can a reliable signal in till obwells develop within time-frame of traditional one to five-day constant-rate test?
  - Evaluate signal reliability

    Individual - obwell response is log-linear over time?

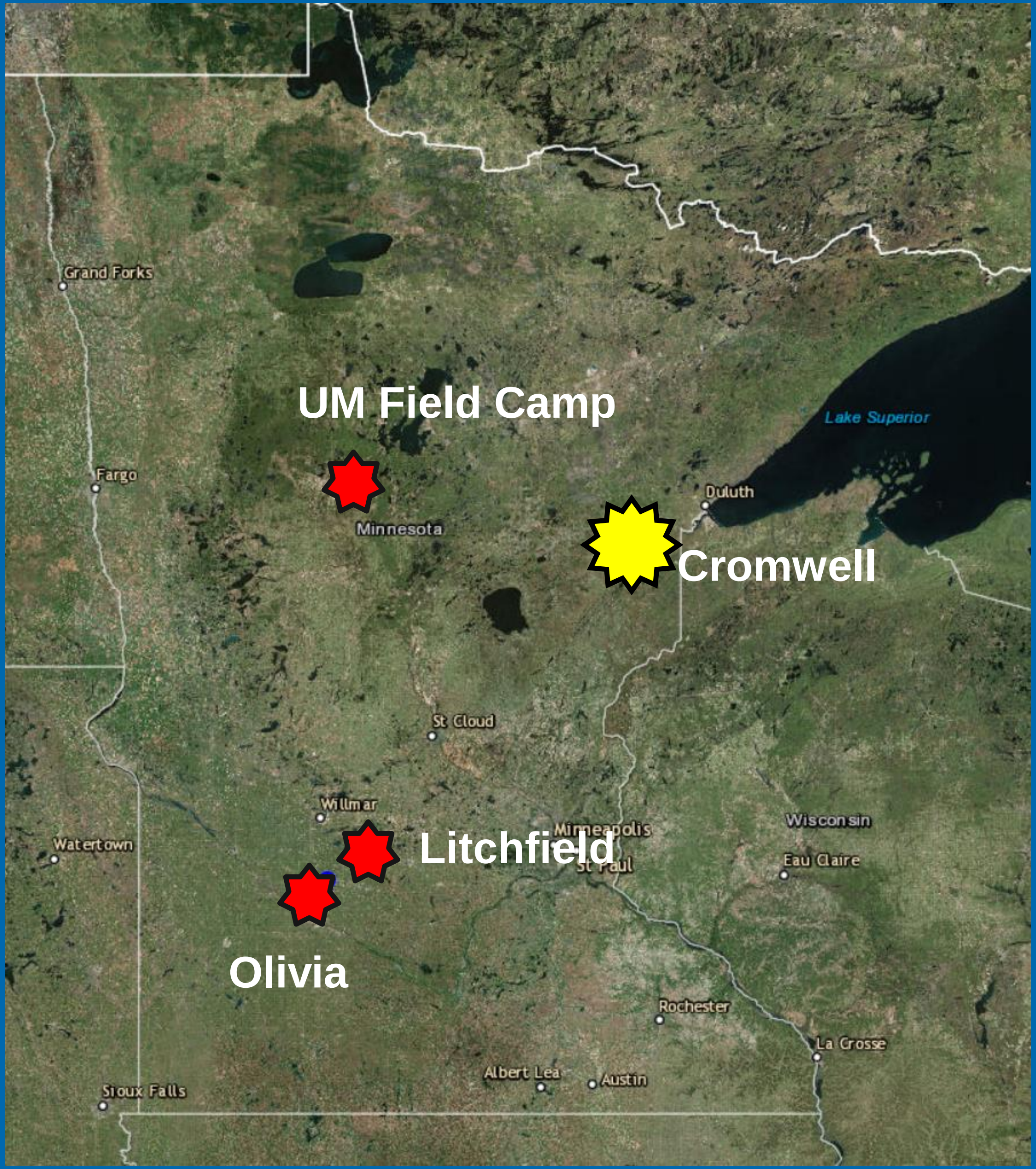
    Aggregate - nest (till thickness / drawdown) is linear?
  - Evaluate effective thickness of till

    Is response linear over the full or partial thickness of till?

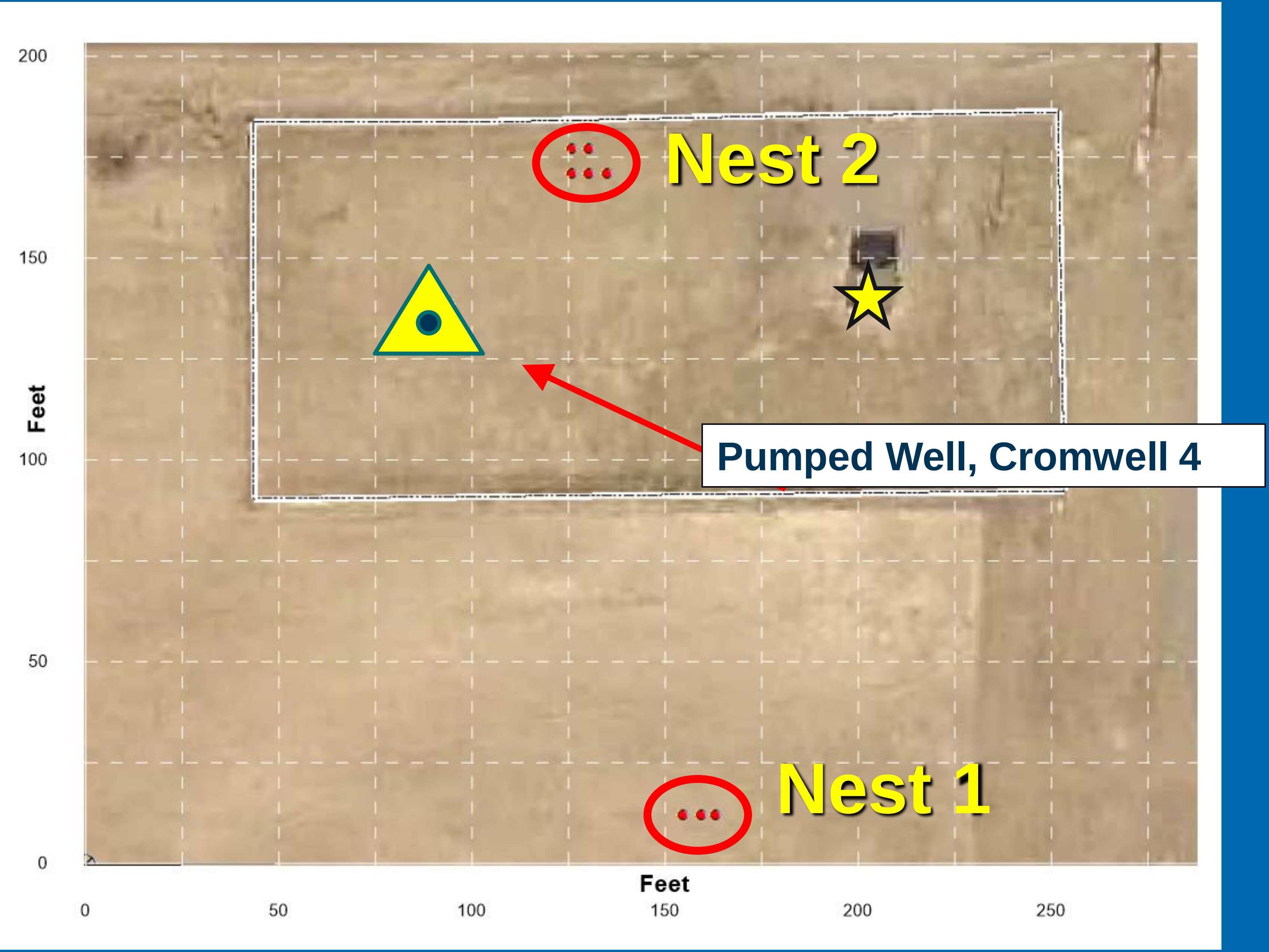
Analysis Process

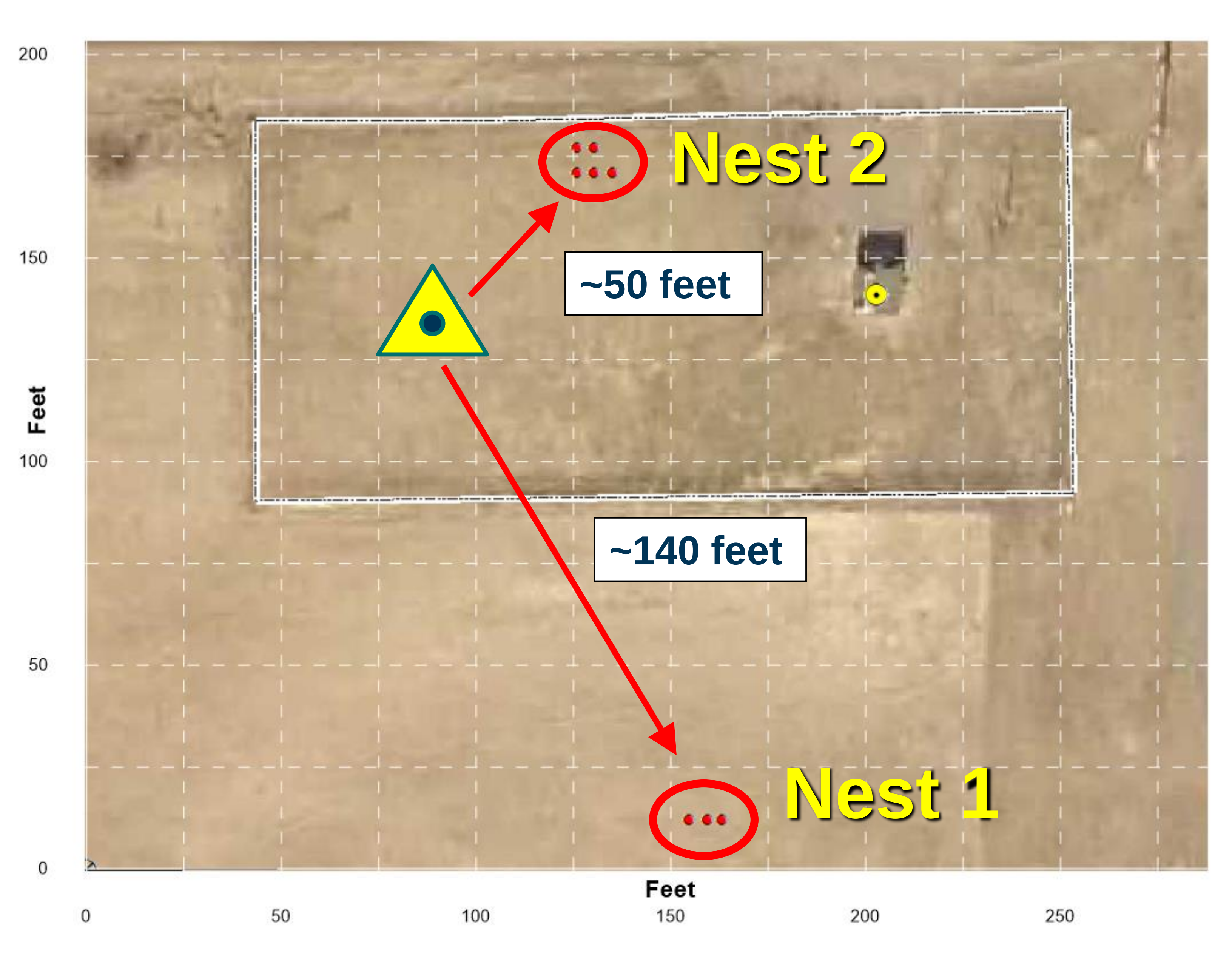
- Characterize aquifer properties (Theis & Hantush-Jacob)
- Verify
  - Drawdown in aquifer at till nest, estimate if necessary
  - Transient response of each till obwell is log-linear
- Estimate effective thickness of till
- Model till obwell data with Aqtesolv, Neuman-Witherspoon solution

Cromwell Location



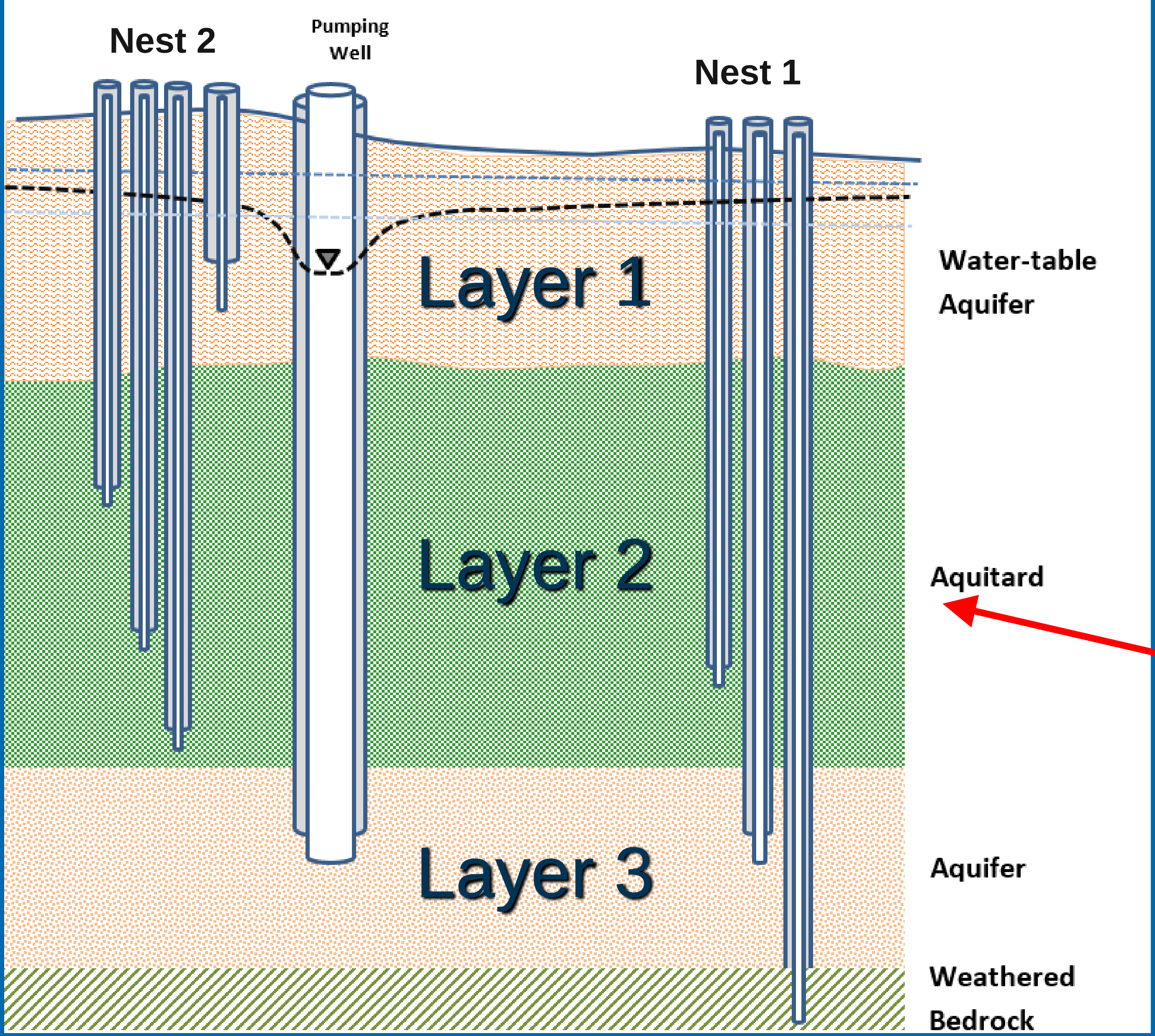
Cromwell Test Site



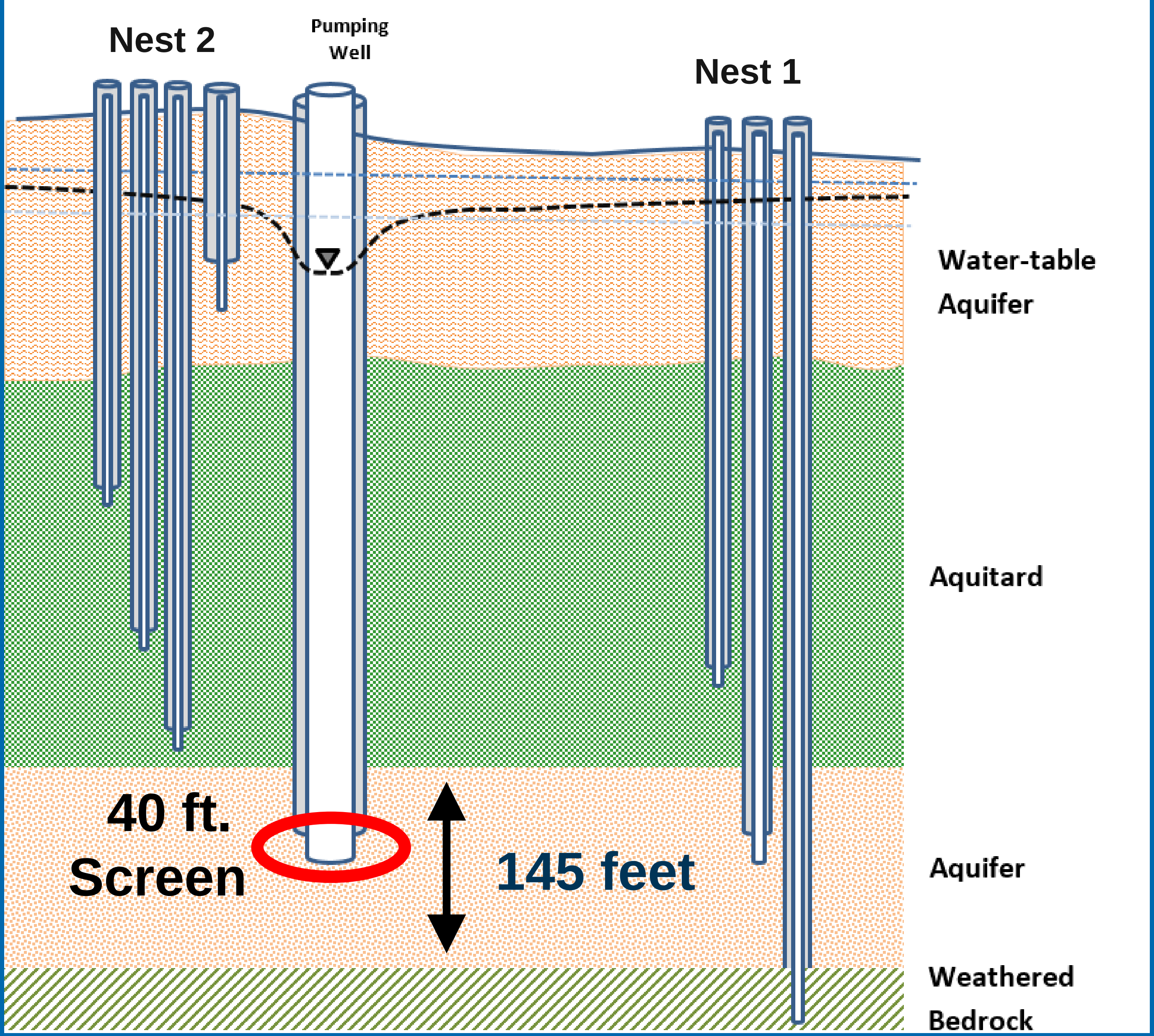


Cromwell Test Site

Cromwell Aquifer Setting



Sandy Superior Lobe Till



Cromwell Aquifer Test

Well is Partially Penetrating:

40 ft. Screen over ~145 ft. Aquifer Thickness

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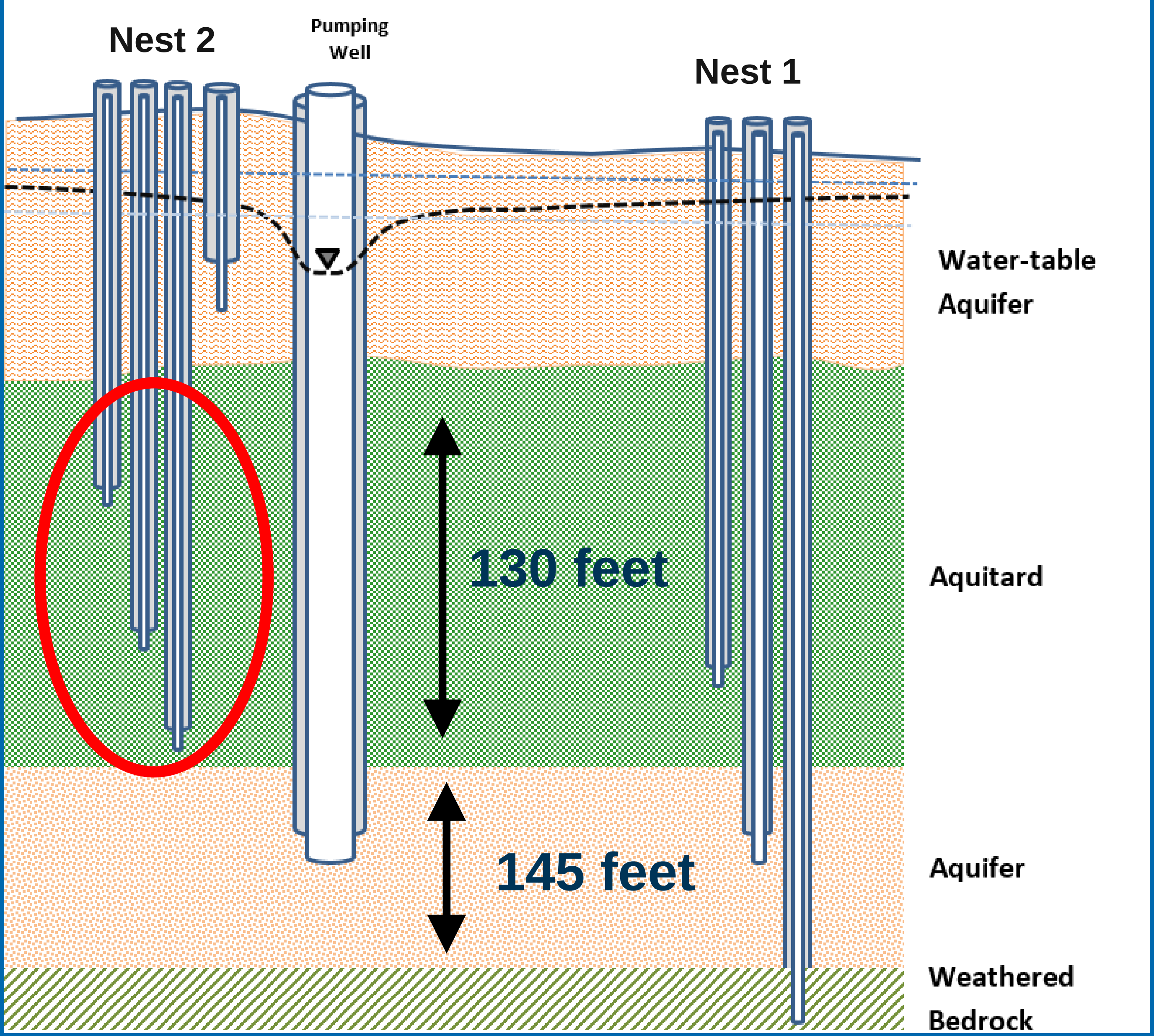
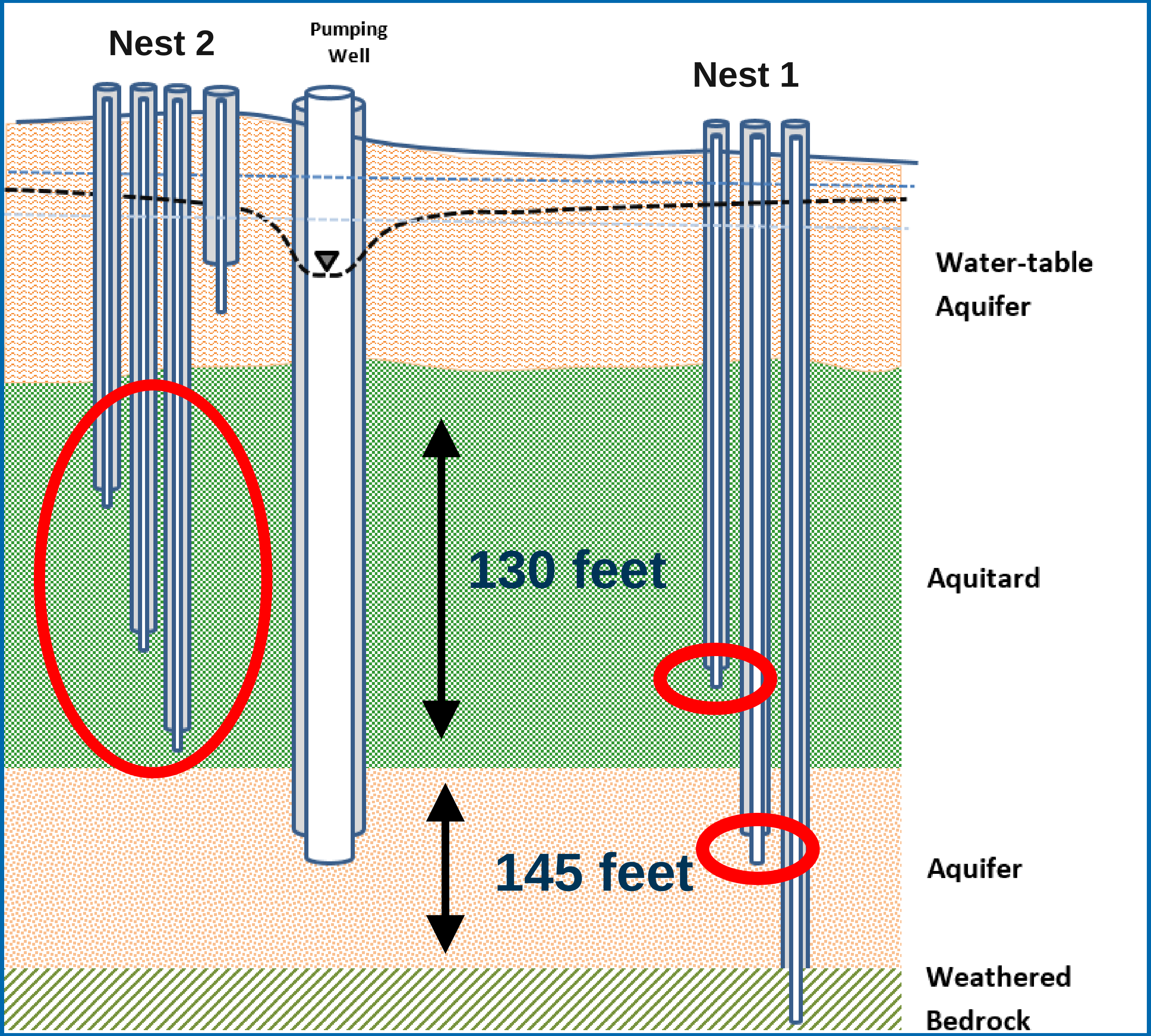


Cromwell Aquifer Test

Nest 2

Four Till Obwells,

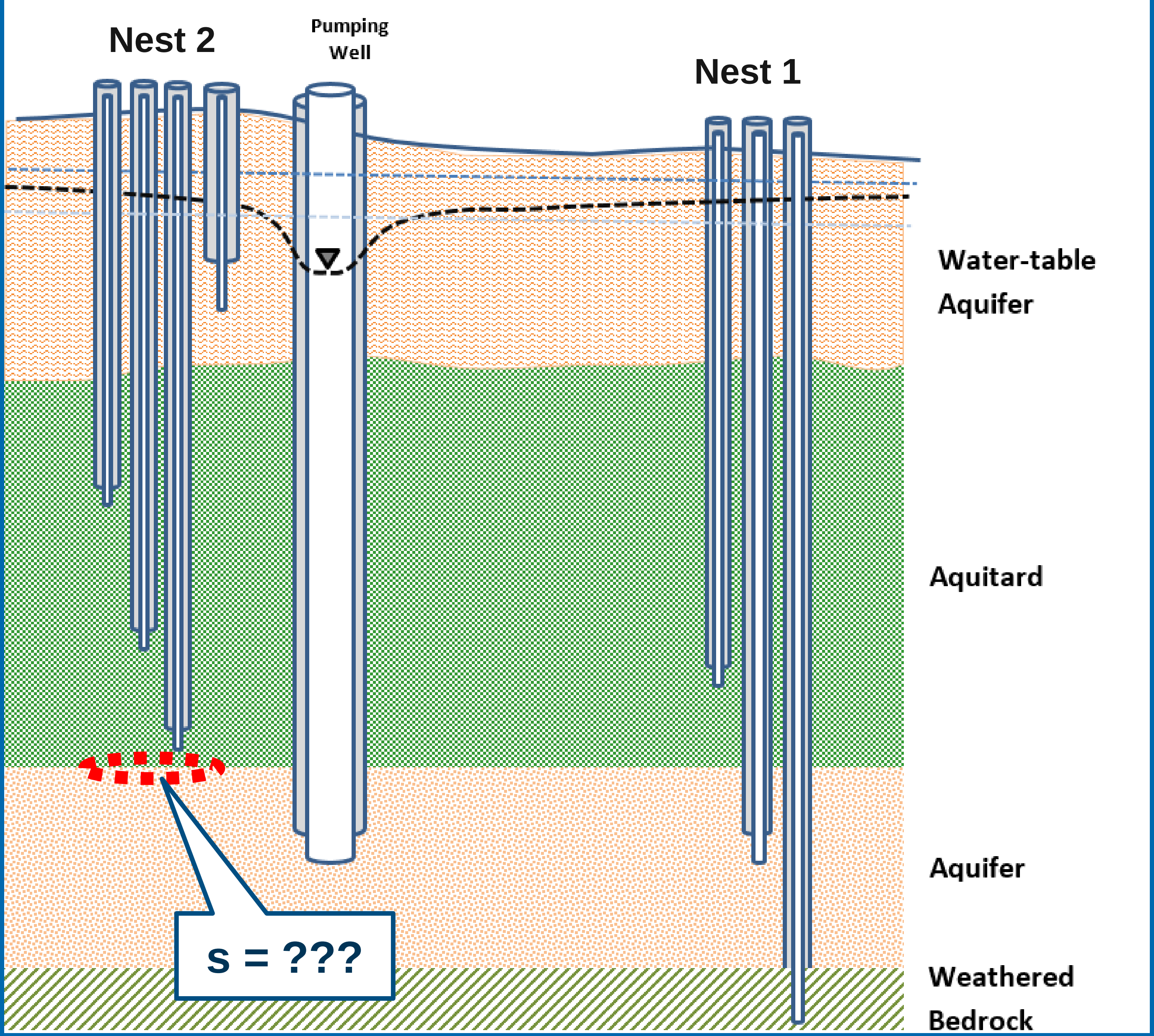
No Obwell in Aquifer



Cromwell Aquifer Test

Nest 1

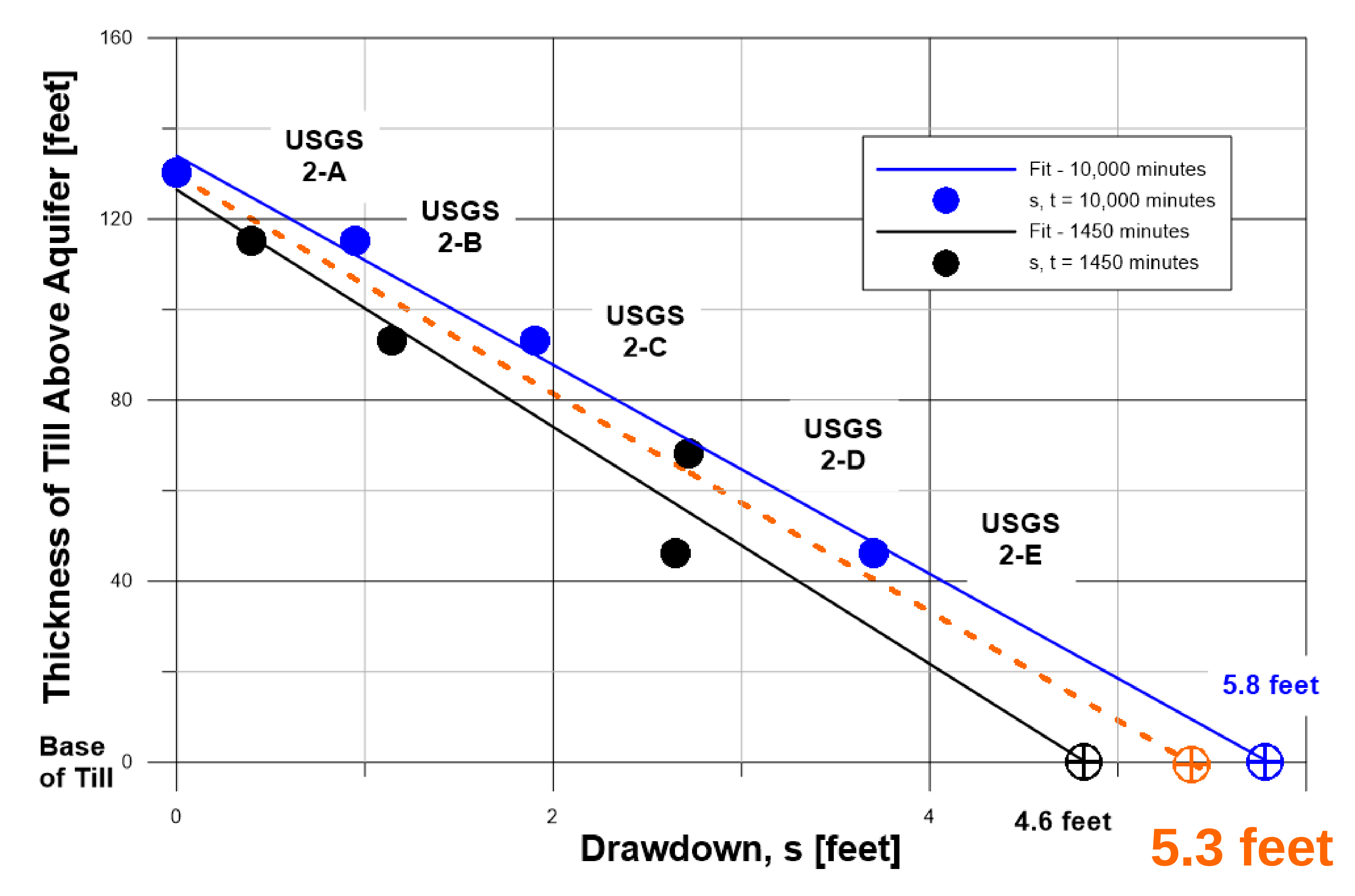
Obwell in Aquifer & Aquitard



Cromwell Aquifer Test

Question:

What is drawdown at top of aquifer - base of till at Nest 2 ?



Cromwell Nest 2

Drawdown at Top of Aquifer

Cromwell Comparison

Method	Well	Transmissivity T (ft^2/day)	Storativity S	Leakage Factor L (feet)	Vertical Hydraulic Conductivity k' (ft/day)
Aqtesolv Hantush-Jacob	**Aquifer** USGS 1-B	4,380*	7.8e-3	330	2.6
	Top of Aquifer	**2,190**			
Aqtesolv Neuman-Witherspoon	**Till** - Nest 1	**2,200**	5.0e-4	590	**0.83**
Aqtesolv Neuman-Witherspoon	**Till** - USGS 1-A & 2-E	1,590	5.5e-2	224	**4.1**

*** Anisotropy $k_z/k_r = 0.5$**

Cromwell Comparison

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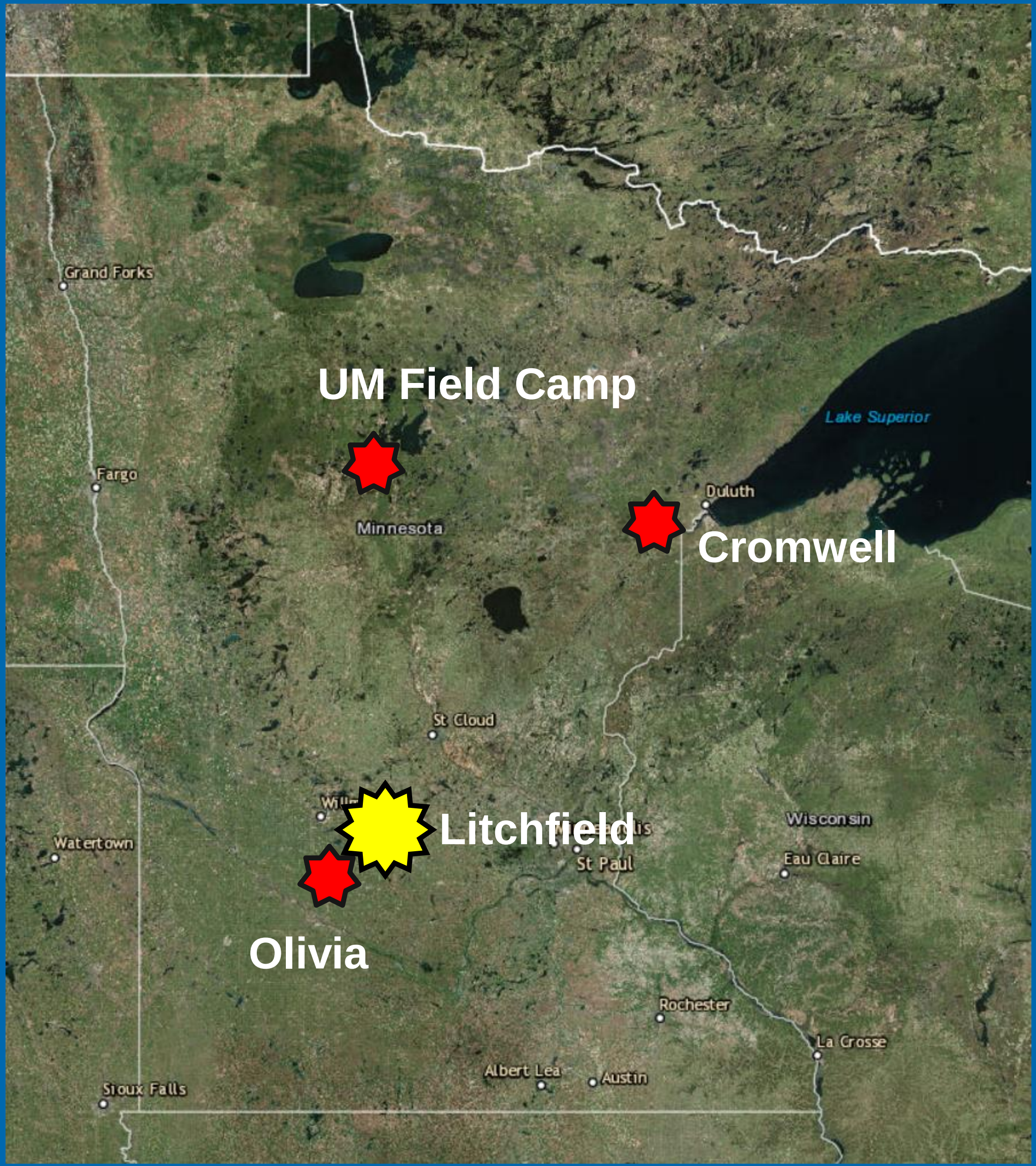
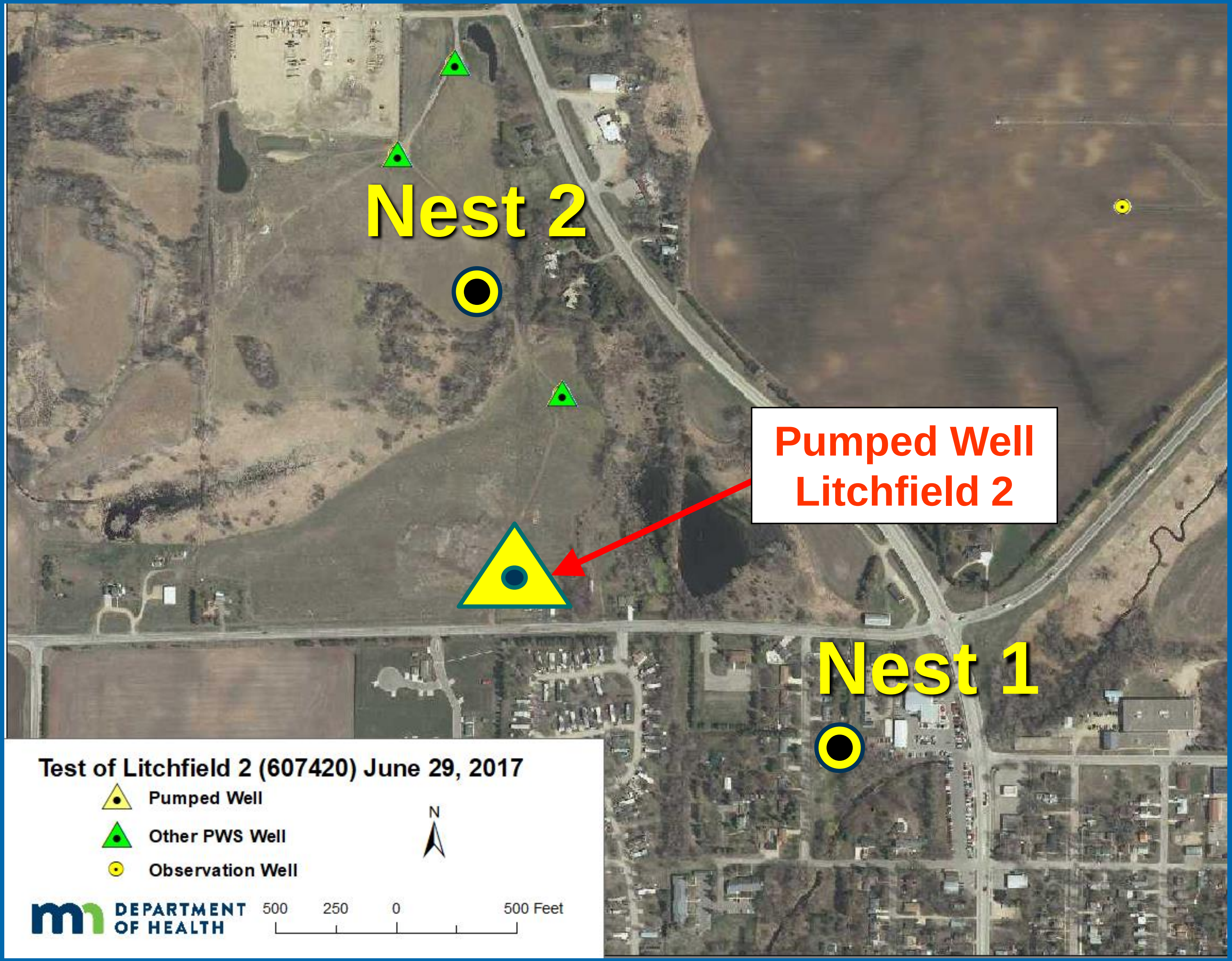
Geometric mean = 2.2

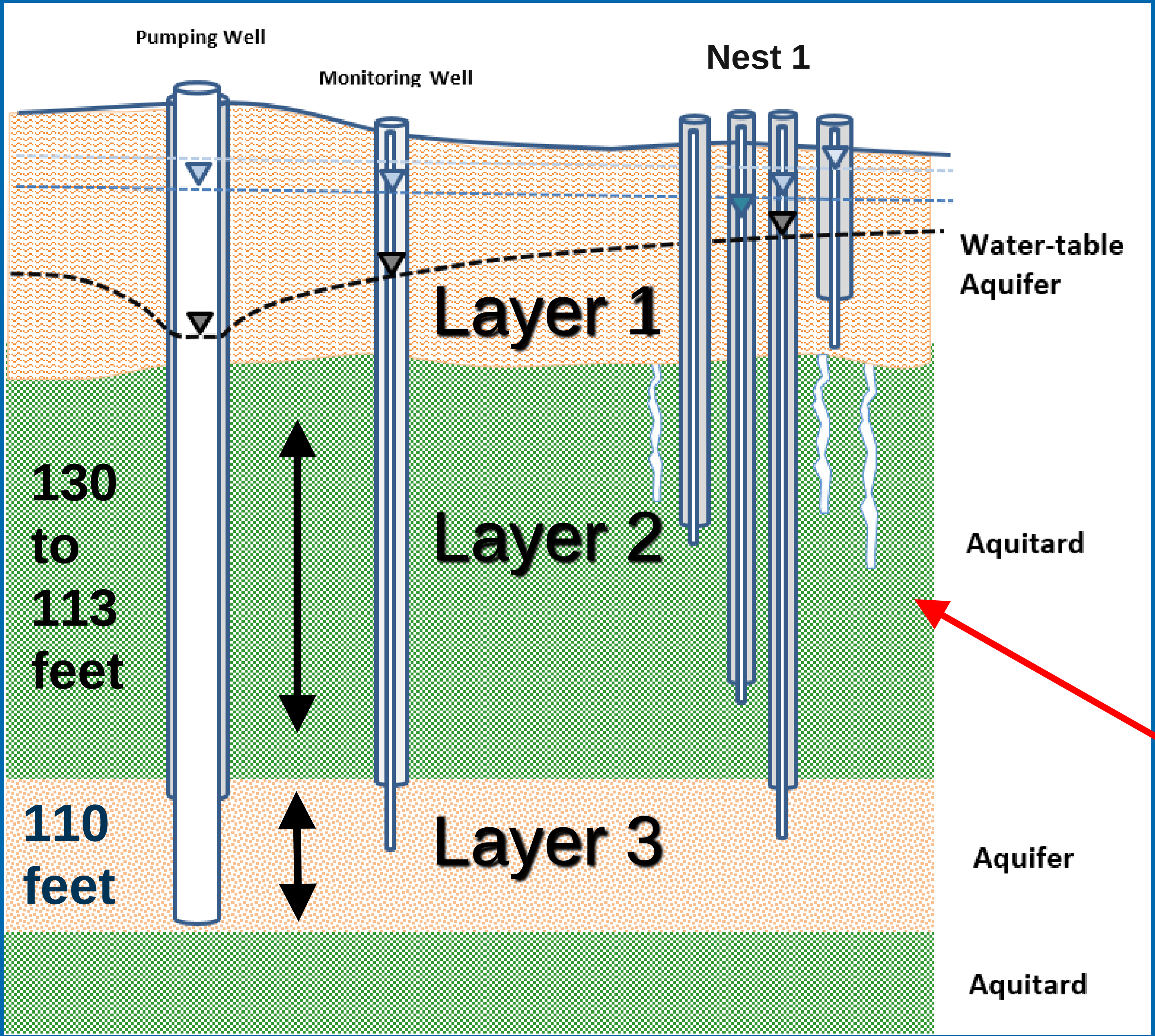
*** Anisotropy k_z/k_r = 0.5**



Litchfield Location

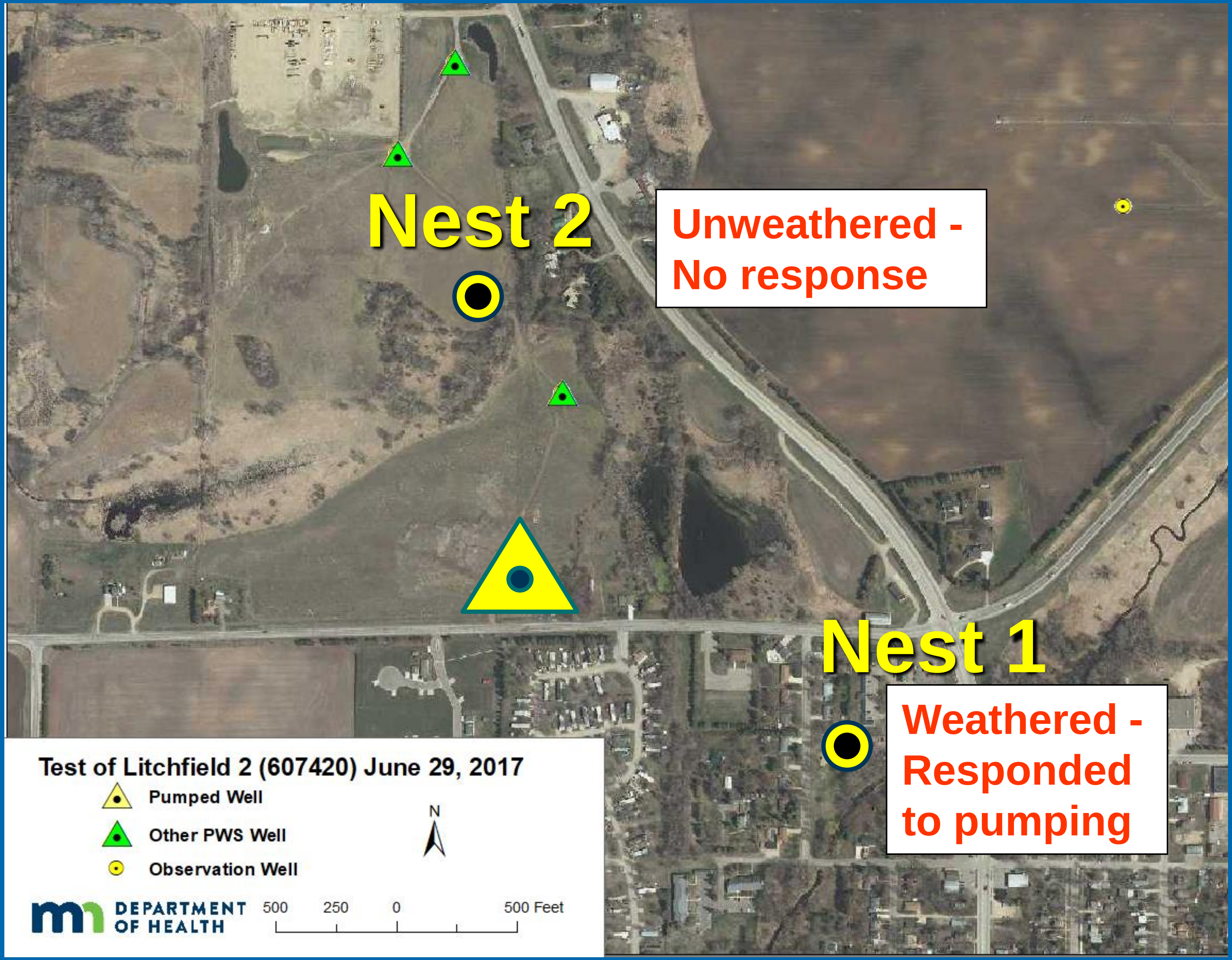
Litchfield Test Site





Litchfield Aquifer Setting

Heavy Clay Till, Weathered in Places



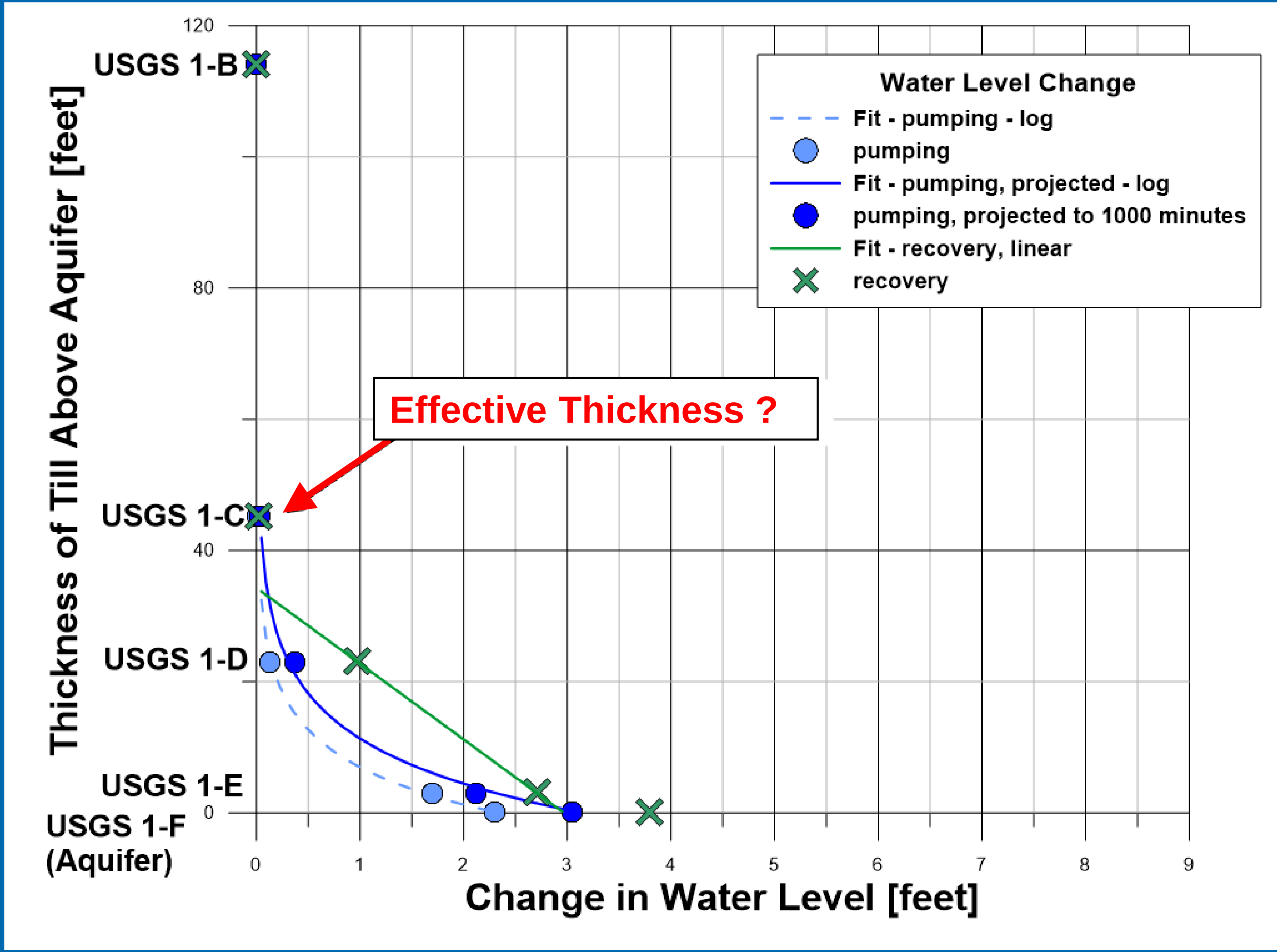
Short-Term Test

Effects of Pumping Only Seen in Till at Nest 1

Litchfield
Analysis of Short-Term Test

Method	Well	Transmissivity T (ft^2/day)	Storativity S	Leakage Factor L (feet)	Vertical Hydraulic Conductivity k’ (ft/day)
Manual Theis t/r^2	**Aquifer** MW (607417)	9,350	1.6e-4	NA	**NA**
Manual Hantush-Jacob	**Aquifer** All	9,170	2.0e-4	24,100	**0.0018***

*** Assumed till thickness of 113 feet, full thickness at Nest 1 site**

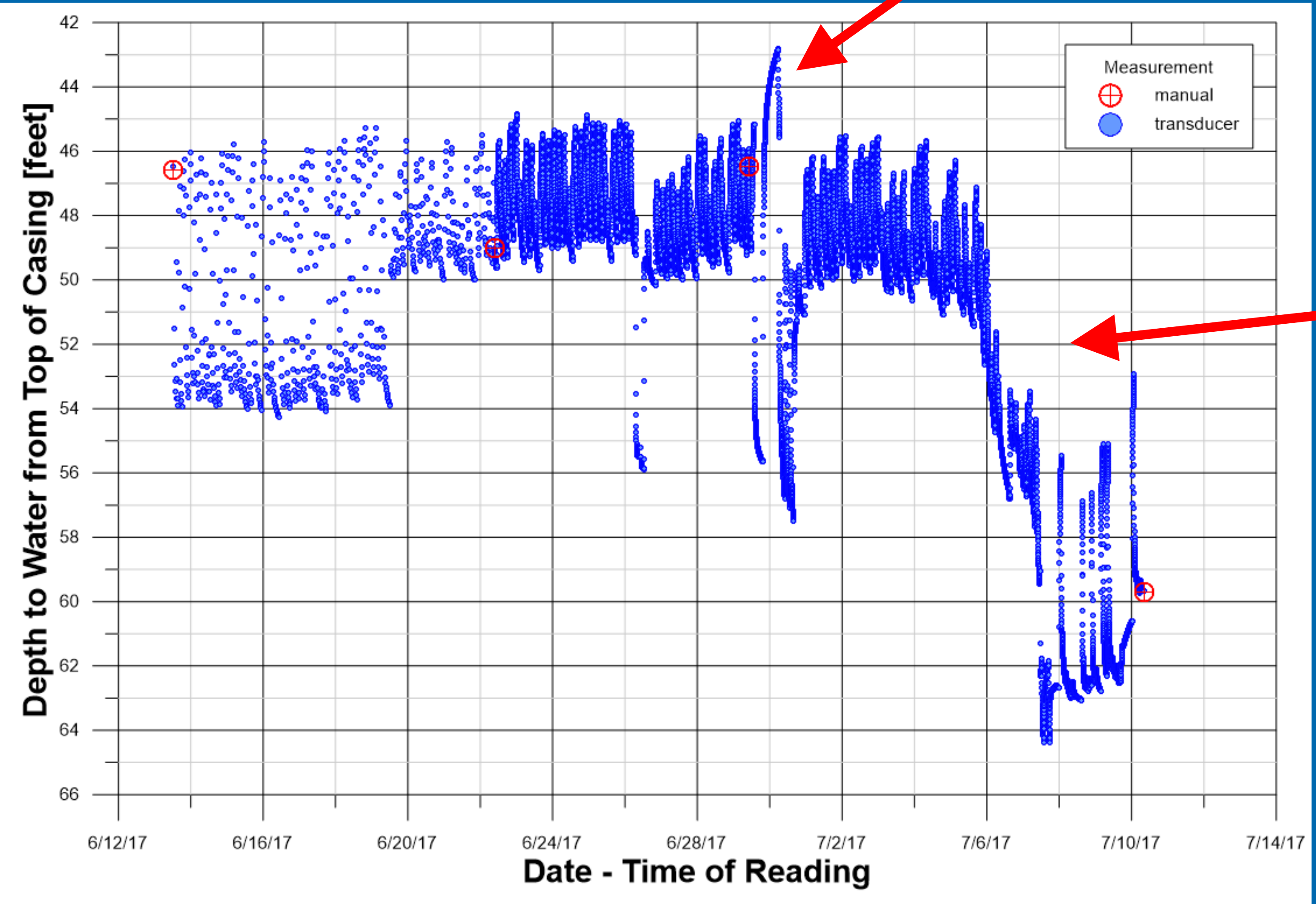


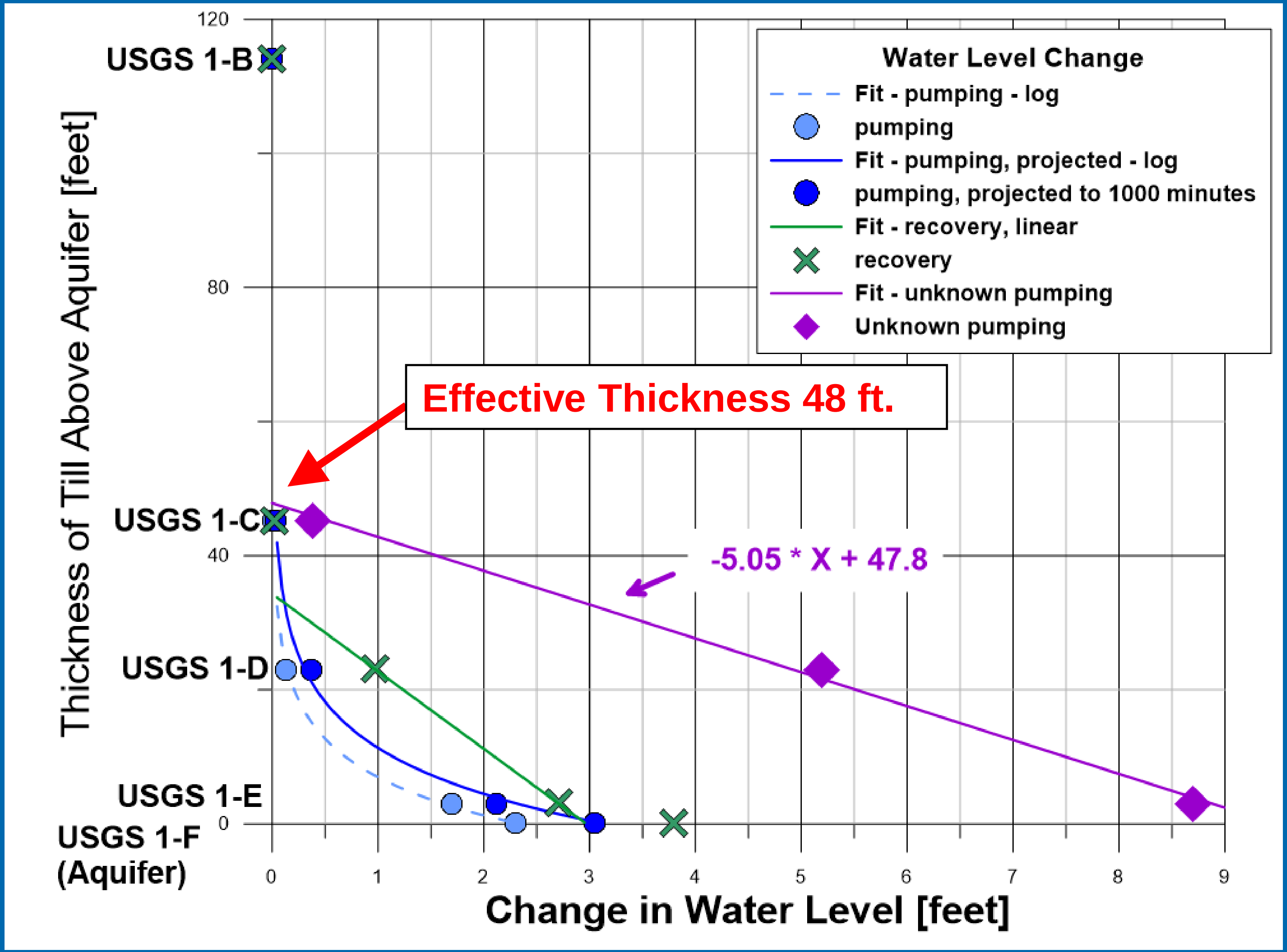
Litchfield Nest 1 Short-Term Test

Non-linear Response in Till… ☹

16-hr Test, June 29, 2017

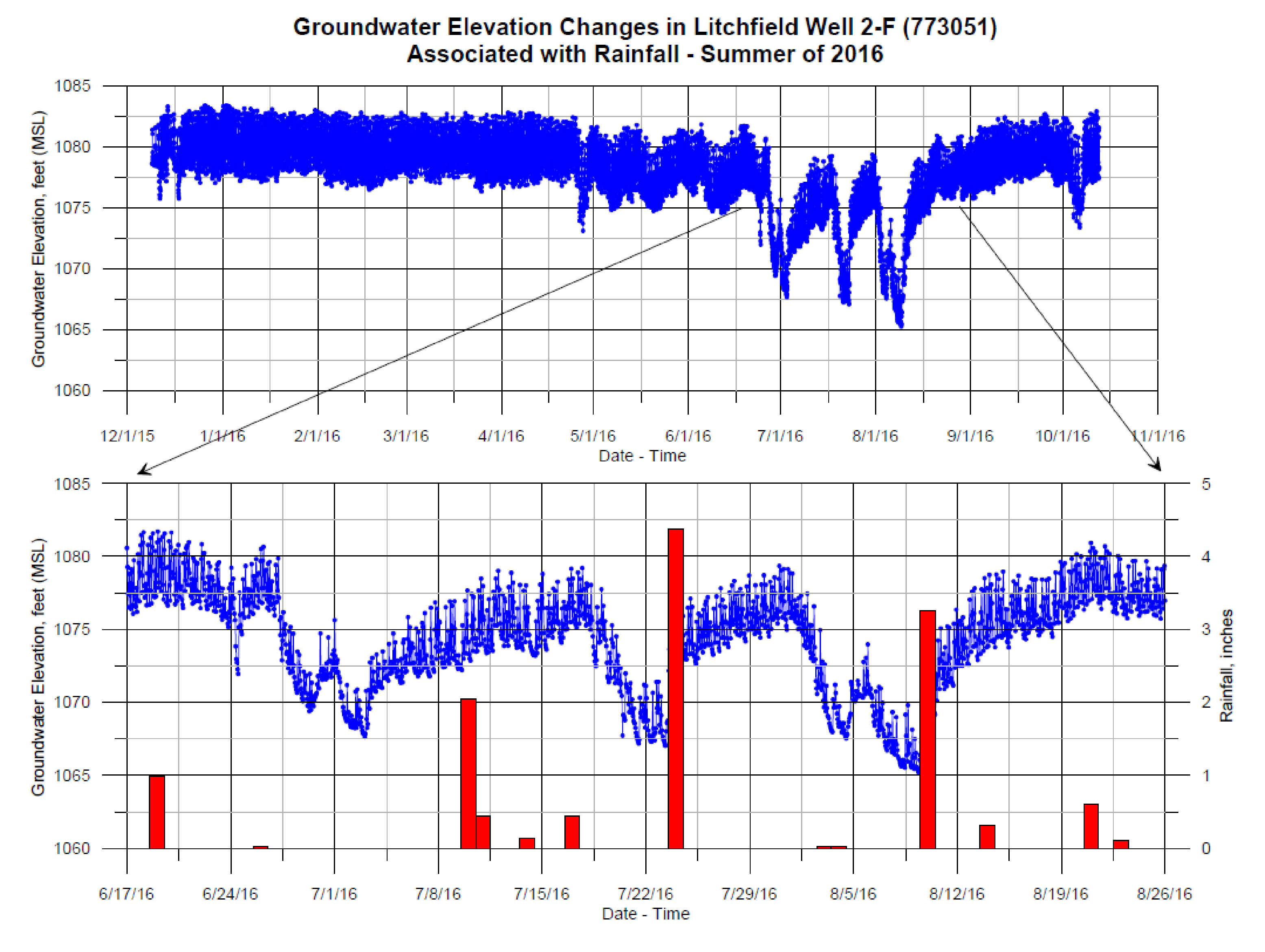
Litchfield MW (607417) Influence of Unknown Wells July 5 - 9, 2017





Litchfield

Linear Response in Till from Pumping of Unknown Well(s)



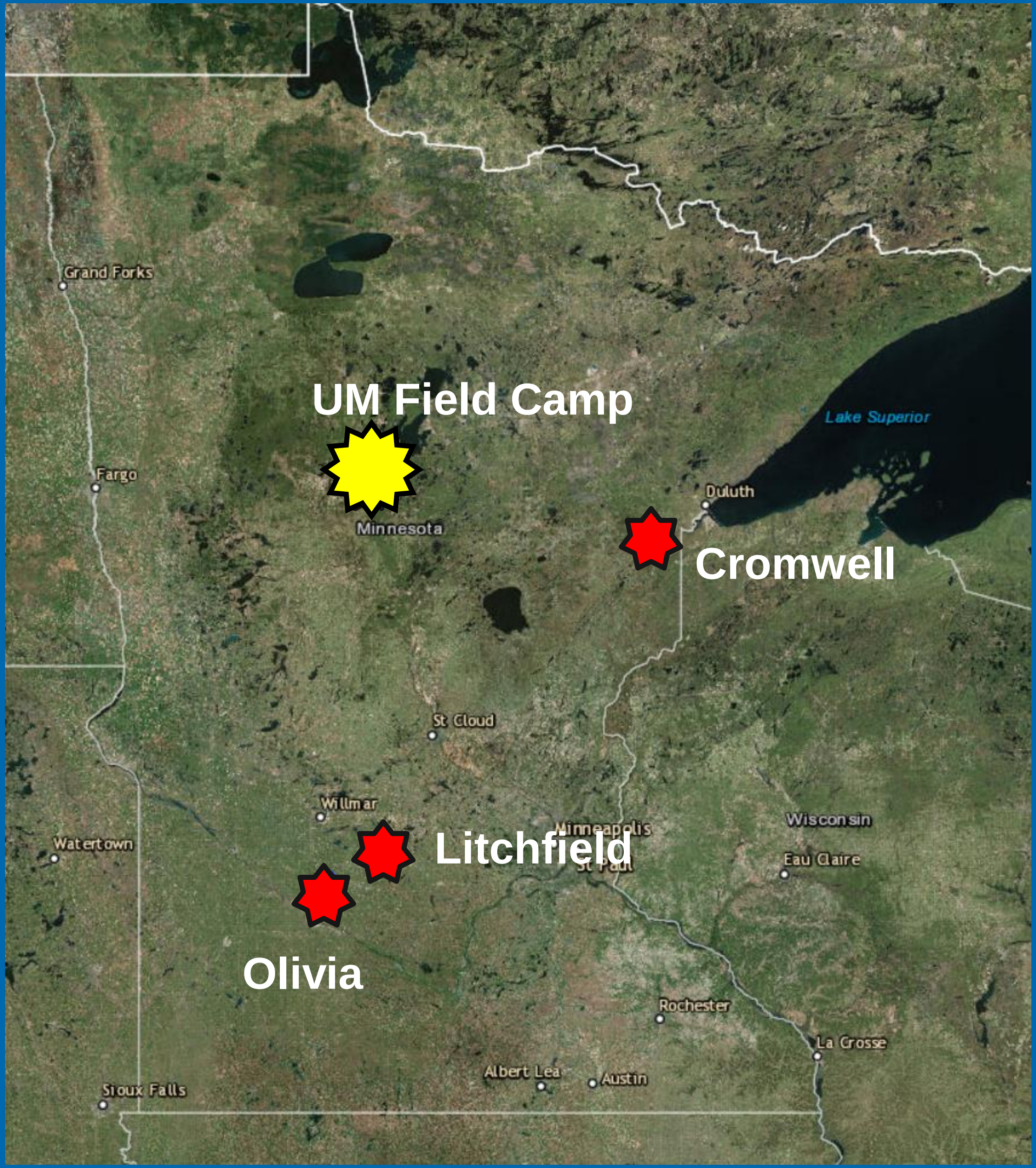
Litchfield

Impact of Regional Irrigation Pumping During 2016

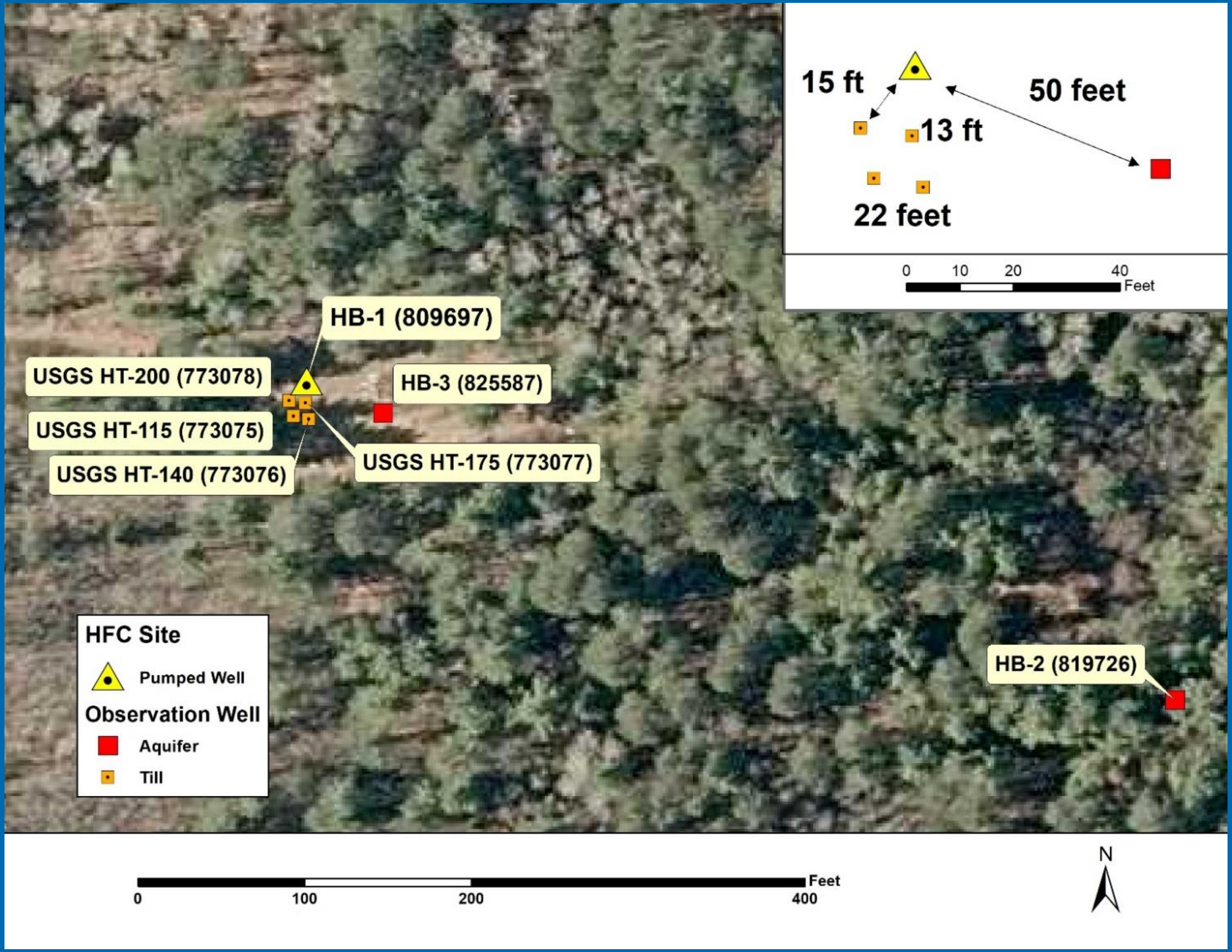
Litchfield Comparison

Method	Well	Transmissivity T (ft^2/day)	Storativity S	Leakage Factor L (feet)	Vertical Hydraulic Conductivity k' (ft/day)*
Manual Hantush-Jacob	Aquifer	9,170	2.0e-4	24,100	**0.0018** (full thickness)
					0.00079
Aqtesolv Hantush-Jacob	Aquifer	11,000	9.5e-5	24,100	0.0009
Aqtesolv Neuman-Witherspoon	**Nest 1**	**8,000**	**2.0e-4**	**20,000**	**0.001**

*** Assumed effective till thickness of 48 feet, partial thickness at Nest 1 site**

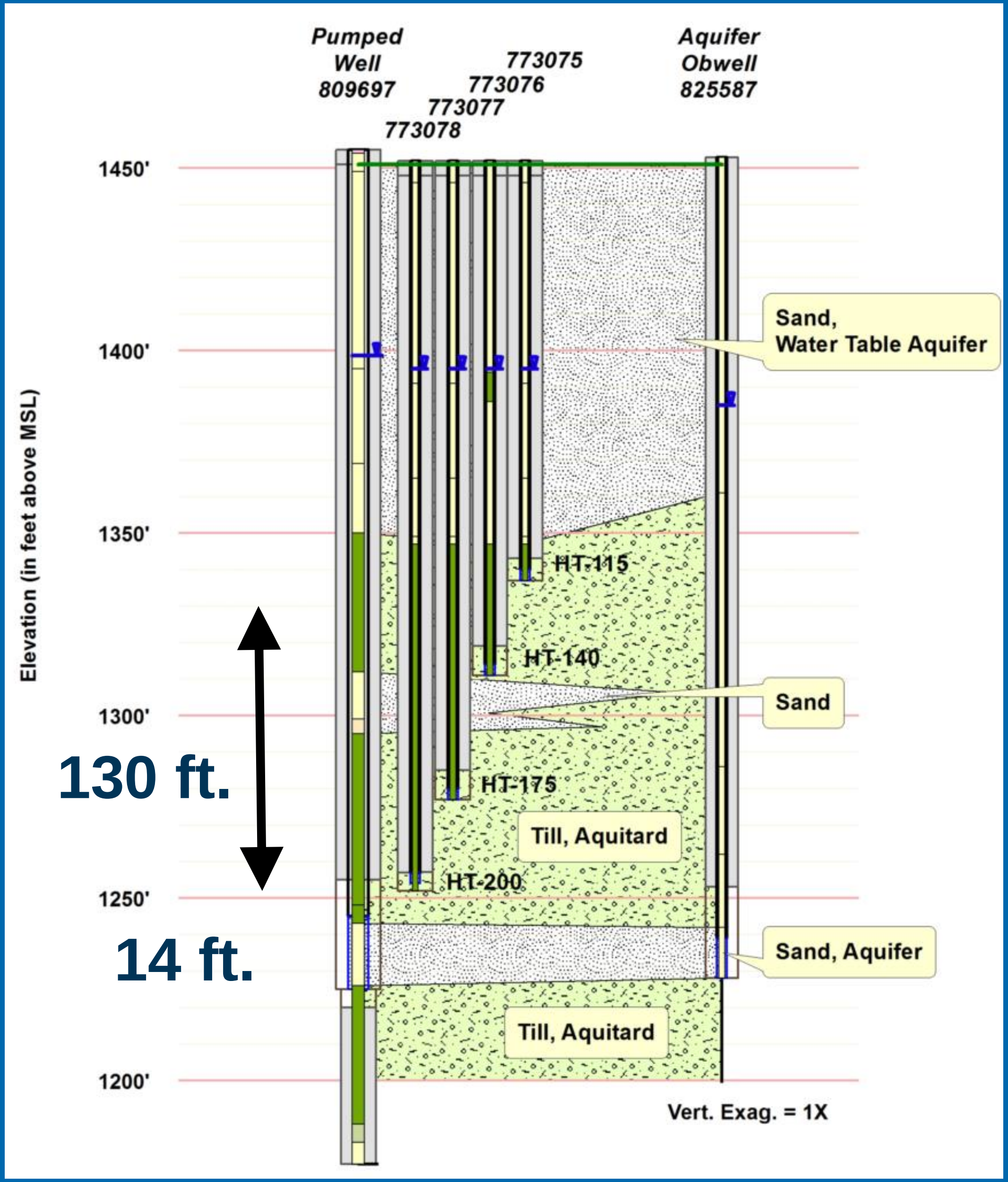


Hydrogeology Field Camp Location



U of M Hydrogeology Field Camp Site (HFC)

HFC Schematic Cross-Section

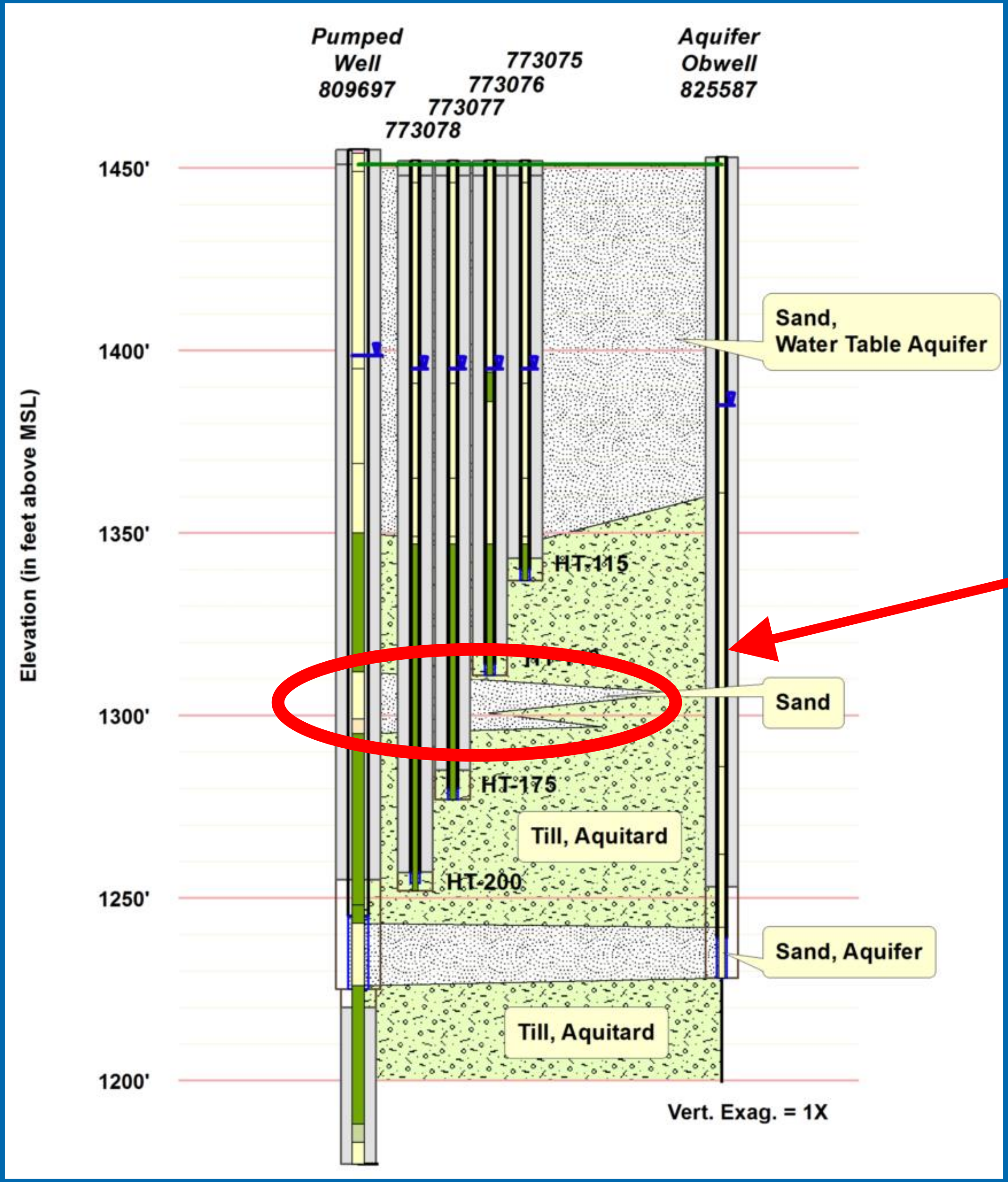


Layer 1 – water table

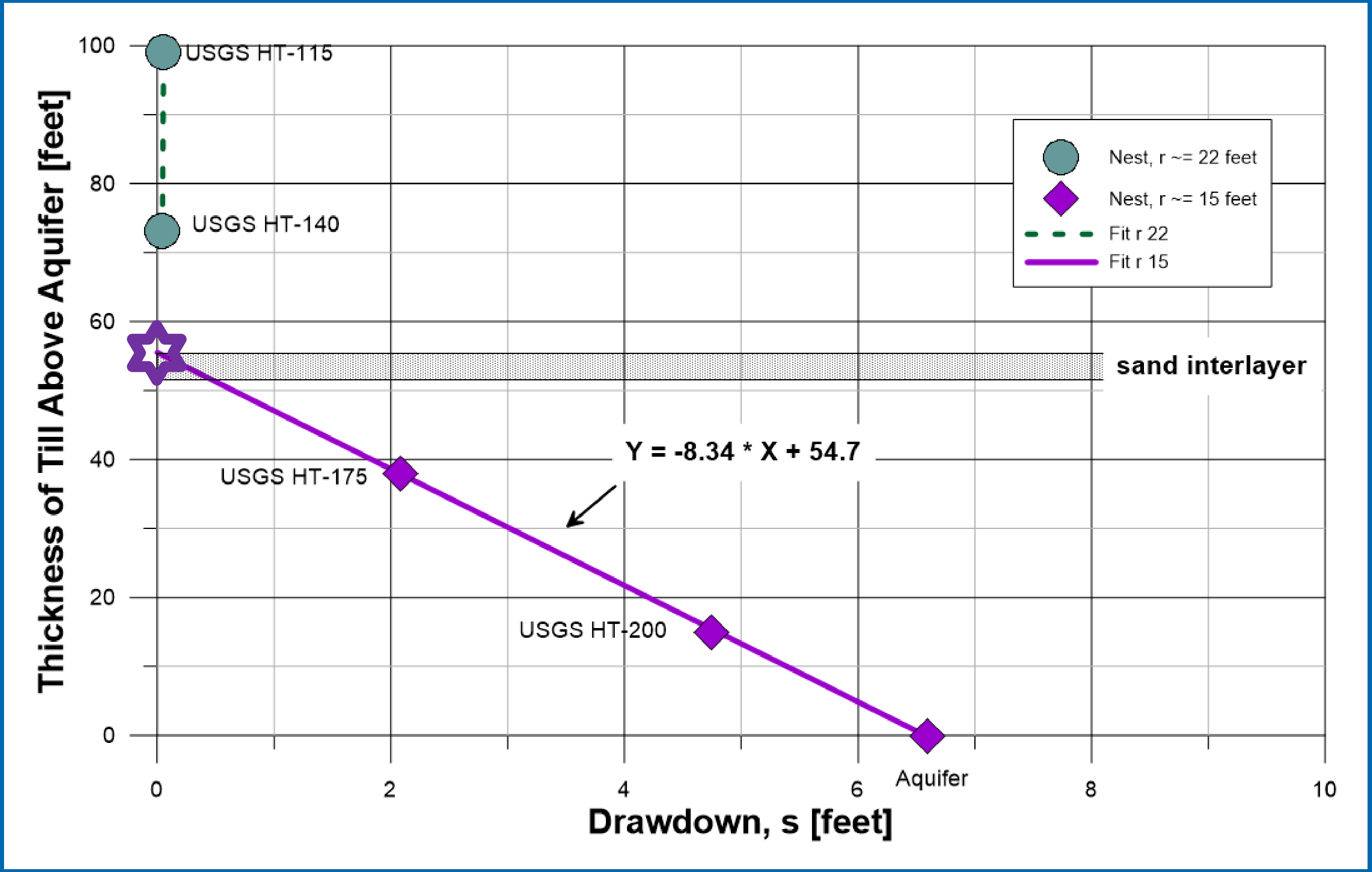
Layer 2 – sandy till

Layer 3 - aquifer

HFC Schematic Cross-Section



Till Heterogeneity, Local Sand Interlayer with Limited Extent



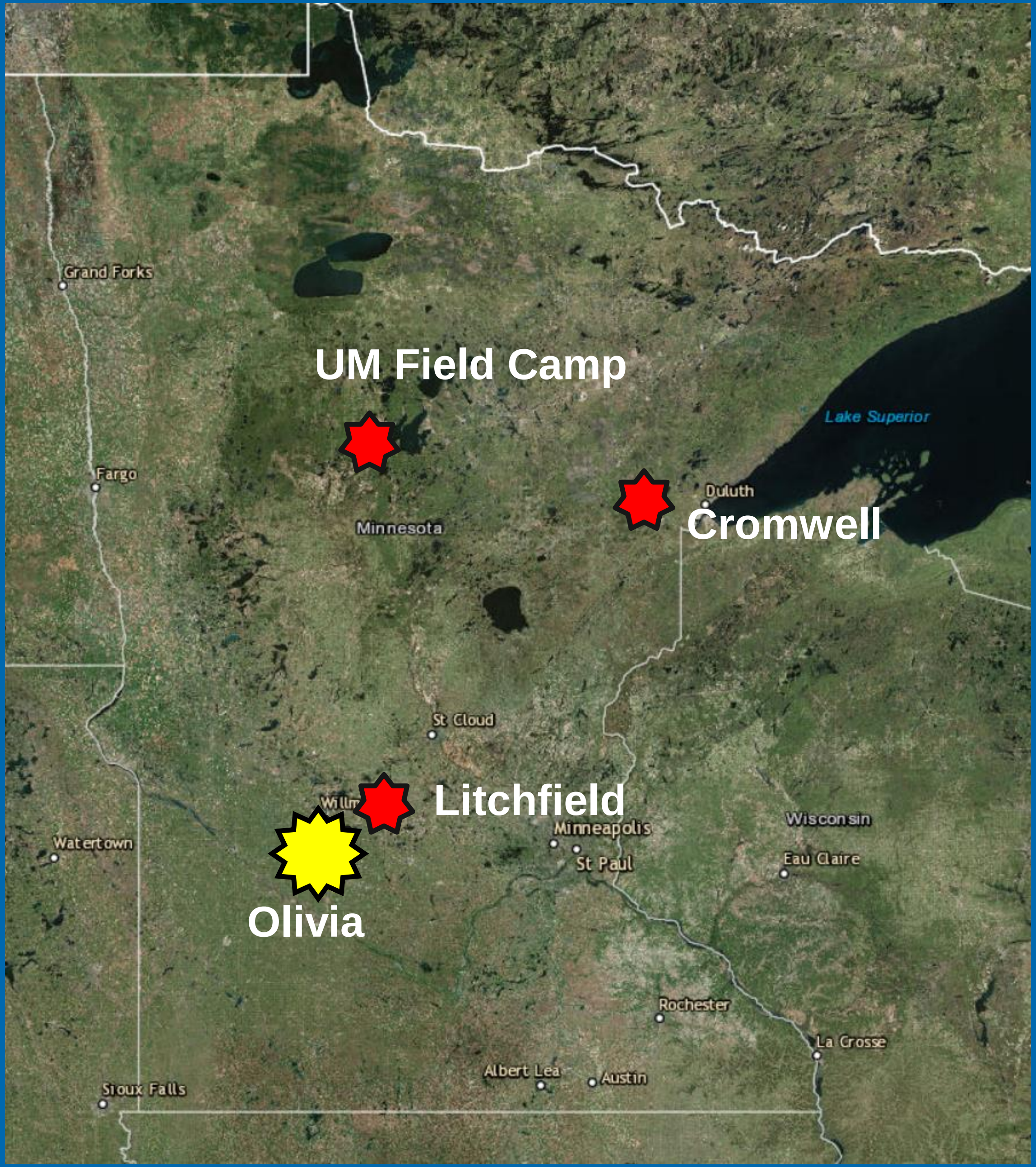
HFC Effective thickness of Till ~ 55 feet

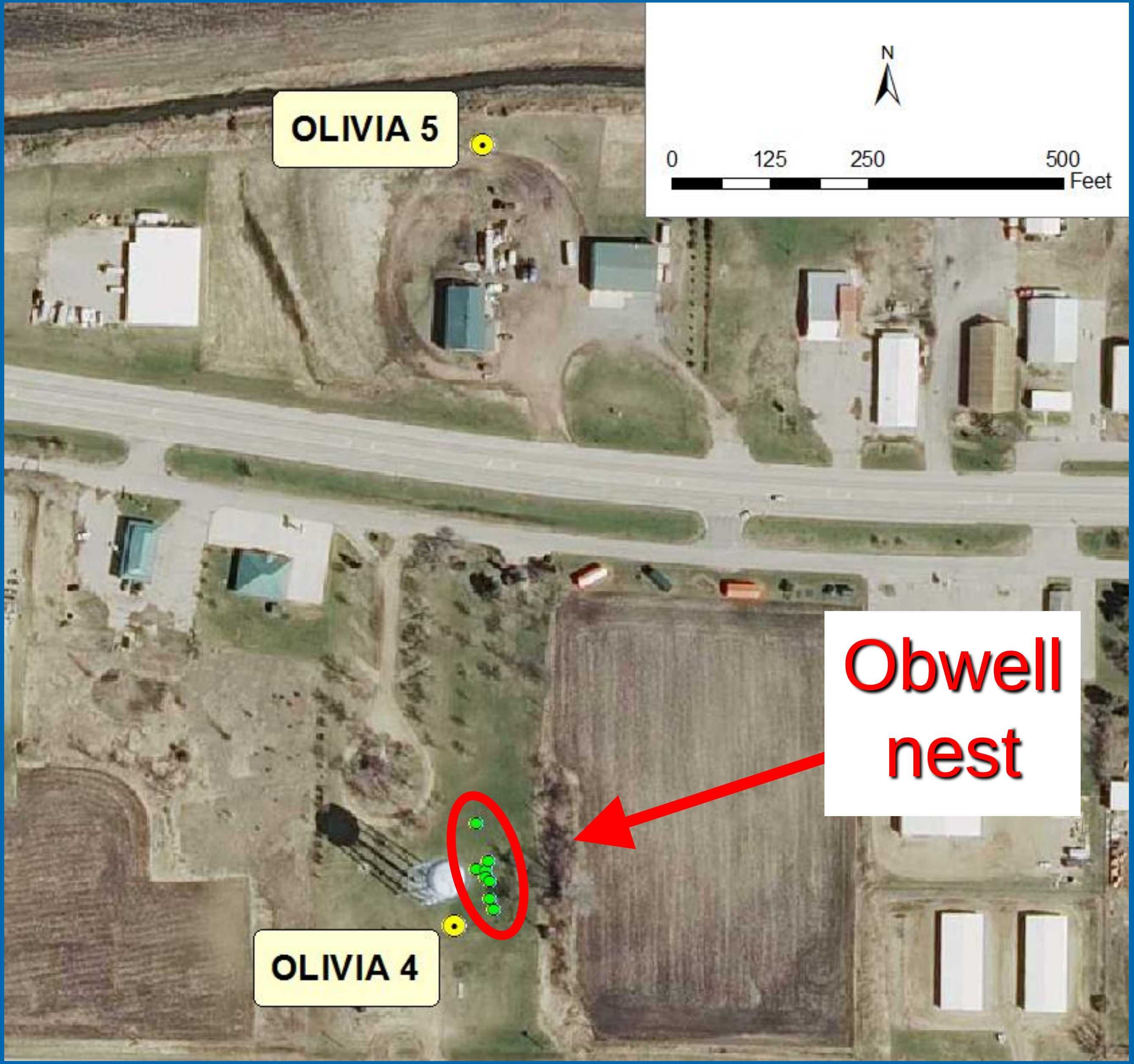
HFC Comparison

Method	Well	Transmissivity T (ft^2/day)	Storativity S	Leakage Factor L (feet)	Vertical Hydraulic Conductivity k' (ft/day)
Manual Hantush-Jacob	Aquifer	1, 380	7.3e-4	2,630	0.023
Aqtesolv Hantush-Jacob	Aquifer	1,360	5.8e-5	2,330	**0.029**
Aqtesolv Neuman-Witherspoon	Aquifer	1,340	5.8e-5	2,350	0.027
Aqtesolv Neuman-Witherspoon	**Till Obwell**	1,430	6.9e-4	2,770	**0.0093***

*** Assumed till thickness of 55 feet, partial thickness deep till obwells**

Olivia Location

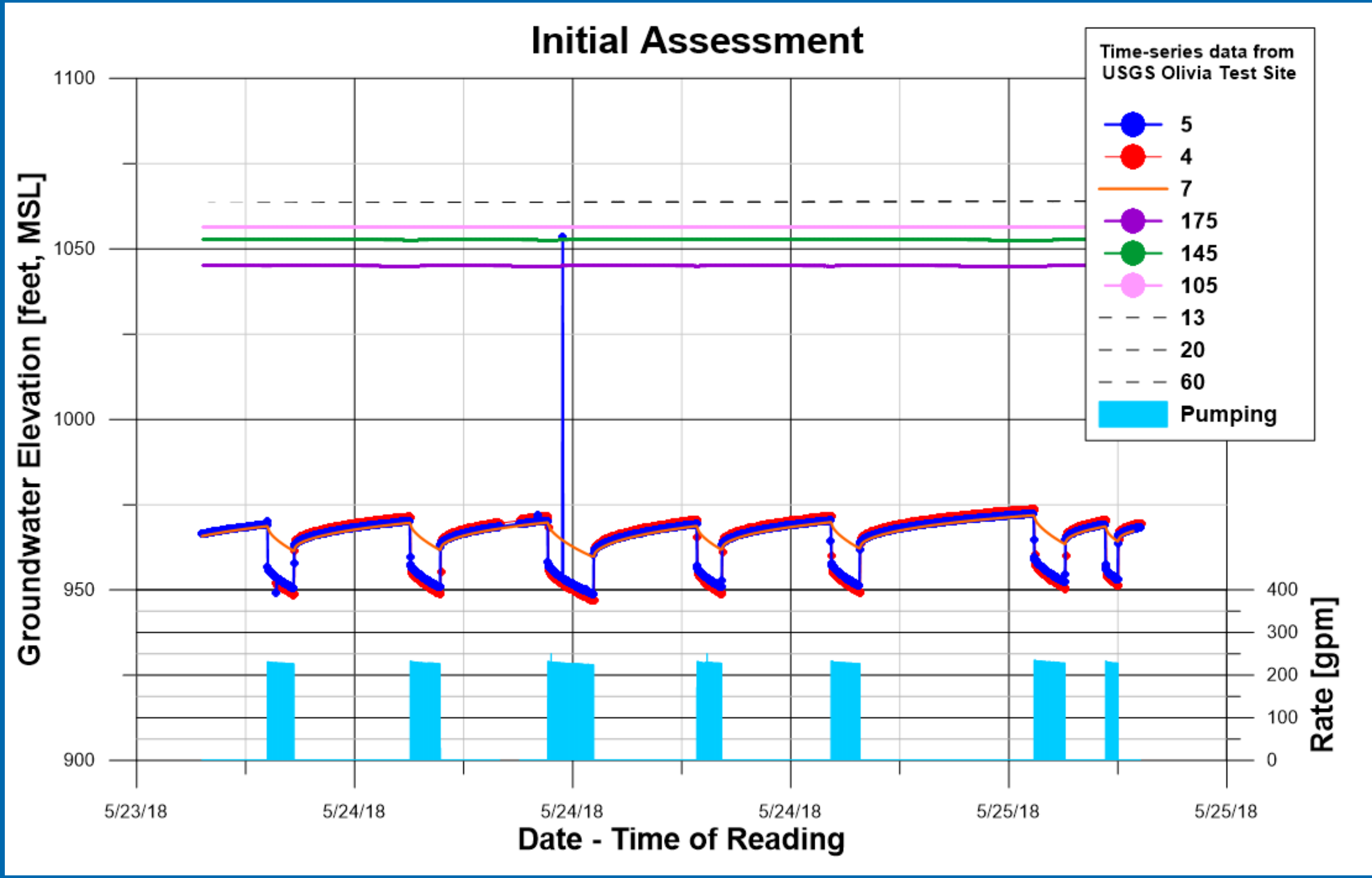




Olivia Test Site

140 ft. Heavy Clay Till & Lacustrine Sediments

USGS Long-Term Monitoring at Olivia



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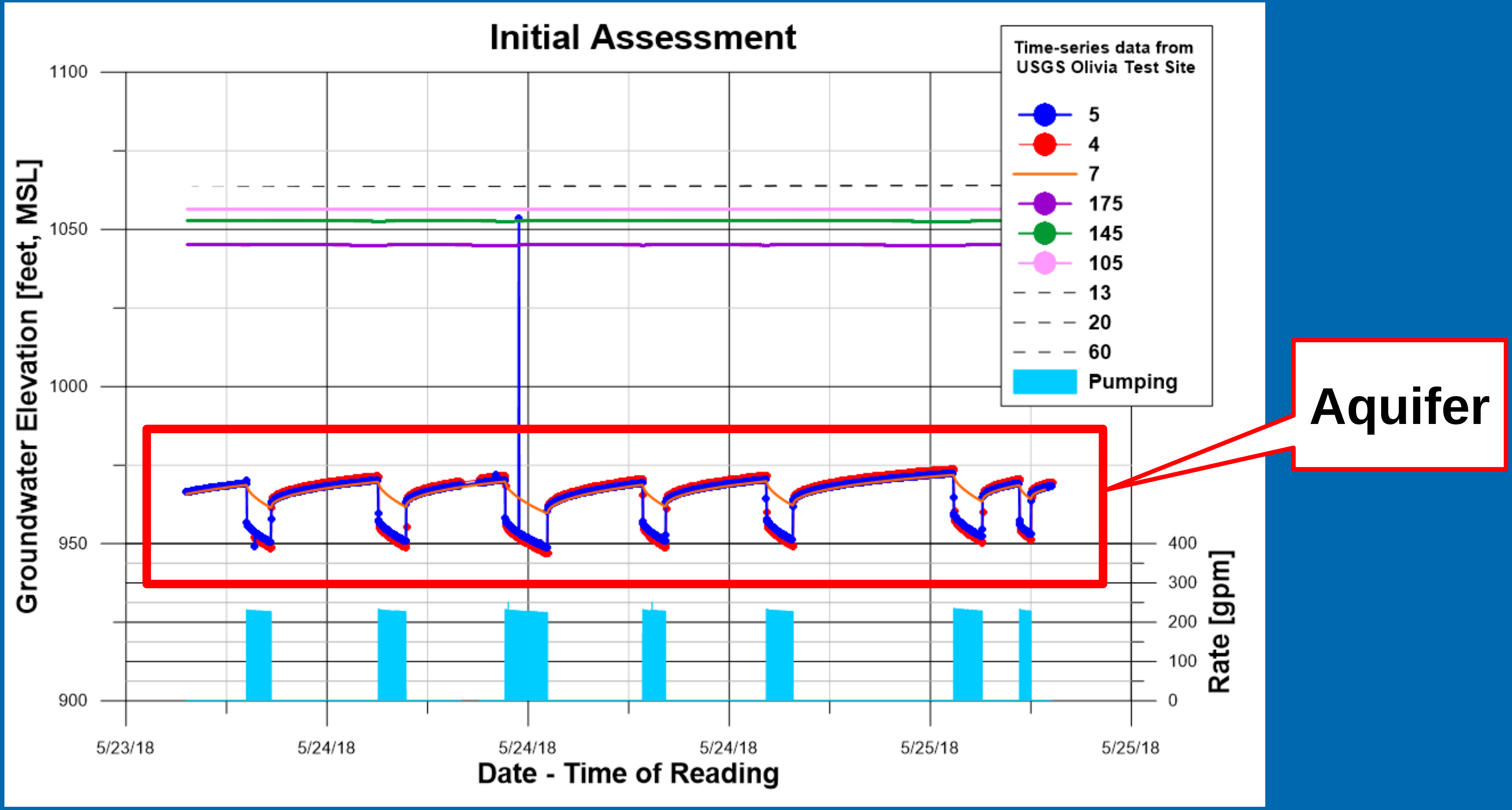
USGS Long-Term Monitoring at Olivia



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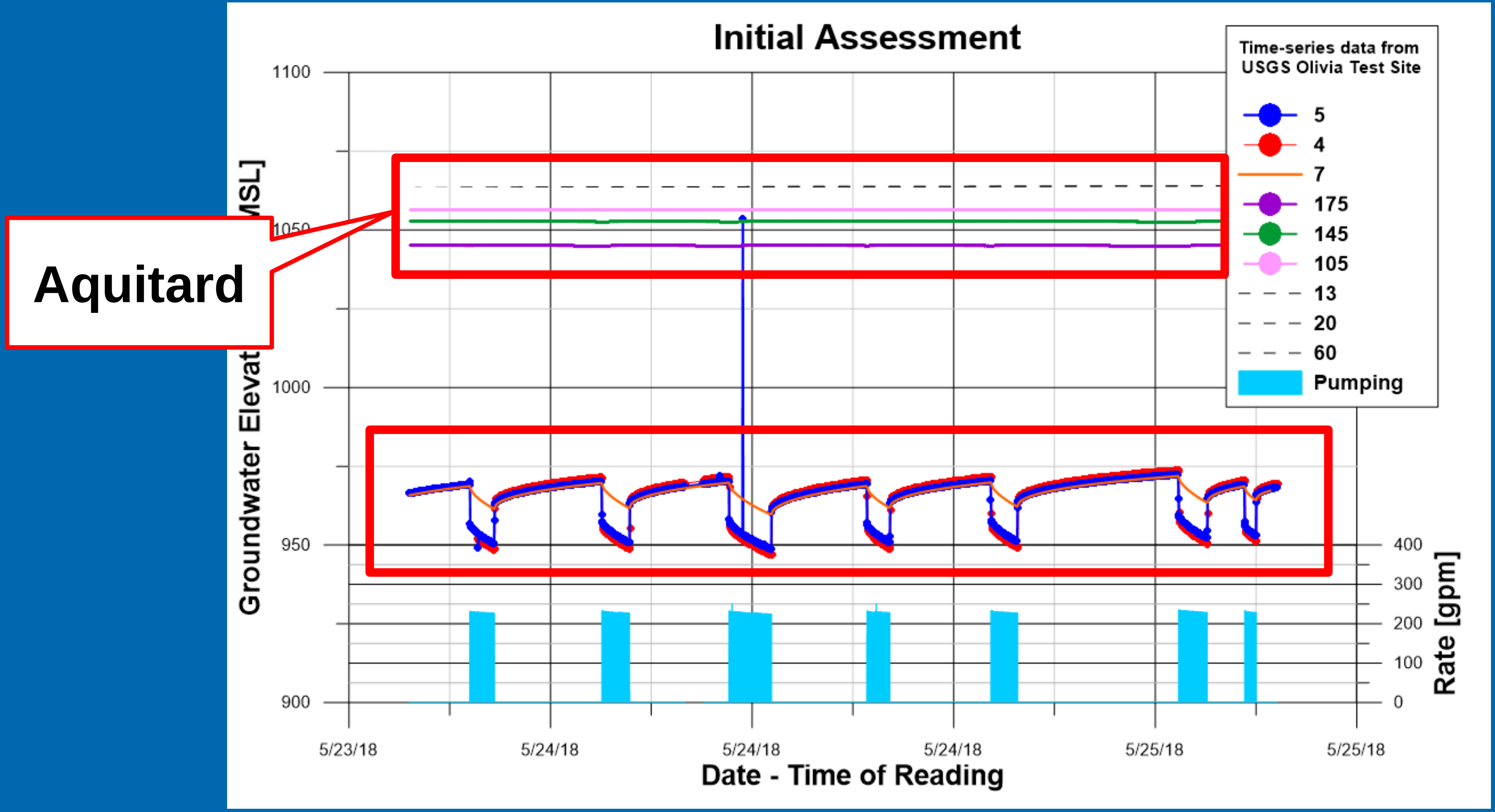

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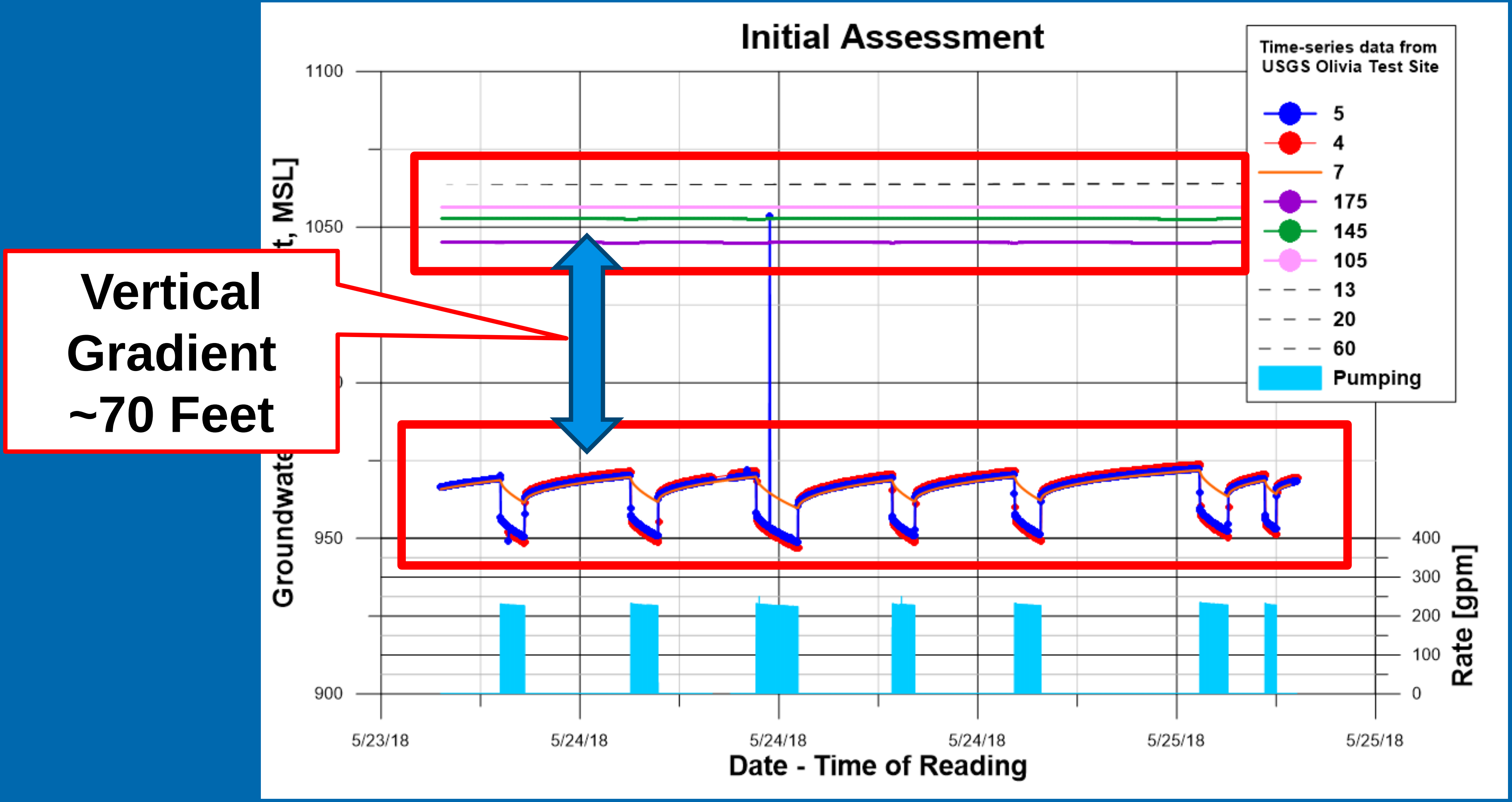
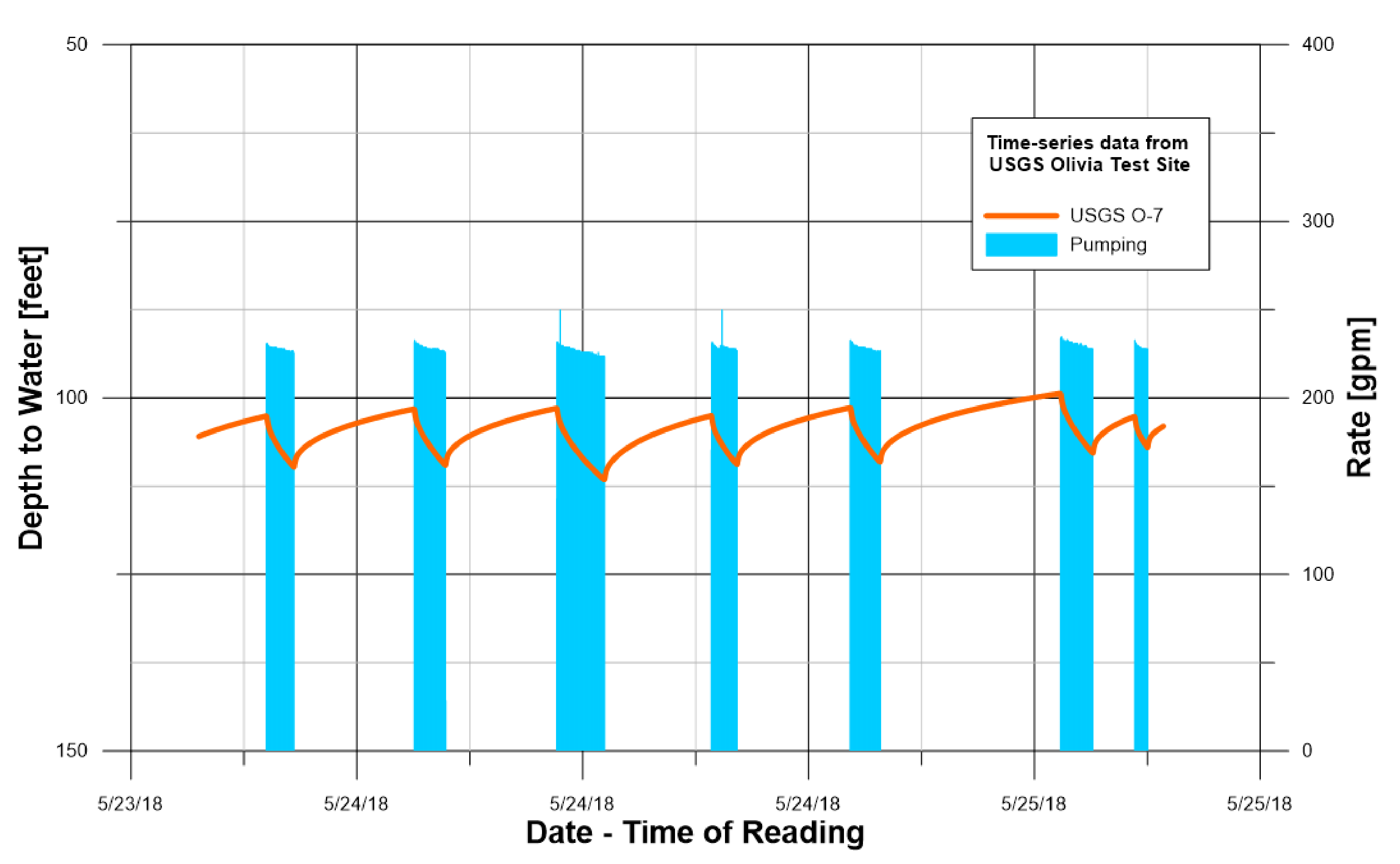
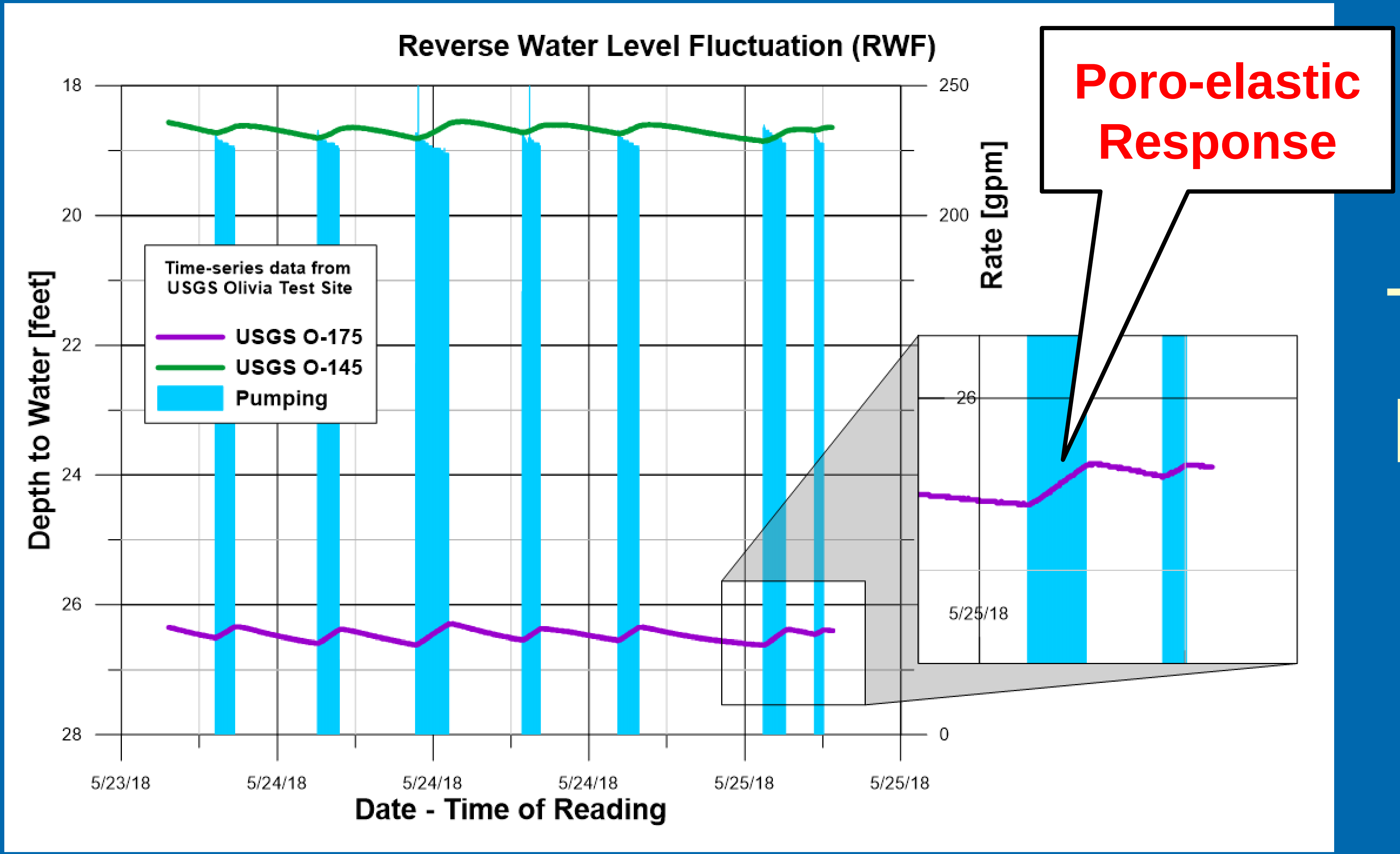
USGS Long-Term Monitoring at Olivia



Blum, MGWA, Spring 2019

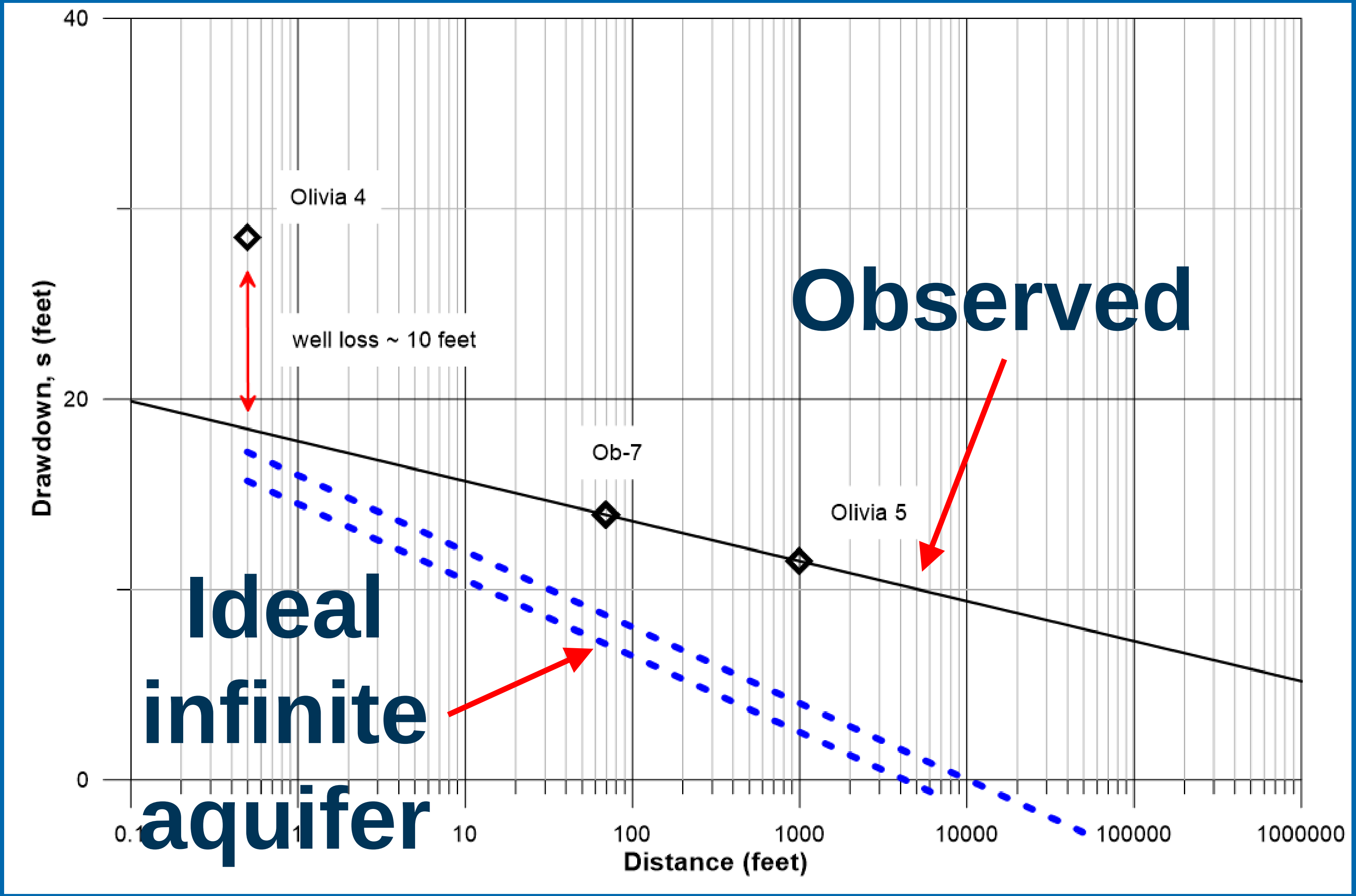


Olivia Aquifer Obwell Response vs. Pumping



Olivia Till Obwell Response vs. Pumping

Olivia Comparison Actual and Unbounded (Ideal) Aquifer Response



Olivia Comparison

Method	**Well**	**Transmissivity T (ft^2/day)**	**Storativity S**	**Leakage Factor L (feet)**	**Vertical Hydraulic Conductivity k' (ft/day)**
Agarwal Recovery	Olivia 4	4,070	1.3e-6	NA	NA
Agarwal Recovery	O-7	3,870	1.4e-3	NA	NA
Hantush-Jacob	Aquifer	7,800	**1e-11**	**2e+8**	~7e-7
Hantush-Jacob Small L	**Simulation**	**4,100**	**2.6e-6**	**3,700**	**0.042**
Hantush-Jacob Large L	**Simulation**	**4,100**	**4.6e-7**	**8,800**	**0.0074**

Comparison - Four Sites

Site	Transmissivity T (ft^2/day)	Storativity S	Leakage Factor L (feet)	Till Thickness b' (feet)	Range in Vertical Hydraulic Conductivity k'(ft/day)
Cromwell	4,380	7.3e-4	550	130	**0.83 to 4.1**
Hydrogeology Field Camp	1,430	6.9e-4	2,770	130 (55)*	**0.0093* to 0.029**
Litchfield	9,000	9.5e-5	24,000	113 (48)*	**< 0.0008 to 0.0018 0.0009***
Olivia**	~ 4,100	~ 1.0e-6	~ 5,940	140	**< 0.016**

*** (x) Effective till thickness used for k', ** Estimated properties of unbounded aquifer**

Conclusions - Test Methods

- Two different measures of vertical conductivity, k'
  - Bulk k' from the aquifer response
  - Local k' from till obwell response (Neuman-Witherspoon)
- Heterogeneous till complicates the comparison of k' types
  - Bulk k' bias to high value - large-scale till heterogeneity within ~1.5 L radial distance from the pumped well (Cromwell, Litchfield)
  - HFC nest disturbed by local heterogeneity, but the aquifer bulk and till nest k' (unexpectedly) nearly same value
  - Olivia was a null result because of bounded aquifer and lack of appropriate conceptual model to deal with observed response in till

General Conclusions

- L and k’ from aquifer tests strongly influenced by most highly conductive till
- Where obwells showed a response
  - Site-specific Nest k’ consistent with aquifer bulk k’
  - Similar k’ from different methods: Hantush-Jacob, Neuman-Witherspoon
  - k’ range was within +/- 0.5 of geometric mean – within the typical range of variability of aquifer k from aquifer testing
- Lithology of till matters (sandy till vs. heavy clay-till)
  - Vertical flow is ‘focused’ at the heavy clay-till sites
  - The flux in or out of the aquifer (recharge/discharge) is determined by the most highly conductive areas of aquitard

Questions & Implications

- How to protect drinking water from contamination in settings with focused recharge?
- From these investigations, additional information about aquitards is needed for improved models
- To start, methods to distinguish till settings & types of till & would be quite helpful to focus additional data collection (testing, etc.)
  - Weathered / Unweathered
  - % Clay / % Sand
  - Vertical gradient across till

References

Authors	Reference, DOI
• Kruseman & de Ridder	google search – open access
• Hantush-Jacob (1955 a & b)	10.1029/TR036i001p00095 10.1029/TR036i002p00286
• Neuman-Witherspoon(1969)	10.1029/WR005i004p00803
• Zhou (2011)	10.1007/s10040-011-0762-x
• Butler & Tsou (2003)	10.1029/2002WR001484

MDH Public Report URL

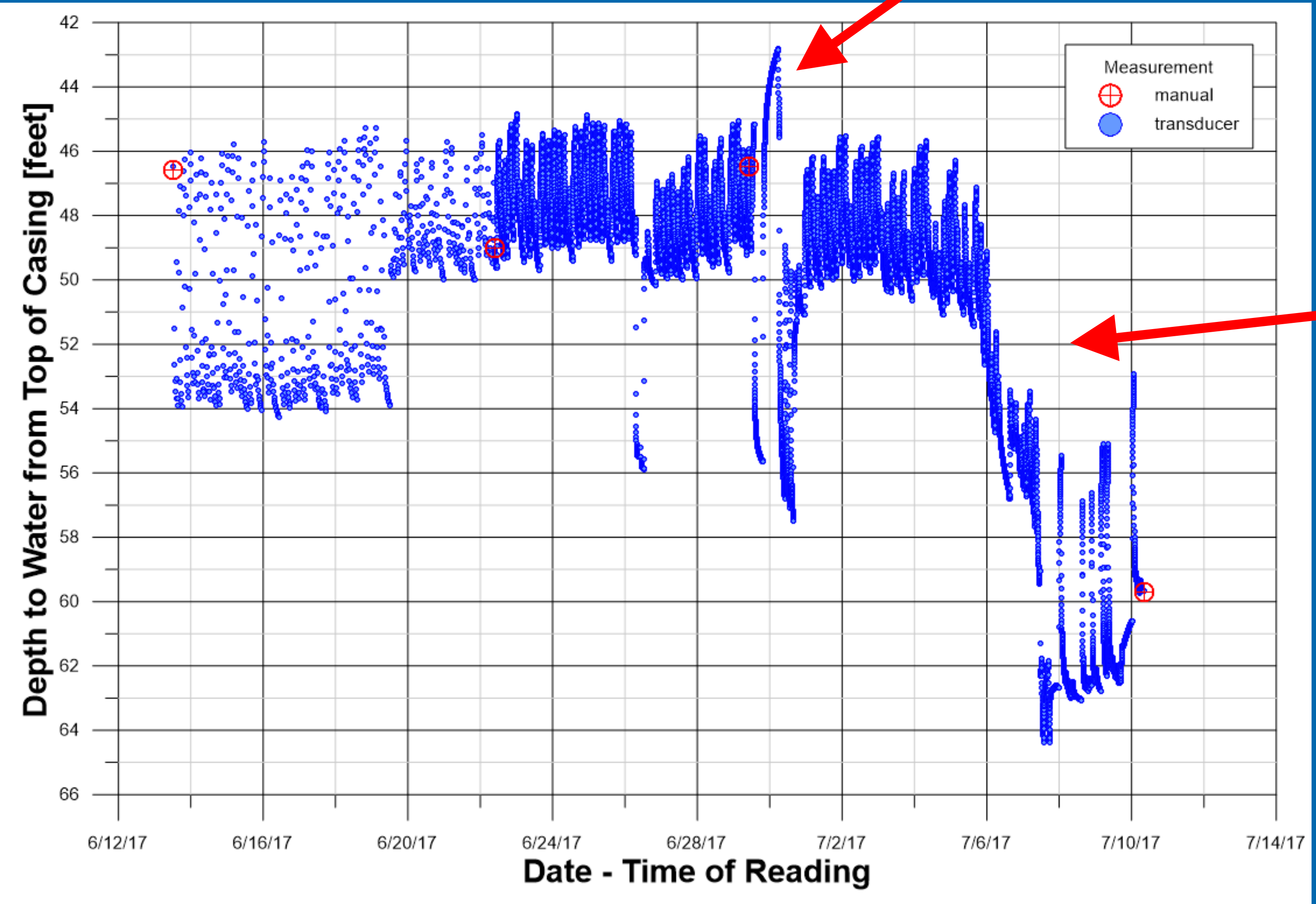
- Cromwell

https://www.health.state.mn.us/communities/environment/water/docs/swp/testcromwell.pdf

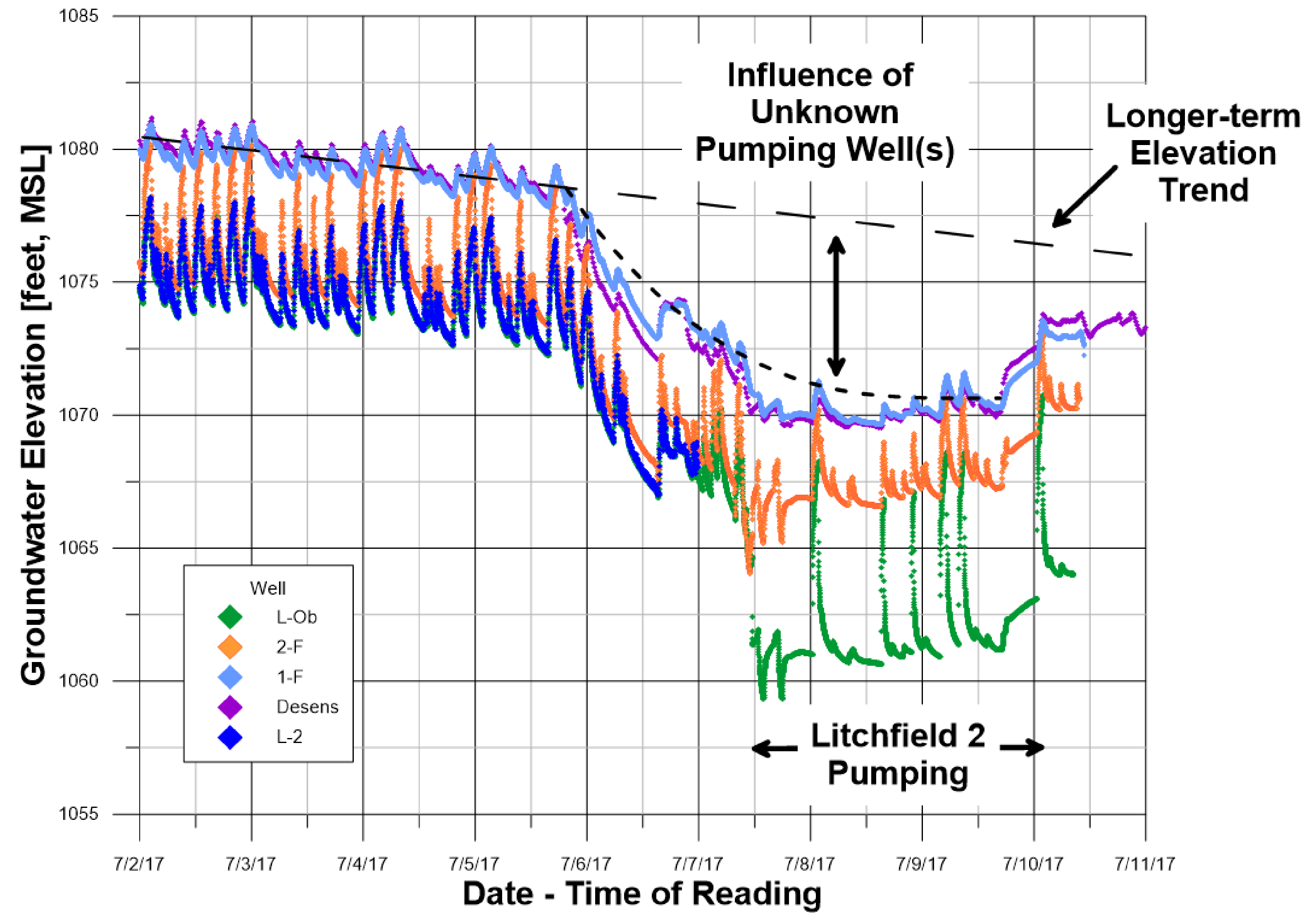
- Litchfield

https://www.health.state.mn.us/communities/environment/water/docs/swp/testlitchfield.pdf

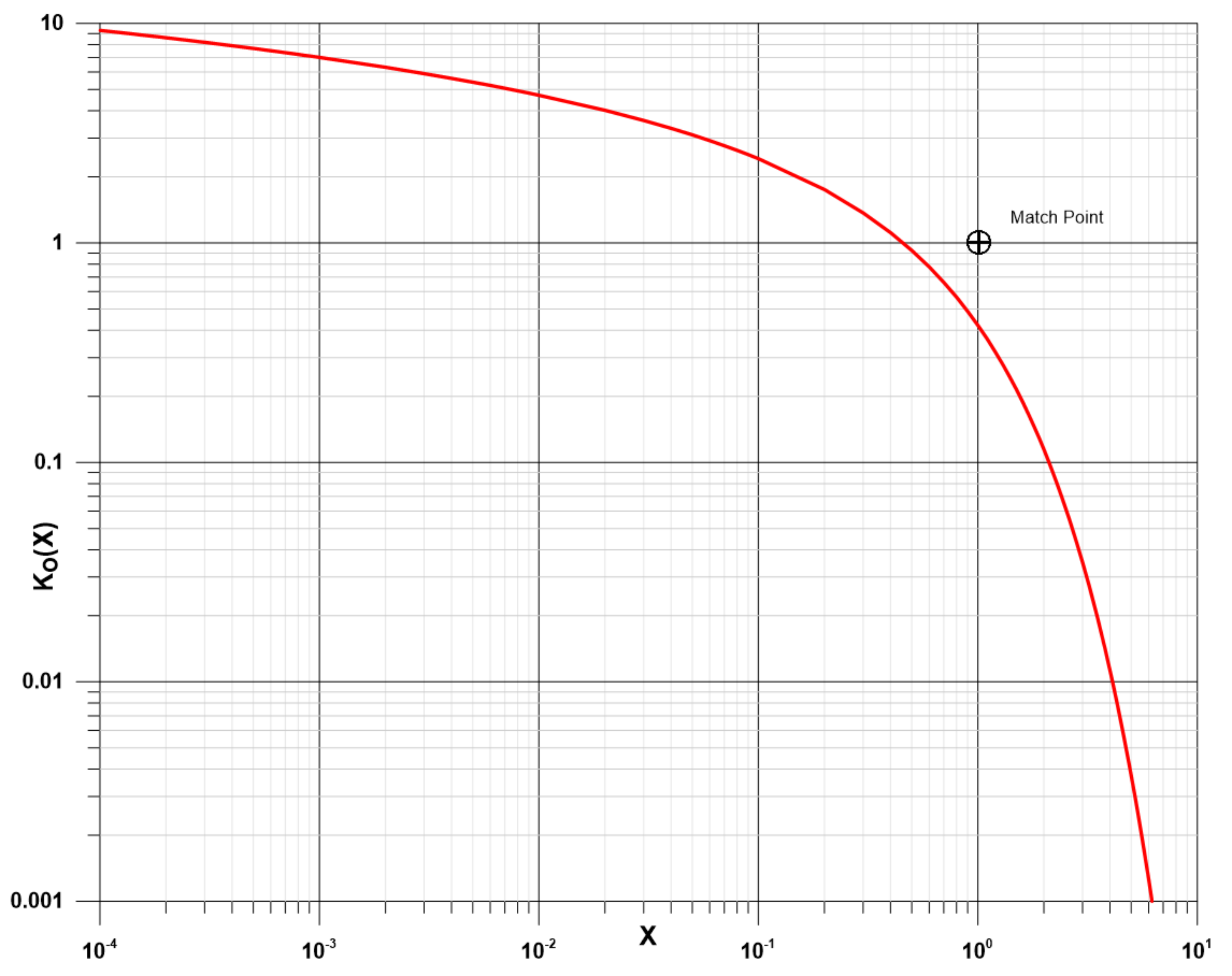
16-hr Test, June 29, 2017



Litchfield MW (607417) Influence of Unknown Wells July 5 - 9, 2017



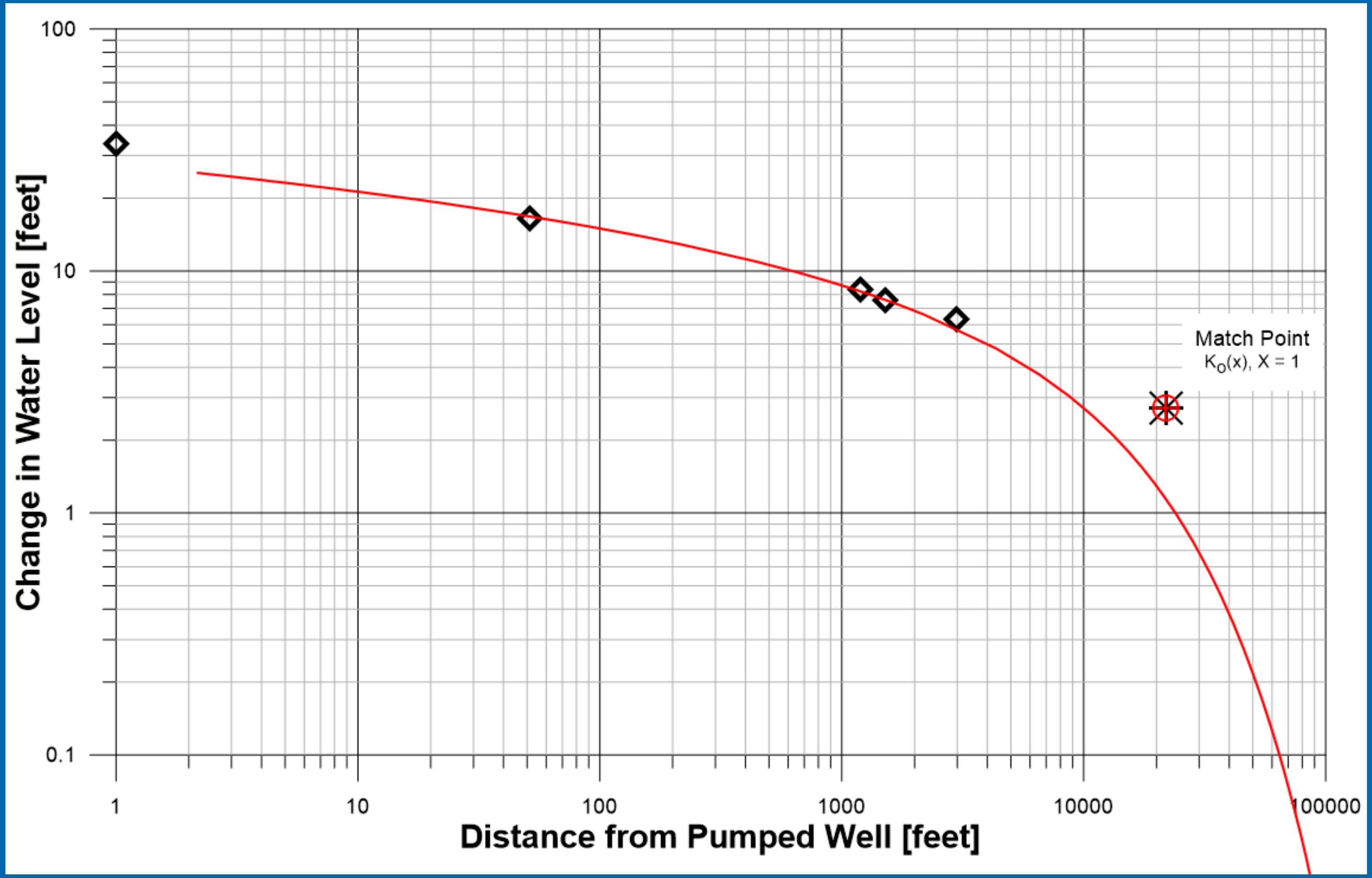
Litchfield Pervasive Effect on Wells in Aquifer, Drawdown **8** to **9** Feet



Steady-state Type-Curve de Glee (1930), Hantush-Jacob (1955)

Steady-State Well Curve, de Glee (1930)

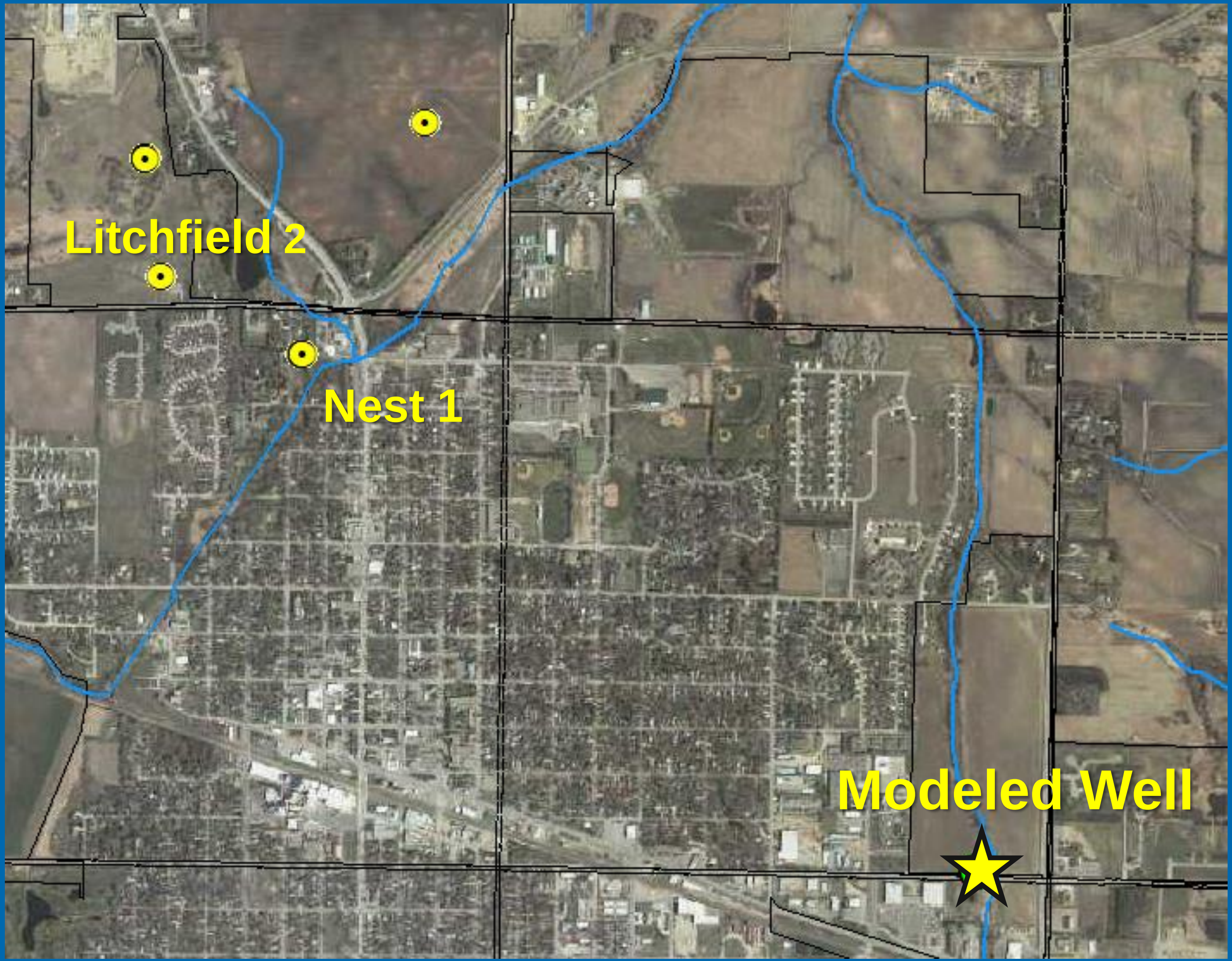
s



r

Different Q

Shifts Curve on Y-axis Only

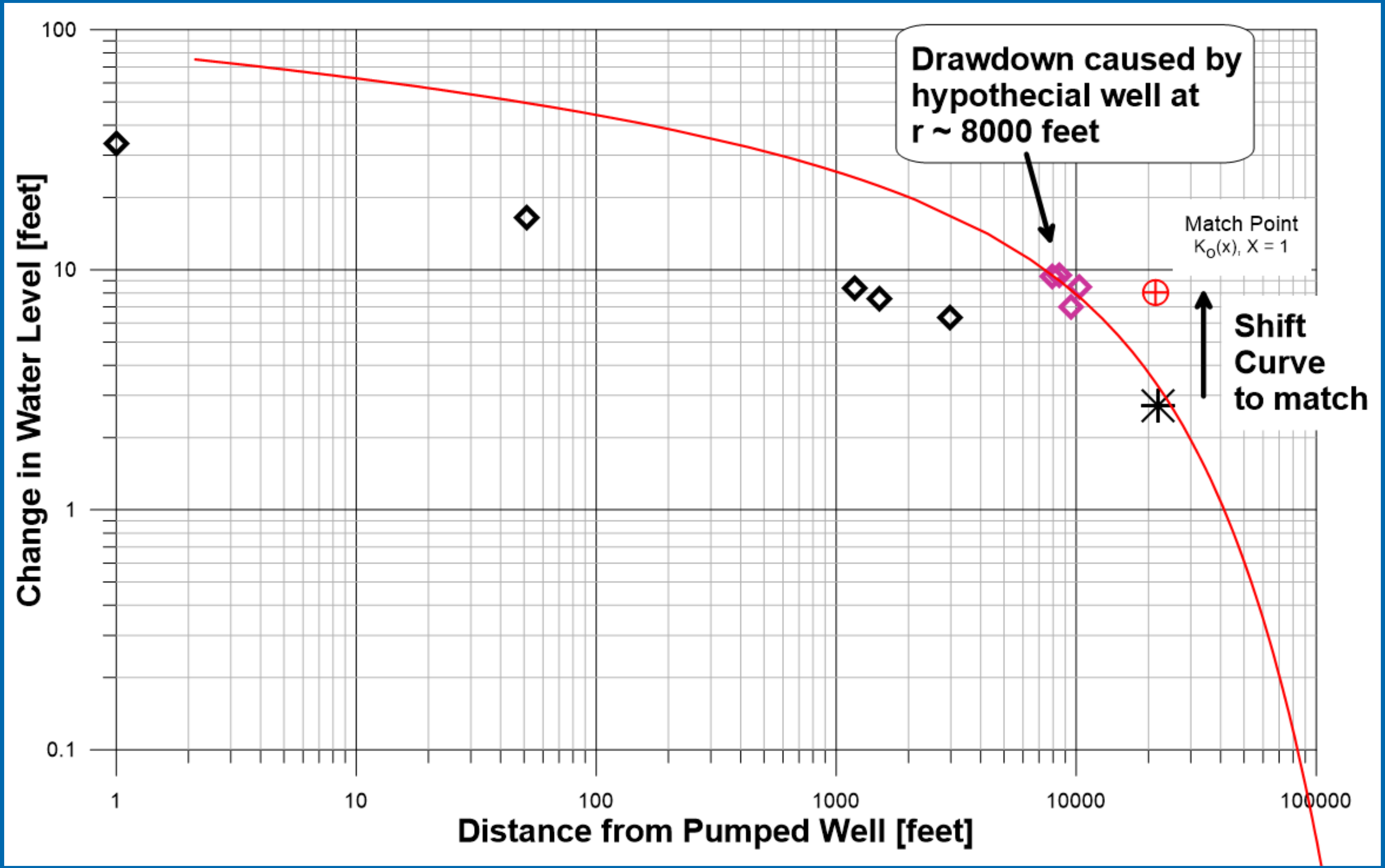


Litchfield Hypothetical Well to be Modeled

r = 8,000 feet
T= 9,000 ft^2/day
L= 22,000
Q = ???? gpm

Apply Steady-state Flow Model

- Known
  - aquifer properties,
  - effect on aquifer obwells
- Unknown
  - well location(s), and pumping rate(s)
- Model with Bessel function
  - Choose hypothetical well location, r = 8000 feet
  - Solve for pumping rate of hypothetical well… Q = 2300 gpm



$$Q = \frac{T \ * s_m}{70.6}$$

$T = 9{,}000\ ft^2/day$

$S_m = 18\ ft.$

$\mathbf{Q = 2,300\ gpm}$