Advances in Geophysical Tools for Estimating Hydrologic Parameters and Processes

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Motivation

Need to quantify the operation of aquifer parameters controlling flow and transport

- To determine availability of water for removal
- To assess risk & create schemes for contaminant cleanup

[Singha, CSM]
Motivation

The problem...

[Hartman et al., JCH, 2007]

[British Geological Survey, 2004]

[Binley, Lancaster]
Motivation

We have these:
Motivation

Or we might be lucky and have one of these:
LeBlanc et al., 1991, *WRR*, Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 1, Experimental design and observed tracer movement
Advantages of Geophysics

Geophysics offers advantages over conventional sampling to the hydrologist because of:

*High data sampling density*

*Relative lower cost of measurements*

*Minimally invasive*

*Larger measurement volume*

[Binley, Lancaster]
Scale of measurement

Acquisition approaches near this end of the chart provide low resolution information over large spatial extents.

SCALES OF INVESTIGATION

Laboratory or Point

Regional

Local

~10^{-4} to 10^{-1} ~10^{-2} to 10^2 ~10^1 to 10^4...

RELATIVE RESOLUTION

High Moderate Low

Acquisition approaches near this end of the chart provide high resolution information over small spatial extents.

[Rubin and Hubbard, 2005, Hydrogeophysics]
History

Early geophysical studies concentrated on defining lithological boundaries and other subsurface structures.

[Zohdy, 1965, GW, Geoelectrical and seismic refraction investigations near San Jose, California]
Moving Forward with Static Images

- Can distinguish lithologic units in some geologic settings
- Characteristics of GPR reflectors differs with depositional environment

History

• During the 1990s there was a rapid growth in the use of geophysics to provide *quantitative* information about hydrological properties and processes.

• Much of this was driven by the need to gain information of direct value to hydrological models, particularly given the developments of ‘data hungry’ stochastic hydrology tools.


[Binley, Lancaster]
<table>
<thead>
<tr>
<th>Method</th>
<th>Property of Interest</th>
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<tbody>
<tr>
<td>Gravity</td>
<td>Density</td>
</tr>
<tr>
<td>Seismics</td>
<td>Seismic velocity</td>
</tr>
<tr>
<td>Direct-current resistivity</td>
<td>Electrical conductivity</td>
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<tr>
<td>Induced polarization</td>
<td>Chargeability</td>
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<tr>
<td>Electromagnetic induction</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>Ground-penetrating radar</td>
<td>Dielectric permittivity</td>
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</table>
Some Hydrologic Problems Where Geophysics Can Help

• Determining preferential pathways
• Quantifying movement of conductive contaminants
• Monitoring gas transport
• Exploring groundwater-surface water exchange

A few applications...
Imaging preferential pathways: GPR

Surface radar reflectance for a 0.9 x 2.0 m area

Water released to flow down slope from a shallow trench.

Before water release

After addition of 26.5 liters

Water released to flow down slope from a shallow trench.

[Nyquist, Temple]

[Nyquist et al., in prep]
Fractured Rock: ER

4 h injection @ 15 m depth
38 g/L NaCl @ 500 L/h

[Robert et al., 2012, Geophysics, A salt tracer test monitored with surface ERT to detect preferential flow and transport paths in fractured/karstified limestones]

[Nguyen, Liege]
Hydrofacies from GPR & direct-push data

Coupling high-res characterization tools to improve flow and transport simulations at MADE site:
- Full-resolution 3D GPR
- Direct-push K measurements (HRK)

[Dogan, Van Dam, Bohling, Butler, Hyndman, 2011, GRL, Hydrostratigraphic analysis of the MADE site with full-resolution GPR and direct-push hydraulic profiling]
Enhanced gold recovery: ER

- Imaging subsurface injection of 800 gpm using 150 electrodes on surface and within 6 boreholes. Isopleths represent 3, 6, and 12% change in resistivity from background conditions (prior to injection).

*Rucker, Crook, Winterton, McNeill, Baldyga, Noonan, and Fink, in review, NSG*

[Rucker, HGP].
Thermography

Heated water (48°C) was injected for 70 hours at the rate of 87 L/h in a 10.5°C aquifer.

Observed (o) and modeled (-) temperature log

[Hermans et al., 2012, Geophysics, A shallow geothermal experiment in a sandy aquifer monitored using electric resistivity tomography]
How is free-phase carbon gas distributed in peatlands? (GPR)

[Parsekian, Comas, Slater, and Glaser, 2011, JGR, Geophysical evidence for the lateral distribution of free phase gas at the peat basin scale in a large northern peatland]

Sturgeon River Bog, MN

[Slater, Rutgers]
Mineral soil contact

[Slater, Rutgers]
Effective rooting depth: ER

Time-lapse ER for soil moisture dynamics reveals rooting depth differences of forest and grassland.

Data enables improved root parameterization in global climate and landscape hydrology models.

[Jayawickreme, Van Dam, Hyndman, 2008, GRL, Subsurface imaging of vegetation, climate, and root-zone moisture interactions]
Infiltration Pond Study: ER

[Pidlisecky, Cockett, Knight, 2012, VZJ, The development of electrical conductivity probes for studying vadose zone processes: advances in data acquisition and analysis]

[Pidlisecky, Calgary]
In some cases it is difficult to get access to what we want to look at even with conventional methods.
Groundwater-Surface Exchange: FLIR

- Thermographic images collected in Kansas to explore gw-sw exchange

[Loheide and Gorelick, 2005, RSoE, A High-Resolution Evapotranspiration Mapping Algorithm (ETMA) with Hydroecological Applications at Riparian Restoration Sites]
Tracer lingering in hyporheic zone: ER

3. Porewater sampling of frozen core confirms tracer

1. Well breakthrough curves

2. Electrical evidence of tracer along stream flow direction

[Toran, Nyquist, Fang, Ryan, and Rosenberry, 2012, HP, Observing heterogeneity in hyporheic flow with electrical resistivity and subsurface well sampling during a stream tracer test]

[Nyquist, Temple]
Some Questions About Exchange Controls

1. How seasonally and spatially consistent is the size of the hyporheic zone?

2. How are changes controlled by valley-scale morphology and gradient?

[Singha, CSM]
Tracer Injections During Baseflow Recession

[Ward, Fitzgerald, Gooseff, Voltz, Binley, Singha, 2012, WRR, Hydrologic and geomorphic controls on hyporheic exchange during baseflow recession in a headwater mountain stream]
Many, many applications

- Mapping depth to rock, lithologic changes
- Monitoring changes in soil moisture, injection of ionic compounds → quantify clogging of infiltration ponds, fracture patterning, operation of parameters controlling flow and transport
- Imaging carbon gas
- Exploring changes in temperature in the subsurface
- Quantifying hyporheic zone extent
We also spend a lot of time trying to figure out what goes on in a small part of the ground ...
... when lots of folk need to know what is happening at a larger scale.
Hanford 300 Area

Contamination legacy:
- 241 metric tons of copper
- 117 metric tons of fluorine
- 2060 metric tons of nitrate
- 33 and 59 metric tons of uranium

What is the spatial and temporal variability in exchange between uranium contaminated groundwater and river water?

[Slater et al., 2010, WRR, Use of electrical imaging and distributed temperature sensing methods to characterize surface water–groundwater exchange regulating uranium transport at the Hanford 300 Area]

[Slater, Rutgers]
Pebble to boulder size gravels and interbedded sands

[Higher K ~ 100 m/day]

Highly heterogeneous, granule to cobble size gravels interbedded with fine sand and silt.

[Lower K – 0.2 m/day,]

Improvements in hydrogeological framework required along corridor of surface-water/groundwater exchange

aquifer/river interaction is increasingly considered to exert a dominant control AND IMPART COMPLEXITY on transport at the site

[Slater, Rutgers]
GW-SW exchange: DTS, ER, IP

- Spatial geometry of Hanford and Ringold Units
- Identification of focused exchange: temperature anomalies at low stage; correlation between stage and temperature occur where Hanford unit thickest; exchange muted/absent where Hanford is thinnest

DTS data

locally-incised paleochannels?

[Slater, Rutgers]
Deep H-R contact, temperature anomalies and stage-temperature correlation coincide with known uranium seeps (but there appear to be others).

Shallow H-R contact, no temperature anomalies, and no known uranium seeps.

[Slater, Rutgers]
Even bigger: airborne geophysics

Airborne resistivity: ~ 100 km / hour

Ground-based resistivity
~ 1 km /day

Lake talik
permafrost

[Minsley, USGS]
Informing groundwater models in Nebraska

As of 2007 NE is the top irrigator in the US surpassing CA and TX irrigators.

Cost of irrigating from wells in NE in 2008: $43/ac

TX: $105/ac, CA: $114/ac

[2008 Farm and Ranch Irrigation Survey, USDA, National Agricultural Statistics Service]

2004 passage of LB962, meant to strike a balance between water supply and water demand in the state's river basins, put a cap on new irrigation development across much of the state.

[Minsley, USGS]
Permafrost Mapping

[Minsley et al. 2012, GRL, Airborne Electromagnetic Imaging of Discontinuous Permafrost]
Geophysical monitoring of seawater intrusion


[Minsley, USGS]
How do we bring all these data together to form one consistent, improved model of the system?

[Binley, Lancaster]
A Problem

• Geophysical methods image rock properties not necessarily related to hydraulics

• Need appropriate relation to use geophysical information quantitatively

• How do we relate geophysical parameters to hydrologic properties?
State of The Practice

Hydrogeophysical studies often use a lab-scale or field-local petrophysical relation to estimate the parameter of interest in the field.

[Singha, CSM]
A Large Inverse Problem...

Minimize data model

where $\alpha$ is a trade off parameter between model misfit and data misfit that determines the relative contribution of each misfit type

Problem: may have 1000s of data and 10s of 1000s of parameters

[Sinha, CSM]
Impact of Variable Resolution

[Day-Lewis, Singha and Binley, 2005, JGR, The application of petrophysical models to radar and electrical resistivity tomograms: resolution dependent limitations]
A big challenge

Geophysical data that is (sometimes) linked to our hydrological property of interest.

We may have multiple datasets measuring different geophysical properties at different support volumes and at different resolution and accuracy.

But we will also have other hydrological, hydrogeological and geochemical data together with a starting conceptual model of our site.
Alternate Parameterizations: GPR w/ 1600 data

Alternate Parameterizations: GPR w/ 100 data

[Pidlisecky, Singha, Day-Lewis, 2011 GJI]
Advances in Inversion Techniques

Ray Based Methods

Input data:
- First arrival times
- First cycle amplitudes

Waveform Methods

Input data:
- Significant parts of wavefields
- Inversion based on Maxwell’s Eq.

First arrival times
First cycle amplitudes

Observed data

Time [ns]

Depth [m]

inexpensive, coarse structures
detailed sub-wavelength structures, more expensive

[van der Kruk, Julich]
Advances in Inversion Techniques

Ray-based Inversion Results

Velocity - Full-waveform Inversion

Conductivity - First Cycle Amp. Inversion

Conductivity - Full-waveform Inversion

[van der Kruk, Julich]
Advances in Inversion Techniques

Full-Waveform Inversion Results

Velocity - Full-waveform Inversion

Conductivity - Full-waveform Inversion

[van der Kruk, Julich]
Advances in Inversion Techniques

Crosshole GPR full-waveform inversion: Characterization of waveguides that act as preferential flow paths within aquifer systems


[van der Kruk, Julich]
To assure structural resemblance of the inverse models, the objective function is formulated as

$$\phi = \phi_d + \phi_m + \phi_{CG}$$

where

$$\phi_{CG} = \sum_{q=1}^{Q} \sum_{r>q}^{R} \lambda_{qr} \| t_{qr}(m_q, m_r) \|$$

and

$$t_{qr}(x, y, z) = \frac{\nabla m_q(x, y, z) \times \nabla m_r(x, y, z)}{|m_q(x, y, z)| \cdot |m_r(x, y, z)|}$$

[e.g., Gallardo and Meju, JGR 2004; Tryggvason and Linde, GRL 2006; Linde et al., WRR 2006; Linde et al., Geophysics 2008; Doetsch et al., Geophysics 2010; Doetsch et al., GRL 2010]

[Linde, Lausanne]
Application to geophysical and hydrological data

Methods

- crosshole GPR traveltime tomography
- hydraulic tomography (HT) = multilevel crosshole slugtests
  - hydraulic conductivity $K = \text{diffusivity} \times \text{specific storage}$
  - peak arrival times and attenuation data
- Tracer mean arrival time inversion
  - temporal moments of breakthrough curves

[Linde, Lausanne]
Conclusions

• Many applications of geophysical tools to hydrologic problems

• Some issues
  • Not measuring hydrologic parameters directly
  • Resolution varies
  • Rock physics are uncertain

• Working on how to scale up—fundamental to watershed-scale work, support of large-scale observatories

• How do we capitalize on time-lapse changes?