hydrogeophysics research group

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Long-Term Monitoring of Infiltration at a Managed Aquifer Recharge Site Using Electrical Resistivity Probes

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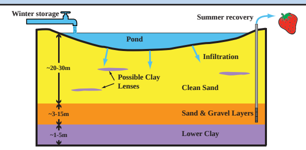
1) Motivation & Introduction

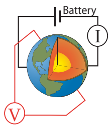
Decreasing Infiltration

An artificial recharge pond has been created in Watsonville, California to augment groundwater resources. Infiltration rate in the pond decreases over time due to clogging (Pidlisecky & Knight, 2010).



Using Electrical Conductivity (EC)

Treat the earth as a simple circuit and use the conductance ($C = I/V$) to calculate the EC. These EC measurements are dependent on: a) saturation; b) water chemistry; c) sediment chemistry (e.g. adding clays); and d) temperature.



Probe Data

Time-lapse EC data have been collected from multiple 2m long probes in the artificial recharge pond. EC measurements are taken every 18 minutes over the four months of the infiltration process.

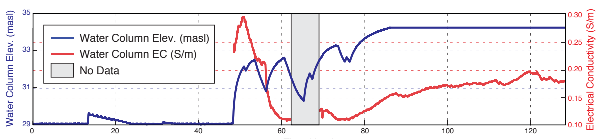
Probe Installation

The EC probes were installed using a direct push sampling rig. A soil boring tool, with an outside diameter of approximately 65% of the probe diameter, was used to obtain continuous core at the installation site. Following the coring, the probes were installed to a depth of 2m in the same hole as the core was obtained. This type of emplacement was desirable as it minimized the potential for voids and, consequently fast paths along the length of the probe.

2) Raw Data

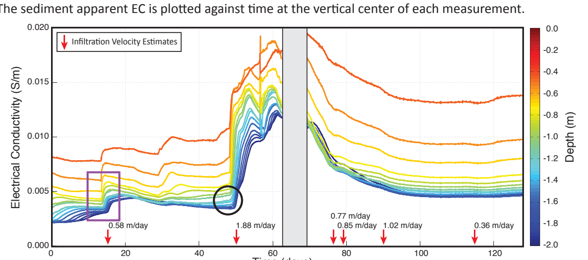
Water Column Parameters

Water column parameters were measured continuously. The water column height was monitored by a pressure transducer in the pond bottom and the water column EC was calculated by averaging two measurements from each probe; one Dipole-Dipole and one Wenner Array.



Sediment Electrical Conductivity

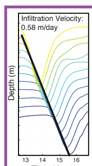
The sediment apparent EC is plotted against time at the vertical center of each measurement.



Infiltration Velocity

Over the length of the experiment, many distinct pulses of water with different ECs enter the sediment (these are highlighted by the arrows in the above plot: ↓). These variations can be treated as tracer experiments from which we can derive estimates of infiltration rates.

The infiltration velocity was found for 6 distinct times by calculating the temporal derivative of the signal and calculating the phase shift between signals as a function of depth. This analysis yields the travel time of a pulse to a given depth, and thus can be used to estimate infiltration rates.

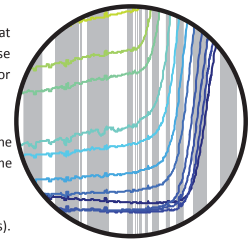


The normalized temporal derivative of the measured data, plotted as a function of depth. The slope of the line is the infiltration rate of the conductive pulse. The process of picking travel times can be performed manually or automatically using cross-correlation.

3) Data Binning & Error Analysis

Data Binning

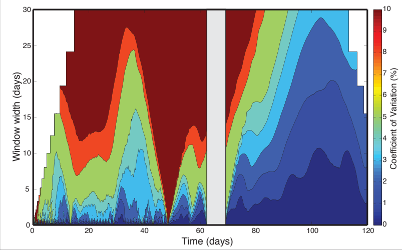
The long-term record consists of repeated measurements at a temporal sampling rate that is greater than the evolution rate of the measured hydrogeologic processes. Thus, we use data binning to a) reduce the number of required inversions, and b) construct an error model for these inversions.



Sediment EC against time showing bin width.

Method

1) Calculate the coefficient of variation (*COV*) the standard deviation (*std*) divided by the mean (μ) at a given time (i), for a certain window width (w). This is done for entire time record (all data at all times), for a window widths ranging from 1hr to 30days.
2) Rank the *COV* at each time and window (w) for all measurement locations.
3) Calculate the mean of top 10% of the sorted *COVs* (i.e. take the worst case scenarios).

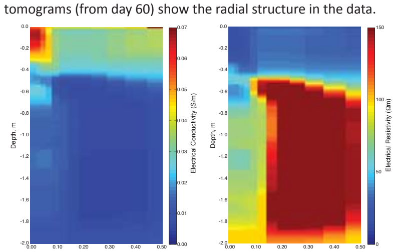


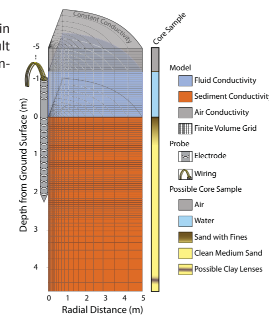
4) Set a variation threshold that is equal to modeling noise (e.g. 2%), and find window widths that correspond to this threshold.
5) Construct a compressed data set where the data representing a bin are the computed using the mean and the standard deviation of the data within that window.
6) The inversion error model now becomes: $std_{inv} = std_{bin} + std_m$ where std_m is the error associated with numerical modeling.

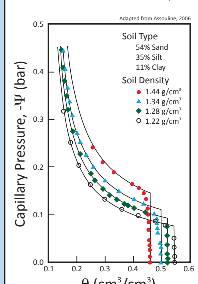
4) Results

Inversion

The time-lapse data are inverted individually using a variant of RESINVM3D written in cylindrical coordinates to approximate the L1-norm (Pidlisecky et al. 2007). The result of the inversion is a tomogram that represents a cylindrical cross-section. These inverted tomograms (from day 60) show the radial structure in the data.







Disturbed Zone

The volume close to the probe is always more conductive than the volume farther away from the probe. We hypothesize that this represents an area of higher saturation due to the relationship between capillary pressure and soil compaction. During probe emplacement, the horizontal stress immediately adjacent to the probe increases, resulting in soil compaction. As demonstrated for a similar soil by Assouline (2006), soil compaction will shift the soil water retention curve such that the moisture content will be higher, for a given matric potential, in the compacted soil. The soil used is similar in porosity and composition to the soil at the infiltration pond.

Radial Averaging

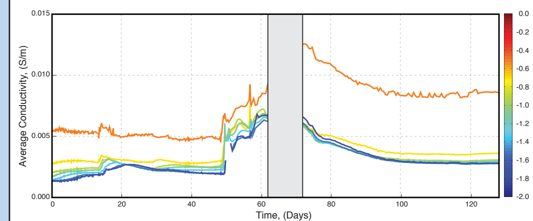
A simple way to analyze and interpret the data is needed for future work, thus a binned 1D average of the tomogram is obtained with depth. The data sensitivity matrix is used to define the maximum radial extent over which to average. Additionally, the disturbed zone is removed by fixing a minimum radial extent. The depth average is then binned into a depth profile to get representative averages.

It should be noted that this would not be possible if the data was simply inverted in one dimension: compressing the results of a 2D inversion is fundamentally different than using a simplistic 1D framework for the inversion.

5) Depth Averages & Rock Physics

Average Conductivity Over Time

The depth profile of conductivity can be plotted against time to yield estimates of conductivity.



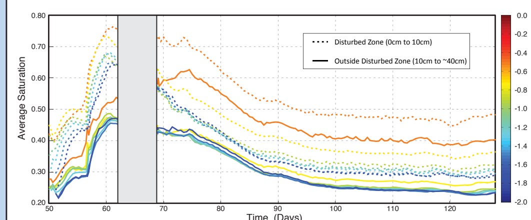
Saturation

The preliminary analysis of these results is to use Archie's law to find saturation values over time. The fluid conductivity is lagged with depth using the infiltration velocities. It is seen that the disturbed zone has a higher saturation than the undisturbed zone.

Archie's law:

$$\sigma_b = \sigma_f \phi^m S_w^n$$

$\phi = 0.38$ $m = 1.3$ $n = 2$



6) Conclusions & Comments

Take home messages:

1) Resistivity probes can be used to obtain infiltration rates when there is a change in fluid EC.

2) High temporal sampling rates facilitate data binning, which improves signal-to-noise as well as provides a method for building a noise model.

3) Using a measurement scheme that allows for inversion of the data allows one to "See" beyond the disturbed zone.

4) Once the disturbed zone is identified its effects can be removed and rock physics transforms can be applied to model outside of the disturbed zone.

5) At our field site, simply application of Archie's law highlights the differences in saturation between the disturbed zone and native material. Furthermore, the trends in saturation with time are consistent with the decay in infiltration rates observed at the site.

Future work:

1) Develop a suite of inversion results to better characterize model variability.

2) Perform lab- and numerical- rock physics modeling to develop a site specific transform between EC and saturation.

7) References & Acknowledgments

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