The state of the science and vision of the future: Report from the Hydrogeophysics Workshop

Society of Exploration Geophysicists
The international society of applied geophysics

American Geophysical Union

In July 2012, 72 hydrogeophysicists from around the world gathered at the Hydrogeophysics Workshop in Boise, Idaho, USA. This was the first workshop to be jointly sponsored by the Society of Exploration Geophysicists (SEG) and the American Geophysical Union (AGU), and brought together members from both societies, primarily from the Near-Surface Geophysics Section of SEG and the Near-Surface Focus Group and Hydrology Section of AGU. The intent of the workshop was to address current hydrogeophysical approaches for determining, predicting, and studying hydrologic properties and processes in both the saturated and unsaturated zones, at scales ranging from centimeters to watersheds.

The workshop was organized around three general sessions: (1) Characterizing Near-Surface Structure and Properties, (2) Thinking About Scaling Up: Geophysical Methods at the Watershed Scale, and (3) Advances in Time-Lapse Monitoring. In addition there was one "homework session" titled The Tomography Bake-Off, where all participants worked with crosshole ground-penetrating radar (GPR) and seismic data from the Boise Hydrogeophysical Research Site that had been provided earlier in the year. To promote discussion, all submitted papers were presented as posters, with a three-minute oral presentation as an introduction. After viewing of posters, all sessions reconvened for a panel-led discussion. The amount of time for discussion, around the posters and with the panel, gave us an opportunity to reflect on the changes in the field since the first SEG Hydrogeophysics Workshop in Vancouver in 2006, and to contemplate the future of this rapidly growing area of research, that bridges hydrology and near-surface geophysics.

Instrumentation and data acquisition

Many of the advances in hydrogeophysics are closely tied to the availability of instrumentation capable of making the desired field measurements at the appropriate levels of spatial and temporal resolution. Most of the essential physics that is the basis for (hydro)geophysical methods (electrical/electromagnetic, GPR, seismic, gravity, magnetics, well logging) has not changed much in recent decades. There have been some important advances in methods of deployment, with significant growth over the past five years in the use of multichannel acquisition systems for both electrical resistivity tomography (ERT) and seismic; surveys involving thousands of sensors and hundreds of thousands of individual measurements are now possible. There is also increasing use of wireless communication which has allowed greater logistical flexibility when dealing with roads, streams, and challenging terrain, and also provides for higher productivity and reduced downtime associated with cable repairs.

One method which has seen rapid development and adoption in the last five years is nuclear magnetic resonance (NMR), for both surface and borehole applications. Based on the work presented at the workshop, it appears that NMR has now achieved mainstream status and that data volumes continue to grow, especially with regard to time-lapse. NMR directly measures water content, can discriminate between free and bound water, and measures a relaxation time constant that can be related to hydraulic conductivity, so it is a new and powerful hydrogeophysical tool. Surface-based NMR was in its infancy in the 1990s but has made great progress in the last decade, enabling soundings to ~100-m depth. Decreases in post-pulse "dead time" and the use of remote reference coils have increased the signal-to-noise ratio. Borehole logging systems, a well-established technology in oil and gas, have recently been developed for small-diameter monitoring wells and direct-push borings used in groundwater investigations. NMR was shown in some presented case studies as being adopted as the sole "ground truth" measurement for airborne electromagnetic water-resource surveys. Interest in NMR was high at the Boise meeting.

Recent advances in instrument design now make it possible to acquire high-precision gravity data (<20 μgal). The advent of field-portable absolute gravimeters, provides the ability to conduct high-precision microgravity surveys in a fraction of the time normally required using relative meters only. Although expensive to deploy, there is the potential for considerable time savings when microgravity survey operations are augmented with absolute gravity data obtained using these field-portable instruments.

Looking forward, an important issue for data acquisition is obtaining the needed spatial and temporal extent along with the needed resolution. The spatiotemporal scales of interest challenge acquisition and processing; for example, survey times for one round of data acquisition with large ERT arrays can now exceed the desired repeat time for temporal sampling. As sensor-array sizes increase, autonomous systems can improve acquisition efficiency, especially for time-lapse applications. The use of remotely piloted or autonomous vehicles, particularly unmanned aircraft systems (UAS) would offer a quantum leap in geophysical surveying, with the potential for including sensors for altimetry, imaging, spectroscopy, gravity, magnetics, and electromagnetics.

Data analysis and inversion

Different geophysical data sets are now being routinely integrated by a joint inversion, a reparameterization of the forward problem, and/or structural or cross constraints in the spatial or temporal regularization. When appropriate, in an increasing number of cases the forward problem is based on a hydrological model using appropriate petrophysical relationships, which results in a coupled hydrogeophysical data integration. Faster and improved modeling tools have become available that better describe all details present in experimental data. Current inversion algorithms are increasingly based on these improved modeling tools, such that the information content present in the recorded signal is optimally used and the number of approximations reduced. One example is the recent improvement in full-waveform inversion approaches. At the last Hydrogeophysics Workshop (2006), we saw one of the first inversions of experimental GPR data using a full-waveform inversion method. At this meeting, the crosshole GPR data of the Tomography Bake-Off session was best inverted by a full-waveform inversion approach.

Recent advancements in software and hardware have increased the speed of processing and inversion of large data sets using cluster- or supercomputers. However, the necessary parallelization of the software remains a challenge. Improvements for inversion are possible by reparameterization or the use of a-priori information. Although not clearly a barrier at this point, nonlinearity, especially in full waveform inversion, is likely to play a limiting role as inversions attempt to extract larger numbers of parameters (improved spatial or temporal resolution) from field data. Nonlinear inversion schemes, even approximate ones, may ease this limitation by increasing parameter accuracy and decreasing the "noise" from low eigenvalues (whether explicitly evaluated or not).

Addressing and quantifying uncertainty

It was generally agreed by the workshop participants that the assessment of uncertainty remains a critical challenge in all forms of hydrogeophysics research. Uncertainty estimates regarding geophysical and hydrological model parameters are critical for the assessment of prediction uncertainty for the corresponding hydrological system, which in turn is essential for sound decision making and the development of effective management strategies. Further, uncertainty quantification brings us to a better understanding of the value of geophysical measurements in hydrological investigations, and it allows us to target where and/or how additional data should be collected.

A number of key challenges exist regarding the quantification of uncertainty for problems in hydrogeophysics research. One of these is that traditional linearized uncertainty estimates, based upon the last iteration of a deterministic inversion procedure, are known to underestimate model parameter uncertainty for many problems, and thus often lead to unrealistic, overly optimistic ranges of predictions. Furthermore, linearized schemes can bias the spatial pattern of uncertainty affecting, both quantitatively and qualitatively, uncertainty estimates. Bayesian Markov-chain-Monte-Carlo inversion methods, in theory, allow this limitation to be overcome through a more exhaustive investigation of the model space. However, in practice, they are plagued by the "curse of dimensionality" and thus become, in their standard form, computationally infeasible for spatially distributed geophysical and/or hydrological inverse problems with thousands, if not millions, of unknowns. Advances in available computational resources have partially helped to address this, though more promising solutions to the latter issue involve the use of parameter reduction strategies coupled with informed prior information. Another solution may be the use of joint deterministic-stochastic inversion methods, whereby results from one or a series of deterministic inversions are used for a subsequent stochastic exploration of the model space.

A final challenge is the communication of information about uncertainty to the end-users of a geophysical or hydrogeologic model. Visualizing a single large three-dimensional model can be complicated enough, but conveying details about variable parameter uncertainty at every location throughout a model can be extremely daunting. Stochastic estimates of uncertainty are often derived from many thousands of model results, which must be aggregated in a way that is both meaningful and visually intuitive. As a scientific community, we need to continue to stress the importance of producing model estimates that are directly tied to estimates of uncertainty—without this we run the risk of misleading our collaborators (and ourselves) by not representing the true range of possibilities suggested by our data.

Estimating hydrogeological properties

The ability to determine hydrogeologic properties and hydrological state variables from measurable geophysical attributes remains an important area of research, and is an essential part of using geophysical methods for hydrologic applications. Key research questions at present involve the issue of scale: how to scale up hydrogeological-geophysical parameter relationships established in laboratory studies at the sample/core scale to (1) the various spatial resolution scales of geophysical methods and (2) the different spatial scales at which effective parameters are needed in groundwater models? One specific challenge discussed at the workshop was the need to improve the hydrogeological characterization capability of airborne methods; for example, how can we overcome the fact that airborne EM cannot distinguish between clay and high-salinity groundwater?

There has been notable progress over the past five years in some areas discussed at the workshop. The use of the new full-waveform inversion schemes for GPR data now provide images that can capture small-scale (down to sub-decimeter) structural heterogeneity in terms of hydrogeologically relevant parameters. With spectral induced polarization (SIP) and NMR, measurement methods have been established that allow the estimation of hydraulic conductivity at the sample/core scale within one order of magnitude. Modern direct-push technologies are now increasingly being used in near-surface hydrogeological studies, providing dense spatially sampled information on hydrogeological properties that can be used for the development of site-specific hydrogeological-geophysical parameter relationships and hydrogeological model calibration.

Future directions for research in the estimation of hydrogeological properties include the use of full-waveform inversion schemes for the inversion of GPR/seismic data to infer structural heterogeneity beyond the scale of interest of effective hydrogeological parameters and by this improve the characterization of the latter; the inclusion of anisotropy (typically present in hydraulic properties at the effective scale of groundwater models) in geophysical modeling and inversion algorithms; the joint inversion of multiple geophysical data sets in conjunction with established geophysical-hydrogeological parameter relationships to reduce inherent ambiguities in the quantification of hydrogeological parameters; the use of SIP and NMR methods to provide one-order-of-magnitude estimates of hydraulic conductivity in field implementations involving 1D, 2D, and 3D data inversion. Some of the impediments to progress are the lack of models and (still) limited computational capabilities to compute effective geophysical properties, and the interdependencies between different properties, on the basis of pore-scale parameterizations. There is also a lack of commercially available hardware and software to exploit the more recently demonstrated potential of selected methods for the characterization of hydrogeological properties (e.g., NMR, SIP, full-waveform GPR).

Model-data fusion

Hydrogeophysical model-data fusion involves the use of geophysical measurements both for conceptualizing (e.g., zonation, new process understanding) as well as parameterizing hydrological models. The use of hydrogeophysical measurements to conceptualize models is now firmly established in the science community. The applications of airborne EM surveys and NMR measurements were highlighted at the workshop as representing important recent advances for improving the conceptual models for the structure of aquifer systems. Though improving the conceptual understanding of hydrologic processes is less common, this is an emerging area that is likely to grow in importance.

Model parameterization using hydrogeophysical measurements either relies on direct relationships between measured geophysical attributes and hydrological model parameters, or time-lapse geophysical measurements of changes in model states are used to inversely estimate hydrological model parameters. In the last five years, considerable progress has been made on the second problem where time-lapse geophysical data are used to calibrate hydrological models using a new inversion approach now widely referred to as coupled inversion. In the approach, the geophysical data are used to directly estimate hydrologic properties without the need for an implicit geophysical inversion. One of the key advantages of coupled inversion is that hydrologic processes provide an implicit constraint on probable distributions of geophysical properties in the subsurface, effectively regularizing the problem by limiting the size of the feasible parameter space.

Coupled inversion has been shown to work well for the estimation of effective hydrological model parameters of relatively homogeneous systems that are well understood in terms of hydrological processes. However, it has become evident that unresolved processes will bias any attempt to parameterize models with the coupled inversion. In addition, it remains a challenge to use coupled inversion for heterogeneous systems because of computational challenges, the required information content of the time-lapse geophysical data to estimate spatially variable hydrological model parameters, and the nonstationnarity of petrophysical relationships. Finally, model-data fusion has strongly focused on the field scale, particularly in unsaturated and hillslope hydrology.

With the increase of computational power, it will become more feasible to consider spatially variable model parameters in the coupled inversion framework. It will also be necessary to consider strategies where conceptualization and parameterization are combined in a single coupled inversion in order to reduce potential errors because of a wrong model conceptualization. Nevertheless, it will also be important to come up with alternative model-data fusion approaches to use process information from hydrological models in the interpretation of (time-lapse) geophysical measurements that are less rigid in the underlying assumption than the coupled inversion approach.

Field observatories

A recurring discussion at any gathering of hydrogeophysicists is the need for field observatories, where researchers can go to test new methods of data acquisition and analysis in a setting where they can build on, and benefit from, previous work at the site. These observatories are also critical to the development, calibration and validation of models of hydrologic processes. The more that a site is used, the more valuable it becomes, as every new measurement adds to the understanding of the subsurface properties and processes, which is key information in the assessment of new methods. In addition, with a variety of acquired forms of data, the field observatories provide outstanding opportunities to study new approaches to data integration.

In our discussion at the workshop, we quickly moved from talking about a need for more field observatories to a need to know about existing field observatories. Following the meeting, we compiled a list of field observatories. These observatories can be described under four broad categories.

One popular use of field sites is for testing of new methods for subsurface hydrologic characterization. The European Union has the H+ network which provides well-characterized sites for testing new logging systems and tools, running tracer tests, developing new field procedures, etc. We are unaware of anything similar to this in the United States. There were a number of field observatories, referred to as the WATERs Networks, developed for hydrologic characterization with three-year funding from the U.S. National Science Foundation (NSF); but funding for these sites no longer exists.

Interest in field methods for ecological monitoring, particularly related to climate change, continues to grow in the United States and Europe. In the United States, NSF has supported (since 1980) the Long Term Ecological Research Sites (LTER) *http://www.lternet.edu/* and now has 26 of these sites. Europe has several similar infrastructures attempting to comprehensively study compartments of the terrestrial environment, including the TERENO sites in Germany and future Mediterranean sites within the context of TERENO-MED. More recently, NSF has funded new ecological observatories under the NEON program *www.neoninc.org*, which is a program to compile ecological data for the entire country. Given the growing use of geophysics in rivers and streams to image substream sediments and monitor processes, there was particular interest among some at the workshop in STREON, stream observatories related to this program.

The third broad category of sites includes the Critical Zone Observatories (CZO), which exist in the United States *http://www.criticalzone.org/* and in Europe *http://www.soiltrec.eu/index.html*. As defined on the NSF Web site, the Critical Zone (CZ) "is the environment that extends from the top of the tree canopy to the bottom of our drinking water aquifers; where terrestrial life flourishes and feeds most of humanity. The heart of the CZ is where soils are formed, degrade and provide their essential eco-services." NSF currently funds six CZOs and is expected to fund another eight.

The fourth category includes the large-scale observatories that involve studies of deep Earth processes, the example in the United States being EarthScope, aimed at understanding the lithosphere. While the near-surface geophysics and hydrogeophysics community have not traditionally been involved with these types of observatories, near-surface characterization could play an important role, and might find that some of the methods could be used to address near-surface characterization problems.

Applications and motivation for research

Hydrogeophysical methods can be used for a wide range of applications. Examples presented at the workshop included the development of three-dimensional frameworks for groundwater models; estimation of water content and hydraulic conductivity; detection and/or monitoring of subsurface contamination, infiltration, flow in fractures; mapping of saltwater intrusion, leakage from irrigation canals, and the distribution of permafrost; quantifying groundwater/surface water interactions. In some cases these represented novel applications of established technologies, but in many cases new applications were driven by advancements in technology and/or data analysis.

The most notable change in terms of applications over the past five years is the rapid growth of interest in watershed-scale investigations. There was general consensus that hydrogeophysics can make significant contributions to the conceptualization and parameterization of watershed-scale hydrological models. In some studies described at the workshop, airborne methods are being used for assessing watershed-scale aquifer geometry and water quality, with the information then combined with other aquifer characterization methods applied at a smaller scale. An emerging focus of current research is thus the challenge of moving between various scales of measurements. It is important, for example, to develop an understanding of how small-scale measurements on the order of meters or tens-of-meters can be extrapolated to a larger scale of interest, such as a watershed or catchment. Similarly, there is interest in determining how to integrate small-scale measurements made at fine spatial or temporal scales with separate data sets collected at coarser resolution. An example of this would be making dc resistivity measurements at a field site, and then using that information to design or to interpret an airborne EM survey of a watershed.

A look to the future

A number of exciting topics on the cutting edge of basic hydrology research are likely to become the focus of hydrogeophysical research and applications in the near future. There is a demand for watershed-scale science and hydrogeophysical observations are a clear avenue to obtain data at increasingly larger spatial scales and over increasingly finer time scales. We see hydrogeophysics as providing a valuable link between microscale and macroscale processes across a range of hydrogeologic disciplines including biology and chemistry. New methods for managing water resources such as water injection/extraction and aquifer storage and recovery may be supplemented by hydrogeophysical monitoring. We see key opportunities for geophysical observations to integrate hydrologic and ecosystem studies, as well as related plant biology investigations. There are opportunities to develop strong, interdisciplinary links between the geosphere, hydrosphere, biosphere and atmosphere with geophysical support. In the near future, we see opportunities to focus hydrogeophysical research related to impacts of hydrofracking and other natural resource development issues on drinking water supplies. There is often a "deep" component (related to the >1 km wells) to energy resource development questions, however there are impacts in water quality and quantity in relatively shallow aquifers that would have relevance to readily available hydrogeophysical investigation methods.

As we discussed the future of hydrogeophysics, we all agreed that critical to the continued success and advancement of our field was a need to better engage and communicate with the rest of the hydrogeological community. As geophysical data increase the potential for understanding hydrologic processes in greater detail, there is a need for continual refinement of hydrologic models and development of new geophysical measurement strategies in line with hydrogeological objectives. As a result, establishing close relationships between hydrologists and geophysicists, or training young scientists to simultaneously understand the hydrologic and geophysical issues in detail, is critical for continued progress in efforts to incorporate geophysical data into hydrologic investigations. We also noted the tremendous benefits of collaboration at an international level in order to have access to a diversity of ideas and talents.

Several high-level needs, related to groundwater management, that were mentioned repeatedly during the meeting highlighted the need for close collaboration, not only with hydrologists but also with the managers and those responsible for decision-making. These needs include evaluating total water supply, both quantity and quality including brackish and saline water assessment; improving the predictive accuracy of groundwater models used as decision making tools; simulating nature at a more realistic level in order to have greater confidence in the predictive results for water management activities; and meeting water supply needs for increasing energy and mineral extraction, agriculture and municipal supply. All of these needs require the use of innovative mixtures of geophysics and hydrology. And they all require a teamwork approach, from the start to finish of any project, where the team is not just scientists from different disciplines or institutions but includes managers and decision makers. By obtaining broad input at the start of the project good decisions can be made, for example, about the scale at which information is required. It is important to keep the ultimate data needs at the forefront even at the initial stages of designing a hydrogeophysical investigation, and this is best done by involving all key people on the team.

When we consider the use of hydrogeophysics as an integral part of groundwater management or the remediation of contaminated sites, two of the impediments to the adoption of geophysical methods are the lack of awareness of the capabilities and the cost of geophysical surveys. In terms of the former, there is a need for improved communication with decision-makers and managers, for example, by making available more case studies and success stories. Increased utilization of hydrogeophysical methods by practitioners will also require that the hydrogeophysical research/user community works towards clearly demonstrating the economic benefits of geophysical applications for a range of applications. It is challenging to convince a water manager to adopt cutting-edge technology without clear evidence that the benefit will outweigh the costs.

It is likely that field measurements will continue to improve in accuracy and spatial and temporal resolution, as well as decrease in cost per datum. Society's growing need to know more about its water supply and protect it, along with the decreasing cost of field data, will tend to drive higher field data densities. This in turn will push current inversion schemes and their computational platforms resulting in improved geophysical results that facilitate an improved hydrogeological interpretation and ultimately benefit the study of groundwater resources. Hydrogeophysics may find itself on a trajectory similar to that of seismic imaging of petroleum reservoirs over the last few decades, and may well find some of the lessons learned and solutions developed there helpful.

We concluded the meeting by reflecting on the education and training needed in order to mentor the next generation of true hydrogeophysicists—not geophysicists applying their methods to hydrology, or hydrologists using geophysical methods – but students trained to be hydrogeophysicists. There are clearly educational challenges resulting from the continuously increasing complexity of hydrogeophysical concepts and approaches intertwining various disciplines/subjects including geophysics, hydrology, petrophysics, geostatistics, inversion theory … Reflecting on all that is involved in hydrogeophysics was an ideal way to end the meeting, with a commitment to continue working together across disciplinary and international boundaries in this exciting and important field of Earth sciences. Join us at the Hydrogeophysics Workshop in 2017! TLE

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