Study Institute Assesses the State of Hydrogeophysics

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A North Atlantic Treaty Organization (NATO)-funded Hydrogeophysics Advanced Study Institute (ASI), held at the Trest Castle in the Czech Republic in July 2002, brought together for the first time a leading group of researchers and students active in this emerging discipline. Approximately 60 hydrogeologists interested in incorporating geophysical data into their subsurface characterization problems, and geophysicists involved in subsurface hydrogeological characterization, attended the institute.

Hydrogeologists and geophysicists often use different yet complementary approaches to investigate subsurface problems. The new discipline of hydrogeophysics strives to reconcile information obtained using both hydrogeological and geophysical approaches to improve our understanding of subsurface parameters or processes. The NATO ASI was held to assess the state of the discipline, and to review recent research breakthroughs and obstacles associated with hydrogeophysics.

The shallow subsurface of the Earth is an extremely important zone that yields much of our water resources; supports our agriculture; serves as the repository for most of our municipal, industrial, and government wastes and contaminants; and supports our infrastructure. As safe and effective use of the near-surface environment is a major challenge facing our society, there is a great need to improve our understanding of the shallow subsurface. The increased use of chemical pollutants associated with the technological development of countries with evolving market economies, and the increased need to develop sustainable water resources and infrastructure for growing populations all contribute to the urgent need to better understand the shallow subsurface.

Conventional sampling techniques for characterizing or monitoring the shallow subsurface typically involve drilling a borehole, and either retrieving a soil sample for further analysis, or collecting borehole logs within the hole. These methods can be costly, time-consuming, and invasive, potentially disturbing the in-situ conditions of interest and exposing humans to hazardous chemicals and radionuclides. Because these measurements are typically sparse and often associated with a very localized measurement support scale, they often do not provide sufficient information about field-scale hydrogeologic heterogeneity. With poor subsurface characterization, water resource management or remediation schemes are unnecessarily expensive or ineffective. Just as medical imaging technology provides dense information and has reduced the need for invasive surgery, geophysical methods hold promise for rapid, non-destructive, relatively inexpensive, and vastly improved characterization of the shallow subsurface.

Geophysical Methods are used to assist with many Hydrogeological Investigations, such as:
Mapping the Depth to Water Table and Bedrock
Fault Detection
Fresh/Salt Water Interface Mapping
Hydrostratigraphic/Lithologic Mapping
Landfill Delineation
Water Content Estimation
Fracture/Cavity Detection
Estimation of Hydraulic Parameters (porosity and permeability)
Water Quality Assessment
Assessing Integrity of Waste Containment Structures
Direct Detection of Contaminants
Monitoring Physio-Chemical-Microbiological Processes

Many advances associated with near-surface geophysics have been made in the last decade. These advances, which facilitate the use of geophysical data for hydrogeological characterization, include improvements in understanding geophysical responses in near-surface environments, improved digital technology for acquisition, improvements of many geophysical methods for near-surface imaging, and improved computational speed and capabilities associated with processing, inversion, modeling, and visualization of geophysical data.

Although many successful shallow subsurface characterization studies have been performed using geophysical data, several obstacles still hinder the routine use of geophysics for hydrogeological characterization in this zone. Geophysical methods are being applied to assist with a range of hydrogeological investigations such as those shown in Table 1. Some of the techniques and approaches are well developed for particular applications, while for other applications, the techniques have potential but are not yet well developed.

Some of the key obstacles that prohibit routine success include a lack of understanding of the relationships between the geophysical attributes and the hydrogeological parameters, a lack of methods for handling the non-uniqueness often associated with these petrophysical relationships, and the current inability to integrate disparate data sets. Integration of geophysical and hydrogeological data sets that sample different parameters over different spatial scales using a systematic approach remains a daunting challenge that is so far only attempted, if at all, on a case-by-case basis.

The field of hydrogeophysics has developed in recent years to investigate the potential of geophysical methods for providing quantitative estimates of hydrogeological parameters needed for shallow subsurface studies. This rapidly expanding cross-disciplinary field involves researchers from geophysics, hydrology, geology, statistics, rock physics, and engineering backgrounds.

At the ASI, topics important for hydrogeophysics were systematically covered, starting with the hydrogeological perspective, which included tutorials and case studies associated with geostatistics, hydrogeological inverse modeling, effective properties, and hydrogeological parameter simulation methods. Next, the geophysical perspective was presented, using tutorials and case studies associated with the fundamentals, petrophysics, and applications of many geophysical methods that are being used to characterize the shallow subsurface, including geoelectric, electromagnetic, ground-penetrating radar, seismic, nuclear magnetic resonance, and borehole approaches. After this extensive review of both the hydrogeological and geophysical perspectives, data fusion and integration issues were discussed, followed by a hands-on demonstration of various geophysical and hydrological characterization tools. This systematic approach allowed the participants to appreciate the many different components important to a hydrogeophysical interpretation.

Hydrogeophysics: State of the Discipline

After 10 days of oral presentations, poster presentations, field demonstrations, and lively discussions, a panel discussion was held to develop a consensus of the state of the discipline. Several key themes resonated throughout the presentations; these are briefly described below.

There is a pressing need to develop practical solutions to subsurface problems in the face of incomplete basic theory. Many areas within hydrogeophysics are not well understood yet and will require many years of research to develop sufficiently. For example, many of the petrophysical relationships among granulometric, geophysical, and hydrological variables used within hydrogeophysical research are either empirical or based on simplifying assumptions that may not be valid. Similarly, geophysical responses in three-dimensional, complex shallow environments that have multiple scales of heterogeneity and that are affected by cultural noise are not yet well understood. Hydrogeophysics is currently trying to strike a balance between an improved understanding of basic principles and implementation of pragmatic solutions to subsurface problems. As such, there is a need within the hydrogeophysics community for researchers who will advance our understanding of the fundamental principles, as well as those who can apply the principles toward subsurface characterization and develop pragmatic approaches when the fundamental principles are subject to uncertainty.

Hydrogeological, Geophysical Data Integration Approaches

At the NATO ASI, the approaches used to integrate hydrogeological and geophysical data for improved subsurface characterization fell into two general schools of thought. The choice of methodology typically depended on data density, project objectives, and interpreter background. The approach that is probably most familiar to geophysicists capitalizes on expert skills and intuition to merge the disparate hydrogeological and geophysical data sets. This methodology allows for incorporation of information that is often very difficult to quantify, such as knowledge associated with geophysical signatures and depositional processes. Teams of experts who can best interpret subsurface structures, stratigraphy, and hydraulic properties are used extensively within the petroleum industry. However, with this approach, it is often difficult to quantify the uncertainty associated with the components of the problem, such as the conceptual model, the hydrogeological parameter estimate, and the geophysical data inversion procedure.

Other presentations at the ASI approached the integration problem using stochastic methods. These methods provide a systematic framework for assessing or handling some of the complexities that arise in fusing disparate data sets, such as those associated with spatial variability, measurement error, model discrimination, and conceptual model uncertainty.

Hydrogeophysicists are still struggling with obstacles such as how to best capture expert knowledge within these frameworks, and experience within the hydrogeophysical community with stochastic methodologies is still limited. However, in light of the need to develop pragmatic solutions given an incomplete understanding of underlying mechanisms, the stochastic approach for assessing uncertainty holds great promise.

There is a division in geophysical training between specialization and broad-based skills. Currently, hydrogeophysicists are striving to strike the right balance between having a working knowledge of all geophysical methods, and understanding the nuances of a few methods and the impact of those nuances on the hydrogeophysical interpretation. The importance of thoroughly understanding the geophysical data was highlighted as a crucial component of the hydrogeophysical investigation. Many of the presentations illustrated potential pitfalls that can occur if the interpreter is not intimately involved with the geophysical data acquisition, inversion, and display. Assessing the error associated with geophysical data through repeated or reciprocal acquisition tests was recognized as an important goal. Understanding the effects of data inversion on the geophysical estimate, and how the inversion artifacts translate into both point and spatial correlation estimates of hydrogeological parameters, is a current topic of research and was also a resonating theme. The importance of the influence of visual displays and their influence on the message conveyed was discussed. Although a thorough understanding of the geophysical data is required to assess confidence in the hydrogeophysical interpretation, it is difficult in practice for an investigator to be a master of all geophysical techniques.

Individual Science Needs

In addition to the key challenges mentioned above, the ASI participants indicated that more studies were needed to assess the utility of using geophysical multi-method and multi-geometric approaches for resolving scale and non-uniqueness issues; to quantify errors associated with data acquisition, inversion, and estimation; to evaluate the relative contribution of stratigraphic information versus detailed hydrogeological parameter estimates to the flow and transport problem; and to modify existing geophysical instrumentation for near-surface use. Among many others, the discussed science needs that were associated with particular geophysical methods included theory to support forward modeling and interpretation of three-dimensional controlled source electromagnetic induction responses in systems with hierarchical scales of heterogeneity; a better understanding of many geophysical responses in unconsolidated sediments; and more research directed toward emerging methods for hydrogeological applications.

The participants expressed the benefits of the ASI for recognizing the current limitations, as well as for creating the enthusiasm and collaboration necessary for tackling some of the challenges that exist within hydrogeophysics. We expect that the need for improved understanding of subsurface parameters and processes will continue to grow, and we think that judicious use of geophysical data integrated with hydrogeological data holds great potential for improved subsurface characterization and monitoring. Advances within the discipline are expected to be facilitated through increased fundamental studies, increased collaboration; increased publications of hydrogeophysical studies and manuals; increased hydrogeophysical education; and with increased personal experience.

Individual as well as group efforts are under way to proliferate the spirit of the hydrogeophysics ASI to the greater community. For example, many of the participants are developing the first hydrogeophysics textbook, which will be published in 2004. Similarly, hydrogeophysics sessions are now held at most professional meetings, including the joint AGU-European Geophysical Society Spring Meeting, which will be held in Nice, France, in April 2003. For more details about the lectures and posters presented during the ASI as well as a list of participants, please visit our Web site: http://lnx.lbl.gov/hydroASI/home.html.

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