Monitoring near-surface thermal properties in conjunction with energy and moisture budgets to facilitate the optimization of ground-source heat pumps

SHAWN NAYLOR
Research Hydrogeologist
Center for Geospatial Data Analysis
Indiana Geological Survey

Kevin Ellett
Research Scientist
Indiana Geological Survey

Andrew Gustin
Environmental Geologist
Center for Geospatial Data Analysis
Indiana Geological Survey

INDIANA GEOLOGICAL SURVEY 1837 INDIANA UNIVERSITY

CENTER FOR GEOSPATIAL DATA ANALYSIS
INDIANA UNIVERSITY

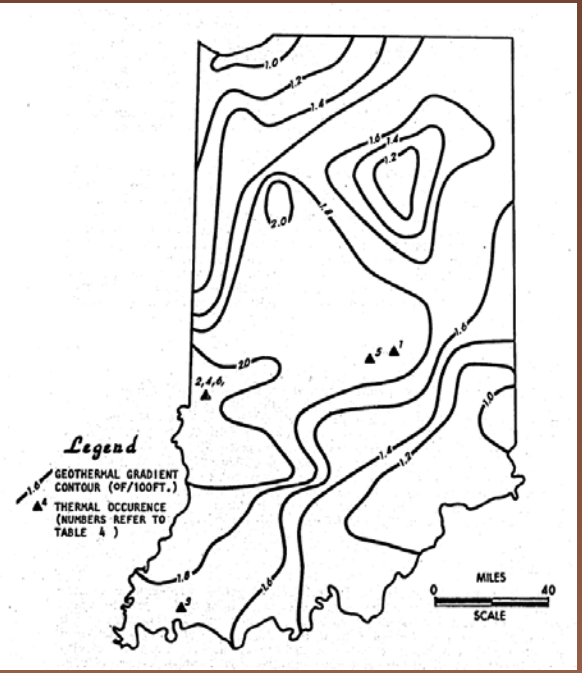
Presentation overview

- Study rationale and goals
- Monitoring network and sample collection
- Instrumentation and field data collection
- Laboratory analyses

Geothermal power generation – the reality of living in a low-temperature state

- Vaught (1980) noted that toward the center of the Illinois Basin in SW Indiana, temperatures as high as 190 F may be reached at depths of 10,000 feet

- Binary power generation is possible for low and moderate temperatures resources, but Rafferty (2000) calculated that, for a 210 F system, the cost to produce electricity from a 3,000 foot well is $0.48 per kWh



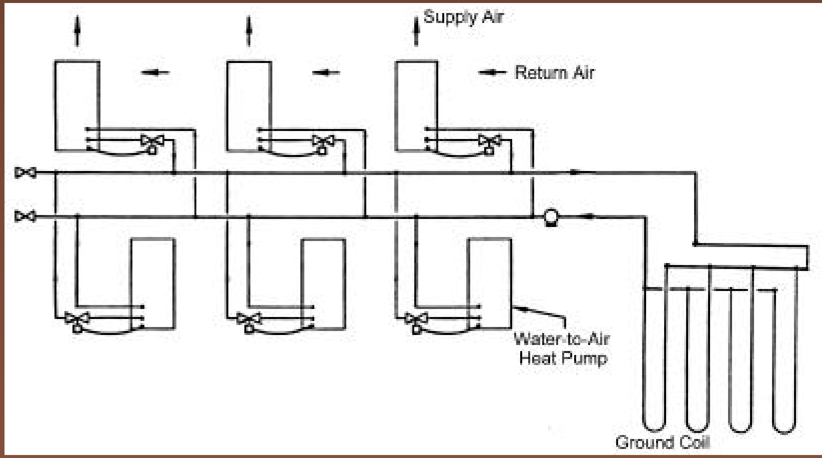
Geothermal gradient in Indiana (from AAPG and USGS, 1976)

electric power is a long-shot but.....

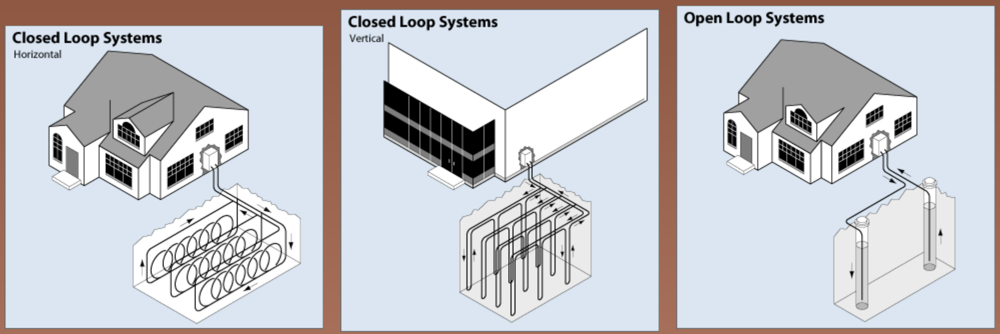
We do have (geo) thermal mass that can be exchanged via ground-source heat pumps (GSHPs)

700,000 GSHP units installed in U.S. (most in midwestern and eastern states)

15% annual growth (Lund, 2007)



Commercial ground-coupled (closed loop) heat pump system



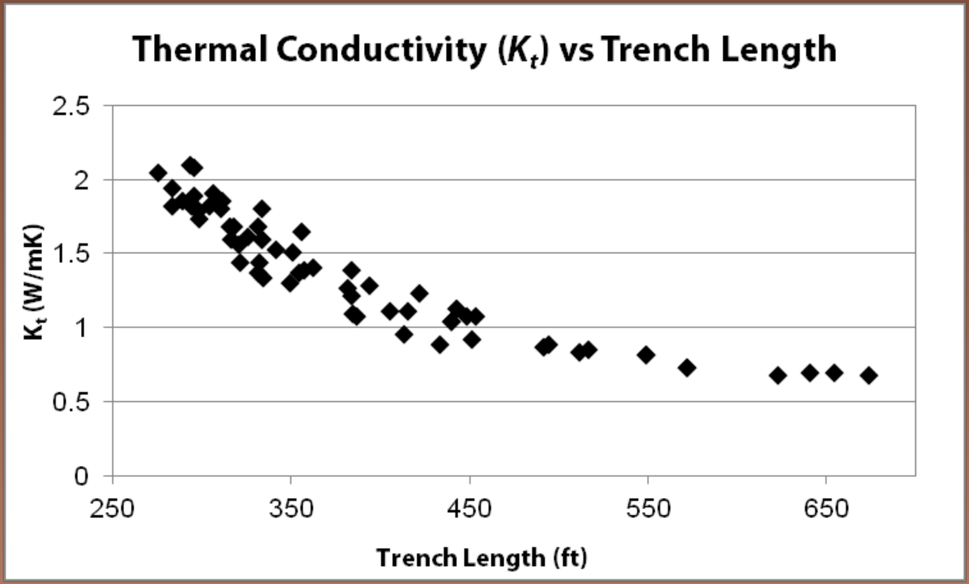
GSHP configurations, U.S. DOE

Rationale

- Software exists for ground-source heat pump (GSHP) installers to calculate optimal loop lengths for ground-coupling systems

- Uncertainties exist for input parameters such as soil thermal properties and earth temperatures

- Due to variations in thermal conductivity, trench lengths for horizontal GSHPs can range from 300 to 600 feet per ton of heating demand



Objectives

Establish datasets that provide designers with:

1. near-surface, year-round temperature gradients

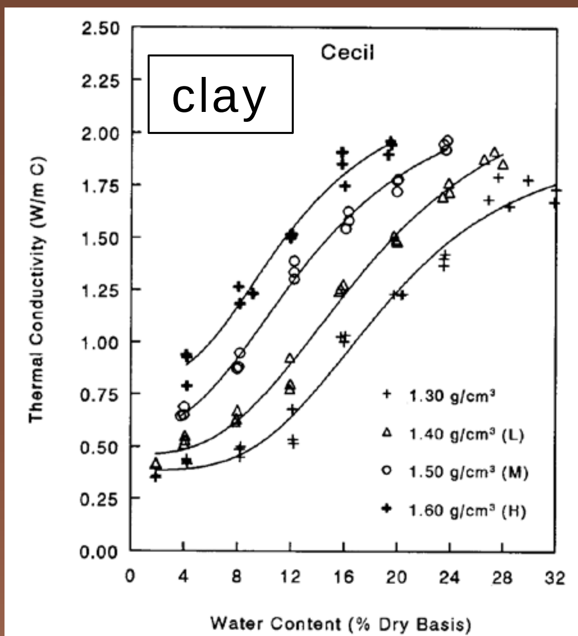
2. continuous measurements of thermal conductivity and thermal diffusivity such that seasonal variations can be considered

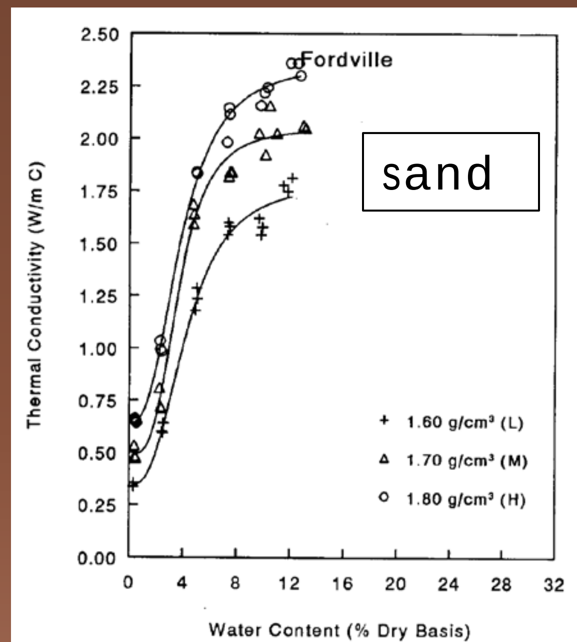
3. continuous soil moisture data and therefore end members for various unconsolidated materials and hydrogeologic settings

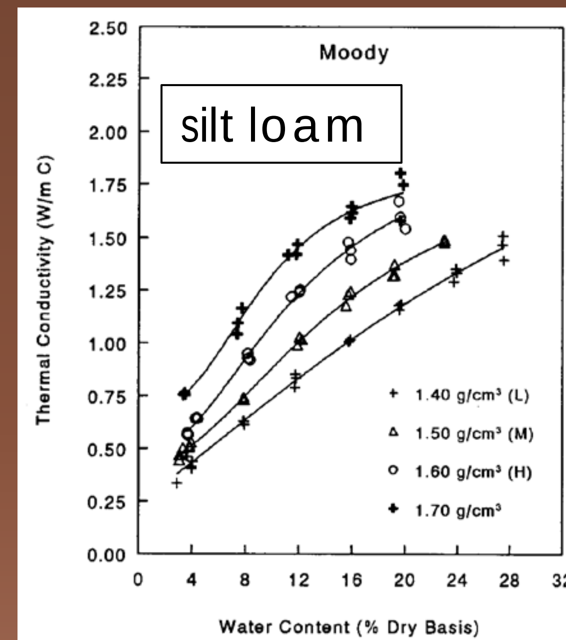
4. laboratory measurements of thermal properties for glacial sediments in Indiana

Unconsolidated thermal conductivity (K_t) controls

Texture, moisture content, and bulk density are primary controls on thermal conductivity of unconsolidated materials



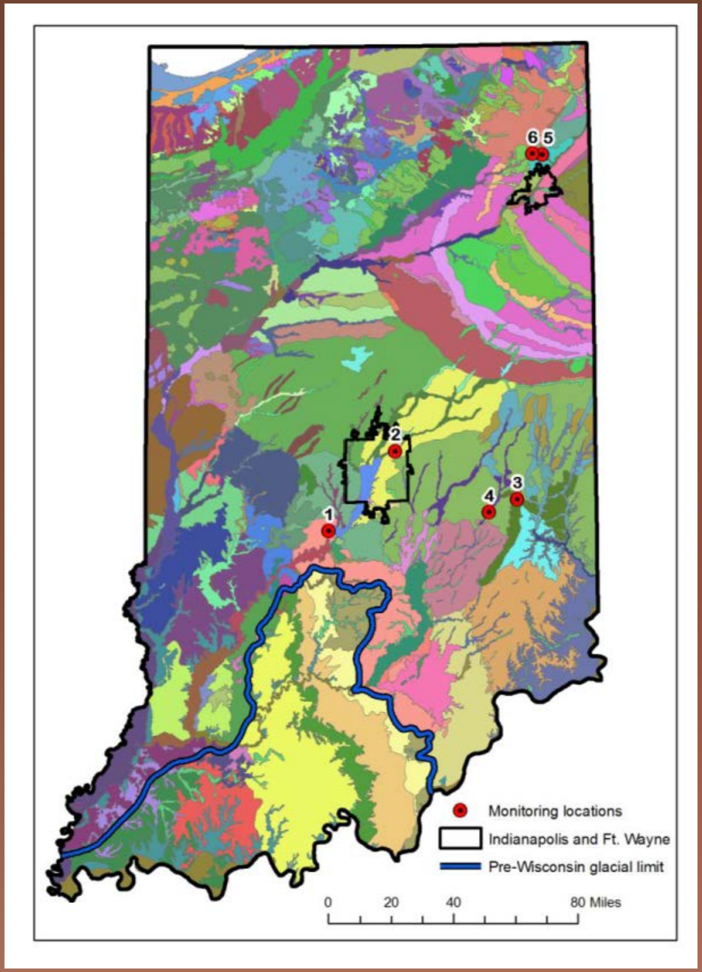




(figures from Remund, 1994)

$$K_T = \alpha \, \rho \, C_p$$

Site locations relative to hydrogeologic settings



Hydrogeologic settings mapped by Fleming (1995)

<u>Northern Indiana</u>

- Outwash terrace (sandy loam, #6, “Eel River”)
- Moraine crest (silty clay till, #5, “Wabash”)

<u>Central Indiana</u>

- Supraglacial till adjacent to major tributary of E. Fork White R. (clay loam, #4, “Flat Rock”)
- Moraine crest (clay loam till, #3, “Shelbyville”)
- Alluvial terrace adjacent to W. Fork White R. (silt loam, #1, “Bradford”)

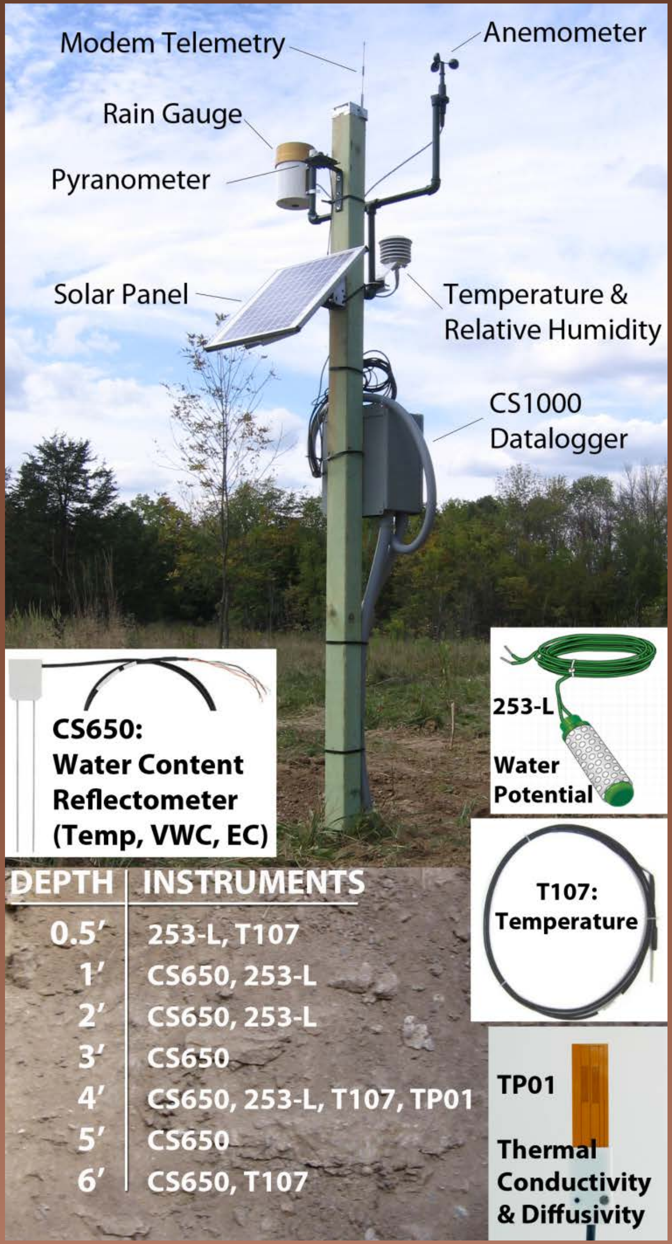
Monitoring approach

Establish continuous temp. gradients and thermal properties and link these measurements to

a. Unconsolidated material texture and bulk density

b. Energy budgets

c. Water budgets



Trench excavations

Trenches excavated to 6’ depth (typical installation depth for horizontal GSHP installations)

Sediment sampling

Samples collected at 1’ intervals from 1-6’ below ground surface

Samples collected in 2” x 4” core liners for bulk density determination and grain size analysis

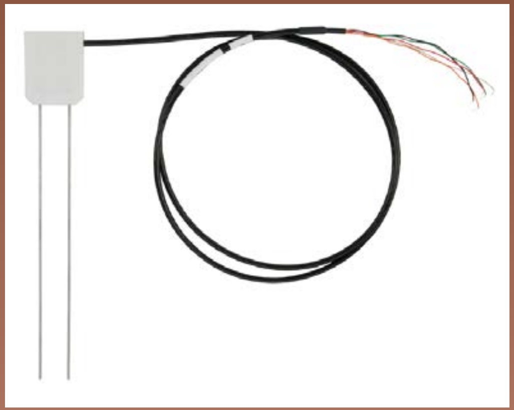
3” x 6” cores also collected for laboratory thermal conductivity measurements

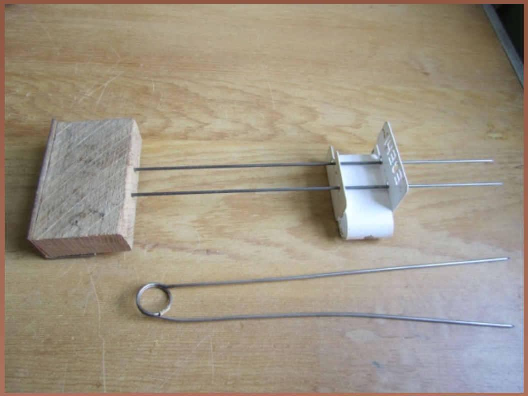
Instrumentation (water budget)

Tipping bucket rain gauge installed to measure precip.

Micrometeorological parameters measured to determine evapotranspiration (e.g., wind speed, solar radiation, relative humidity)

Campbell CS650 soil water content reflectometers installed to measure volumetric moisture content (θ_v) at 1’ depth intervals





Site-specific reflectometer calibrations

Water content reflectometers use an oscillator to induce an electromagnetic wave between two stainless steel rods. Two-way travel times for the waves are measured and these vary based on the dialectric permittivity of the surrounding medium

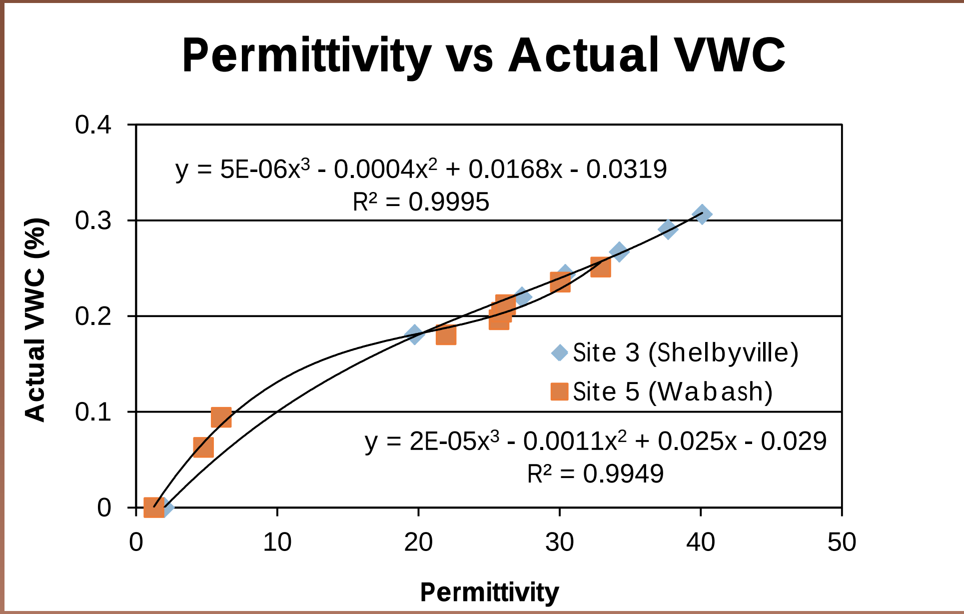
Permittivity (K_a) is converted to volumetric water content (θ_v) using the Topp equation (Topp, 1980). The relationship works for most soils but those with **high clay contents and/or bulk densities can require site-specific calibrations**

$$\theta_v = 4.3 * 10^{-6} K_a{}^3 - 5.5 * 10^{-6-4} K_a{}^2 - 2.92 * 10^{-2} K_a - 5.3 * 10^{-2}$$

Site-specific reflectometer calibrations

- Bucket samples were collected and re-packed in the laboratory to a bulk density similar to the density determined from core samples.

- Lab experiments were then conducted by varying moisture content and collecting permittivity readings to develop site-specific polynomial functions



Instrumentation (energy budget)

Pyranometer used to measure incoming solar radiation

Thermister (+- 0.1 deg. C) used to measure air temperature

Campbell CS650 sensors used to measure soil temperature (+- 0.5 deg. C) at 1’ depth intervals

Data-logging using Campbell CR1000 dataloggers

All instruments, including Hukseflux thermal properties sensor, were connected to CR1000 dataloggers and programmed to collect data at hourly intervals

Data are downloaded remotely using cellular modems

Instrumentation (thermal properties)

Thermal conductivity (K_T) and diffusivity (α) determined:

1. Across trench face to determine spatial variability within 6' x 6' grid (Decagon KD2 Pro)

2. In laboratory using cores (Decagon KD2 Pro)

3. In-situ using sensor connected to datalogger (Hukseflux TP01 sensor)

Hukseflux TP01 Thermal Properties Sensor

- Measures radial diff. temp. around heating wire using 2 thermopiles
- Designed for long term installation in soil

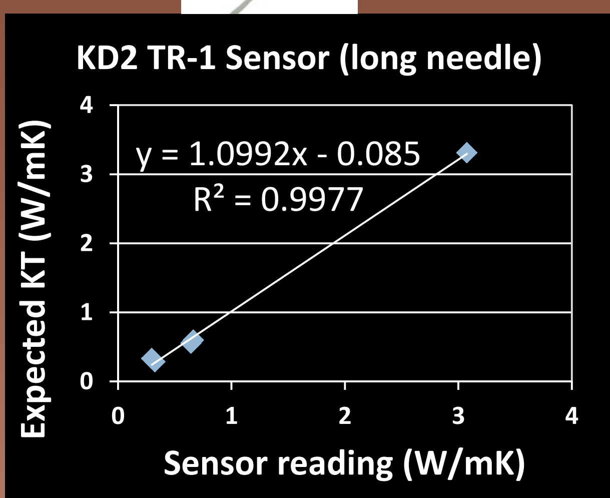
Decagon KD2 Pro Thermal Properties Sensor

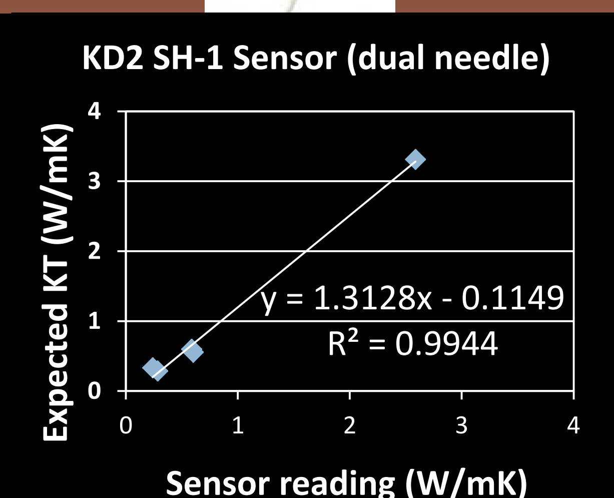
- Measures thermal props. using transient line heat source
- Designed for laboratory and spot measurements

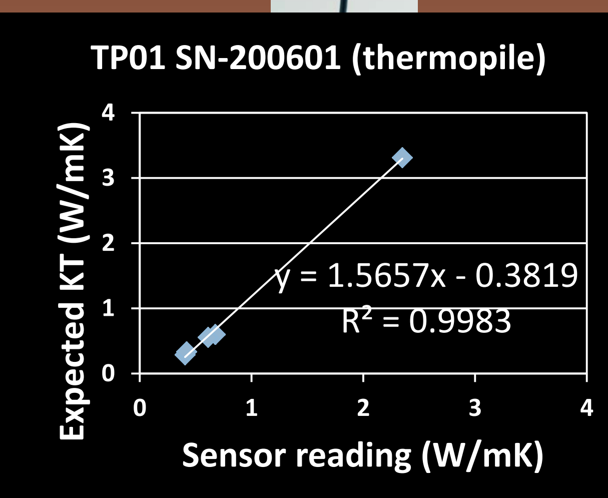
Sensor K_T calibrations

K_T determined in laboratory for following unconsolidated standards:

Glycerin (0.285 W/mK)
0.5% agar gel (0.598 W/mK)
5% agar gel (0.554 W/mK)
Dry Ottawa sand (0.332 W/mK)
Saturated Ottawa sand (3.31 W/mK)

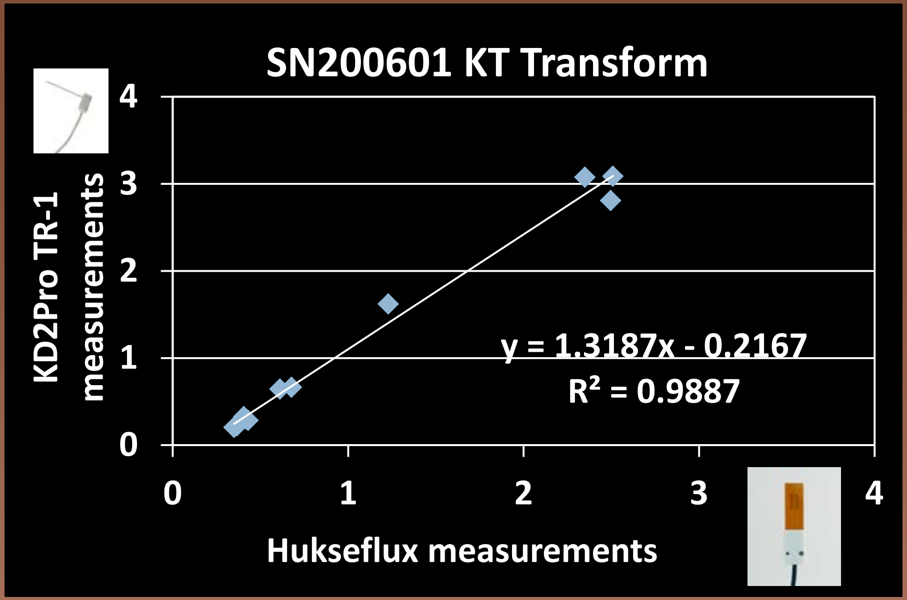




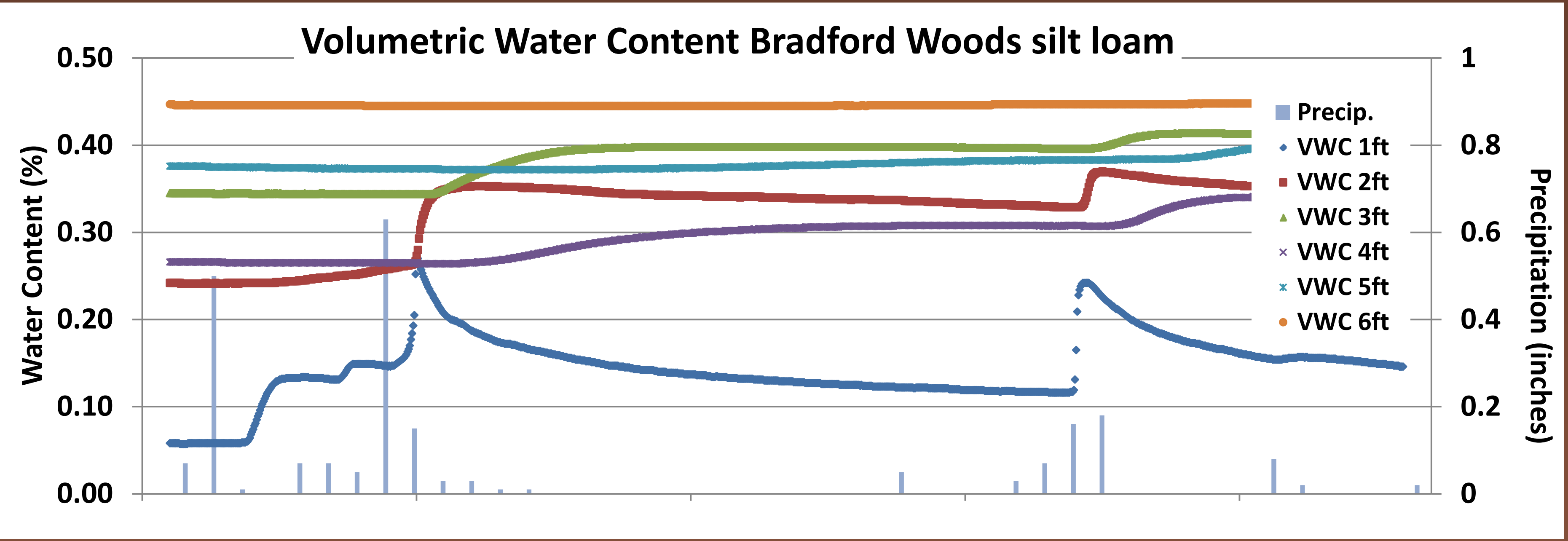


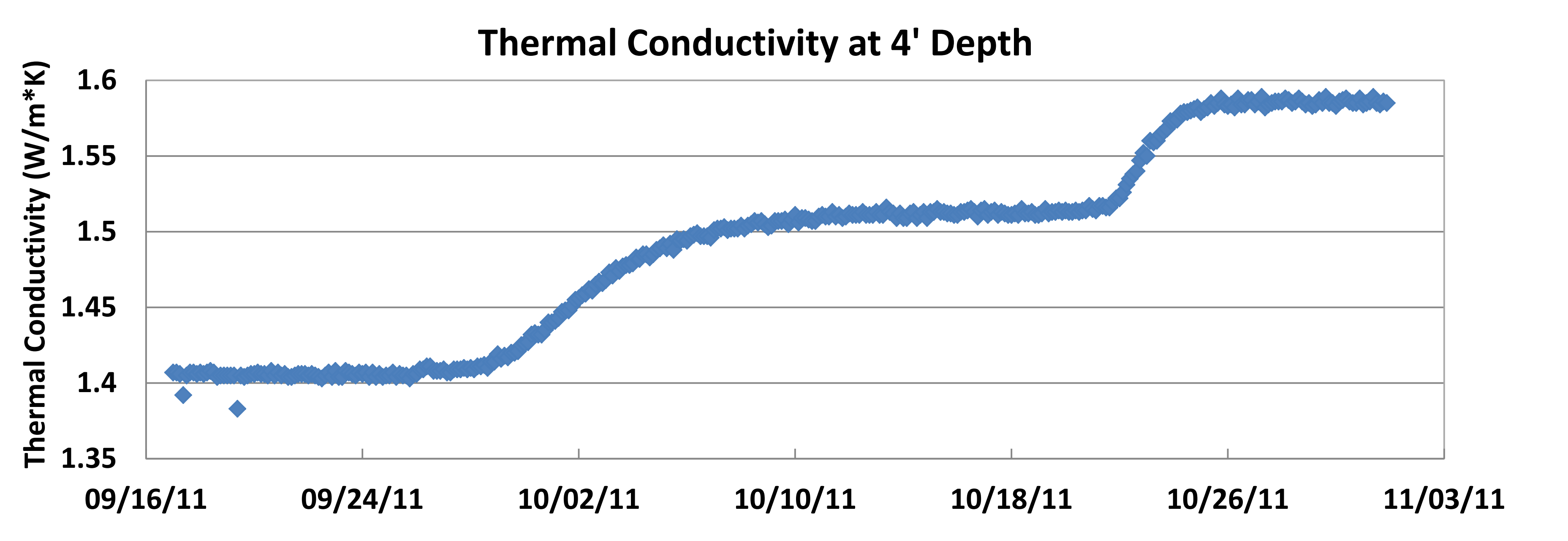
In-situ K_T measurements

- Datalogger program written to record K_T measurements every 3 hours
- Transform equation developed based on calibration measurements to correct for in-situ sensor's tendency to underestimate K_T
- KD2 Pro sensors installed adjacent to Hukseflux sensor at one of the sites to provide comparison measurements



Preliminary data





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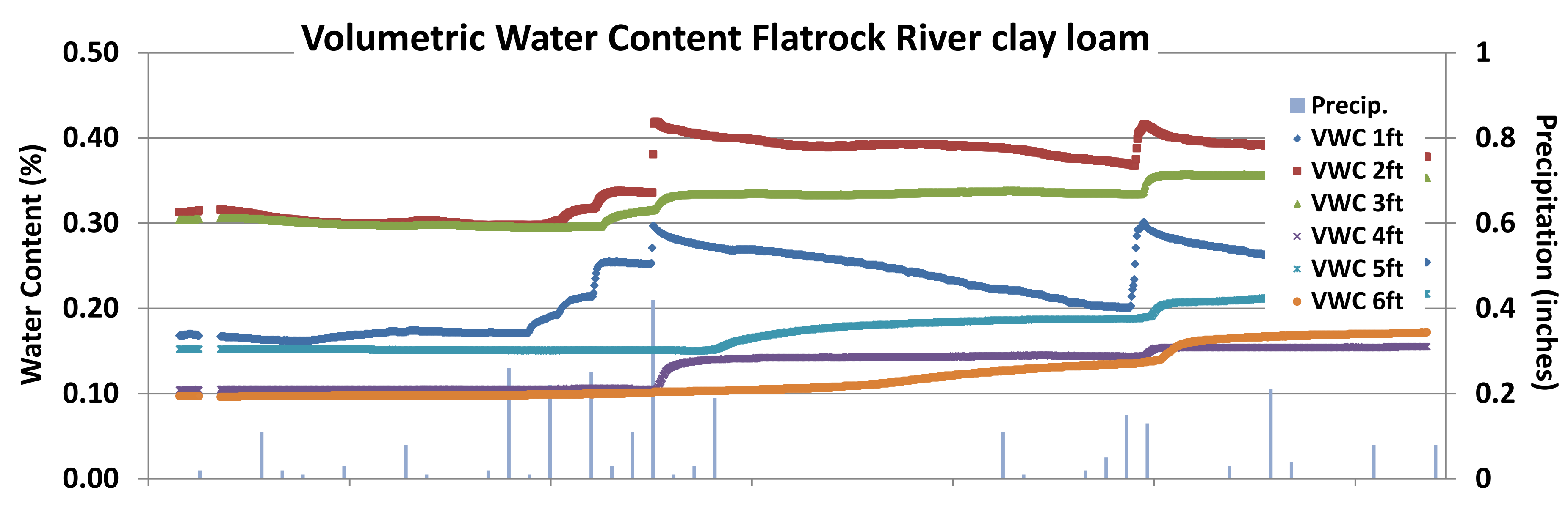
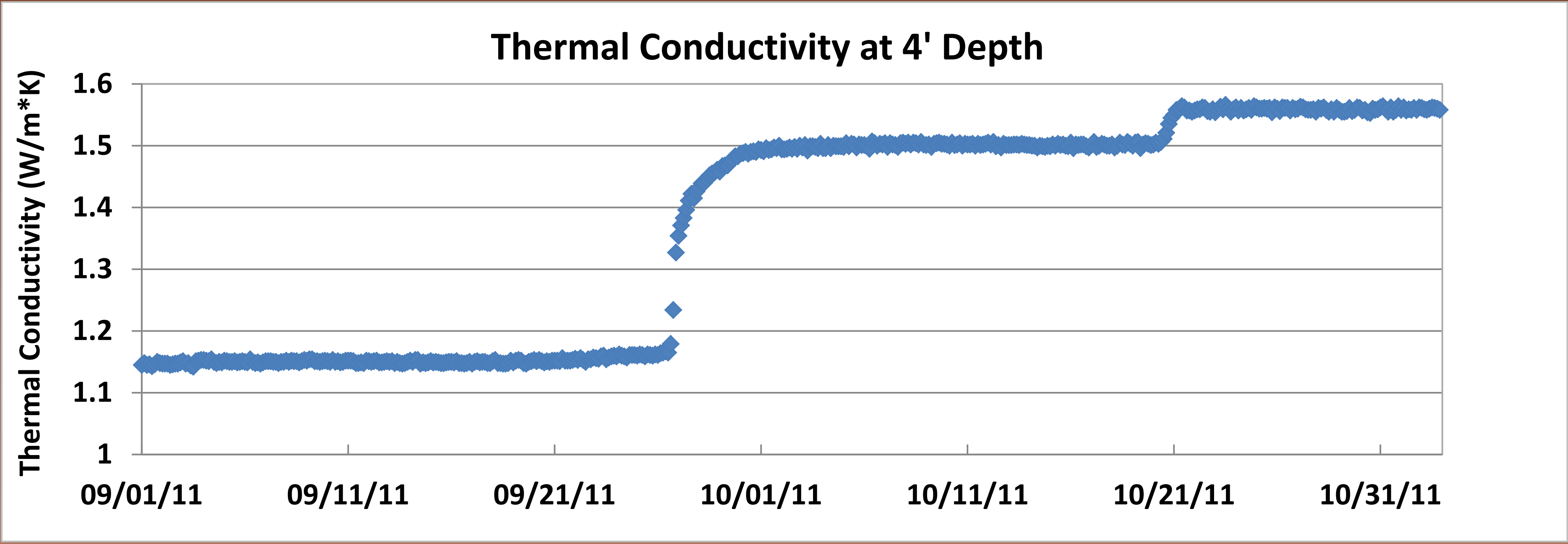
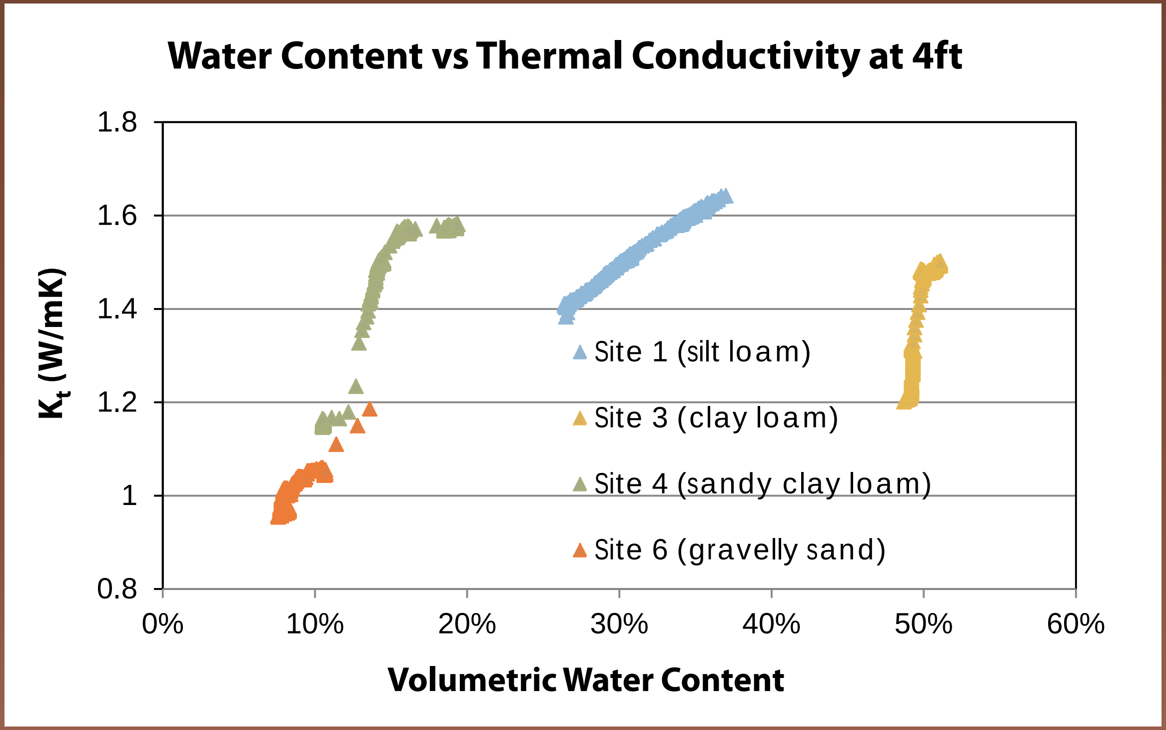




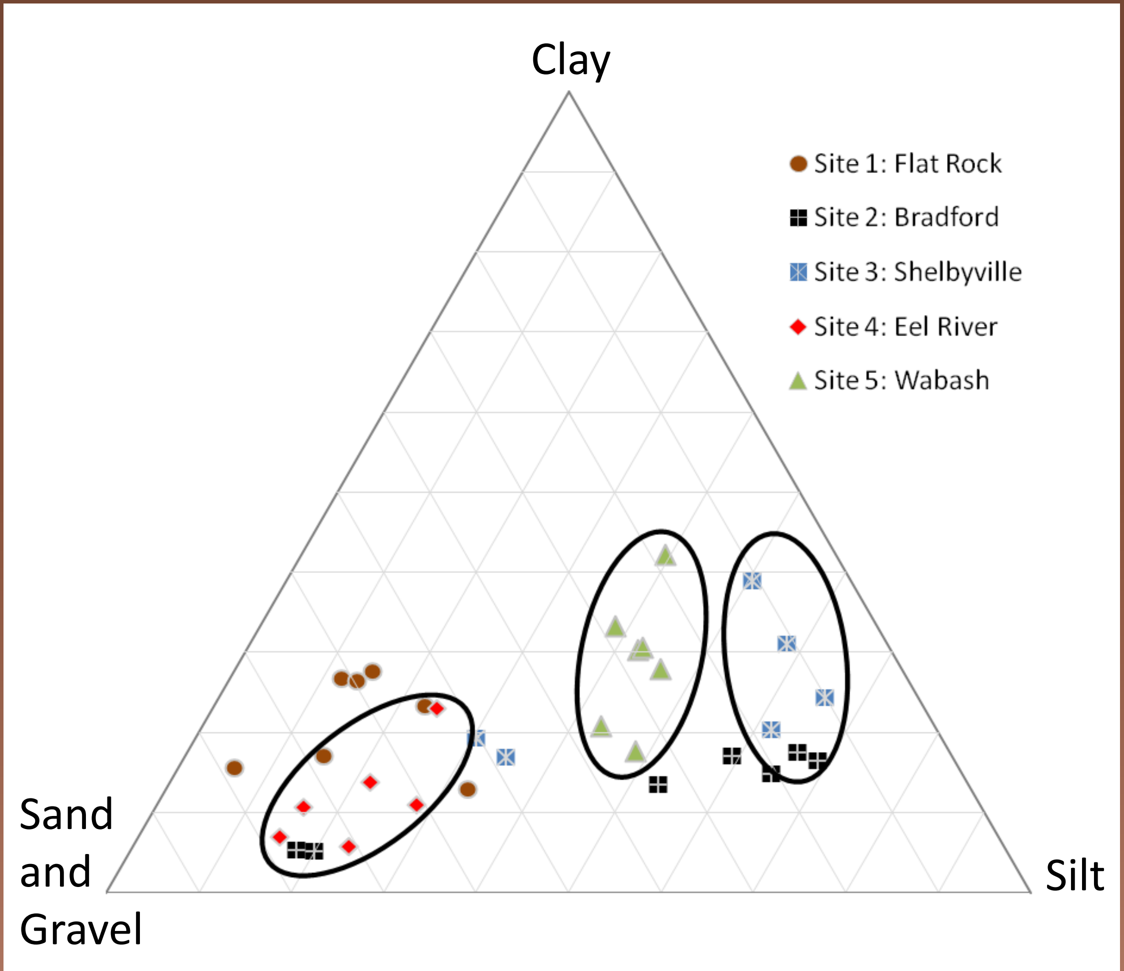
θ_v vs K_T for monitoring sites



Sample laboratory analyses

- Particle size analyses
- Bulk density determinations
- Thermal conductivity measurement
- Thermal dryout curves

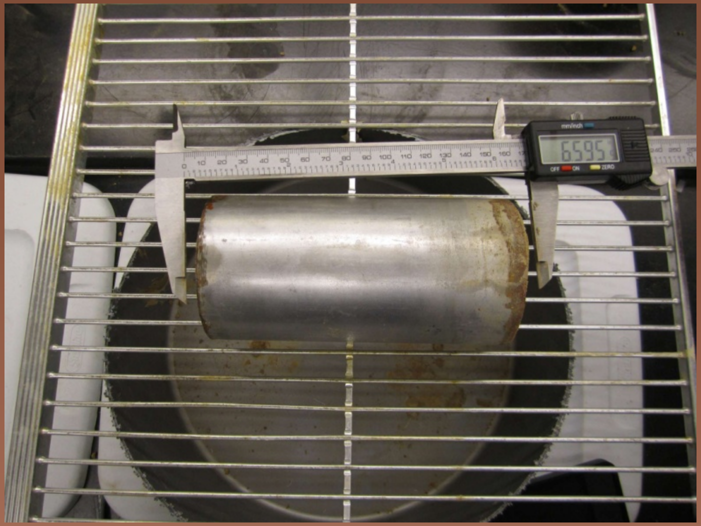
Particle size analyses



- 35-70 gram splits separated from bag samples for each depth
- Chemical dispersion using Na-hexamataphosphate (HMP)
- Simplified 4 point hydrometer analysis used (30 sec., 60 sec., 1.5 hr., 24 hr. readings) to determine clay, silt, sand fractions

Bulk density (ρ_b)

- Determined using 2" x 4" cores and 3" x 6" cores for comparison



Laboratory determinations of the relationship between K_T and moisture content – the thermal dryout curve

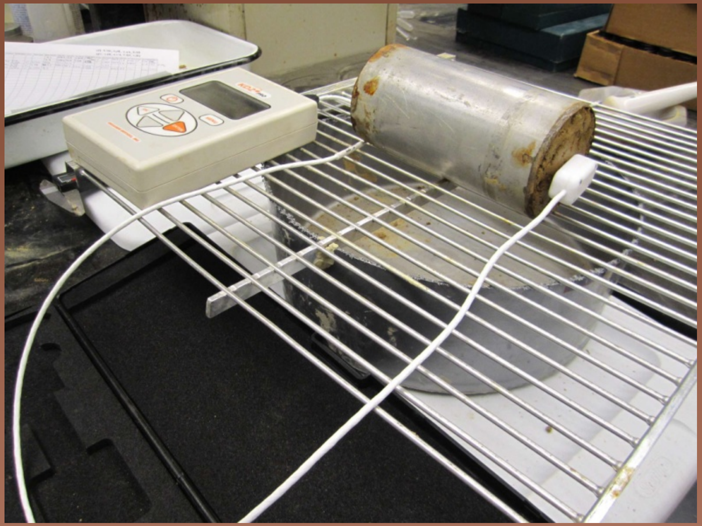
$$K_T = K_{T(wet)}\, g + K_{T(dry)}\, (1 - g) + B\,\theta + 2.8\,\phi\,(\theta - \theta_{wet}\, g)$$

$$\phi = \rho_b / \rho_s$$

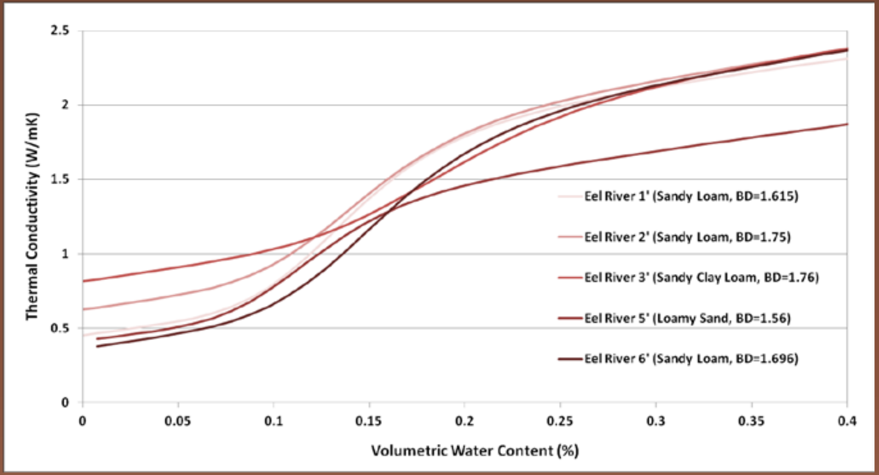
g is a function of θ and clay content

Equation from Campbell et al. (1994)

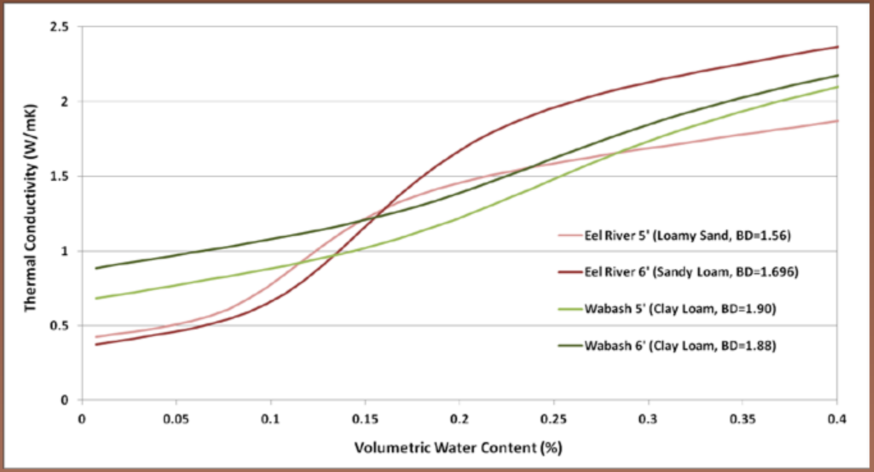
Measuring $K_{T\,(wet)}$ and $K_{T\,(dry)}$



Thermal dryout curve results



Outwash terrace – red
Moraine crest - green



Modeling soil temperature profiles with time

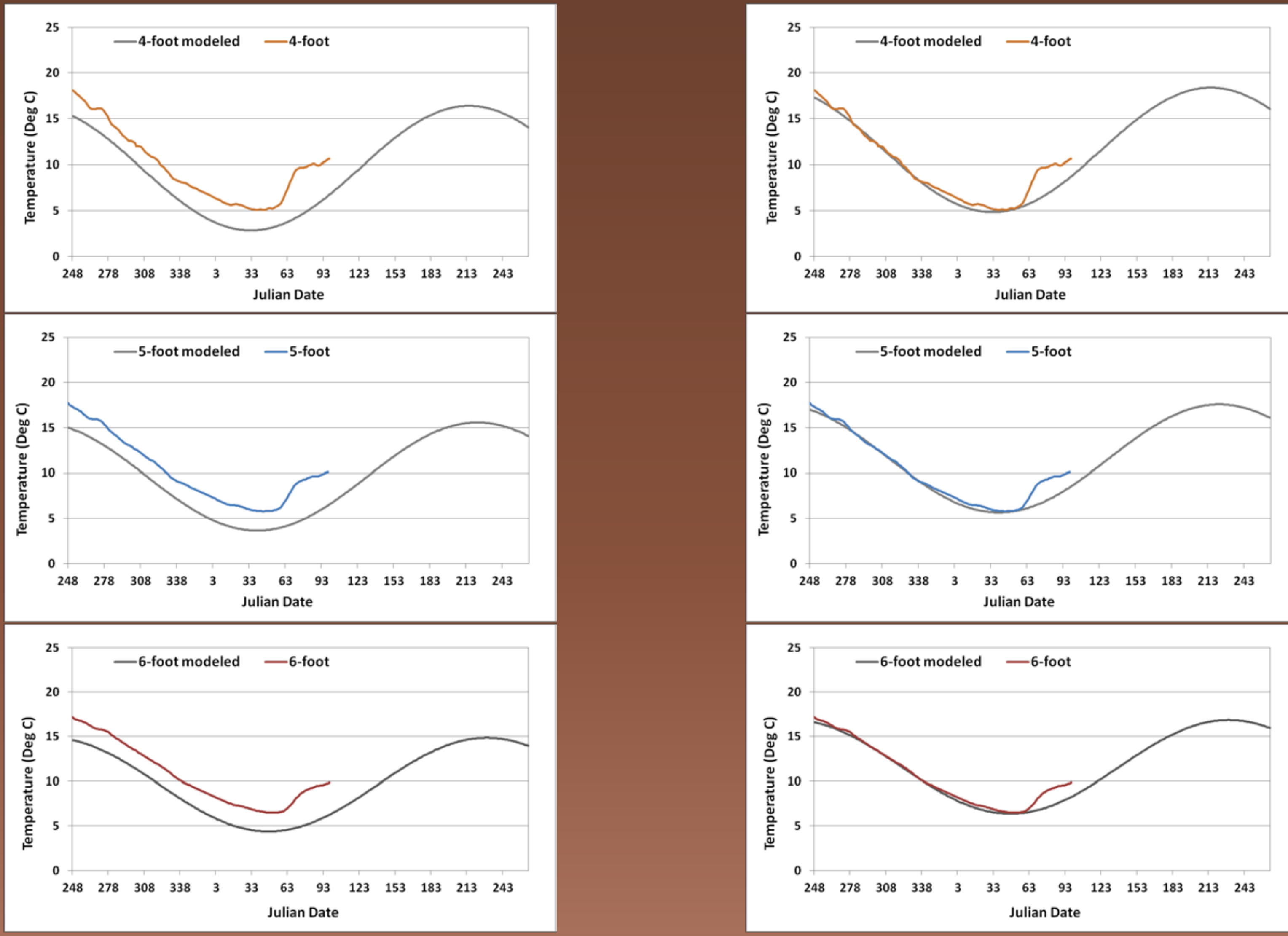
$$T(z,t) = T_a + A_0 e^{-z/d} \sin\left[\omega t + \varphi_0 - \frac{z}{d}\right]$$

$T(z,t)$ = soil temp. at time t and depth z (^0C)
T_a = avg. soil temp. (^0C)
A_0 = annual amplitude of the surface soil temp. (^0C)
t = Julian day
$\varphi_0 =$ phase constant (dependent on t_0 and ω)
t_0 = time lag to minimum temperature (days)
$\omega =$ radial frequency
d = damping depth of annual fluctuation (m)

$$d = \left(\frac{2D_h}{\omega}\right)^{1/2} \qquad \omega = \frac{2\pi}{365}$$

D_h = thermal diffusivity

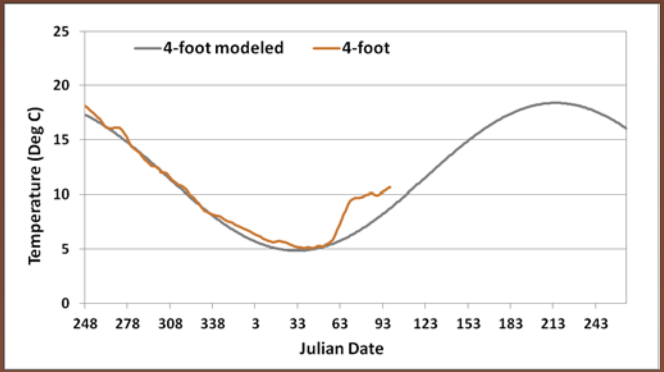
Temperature profile results (Wabash Moraine site)

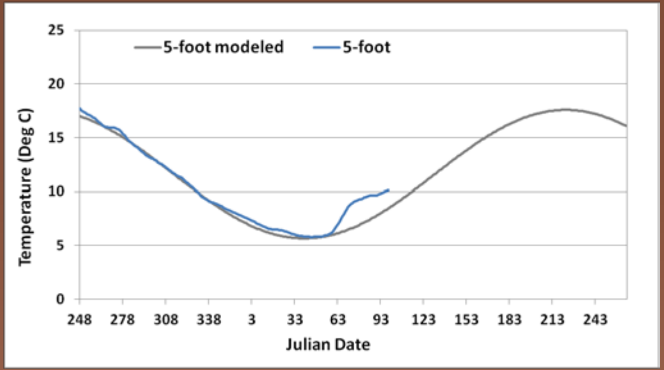


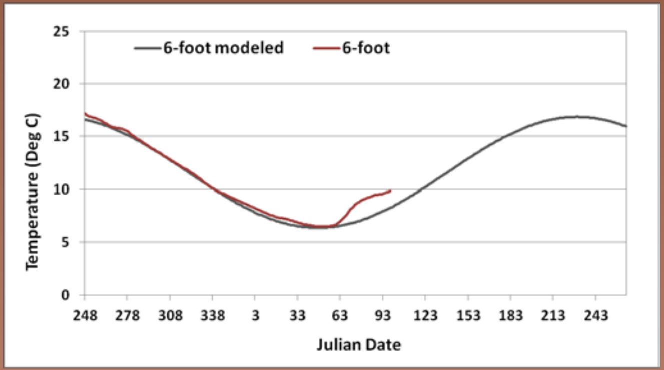
Model consistently underestimates temps. by 2 deg.C (35.6 deg. F)

Temp. profile comparison between sites

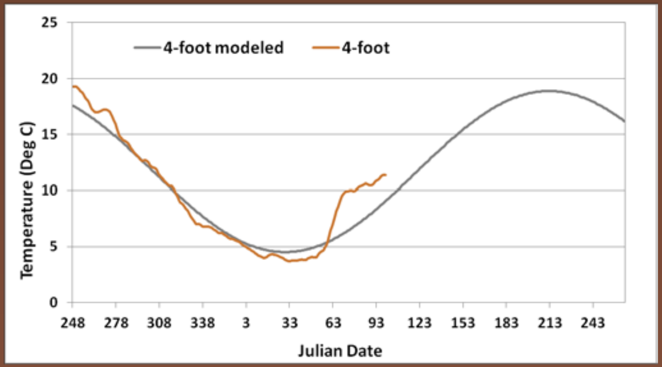
Wabash Moraine crest

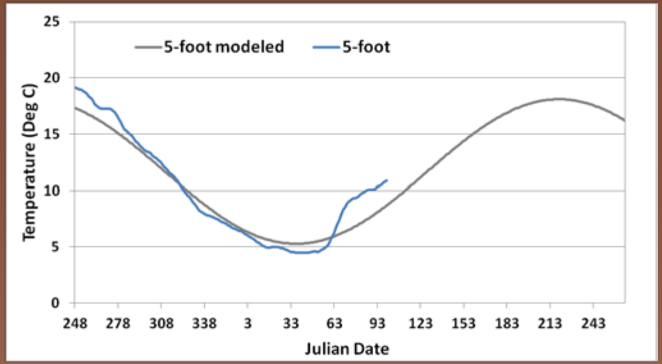


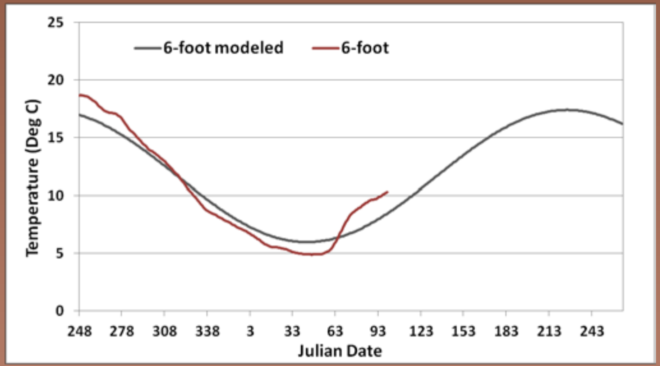




Eel River outwash terrace







Questions? / Feedback?

References

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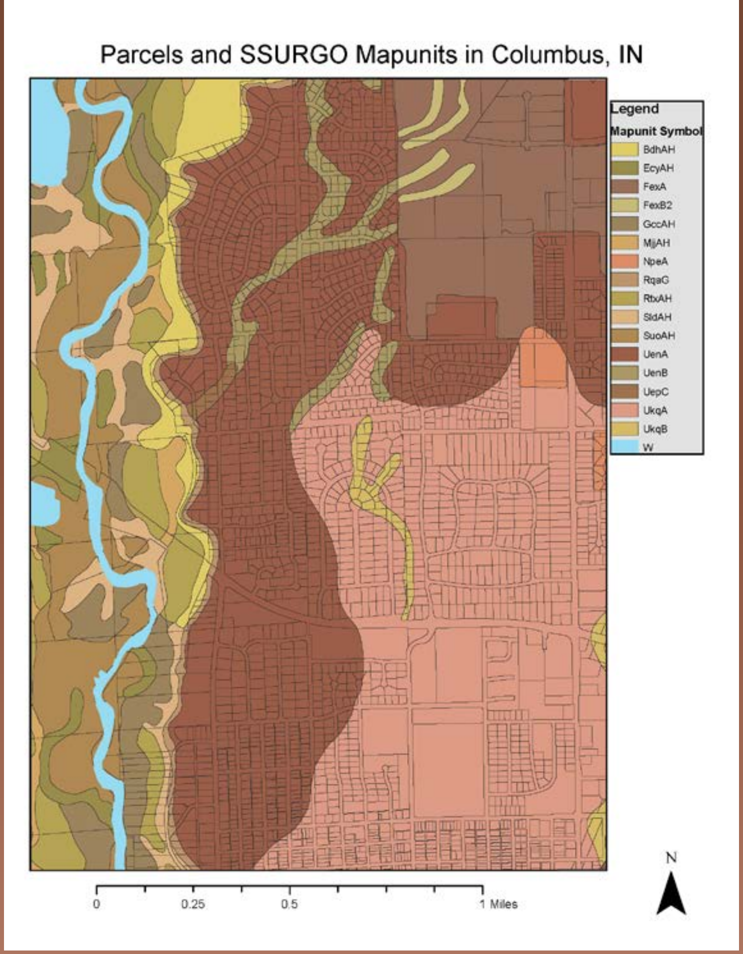
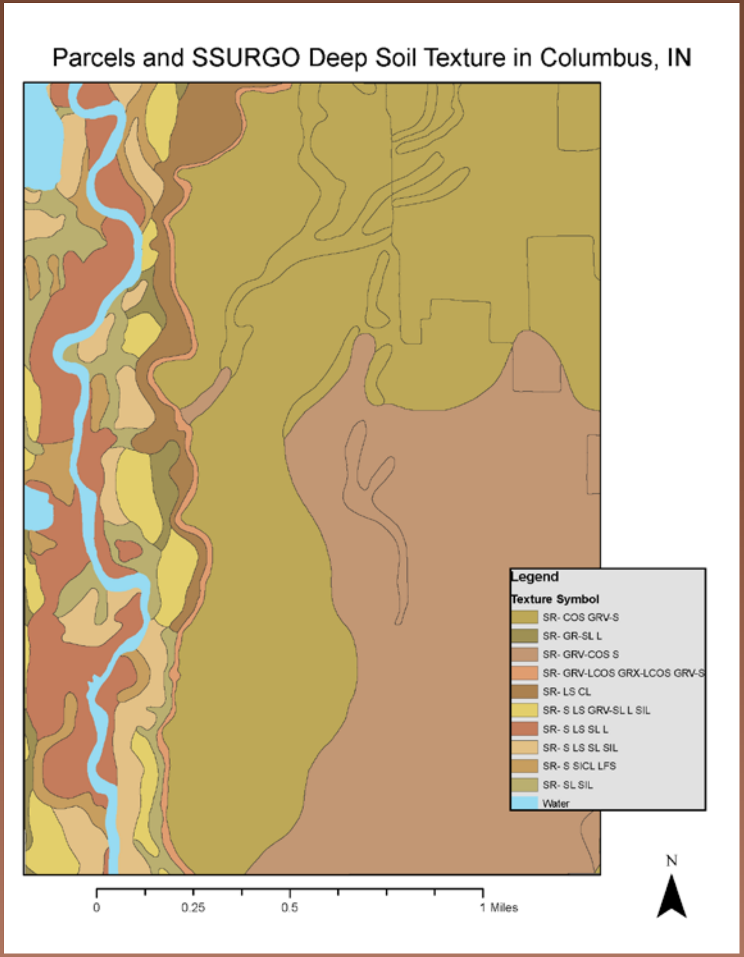
SSURGO data related to horizontal GSHP design

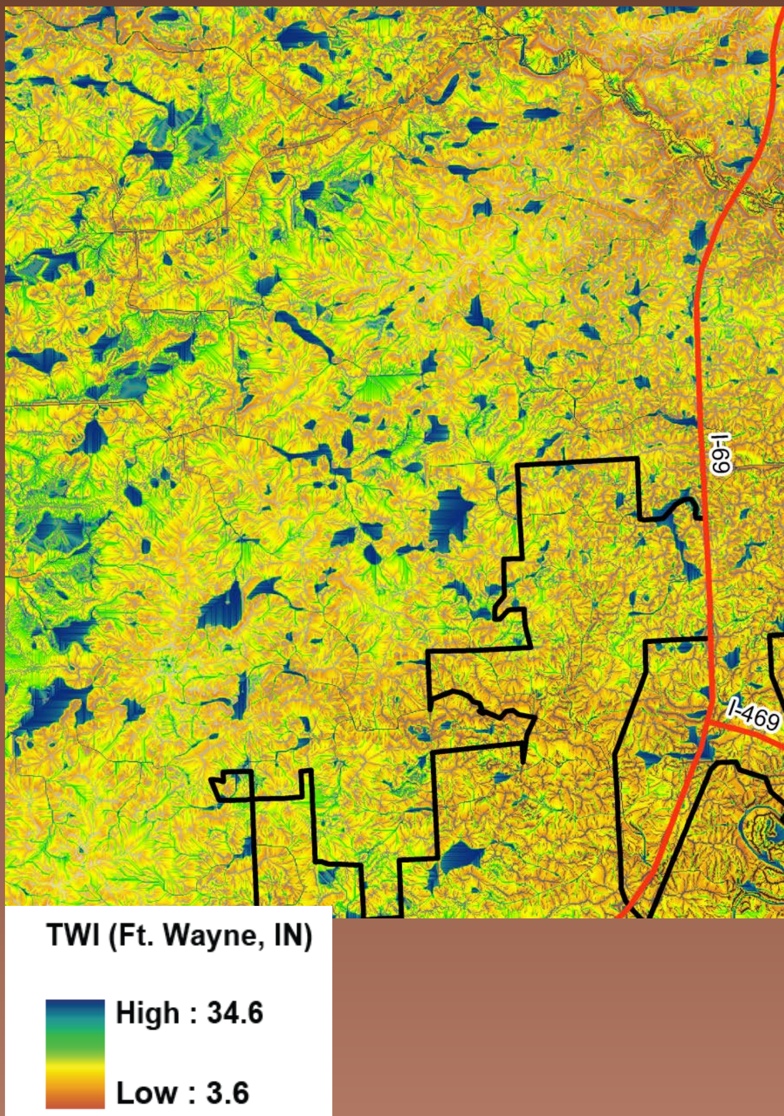
Parcels and mapped units



Deepest soil horizon textures (parent material)



Potential for mapping predominant soil moisture characteristics across Indiana



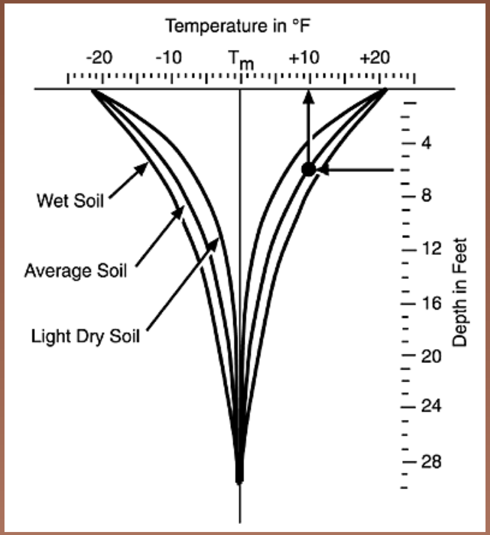
Topographic wetness index (TWI) - algorithm based on surface slope and area draining toward particular point on landscape

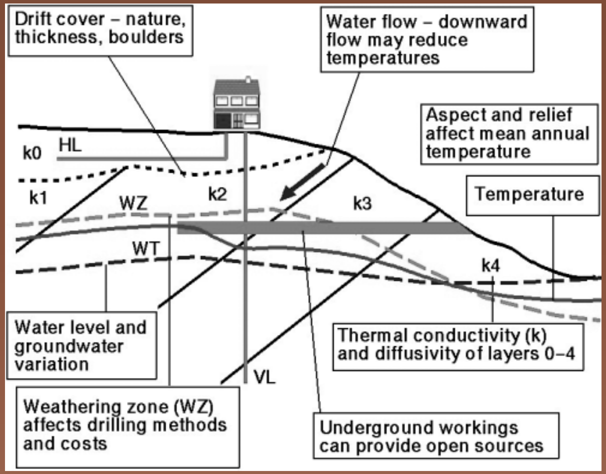
TWI = ln (a/tanB)

a = upslope contributing area
B = local slope

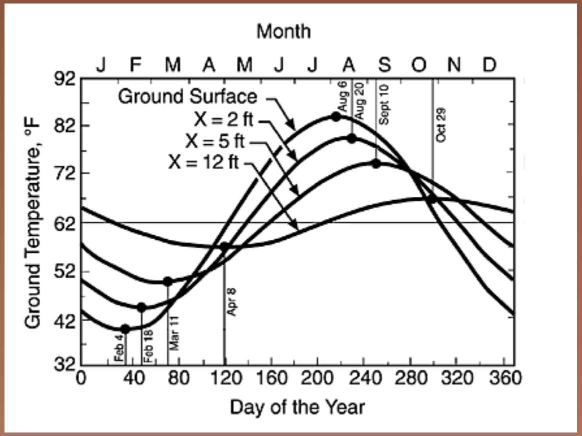
Local-scale influences of groundwater flow on near-surface temperature gradients

We assume that near-surface temps will be constant at depths greater than ~30'

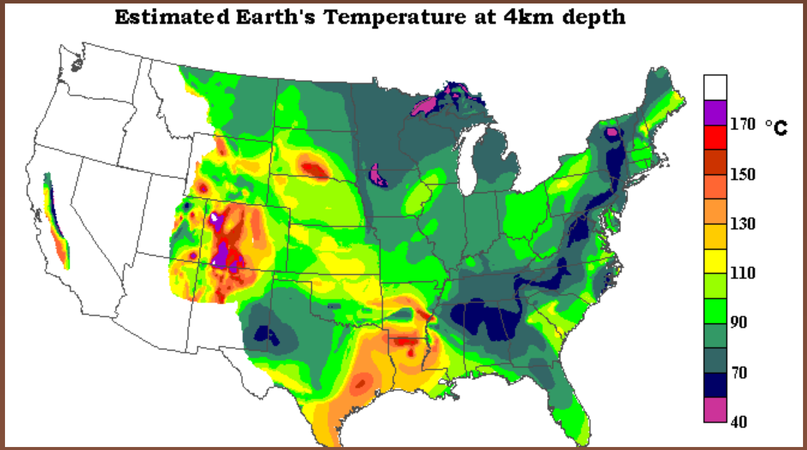




GW recharge settings may have reduced temps relative to adjacent discharge settings



Renewable Energy Technology
Geothermal Heat Pumps



- Binary geothermal power plants can utilize geothermal resources with temperatures below 400 deg F and down to 135 deg F (57 deg C).

- Wells would need to be drilled to 3-4 km depth in order to encounter temperatures in this range

- Considering the drilling costs and efficiency after pumping water from that depth, these systems are not currently economical in Indiana