

# Integrated Hydrogeophysical Inversion

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## 1 Overview of the Field

Managing groundwater resources and remediating contaminated groundwater require mathematical models to predict groundwater fluxes, quantify groundwater volumes and chemical transport. The models require definition of the physical system geometry, boundary conditions and specification of the values of parameters such as hydraulic conductivity. All of these parameters always are known with significant uncertainty because data are limited in space and time and often also have uncertainty associated with them. Hydrologic targets of primary focus for the meeting will be the rates and pathways of water flow, chemical transport and degree of water storage in the subsurface. These processes are dynamic and occur at a wide range of spatial scales. Also, as with most subsurface hydrologic processes, spatial heterogeneity of the hydraulic properties must be accounted for in quantitative analysis. Typically, the challenge for quantifying these processes lies in a severe lack of temporal and spatial to describe complex systems. Geophysical methods based on physical principles including electrical, electromagnetic, seismic, nuclear magnetic resonance, and gravity have been used to assess hydrologic parameters and processes. Geophysical methods are useful because properties such as electrical conductivity can be correlated to hydrogeologic parameters such as moisture content and hydraulic conductivity. Typically, the challenge for geophysical interpretation lies in the underconstrained nature of the data sets, leading to uncertain interpretations. Coupled with limitations to the petrophysical models that relate the measured properties to the properties of interest to hydrologists, this often results in geophysical data that are only qualitatively useful for hydrologic analyses.

During the 1980s and 1990s, major advances in the field of hydrogeologic parameter estimation and hydrogeological inverse analysis were made by workers such as Mary Hill ([9]), Richard Cooley [1], [2] and Jesus Carrera ([3], [4], [5]). However, the field has not experienced major progress in recent years, mainly due to the limited spatial data density and limited frequency of measurements. At the same time, improvements in geophysical data acquisition technology and computational capacity have lead to a new generation of geophysical instrumentation that produce much more higher quality data than in the past. Relevant examples are commercial ground-penetration radar units and multichannel electrical resistivity recording systems. Similarly, near surface geophysical inverse methods have seen major advancements in recent years through the work of researchers such as Doug Oldenberg ([10], [11]), M.H. Loke ([13], [14]), Bill Daily, Andy Binley and Doug LaBrecque ([6]). More recently there has been interest in the development of algorithms that permit the joint-inversion of multiple geophysical data; examples targeted in hydrogeophysics include those of Gallardo, Meju ([8]), Linde ([12]) and others.

Geophysical data also suffer from data sparsity and regularization methods are commonly used to stabilize the inversions at the cost of smoothing the resulting images. It has long been recognized that geophysical data

could provide spatially dense data that has the potential to reduce problems associated with hydrogeologic data sparsity, and, in recent years, attempts have been made to constrain hydrological inversion with geophysical inverse results. However, recent work by Fred Day-Lewis, Kamini Singha, Andrew Binley and others ([7]) have shown that the most common approaches suffer from variations in geophysical image resolution through space and time. This body of work points to joint inversion of hydrogeological and geophysical data. The partial differential equations that describe hydrogeological processes provide a constraint on the feasible states of the petrophysical parameters that influence geophysical data and the geophysical data along with petrophysical relationships provide a dense set of data that can constrain feasible hydrogeological parameters and state.

Finally, the use of hydrogeophysical inversion is in its infancy. Some of the definitions and terminology is yet to be standardized. It still is not clear how hydrogeophysical fits into overall project work flow. These and other issues were the focus of the 5 day workshop

## 2 Hypothetical Case Studies

Since every individual case study has unique features, the workshop participants designed hypothetical case studies. The objective was to look at aspects of hydrogeophysical inversion in a holistic manner, from project design to processing and interpretation procedures. Each of three hypothetical case studies had unique aspects and it was anticipated that general principles would arise that were common to the design of the three hypothetical case studies. Following the discussion surrounding the hypothetical case approaches, definitions, an overall framework and a set of priority research directions were proposed. The three hypothetical case studies were motivated by real challenges or geological situations that various individuals attending the workshop were being faced with. The three studies were an unconfined aquifer storage and recovery study, a confined aquifer storage and recovery study and a watershed scale characterization study.

Unconfined Aquifer Storage and Recovery (Group: Ty Ferre, Tim Johnson, Ian Knowles, Sander Huisman, Larry Bentley)

There is growing recognition of the need to store water for public use in underground storage facilities. In the Southwestern United States, in particular, the use of unconfined aquifers for ASR facilities offers several advantages. First, water can be applied directly at the ground surface and allowed to infiltrate, greatly reducing operating costs compared to injection. Second, infiltration through a thick (100-200 ft) unsaturated zone provides initial filtration and opportunities for aerobic degradation. Third, mixing with groundwater of marginal quality can extend the volume of potable water for public use.

Given the importance of the water supply for public health and safety, above ground ASR facilities are seen as a potential target for terrorist activities. Specifically, the large scale and often relatively remote location of ASR facilities can leave them susceptible to intentional contamination. Therefore, we recognize that it is important to have procedures in place to respond to such an event. The primary challenge in responding to contamination is predicting the time required for the contaminated water to reach a recovery well and the expected concentrations of the contaminant in the recovered water. We seek proposals to develop practical methods to predict these quantities. In this initial stage, the methods will be designed for a specific but unnamed ASR facility. But, the method should be transferable to other unconfined ASR facilities.

### *Site description*

The study site is located in the center of an alluvial valley in the basin and range province of the southwestern United States. Sediments are interbedded lenses with textures ranging from fine sand to gravel. Buried stream channels are common in the region, but their presence or locations are unknown for the site. Caliche layers may form or may have formed, leading to very low permeability layers in the upper 10 m. Geological, hydrologic, and petrophysical properties are available from one continuous core that was collected when drilling a borehole in the center of the infiltration basin. The background depth to the water table is approximately 33 m. The infiltration pond dimensions are approximately 460 m by 180 m. Very accurate records of inflow volume, water level in the pond, and atmospheric conditions are available over the past two years of operation. The facility is flooded for three weeks then allowed to drain for one week. Once drained, the surface is scraped to remove any biological clogging layers. In addition, the facility is allowed to drain for two months for annual maintenance, including more intensive surface scraping. The water table elevation is monitored in the pumped well (located 450 m from the nearest point of the basin) and in a single, metal cased

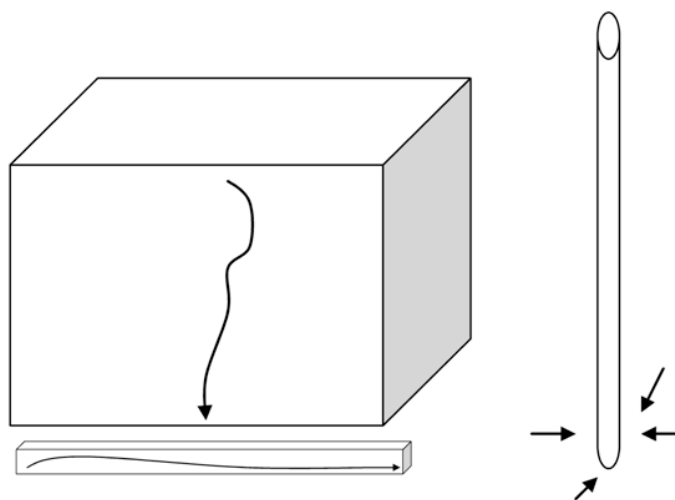


Figure 1: Conceptual model for transport and capture of aquifer storage water.

2? diameter monitoring well located in the center of the basin. Only natural tracers may be used and no radioactive or otherwise hazardous methods may be employed. The maximum height of the water table mound at the center of the basin is approximately 5 meters. Annual potential evapotranspiration is approximately 1.0 m. Precipitation is approximately 0.3 m; 60

The budget is large after all, we are Homeland Security.

#### *Proposed solution*

The key prediction of interest is the concentration in the recovery well as a function of time. This response can be used to infer the maximum expected concentration, which may determine whether any remedial action is necessary. The response will also define the time of first arrival, which determines the urgency of a response. Finally, the response will define the residence time of the contaminant in the system. We will provide probabilistic break through curves that could be used for risk-based decision-making.

We conceptualize the problem as having three related parts: percolation and solute transport through the unsaturated zone; predominantly lateral flow and solute transport through the aquifer; and mixing of infiltrated water and groundwater during capture by the well. The conceptual model is shown in Figure 1:

It is currently not feasible to condition a fully heterogeneous three-dimensional saturated-unsaturated flow model at this scale. Therefore, we propose a staged investigation to define the simplest acceptable conceptual model.

Our first level analysis is based on the expected dilution of the infiltrated water by mixing during capture by the well. We propose to conduct a major anion end member mixing analysis to determine the time-varying dilution of the input water in the extraction well. To minimize the impact of reactions in the vadose zone, we will use samples collected immediately below the water table in the monitoring well located within the pond. This analysis requires that the major anion composition of the ambient groundwater is different than that of the water pumped from the recovery well.

Our analysis of the unsaturated flow and transport begins with a classification of the important processes controlling flow and transport. Our baseline assumption is that the medium can be represented as homogeneous with effective hydraulic properties. We will consider the impacts of heterogeneity through ensemble parameter estimation. We will then investigate the importance of two structural complications: dipping layers and discrete channels. We hypothesize that the plan view recharge patterns from each of these classes will have important differences. The general expected patterns for homogeneous, dipping, and discrete feature classes are shown schematically in Figure 2 A, B and C, respectively with the outline of the recharge basin overlain as a dashed line.

Initially, we will collect ERT data to assess the importance of dipping layers and buried channels. We will use two orthogonal lines that cross the pond to identify dipping layers. We will use ERT lines around the boundary to identify flow beyond the boundaries of the pond due to channelized flow. ERT data would

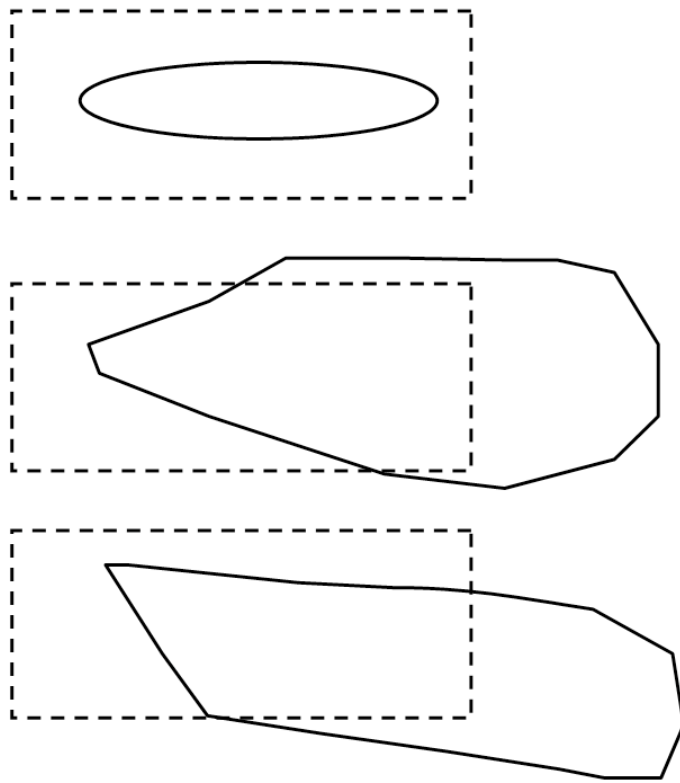


Figure 2: Recharge patterns for A. Homogeneous unsaturated zone, B. Unsaturated zone with a dipping aquitard layer and C. Fracture causing preferential flow path. The dashed line indicates the infiltration basin.

be collected at the end of the extended period of drainage and during the first ponding event following this period. We expect that dipping layers will result in dry regions below the updip end of a layer and wetter regions below the downdip end. This should result in relatively continuous changes in electrical conductivity along one or both of the lines placed within the basin. Time varying, localized changes in electrical conductivity along one of the boundary lines would indicate channelized flow. If we find that dipping layers are likely present we would use higher resolution time lapse ERT, GPR, or refraction seismics depending upon the conditions. Similarly, if channels are present, we would design a similar survey to better define their geometry.

Once we have classified the likely dominant flow processes we will generate multiple realizations of hydrologic and petrophysical model parameter values that honor the unsaturated flow conceptualization and the available geophysical data and the parameter value ranges seen in the core. For each realization, we will predict the geophysical responses corresponding with the geophysical observations. We will use DREAM to define the likelihood of each parameter set based on their consistency with the geophysical data, defined as a weighted misfit of the predicted and measured geophysical responses weighted by the inverse of the measurement error for each measurement type.

Once we have our parameter sets defined we will predict the pattern of recharge. We will then formulate a probability-weighted recharge pattern based on the ensemble of realizations. We will use this predicted recharge patterns to choose locations for four additional monitoring wells. We will conduct temperature tracer injection tests in each pair of the new monitoring wells to estimate the saturated zone transport parameters between each pair of monitoring wells. In addition, we will install a fiber optic distributed temperature sensing (DTS) cable along one of the wells and electrodes along the other wells.

Once the wells are installed, we will conduct a hot-water-infiltration experiment. We will monitor the advance of the wetting front using simple resistance measurements made with the electrodes. Simultaneously, we will use the DTS measurements to infer the transport parameters above the wetting front. We will use the wetting front measurements to further refine the vadose zone model likelihood assessment. Then we will update our recharge estimations based on the updated vadose zone models.

We will conduct slug tests in each of the monitoring wells to get local hydraulic conductivity estimates. We will conduct a pumping test in the recovery well, monitoring head in the monitoring wells as well as time-lapse gravity and SP data. We will interpret these measurements simultaneously in the coupled hydro-geophysical framework described above to infer the larger scale transmissivity, storativity, and specific yield values. Specifically, we will assume all transport and hydraulic properties are isotropic in the saturated zone with the exception of hydraulic conductivity. We will generate realizations that include a range of anisotropy ratios (in two horizontal directions) and we will test which of these ratios best predicts the SP and gravity data. The gravity data will help to constrain estimates of the specific yield and to test for anisotropy.

Our final step is to use the predicted recharge in space and time from each of the accepted unsaturated zone models together with observations in all of the monitoring wells during a ponding event and the inferred T, S, Sy, and anisotropy ratio values from pumping and slug tests to condition an inverse model of the saturated zone. This model will use Knowles' inverse approach to provide better estimates of the spatial distributions of T and S. This is repeated for each conditioned parameter set and associated recharge distribution.

We will produce independent estimates of the transport parameters in the unsaturated and saturated zones. We will also produce an ensemble of associated petrophysical and hydraulic parameters in the unsaturated zone and hydraulic parameters in the saturated zone. We will use each member of the ensemble of parameter sets to predict a breakthrough curve in the recovery well. These breakthrough curves, with associated likelihoods, will be used to produce a probability weighted breakthrough curve. These responses can be used to assess the risk posed by a contamination event in an infiltration pond.

#### Confined aquifer storage and recovery

(Group: Partha Roth, Mike Cardiff, Burke Minsley, Jonathan Ajo-Franklin, Andreas Kemna)

#### *Problem Description*

Aquifer storage and recovery has been proposed as a means for storing excess treated freshwater in Kuwait for subsequent use as an emergency water supply, as well as meeting variable seasonal demands. Injection of freshwater ( 100ppm) will occur at a rate of 1000 cubic meters/day into a confined saline aquifer ( 6000ppm). Initial pilot tests will use one injection/recovery well, but full production would involve a grid of up to 30 wells over an area of nearly 100km<sup>2</sup>. Success of this project relies on the ability to recover the maximum possible volume of freshwater with salinity less than 1500ppm. Some of the relevant scientific questions to



Figure 3: Aquifer storage and recovery experiment.

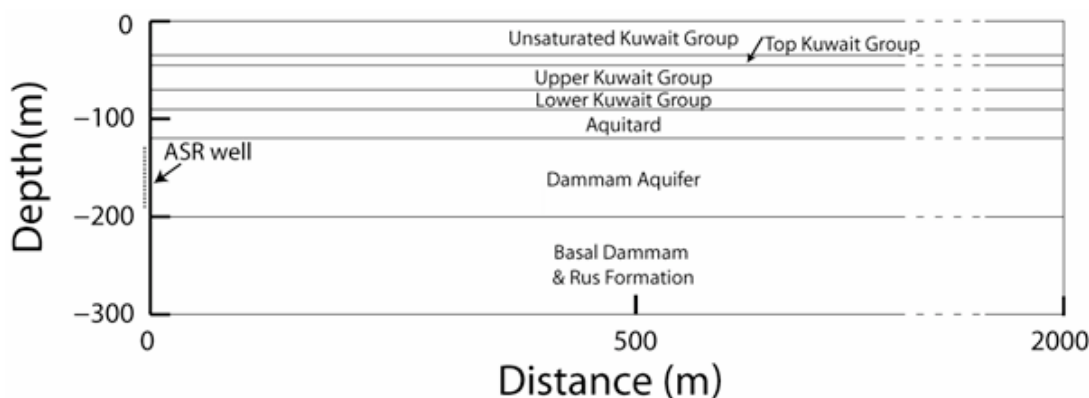


Figure 4: Site Geology.

be answered include:

1. What measurements can be made to help guide the optimal placement of injection & recovery wells?
2. How can the advancement of the freshwater plume effectively be monitored over time?
3. Can loss of freshwater through high permeability zones or fractures in the confining layer be detected?
4. What is the maximum storage period that can be achieved?

#### *Background hydrogeology*

The relevant hydrogeologic units for the Tertiary sedimentary sequence in Kuwait are shown below.

Because its confining nature, as well as clogging problems with pumping in the Kuwait Group, the ASR experiment is planned in the Dammam Formation. Due to its karstic nature, the transmissivity in the Dammam Formation is variable, but shows a general decreasing trend towards the northeast. The silicified topmost part of the Dammam Formation, in conjunction with the basal shaley/clayey layers of the Kuwait Group, form an aquitard that separates the Dammam Aquifer from the overlying Kuwait Group Aquifer, though hydraulic continuity is maintained possibly through fractures that are present in the top part of the Dammam Formation. The anhydritic Rus Formation and the basal shales of the Lower Members of the Dammam Formation act as an aquitard, separating the underlying Umm Er-Radhuma Aquifer from the

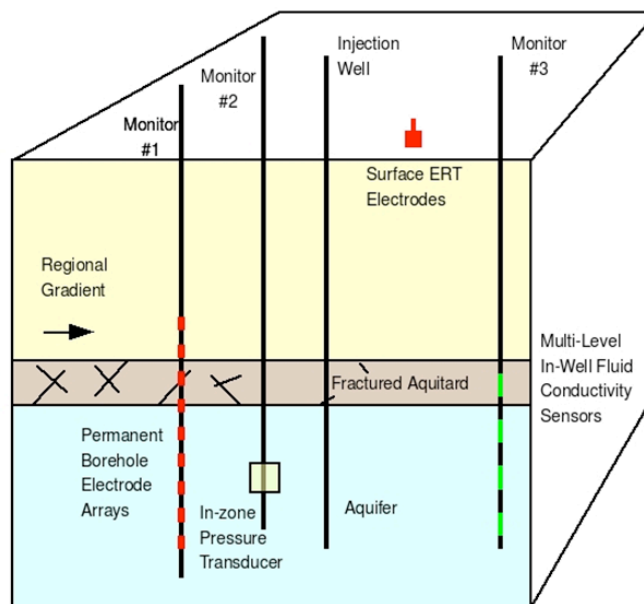


Figure 5: ASR Geometry.

Dammam Aquifer.

Some primary considerations for controlling the fate of the freshwater plume include: - secondary porosity due to fracture flow/karst within the Dammam aquifer - fractures or breaks in the aquitard separating the Dammam/Kuwait Group formations - buoyancy of the freshwater plume due to the salinity contrast *Research deliverables*

The timeframe of the proposed research project is three years. Within this period, the pilot injection and recovery experiment will take place in conjunction with the proposed hydrogeophysical research. The end result of this study should be a report that provides guidance for the full-scale ASR project (100km<sup>2</sup> scale), which addresses the following topics: - what is the optimal design for placement/operation of injection and recovery wells that will allow for a maximum storage period and ability to recover water less than 1500ppm? - a proposed methodology for monitoring losses of injected freshwater - developing a future strategy for long-term hydrogeophysical monitoring of aquifer storage and recovery projects

#### *Program outline*

Phase I Baseline geophysical surveys; Joint structural inversion of baseline geophysical data Phase II Site infrastructure development; Petrophysical core, construct hydrogeologic model, optimal survey design for time-lapse surveys Phase III Acquisition of optimal baseline geophysical survey Phase IV Acquire repeat surveys during injection/storage/recovery phases; Hydrogeophysical inversion, utilize forward modeling and inversion to implement design of full-scale ASR project

Phase I: Baseline hydrogeophysical characterization - ERT/SIP - CSEM - 2x 2D seismic lines to obtain structural information - Pump test at injection well Phase Ib: Joint structural inversion of baseline geophysical data - Joint inversion/interpretation of geophysical datasets for baseline characterization, primarily for structural information

Phase II: Site infrastructure development - Drill monitoring wells (x3) - Acquisition of core from monitoring wells - Logging – ?traditional? (neutron, density, gamma, conductivity, deviation) – fracture-oriented (acoustic televiewer, dipole sonic) – NMR to obtain permeability – Installation of borehole assembly – Casing with ERT electrodes – Multi-level packers with conductivity sensors – In-aquifer pressure transducers

Phase IIb: Petrophysical core measurements & analysis - Permeability - Relationships between bulk conductivity & salinity - SIP of core

Phase IIc: Construct site hydrogeologic model for pilot experiment - Incorporate all information to date

into hydrogeologic model - Simulate pilot injection experiment

Phase II: Optimal survey design for timelapse geophysical experiments - Geophysical method resolution/uncertainty study based on hydrogeologic simulation - Select spatial sampling regime - Frequencies for CSEM

Phase III: Acquisition of pre-injection geophysical surveys (using optimal design) followed by initiation of injection

Phase IV: Acquire repeat surveys during injection/storage/recovery phases - Surveys at end of injection (month 3), end of storage phase (month 10), end of recovery phase (month 15)

Phase IVb: Hydrogeophysical inversion - Demonstrate ability to track the progress of freshwater injection and possible losses through confining unit or preferential flowpaths

Phase V: Utilize forward modeling & inversion to implement design of full-scale ASR project

Watershed (Group: Andrew Binley, Klaus Holliger, Niklas Linde, Jasper Vrugt, Kamini Singha, Jim Yeh, Adam Pidlisecky)

#### *The problem*

Nitrate contamination has long been recognized as a major water quality issue in agricultural watersheds. Efforts to control non-point source pollution require the identification of source areas, the spatial and temporal variability of properties controlling flow and transport, and an understanding of the distributed (or isolated) nature of discharge into streams. Improved water quality monitoring and modeling programs, including development of technologies that are capable of collecting long time-course data, would be useful for scientists studying nitrate transport processes and for development of best management practices in local watersheds. At the hillslope scale, surface and bedrock topography, geologic stratification, antecedent moisture and soil layering all control water flow.

In soils, remnant structure of the original bedrock can lead to preferential flow patterns, leading to spatial concentrations of water and solutes that are not well described by Darcy's approach to uniform flow. In areas with steep slopes, thin soils, and matrix hydraulic conductivities above the maximum rainfall intensity, water moves vertically to depth (as matrix or preferential flow), perches at the soil-bedrock or an impeding layer at depth, and then moves laterally along the lower portion of the profile. Growing evidence suggests that the most common mechanism for delivery of water from slopes into valley bottom and riparian areas is lateral subsurface flow in hillslopes, triggered by a perched water table. This storm flow is particularly important because this near-stream area can change rapidly during rainfall-runoff events, and can serve as the focal point for non-point source loading of nitrogen to streams. Additionally, the collection of point measurements of nitrate concentration or groundwater fluxes to streams is time consuming and often unrepresentative of the process at larger scales, and large-scale, integrated measurements give no estimates of variability. Groundwater contributions to surface water bodies have been found to be spatially heterogeneous, and have been found to vary over several orders of magnitude within short distances and as a function of discharge.

Identifying heterogeneous streambed characteristics that control groundwater discharge and hyporheic exchange is critical to improving quantification of water quality in downgradient rivers and estuaries. Besides heterogeneity, temporal scales are also important: seasonal variations in nitrate concentrations in streams are often attributed to seasonal loading or land use. Unfortunately, few methods are available to collect data at a spatial or temporal scale appropriate for simulating groundwater contributions to stream solute transport along a river continuum through these seasonal changes. Capturing hillslope-scale heterogeneity and the dynamics of precipitation thresholds leading to subsurface stormwater generation may be difficult in field settings where limited probe data are generally available.

For quantifying transport risk, estimating saturation dynamics through time is necessary. However, the investigation of hillslope networks is technology limited, and most methods for accurately identifying and measuring subsurface networks in the field are destructive. To understand dynamics at the hillslope or catchment scale, more exhaustive measurements are required than can be measured with point-scale timedomain reflectometry or heat dissipation probes. Noninvasive geophysical techniques may provide spatially exhaustive maps about spatial and temporal heterogeneity not otherwise attainable. However, which methods to use, and what data to collect over these large spatial scales, where small-scale feature may control flow, is an important research question. We will evaluate the worth of geophysical data for forecasting and predicting flow and transport in watershed systems given a filtering framework outlined below. *The solution* We propose a framework for simultaneous inversion of hydrologic and geophysical data for determining changes in soil moisture, a controlling variable in watershed-scale nitrate transport. The idea behind this framework is to



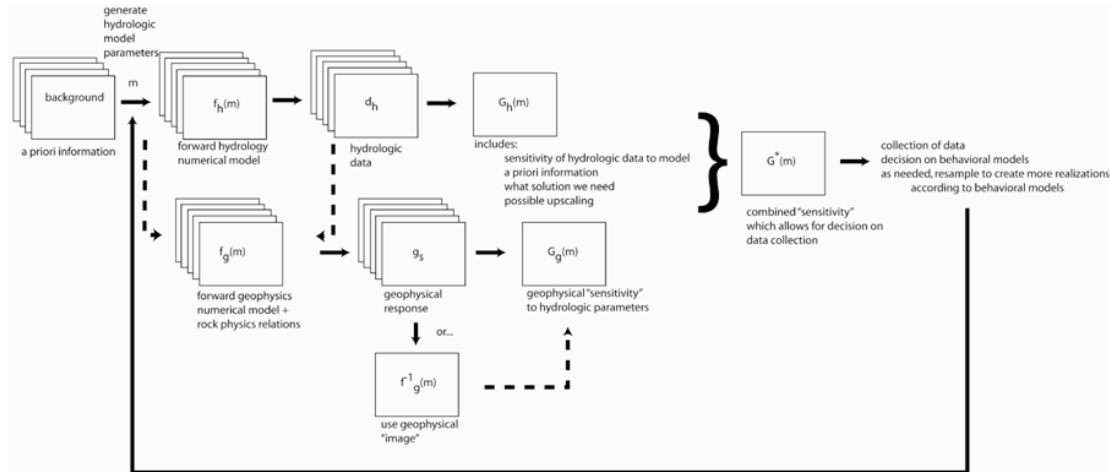


Figure 6: Flow chart for simultaneous inversion of hydrologic and geophysical data.

couple multiple numerical forward models?for flow, transport, and geophysics?to find locations where new data would best help constrain estimates of the state space or model parameters of interest. This could be done either deterministically or stochastically. This framework is outlined in Figure 3, and intentionally kept somewhat general.

Numerous research questions exist, including how to 1) build  $G^*$ , the combined ?sensitivity? metric that determines where to best sample new hydrologic and geophysical data, 2) determine appropriate rock physics relations, 3) quantify model structural error, 4) deal with the issue that geophysical images are not data.

### 3 Outcome of the Meeting

Hydrogeophysics is, by its nature, integrative; but, it is critical that the application of geophysics is driven by hydrologic questions and any hydrogeophysical application remains linked to the hydrologic aims. We refer to the process of integrating geophysical and other data into a hydrologic assessment as hydrogeophysical inversion. Currently, there is much disagreement regarding the differences among approaches to hydrogeophysical inversion, often stemming from a lack of common terminology. To clarify discussions among hydrologists and geophysicists, we propose the following definitions:

*Independent hydrogeophysical inversion:* this is the simplest and often the most practical approach, wherein hydrologic interpretations are based on hydrogeologic properties and states that are inferred from independent interpretations of geophysical surveys. In many cases, the investigation may be considered to be hydrogeophysical because it has a shallow, hydrogeophysical target. But, the geophysical inversion is identical to that used in classical geophysics.

*Joint hydrogeophysical inversion:* in this approach, additional information that describes the relationships among different measurement types is used to interpret instrument responses simultaneously. As with independent geophysical inversion, this includes joint inversion of multiple geophysical methods in a manner that is identical to classical geophysical methods with subsequent use of the results for hydrologic investigations. However, joint hydrogeophysical inversion can also include simultaneous or sequential interpretation of hydrologic and geophysical data.

*Coupled hydrogeophysical inversion:* In some cases, especially when monitoring transient hydrologic processes, a hydrologic model can be used to relate geophysical and hydrologic measurements in time and space. Coupled hydrogeophysical inversion approaches make direct use of a hydrologic process model as part of the geophysical inversion. Often, this can eliminate the need to conduct classical geophysical inversions (e.g. construction of images of geophysical property distributions). The fundamental difference between joint and coupled hydrogeophysical inversion is that the joint inversion combines multiple measurement types

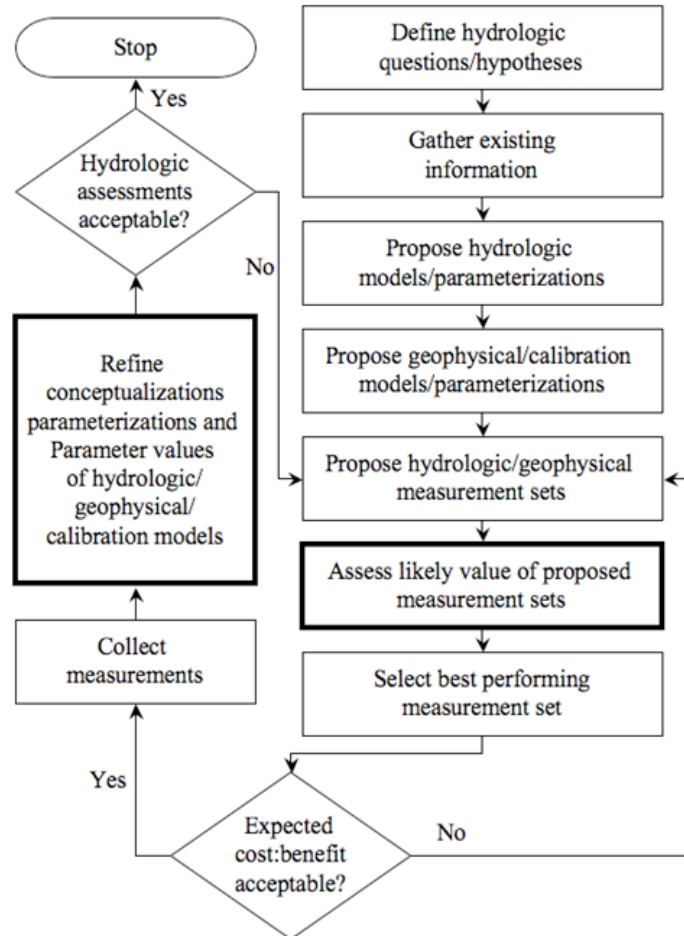


Figure 7: Hydrogeophysical work flow.

through correlative relationships of the inferred properties (i.e. empirical, physical, or statistical relationships between the hydraulic properties of interest and the properties that are measured or inferred with geophysical instruments); coupled inversion integrates hydrologic process models in the geophysical inversion.

One of the key conclusions drawn through our discussions is that geophysics can only be used effectively in hydrologic studies if it is integrated in entire hydrologic analysis. To explain how geophysics can be integrated more completely, we show an idealized workflow for a hydrologic analysis that includes geophysics (Figure 7). The workflow is based on a multi-model approach to hydrologic analysis. These models are intended to capture the range of conceptualizations, parameterizations, and parameter values that represent our physical understanding of the hydrologic system and the responses of geophysical instruments. The physics captured by these models includes hydrologic processes (e.g. flow and transport), geophysical processes (e.g. electromagnetic or seismic responses to controlled or natural sources), and relationships among rock and fluid properties and measurable geophysical properties. Within this workflow, the purpose of hydrogeophysics is to provide information that allows for discrimination among these proposed models. At the conclusion of the hydrologic investigation, the ensemble of models that are plausible, based on all observations, can be used to make probabilistic predictions to support scientific analysis and/or decision-making.

There are two key steps that should include a hydrogeophysical analysis, which are highlighted on the flowchart. First, efficient hydrogeophysical characterization and monitoring requires quantitative assessment of the likely contribution of proposed measurement sets to discriminate among conceptual models and to refine the numerical or analytical model calibrations. This assessment is most effective if it is performed in

the context of the specific hydrologic questions of interest and of the proposed numerical or analytical hydrologic, geophysical, and calibration models that will be used for the analysis. Specifically, when considering geophysical measurements for a hydrologic study, the geophysicist should determine whether the geophysical instrument is likely to respond to the expected hydrologic responses, whether the responses are likely to be large compared to the sources of uncertainty in interpreting the geophysical measurements, and whether the data, if collected, would reduce the bias and/or uncertainty of the hydrologic assessments of interest. Ideally, this should be considered in a quantitative framework that allows for the comparison of multiple proposed measurement sets. Second, once the geophysical data are collected, they should be used together with all other data to reject conceptual models that are not consistent with all of the data and to refine the remaining numerical or analytical representations of these conceptual models to be most consistent with all of the observations. This step requires a choice of hydrogeophysical inversion approach. Neither independent, nor joint, nor coupled hydrogeophysical inversion is universally preferred. Rather, the choice of the most appropriate approach depends on the complexity of the problem, the availability of supporting relationships, and whether the process of interest is steady-state or transient.

Through our discussion during the workshop, we identified three primary areas in which substantial progress can be made in the next five years:

1. Hydrologists are currently working to develop effective methods to generate ensembles of models that capture the range of possible hydrologic conceptualizations and parameterizations. Hydrogeophysicists can adopt some of these approaches to incorporate different conceptualizations of the responses of geophysical instruments to property distributions (geophysical forward models) in their interpretations. This is particularly important for relationships between physical and geophysical properties, which are often very poorly understood and rarely characterized at the field scale;
2. In the past, several hydrologists have had negative experiences with geophysics, in part because of the inappropriate application of geophysical methods to hydrologic problems. Hydrogeophysics would benefit greatly if more objective methods were available to guide in the design of measurement sets that consider the spatial sensitivity patterns of geophysical measurement methods, the spatial resolution of imaging methods, the magnitude and characteristics of the measurement uncertainties (noise), the effects of uncertainty in field-scale rock physics relationships, and the complementarity of different measurements types;
3. The likely value of geophysical (or other) measurements must be defined on the basis of the likely improvement that they will provide for specific hydrologic questions. We need to develop quantitative approaches to compare proposed measurement sets to consistently identify high-value geophysical measurement sets that add to existing information and improve specific hydrologic analyses.

We expect that some progress will be made through the judicious use of synthetic studies. In particular, these synthetic studies should be designed to demonstrate the limitations of proposed measurement methods or analysis approaches with the aim of moving the methods to the field. We propose to establish a central portal for the sharing of these synthetic models to allow for inter-comparison of measurements and analyses. Fundamental advances will require that synthetic studies move to field trials.

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