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Characterization of Subsurface Flows within a Headwater Catchment

Introduction

The hydrologic cycle governs the patterns of life on this planet. The distribution, timing and storage of water are crucial parts of the climate. An understanding of catchment-scale runoff and subsurface processes is vital to overall comprehension of the hydrologic cycle.

Within Oregon's Cascade Range, two different geologic-based flow regimes characterize the region: Western and High Cascades (Tague, 2004). The High Cascade streams are fed by regional aquifers, have higher water retention rates, and have more constant yearly flow patterns. The Western Cascade fed streams rely on surface and shallow subsurface runoff, and therefore they have declining flow levels throughout the water year. In the low flow summer months, the Western Cascade stream are heavily dependent on subsurface connections with the surface stream flow. These subsurface connections play a vital role in buffering stream temperature. Low, constant stream temperatures are important for the survival of the Pacific Northwest's cold-water salmonids during spawning and rearing.

The focus for this project is to gain insight into snow and rain storage and runoff processes that occur in the subsurface and its impacts on headwater stream temperatures. Watershed 7 within the HJ Andrews Experimental was chosen as the study site for this project. Our research was focused on answering two general questions:

1) What is the influence of subsurface topography on water movement through the downslope profile of a watershed?
2) How can tracer studies and stream temperature measurements be used to quantify subsurface sinks and sources to instream flow?

To understand the storage dynamics of Watershed 7, we performed a salt and Resazurin tracer release study throughout a 300-meter stream reach. The salt tracer data gives an understanding of groundwater inputs and stream residence times. Resazurin, a fluorescent dye and smart tracer, provides information of solute transport and microbial activity in sediment-water interfaces (Haggerty 2008).

To map the subsurface topography we used dynamic cone penetrometers, also known as knocking poles, to measure and map both the depth to refusal and soil penetrability (Shanley 2003). Within the knocking pole holes, permanent wells were inserted, which will be used to track groundwater levels throughout the year.

A Distributed Temperature Sensing (DTS) fiber optic cable laid throughout 1.5 km of the stream provides information on the location, discharge, and temperature of subsurface inputs. The DTS is able to give spatially and temporally distributed measurements of stream temperature at an extremely high resolution (Selker 2005). With these several field methods, the project's questions begin to be answered and provide the foundation for further work to unravel the complex processes of subsurface water flows.

Site Description

HJ Andrews Experimental Forest is 6400 ha basin that drains Lookout Creek within the Western Cascades of Central Oregon. Watershed 7 within the Andrews, a south facing catchment at a mean elevation of ~1200 m, was our area of focus. Watershed 7 is a 15.378 ha headwater catchment defined by long hillslopes (>250 m) and slope angles around 10°-20°. Soils within WS 7 are estimated to be less than 3 m of poorly developed Inceptisols with a thick layer of organic rich topsoil and are underlain by andesitic and basaltic bedrock. Adjacent, and assumed hydrologically similar, WS 8 demonstrates residence times on the order of roughly 3 years (McGuire et al., 2005). Watershed 7 was harvested in the mid-1990. The vegetation is primary growth, predominately low to the ground shrubs.

Methods

Tracer studies

A salt and Resazurin study was conducted on July 7th at 14:00 and ending July 9th at 22:00. The carboy pump stopped injecting a 220L solution of 13.5kg of NaCl and Resazurin at 3:00 on July 9th. A 300-meter stretch of the watershed was designated for study. Two breakthrough curve locations (BTC) were selected for continuous sampling, one 30 meters from the carboy, the other 300 meters from the carboy. At these sites, bottled samples of water were taken every 15 minutes for the first 2 hours of the injection and then every hour to be tested for Resazurin content in a lab. To follow the salt pulse, electroconductivity (EC) readings were also taken in conjunction with the Resazurin sampling. In addition to these continuous readings, EC readings were taken at each 10-meter stretch at the top of every hour to give us finer spatial resolution in our tracer readings. All EC readings were taken with a temperature reading. At the end of the 3-day period, an YSI Multisonde was left at the bottom of the 300-meter reach until its batteries ran out (2 days) to record the tail end of the NaCl pulse.

Knocking Poles

To help interpret the data given to us by the tracer studies and the DTS, we mapped soil depths and stratigraphy to understand the effects of topography and soil storage on stream flow and temperature.

To map the bedrock, we used knocking poles. Knocking poles are extendable rods with an attached anvil that allows a known weight to be dropped from a known height onto the rod. Since the force of penetration is known, approximate soil horizons can be mapped using soil compactness. The knocking pole method can help to explain most of soil water conductivity, though it does not explain the effects of differences in soil type or porosity. For our project, the main purpose of the knocking poles is to map the depth-to-bedrock, though in some cases it is impossible to differentiate between bedrock and compacted clay.

The knocking data was recorded as the depth traveled with each impact until reaching a final depth of refusal. From July 21 – 24, twenty-nine locations were measured using the knocking poles. Nine transects of knocking poles were taken going upstream 340 m. Each transect had one location directly next to the streambed and locations going perpendicular to the stream up to ridgeline. After the depth to bedrock was determined, 10-foot galvanized steel pipes were placed into the knock holes. The pipes had 1/8 inch holes drilled every 6-inches to allow for water infiltration.

Mini-Trolls

The galvanized steel acted as water wells. Row 1 Stream Side and Transect 5 had water within the well. Mini-Troll Data Loggers were placed into the wells to measure the fluctuation of the groundwater level. The Mini-Trolls measure pressure changes that can be translated into water level by subtracting atmospheric pressure. The Mini-Troll was placed into Row 1 Stream Side August 8th at 8:40 and removed August 11th at 16:00. The Mini-Toll was placed in Transect 5 August 12th at 9:30 and removed August 14th at 8:30.

Distributed Temperature Sensing

Since subsurface flow is buffered from the energy fluxes that define surface flow temperature, subsurface feeds into a stream can be tracked using temperature data distributed along a stream. To track temperatures, we laid a fiber optic cable along an 800 meter stretch of the main stream in Watersheds 6, 7, and 8. The cable was submerged in as much of the stream as possible (logjams prevent complete submersion) and then hooked up to a Distributed Temperature Sensing (DTS) computer. To calibrate the DTS, the first 10 meters of cable were placed into an ice bath. The DTS recorded temperature data at every meter every 5 seconds. The DTS collected data from 5:35 PM on August 15th to 10:45 AM on August 16th.

Results/Discussion

Tracer Study

Salt Tracer

The salt tracer study allows us to characterize the flow paths, the location and approximate size of groundwater inputs and outputs, and the residence times along the 300 m of the reach within Watershed 7. The hourly specific conductivity (SC) longitudinal profiles provide a clear picture of the surface and subsurface interactions.

Figure 1 gives the breakthrough curves (BTC) at each wetted flag (1-9 at the lower reach, 20-27 at the upper reach) for the entire length of the study. These curves begin with the background stream SC. Once the salt injection is begun, each flag increases in SC to a plateau. Flag 27 has the largest plateau value, 222.9 μS/cm. The dramatic dips in the upper reach SC correspond to points when the pump broke down and stopped the salt concentration injection. The pump malfunctions occurred on July 8 at 11:00am and July 9 at midnight. The pump was turned off on July 9 at 3:00am. After turning off the pump, SC levels throughout the stream begin to return to background levels. The differences between the time to reach plateau levels and return to background levels reflect increasing groundwater inputs and residence times of water.

Figure 1 shows two significant groundwater inputs into the upper stream reach. The lower specific conductivity is a result of groundwater input, which dilutes the salt concentration. Groundwater inputs can be clearly seen between flags 27 and 26 and flags 24 and 23. After flag 20, the stream goes completely subsurface until the stream reappears at flags 9 and 8. Less distinguishable inputs exist between nearly all flags, accounting for the slight translations in SC data for all times.

Using conservation of mass and the known discharge to be 1.25 L/sec at flag 23 where the stream gauge was located, the discharge at each flag was calculated. Flag 27 had a discharge of 0.993L/sec and Flag 1 had a discharge of 2.541L/sec. The total increase in discharge was 1.548 L/sec. The three substantial groundwater inflows between flags 27 and 26, 24 and 23, and 20 and 8 were calculated to have 0.135, 0.113, and 1.127L/sec inputs, respectively. Figure 2 plots the discharge at each flag using two different methods: the blue dots are the discharge computed from the plateau values and the red dots are the plateau values computed using integration under the curve. The discrepancy in the discharge values in the lower reach comes from the fact that the tracer study ended before the entire tail of the salt tracer could be captured. The graph curiously presents a linear increase of discharge through the 300m stream reach.

Flag 9 appears to be an anomaly to the stream's overall surface and subsurface flow pattern. It is located at an isolated pool, with no surface connection to the stream. The stream was dry above it until flag 20, and dry below it until flag 8. The SC took approximately 17 hours to get above background levels and never reached a plateau SC value. This suggests that flag 9 has a different flow path than flags 1-8. While it is connected to flags 20-27, its connection is considerably slower or smaller than the upper reach stream water, which goes to flags 1-8.

This anomaly challenges the assumption that allows us to use conservation of mass to compute the lower reach stream discharges. The flag 9 data proves that there exists multiple subsurface flow paths, so it is entirely possible that the lower reach has lower SC not only because of subsurface inputs, but also because of subsurface flow paths that circumvent the study reach entirely, bringing the tracer salt to a location further downstream. Despite this, the concavity of the local topography and the significant drops in stream temperature that accompanied the lower SC readings back up our assumptions.

Temperature

Along with the SC data, temperature readings were also taken during the hourly profiles. Figure 3 relates temperature as a function of time and flag. This figures shows that there is a diurnal stream temperature fluctuation, with the exception of flag 9. The maximum temperatures occur around 2:00pm and the minimum temperatures occur around 7:00am. There is a substantial decrease in stream temperature between flags 20 and 9. The subsurface flow between the upper and lower reach provides a buffer for the stream temperature. The groundwater buffer is important component during the summer when the stream has lower flow and is receiving higher energy inputs, e.g. short and longwave radiation and sensible and latent heat fluxes. This groundwater temperature buffer is clearly seen at flag 9. Flag 9 does not have a diurnal cycle; instead it has a roughly constant temperature of 7 ^{o}C. This provides greater evidence of a large groundwater composition in Flag 9.

Figure 4 plots the specific conductivity longitudinal profile as the height with stream temperature overlaid with a heat map. During the plateau period, there is a small diurnal SC cycle that corresponds with the stream temperature diurnal cycle. The trough of the temperature cycle coincides with a trough in specific conductivity. This says that more groundwater is being input into the stream lowering the temperature and diluting the salt concentration. The opposite occurs during the crest of the temperature and SC diurnal cycle. This pattern highlights a relationship between ground and surface water and the diurnal evapotranspiration pattern of the surrounding vegetation.

Fluorescent Tracer

Raz and Rru Tracer study provided murkier insights than the salt tracer. Both Raz and Rru concentrations were seen at the upper BTC location (flag 24), but neither Raz nor Rru was seen at the lower BTC location. Figure 5 shows the concentrations over time. There could be several explanations for this occurrence. When the stream went entirely surface the Raz and Rru concentrations traveled too slowly or became adhered to organic material during subsurface activities. The initial concentration might also have been too small to detect the Raz and Rru at the lower BTC site. Difficulties in the lab analysis prevented us from obtaining more data from the Raz and Rru tracer.

Knocking Poles

Soil depths and stratigraphy were sampled at 29 different points throughout Watershed 7 using knocking poles. A sample knock is shown in Figure 6, which is indicative of all the knocks done. The y-axis is depth below soil and the x-axis is the number of knocks taken to get to the given depth. To better interpret this data, soil hardness per every 10 cm was found. Soil penetrability is measured as knock/cm. This is computed from a first order forward finite difference of the depth vs. cumulative knock graph. Finding soil penetrability per every 10 cm allows a comparison between all knocks. The penetrability and depth to refusal data for all 29 knocks is shown in Figure 7. The histogram shows the number of knocks that hit the depth of refusal within the given 10 cm range. The bulk of the soil depths center around 160 cm, with roughly half the knocks going deeper or shallower. The other half of the figure is the median penetrability, plotted as interpolated triangles. For any given 10 cm section, soil penetrability was taken for the remaining (i.e. had not hit depth of refusal) knocks. This plot gives a clear pattern. Between roughly 0-50 cm there exists a well defined till layer, which is easily penetrable. Between roughly 50-120 cm there exists a till/soil horizon, after which the soil hardness very slowly increases. This two-horizon behavior makes sense considering Watershed 7 soils are mainly Inceptisols. Shanley et al. found similar results when they performed a knocking pole study in Vermont in Inceptisol soils (Shanley et al. 2004). Massive variability within small knocking depths is often attributable to clasts or roots which show up in the knocking data as areas of much higher penetrability.

The assumption was made that the depth of refusal is analogous to bedrock. Many of the knocks ran into very compacted clays, which were difficult to distinguish from bedrock. Without digging a pit, we cannot say that depth of refusal is always equivalent to depth to bedrock. We assumed that soils that hard would act similarly to bedrock with respect to water infiltration. Oftentimes the knock pole could be made to go farther into the ground, but when driving into something with little penetrability, like the clays, this often resulted in a serious bending of the knock pole. Bending clearly is a problem as a bent pole gives a higher-than-actual depth.

While doing the knocking field work, it quickly became apparent that depth to refusal varies on a very local scale. Several knocks that were done within .5 m of each other gave soil depths that varied up to .3 m. Thus any conclusions based on soil depths interpolated from the data as is must be carefully reasons.

Despite this intrinsic variability, patterns were visible within our data. The median depths to refusal for east of the stream channel, stream channel, and west of the stream channel were 147, 163.5, and 249.5cm, respectively. The west side trended to have the deeper soils, and the east side trended to have the shallowest soils. The reason for this is unknown. Figure 8 shows a map of the topography of

Watershed 7 overlaid with a heat map of soil depths. The stream channel can be seen in the center of the image as the local altitude minimum.

Mini-Trolls

The wells in Transect 5 and Flag 24 contained groundwater. The Mini-Troll placed into Transect 5 offered evidence of a groundwater diurnal fluctuation. This can be seen in Figure 9, which graphs groundwater levels above depth to refusal over a three-day interval. In the morning, the vegetation increases transpiration rates, taking up more groundwater and lowering the groundwater levels. Moving from afternoon to night, the vegetation decreases transpiration rates and groundwater levels are raised. During the night, little transpiration is occurring and groundwater levels are constant. This trend is also highlighted in Figure 4 from the salt tracer study.

DTS

Due to problems associated with heat and the DTS computer, only 17 hours of DTS data was able to be collected. Our data spans from 5:35 PM on August 15th to 10:45 AM on August 16th. A representative plot of our data is shown in Figure 10. The x-axis is distance downstream, the y-axis is Julian time and the color overlay is temperature.

It is difficult to extract information from the stream as is due to the extremely low flow. The cable was out of the stream for the bulk of the stretch and due to fallen logs was not always capable of being in the stream even when there was surface flow. Much of our previous data was also very subtle - tenths of degree differences in temperature were good indicators of differences for groundwater inflows. But here we have to deal with the overriding air temperatures (>30° C), which skews the scale in such a way as to make it difficult to tease out small differences in stream temperatures. The data needs to be cleaned up so that only in-stream measurement points are plotted.

Despite this, many of the features we noticed during the tracer study can be seen in this plot. Our two calibrating ice baths can be seen at meter marks 0 and 394. Where the stream first manifests from groundwater flows at meter mark 284 the temperatures are noticeably cold. Temperatures downstream rise slowly as there is little canopy cover to shade the stream. Between meter marks 410 and 500 lies the upper reach of the tracer study. As was seen then, the temperatures are roughly homogeneous throughout this stretch as there is little difference in vegetation cover and no massive groundwater inputs (<. 15 l/s). Below that stretch, the culvert can be seen on the data around meter 580 as the slightly cooler area. Flags 1-9 begin to show up at meter 660 as cooler water that begins to warm up as it moves downstream, just as it did for the temperature readings in the tracer study. The stream widens considerably after that point as it joins up with another stream of roughly the same size.

Conclusion

The focus of this Eco-Informatics Summer Institute project was to characterize the effect of subsurface topography on water movement in a headwater catchment, and how the subsurface flows interact with the surface stream water. A variety of field techniques were used to give answers and insight into the project's questions.

The knocking poles gave a clear characterization of the depth to refusal throughout the catchment. They also highlight the two distinct soil layers that are found within Watershed 7. The wells, in combination with the Mini-Trolls, allow for further quantification of the groundwater throughout the year. It will be especially important to record the groundwater movement during high snowmelt periods.

The salt and Resazurin tracer studies provided a clear picture of the inflows and outflows within the 300-meter stream reach. Further analysis can provide information on the residence time of water within the stream. The subsurface inflows were further highlighted within the DTS data. Even though the data was collected over a month apart and the stream had significantly lower flows, similar temperature and surface-subsurface patterns were discovered.

The combination of knocking pole, salt and Resazurin tracers, and DTS methods provide valuable insights to the subsurface character of Watershed 7. This summer's work is only the beginning of research that will lead to the full characterization of the subsurface flows within

Watershed 7.

Figures

Figure 1: Longitudinal Profile Specific Conductivity

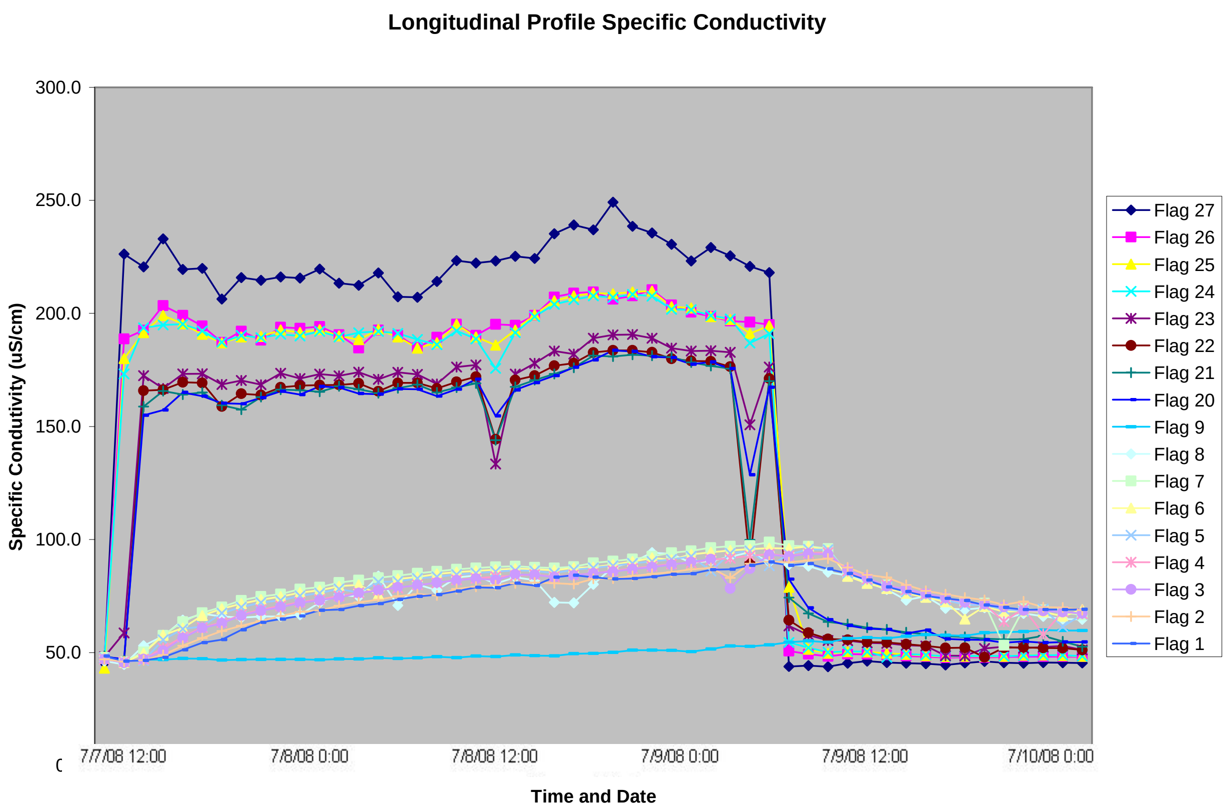


Figure 2: Discharge at Each Flag: Integration and Plateau Values

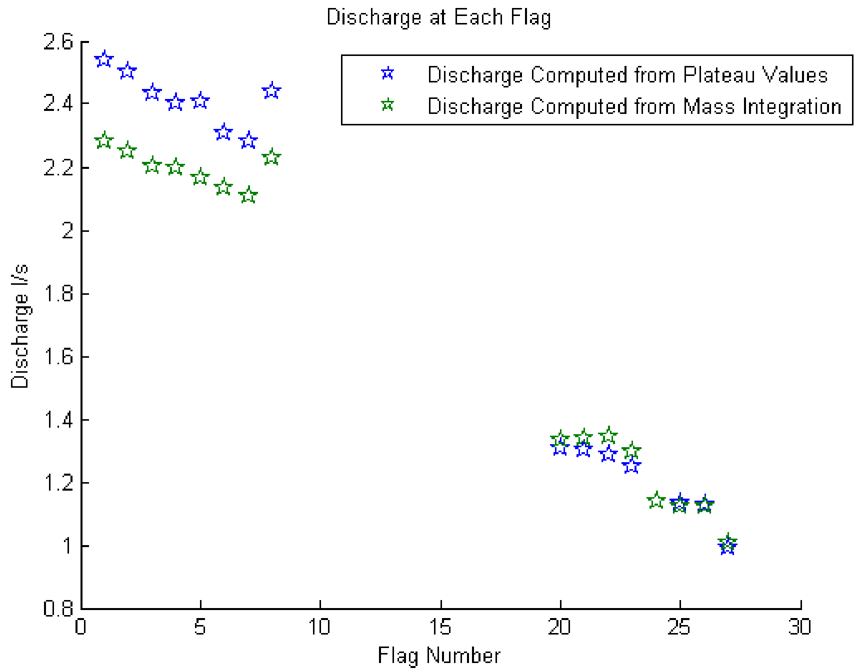


Figure 3: Longitudinal Temperature Profile

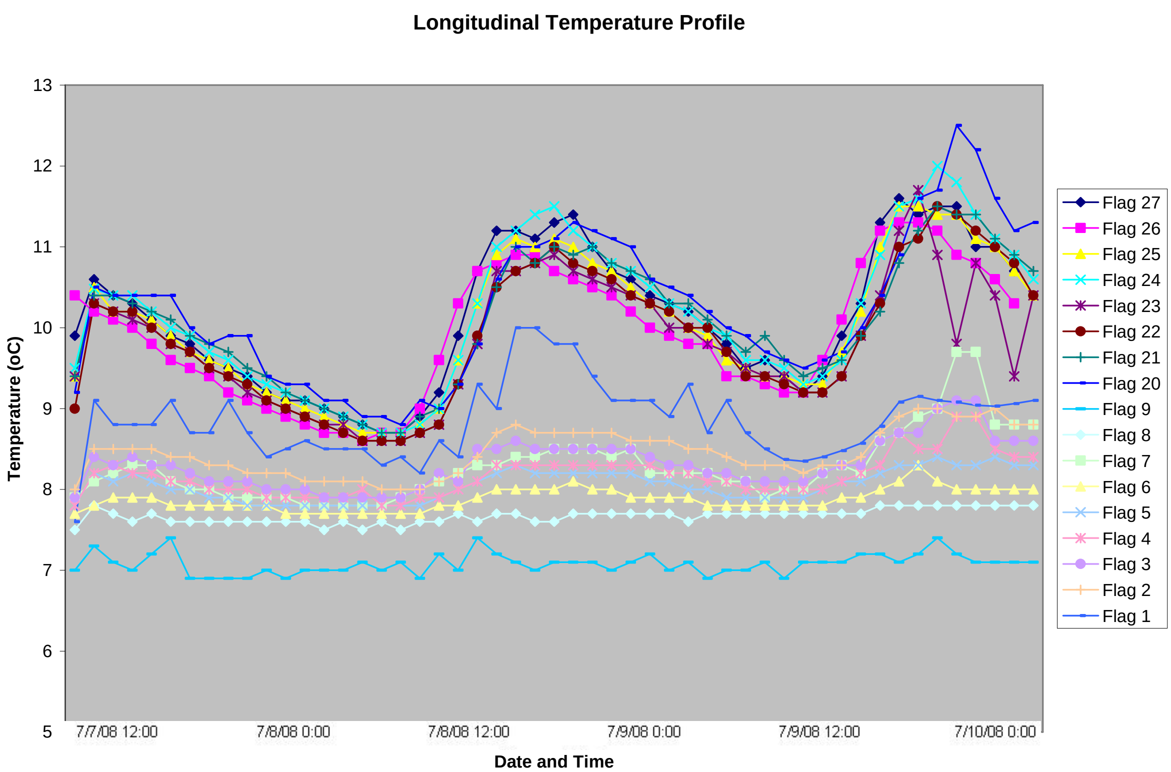


Figure 4: SC and Temperature vs. Space and Time

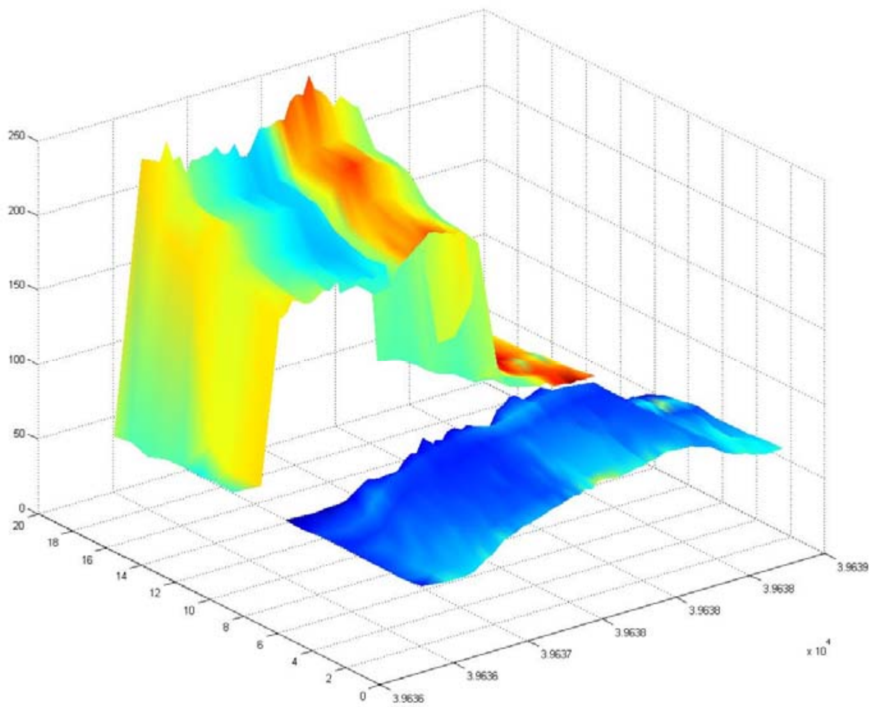


Figure 5: Upper and Lower BTC Raz and Rru Concentration

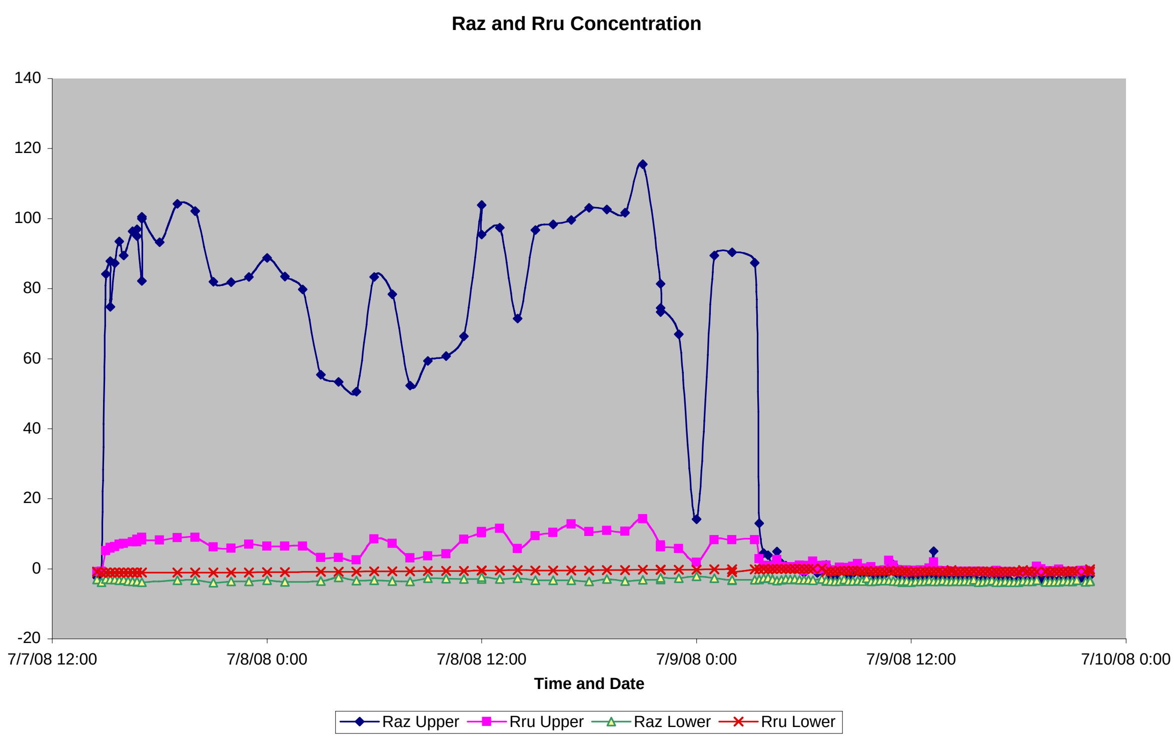


Figure 6: Soil Penetrability Profile of Transect 6

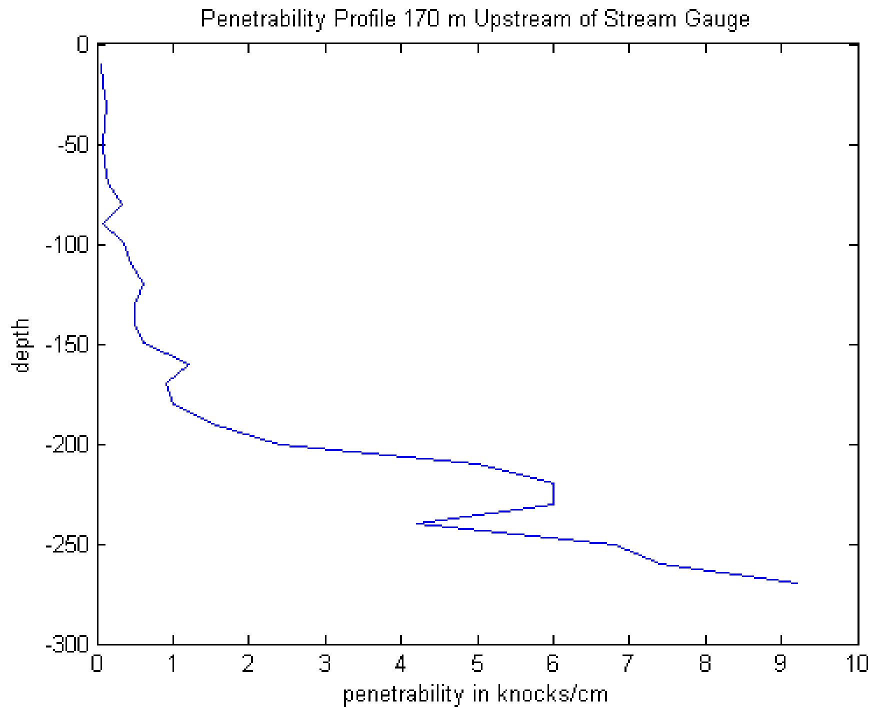


Figure 7: Histogram of depth to refusal and Median resistance from 29 sites vs. depth

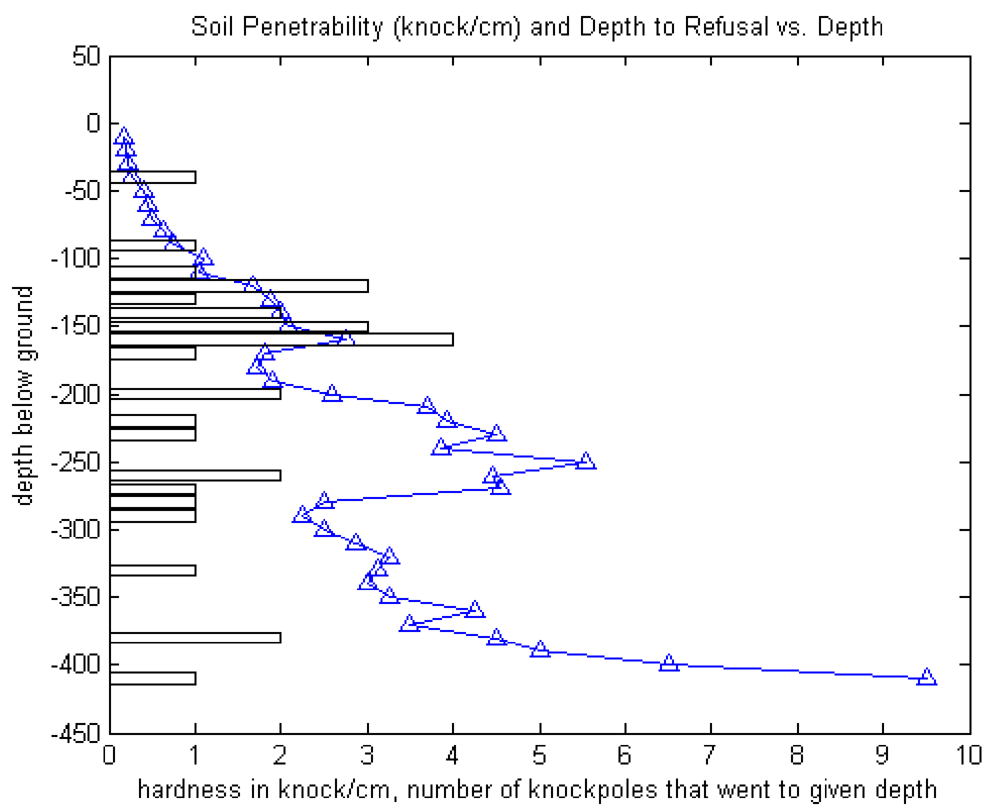


Figure 8: Soil Topography

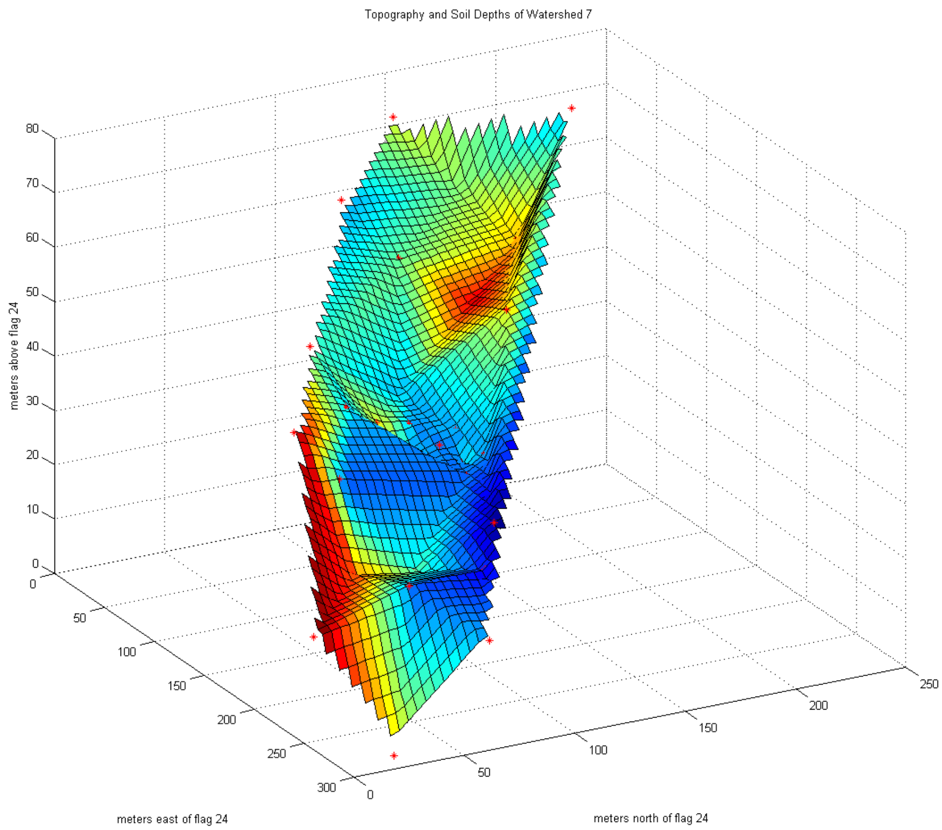


Figure 9: Mini-Troll Groundwater Level Transect 5

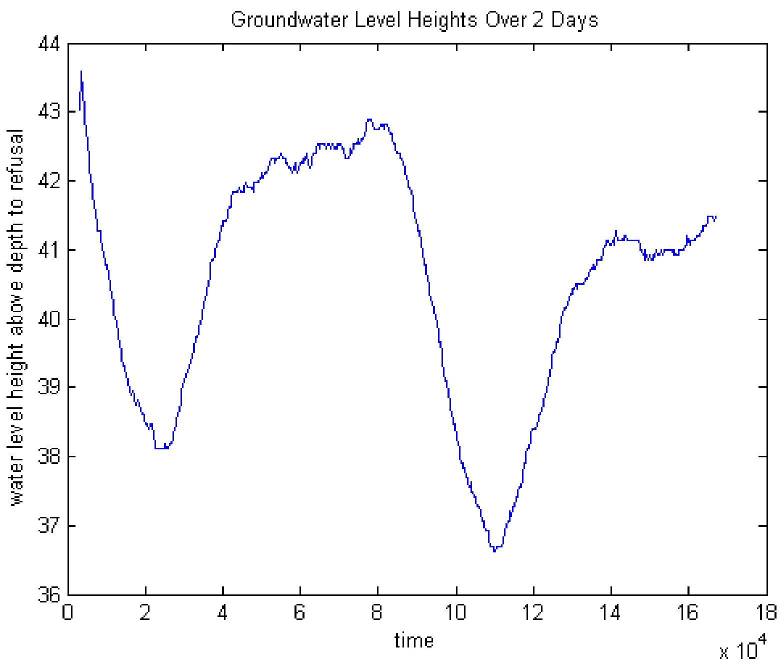
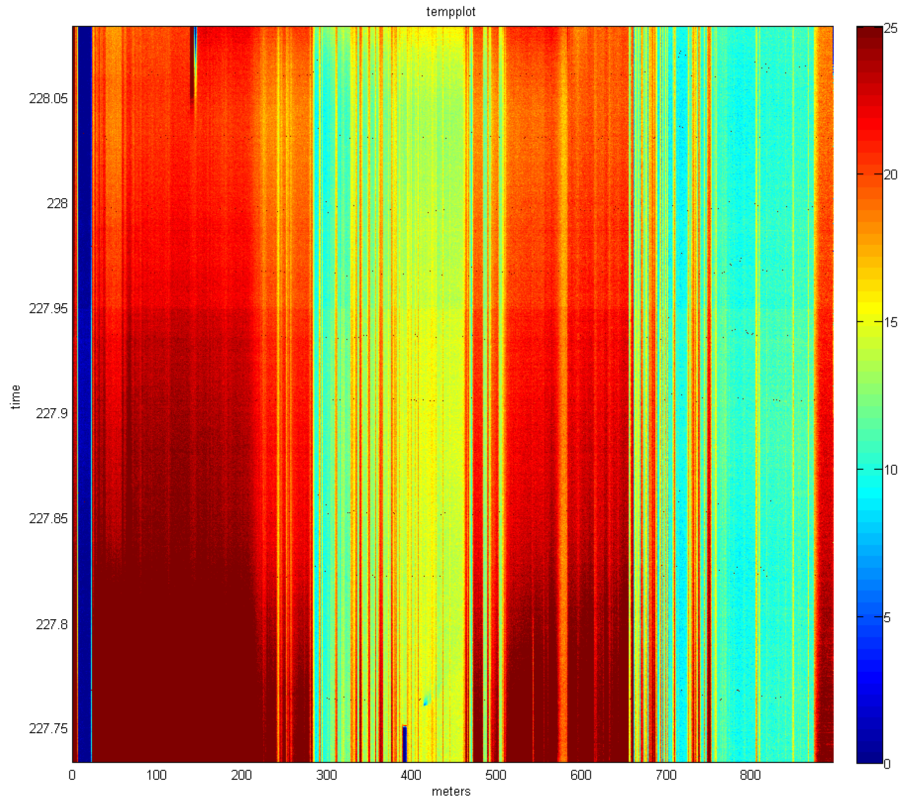


Figure 10: DTS



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