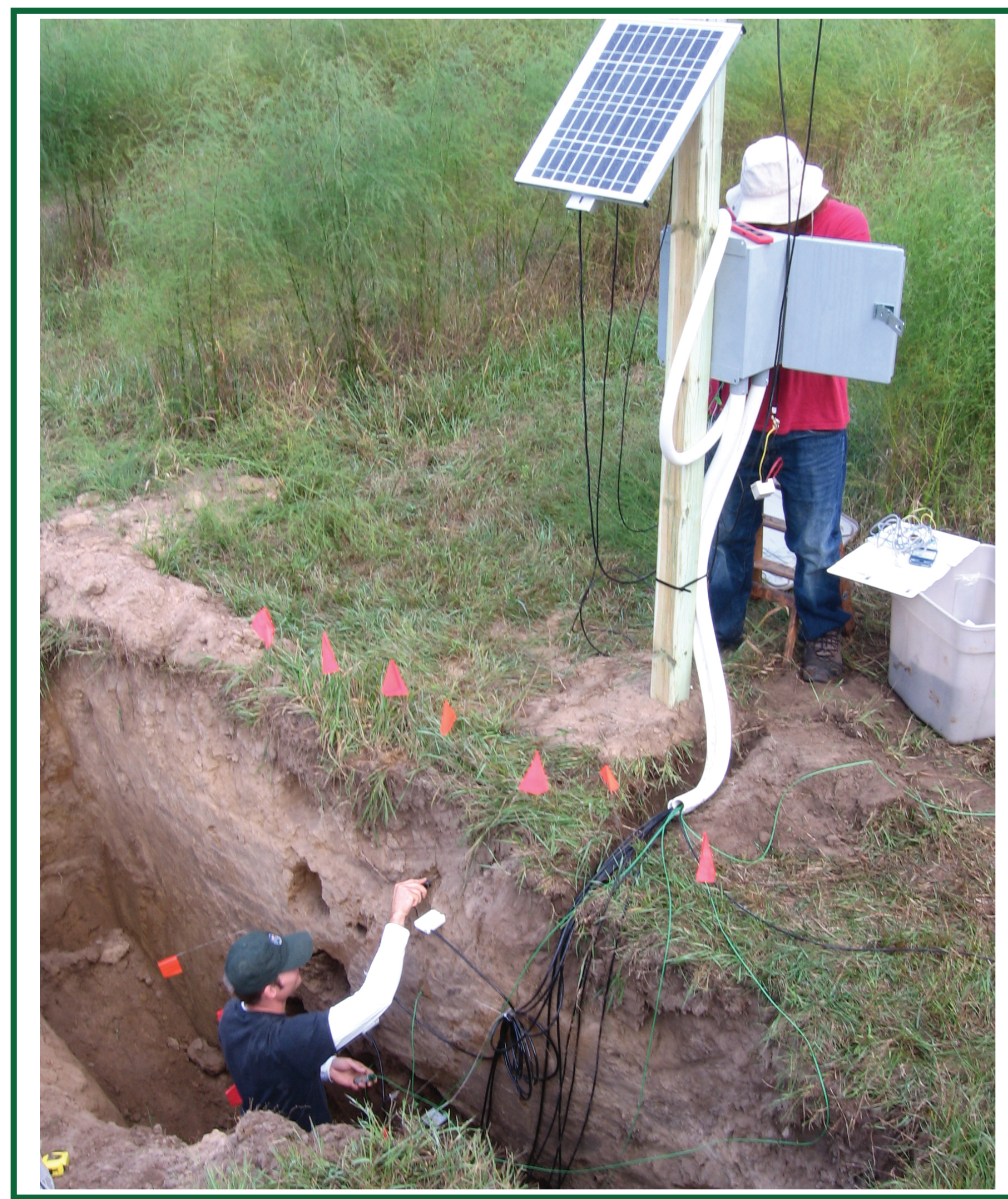
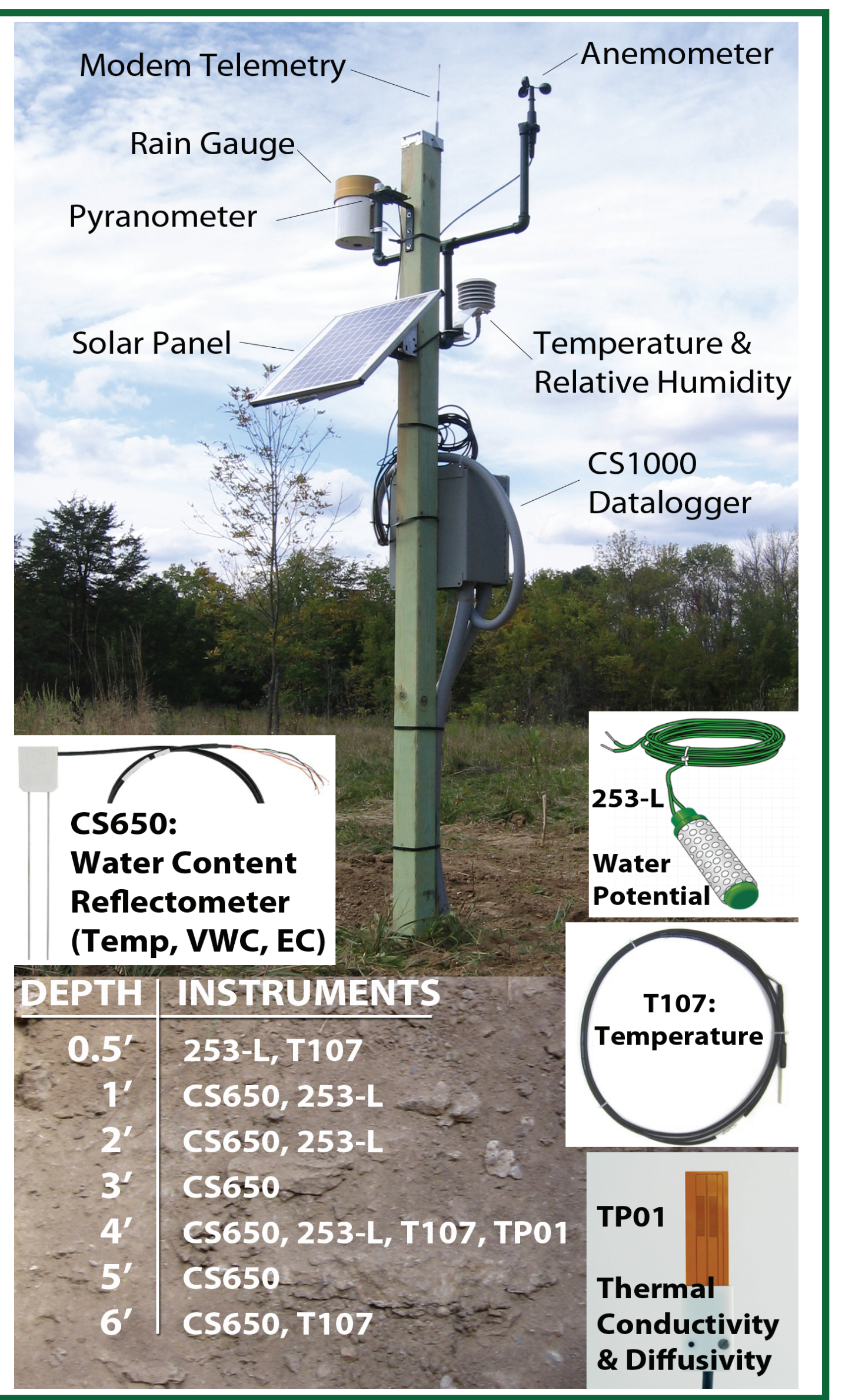
The Indiana Shallow Geothermal Monitoring Network: A test bed for optimizing ground-source heat pumps in the glaciated Midwest

CENTER FOR GEOSPATIAL DATA ANALYSIS
INDIANA UNIVERSITY

Andrew R. Gustin (angustin@indiana.edu), Center for Geospatial Data Analysis, Indiana Geological Survey, Indiana University, Bloomington, Indiana.
Shawn Naylor (snaylor@indiana.edu), Center for Geospatial Data Analysis, Indiana Geological Survey, Indiana University, Bloomington, Indiana.
Kevin M. Ellett (kmellett@indiana.edu), Indiana Geological Survey, Indiana University, Bloomington, Indiana.

Project Collaborators:
THE ARIZONA GEOLOGICAL SURVEY
AASG Association of American State Geologists
U.S. DEPARTMENT OF ENERGY





DEPTH	INSTRUMENTS
0.5′	253-L, T107
1′	CS650, 253-L
2′	CS650, 253-L
3′	CS650
4′	CS650, 253-L, T107, TP01
5′	CS650
6′	CS650, T107

Abstract (#202689)

Ground-source heat pumps (GSHP) represent an important technology that can be further developed by collecting data sets related to shallow thermal regimes. Computer programs that calculate the required lengths and configurations of GSHP systems use specific input parameters related to the soil properties to improve the efficiency of system designs. The thermal conductivity of sediments varies significantly depending on texture, bulk density, and moisture content, and it is therefore necessary to characterize various unconsolidated materials under a wide range of moisture conditions. Regolith texture data are collected during some installations to estimate thermal properties, but soil moisture and temperature gradients within the vadose zone are rarely considered due to the difficulty of collecting sufficient amounts of data.

Six monitoring locations were chosen in Indiana to represent unique hydrogeological settings and glacial sediments. Trenches were excavated to a depth of 2 meters (a typical depth for horizontal GSHP installations) and sediment samples were collected at 0.3-meter intervals for a laboratory analysis of thermal conductivity, thermal diffusivity, bulk density, and moisture content. Temperature sensors and water-content reflectometers were installed in 0.3-meter increments to monitor changes in temperature and soil moisture with depth. In-situ thermal conductivity and thermal diffusivity were measured at 1.5-meters using a sensor that detects radial differential temperature around a heating wire. Micrometeorological data were also collected to determine the surface conditions and water budgets that drive fluxes of energy and moisture in the shallow subsurface.

Preliminary results indicate that increases in water content can increase thermal conductivity by as much as 30% during wetting front propagation. Although there is a change in temperature associated with the infiltration of wetting fronts, thermal conductivity appears to be relatively insensitive to soil temperature. By establishing continuous data sets, fluctuations in seasonal energy budgets and unsaturated zone soil moisture can be determined. This information can then be used to establish accurate end members for thermal properties and improve the efficiency of geothermal systems.

Results

Water and energy budgets are highly variable throughout the seasons, and since these factors can have a large influence on the temperature, moisture content, and thermal conductivity / diffusivity of soils, a full annual cycle of data must first be collected in order to comprehensively consider how to best optimize shallow geothermal systems. However, some initial results can still be inferred from the data collected thus far (see **Figures 1-4**). There is no detectable change in thermal conductivity due to seasonal decreases in temperature, but this effect may be masked by simultaneous increases in moisture content. With the rapid temperature increase in late March, thermal conductivity appears to slightly decrease for many of the sites without correlated decreases in moisture content. Temperature fluxes at depth seem to be primarily driven by the infiltration of wetting fronts. Increases in moisture content associated with these infiltration events are linked to a change in both thermal conductivity and diffusivity, generally increasing the former while decreasing the latter. For clay-rich soils it takes a significant amount of precipitation for the infiltration to reach 4ft depth, while sandier soils tend to be more responsive to modest precipitation events.

Discussion

As **Figures 1-4** show, there is a roughly inverse relationship between thermal conductivity and thermal diffusivity above a certain moisture content (Yang & Koike, 2005). For low moisture contents, the relationship between these two properties is direct. This is true because of the low thermal diffusivity of water relative to common minerals (Hukseflux, 2012). The moisture content required to show the inverse relationship varies depending on the porosity, permeability, and mineral content of the soil. Clay-rich soils tend to show a gradual increase in conductivity with increasing moisture and require more water to show the inverse relationship between conductivity and diffusivity. In contrast, sandy soils are more responsive to small changes in moisture content and will transition from a direct to inverse relationship at lower moisture contents. Sandy soils also tend to have a higher hydraulic conductivity, which can reduce their capacity to retain moisture and increase the rate at which water infiltrates. Since water has a much higher volumetric heat capacity than air or common minerals while quartz has one of the highest thermal conductivities of common minerals (Huskeflux, 2012), it follows that the ideal soil for ground-source heat pump installations would be a frequently moist quartz-rich sand with high porosity and permeability. However, as many coarse-grained soils also tend to be well-drained, soils with a higher clay fraction may be better-suited to consistently maintain higher moisture content and thermal conductivity. In **Figure 7**, a relationship between moisture content and thermal conductivity was developed. This was used to generate a range of thermal conductivities for all depths at all sites based on moisture content (**Figure 8**). Using these conductivity values, **Figure 9** shows the range of trench lengths necessary to produce effective GSHP systems. As a more complete dataset is developed, an eventual goal is to generalize expected conductivities for mapped soil units in the SSURGO database. This will allow landowners and GSHP installers to rapidly estimate length requirements for a given system based on its spatial location and hydrogeological setting. Ideally, this will increase the efficiency of designs and decrease the associated installation costs, making shallow geothermal systems a more viable alternative energy option for Indiana.

Sensor Calibrations

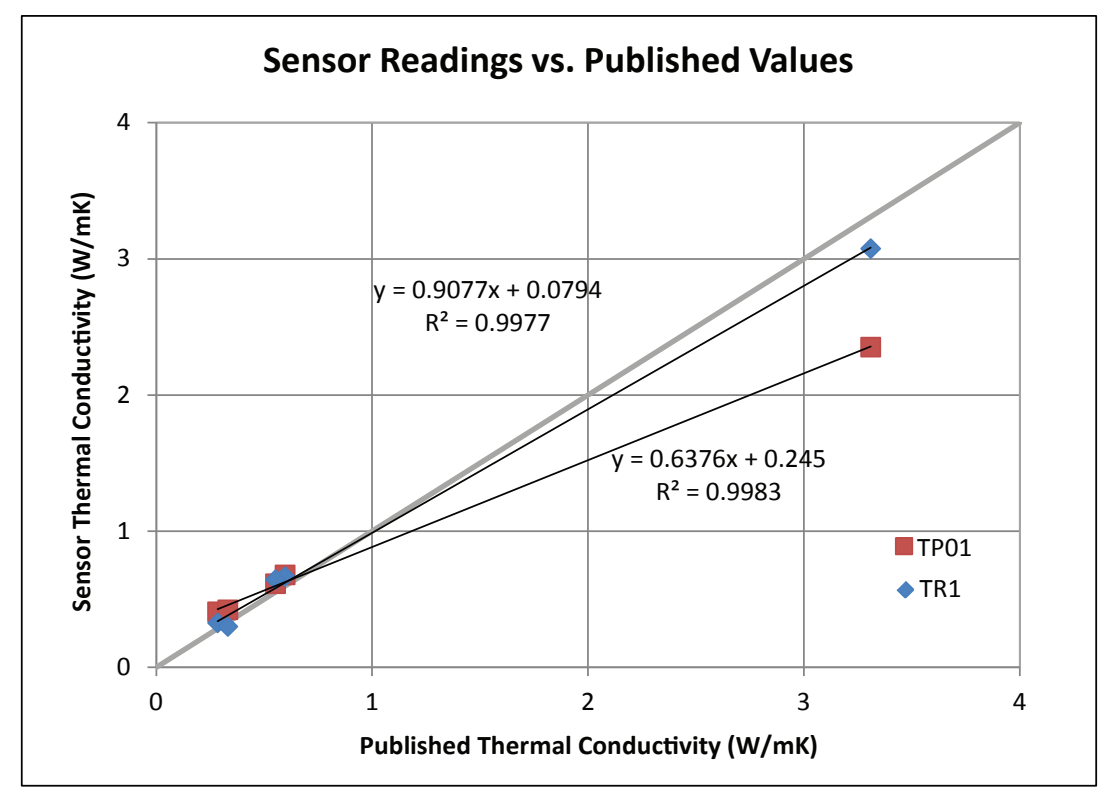
Thermal Conductivity

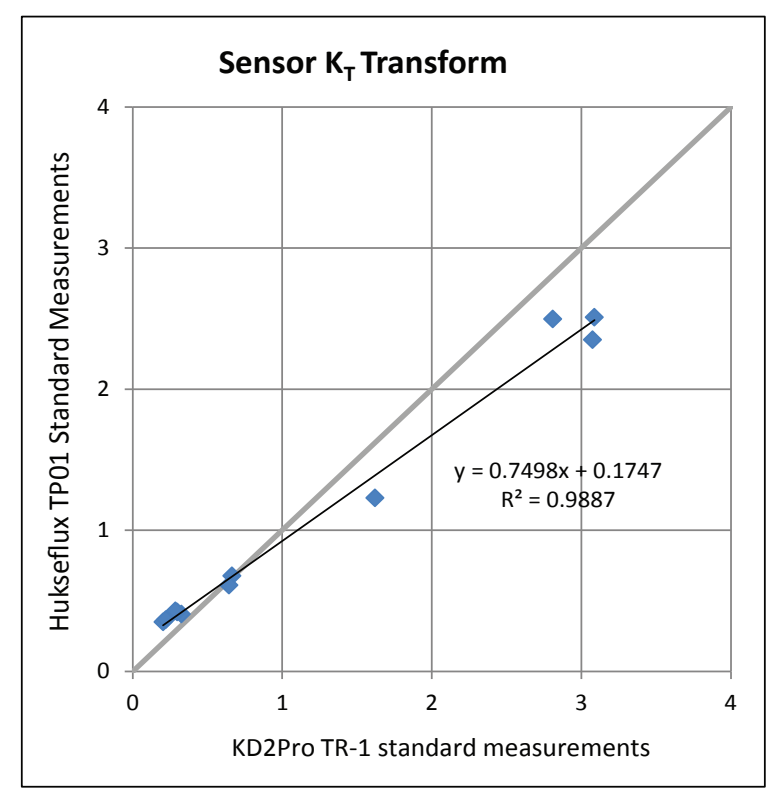
- Continually measured using Hukseflux TP01 sensor installed at all sites
- Measured using Decagon KD2 Pro during site installations and in lab

Known standards were measured with all sensors:

-Glycerin	(0.285 W/mK)
-Ottawa sand (dry)	(0.332 W/mK)
-Agar gel (5%)	(0.554 W/mK)
-Agar gel (0.5%)	(0.598 W/mK)
-Ottawa sand (saturated)	(3.310 W/mk)

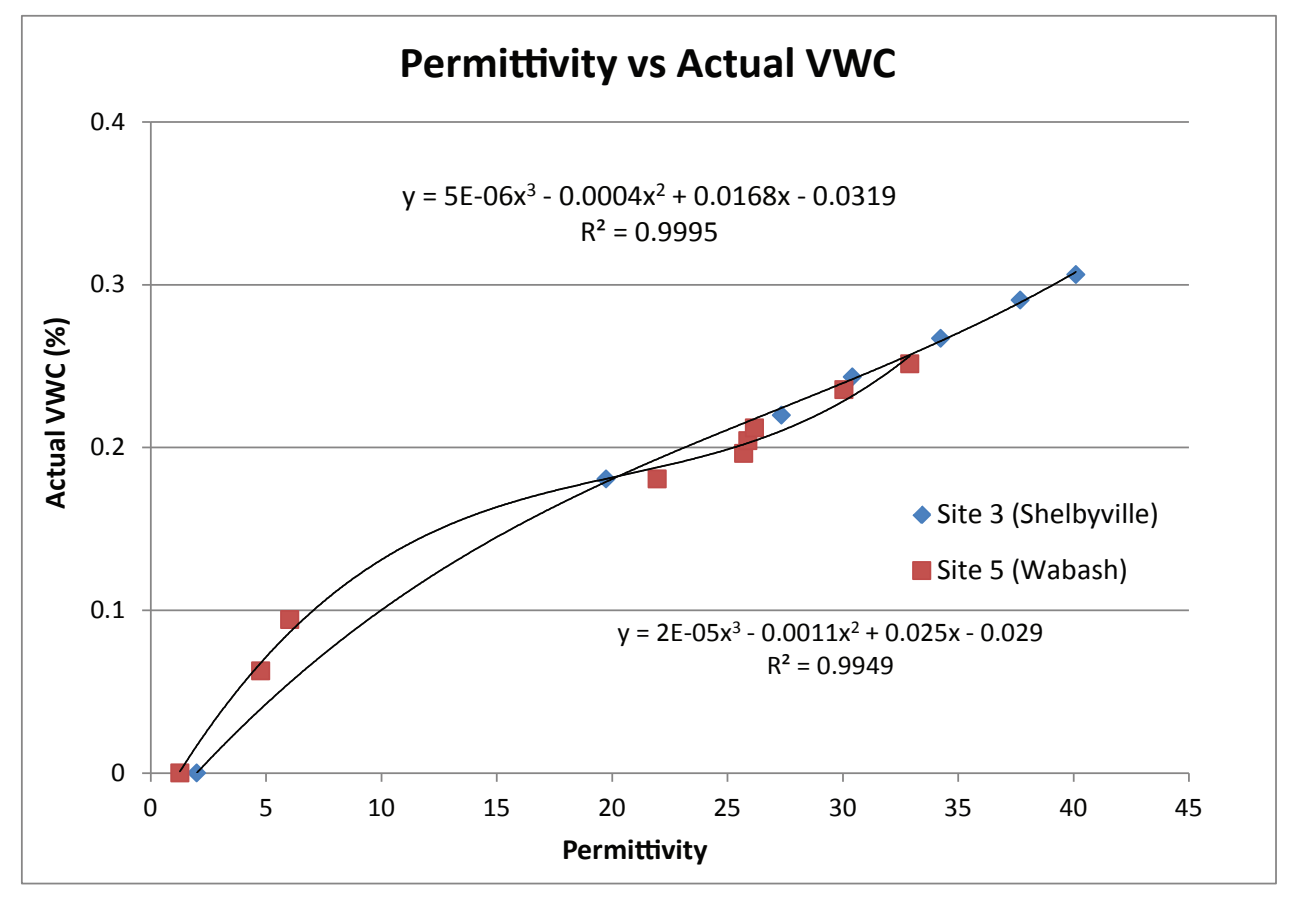
Using the standards, a transform was developed between instruments to correct for the underestimated conductivity of the TP01 sensors.



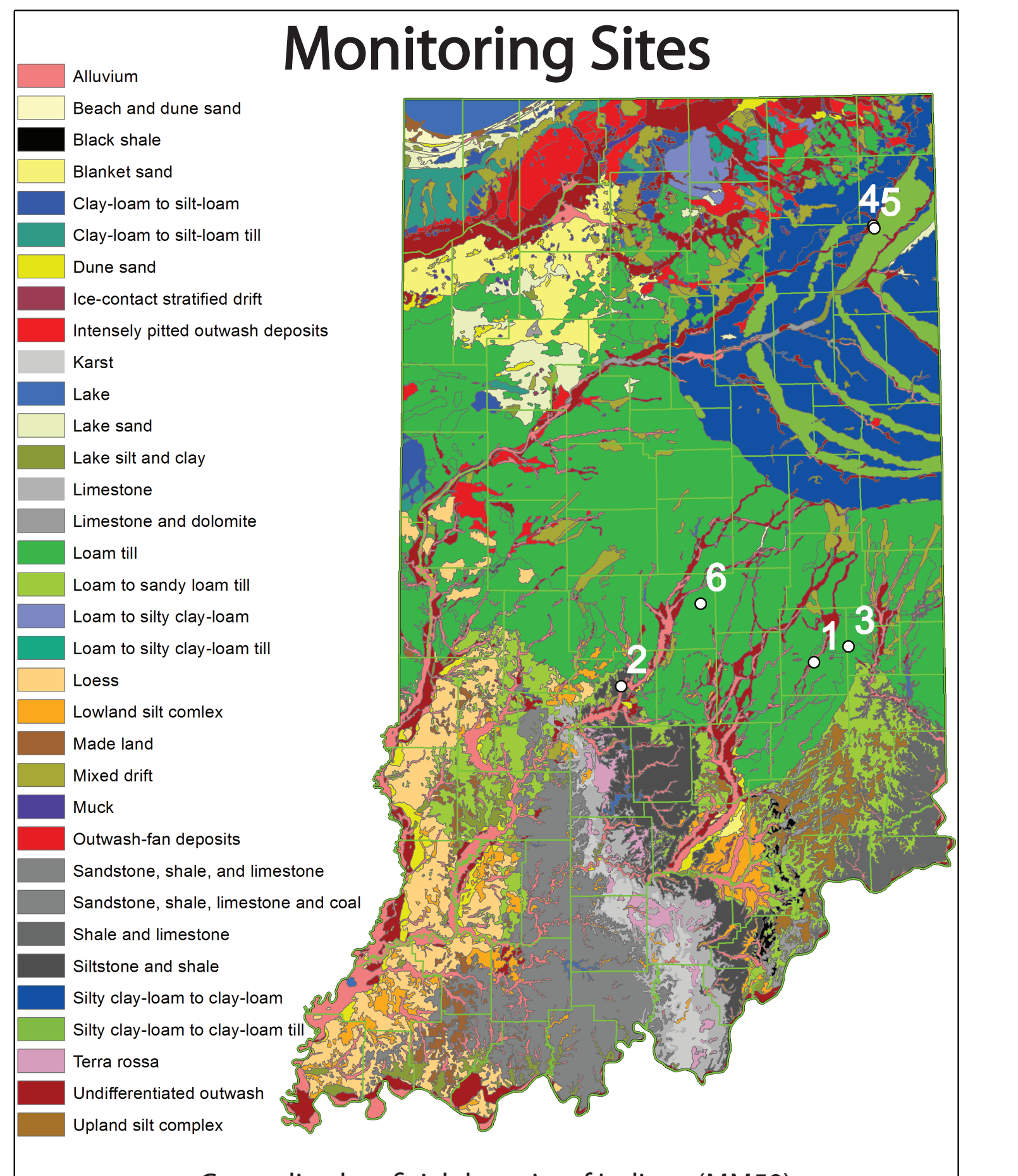


Volumetric Water Content

To allow for the correction of and correlation between volumetric water contents (VWC) measured by the CS650 probes, controlled laboratory experiements were performed on samples taken during site installations. Dried sediment was packed in a large cylinder in an attempt to match field bulk-density, and known volumes of water were sequentially added and allowed to equilibrate until complete saturation was reached. The values of these experiments are used to establish a trend curve that allows field VWC to be transformed into actual VWC for each site using the parameter of permittivity.



Monitoring Sites

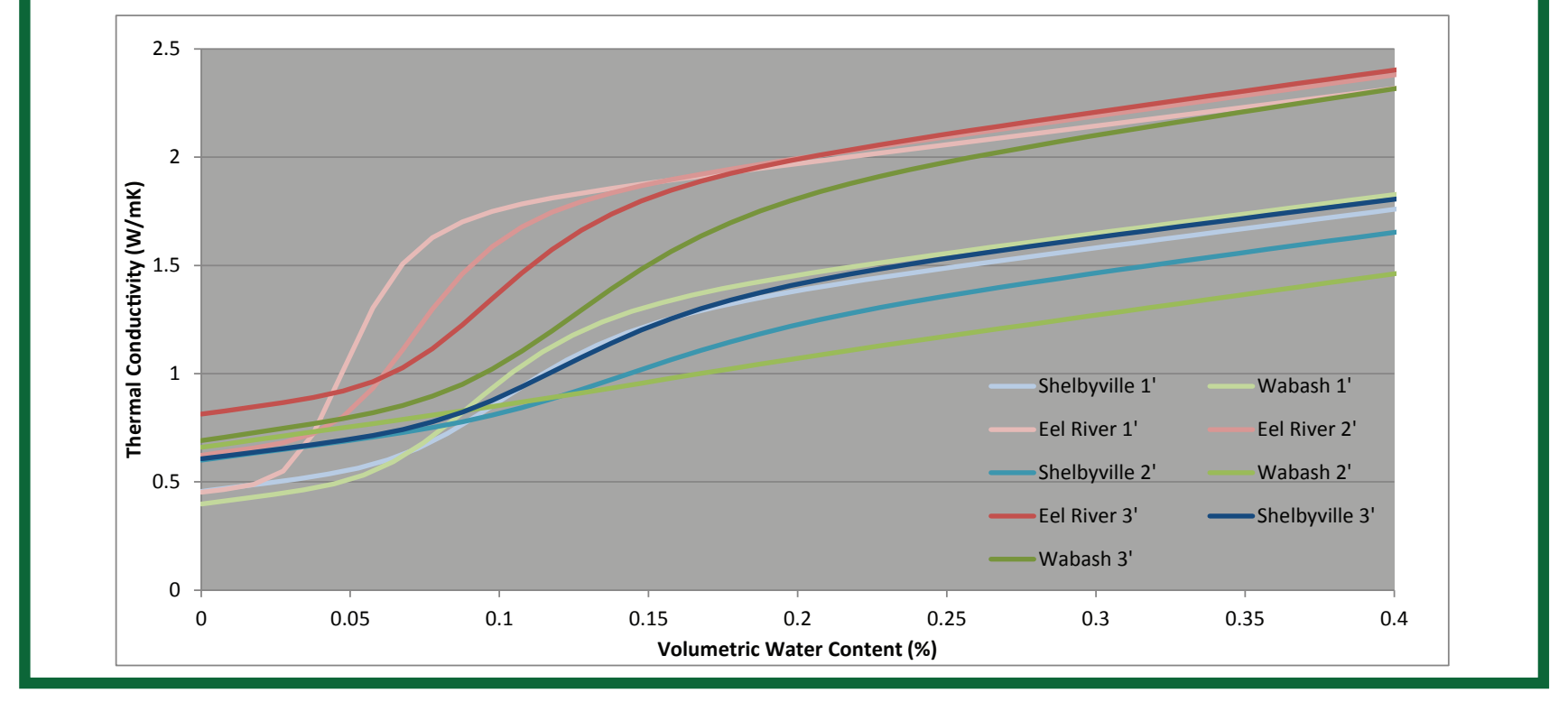


Generalized surficial deposits of Indiana (MM59)

Name	Site #	Geologic Setting	Texture at 4ft	Bulk Density (g/cm^3)
Flatrock	1	Alluvial terrace	Sandy Clay Loam	1.11-1.32
Bradford	2	Alluvial terrace	Silt Loam	1.32-1.58
Shelbyville	3	Moraine crest	Silty Clay Loam	1.41-1.79
Eel River	4	Outwash terrace	Sandy Loam	1.46-1.71
Wabash	5	Moraine crest	Clay Loam	1.64-1.80
Eagle Creek	6	Till plain	TBD	TBD

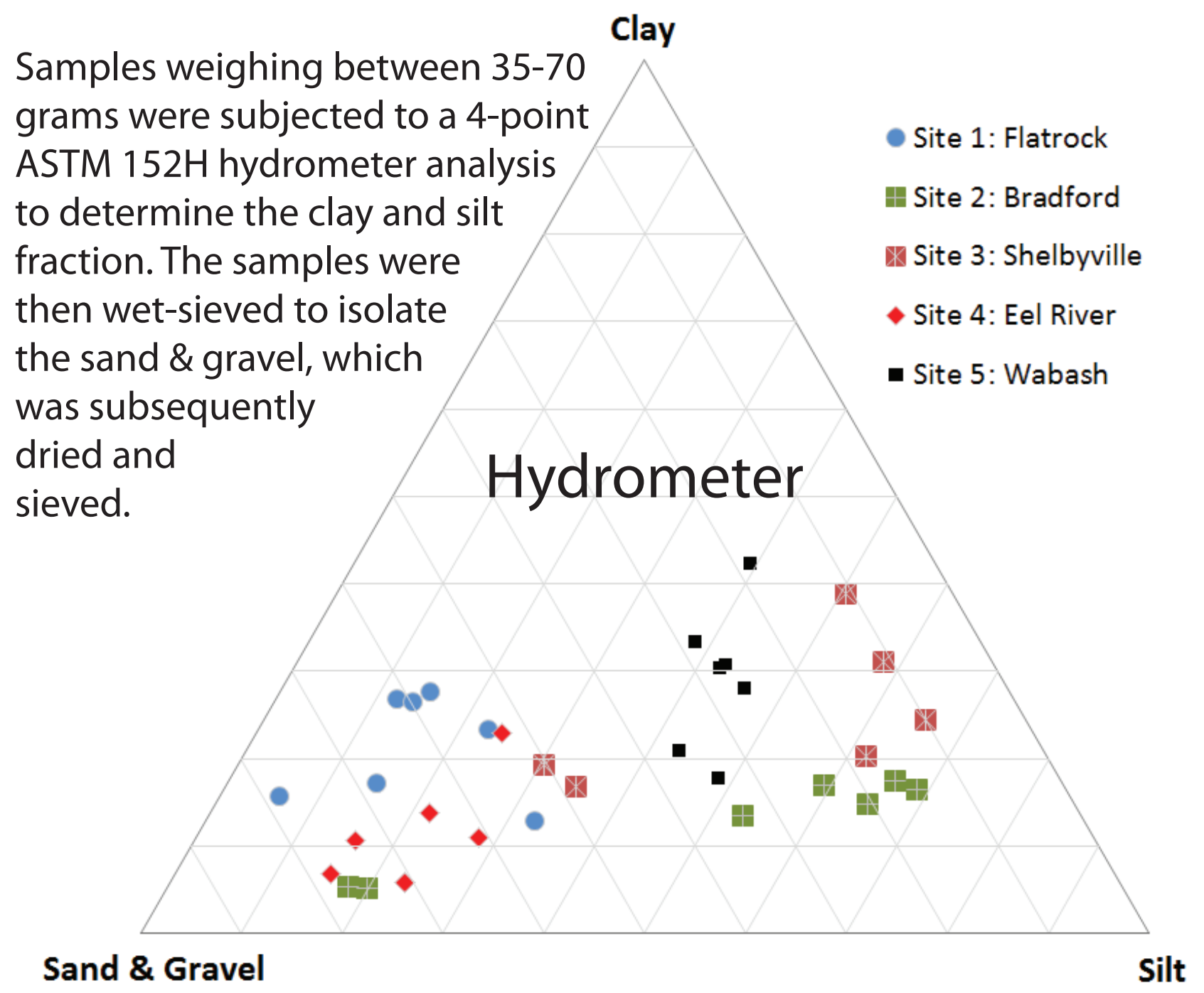
Thermal Dryout Curves

Following the methodology of Campbell (1985) and Decagon (2011), a series of thermal dryout curves were generated using 3″ diameter soil cores collected during site installations. The cores are first saturated under vacuum conditions and then completely dried in an oven. The mass, volume, and thermal conductivity are determined in each of these states and the results are used to produce a hypothetical thermal dryout curve. The dryout curve is modeled using a quadratic equation related to the amount of clay present in the soil. The dryout curves for several sites and depths can be seen in the figures below. While the dryout curve is useful for estimating what hypothetical conductivity values should correspond with given moisture contents, it is difficult to determine how accurately the model matches the field data shown in Figure 6 without a complete annual dataset.

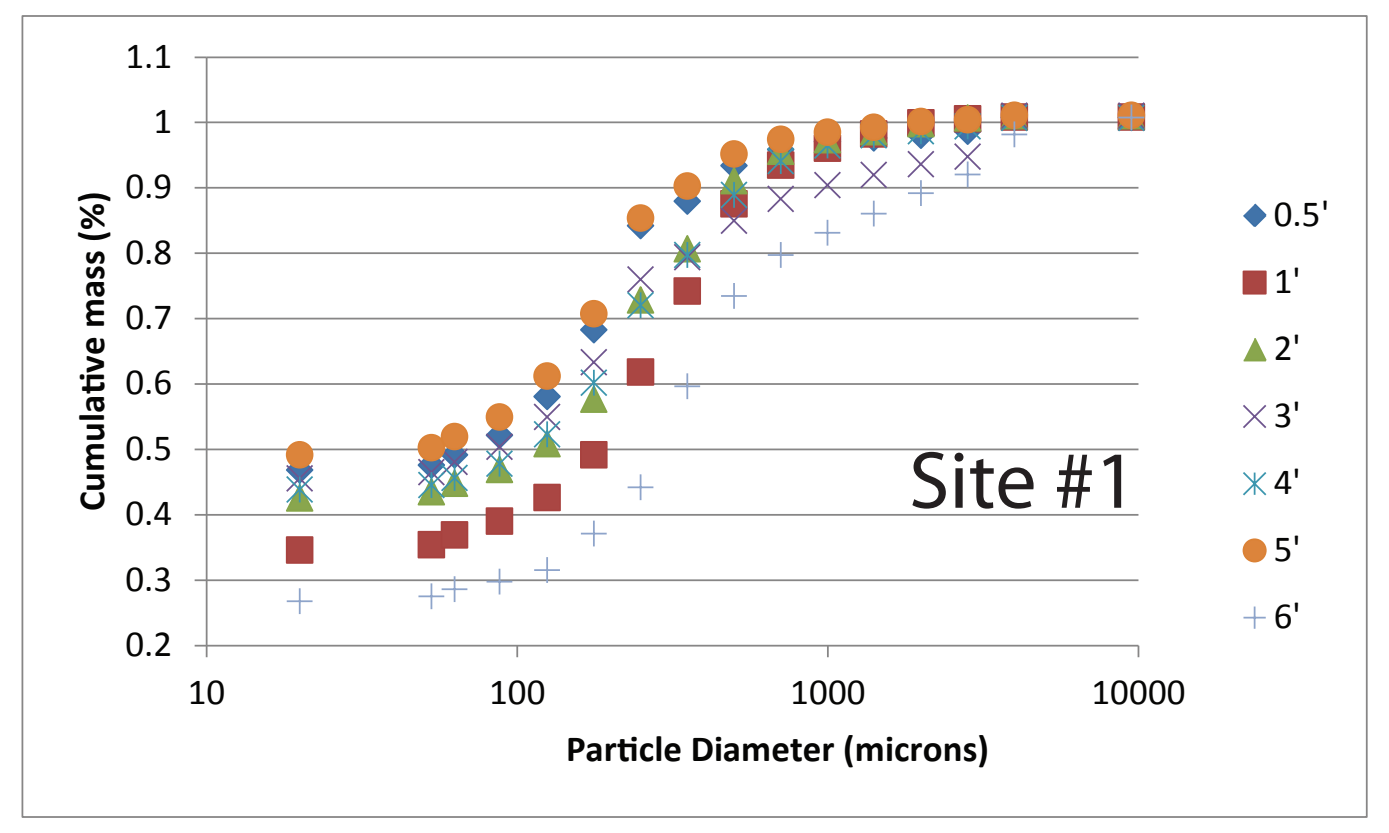


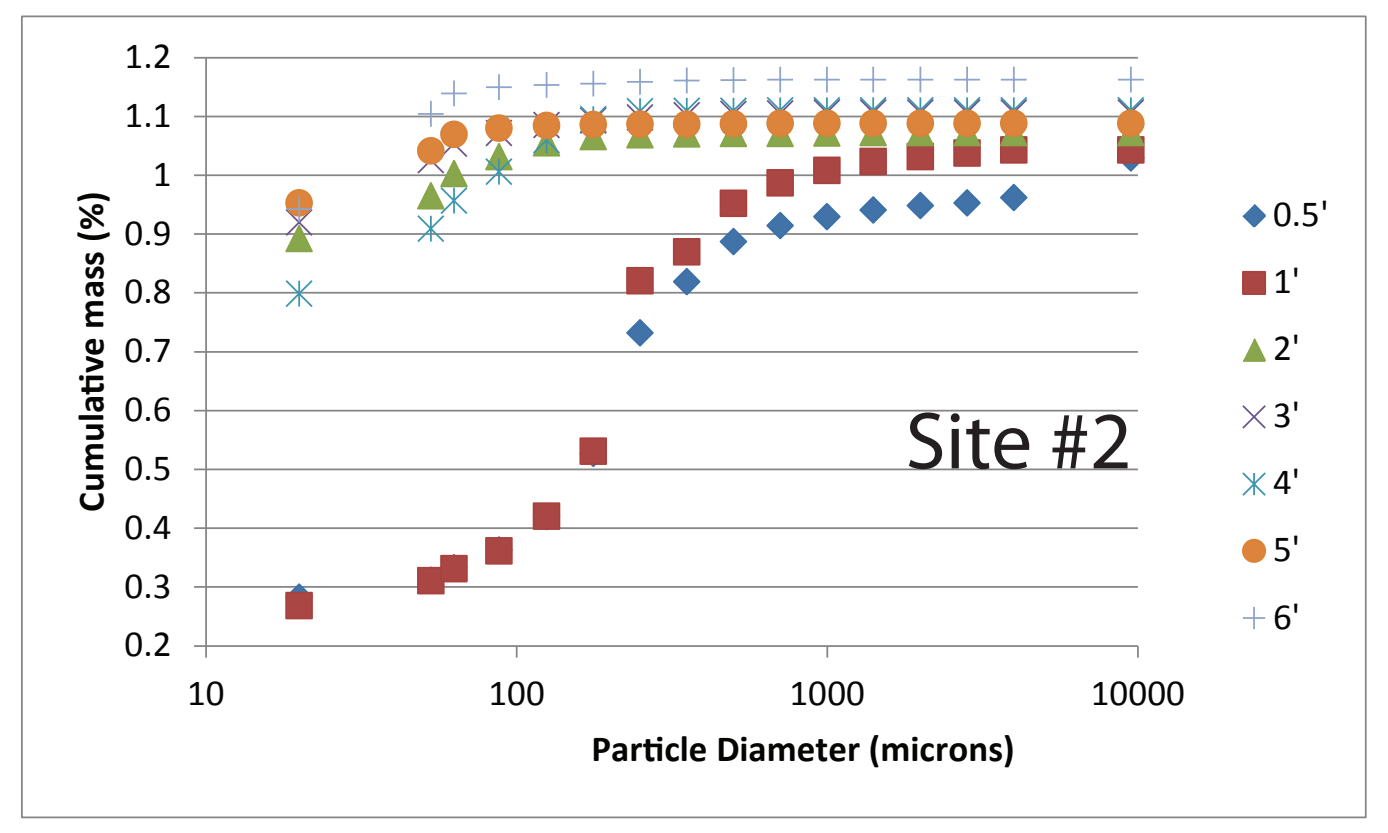
Grain-Size Analysis

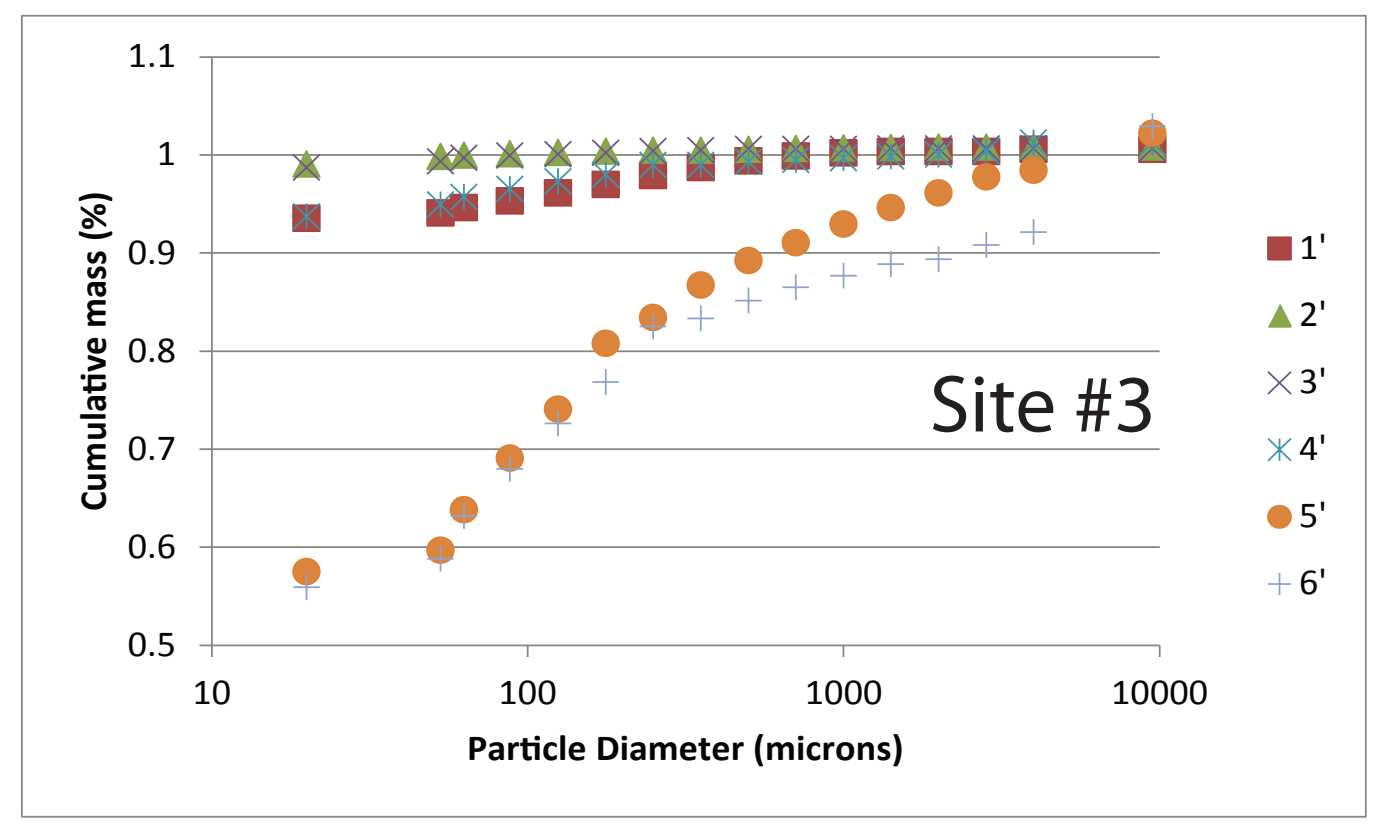
Samples weighing between 35-70 grams were subjected to a 4-point ASTM 152H hydrometer analysis to determine the clay and silt fraction. The samples were then wet-sieved to isolate the sand & gravel, which was subsequently dried and sieved.

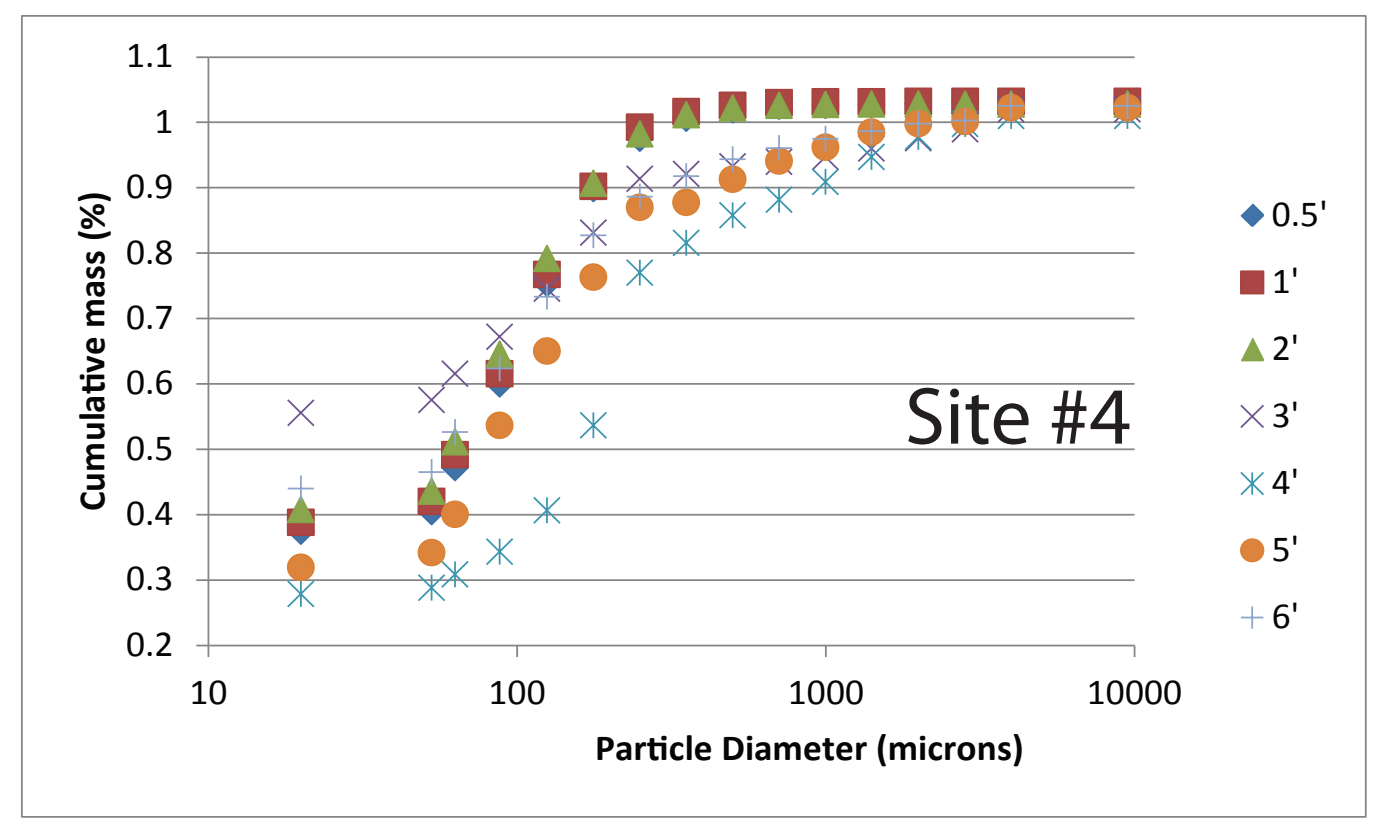


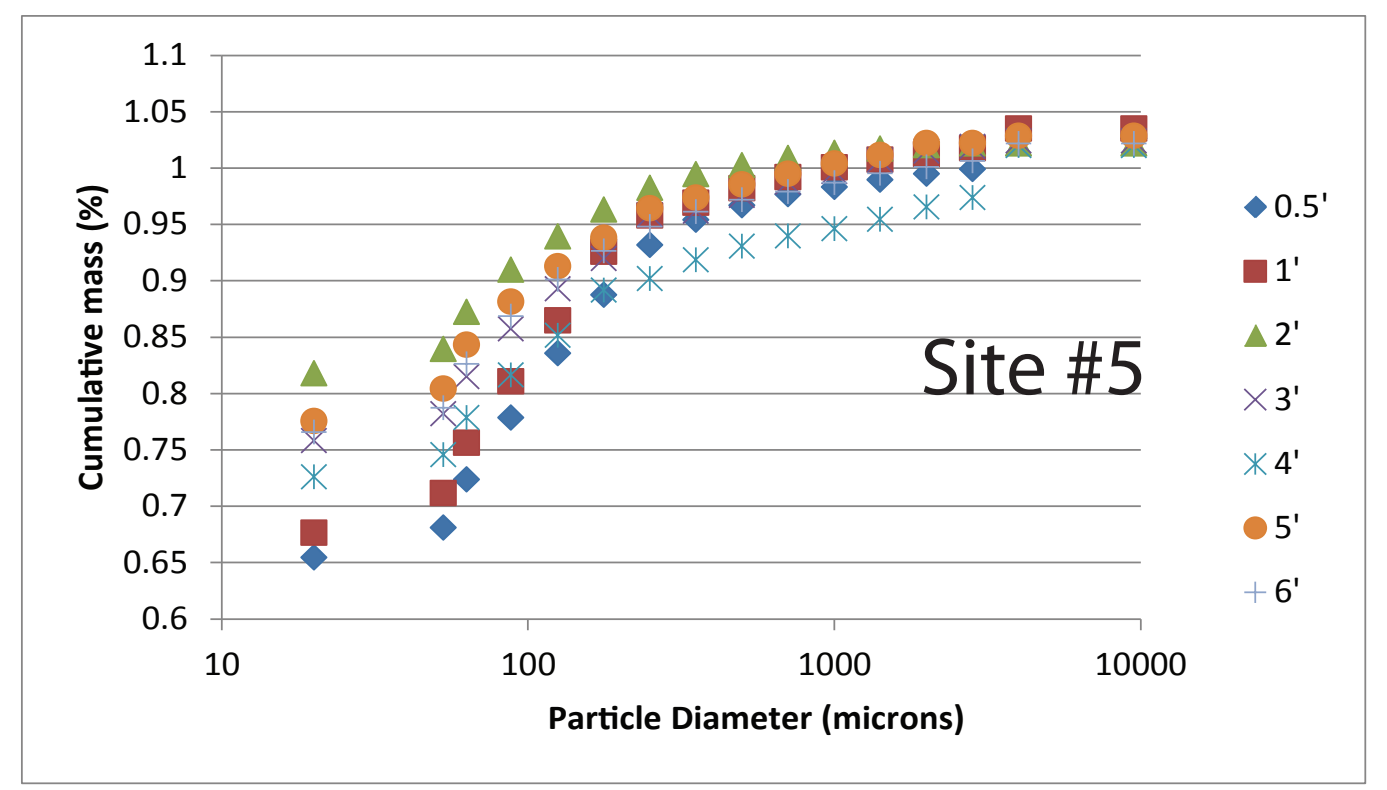
Sieve Results











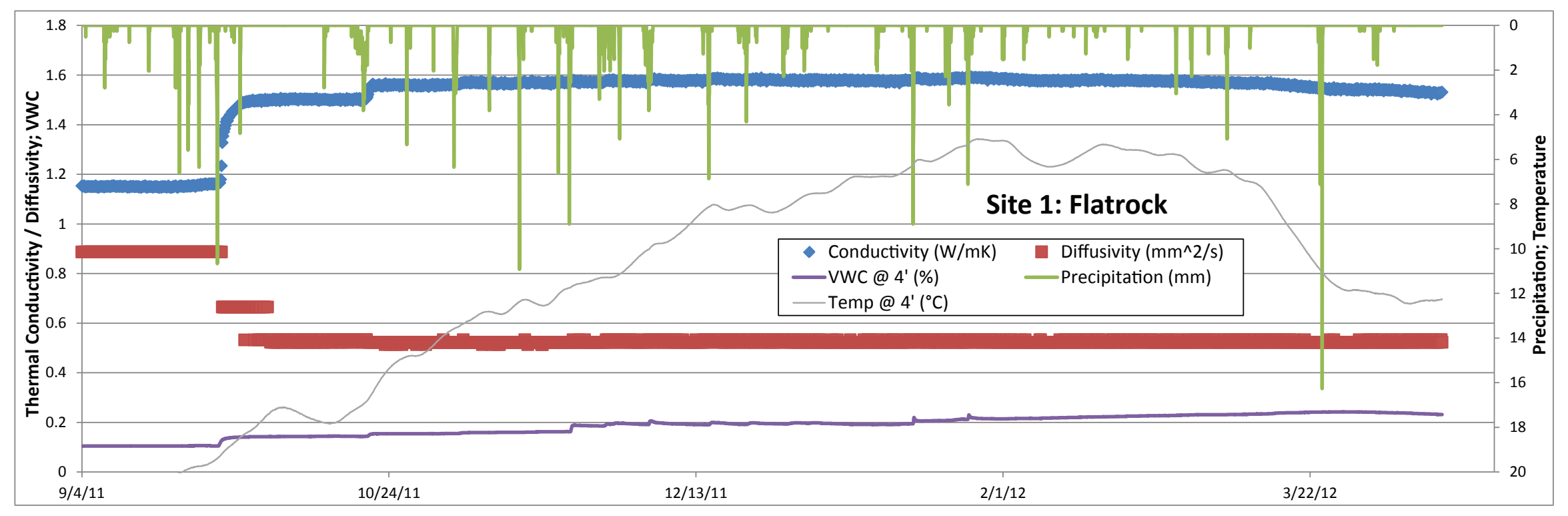


Figure 1: Selected data from site #1 (Flatrock)

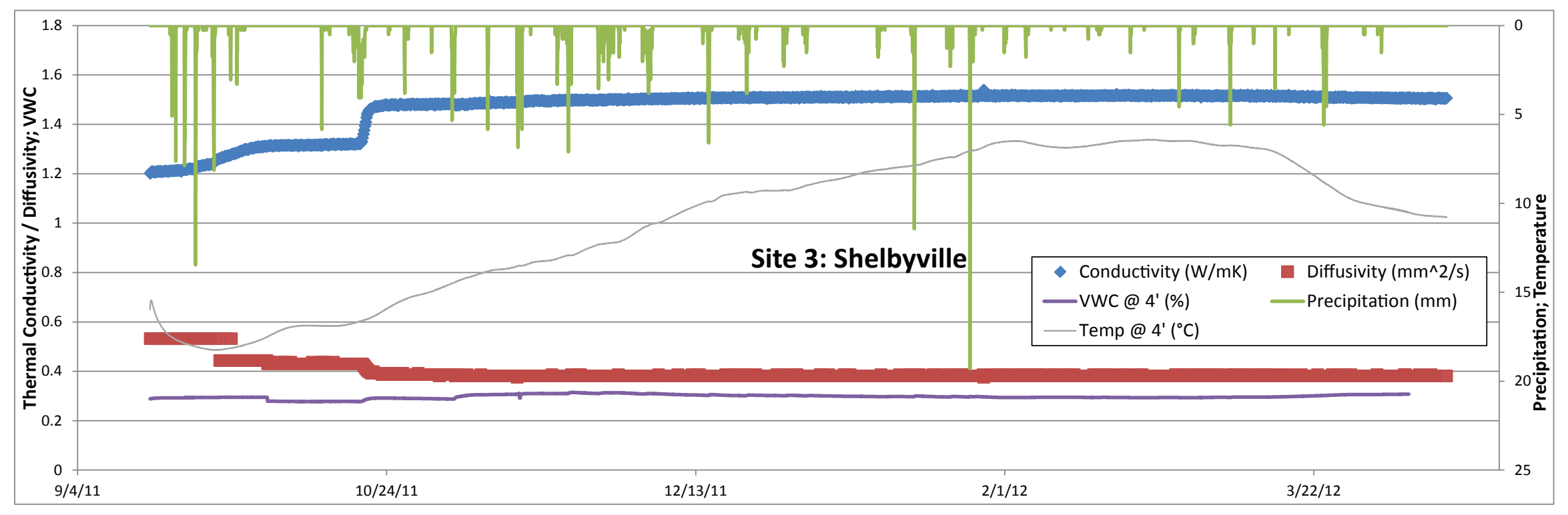


Figure 3: Selected data from site #3 (Shelbyville)

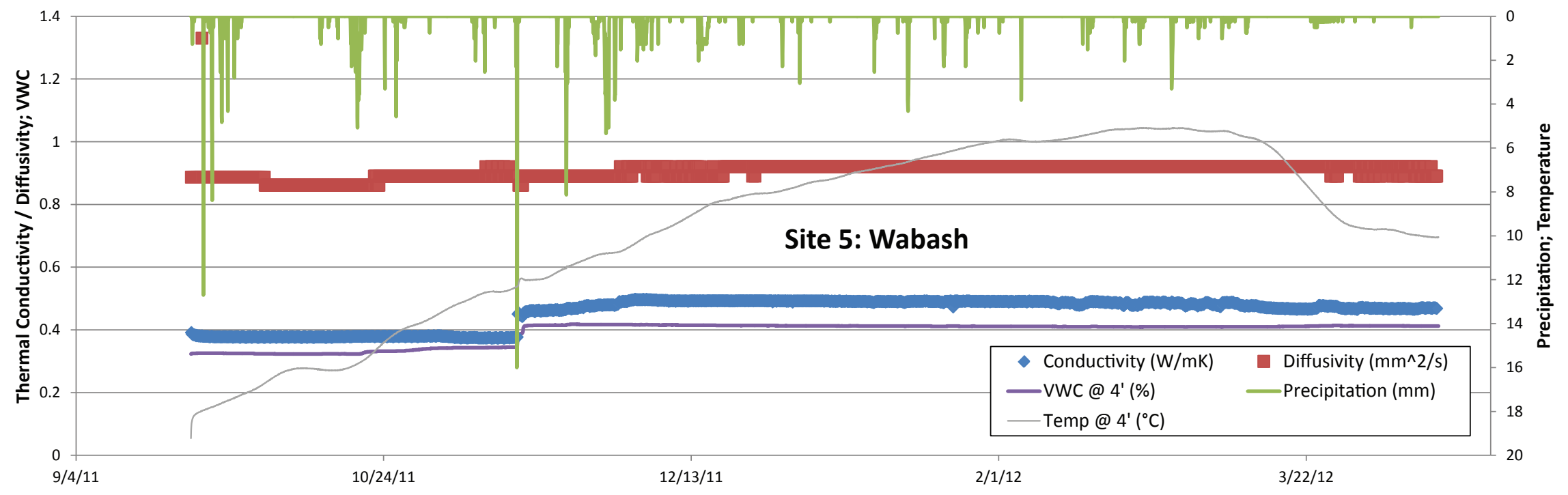


Figure 5: Selected data from site #5 (Wabash) *Note: It is suspected that the TP01 sensor is not making complete contact with the surrounding substrate, yielding anamolous readings. For this reason, the conductivity data is not considered in **Figure 7**.

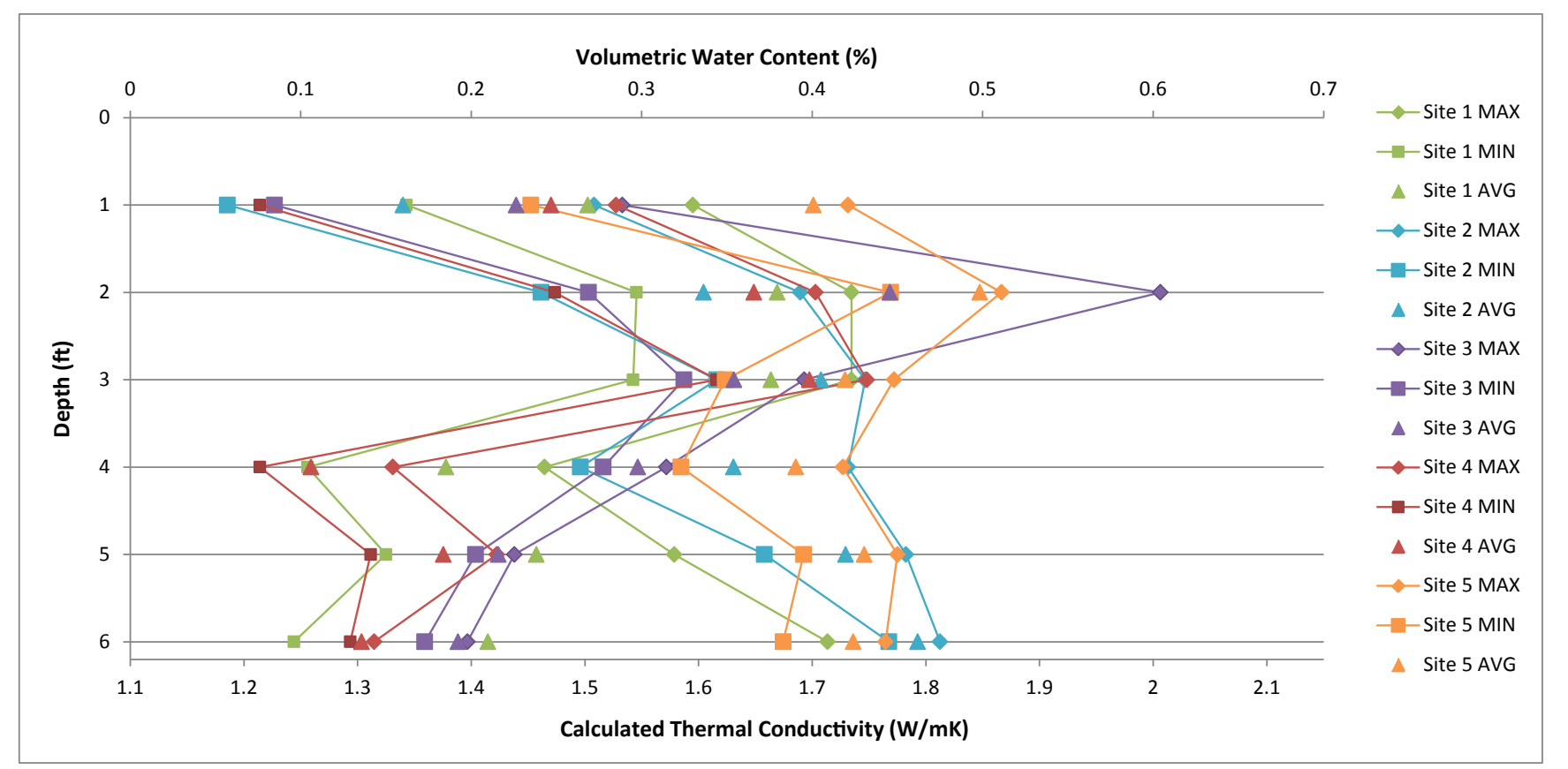


Figure 8: Plot showing maximum, minimum, and average values of VWC and calculated thermal conductivity (based on **Figure 7)** for all sites at all depths.

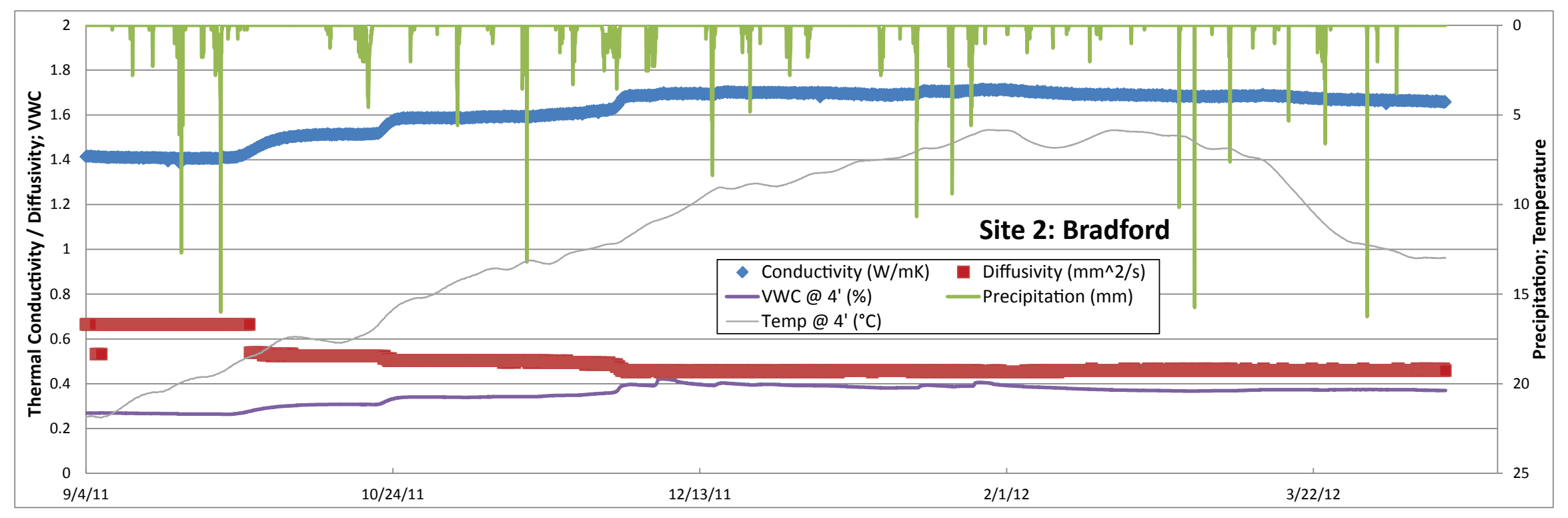


Figure 2: Selected data from site #2 (Bradford)

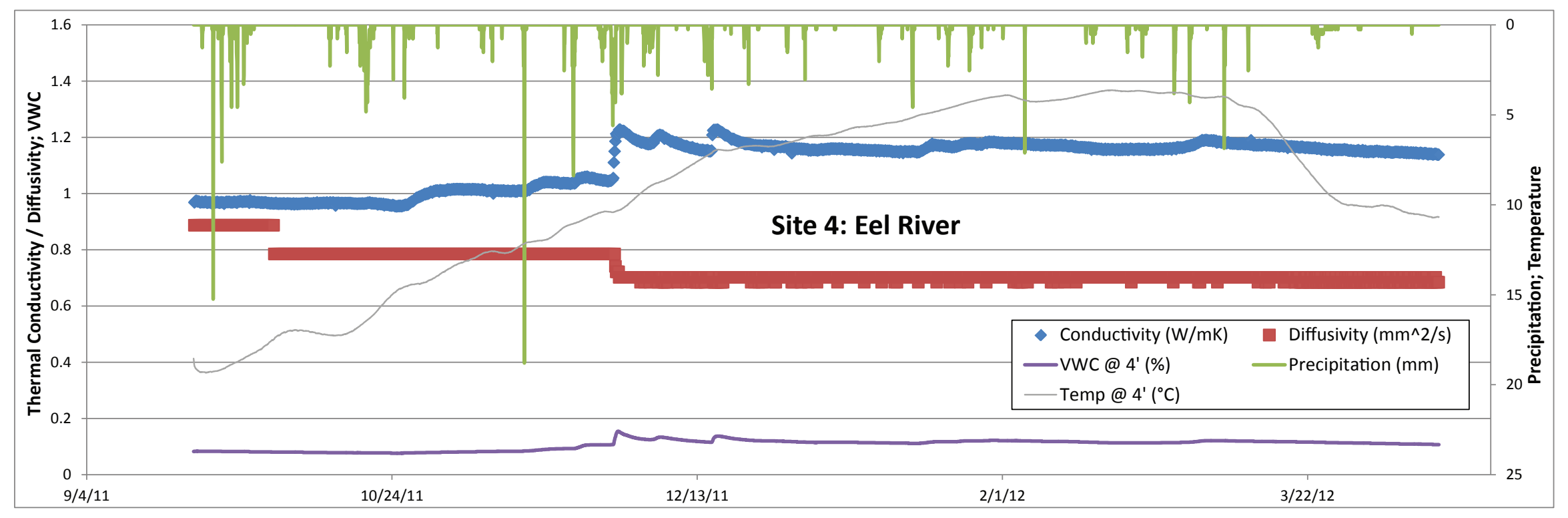


Figure 4: Selected data from site #4 (Eel River)

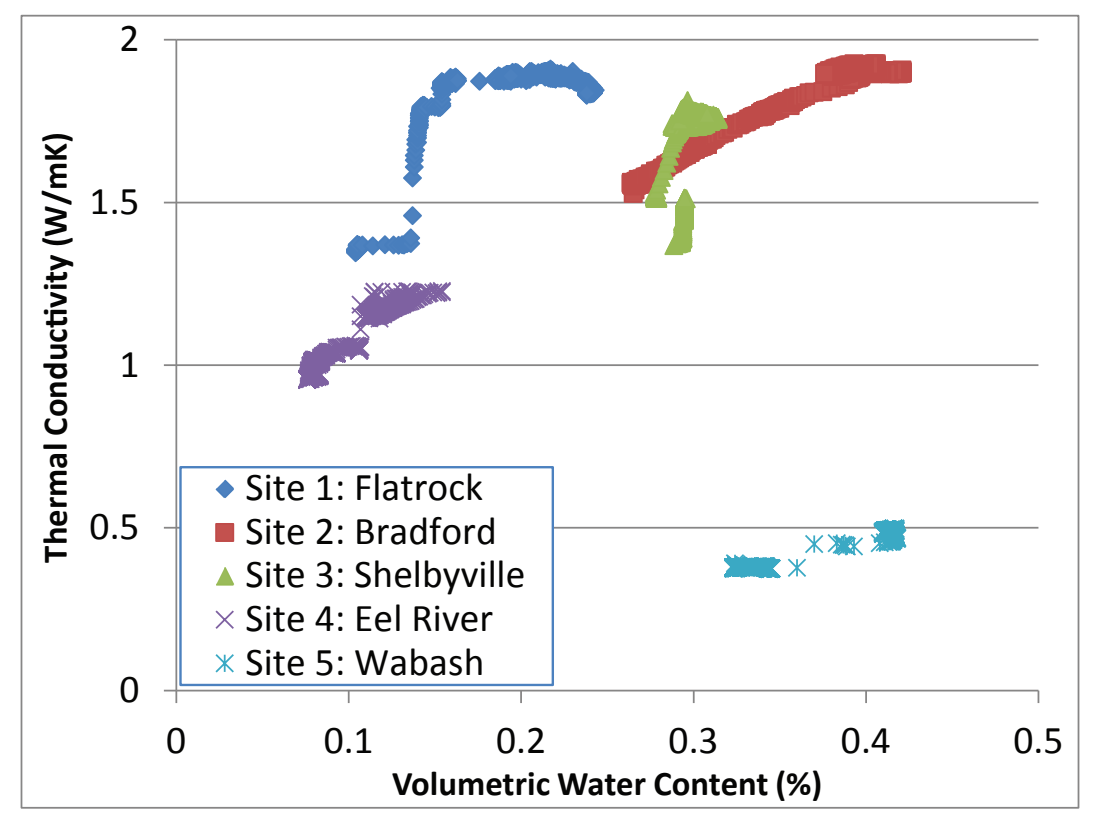


Figure 6: VWC vs Thermal Conductivity for all sites

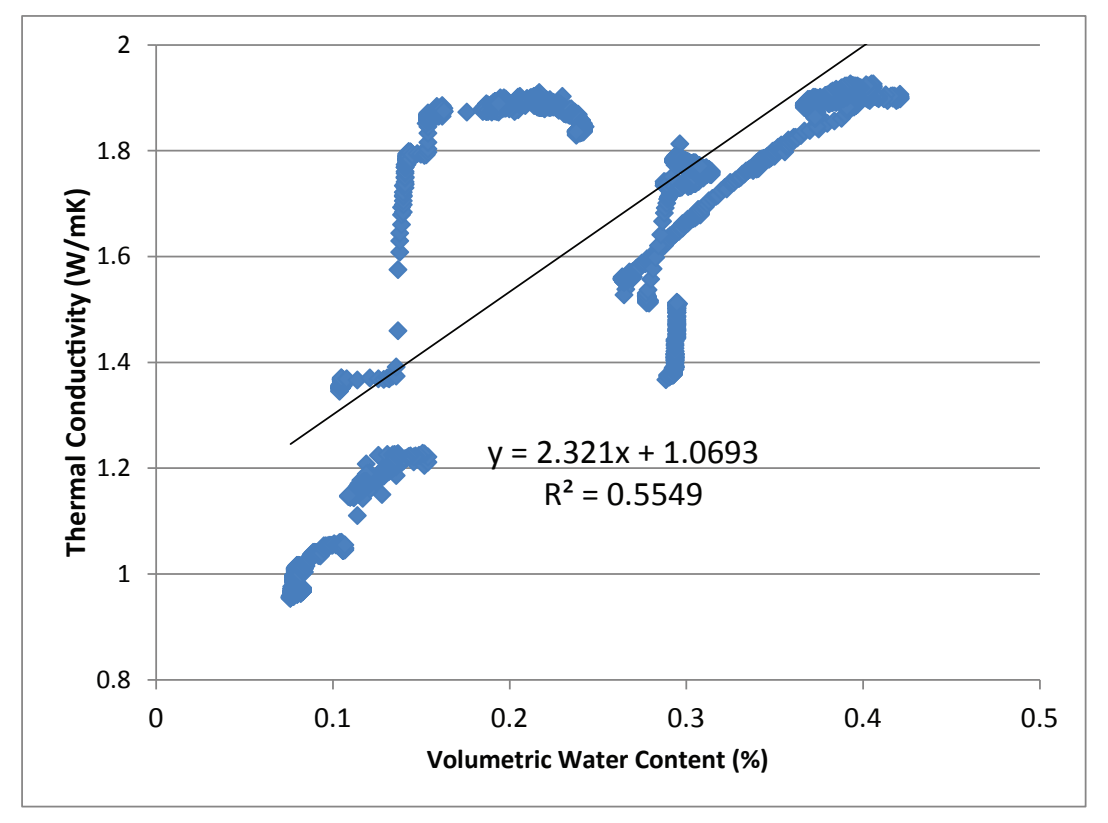


Figure 7: Generalized trend of VWC vs. Thermal Conductivity for the first four sites.

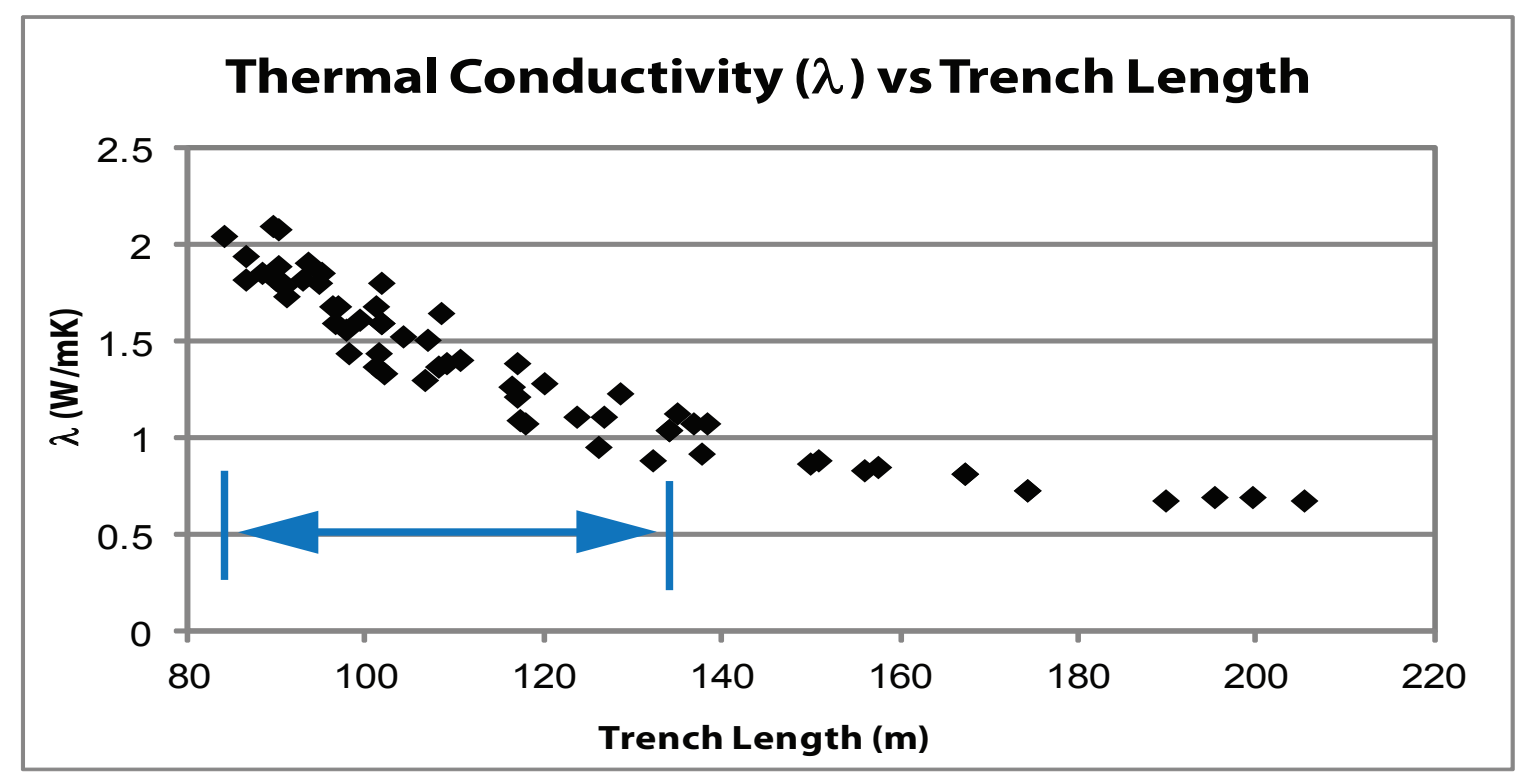


Figure 9: Thermal conductivity vs. calculated horizontal trench length for a 1.25-ton system in heating mode (from "LoopLink" GSHP design software). Arrows indicate length range required for all five sites.

References

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