Groundwater flow through till: tortoise, hare, or not in the race?

Good Thunder Fm., Olivia, MN

Well nest, Litchfield, MN

Cromwell Fm., Cromwell, MN

[1]**Jared Trost**, [2]**William Simpkins**, [1,2]Anna-Turi Maher, [2,3]Alyssa Witt, [1]Andrew Berg, [1,4]James Stark, [5,6]Bob Tipping, [6]Justin Blum, [1]Daniel Feinstein

[1]U.S. Geological Survey, [2]Iowa State University, [3]Golder and Associates, [4]Legislative Water Commission, [5]MN Geological Survey, [6]MN Department of Health

A collaborative effort

- A 5-year collaborative project among:
  - U.S. Geological Survey
  - Iowa State University
  - Cities of Litchfield, Cromwell, and Olivia
  - Minnesota Depts. of Health and Natural Resources
  - Minnesota Geological Survey
  - University of Minnesota
- Major funding:
  - MN Environment and Natural Resources Trust Fund
  - USGS Cooperative Water Fund Program
- Major in-kind support:
  - Bill Simpkins, Iowa State University

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

A preview of today's presentations

This talk:

- Study design
- Variability: geology, K, hydraulic relationships, isotope geochemistry, and contamination
- Interpretive modeling

Afternoon talk:

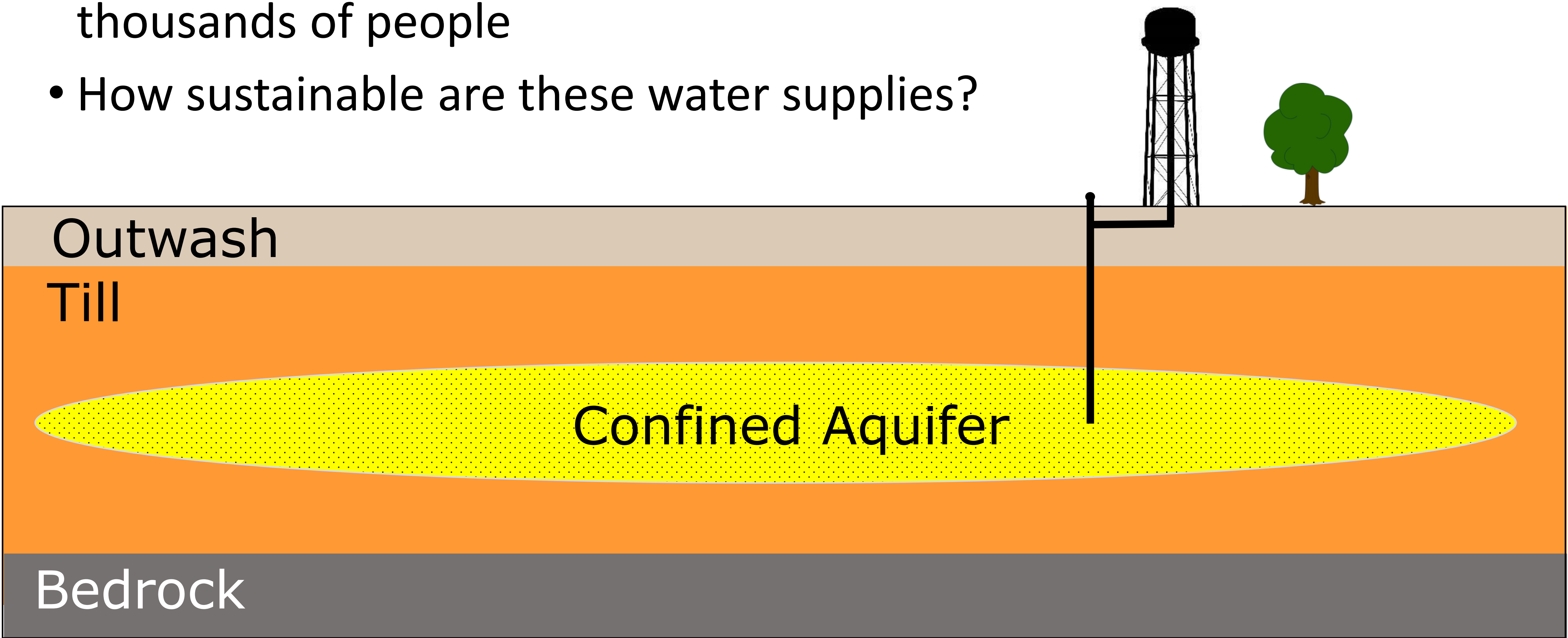
Justin Blum: a presentation about lessons learned from aquifer tests at each site.

Two Posters

Hewitt Fm.
near Akeley, MN

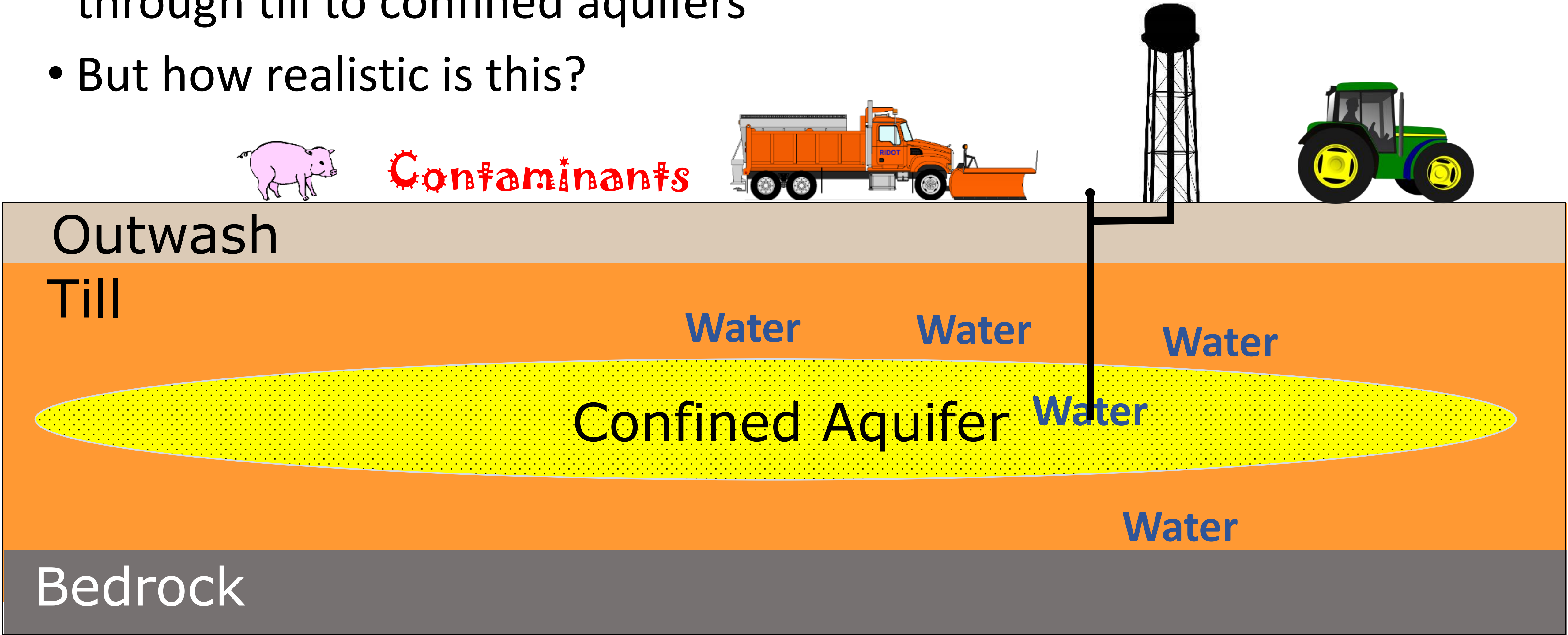
Motivation

- Confined aquifers supply drinking water to thousands of people
- How sustainable are these water supplies?



Motivation

- How we *like* to conceptualize groundwater flow through till to confined aquifers
- But how realistic is this?



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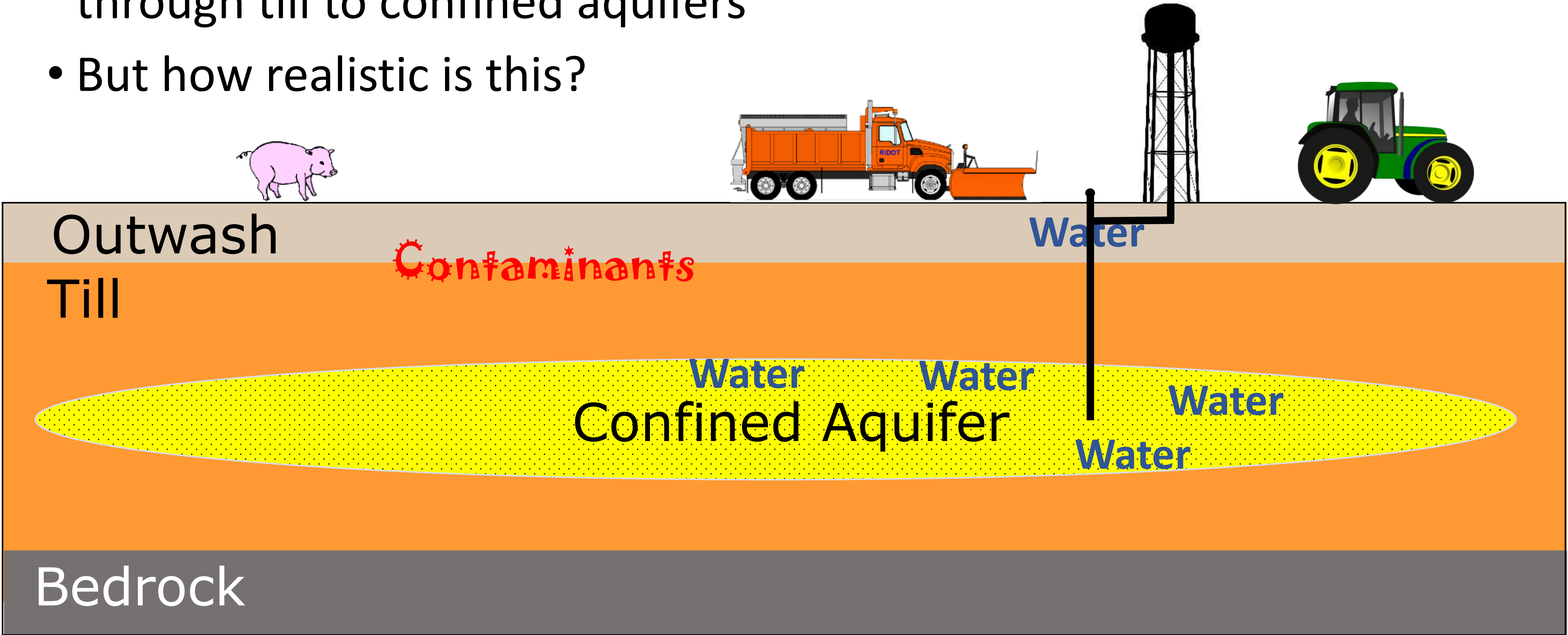
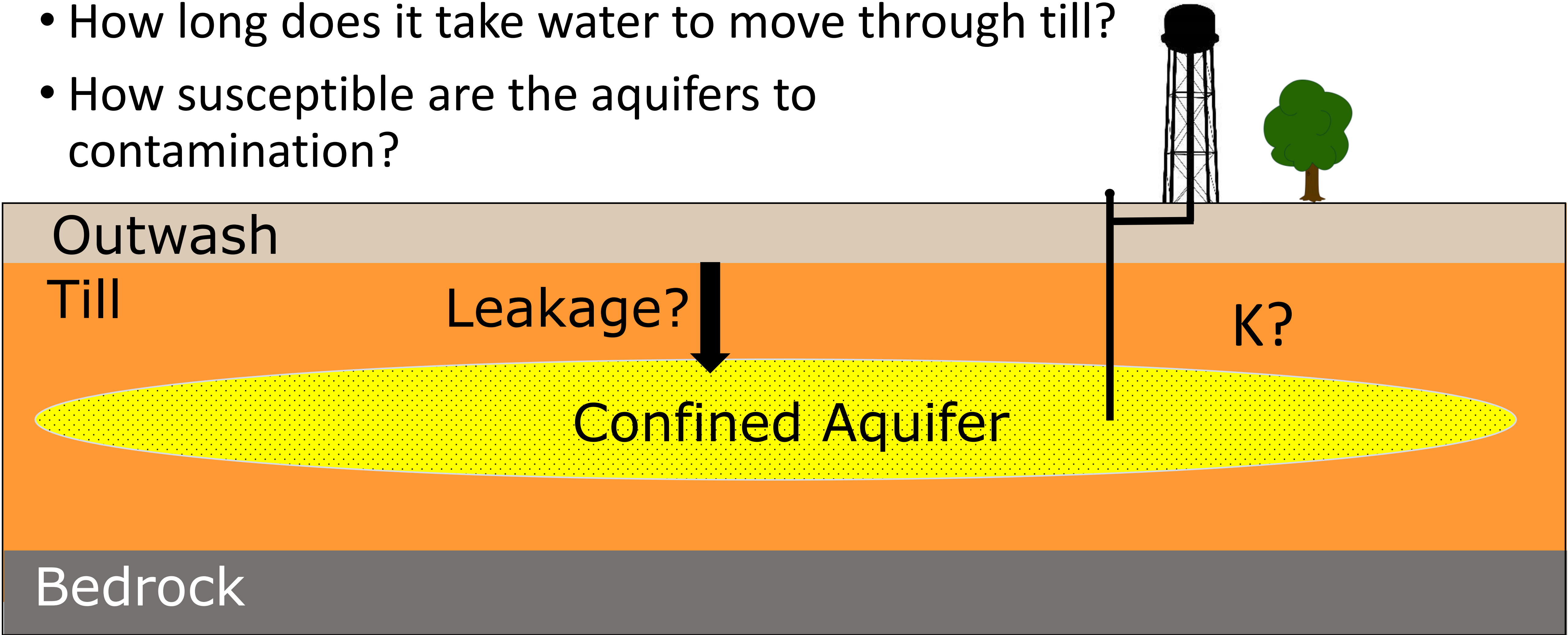


Motivation-a focus on till

- How does groundwater flow through till?
- How long does it take water to move through till?
- How susceptible are the aquifers to contamination?



Project Goal

Better understand the sustainability of water supplies from confined aquifers.

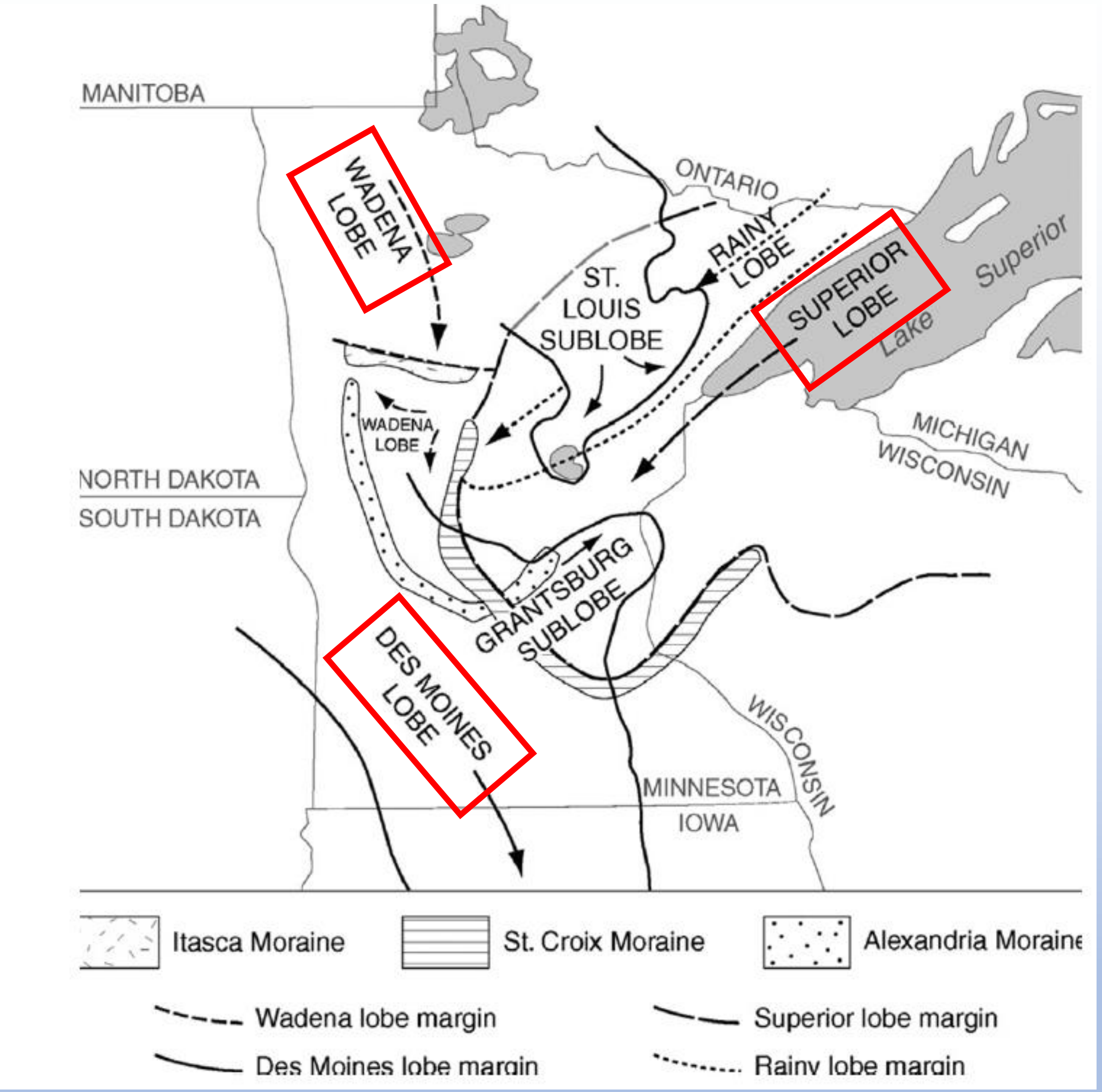
Approach: for different glacial lobes and till units in Minnesota, we quantified:

- Variability of till hydraulic properties
- Leakage of water from till confining units to buried confined aquifers

Rotosonic coring in Olivia, MN, 2017

Study site selection

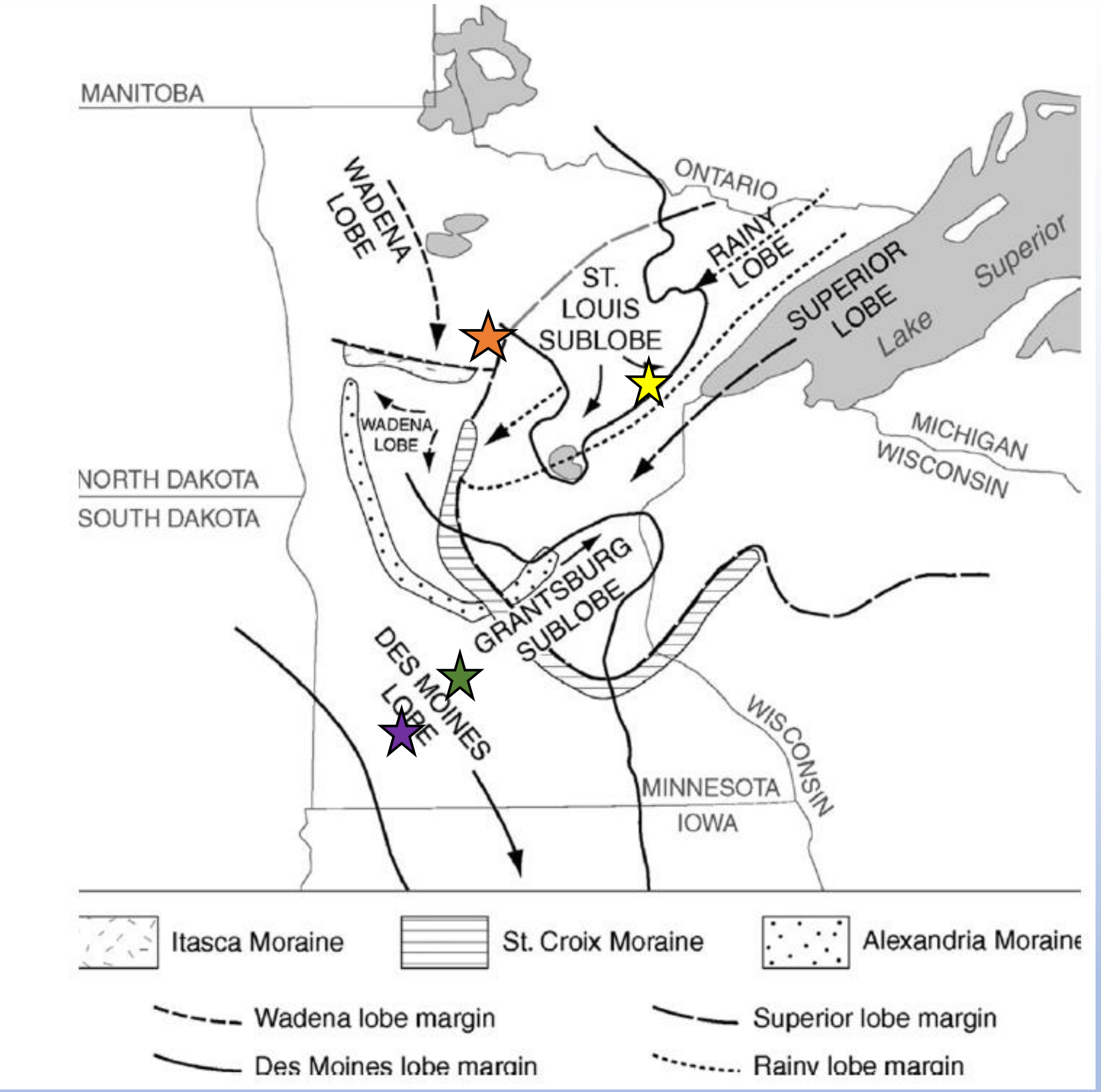
- Detailed hydrogeologic information available
- Physical setting characteristics
  - Small number of high capacity pumping wells
  - less than 300 ft below land surface
  - High-capacity well construction integrity
- Logistical requirements
  - Cooperative water operator
  - Accessible with large drill rig



Glacial Lobes and Sublobes of Late Wisconsin age (Jennings and Johnson, 2011)

Study sites

Site	Lobe	Population	Pumping (MGY)
UMN hydrogeology field camp (HFC)	Wadena	~30-40 for 3 weeks in July	NA, good for long-term aquifer tests
Cromwell	Superior	231	6
Litchfield	Des Moines	6,630	340
Olivia	Pre-Illinoian	2,350	97



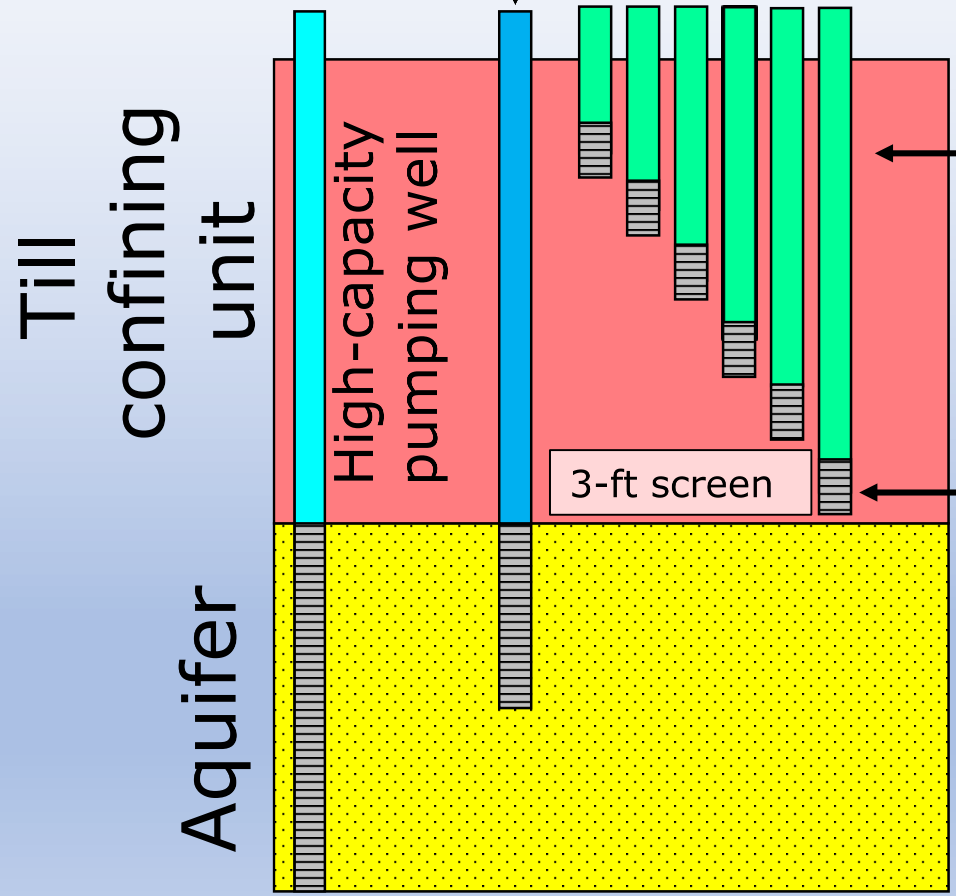
Glacial Lobes and Sublobes of Late Wisconsin age (Jennings and Johnson, 2011)

Well nest design and installation

Characterize profile with continuous core to place screens

Well nest design and installation

Continuous core collected to characterize profile and place screens



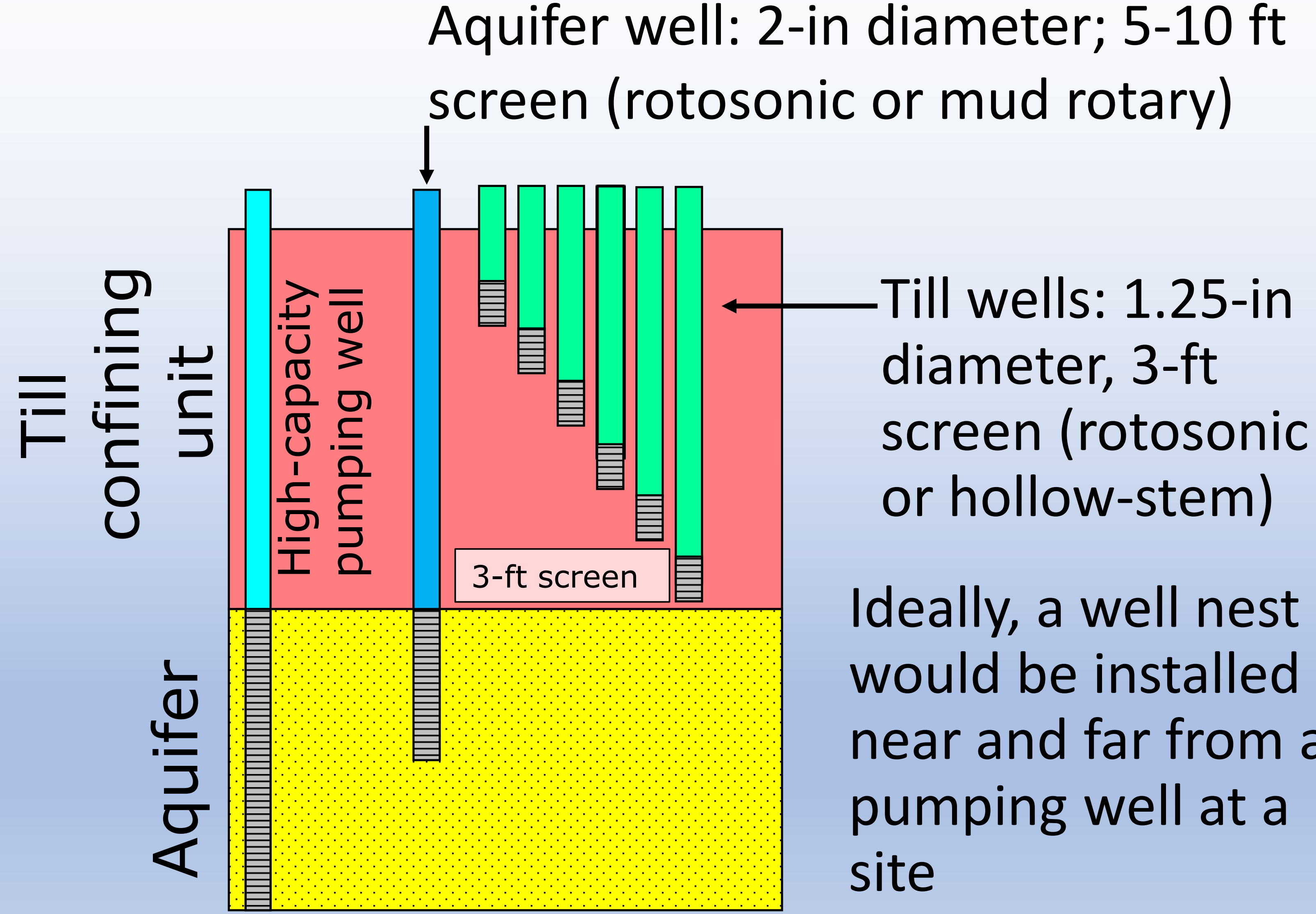
Aquifer well: 2-in diameter; 5-10 ft screen (rotosonic or mud rotary)

Till wells: 1.25-in diameter, 3-ft screen (rotosonic or hollow-stem)

Core-section retrieved from screen interval and squeezed to get pore-water sample

Well nest design and installation

Characterize profile with continuous core to place screens



Ideally, a well nest would be installed near and far from a pumping well at a site

Data collection

- Hydrology
  - Water levels and precipitation
  - Slug tests on all wells
  - Aquifer tests at 4 sites (led by Justin Blum)
- Geochemistry of groundwater and pore water
  - Major ions and nutrients
  - Stable isotopes ($\delta^{18}O$, $\delta^{2}H$)
  - Enriched 3H (GW only)


Till Confining Unit
(a.k.a. Till Aquitard)
Confined Aquifer

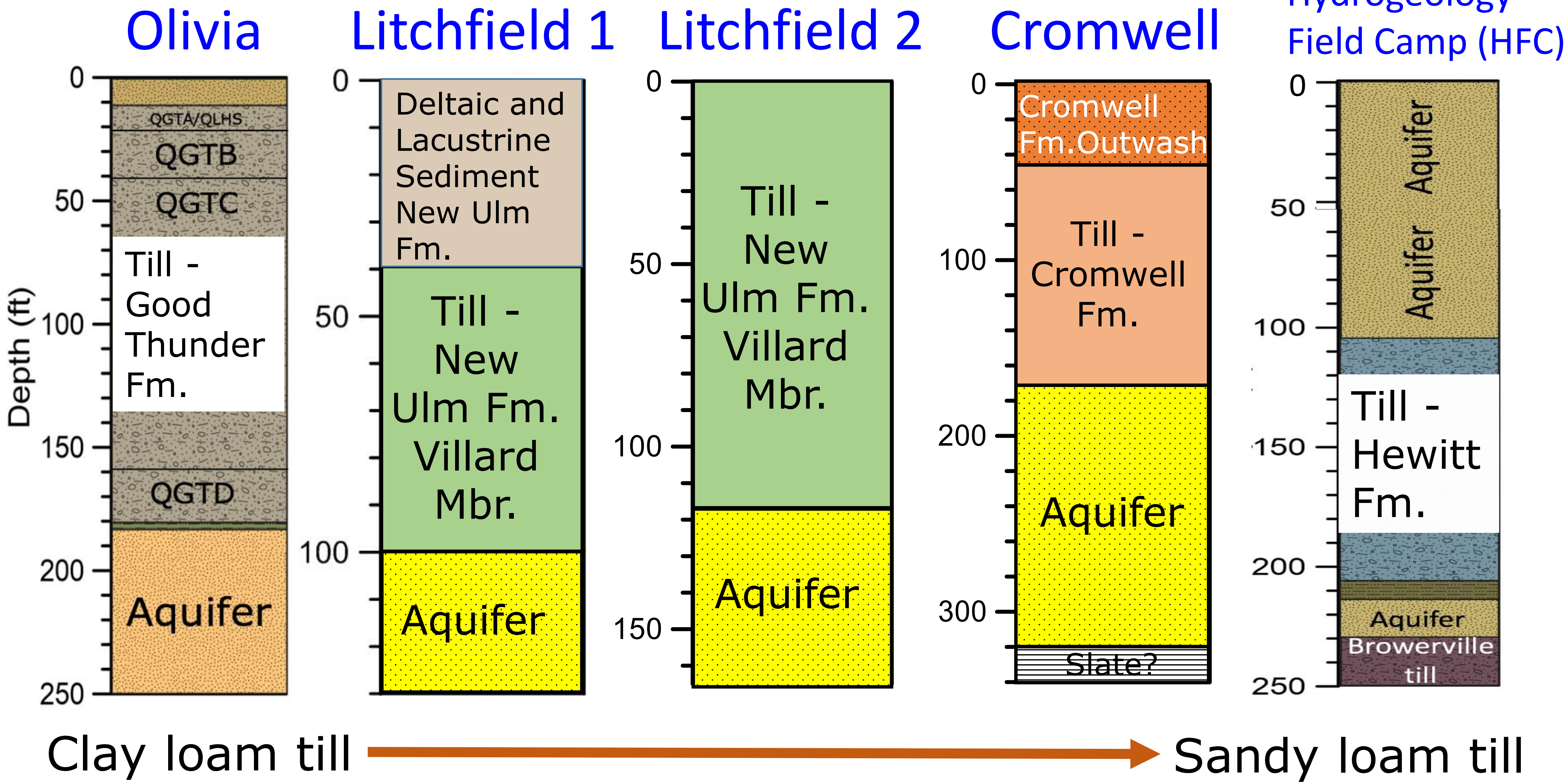
Till Characterization

Site	Olivia	Litchfield	Cromwell	HFC
Lobe	Undetermined	Des Moines	Superior	Wadena
Age	Pre-Illinoian	Late Wisc.	Late Wisc.	Late Wisc.
Formation	Good Thunder	New Ulm Villard Mbr.	Cromwell	Hewitt
Grain Size [Sand:Silt:Clay]	37:40:23	50:32:17	57:31:13	67:22:11
Texture	Clay loam to loam	Loam to sandy loam	Sandy loam	Sandy loam Loamy sand

Staley et al., 2018

Staley et al., 2018

Site Stratigraphy



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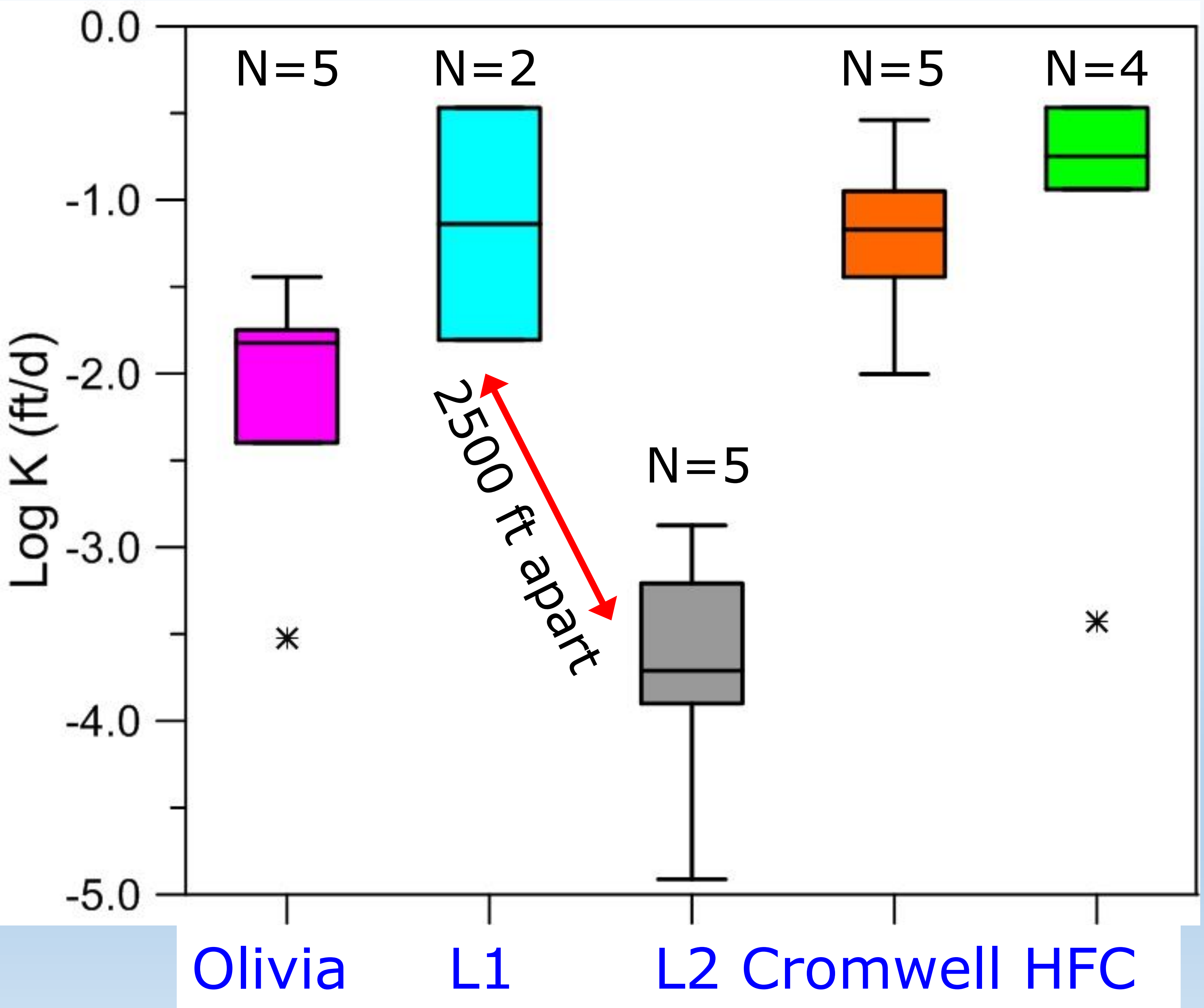
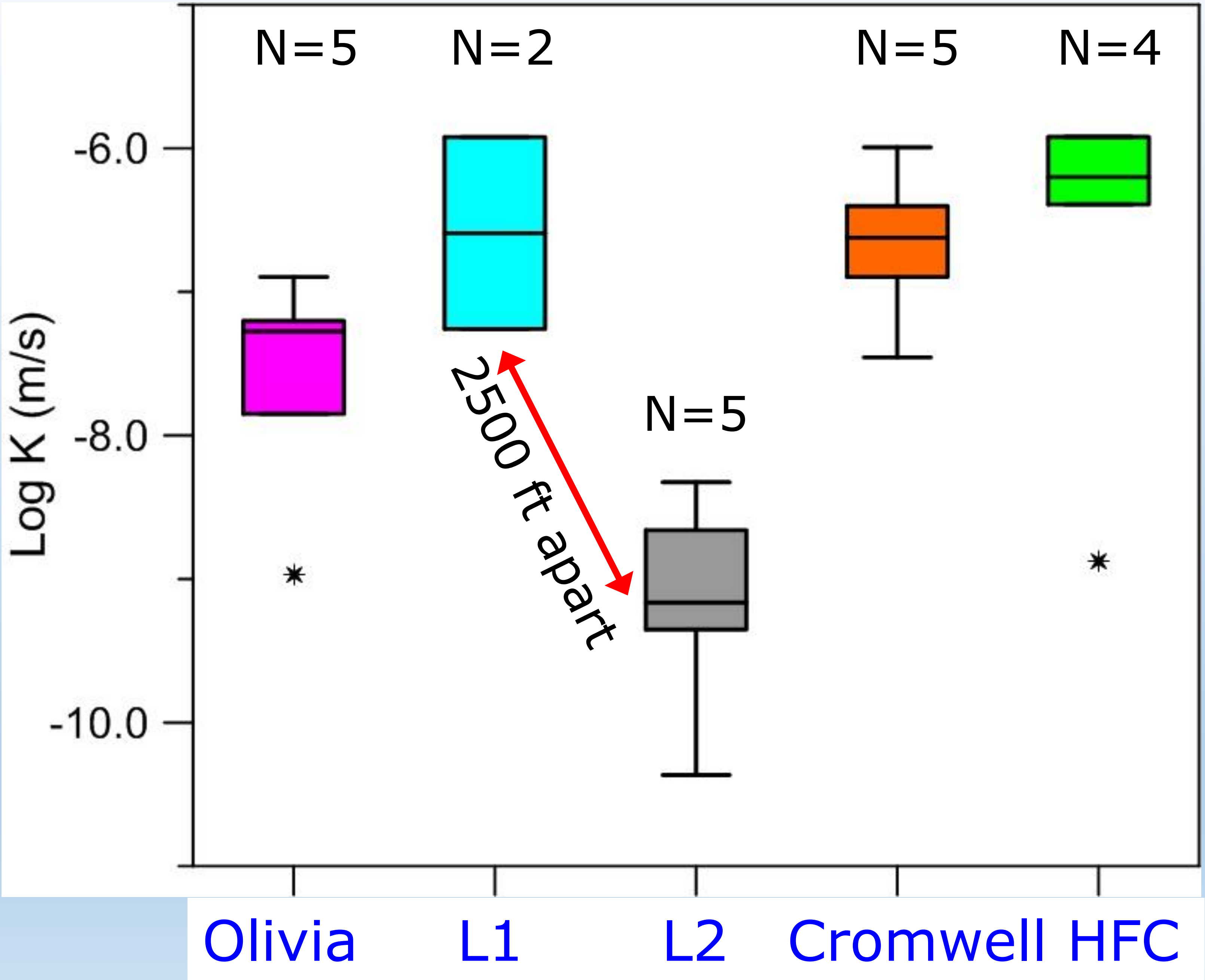


Box plots of Log K for all study sites

Data from slug tests

Units in feet/day



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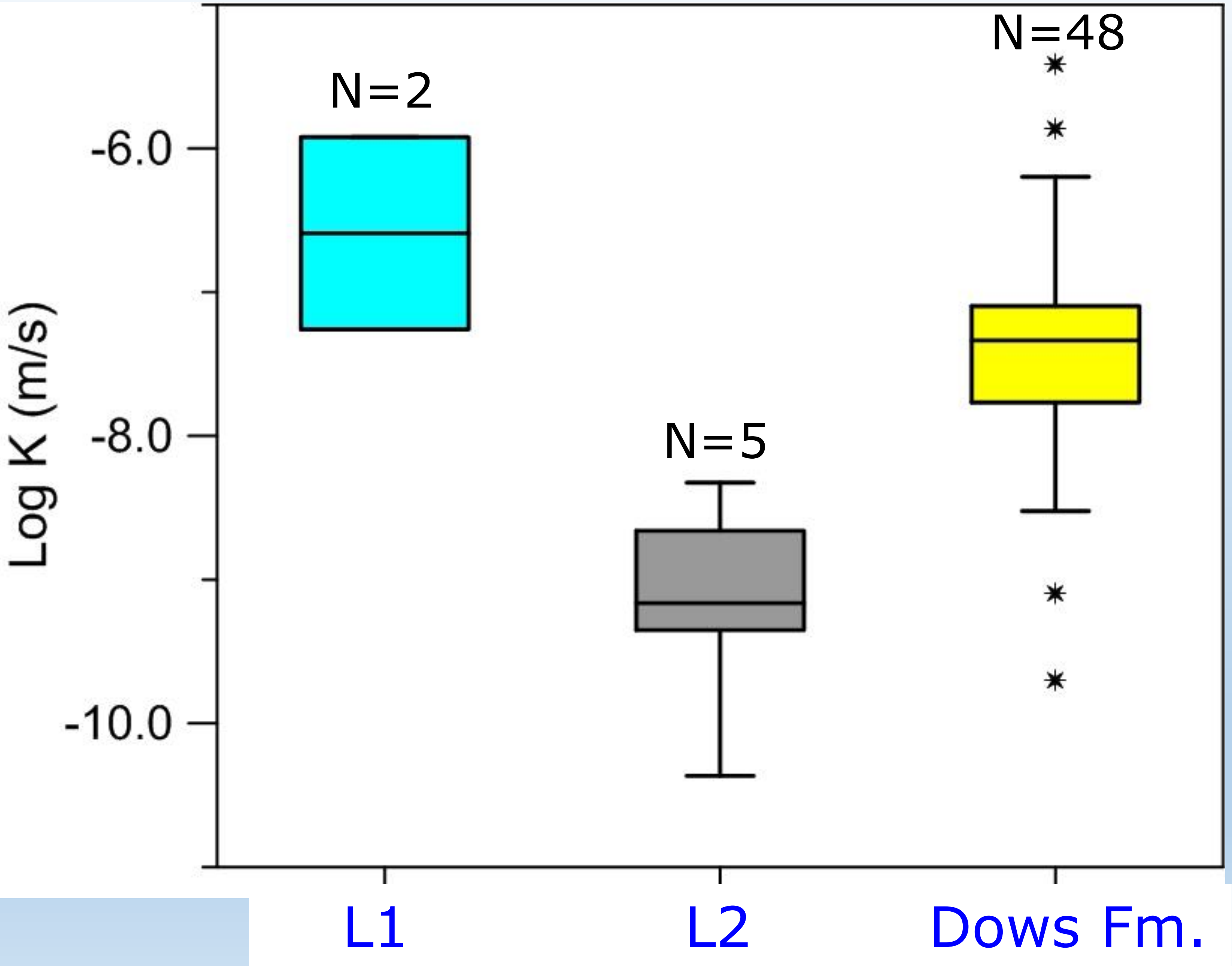
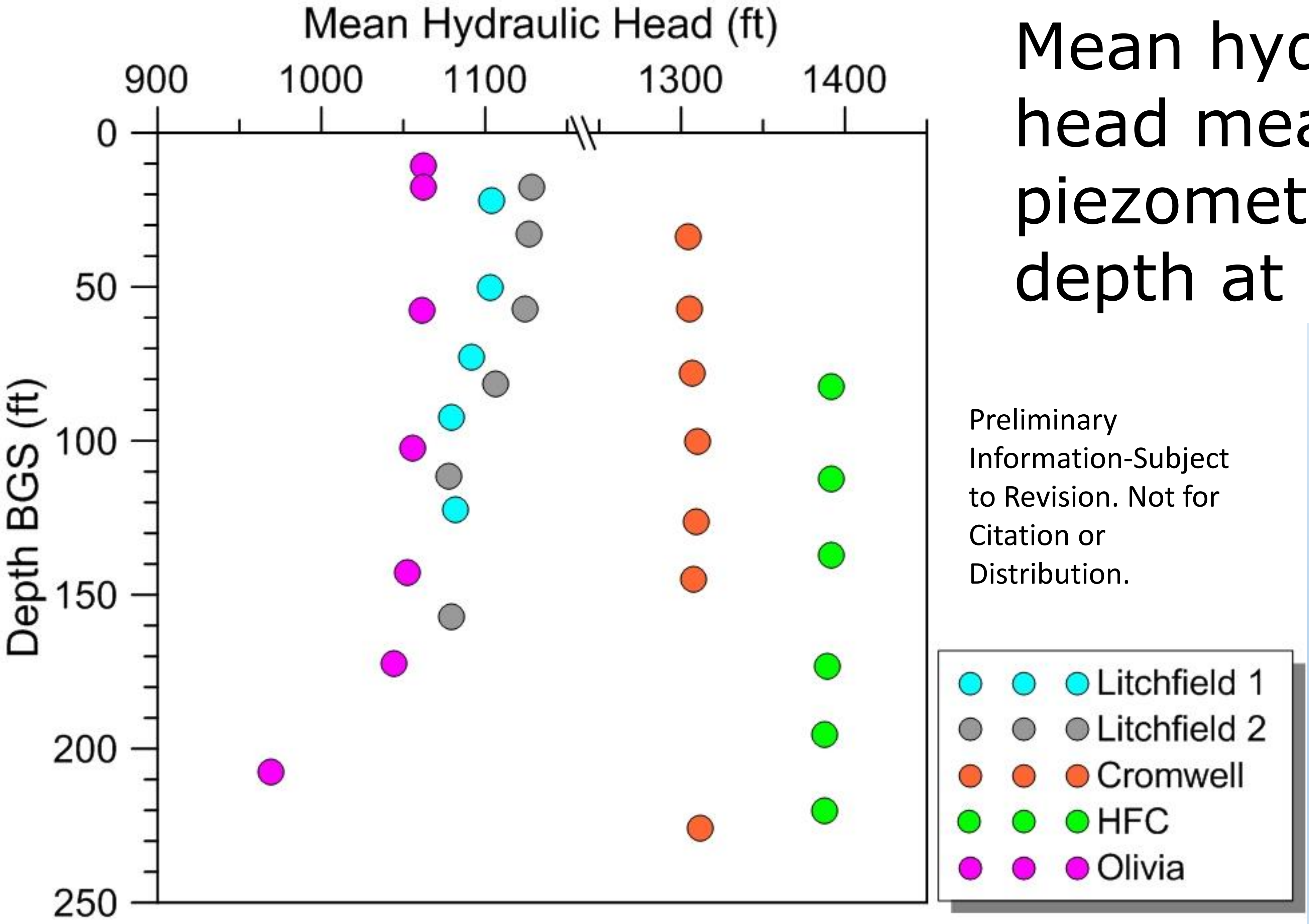


Box plots of Log K for Litchfield and the Dows Fm. in Iowa

Data from slug tests

Units in meters/sec

Mean hydraulic head measured in piezometers vs. depth at all sites



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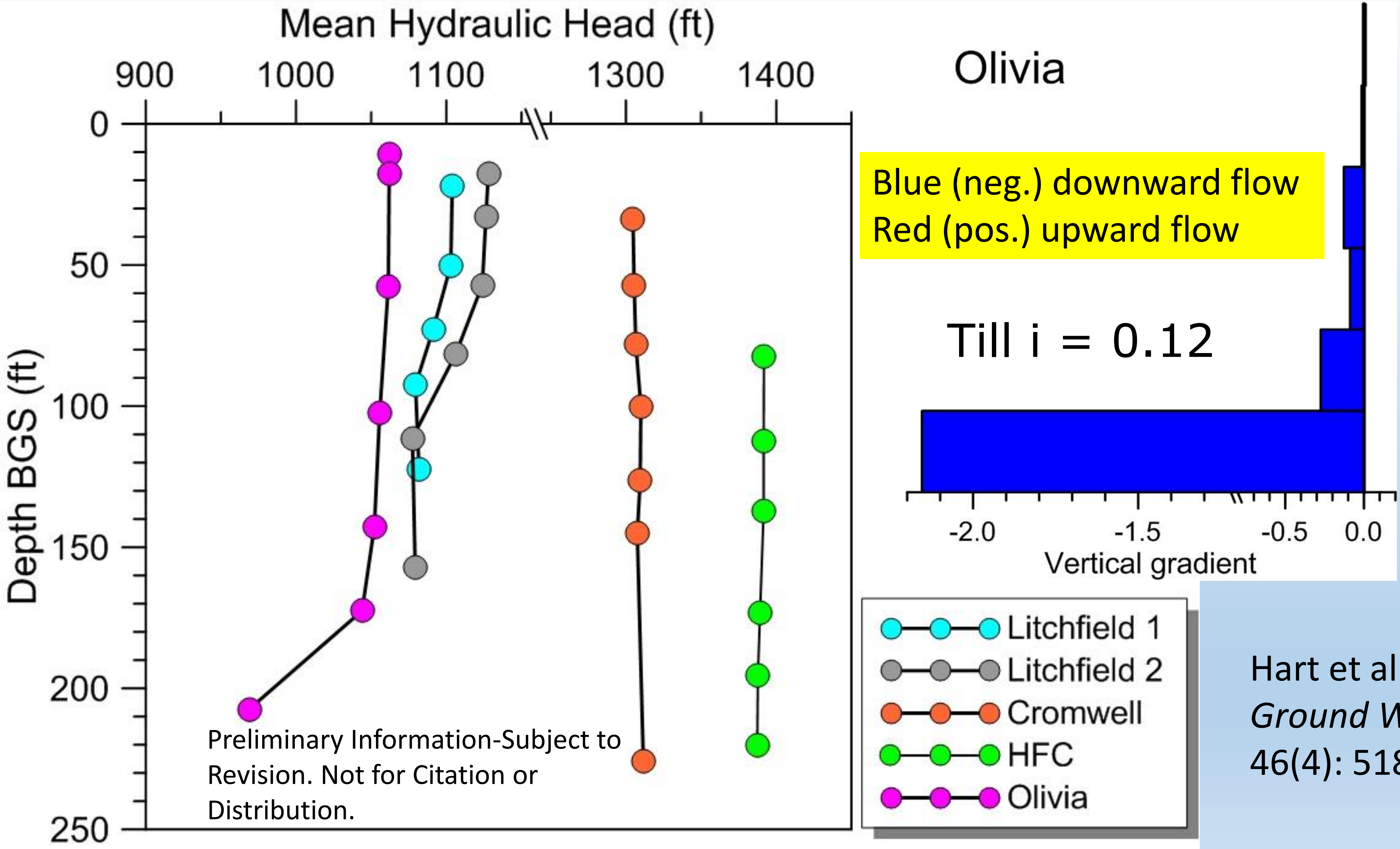
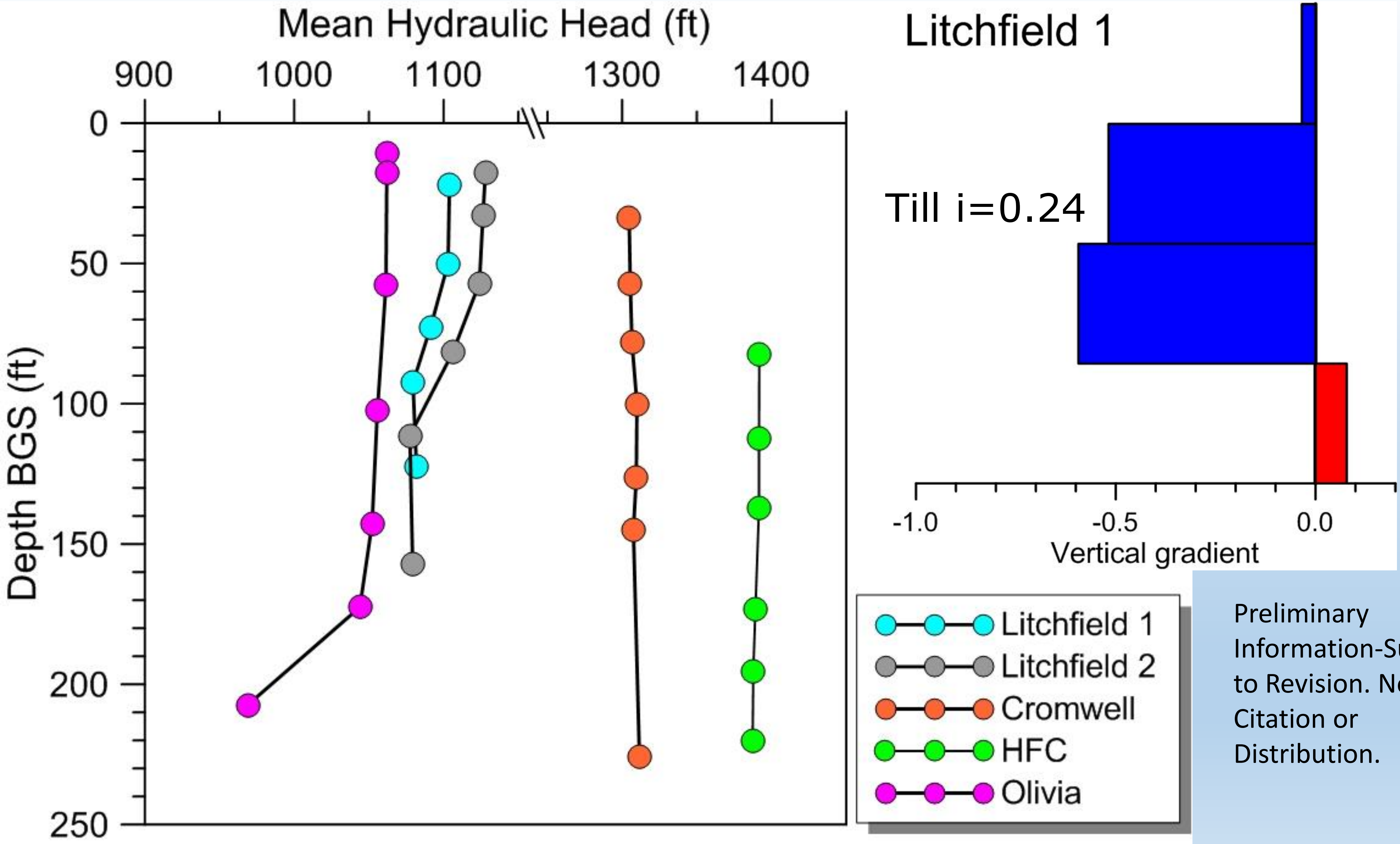


Hart et al., 2008.
Ground Water
46(4): 518-520



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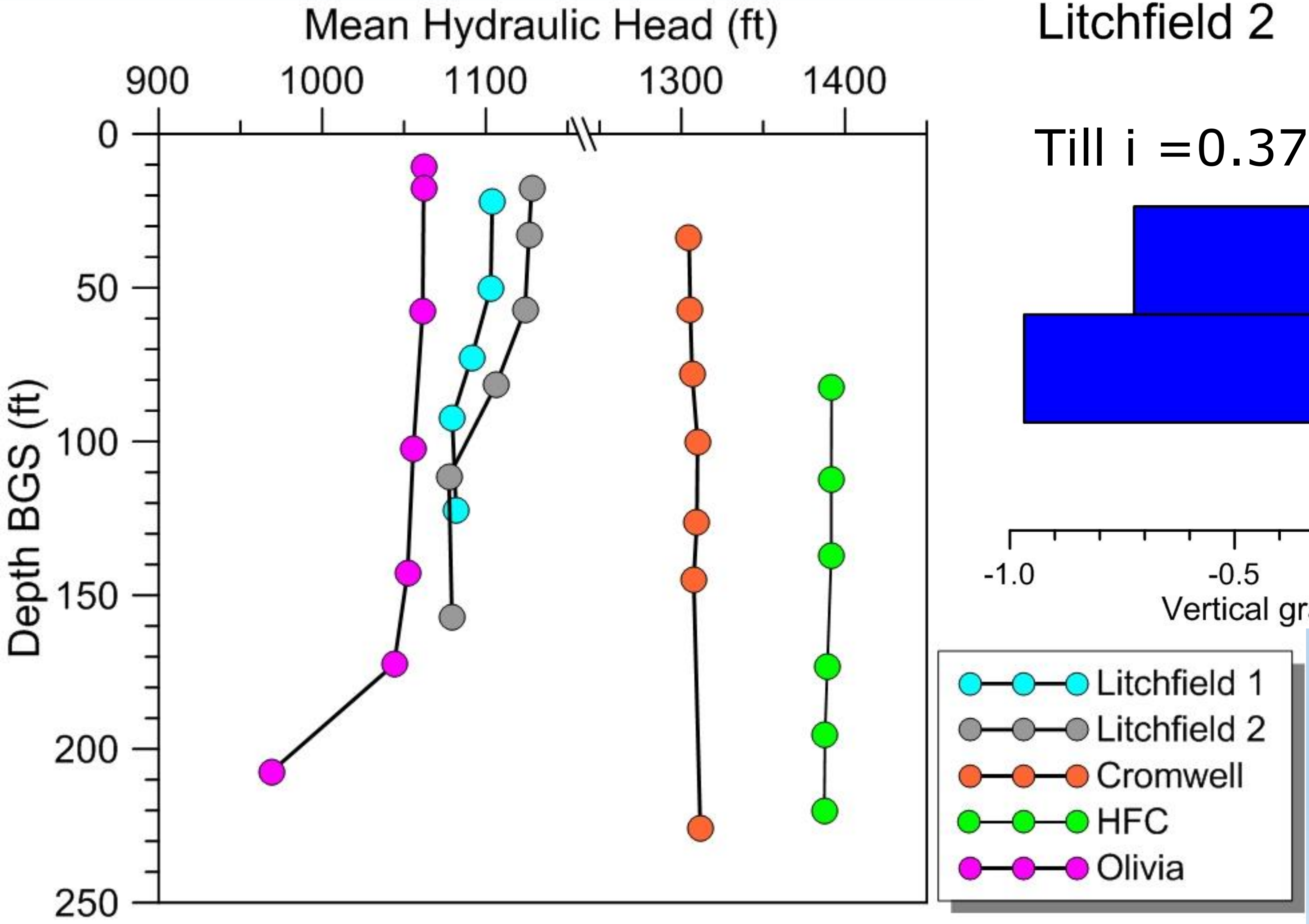

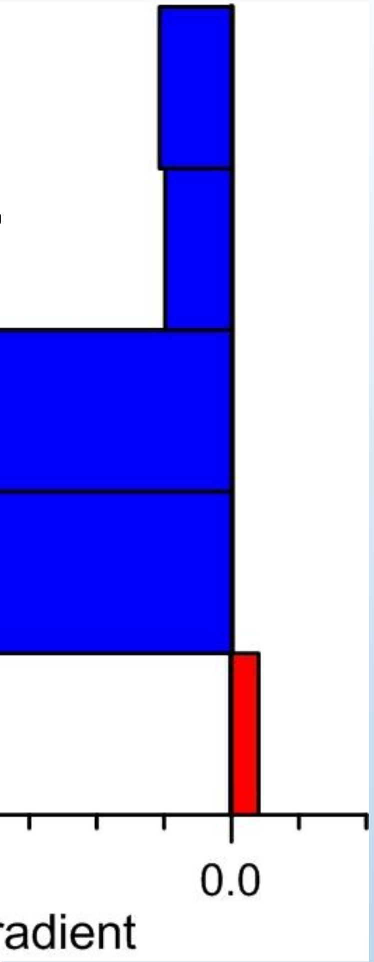

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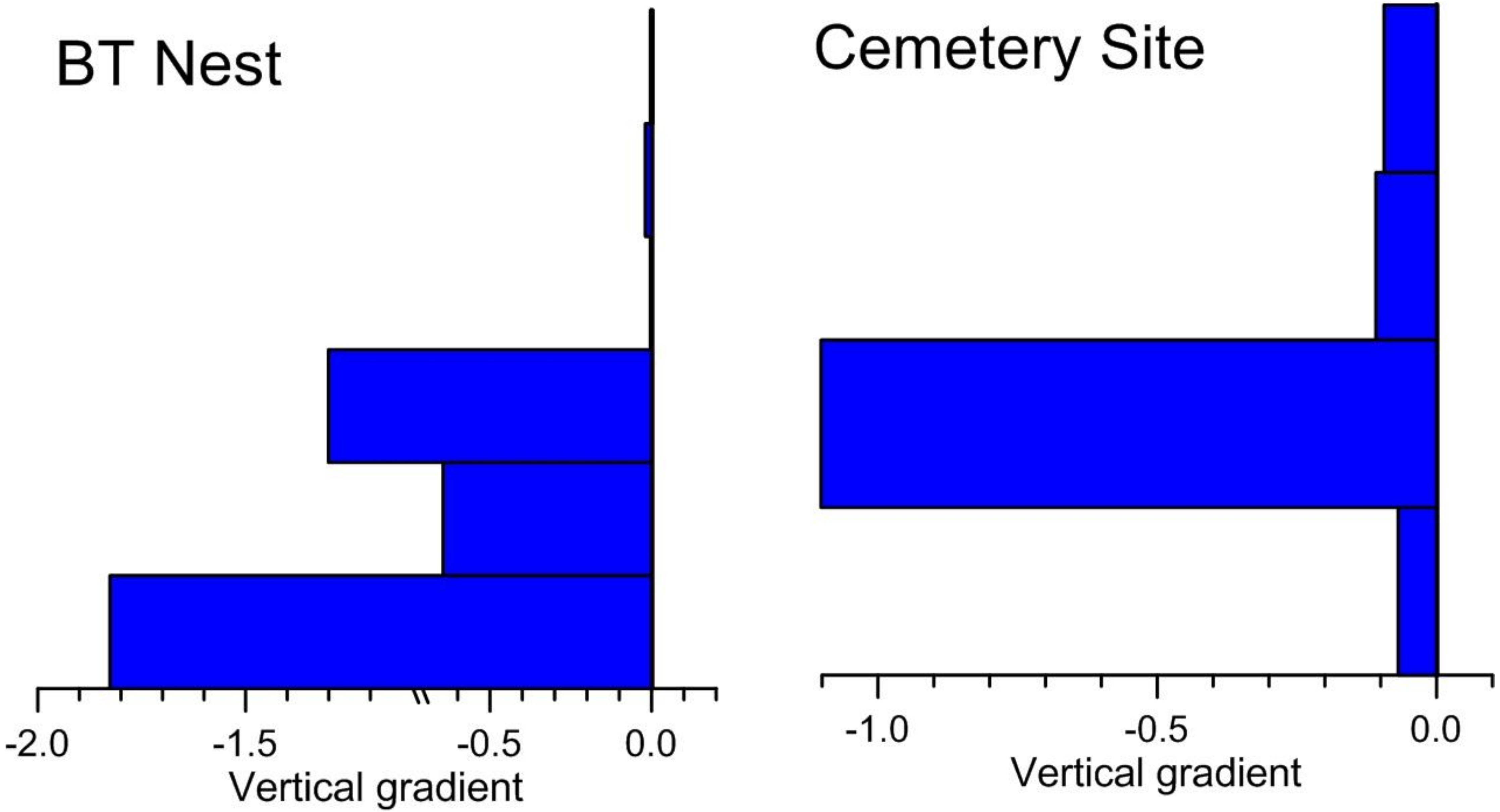
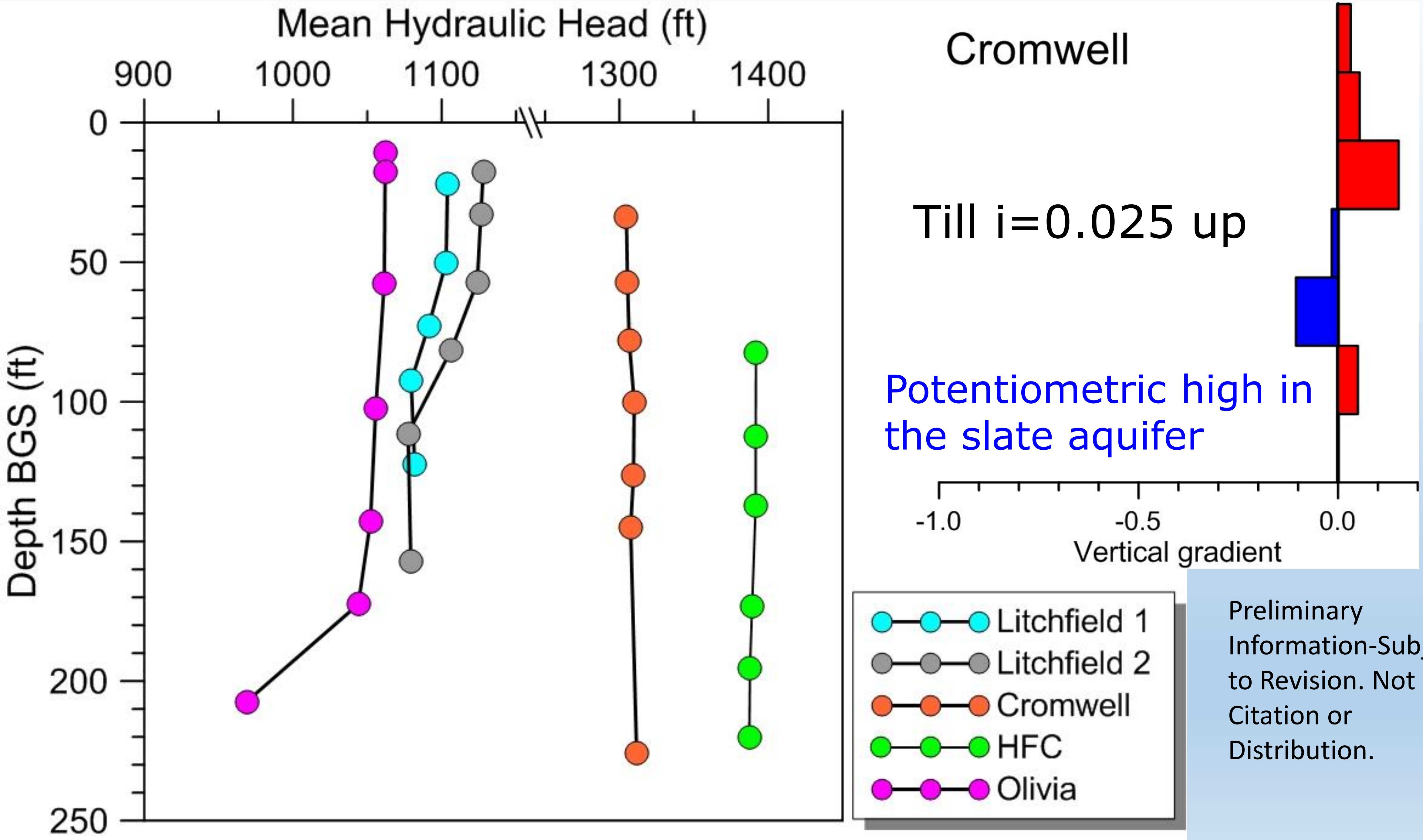
Till Sites from the Des Moines Lobe in Central Iowa



Beth Johnson and Jim Eidem, personal communication



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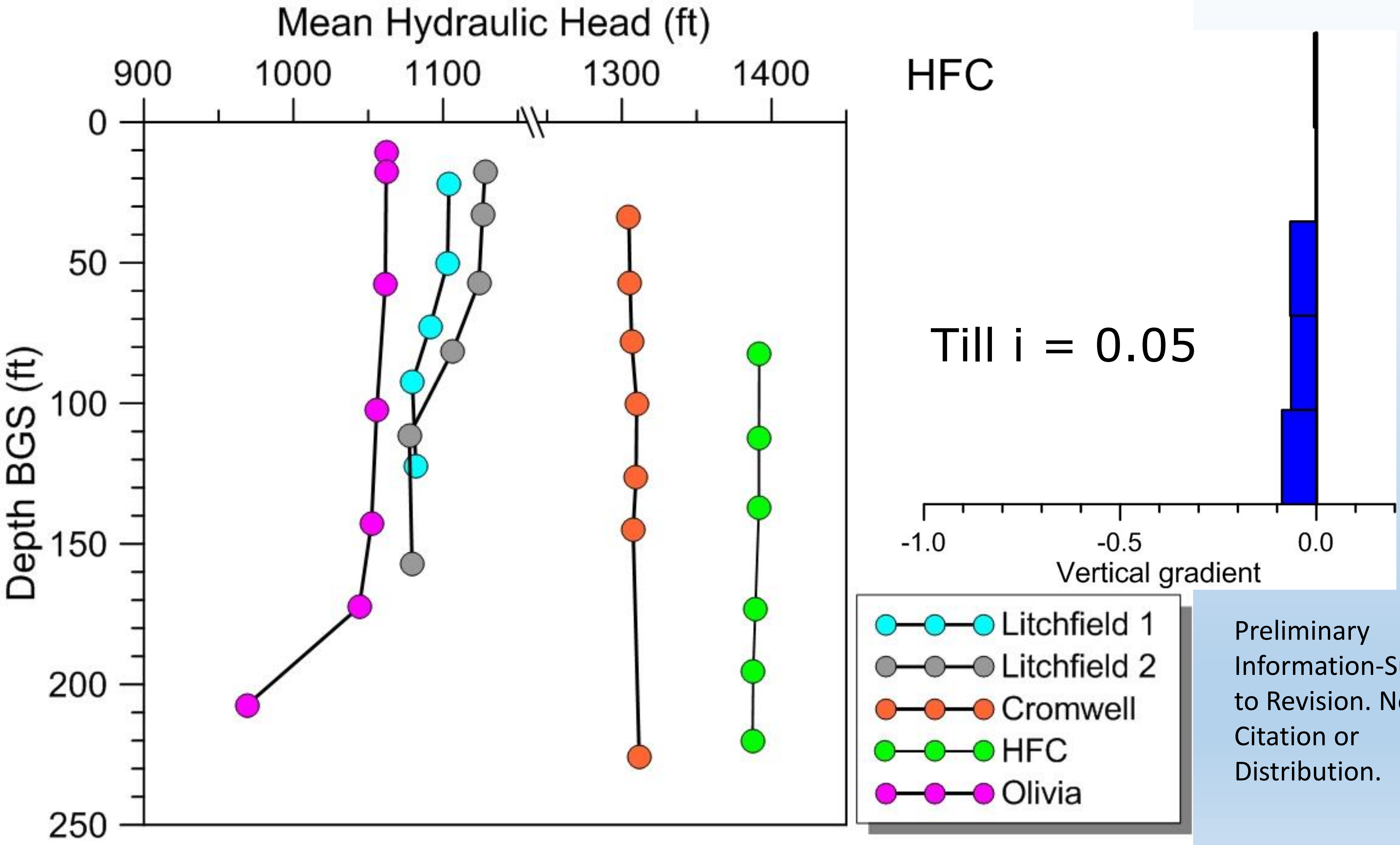

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Groundwater Velocity and Travel Time

Site	ALV from K_h (ft/d)	Bottom of Till (yrs)	ALV from K_v (ft/d)	Bottom of Till (yrs)
LF-1	7E-02	2	2E-03	91
LF-2	3E-04	1,026	2E-04	2,129
Olivia	3E-03	125	3E-04	1,588
HFC	9E-03	30	2E-03	147

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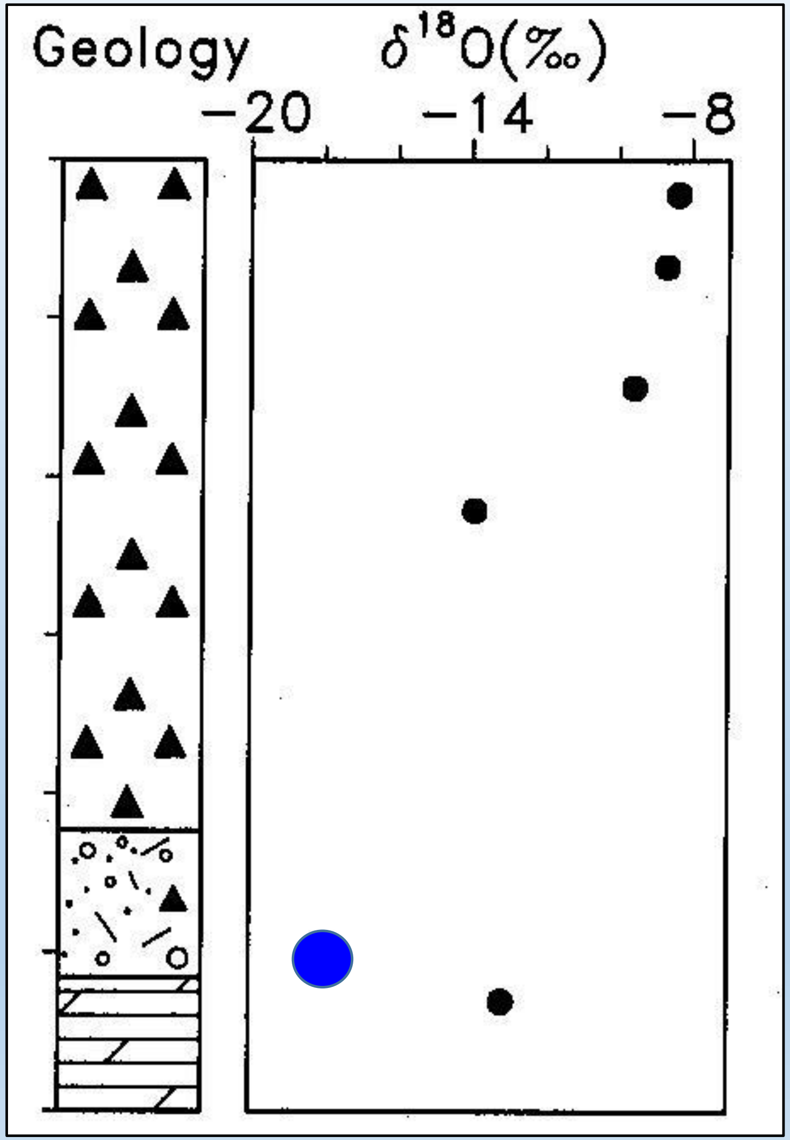
$$Average\ linear\ velocity\ (ALV) = \frac{Ki}{n}$$

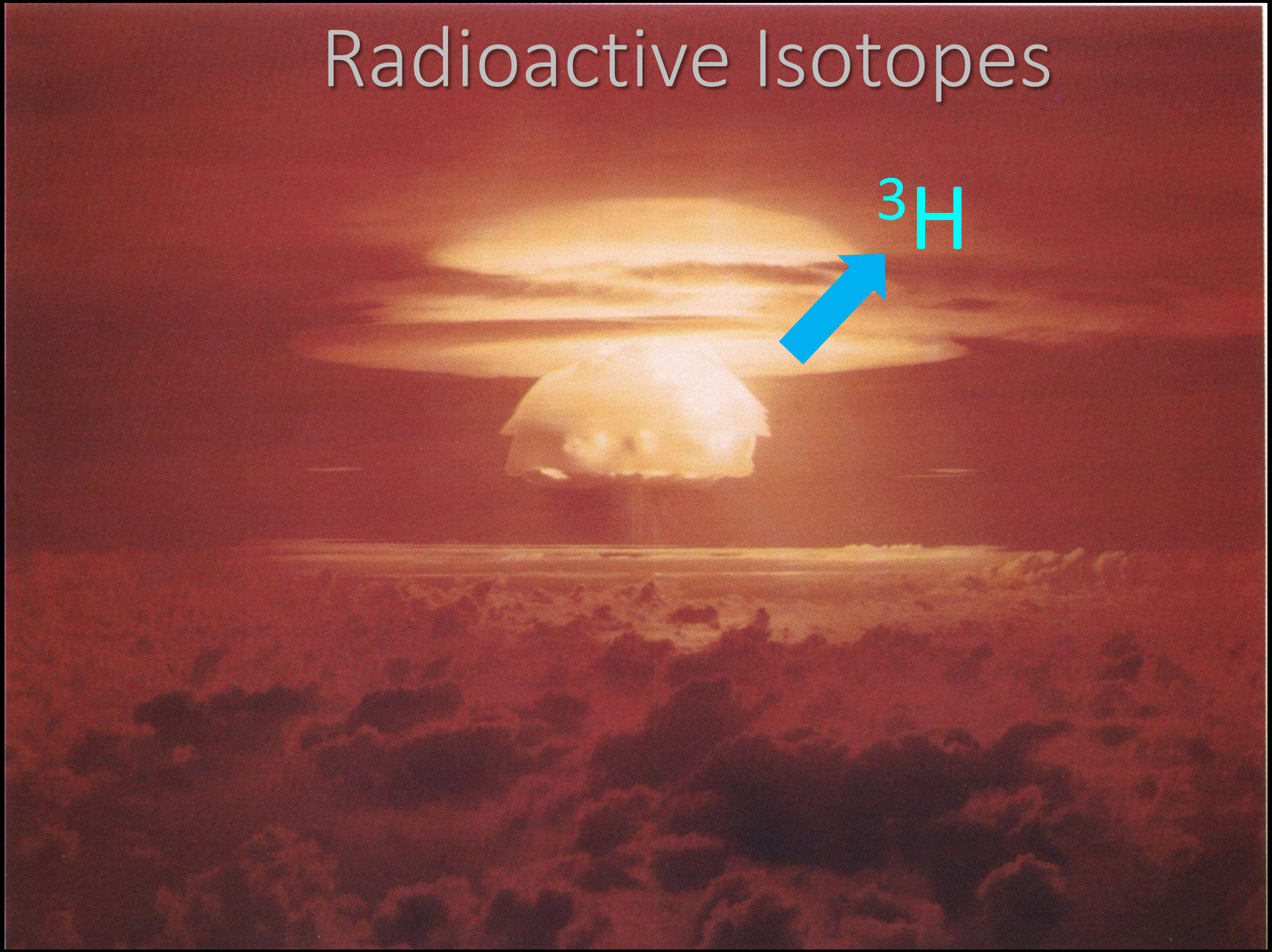
$n = 0.25$

Chemistry to the Rescue

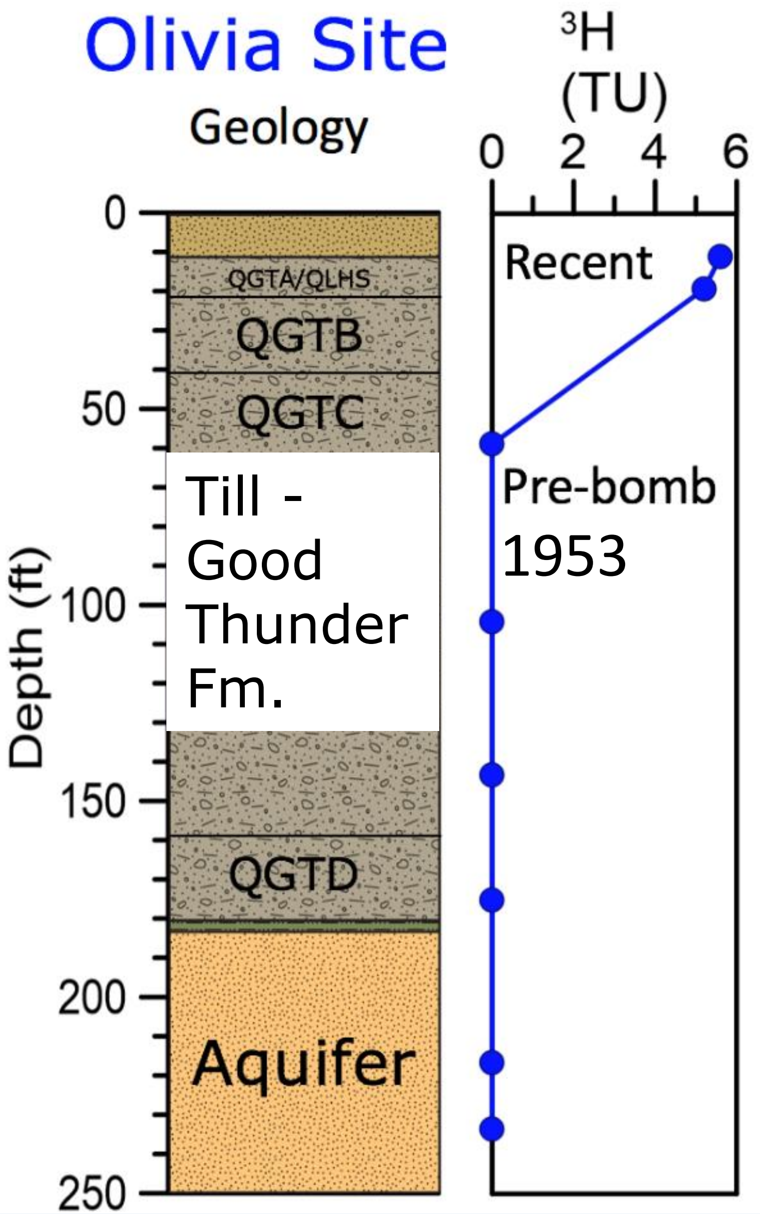


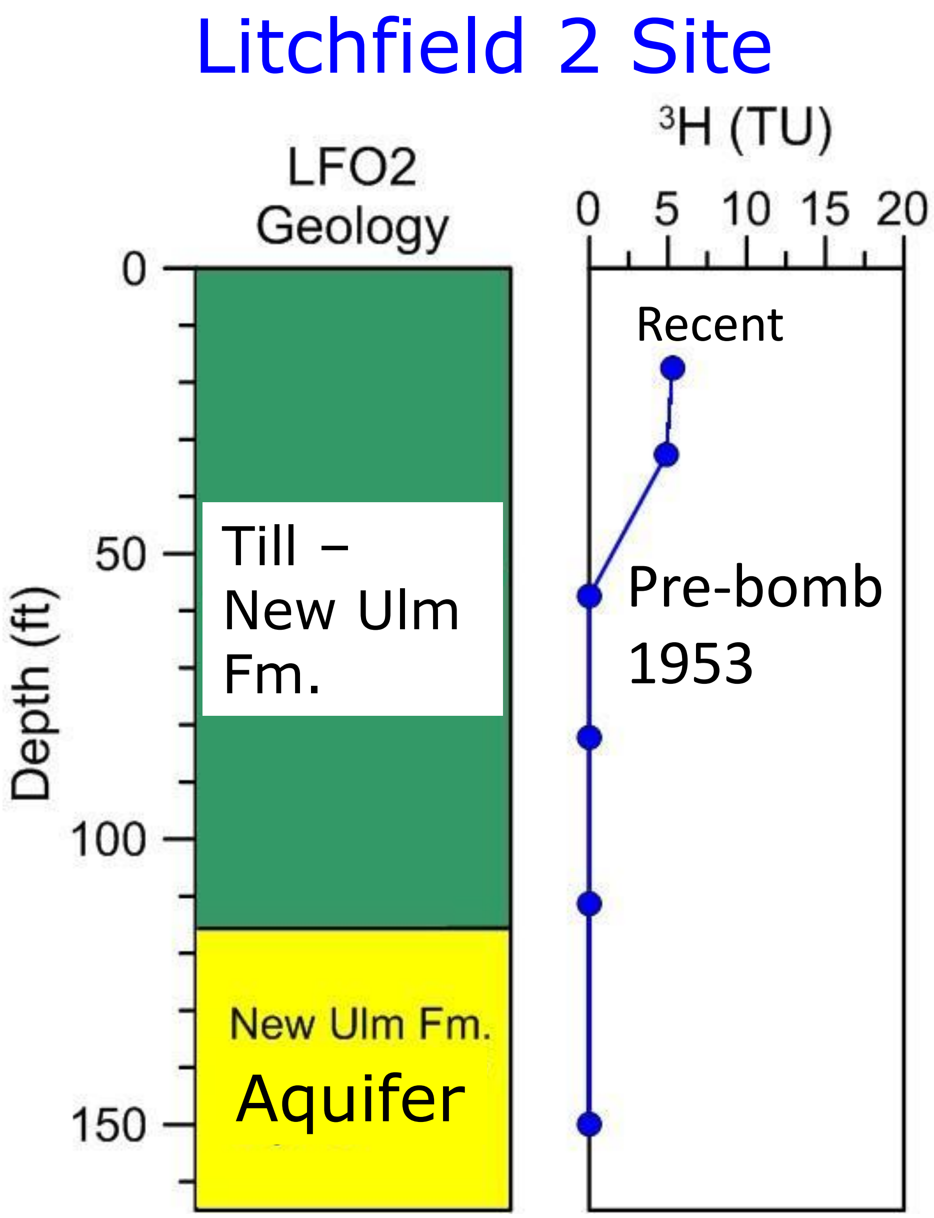
Age Estimates from $\delta^{18}O$

Source	$\delta^{18}O$ (‰) VSMOW
Glacier Ice (Paterson and Hammer, 1987)	-40 to -55
Lake Agassiz, southern Manitoba and North Dakota (Remenda et al., 1994)	-19 to -25
Beneath Lake Agassiz sediments in Clay County-Geologic Atlas B (Berg, 2018)	-19 to -23
Oak Creek Fm. till, Southeast Wisconsin (Simpkins and Bradbury, 1992)	-18
Preliminary Information-Subject to Revision. Not for Citation or Distribution.	
This study: pore water and groundwater are not glacial age	-8.33 to -11.61



Nuclear weapon test Bravo on Bikini Atoll, Feb. 28, 1954. USDOE, public domain.





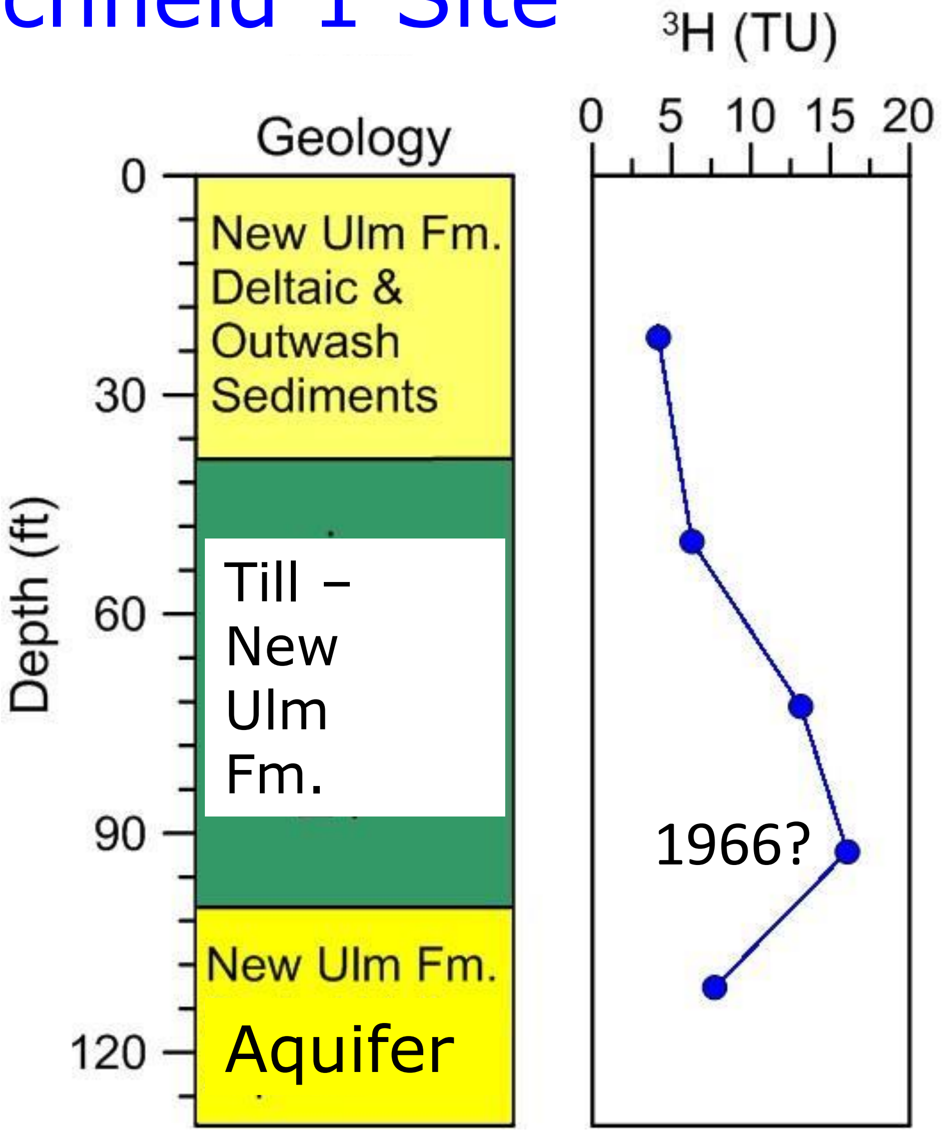
TU=Tritium units

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

Higher K, Moderate head gradient

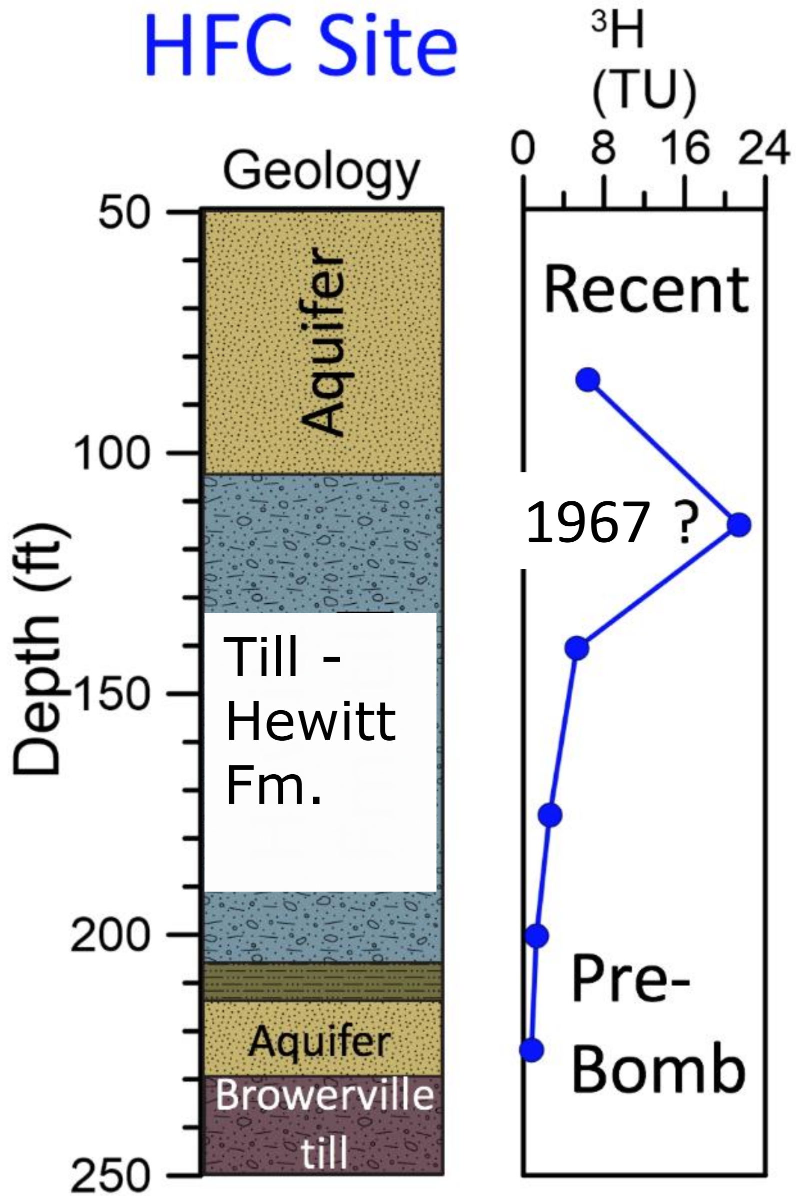
Lowest K, Steepest head gradient

Litchfield 1 Site



Higher K, Steep gradient

HFC Site



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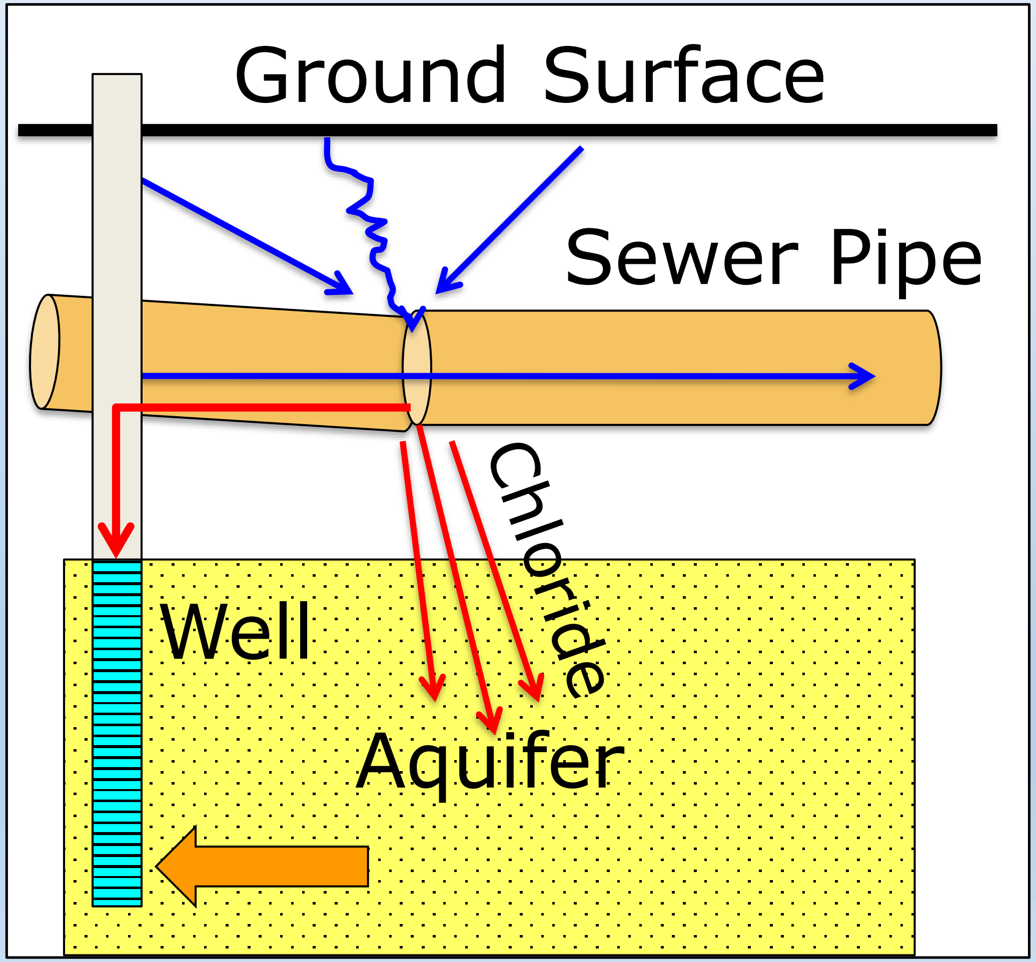
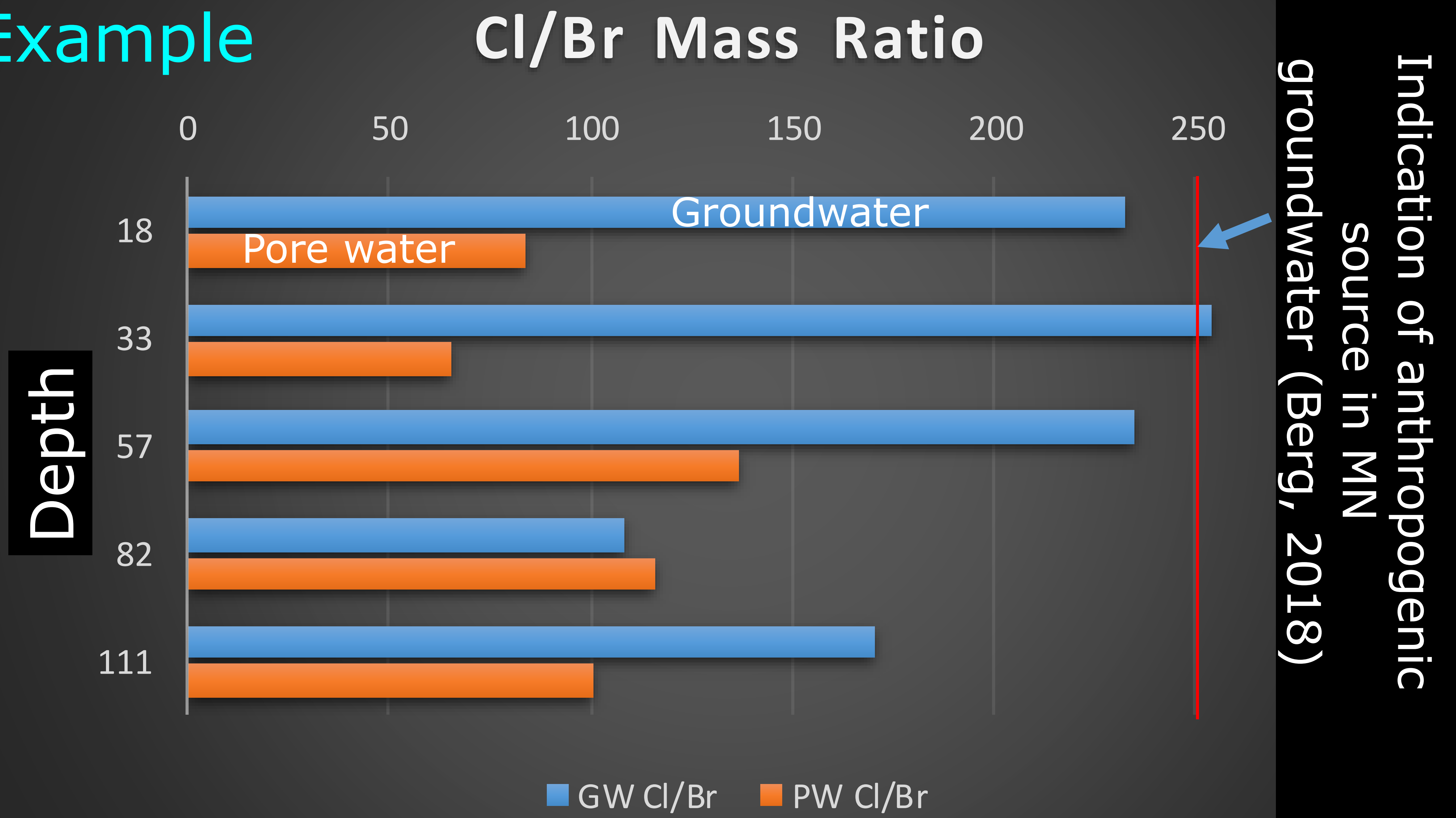
Highest K, Shallow gradient

Anthropogenic Tracers



Example



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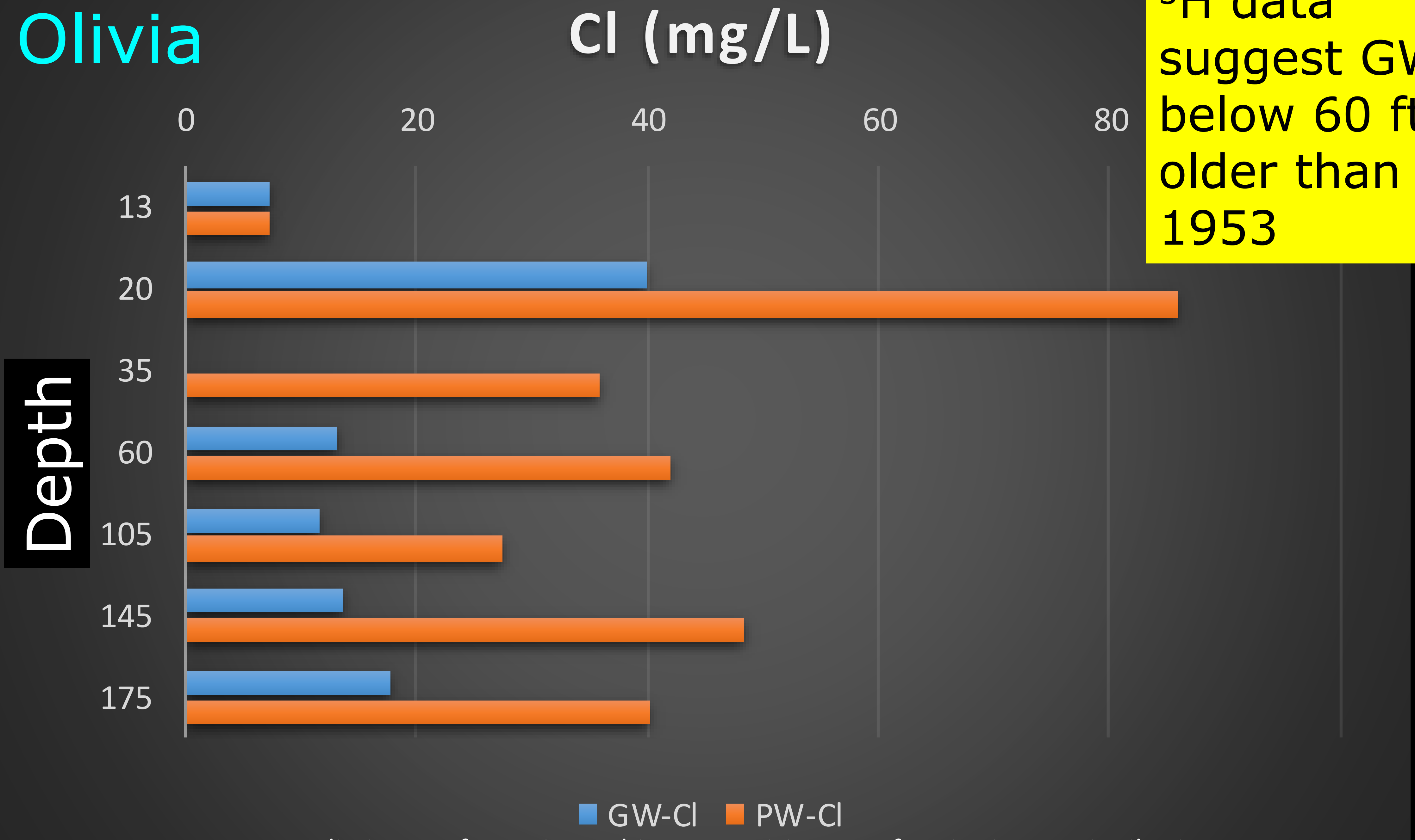
Olivia

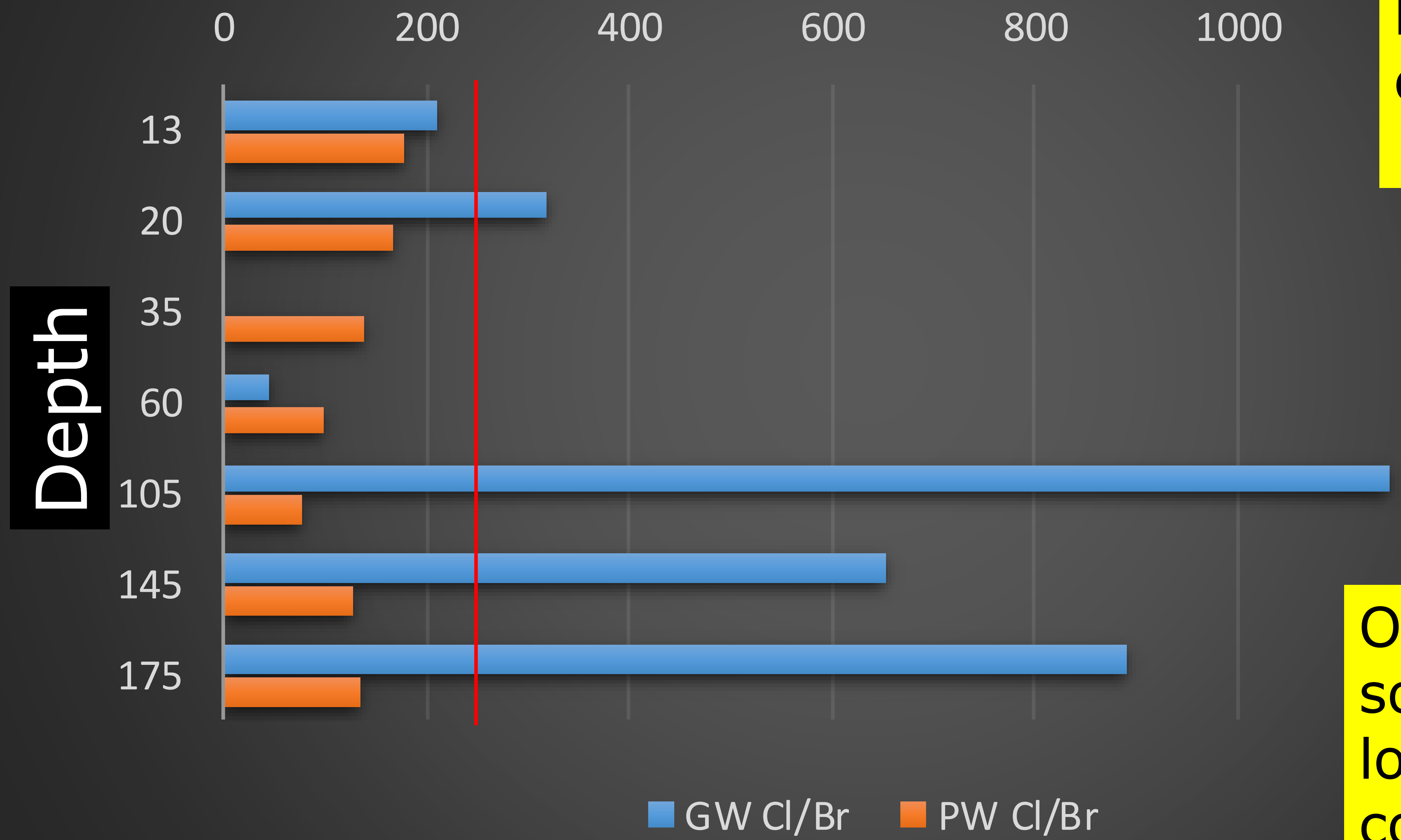


^3H data suggest GW below 60 ft is older than 1953

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

Olivia

Cl/Br Mass Ratios



^3H data suggest GW below 60 ft is older than 1953

Olivia has some of the lowest Br concentrations

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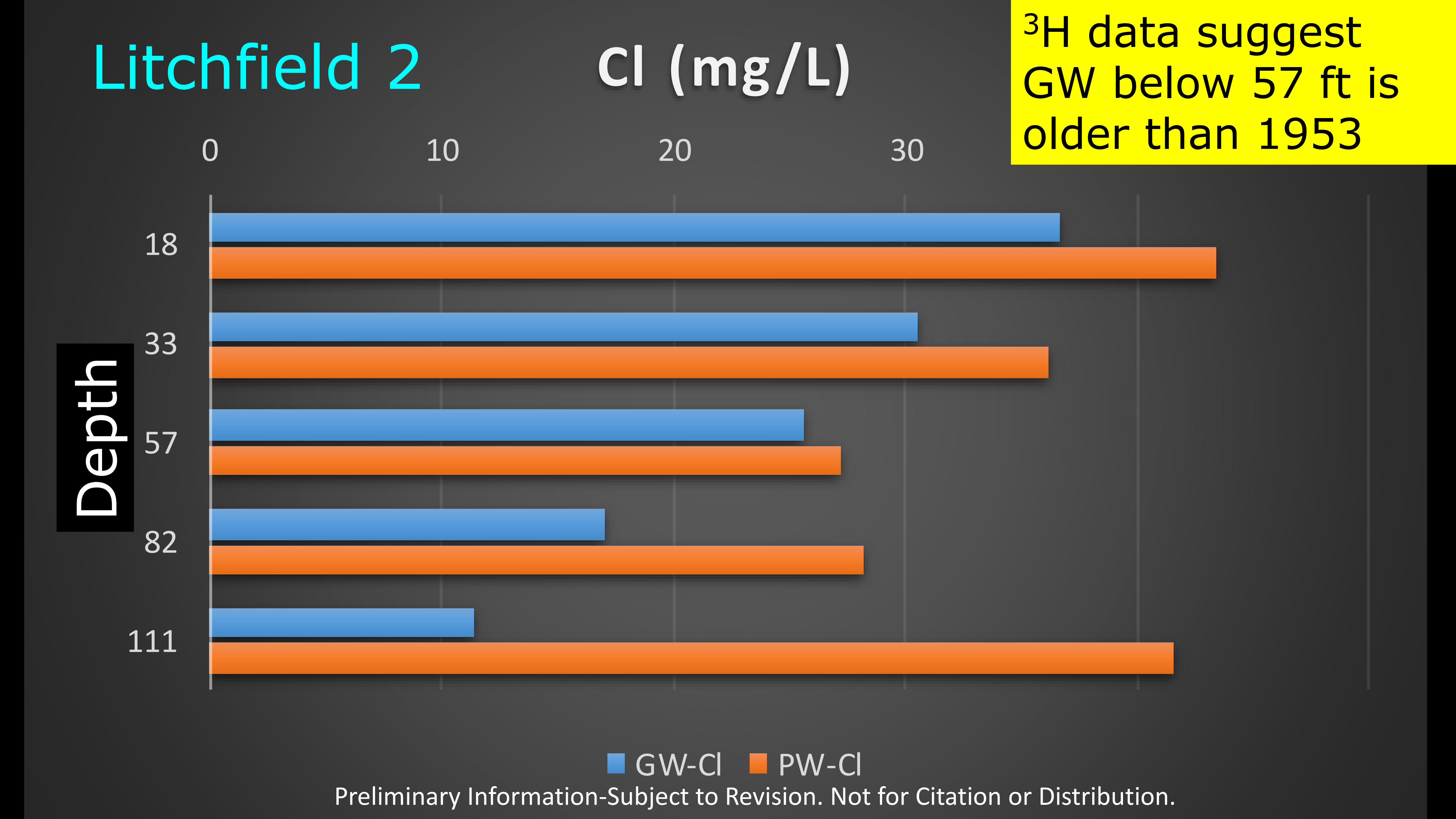
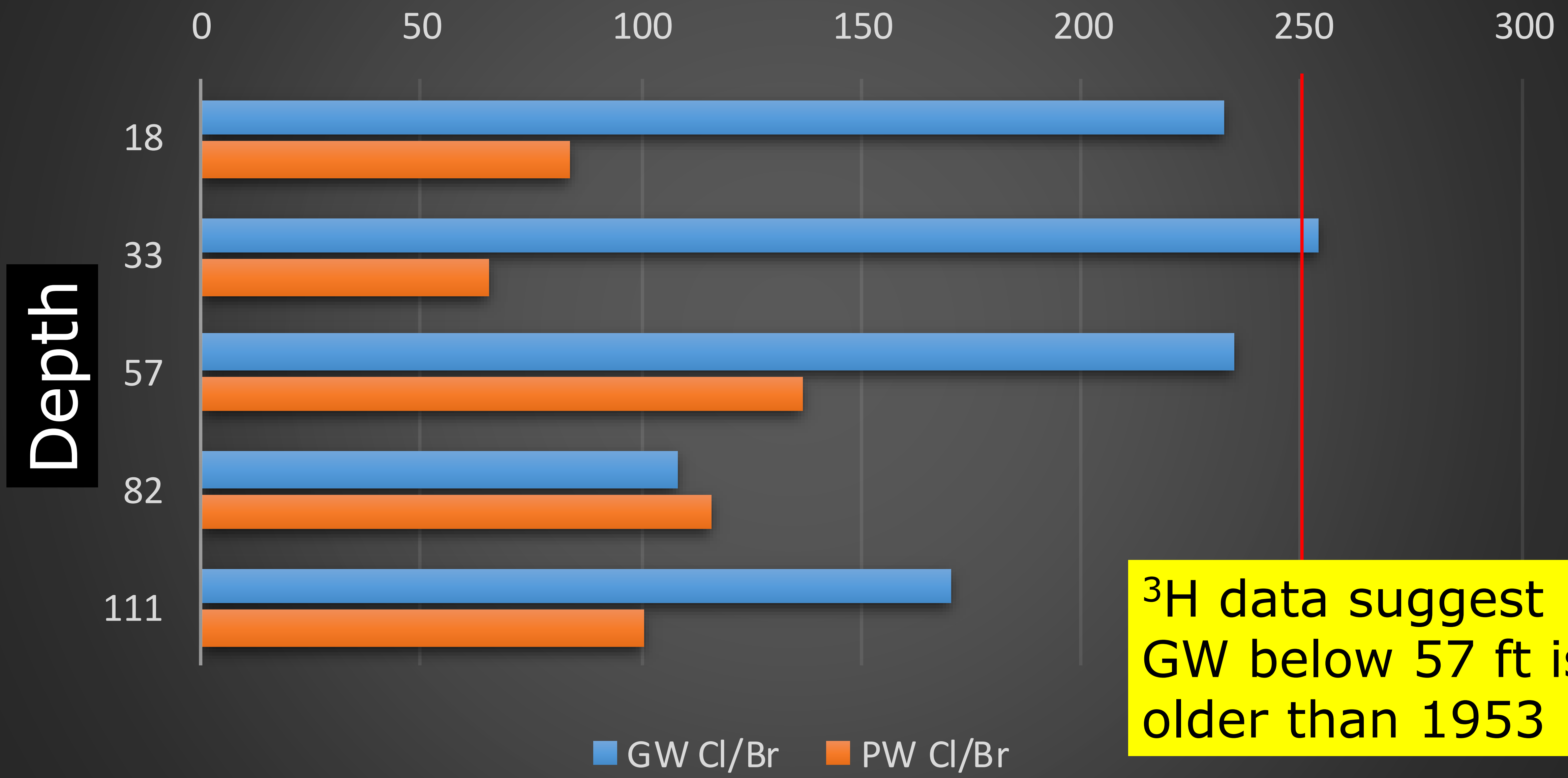

Litchfield 2
Cl (mg/L)
³H data suggest GW below 57 ft is older than 1953
0
10
20
30
18
33
57
82
111
Depth
GW-Cl
PW-Cl
Preliminary Information-Subject to Revision. Not for Citation or Distribution.

Litchfield 2 **Cl/Br Mass Ratio**



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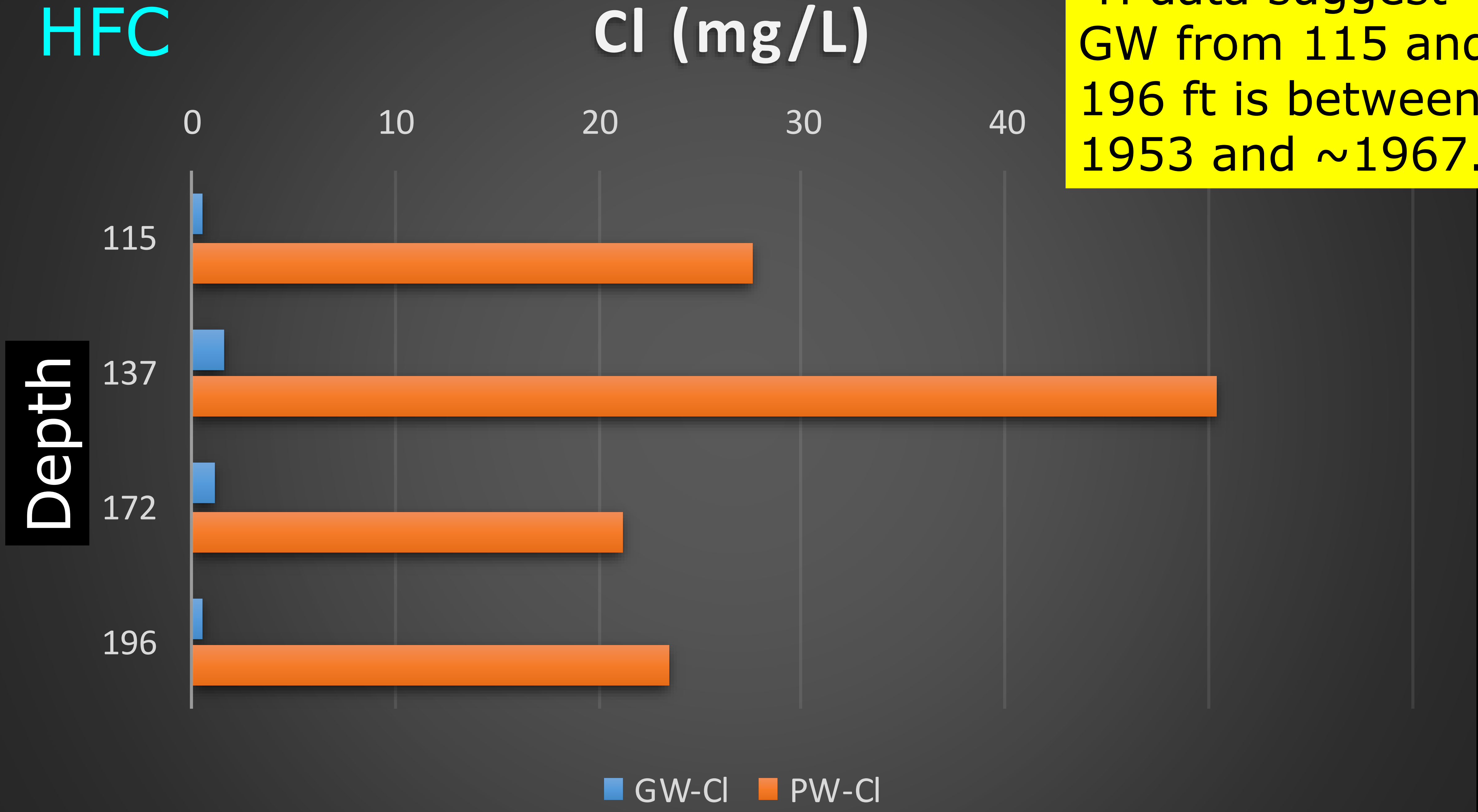
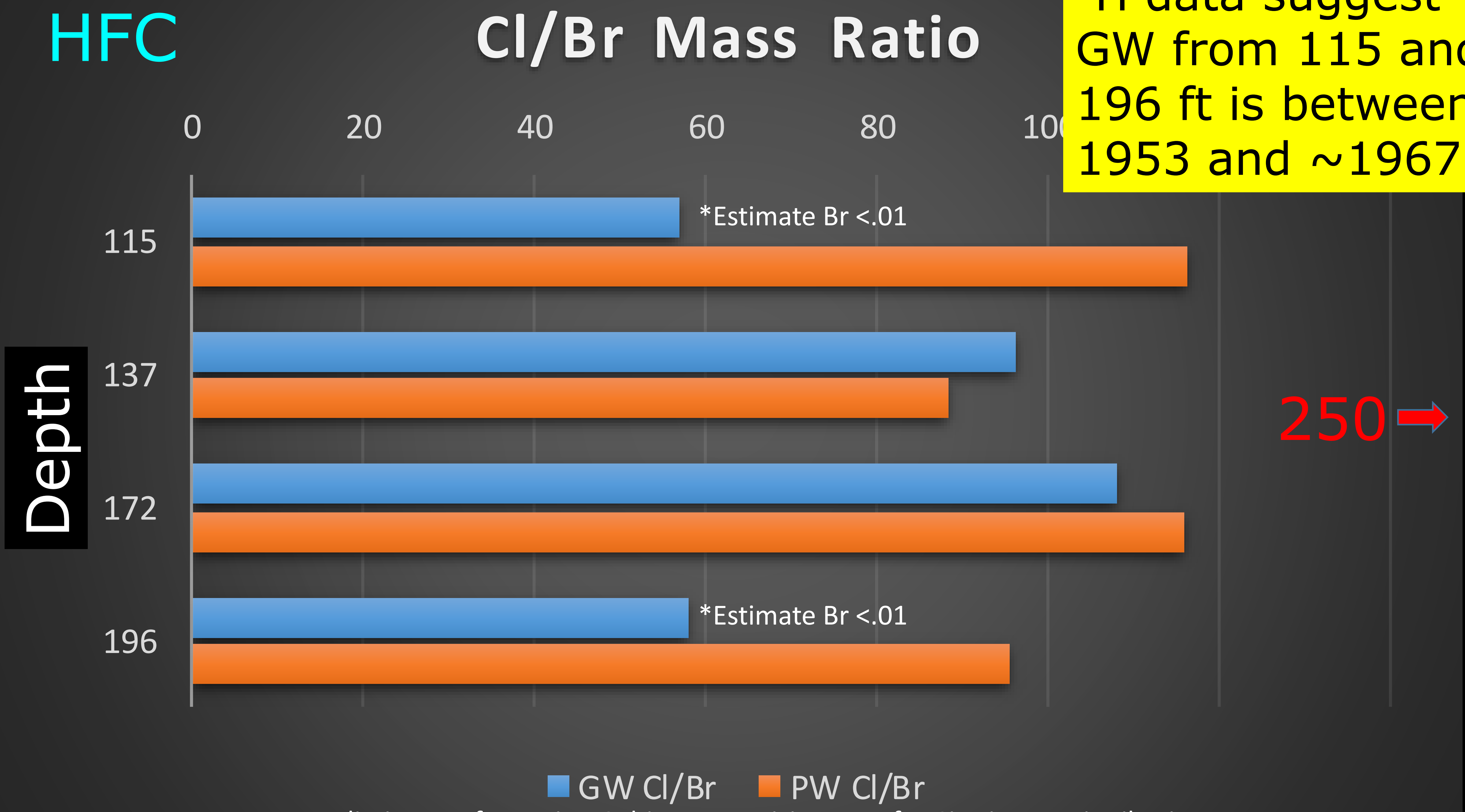
HFC



^3H data suggest GW from 115 and 196 ft is between 1953 and ~1967.

HFC



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Summary

- Hydraulic head relationships suggest that groundwater in till “leaks” to the underlying confined aquifer (except Cromwell), but the “leak” magnitude reflects site-specific conditions
  - Travel times shorter than expected for “impermeable” till

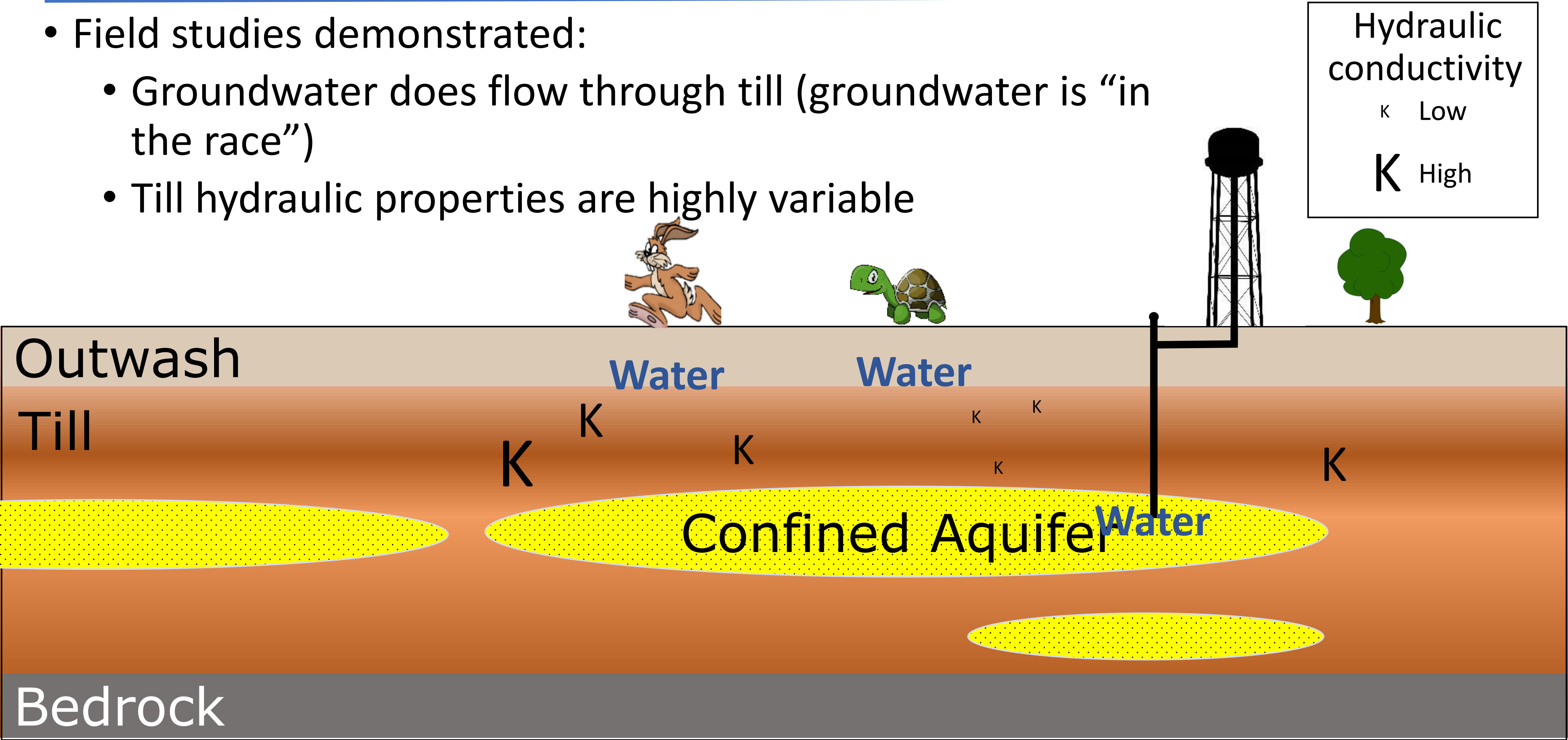
- $\delta^{18}O$ data suggest post-glacial groundwater age at all sites
- ^{3}H data suggest ~1960s age at Litchfield 1 and HFC sites

- Cl and Cl/Br ratio data suggest possible penetration of anthropogenic tracers (deicing salt?) to depth, particularly at urban sites

- Pore-water vs. groundwater geochemistry?
  - Possible explanations: sampling scale, crushing of grains with Cl, sample contamination, and fracture/matrix interaction

Quick Review

- Field studies demonstrated:
  - Groundwater does flow through till (groundwater is "in the race")
  - Till hydraulic properties are highly variable



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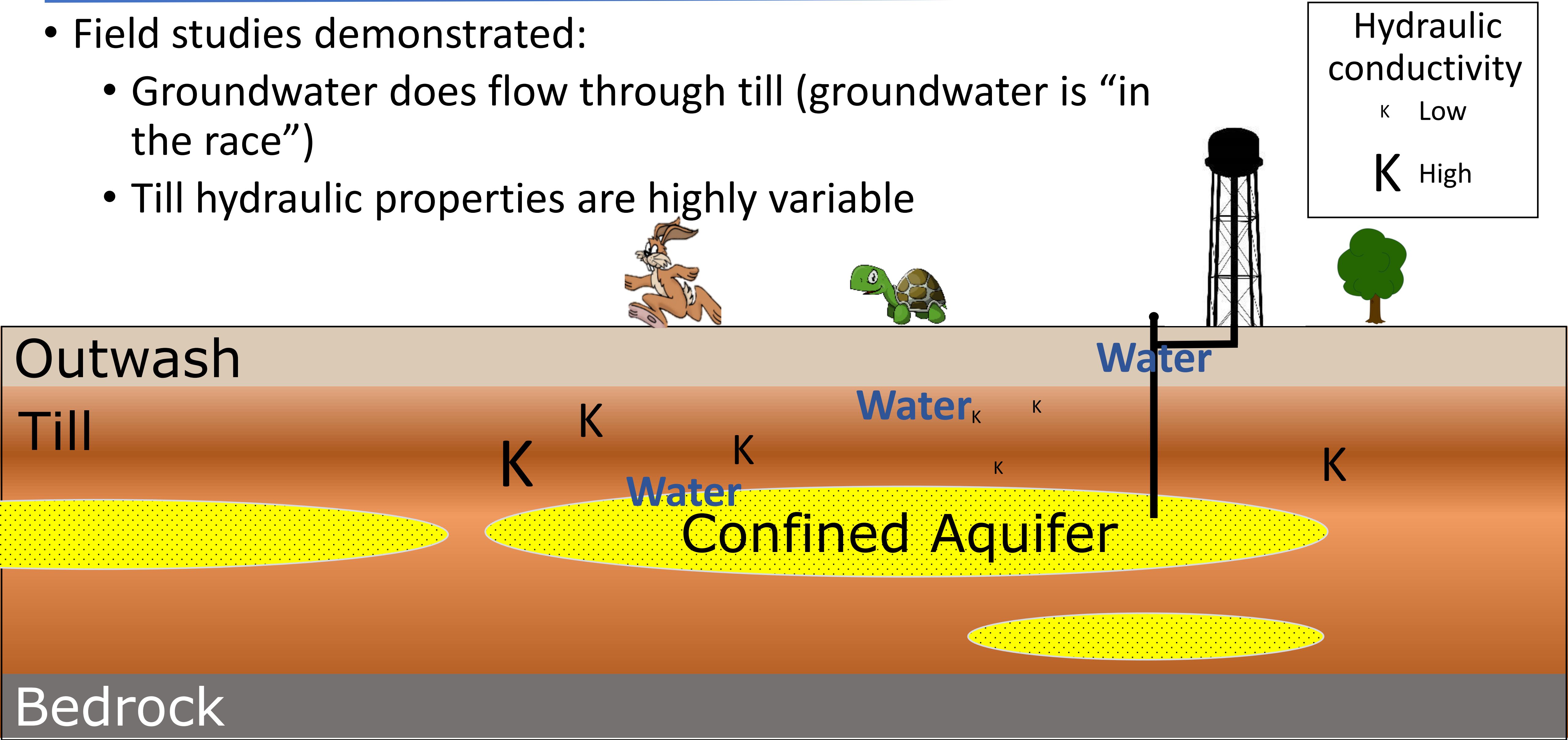
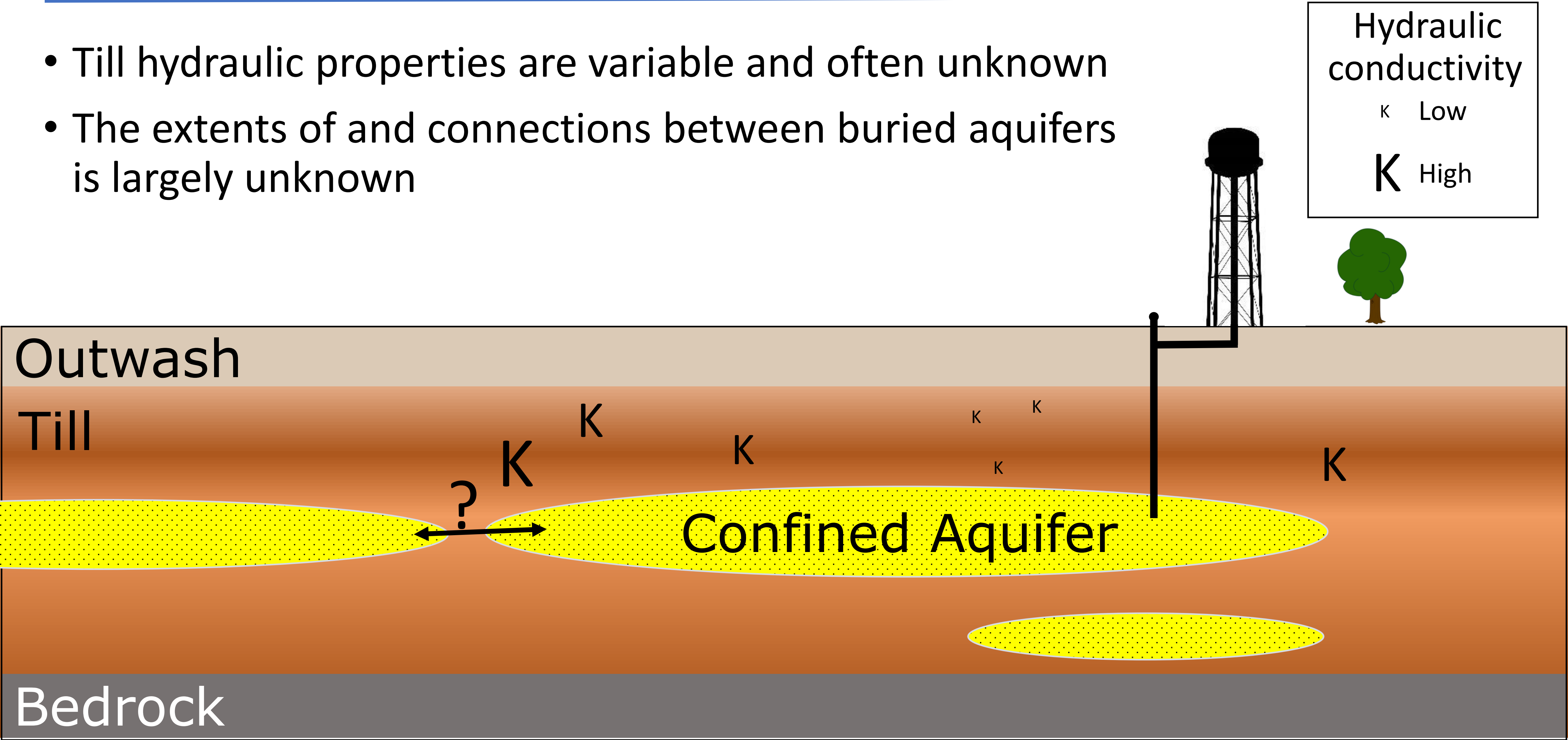


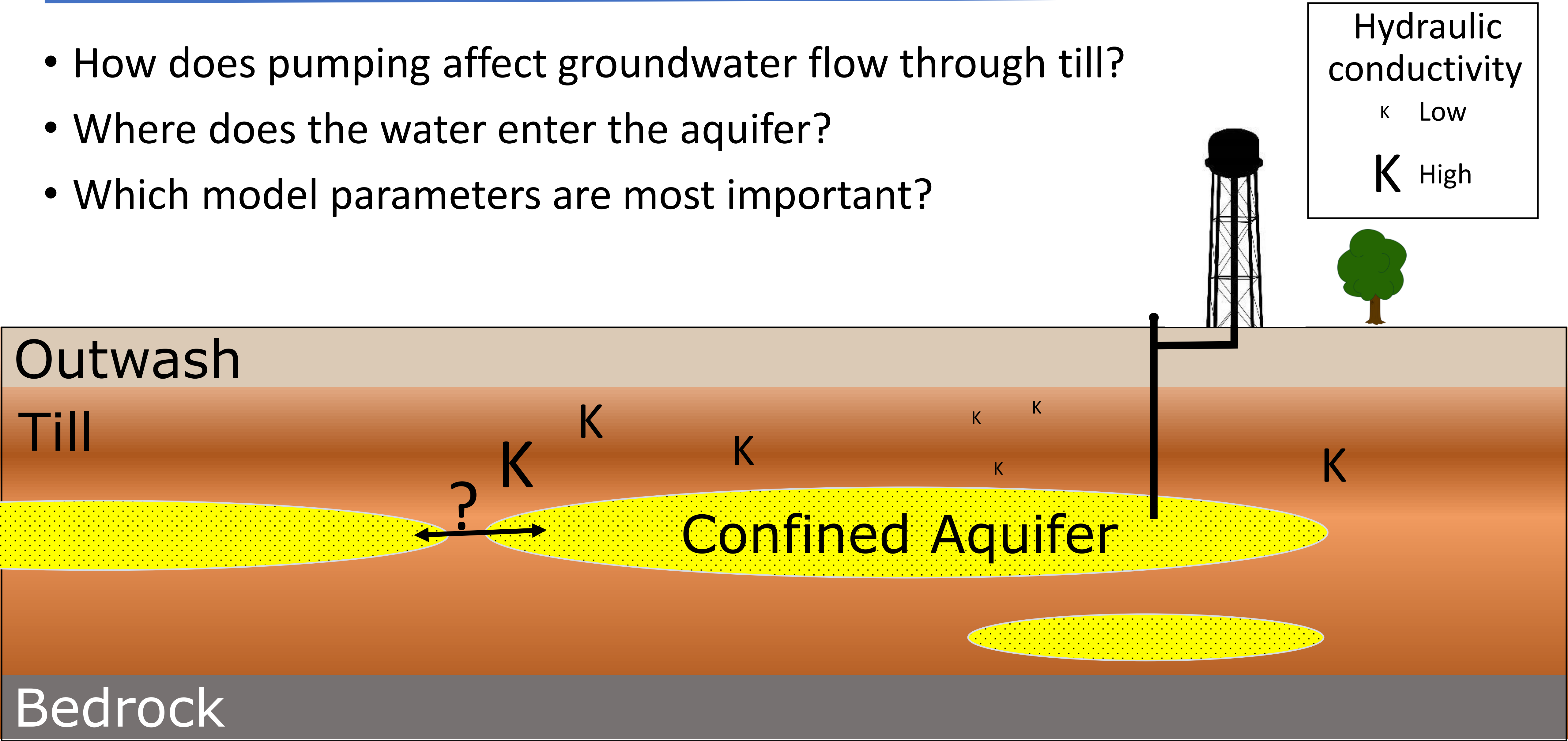
Modeling challenges

- Till hydraulic properties are variable and often unknown
- The extents of and connections between buried aquifers is largely unknown

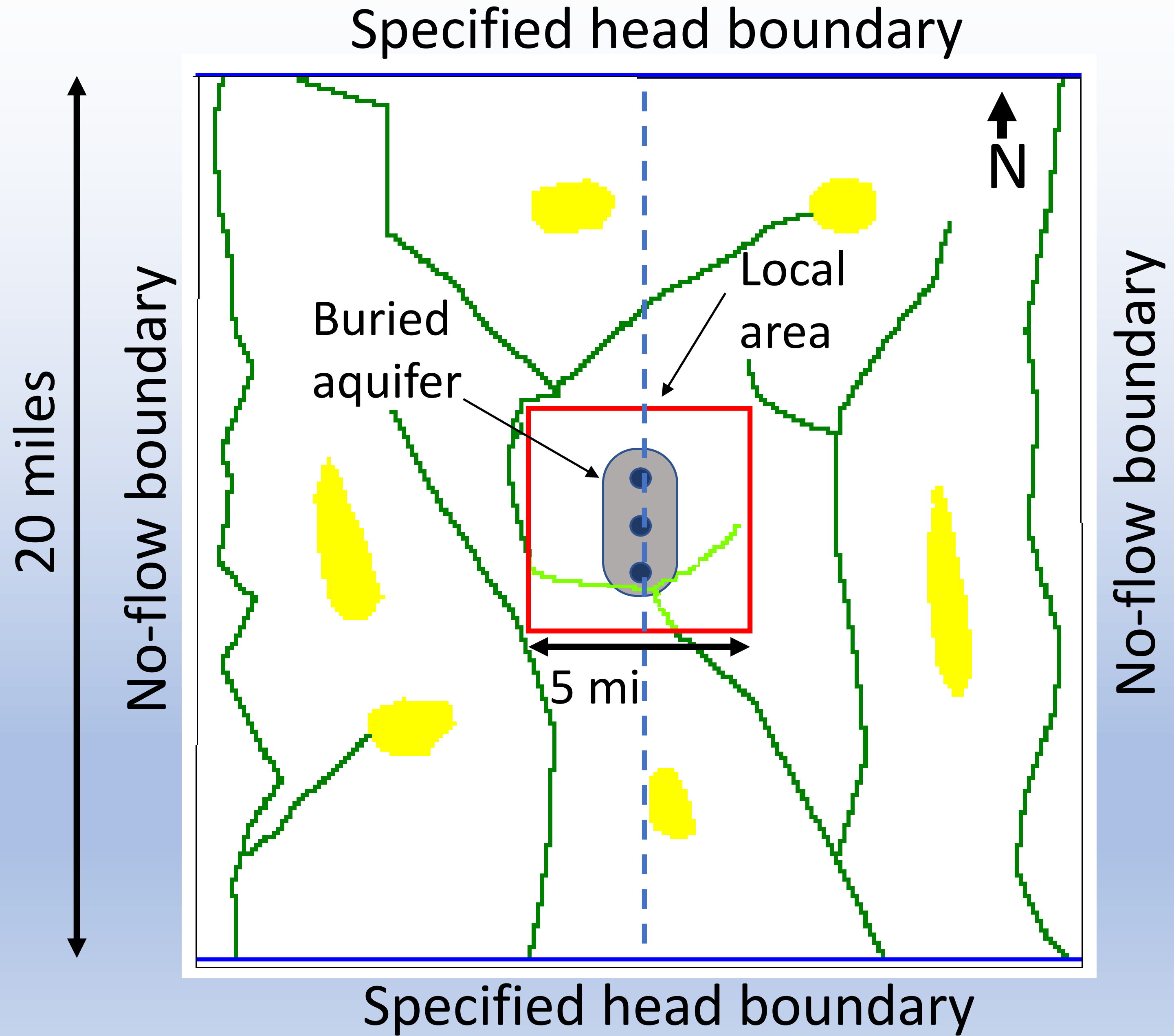


Questions for Modeling

- How does pumping affect groundwater flow through till?
- Where does the water enter the aquifer?
- Which model parameters are most important?



Model construction

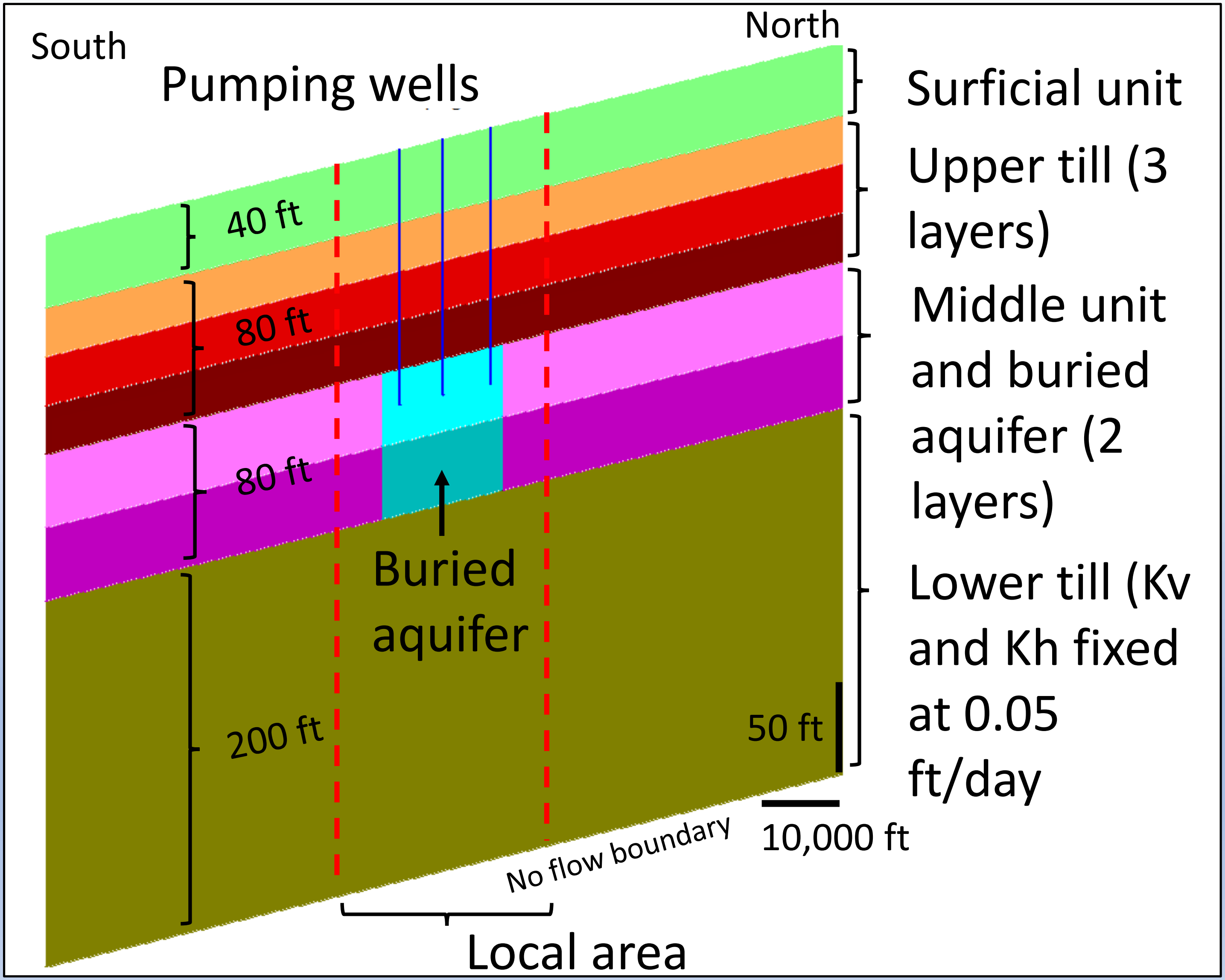


- MODFLOW 2000
- 500 x 500 ft cells
- N-to-S hydraulic gradient of 0.001
- Vertical downward gradient=0.15
- Recharge = 4 in/yr
- Local area used to calculate fluxes

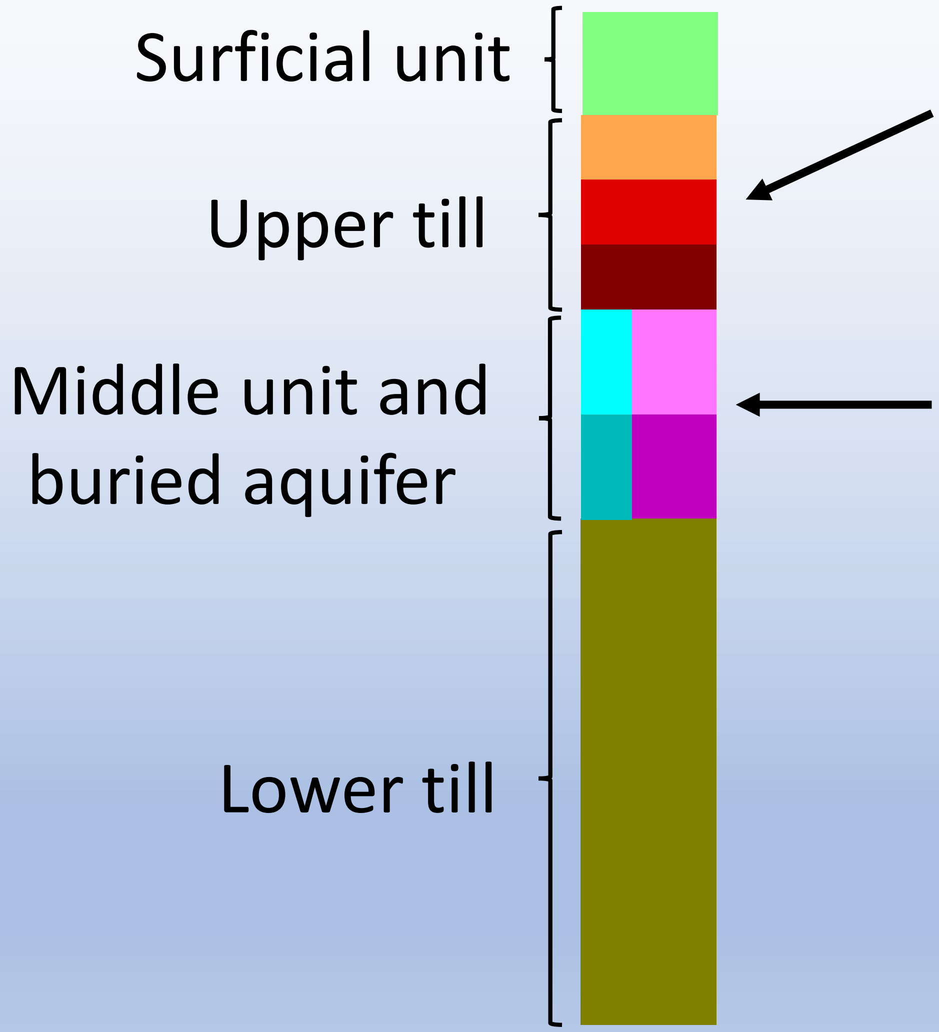
Explanation

- Rivers (RIV pkg)
- Lakes (DRN pkg)
- Pumping wells (MNW2 pkg)

Model construction



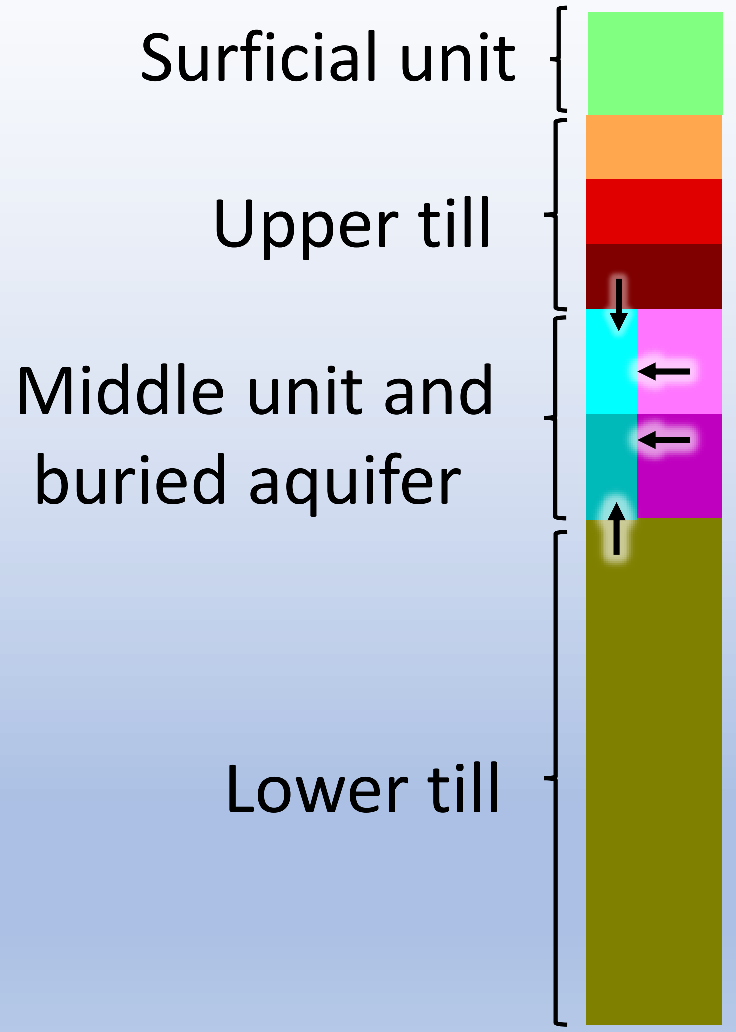
General description of model scenarios



Vary vertical hydraulic conductivity (K_v) of upper till

Vary horizontal hydraulic conductivity (K_h) of the middle unit

Leakage (flux) into aquifer



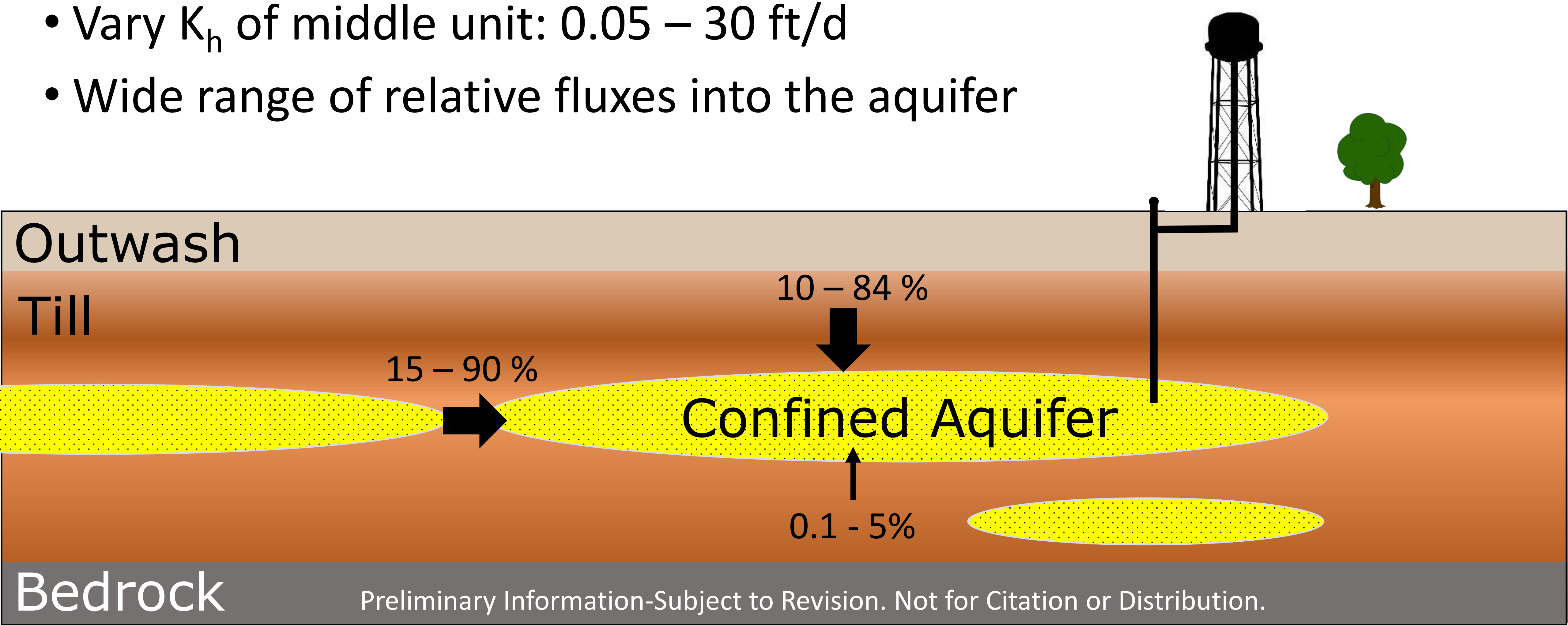
Response variable

The percent of the total volume of water entering the aquifer from:

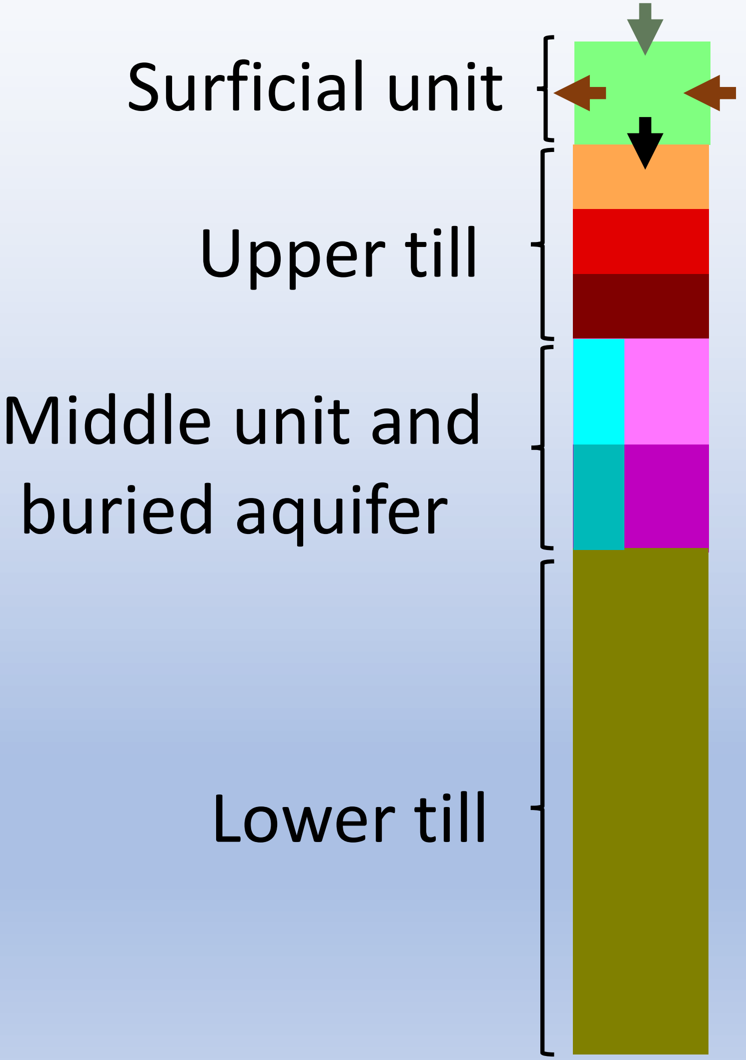
- Above (downward flux)
- Laterally (lateral flux)
- Below (upward flux)

Leakage (flux) into aquifer

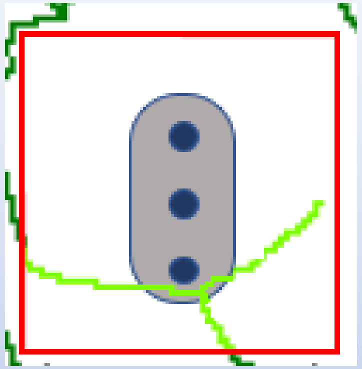
- Vary K_v of till 0.001 – 2.0 ft/d
- Vary K_h of middle unit: 0.05 – 30 ft/d
- Wide range of relative fluxes into the aquifer



Leakage (flux) into till from surficial unit



25 mi^2 "local area" of model

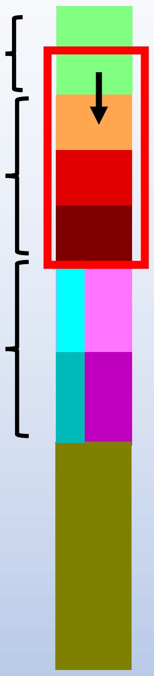


Response variable

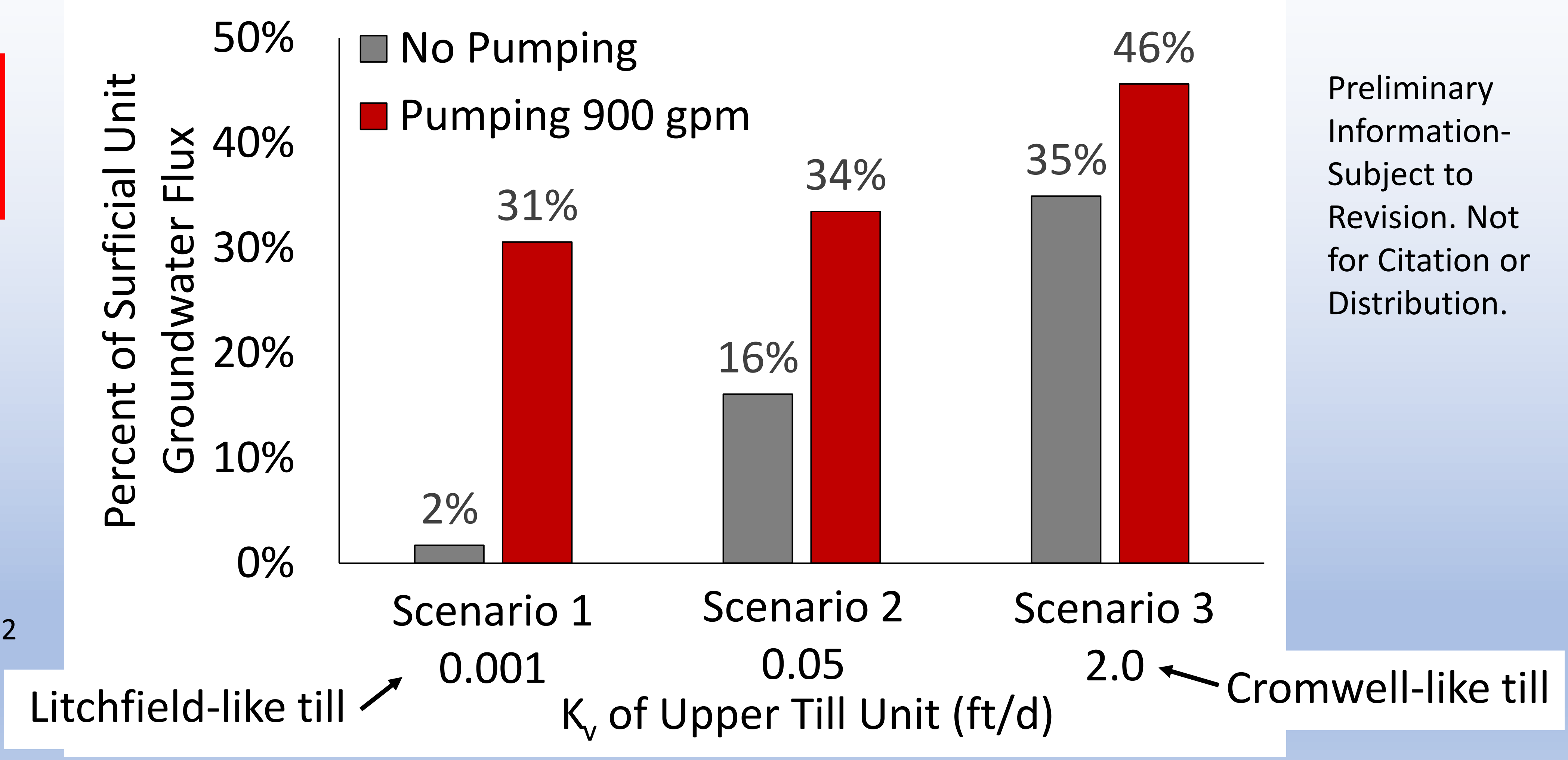
The percent of total surficial unit groundwater flux that flows into upper till

$$\text{Percent downward flux} = \frac{V_{down}}{V_{down} + V_{lat} + V_{rech} + V_{ind}} \times 100$$

Pumping-induced changes to groundwater flow into till from surficial aquifer



- Aquifer areal extent: 4.5 mi^2
- Middle unit K_h: 0.05 ft/d



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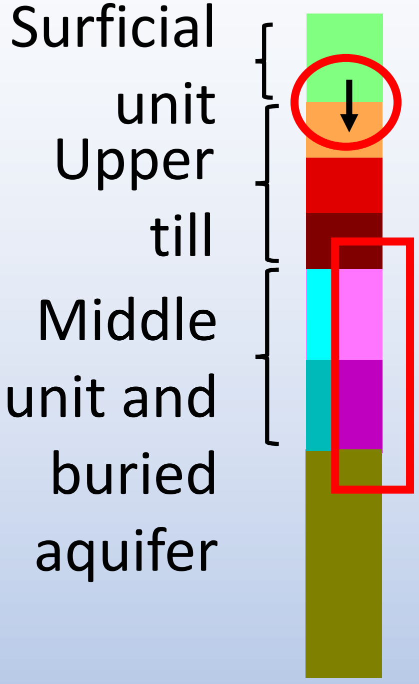
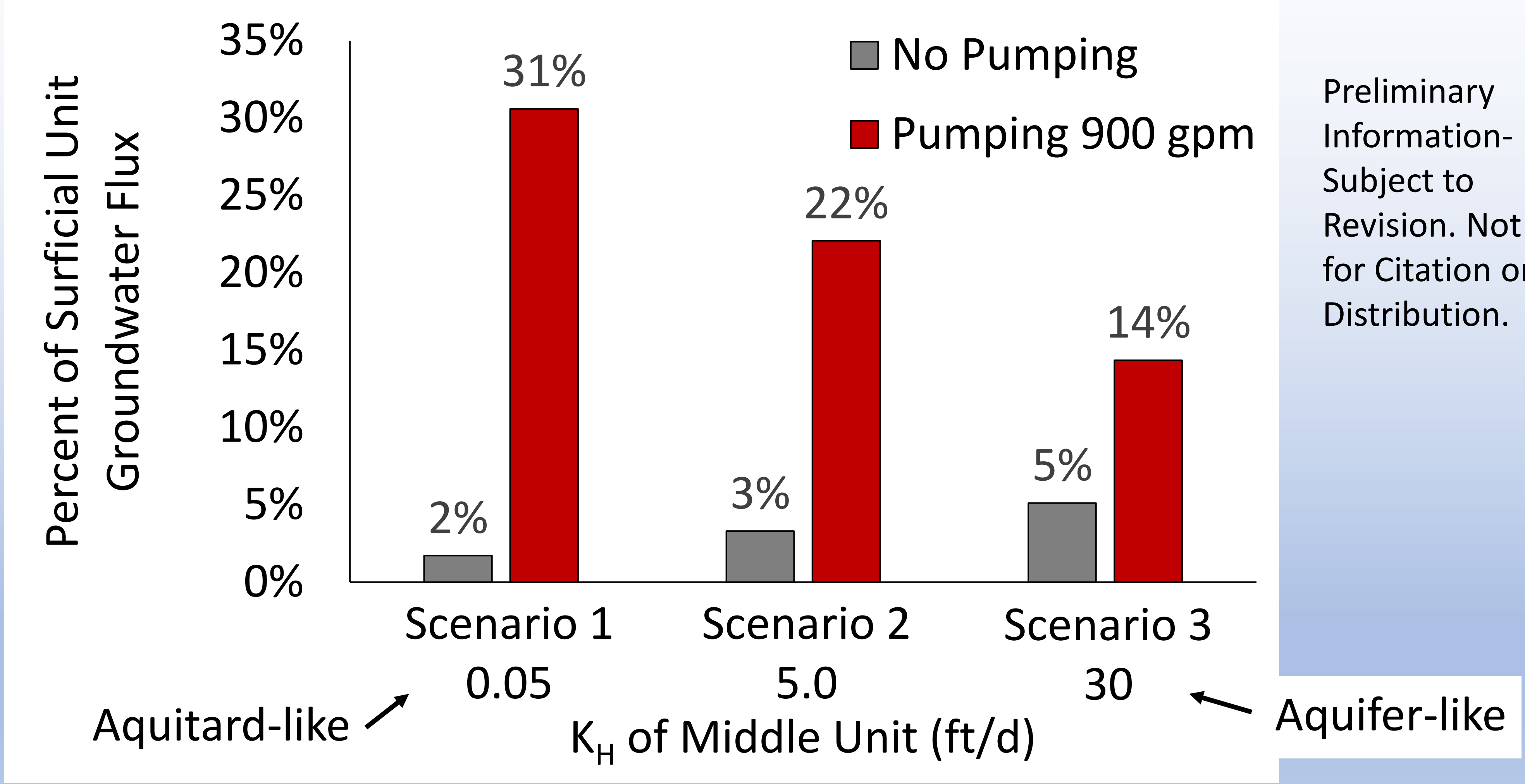
Varying till vertical hydraulic conductivity (K_v)

Pumping-induced changes to groundwater flow into till from surficial aquifer





Preliminary Information- Subject to Revision. Not for Citation or Distribution.

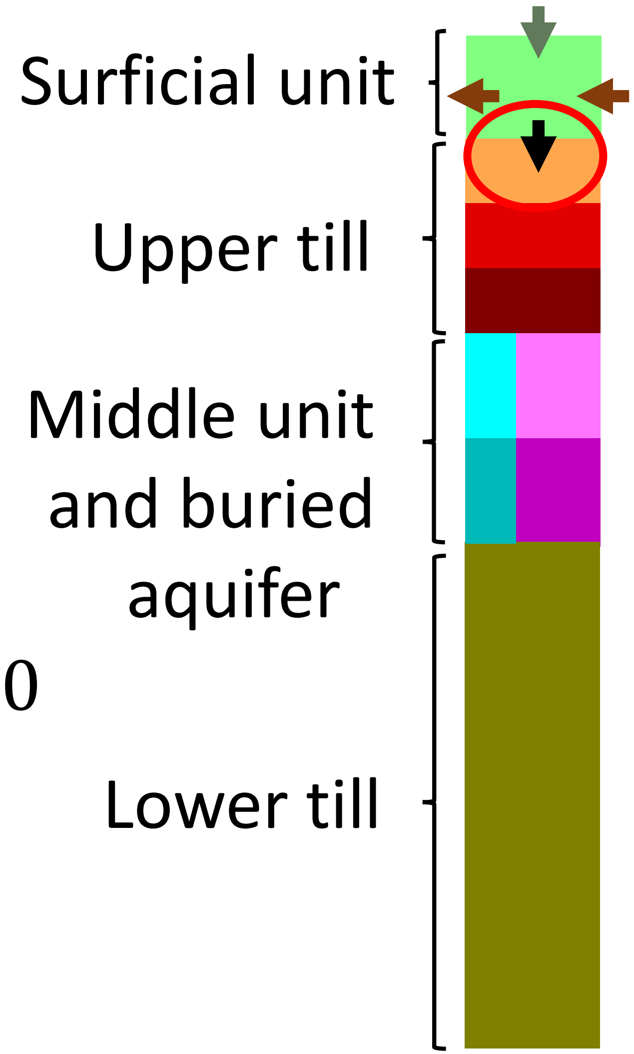
- Aquifer areal extent: 4.5 mi^2
- Upper till unit K_v: 0.001 ft/d

Varying horizontal connectivity of aquifer

Sensitivity Analysis

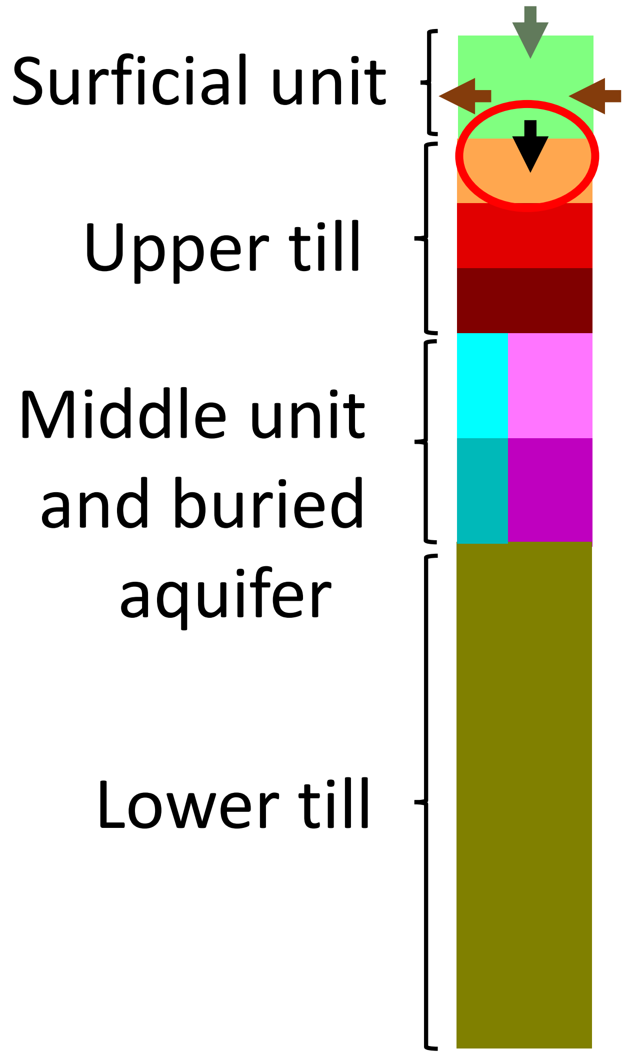
- Calculated the relative sensitivity of **downward flux** for all model runs compared to the base model

$$\frac{Percent\ change\ in\ downward\ flux}{|Percent\ change\ in\ model\ parameter\ value|} \times 100$$



Sensitivity Analysis

- **Most sensitive parameters:**
  - K_v of upper till unit
  - Areal extent of conductive materials:
    - Buried aquifer
    - Lateral connectivity (middle unit K_h)
- **Less sensitive parameters:**
  - Aquifer K_h
  - Pumping rate
  - Screen length (partial penetration)
  - Upper till thickness



Modeling conclusions

- Groundwater flows through till to a confined aquifer.

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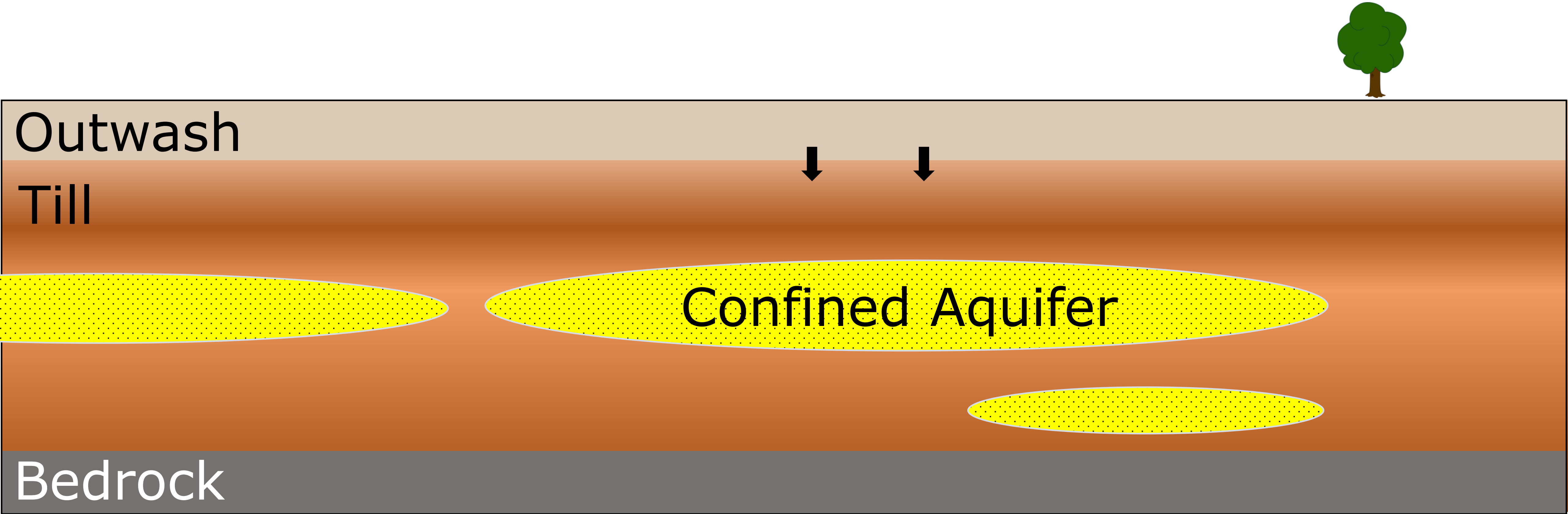

Modeling conclusions

- Groundwater flows through till to a confined aquifer.
- Pumping increases the leakage of water into till

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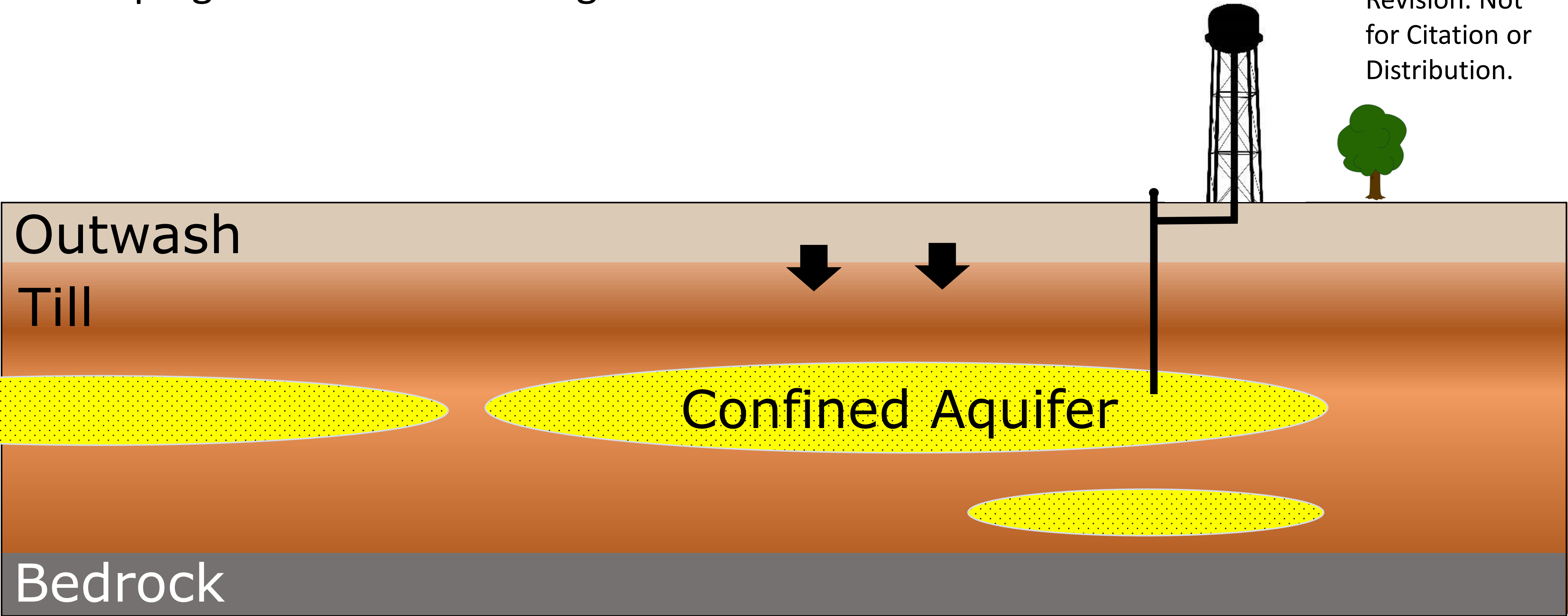

Modeling conclusions

- Groundwater flows through till to a confined aquifer.
- Pumping increases the leakage of water into till
- Leakage into till induced by pumping is sensitive to hydraulic properties of till

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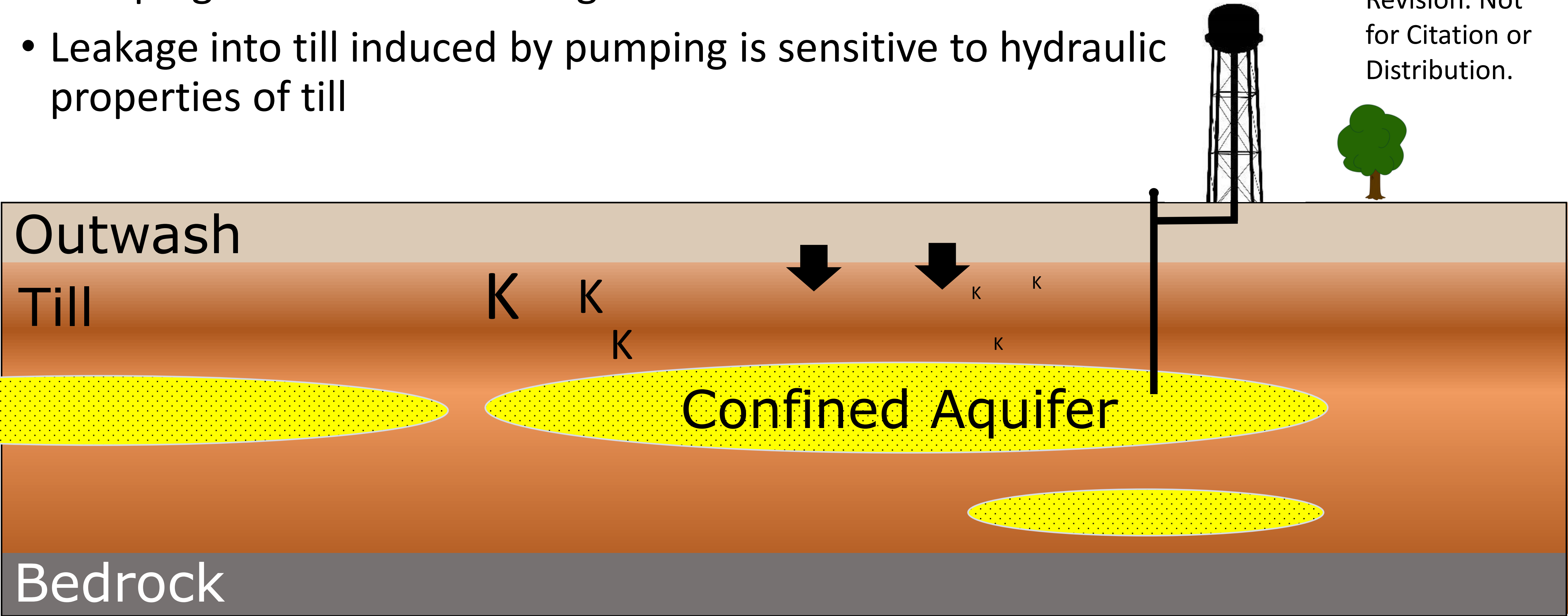

Modeling conclusions

- Groundwater flows through till to a confined aquifer.
- Pumping increases the leakage of water into till
- Leakage into till induced by pumping is sensitive to hydraulic properties of till
- Leakage into aquifer dependent on hydraulic properties of till

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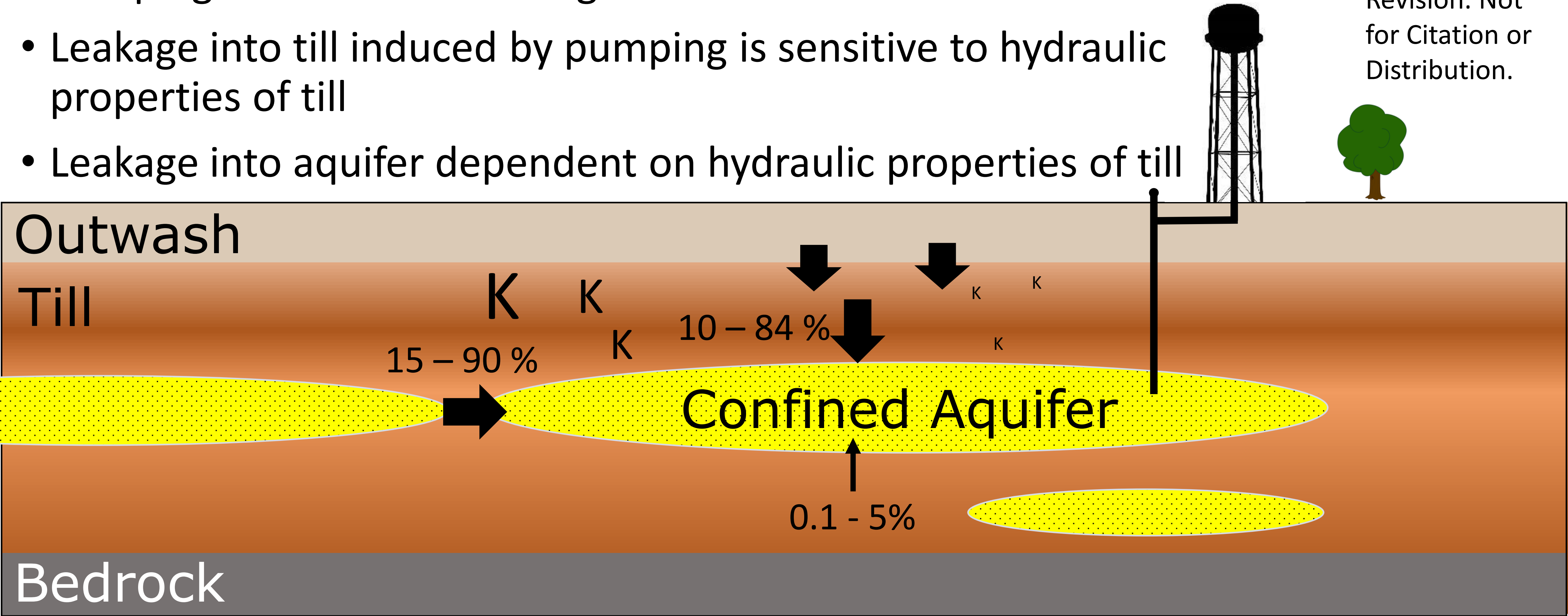

Project Goal

Better understand the sustainability of water supplies from confined aquifers.

Approach: for different glacial lobes and till units in Minnesota, we quantified:

- Variability of till hydraulic properties
- Leakage of water from till confining units to buried confined aquifers

Rotosonic coring in Olivia, MN

Overall conclusions

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

- Groundwater in till is “in the race”; multiple lines of evidence for groundwater flow through till:
  - Hydraulic head relationships demonstrated primarily downward flow with some faster than anticipated rates
  - Post-glacial groundwater found throughout till profiles
  - Anthropogenic tracers at depth at urban sites
  - Modeling showed that pumping can increase leakage rates
- Tortoise or hare? Both!
  - Evidence for wide-ranging leakage rates, even at a single site.

Implications

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

- Implications for sustainability:
  - Modeling suggests that hydraulic information about till is just as important as aquifer mapping for understanding sustainable withdrawals.

Implications

- Implications for conceptualization of till:
  - Expect surprises!
  - Simple conceptual models are likely not applicable.
  - Till is not impermeable and velocities may be higher than previously assumed.

Questions?

Olivia, MN field site


Iowa State Field Crew

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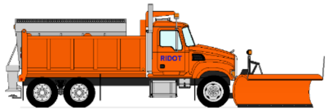

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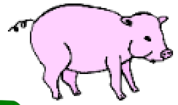

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