A Vision for Geophysics Instrumentation in Watershed Hydrological Research.

A Report to the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc.

by

D.A. Robinson, Stanford University
A. Binley, Lancaster University
N. Crook, Stanford University
F.D. Day-Lewis, USGS
T.P.A. Ferré, University of Arizona
V.J.S. Grauch, USGS
R. Knight, Stanford University
M. Knoll, Boise State University
V. Lakshmi, University of South Carolina
R. Miller, Kansas Geological Survey
J. Nyquist, Temple University
L.Pellerin, Green Engineering
K. Singha, Penn State University
L. Slater, Rutgers University

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Preface

The main purpose of this report is to provide a vision for the use of geophysical instrumentation in watershed-scale hydrological research. The aim of the report is to identify instrumentation that could significantly advance geophysics in hydrology during the next 3-5 years. The criteria for the development of this report were to develop a strategic vision for geophysical instrumentation support in hydrology. The vision has to provide researchable elements rather than routine characterization, focused narrowly enough as to be practicable in a 3-5 year time frame; we acknowledge that this is one of a number of possible ways forward. Thus this report focuses on geophysical methods that can be used to determine geological structure and identify flow paths at multiple scales within a watershed. The report identifies instruments, describes what they are, and provides examples of their use and 'ball park' prices correct at the time of publishing, October 2006. The reader can use these figures as a guide to basic instrument costs, which does not include the cost of supporting the instruments and data analysis. The report also considers the deployment and costs associated with data collection, as well as examining the interpretation of data, and how the synergy between measurement and modeling can be achieved. Of specific interest are the airborne systems. Although airborne geophysics has been around for a while, it is only in the last few years that systems designed exclusively for hydrological applications have begun to appear, offering a cutting edge, scientific way forward that could revolutionize the hydrogeological interpretations for watershed research.

The Hydrological Measurement Facility (HMF) Geophysics advisory group was formed in the summer of 2005 and has subsequently evolved in membership. HMF is a national committee composed of senior scientists with expertise spanning geophysics, hydrology, and soil science. The team includes two geophysicists from the UK who have recently come to the end of a national 5 year lowland catchment hydrological study (LOWCAR), where geophysics played a significant role. As well as university researchers, the group also includes geophysical contractors with expertise in airborne geophysical survey for hydrological applications, and scientists from the U.S. Geological Survey (USGS).

The HMF Geophysics advisory group is led by Rosemary Knight (Stanford University) and consists of, Estella Atekwana (University of Missouri-Rolla), Andrew Binley (Lancaster University), Bill Clement (Boise State University), Fred Day-Lewis (U.S.G.S), Ty Ferré (University of Arizona), Tien Grauch (U.S.G.S), Mike Knoll (Boise State University), Venkat Lakshmi (University of South Carolina), John Lane (U.S. Geological Survey), Yaoguo Li (Colorado School of Mines), Rick Miller (Kansas State Geological Survey), Jonathan Nyquist (Temple University) Louise Pellerin (Green Engineering, Inc.), Kamini Singha (Pennsylvania State University) and Lee Slater (Rutgers University).

The group began by advising the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc., Hydrologic Measurement Facility (CUAHSI HMF) on the content of the HMF survey (Nov 2005-Jan 2006) regarding near surface-geophysics. The results of a national survey of scientists involved with hydrology (Robinson et al., 2006) have been carefully considered in the development of this report. The group met formally in December 2005 and informally at the AGU Fall meeting in San Fransisco, 2005. This report is the result of nearly 6 months of discussion and dialogue.

The concept to emerge from this work is the development of a multi-method, cross-scale set of geophysical measurements to construct 3-D physical-property models of the subsurface in watersheds, and to have these measurements and models integrate with existing geophysical characterization and ongoing work in other disciplines. The philosophy assumes a 'top-down' approach using airborne methods to identify the dominant architecture of the subsurface. Particular attention is paid to the delineation of flow pathways in the subsurface, and the identification of hydrologically significant interfaces and structures.

The report identifies three main areas in need of research: (1) instrumentation and data analysis, (2) integration of geophysical model interpretation with hydrological modeling, and (3) the development of data archiving methods. The approach recognizes that there is much routine geophysical work that needs to be done, that if applied to hydrology, will be ground breaking research, and may lead to significant advances in the hydrological sciences. Much of the required research is needed to develop geophysical methods for addressing hydrological problems. Issues such as data archiving and quality assurance and quality control must also be addressed; this is a controversial issue and there currently is no national data repository for geophysical measurements outside of U.S.G.S. The U.S.G.S. has policies and activities in place for archiving ground-water, borehole geophysical, aeromagnetic, and gravity data, and to lesser extent airborne electromagnetic data (EM) data. There is a need to examine how near-surface geophysics data collected by CUAHSI could complement such resources. Finally, there is a need to develop partnerships between geophysics and hydrology, partnerships that begin to explore how the application of geophysics can be used to answer critical hydrological science questions, and conversely can be used to provide an understanding of the limitations of geophysical measurements and their interpretation.

1. Introduction

The CUAHSI Hydrologic Measurement Facility community survey (Selker, 2005) was conducted between November 2005 and January 2006. Findings from the survey (Robinson et al., 2006) gave a clear mandate for improving and implementing subsurface science as a key aspect for advancing hydrologic sciences. The need for quantifying the subsurface placed fourth of 23 responses aimed at prioritizing the needs to advance hydrologic science. The need to improve the link between measurements and models, the need to improve the spatial resolution of measurements, and the ability to make more/better measurements through distributed sensor networks placed first to third, respectively. The importance of subsurface quantification to hydrology should come as no major surprise, having been outlined in two recent National Research Council (NRC) reports as a priority area for research (NRC, 2000; NRC, 2001). The purpose of this report is to identify cutting edge technology available in geophysics that can be applied to advance hydrology, in particular to advance our understanding of processes and dynamics in a changing system at the watershed scale. The report offers a strategic vision for advancing watershed research through the incorporation of geophysical measurements; the report provides an assessment of current practice, identifies promising new technologies and state of the art interpretation, and outlines improved linkage between measurement and modeling approaches. Three appendices provide tables of comparison, including, logistics/costs, physical properties inferred, and geophysical/hydrological comparison of measurement scales.

The principal scientific objective underlying CUAHSI infrastructure proposals is "to develop a predictive understanding of storages, fluxes and transformation of water, sediment, and associated chemical and microbiological constituents." Within this, three themes are identified that are intertwined with this core objective, (1) the role of scale in hydrologic storage, fluxes and transformations, (2) the linkage between ecosystems and the hydrologic cycle, and (3) hydrologic prediction. Of these, geophysical measurement is important for the identification and quantification of stocks, fluxes, and transformations in the subsurface through prediction of hydraulic properties, determining the stocks of water available for ecosystems; thus geophysical measurement plays a fundamental role in hydrological prediction. The emphasis on developing synergy between near-surface geophysics and hydrology to develop a continuum understanding of water movement through the landscape is a defining concept in the CUAHSI vision. This is one of the emphasis areas that sets CUAHSI apart from other environmental observatory programs such as NEON (National Ecological Observatory Network).

As CUASHI has emerged, greater emphasis has been placed on dealing with watersheds of any scale, the term watershed, thus becoming somewhat nebulous. For convenience in comparing geophysical methods to watershed scales, we adopt the Center for Watershed Protections (CWP) definitions of watershed management units (Zielinski, 2002), with their approximate corresponding areas; basin (2,500–25,000 km^2); sub-basin (250–2,500 km^2); watershed (80–250 km^2); sub-watershed (1–80 km^2); catchment (0.1-1 km^2). Though these delineations are subjective, they guide the reader in relating geophysical measurements to hydrological scales of interest.

Scaling is a fundamental concept to hydrology. Commonly we measure or study properties at the sample scale and try to determine patterns at the larger scales. Many of the instruments we use measure at the point/sample scale such as soil moisture probes or determine regional patterns such as remote sensing. This often leaves us with the so-called, 'meso-scale gap phenomenon', everything in between, where we are either trying to upscale or downscale to infer processes of interest. We can often measure with high temporal resolution at a point, but as spatial scales increase, so we lose our ability to maintain this high temporal resolution. Figure 1 presents this concept diagrammatically, where we can currently measure at a point with high temporal resolution, but as we want to measure bigger areas it takes us longer. We are, therefore, generally constrained to temporal and spatial measurement scales that are in the blue area below the black arrows (Fig. 1). We desire measurements at spatial and temporal scales along the red arrows. These arrows offer the trajectories of where cutting edge measurement science must go to allow us to observe processes of interest. The pioneering efforts must, therefore, push along these red trajectories to obtain measurements at the meso-scale while maintaining high temporal resolution. It is therefore no surprise that CUAHSI initially defined areas ranging from 10-10,000 km^2 as being the watershed scale of interest, with associated modeling grid squares of 1-10 km^2 (CUAHSI, 2002). Advances in hydrological measurement techniques will allow us to push these boundaries forward, in particular techniques using satellite or airborne platforms allow us to measure over large spatial scales. In this report on geophysical techniques, we emphasize advances in airborne geophysical methods that allow for data collection over watershed to basin scales, in both a rapid and cost-effective manner.

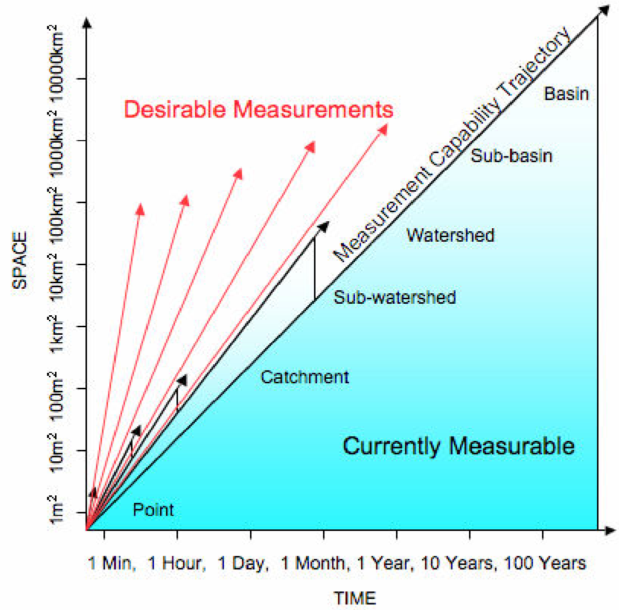

Figure 1. Conceptual diagram of spatial and temporal resolution scales

2. Subsurface Analysis of Watersheds using a Multi-Method, Cross-Scale Approach

Measurement and identification of geological structures, lithologies, and interstitial fluids pertinent to the movement and storage of water are key to understanding hydrological processes and dynamics in the subsurface. Geophysical methods exploit differences in the physical properties of rocks, soils, and sediments to identify geologic features and/or characterize pore fluids. Traditionally, deep-earth research and oil and mineral exploration have used geophysical methods to identify large-scale structure or geologically unique 'targets' such as ore deposits. The aims of geological characterization from the hydrological perspective tend to differ, requiring us to focus on shallower depths and to investigate subtle variations that may have large effects on the dynamics of water movement through the subsurface. Thus, traditional geophysical approaches are not generally appropriate, and no one technique can provide information on all the subtleties that are involved. Instead, a multi-method, cross-scale geophysical approach is necessary that integrates information from geology, chemistry, biology, and hydrology.

An example conceptual model focused on electromagnetic (EM) geophysical techniques (Fig. 2) illustrates one kind of cross-scale approach. In this example, data collection at different scales exploit the same underlying physical principles, allowing data sets to be woven together into a 3-D geo-electrical image of the subsurface over the entire watershed..

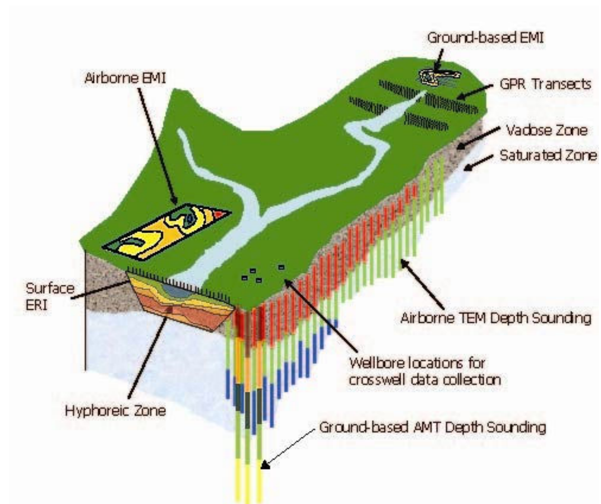

Figure 2. Example conceptual model of how EM geophysical measurements could be used at multiple scales to characterize a watershed.

In the vadose (unsaturated) and ground-water (saturated) zones, the electrical properties of soils, sediments and rocks are highly dependent on water saturation. In the saturated zone, the measurable electrical contrast between quartz sand layers and high activity clay layers creates optimal conditions for identifying structural boundaries. At the regional scale, juxtaposed rocks at faults can correspond to large contrasts in electrical properties.

Such a cross-scale conceptual model can be achieved through a top-down approach, utilizing airborne geophysics as the starting point. The top-down approach offers the advantage of achieving survey efficiency by characterizing dominant features that might be linked to dominant hydrological processes early in the process, in the watershed characterization. Advances in technology and data acquisition speeds allow EM data to be collected while the sensor is moving, either as part of a ground-based platform, or more recently as part of an airborne platform (Sørensen et al., 2005). Airborne EM surveys in Australia have covered areas of up to 18,000 km^2 with a spacing of between 200 and 400m between data points (Lane et al., 2000). Advances in airborne systems have led to joint acquisition of EM and magnetic data as common practice, expanding the breadth of subsurface characterization to include both electrical and magnetic properties. Airborne EM induction methods can provide spatial patterns of ground conductivity with depth that can be used to identify regional-scale subsurface flow paths, whereas aeromagnetic methods reveal faults and buried bedrock to even greater depths, providing additional information on flow paths and on aquifer characteristics. Time-domain electromagnetic (TEM) sounding methods can generally sense the subsurface architecture to depths of 100 m, which makes these methods suitable for identifying aquifers, aquitards, and depths to clay layers. A combination of all these data could be used to reconstruct regional geologic structure within a watershed and identify areas that require more intensive study at smaller scales.

Soils play a fundamental role in hydrology, affecting the pattern of stream flow response, especially when observed at shorter time scales in drier regions (Atkinson et al., 2002). Two properties of major interest in hydrology are the location of flow paths in soils and soil depth, which is a first approximation of soil-water storage. Geophysics can be used to improve the quantification of both of these aspects of soils. Ground-based electromagnetic induction (EMI) can be used to map soil texture where strong electrical contrasts exist between the clay and coarser mineral components of the soil (Lesch et al., 2005). EMI can be used to identify catchment-scale flow pathways and subsurface spatial patterns where electrical contrasts exist between wet and dry areas. Ground penetrating radar (GPR) can be used to collect line transect data, which can aid in the identification of depth to impermeable layers. This type of information may also give insight into the nature of the soil/impermeable layer subsurface topography. The strength of these techniques lies not in the individual instruments but in utilizing them together to construct a seamless 3-D image of the subsurface.

3. Regional, Sub-Watershed to Basin-Scale Remote Sensing and Airborne Survey

Measurement at regional scales can be used to draw general conclusions about the regional subsurface architecture. Spatially exhaustive data are of great utility in identifying zones of interest and directing subsequent, more costly, ground-based surveys over limited spatial areas. Information is available from satellite remote-sensing platforms but is limited in penetration depth, whereas airborne techniques can be used to determine spatial patterns and provide more detailed depth information.

3.1 Satellite-Based Active and Passive Microwave Remote Sensing

Satellite remote sensing using active and passive microwave sensors is predominantly used to obtain soil moisture over large regions from the catchment to basin scale. Microwave remote sensing provides a unique capability for direct observation of soil moisture with a global coverage, all weather, day and night viewing capability. The technique relies on the high contrast between dielectric constant of dry soil (~3) and water (~80). A four-component, dielectric mixing model is used to evaluate the dielectric constant of soil – water mixture depending on parameters of soil moisture, texture, bulk density, specific surface area, and frequency of the instrument (Dobson et al., 1985). Brightness temperatures and radar backscattering coefficients for the target are obtained from passive and active sensors and used to estimate the dielectric constant of the soil surface at the given frequency of sensor operation, thereby obtaining a soil moisture estimate. Passive techniques rely on black body emission from the land surface whereas active sensors employ their own source of electromagnetic radiation (Ulaby et al., 1986). Because of the nature of interaction between radiation and the soil surface and overlying vegetation canopy, passive sensors are less affected by soil roughness and vegetation canopy parameters, allowing soil moisture retrieval to be performed with lower ancillary data requirements under bare to moderately vegetated conditions. Current methods for soil moisture retrieval from radar data work for bare soil surfaces only. Radar, however, provides much higher spatial resolution than radiometers. Frequency of sensor operation determines the ability of the signal to penetrate through vegetation and the soil surface and also dictates the antenna length. The L-band (1.5 GHz) is widely considered to be the optimal frequency for space-based soil moisture retrieval, and at this frequency, an average soil penetration depth of around 0.05 m is achieved (Jackson et al., 1996). With currently available sensors, airborne surveying techniques can use even lower frequencies to achieve higher canopy and soil penetration beyond 0.05 m (Blumberg et al., 2000). Airborne surveys can be used to observe soil dry-down after precipitation events thus providing valuable information about soil texture and hydraulic conductivity; this can lead to identification of spatial patterns that can direct where ground-based geophysical techniques might be used to explore further. The frequency at which airborne surveys can be scheduled for fly over is up to the investigator and the availability of the aircraft. Under normal circumstances for soil moisture, daily flights are scheduled in the dry-down portion of the campaign (i.e., wet soil drying down because of evapotranspiration). Aircraft can normally fly every day for a few days (4-5) and then require a day off for maintenance and repair (if needed).

Active microwave estimation of soil moisture will benefit from improved parameterization of vegetation canopy structure and water content. High repeat pass measurements can be used to simplify the problem of soil moisture estimation for vegetated surfaces because the natural temporal variability of soil moisture is much higher than that for vegetation. Space-borne radars, however, currently do not provide frequent measurements (ALOS - 26 days, ERS 1/2 - 35 days). Space-borne estimates of soil moisture obtained using passive remote sensing have a spatial resolution of the order of tens of kilometers. These estimates can be improved in spatial resolution by combination with active microwave data (Narayan et al., 2006). Simultaneously obtained active and passive data are needed for such research and are not available from satellite instruments that are currently operational. Microwave remote sensing provides an estimate of near-surface soil moisture. Data assimilation techniques can be used to retrieve a soil moisture profile (depth of few meters) by updating a hydrological model with remote sensing observations (Entekhabi et al., 1994). These methods require long-term (several days) measurements of brightness temperature in the 1 – 5 GHz frequency range.

Airborne survey data are driving research in the above-mentioned areas since satellite measurements at lower frequencies such as L (1.5 GHz) and S (2.6 GHz) band are not available. The AIRSAR instrument, for example, obtains fully polarimetric radar observations in the C (6.6 GHz), L (1.5 GHz), and P (500 MHz) bands at meter spatial resolutions. The PALS instrument developed by the Jet Propulsion Laboratory (JPL) provides simultaneous active and passive data in the L (1.5 GHz) and S (2-4 GHz) bands for individual pixels at 400 m spatial resolution. ESTAR is a passive microwave radiometer that has been used for large-scale airborne mapping of soil moisture. AMSR-E and SSM/I are among the satellite-based passive sensors that have been used for soil moisture remote sensing. The SMOS radiometer scheduled to be launched by ESA in 2007 will be the first L-band (1.5 GHz) radiometer in space. Among satellite-borne radars used for soil moisture estimation are ERS, RADARSAT, and the recently launched ALOS-PALSAR.

3.2 Airborne Electromagnetic Survey

Airborne surveying is a cost effective method of obtaining regional survey information from the sub-watershed to basin scales. Airborne electromagnetic (AEM) methods can be implemented in either the frequency or time domain and on a helicopter or fixed-wing aircraft. Traditionally frequency-domain EM was used on a helicopter (HEM) and time-domain EM on a fixed wing (FWEM), but recent developments are making helicopter time-domain (HTEM) surveys more common. All of these techniques are used to develop a regional-scale image of the electrical resistivity of the subsurface, a physical property directly related to rock type, porosity, and the ionic strength of the pore fluids. The earth's subsurface is excited inductively and the resulting magnetic field is measured. Apparent resistivity maps, conductivity depth imaging (CDI) or inverted models are computed from the field measurements, and the resistivity may be related to basic geological structure, such as depth to basement, stratigraphy, faults, fractures, paleochannels, and hydrogeological features such as depth to ground water and aquifer characterization. One should not expect, however, to distinguish between the unsaturated and saturated zone because of potential overprint of stratigraphic and structural uncertainties, but useful information about the conductivity structure and the quality of the aquifer can be gained.

The high conductivity of saline water, whether in the subsurface or intruding seawater, makes it an excellent target for EM detection. The Florida Everglades is an example where high rates of ground-water extraction interfered with ground-water flow and led to intrusion of seawater (Fitterman and Deszcz-Pan, 1998). Repeated AEM was used to monitor variation of the intrusion with time. Farmland can be ruined by rising saline ground water; AEM can be used to map the distribution and depth to the saline water over large areas and has been used over thousands of square kilometers in Australia.

All EM measurements of the earth are distorted by cultural noise sources and AEM methods are no exception. In general, data are affected 100-200 m from 2D linear features such as powerlines and pipelines. The zone is smaller for 3D targets such as a building < 100 m away (Sørensen et al., 2001). The high density of airborne data allows for culling of the distorted data, while leaving enough coverage for interpretation. By their nature, airborne methods are cost effective for covering large survey areas and should be used early in an investigation. The airborne results can guide subsequent ground surveys that are used for more detailed and deeper exploration. Airborne surveys are typically contracted; raw data along with various maps and profiles are then delivered for geologic interpretation.

3.3 Helicopter Electromagnetic (HEM)

The HEM frequency-domain transmitter and receiver coils are located in a cylindrical rigid bird slung beneath a helicopter. Frequencies range from approximately 100 kHz to 500 Hz for depths of investigation from a few meters to roughly 100 m. Coil configurations include both horizontal coplanar (HCP) and vertical co-axial (VCA) as shown in Figure 3. The HPC is ideal for mapping horizontal features, such as a ground-water interface, and the VCA is ideal for delineating vertical structures such as faults. Spatial resolution of the targets is good because of the small footprint of the system, and helicopters have the ability to maintain consistent terrain clearance in mountainous areas. HEM is extremely efficient for surveying small or irregularly shaped areas.

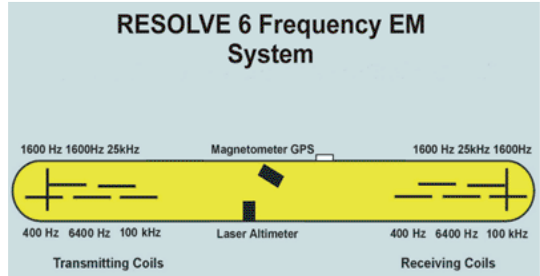

Figure 3. Array configuration for the RESOLVE frequency-domain EM system.

Typically, interpretive maps are apparent resistivity maps for each frequency and coil configuration. Although research continues in multi-dimensional inversion, because of the relatively sparse temporal sampling, 1D inversion is more stable, and with the dense spatial density, it can be used to recover an approximate 3D distribution (Sengpiel and Siemon, 1998; Farquharson et al., 2003). Pricing is based on several variables such as location, area, terrain, line spacing, final products, but rough estimates for hydrological surveys can vary from approximately $75,000 for 400 line-km to $100,000 for approximately 1,200 line-km.

3.4 Fixed-Wing Time Domain Electromagnetic (FWEM)

Fixed-wing surveys (Fig. 4) utilize a large transmitter loop and operate in the time domain, hence measurements are broadband as compared to the select few frequencies in HEM systems. Measurement in the receiver bird is typically of the three orthogonal components of the secondary EM field. The FWEM method can have depths of investigation greater than 200 m, depending on the resistivities of the near-surface materials. FWEM is more cost effective than helicopter methods, but lacks resolution of the near surface and the ability to work in rugged terrain. In general, costs are on the order of $100 to $125 per line km of survey plus a mobilization charge to the survey area, which can be upwards of $10,000. Resulting maps and sections that are used for geophysical interpretation often include energy envelope, conductivity-depth sections, realizable resistive limit maps and stationary current images (Macnae et al., 1991; Smith et al., 2005).


Figure 4. The GEOTEM time-domain fixed-wing EM system.

3.5 Helicopter Time Domain Electromagnetic (HTEM)

In the past few years, the time-domain EM method has been adapted to helicopter use. Several systems have been designed for mineral exploration and may be adaptable to hydrologic studies. SkyTEM*[1] was designed specifically for hydrogeophysical and environmental investigations (Sørensen and Auken, 2004). The transmitter, mounted on a light weight wooden lattice frame, is a 283 m^2 multi-turn loop with variable moment to optimize resolution. The shielded, over-damped, multi-turn receiver loop is rigidly mounted on the side of the transmitter loop in a near-null position of the primary (transmitted) field, which minimizes distortions from the transmitter, with a 2 m vertical offset. Hence, this configuration can be compared to a central-loop configuration, and the data are processed and inverted as such. Independent of the helicopter, the entire system is carried as an external sling load suspended as shown in Figure 5.

Figure 5. The SkyTEM helicopter time-domain EM system.

The SkyTEM system is unique in its ability to acquire accurate data where resistivity contrasts could be from 50 to 80 ohm-m, as compared to mineral exploration where the target is highly conductive. A dual transmitter allows for high vertical resolution of the near surface in addition to deep penetration of the subsurface. The low moment, corresponding to near-surface investigations, has a transmitter of 1 turn, current of ~37 A, and a repetition rate of ~240 Hz. Measurement times are from 10 µs to about 1 ms. The high moment, which has deeper depth of penetration, is a transmitter with 4 turns, current of ~95 A, and repetition rate of ~30 Hz. The measurement times are from 50 µs to ~5.6 ms. Thematic maps, such as interval resistivity or depth to bedrock, can be

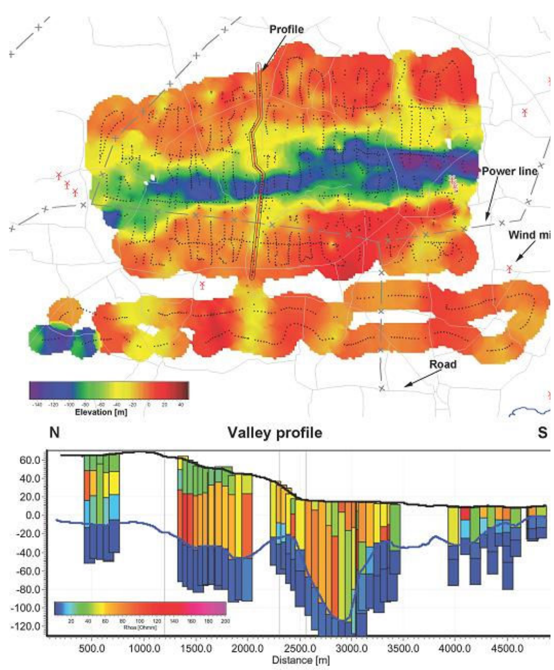

Figure 6. Thematic map showing elevation of low resistive Tertiary clay and delineation of a buried valley.

[1] The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Government. All prices are given in USD amounts.

produced for interpretation. For example the depth to Tertiary clay map shown in Figure 6, clearly depicts a buried valley. The corresponding resistivity depth section can be used to characterize the aquifer (Auken et al., 2004). The width of the buried valley is approximately 1000 m in both views. A conductive clay cap is defined to the north and south of the valley and sandy fill within the valley with no cap. Depth of investigation can be >200 m over thick (~200m) resistive rock outcrop. Costs are ~$120 per line mile plus mobilization cost to the site.

3.6 Aeromagnetic Surveys

During the past decade, the utility of airborne magnetic surveys for mapping subsurface geology has advanced significantly beyond the traditional role of solely mapping deep crystalline basement (Nabighian et al., 2005a). Modern aeromagnetic surveys carry more sensitive instruments and are flown along lines that are lower and more narrowly spaced than is done for conventional aeromagnetic surveys. These new high-resolution surveys allow detection of subtle magnetic contrasts in the sedimentary section and increased ability to image the distribution of igneous rocks within the top 500 m of the surface at watershed to basin scales. Although aeromagnetic measurements do not respond to the presence of water, they do contribute directly to understanding the geologic controls on ground-water systems and are much less sensitive to power-line noise than EM data. As a negligible add-on to the cost of an AEM survey, a combined magnetic-EM survey provides complementary information that is more powerful than one method alone.

Aeromagnetic data represent variations in the strength of the earth's magnetic field that reflect the spatial distribution of magnetization throughout the ground. Magnetization of naturally occurring materials and rocks is determined by the quantity of magnetic minerals and by the strength and direction of the permanent magnetization carried by those minerals. Geologic features are interpreted from characteristic patterns and/or ranges of data values on aeromagnetic maps that are a function of the differences in magnetization as well as the volume and depth of the rock body or collection of poorly consolidated materials.

High-resolution aeromagnetic surveys have recently gained special significance for mapping intrasedimentary faults, owing to the mounting recognition that faults commonly compartmentalize aquifers or act as barriers to flow within alluvial basins. A high-resolution aeromagnetic survey from the Albuquerque basin, New Mexico, (Fig. 7) revealed many more faults in the shallow subsurface than previously known (Grauch et al., 2001), some of which are demonstrably bounding areas of subsidence related to well pumping (Heywood et al., 2002). Moreover, ground-based investigations of sediments juxtaposed to these faults show a general correlation between coarser grain size and stronger magnetization (Hudson et al., 1999). This relation indicates that aeromagnetic data can provide clues about contrasting aquifer characteristics of sediments (Grauch, 2001), a subject of ongoing research at U.S.G.S.

To obtain optimum resolution for geologic interpretation, surveys should be designed so that the spacing between flight lines equals the height of the magnetometer above the ground (Nabighian et al., 2005a). Considering factors related to cost and flight regulations, a reasonable guide is a line spacing of 150-200 m and terrain clearance of 150 m for basin-scale studies. Surveys are normally contracted to airborne geophysical companies that acquire and process the data to the point where they are ready for geologic interpretation and analysis. Cost per line km for acquisition of solely magnetic data ranges between $15-30 for fixed-wing aircraft and $40-65 for helicopter, depending on the market. Magnetometers are commonly added to towed-bird AEM configurations at little to no additional cost.

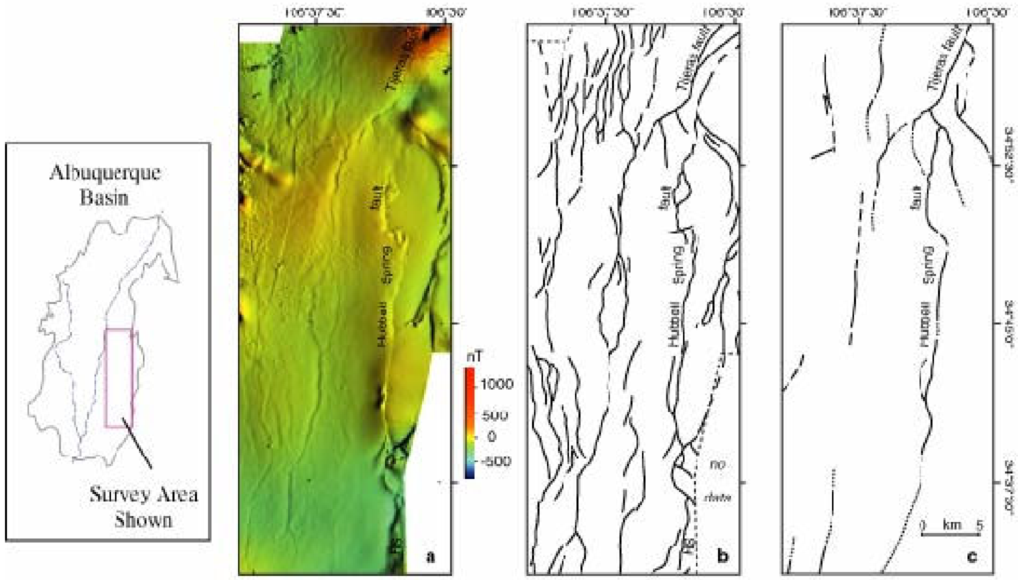

Figure 7. Mapping intrasedimentary faults with aeromagnetic data in the Albuquerque basin, Rio Grande rift (Grauch et al., 2001). The semi-linear, generally northerly-striking anomalies (2-10 nT amplitude) in the high-resolution aeromagnetic image (a) are primarily due to faults that offset different strata within the sedimentary basin fill. A map of these aeromagnetically inferred faults (b) substantially increases the information on faults known previously only from surface evidence (c).

4. Local, Catchment-to Sub-Watershed-Scale Electromagnetic Survey

Instruments used in airborne surveys such as TEM and EMI can also be used on the ground. For small numbers of measurements over small areas, ground-based measurement is generally more cost effective. Some ground-based measurements should be made as the precursor to any regional airborne survey to determine the feasibility of collecting high-quality data from an airborne survey that will also achieve the target exploration depth. Once an airborne survey has been confirmed to be feasible over a wide area, information obtained from these airborne regional surveys can be used to direct local-scale surveys, which are ideally suited to the sub-watershed and catchment scales.

4.1 Electromagnetic Sounding Methods

Electromagnetic sounding methods can give the greatest depth of penetration of all electrical and EM techniques. The two basic categories are (1) the time domain electromagnetic (TEM), and (2) the magneto telluric (MT), audio magneto telluric (AMT) and controlled-source AMT (CSAMT) methods. Data acquired along a profile line can be inverted to create a 2 D or quasi-2 D resistivity model from depths of tens of meters to tens of kilometers.

TEM is an inductive method where the earth is energized with a loop of current on the surface and the vertical, and sometimes also the horizontal, component of the resultant magnetic field is measured at different gates or time delays after the exciting current is turned off. The MT and AMT methods utilize naturally occurring fields over a range of frequencies for increasing depth of investigation. Measurements are made of both the electrical and magnetic field; the impedance of the earth being a function of the ratio of the electric to magnetic field. This method exploits both inductive and galvanic current flow.

4.2 Time Domain Electromagnetic (TEM)

The TEM method has gained increasing popularity over the past decade. Many portable systems for single-site measurements are commercially available. Being an inductive method, TEM is particularly good for mapping the depth to, and extent of, good conductors, and relatively poor for distinguishing conductivity contrasts in the low conductivity range. Clay and salt-water intrusion constitute conductive features of special interest in aquifer delineation. The method is well known in hydrogeophysical investigations to characterize aquifers (Fitterman and Stewart, 1986; Hoekstra and Blohm, 1990; Sørensen et al., 2005).

A TEM survey was undertaken in Denmark to focus on potential ground-water resources and hydraulic properties (Danielsen et al., 2003). The survey area of approximately 40 km^2 was covered by the equivalent of 40x40 central-loop TEM soundings. There were no topographic, geomorphologic or geological data to indicate the presence of a buried valley system, which was revealed solely by the TEM survey (Fig. 8). The map of the elevation of the conductive Tertiary clay defines the basal layer with resistivity below 15 ohm-m as derived from parameterized 1 D inversion (Effersø et al., 1999). Two main features are apparent: one striking north-south and the other southeast-northwest. The steep part of the buried valley descends from approximately 35 m above sea level (yellow colors) to approximately 50 m below sea level (green-blue colors) over a few hundred meters. A variety of systems are available with varying capabilities, including the Geonics EM-37, 47, 57, Protem and Protem D (Geonics, Inc., Mississauga, Ontario,

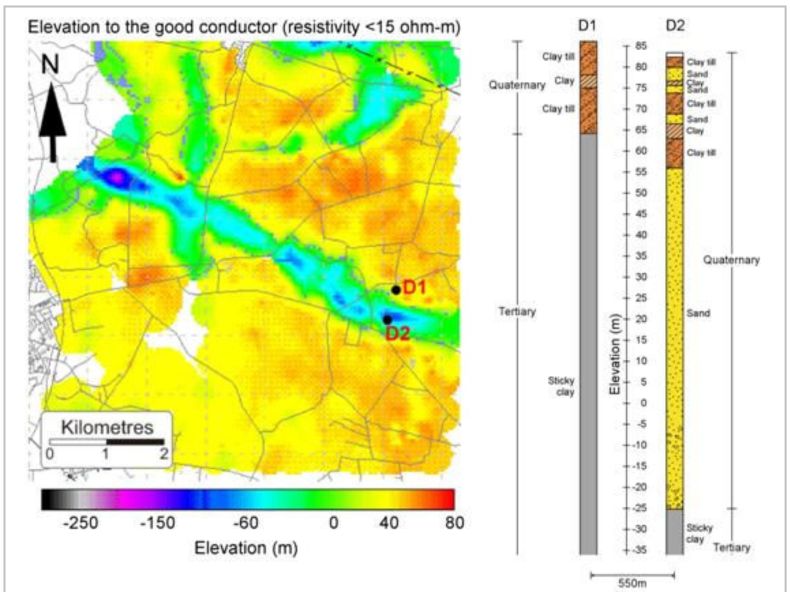

Figure 8. Map showing depth to good conductor map derived from 1 D inversion models of TEM data.

Canada), Zonge engineering GDP 12, 16 and 32 Systems Zonge engineering, Tucson, AZ), Phoenix Geophysics V-5 System (Toronto, Ontario, Canada). Cost of a TEM system ranges from \$60,000 for a fairly low-powered system, such as the Geonics ProTEM 47, which has limited depth of exploration, but is portable and useful for a wide variety of applications in the near surface. Increasing depth of investigation to 300-500 m would incur an investment of a more powerful transmitter with costs on the order of \$15,000 to \$25,000 more.

4.3 Magneto Telluric (MT) /Audio Magneto Telluric (AMT)

The MT and AMT plane-wave methods have great depths of penetration (from about 10 m to a few tens of km), and utilizing electric field measurements, MT and AMT enhance the resolution of low-contrast boundaries and resistive units. Portable systems for single-site and simultaneous multi-site measurements are commercially available. Traditional CSAMT systems commonly use a single grounded electric source for scalar measurements; the StrataGem® system (Fig. 9) by Geometrics uses an orthogonal magnetic source for tensor measurements. The controlled source transmits higher frequencies where natural signal strength is low. Fields from a controlled source can be regarded as plane at distances greater than roughly three skin depths from the source, thereby putting a constraint on the transmitter-receiver separation (Zonge and Hughes, 1991).

The plane-wave methods have the significant advantage in that multi-dimensional modeling capabilities are well developed from the crustal studies community and directly applicable to the watershed problem. Presently, there are several 2 D inversion codes (de Groot-Hedlin and Constable, 1990; Smith and Booker, 1991; Rodi and Mackie, 2001). Three-dimensional inversion codes are beginning to be used (Newman and Alumbaugh, 1999; Mackie et al., 2001; Sasaki, 2001; Haber et al., 2004), but it is time consuming and expensive to collect a data set that justifies 3 D inversion or 3 D forward modeling. Greater depth of penetration takes more time; thus, the MT/AMT methods can be relatively slow in data acquisition compared to other methods. The MT and AMT are becoming more widely used because of both the ability for greater depth of investigation and also because the quality of the aquifers can be characterized (Deszcz-Pan et al., 2001). These methods have also been used in mapping clay content of the subsurface (Rodriguez et al., 2001) A StrataGem® system costs approximately \$60,000, and an Electromagnetic instruments MT24LF or MT24HF system is about \$50,000.

Figure 9. Schematic showing the StrataGem® AMT system, photo courtesy of Geometrics, Inc.

4.4 Electromagnetic Induction (EMI) Ground Conductivity Meters

Spatial architecture of the near subsurface (0-10 m) is important for identifying flow pathways and networks, which are of interest in hydrology and affect stream-flow response (Grayson and Bloschl, 2000). Electromagnetic Induction (EMI) is a highly adaptable non-invasive geophysical technique, originally developed for borehole logging (Keller and Frischknescht, 1966). The instrument measures bulk electrical conductivity of the ground (ECa), and consists of a receiver and transmitter loop spaced 1 m or greater apart. The transmitter is energized and creates magnetic field loops in the subsurface; this produces electrical field loops which in turn create a secondary magnetic field. At low induction numbers, the combined primary and secondary magnetic fields measured in the receiver are proportional to the bulk ground conductivity (McNeill, 1980). The EMI method has been used extensively in mapping soils after first being reported by (De Jong et al., 1979); it has been particularly useful for mapping saline soils (Rhoades, 1993), within precision agriculture (Corwin and Lesch, 2003) and increasingly useful in mapping clay content of soils (Triantafilis and Lesch, 2005).

A variety of instruments are available, perhaps the more well known being the EM-38, EM-34, and EM-31, made by Geonics (Mississauga, Ontario, Canada). The different model numbers have different loop separations; the further apart the loops the deeper the penetration into the ground. The orientation of the loops also affects the field penetration into the ground. The nominal depth of penetration for these tools is 0.75 times the transmitter-receiver loop spacing for a horizontal electromagnetic dipole configuration, and 1.5 times the spacing for a vertical dipole. The EM-38 has a1-m loop spacing, and the EM-31 a 3.66-m spacing, whereas the receiver and transmitter loops of the EM-34 can be spaced 10, 20 or 40 m apart. The instruments are robust, relatively simple to use and can be linked to a field computer and GPS to provide real-time mapping, 'on the fly'. A dual dipole system retails for a little over $20,000, the electronic stability of the instrument, however, has been questioned (Sudduth et al., 2001) especially in hot sunny climates like the south western United States. Work by Robinson et al. (2003a) indicated that unstable readings occur when instrument temperatures rise above 40^{o}C, and discussion with other instrument makers suggests that this is a problem common to the type of instrument.

A new generation of EMI sensors has been developed by DUALEM (Milton, Ontario, Canada); their range of cutting edge EMI instruments are reported to be less temperature sensitive. The instrument is housed in a tough yellow casing and has internal, automatic calibration (Fig. 10), making it easy to use. The instrument is available with dual dipole and 1.1-m coil spacing at a cost of around $14,000; coil separations up to 4 m are available. The DUALEM 1-s has similar characteristics to the EM-38 with similar loop separation, giving it similar ground penetration. The instrument also has an internal memory for recording measurements; it is

Figure 10. Field mapping ground conductivity using a Dualem EMI sensor at the USDA - Reynolds Creek experimental watershed in Idaho.

easily linked to field computers and GPS to give real-time measurements, ‘on the fly’.

Another emerging instrument is the EMP-400 (GSSI, Raleigh, NC), which offers multi-frequency operation between 1 and 16 kHz. Due to be on the market in 2006, the user can select up to 3 frequencies to record in a second to provide 3 effective depths of penetration. The instrument coil spacing is 1.25 m and the length of the instrument is a little over 1.4 m.

The technology to collect, geo-reference, and process data has come a long way in the last few years. Tough field computers such as the Trimble (Trimble Navigation Limited, Sunnyvale, CA) Recon and Allegro (Juniper systems Inc., Logan UT) provide the opportunity to synchronize data collection from different instruments. GPS technology is becoming more accurate, and more compact for a lower cost. An example is the Trimble PROxt, which has a reported accuracy of 0.3 m in the x-y direction, has wireless ‘Bluetooth’ communications technology if needed, is light weight and costs around $2,500.

Examples of what EMI could bring to hydrological research include providing high spatial resolution maps of ground conductivity. These maps then can be calibrated to provide information on ion concentration, soil texture, and wetness. These are common applications in agriculture (Lesch et al., 2005) and directed sampling calibration methods (Lesch et al., 1995a,b) have been used to reduce invasive calibration to a minimum, often requiring only 12 samples to obtain a statistically valid calibration. An example of a ground conductivity map of a small watershed is shown in Figure 11; the brown areas indicate zones of higher electrical conductivity and deeper soils.

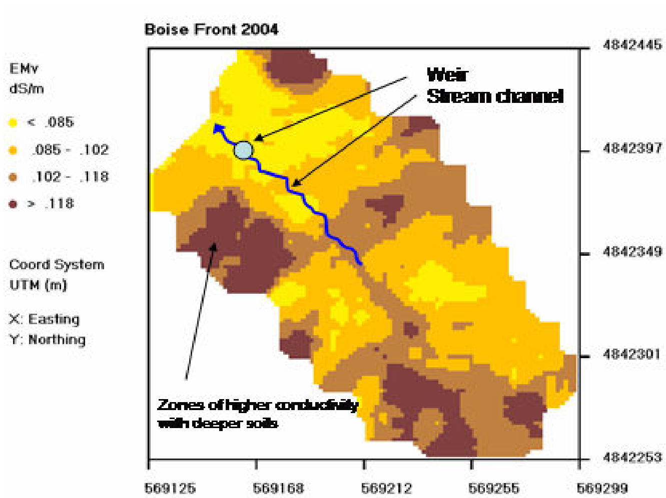

Figure 11 Bulk electrical conductivity of a catchment, zones of higher conductivity indicating locations of greater soil development.

4.5 Ground Penetrating Radar (Surface-based GPR)

Ground penetrating radar (GPR) is an electromagnetic method that utilizes the transmission and reflection of high frequency (1 MHz to 1GHz) electromagnetic (EM) waves within the subsurface; typically sub-meter to tens of meters and even greater over thick resistive out crop. Descriptions of the fundamental principles of GPR can be found in publications by Daniels et al. (1988) and Davis and Annan (1989); and an overview of its use for environmental applications is given in Knight (2001) and for soil water determination in Huisman et al., (2003). GPR data can be collected using a surface-based system, where the transmitter and receiver antennas are moved across the earth’s surface; or in a cross-hole system, where the antennas are positioned in boreholes; or a combination of the two. In all cases, the acquired GPR 'image' is a representation of the interaction between the transmitted EM energy and the spatial variation in the complex, frequency-dependent EM properties of the earth materials in the subsurface.

In the interpretation of GPR data, it is commonly assumed that the primary control on the velocity of EM waves, and the reflection of EM energy, is the dielectric constant κ' (the real part of ε, normalized by ε of free space). Because of the large contrast between κ' of water (κ'=80) and that of air (κ'=1) and minerals (κ'~5), GPR data contain information about the subsurface variation in water content. It is this sensitivity to water content, or water-filled porosity that is the basis for many of the hydrologic applications of GPR. The electrical conductivity of the subsurface has a significant impact on the attenuation of EM energy, thus limiting the depth range of the GPR measurement.

GPR can be used to image the structure of the subsurface over a large area (kilometers or more) or at a specific test site (a few meters in lateral extent). GPR data are recorded as the arrival time of reflected energy and used to obtain a time section; to convert to a depth section, the EM velocity must be known. Given that EM velocity varies laterally, as well as with depth, understanding the possible errors in the depth sections is a critical part of considering the acquisition and interpretation of GPR data. If wells are present, GPR data can be acquired between wells, and information from the wells can be used in the interpretation.

The resolution and penetration depth of the resulting GPR images can be varied through the use of different antennae frequencies. Typically, higher frequencies increase the resolution at the expense of the depth of penetration. GPR data can be used to image specific features or boundaries such as the water table, depth to bedrock, and fractures. GPR images also contain information about the subsurface variation in lithologic units or lithofacies, and about the sedimentary structure within lithofacies. The interpretation of GPR data typically uses an approach referred to as radar facies analysis (e.g., Beres and Haeni, 1991), which divides the radar image into regions similar in appearance, and then assumes a link between the radar facies and lithofacies.

There is much interest in the use of GPR data to obtain estimates of subsurface properties such as water content in the vadose or unsaturated zone, porosity in the saturated zone, and permeability. This requires two steps: obtaining the subsurface model of EM velocity, and transforming the velocity model to the subsurface property of interest. While there have been studies that have obtained estimates of EM velocity to depths of tens of meters from surface-based GPR data (e.g., Greeves et al., 1996) the data acquisition is time consuming and likely to yield velocity estimates with spatial resolution on the order of meters to tens of meters. The one relatively simple application of GPR, where good estimates of EM velocity can be obtained, is through the detection of the direct ground wave, which travels from the source to receiver antenna through the top-most layer of the soil (Du, 1996). The uncertainty in this method is the true depth of the sampled region.

The transform of the velocity model to a model of the subsurface property of interest requires knowledge of the rock physics relation that relates the geophysical parameter, EM velocity, to the material property of interest. These relations studied in the laboratory, are site-specific and scale-dependent. Two approaches that have been taken are to calibrate the radar data at a field site using other forms of data (e.g., neutron probe), or to assume that the Topp equation (Topp et al., 1980) is valid. But simple models of geologic systems have shown that neglecting heterogeneity can lead to significant errors in estimates of water content. What is required is a means of quantifying the heterogeneity that exists within the sampled regions if radar-based dielectric measurements are to be used to provide accurate estimates of hydrogeologic properties.

The need to quantify spatial heterogeneity introduces another way in which radar data can contribute to watershed-scale studies. This can be described as an image-based approach where, rather than assigning EM velocities to specific volumes in the subsurface, we use all of the sub-meter scale information that can be seen in the radar image to quantify the spatial variability in the imaged, subsurface properties.

For small-scale site-specific experiments, GPR can be used to monitor the movement of water into and through the subsurface. Time-lapse or 4D GPR imaging has been used to capture the movement of water and other fluids into the subsurface during controlled experiments. While these images provide useful qualitative information, the accurate use of these images to quantify subsurface properties requires more research to account for changes in EM velocity during the monitored process.

The use of radar images for near-surface applications can involve both qualitative and quantitative interpretation of the recorded information. The methods currently used for processing and visualization of radar data make it possible to produce well-focused radar images that can be used in a qualitative way to obtain information about the structure and stratigraphy of the subsurface, and to locate regions of anomalous EM properties. For some applications, more quantitative information about the physical, chemical and/or biological properties of regions of the subsurface are required; for such applications, more research is needed to advance our understanding of what is captured in a radar image.

GPR instruments

A wide variety of GPR instruments are now available commercially. Systems range in the level of complexity based on the envisioned task for the instrument. Instruments of broad interest to hydrological research in watersheds for making surface measurements of 2D sections are available from a range of companies with prices between $20,000 and $30,000 typically. Good examples of robust, general purpose, mobile, field instruments include, the Noggin with smart cart (Sensors and Software Inc, Mississauga, Ontario, Canada) that can be used with 250, 500 or 1000 MHz antennas (Fig. 12). The instrument has a digital video logger enabling the user to see data profiles collected, 'on the fly'. The PulseEKKO system from the same company offers greater depth measurement flexibility to the user. This system can also be mounted on a smart cart with GPS and has antennas ranging from 12.5 MHz to 1000 MHz. The

Figure 12. Noggin smart cart GPR, courtesy of Sensors and Software inc.

Pulse EKKO is adaptable and can also be used with borehole antennas. Similar systems are available from Geophysical Survey Systems Inc (GSSI, Salem, NH) like the 3D capable SIRveyor, which is also GPS compatible; and the RAMAC system (Mala Geoscience USA, Inc., Charleston, SC) with shielded antennas up to 1.6 GHZ for the very near surface.

4.6 Electrical Resistivity Imaging (ERI)

Electrical resistivity imaging (ERI) is defined here as imaging from the surface, whereas electrical resistance tomography (ERT) is used to describe borehole measurements. ERI is a direct-current (or low-frequency alternating-current) resistivity method that can be used to estimate the distribution of electrical resistivity (the reciprocal of electrical conductivity) in the subsurface. In the field, a series of electrodes are attached to the resistivity meter for data collection. Resistance data are collected by establishing an electrical gradient between two source electrodes and measuring the resultant potential distribution at two or more receiving electrodes. This procedure is repeated for as many combinations of source and receiver electrode positions as desired, and usually involves the acquisition of many hundreds or thousands of multi-electrode combinations. Each measured resistance is an average of the electrical properties of both solids and liquids in the system (Keller and Frischknecht, 1966). After data inversion, ERI can provide a series of 2 or 3D tomograms, where each tomogram shows the distribution of electrical resistivity in the subsurface. Electrical imaging is possible at the sub-meter- to tens-of-meters scale in the field, and can be used to reveal static properties such as subsurface structure and hydraulic pathways as well as temporal changes associated with moisture and/or water quality. Whereas water in its pure state is non-conductive, the presence of even small amounts of chemical salts in solution produces a conductive electrolyte detectable with resistivity methods. Some advantages of resistivity methods for hydrological studies include: (1) many hydrological features, such as clay layers, variable moisture content, high salinity, etc., provide reasonably straightforward targets for resistivity methods; (2) instrumentation is relatively inexpensive, robust, and easy to operate; (3) imaging tools, particularly for surface imaging, are mature and available commercially. Resistivity imaging, however, also includes disadvantages: (1) direct contact with the subsurface is needed (which is problematic in areas with resistive ground cover, such as highways, permafrost, etc.); (2) electrode array coverage of an area can be labor intensive, particularly for long (several 100 m) arrays; (3) data collection can be relatively slow and limit monitoring of some dynamic processes; and (4) processing the data, despite commercially available code, is difficult for quantitative interpretation of hydrogeologic processes. The depth of penetration depends on the electrical resistivity of the subsurface, the spacing of the electrodes, and local noise, and thus is difficult to quantify exactly. Many surface studies image resistivities from a meter below ground surface down a few tens of meters, and cross-well studies commonly have boreholes spaced on a similar scale.

Electrical Resistance Imaging Instrumentation

ERI has been used to determine the extent of conductive contaminant plumes or saltwater intrusion (Zohdy et al., 1993; Frohlich et al., 1994), and for locating voids, such as fractures, mine shafts, and karst terrain (Smith, 1986). Because ERI is sensitive to changes in fluid electrical conductivity and water content, it has been used for monitoring time-varying processes, such as changes in moisture in the vadose zone (e.g., Binley et al., 2002; Yeh et al., 2002) and the transport of conductive tracers in ground water (Slater et al., 2000; Kemna et al., 2002; Slater et al., 2002; Singha and Gorelick, 2005). Improvements in electrical components have advanced ERI technology over the last 15 years. A major step forward lies in the ability of new equipment to measure multiple channels simultaneously rather than having to switch to each one individually to measure.

Several ERI multi-electrode instruments are available, a number of which have multi-channel capability. Systems typically consist of a single control unit with PC connection and multi-electrode cable connection (Fig. 13). Some systems offer 'smart' electrode capability. Such systems allow a reduction of the number of electrical cores in the multi-core cable, thus minimizing the weight of electrode cables. A disadvantage of these systems is the increased cost per electrode (as a signal receiver unit is required for each electrode) and also some constraints on the flexibility of addressing electrodes in mult-channel operation. Several multi-electrode units are available, including: Syscal Pro from Iris (France) (http://www.iris-instruments.com/Pdf%20file/SyscalPro_Gb.pdf); SuperSting from AGI (USA) (http://www.agiusa.com/supersting.shtml); Resecs from Geoserve (Germany), for example, the RESECS (http://www.dmt.de/index.php?id=1060&L=1); Tigre from Allied Associates (UK), (http://www.allied-associates.co.uk/); and SAS4000 from Abem (Sweden) (http://www.abem.se/products/sas4000/sas4000.php).


Figure 13. Example ERI system consisting of control unit, electrode cables and electrodes.

A number of these units offer multi-channel capability and also can be configured to allow remote acquisition of data using telephone connections (see, Daily et al., 2004a for an example of such a configuration for monitoring leaks from underground storage tanks). All units can be used with specific surface array multi-core cables or configured to work with electrodes in boreholes. Many ERI systems also offer induced polarization (IP) capability. A 96-electrode ERI/IP unit complete with surface cables and 10 channels would typically cost around $60,000. Single channel units are less expensive. Recent investigations (Crook et al., 2006; Freyer et al., 2006; Day-Lewis et al., 2006) suggest that ERI may help us to understand ground-water/surface-water interactions, an important component of watershed analysis. These interactions along streams and rivers are currently quantified using point-source monitoring equipment such as mini-piezometers, seepage meters, and temperature surveys (e.g., Conant, 2004); however, because exchange between ground-water/surface-water regimes depends on many complex factors, such as bedrock topography, temporal climatic variations, sediment types, and hydrologic properties of the materials (Oxtobee and Novakowski, 2002), it can be problematic deciding where to deploy monitoring equipment or how to interpolate between point measurements. ERI data can be collected rapidly and continuously by towing a streamer behind a boat, or in non-navigable waters, by laying a multi-electrode cable along the bottom of the stream (Fig. 14). The continuous measurements can potentially be used to guide the placement of seepage monitoring equipment and to interpolate between point measurements.

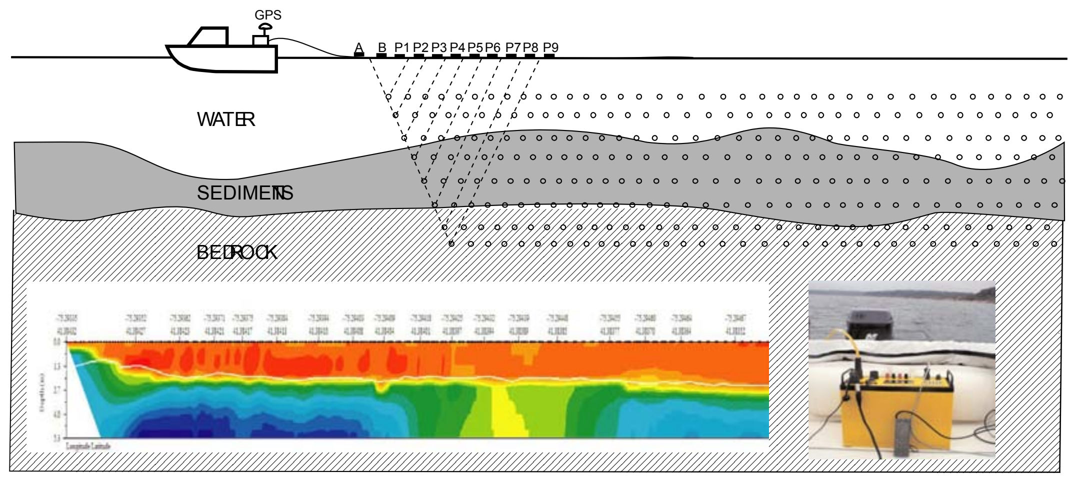

Figure 14. Multi-electrode cable towed by boat with GPS positioning and example resistivity profile.

4.7 Induced Polarization Instruments (IP)

Recent research advances in induced polarization (IP) have made IP a promising emerging hydrogeophysical technology. The measurement is essentially an extension of the traditional four-electrode resistivity technique whereby an electric current is injected between a current electrode pair and the resulting voltage induced in the earth is measured between a potential electrode pair. The IP technique, however, captures both the charge loss (conduction) and charge storage (polarization) characteristics of the soil at low frequencies (< 1000 Hz). *Spectral* induced polarization is a further extension of the four-electrode technique whereby the frequency dependence of the loss and storage terms is also retrieved over some specified frequency range. Exploration depths for IP in hydrogeophysical surveys have been found to range from less than a meter to a few tens of meters.

IP provides some unique information that is not obtainable from established hydrogeophysical surveys. It is important to recognize that the conductivity of the soil is determined as part of the method. The magnitude of the polarization, however, as well as the frequency dependence of the conduction and polarization terms, provide unique information that helps to better constrain the hydraulic characteristics of the soil and could provide a significant hydrogeophysical contribution to the development of a 3D electrical resistivity model of a watershed. At low frequencies, charge storage (polarization) is an interfacial mechanism occurring primarily within the electrical double layer at the mineral-fluid interface. The magnitude of this polarization (obtained from a single frequency IP measurement) depends on both physical and chemical properties of the mineral-fluid interface. When pore-fluid conductivity is within the range typical of natural ground water, the overriding control on the polarization is the amount of the mineral surface in contact with the pore fluid. As a result, IP measurements are found to show a close (near linear) dependence on the specific surface area to pore-volume ratio (S_p) of soils as illustrated in Figure 15a (Börner and Schön, 1991; Slater et al., 2006). This property of the soil is a measure of the inverse hydraulic radius, and therefore, exerts a critical control on hydraulic conductivity. As porosity can be estimated from the conductivity recorded during an IP measurement, electrical derivatives of the Kozeny-Carmen equation can be formulated having an order of magnitude or better predictive estimates of hydraulic conductivity (Börner et al., 1996; Lima and Niwas, 2000; Slater and Lesmes, 2002). Researchers are now beginning to explore how IP measurements may also sense modifications to the physical and chemical properties of the mineral-fluid interface as a result of geochemical and biogeochemical reactions associated with ground-water flow and solute transport (Abdel-Aal et al., 2004; Ntarlagiannis et al., 2005).

Spectral induced polarization (SIP) measurements provide additional unique hydrogeophysical information because the frequency dependence of the conduction and polarization terms is a function of how the specific surface area is spread across the pore (or grain) size distribution of the soil. Frequency-dependent data are most commonly modeled using phenomenological models, such as the Cole-Cole relaxation, from which a characteristic time constant (τ) is retrieved. This time constant is inversely related to the polarization length scale at the mineral-fluid interface. Consequently, empirical relations between τ and pore/pore throat size are reported (Binley et al., 2005; Scott and Barker, 2005). In a recent paper a strong direct empirical relation between τ and K was reported (Fig. 15b), leading the authors to suggest that the length scale of the polarization is directly related to the hydraulic length scale determining ground-water flow (Binley et al., 2005).

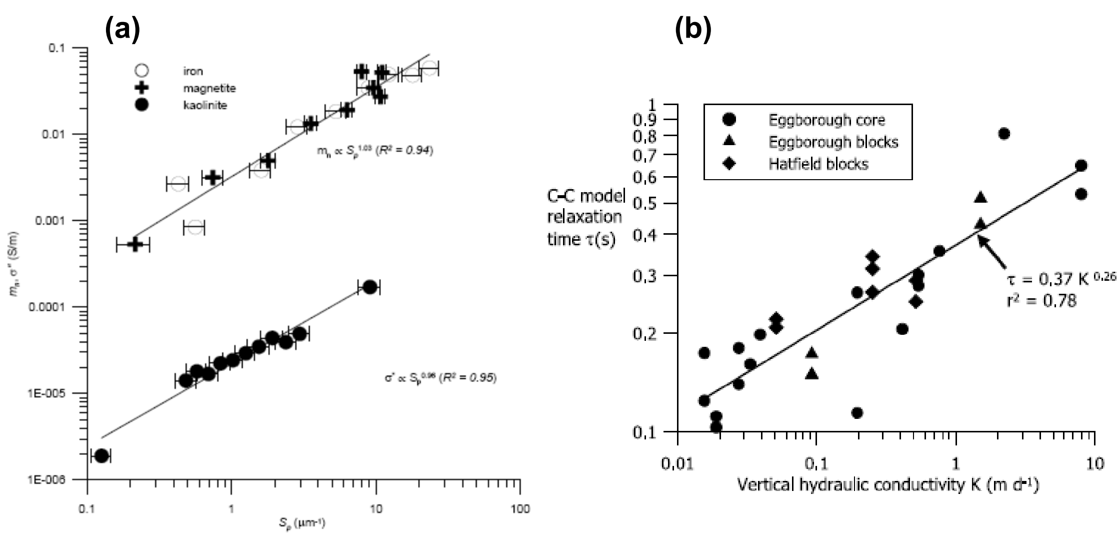

Figure 15: (a) IP parameters (m_n, σ") as a function of surface area to pore volume (S_p) for a range of three artificial soils (data from (Slater et al. 2006) (b) Cole-Cole relaxation time constant (τ) as a function of vertical hydraulic conductivity (K) for sandstone samples (data from Binley et al., 2005).

Induced Polarization Instrumentation

IP instruments fall into two basic categories (1) frequency-domain instruments that sweep a waveform across a range of discrete frequencies and measure the conductivity magnitude and phase shift of the soil relative to a known precision resistor; and (2) time-domain instruments that yield a proxy measure of the phase shift by integrating the voltage decay curve recorded for a soil sample after abruptly shutting off the current source. In this section, we consider only frequency-domain instruments because these instruments offer the potential to exploit the full capabilities of the SIP measurement by accurately capturing the frequency dependence of the electrical properties of the soil.

Two examples of SIP instruments have been utilized in hydrogeophysical research and are adaptable to field scale studies (Fig. 16). The more mature instrument is the Zonge GDP32 manufactured by Zonge Engineering (USA). This instrument (and accessories) was originally built for mineral exploration but has been modified for shallow subsurface studies. The second instrument is the SIP Fuchs II manufactured by Radic Research (Germany) and specifically targeted at hydrogeophysical research. The major difficulty with obtaining accurate SIP measurements in the field is compensating for the effects of electromagnetic and/or capacitive coupling between the wiring that is used to connect the electronics to the electrodes. The Zonge GDP32 attempts to minimize such coupling effects by careful calibration of the pre-amplifiers on all measurement channels. The SIP Fuchs II utilizes fiber optic cables and appropriate decoder boxes to transmit the electrical signals between the instrumentation electronics and the earth. Both instruments also utilize data-processing techniques to estimate and remove coupling effects from the data after acquisition. Either way, user experience indicates that the frequency range whereby reliable IP measurements are obtained is limited in the field (perhaps 10-100 Hz maximum, depending on instrument and site conditions). Data quality is very much a function of site conditions, measurement frequency, and user experience. The phase of soils can be recorded with about 1 mrad accuracy with both instruments when appropriate calibration procedures are performed. Both companies manufacture the hardware and software required to permit automated electrical measurements on an array of electrodes as is now the standard in electrical imaging. Both instruments are ruggedized for field-based research and could be used in a wide range of environments. Instrument costs depend on the application and related supporting hardware requirements. As a general guide, the cost of a field-scale SIP-Fuchs system would be in the range of \$60,000-\$80,000 whereas a Zonge GDP32 system would be in the range of \$80,000-\$100,000. Because IP/SIP is an emerging technology, the current availability of data interpretation

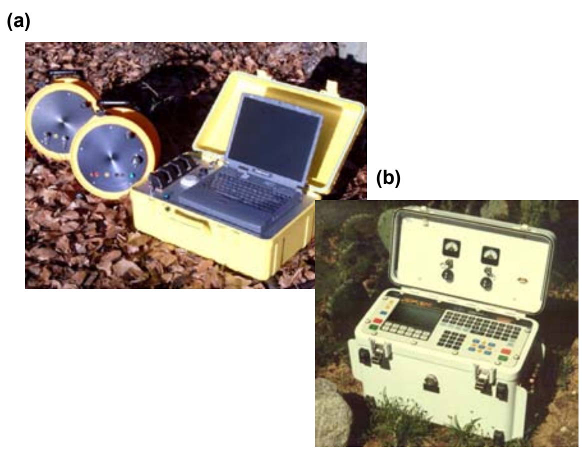

Figure 16: (a) SIP Fuchs II base unit and fiber optic cable reels (b) Zonge GDP32 receiver

packages is limited. Some commercial software does exist to invert basic IP data collected at a single frequency for realizations of the subsurface distribution of electrical conductivity and polarization. Commercial software for the inversion of SIP data is currently non-existent.

5. High Temporal Resolution Measurements at Point to Catchment Scales

5.1 Borehole Methods ERT/GPR

Borehole radar methods measure differences in the propagation speed and amplitude attenuation of electromagnetic radio waves in different materials to detect variations in subsurface properties. Borehole radar reflection logging is similar to surface-radar reflection profiling; the transmitter and receiver are oriented vertically in a single borehole and separated by a fixed distance. Radar waves transmitted into the bedrock surrounding the borehole travel through the bedrock until they arrive at an interface with different electromagnetic properties. At this interface, some of the radar energy is reflected back toward the receiver and some radar energy continues farther into the bedrock. Because borehole radar methods are based on the transmission of electromagnetic waves, they depend on differences in the electromagnetic properties of the medium through which they travel. Borehole radar data are limited by radar wave attenuation in the earth and borehole radar equipment. The radius of investigation and the data resolution depend on the frequency of the radar antenna used (frequencies usually range between 10 and 1000 MHz) and the electromagnetic properties of the surrounding rock and water in the borehole. In highly resistive granitic and gneissic rocks, the depth of penetration may be as much as 40 m from wells. In more conductive media, such as geologic materials containing salt water or mineralogic clay, the penetration of the radar signal may be limited to distances of less than 5 m. High-frequency radar wave surveys provide high-resolution data collection, but a relatively small radius of penetration when compared with most surface-based geophysical methods. Conversely, lower antenna frequency increases penetration distance while reducing resolution.

Borehole radar reflection methods provide information regarding the extent and orientation of features that intersect the non-metal borehole wall as well as features in the surrounding rock. Radar reflection logging can be conducted in non-directional or directional mode. During logging, the transmitter and the receiver, separated with fiberglass spacers, are moved down the borehole. Measurements are often recorded at 0.1 to 1.0 m intervals to maximize vertical resolution. A directional receiver acts like four separate antennas, oriented orthogonally to one other, so the radar signal is received by each of the four antennas at different times. This method allows for the determination of a reflector's orientation, as well as its distance from the borehole. Non-directional antennas do not allow for unique determination of the orientation of a reflector. Two common features detected in single-hole radar reflection surveys are planar surfaces, such as fractures, and point reflectors, such as voids. The ability to delineate fractures and fracture zones is important because secondary fracture systems in bedrock aquifers can control the ground-water flow.

If multiple closely spaced (1-20 m) boreholes are available, cross-hole images may be obtained. Cross-hole tomography is the process by which a 2D (or 3D) image of a section between two (or more) wells is made (see, for example, Binley at al., 2001). These surveys can be used to identify the presence of fracture zones and lithologic changes between wells. Data obtained from these surveys include travel time and attenuation of the radar wave as it travels from the transmitter in one well to a receiver in a second well. For these surveys, the transmitter location is fixed in one borehole, and readings are taken at regular intervals as the receiver is moved down the length of the second borehole. The intervals are kept short to avoid undersampling. The transmitter is then moved to a station farther down the borehole, and the process is repeated until a complete data set is acquired.

Cross-hole ERT can be carried out in the same manner as surface ERI, in this case using electrodes installed in boreholes (and the surface, if required) – see Daily et al., (2004b). Since ERT requires electrical contact between the soil and the electrode, borehole electrodes for vadose-zone studies are usually installed as sacrificial electrodes. In contrast, for saturated-zone ground water investigations, the water column in an open (or slotted) well can be used as contact between electrode and formation and thus electrode arrays may be retrieved after the survey is completed. Care must be taken, however, for such installations as the water column can have a significant affect on the current flow and effectively short circuit current electrodes, resulting in loss of sensitivity of specific measurements (see Osiensky et al., 2004).

5.2 Dielectric Water Content Sensors

The relation between soil water content and stream flow is a fundamental part of understanding the hydrologic cycle, especially the monitoring and modeling of the land surface, water, and energy balance (Arrigo and Salvucci, 2005). In terms of a hydrological stock, soil-water content availability is recognized as the controlling resource in the organization and functioning of many ecological systems (Rodriguez-Iturbe, 2000). Atkinson et al. (2002) demonstrated that in order to predict hydrological response at shorter time scales, model complexity had to be increased, incorporating more subsurface information, with the description of soil storage being critical. Obtaining both high temporal and spatial measurements of soil water content is therefore, an important challenge for understanding and accurately describing hydrological response.

Soil water content determination was revolutionized through improvements in electrical components, which paved the way for the pioneering work of Topp et al. (1980) on time domain reflectometry (TDR); and the development of high frequency capacitance probes (Dean et al., 1987). Since the 1980's, the TDR method has developed and is now recognized in soil science as a standard method for soil water content determination at a point (Dane and Topp, 2002). TDR (Robinson et al., 2003b) is the tool of choice for many applications; systems such as the TRASE and Mini TRASE (Soil Moisture Equipment Corps, Santa Barbara, CA) are rugged field portable instruments and can be attached to probes varying in length using their waveguide connector (Fig. 17). For in-situ monitoring, Campbell Scientific (CSInc, Logan, UT) produces the TDR 100 that is compatible with their range of data logging equipment. TDR can be expected to estimate water content to an accuracy of about ± 2% without soil specific calibration in coarse-textured soils. Where soil composition contains more 2:1 clay minerals, soil-specific calibration will be required. All EM water content sensors perform poorly in saline soils. Several particularly promising devices that are commercially available and could advance hydrological research in the next 3-5 years are discussed in the following section.

Instrumentation

The Acclima, Time Domain Transmission (TDT) sensor is an exciting instrument to emerge in the irrigation market (Blonquist et al., 2005a). This sensor uses cutting-edge, cell phone technology incorporated on a chip, mounted in the head of the sensor (Fig. 17). TDT is much like TDR, other than the signal propagates around a sensor loop rather than being reflected from the end of the sensor electrodes. Evaluation of the sensor demonstrates that it has a rise time comparable with a $12,000 Tektronix TDR (Blonquist et al., 2005a). The manufacturers specification sheet indicates that the sensor can resolve time differences of 25 picoseconds, which relates to differences in water content of 0.2%. The voltage that the sensor works at is about 1 volt, which also gives the TDT better signal penetration into the soil than conventional TDR instruments operating at about 0.3 V. In addition, this sensor is superior to TDR for in-situ measurements because the measurement circuit is mounted in the head of the sensor so that the signal is not distorted running down long lengths of cable; moreover, the sensor simultaneously estimates bulk soil electrical conductivity and soil temperature, both of which are useful for hydrological studies. After the measurement is processed by the sensor chip, the information is sent by conventional twin wire to a data logger. This overcomes the cable length constraint to which TDR measurements have been subject. TDR sensors cannot be placed farther than about 30 m from the TDR to obtain reliable measurements due to signal attenuation along the cable. Chip technology means value for money and presently this sensor retails for about $300, making multiple installation affordable. The manufacturer is currently working on a digital/analog interface so that the TDT can be linked to a traditional data logger, this is due for launch before 2007. One of the constraints with the current design is the use of a loop instead of two rods, which can make it more difficult to install in the soil; though this has not been a limitation to its primary application in turf grass management. The manufacturer is currently working with a prototype of a two-electrode design, similar to a TDR probe, to offer easier installation that would be more suited to hydrological application.

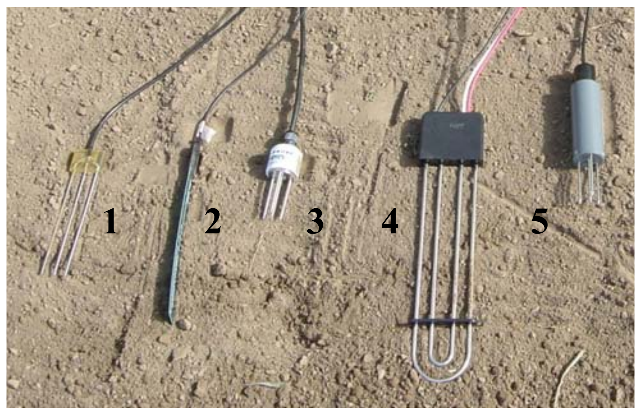

Figure 17. Soil moisture sensors, 1) TDR, 2) ECHO Probe, 3) Hydra Probe, 4) Acclima TDT sensor, 5) Theta probe. As a scale the TDR rods are 0.15 m long.

Impedance probes tend to be short (<0.1m) fixed-frequency devices, operating at lower frequencies than TDR, usually between 50-100MHz, which makes them more susceptible to the effects of dielectric dispersion and bulk soil electrical conductivity

(Blonquist et al., 2005b). Sensors operating at these lower frequencies will need soil-specific calibration for the best results. Field calibration is more important than with TDR or TDT devices. However, impedance sensors have found a good niche for calibrating remote-sensing data because they measure approximately the top 0.05m of soil. The theta probe (Delta-T Devices, Cambridge, UK) has proved popular for a number of years and is easy to use (Gaskin and Miller, 1996). The probe operates at 100 MHz and gives a DC voltage output that can be linked to a data logger or a handheld device that can be purchased with the instrument. An alternative sensor gaining in popularity is the Hydra probe (Stevens-Vitel, Beaverton, OR). Although the Hydra probe operates at 50 MHz, it has circuitry that can determine the bulk soil EC and the real and imaginary parts of the permittivity. This allows water content to be determined from the real part of the permittivity, reducing the interference effects of bulk soil EC; in addition the sensor can measure soil temperature. Recognizing that their first ECH2O probe operated at too low a frequency to give reliable results, Decagon (Pullman, WA) has raised the operating frequency from ~5 MHz to 70 MHz, which should improve performance, though the sampling volume of this sensor remains limited. All these instruments are competitively priced at less than $300.

6. Advances in other Geophysical Techniques

6.1 Seismic Methods

For more than 60 years, surface seismic methods have found applications and challenges on land and water throughout the near-surface engineering and environmental communities (e.g., Haeni, 1986; Miller et a., 1989; Steeples and Miller, 1990; Pullan and Hunter, 1990; Pelton, 2005; Steeples, 2005). Exploration depths range from a few meters to a few hundred kilometers. Unique to seismic relative to all other geophysical methods is the sensitivity to speed of propagation of various types of elastic waves, which is in turn related to both elastic properties and mass density of the medium in which the waves are traveling. Generally, seismic methods involve measurements of time between the generation of a seismic pulse and its arrival as a wavetrain at seismic sensors a known distance away. Some methods only require calculation of relative time between arrivals of the seismic wavetrain at different sensor locations. Measurements of time, combined with source pulse attributes, can be used to extract seismic characteristics of materials, which are related to elastic rock properties (Fig. 18).

Unlike other geophysical techniques, seismic energy is multi-modal (i.e., different types of waves are present in the data) and can be acquired and processed to enhance any one of several different possible components of the wavefield. The methods, configurations, and cost of using seismic surveys vary widely based on application, resolution requirements, and site conditions, but they generally are on the high end of geophysical survey costs. Counter-intuitively, the cost of seismic surveys is inversely proportional to target depth because of the need for closely spaced seismic sensors in shallow surveys. Mapping bedrock with seismic refraction has probably been the most common approach used for hydrology studies. On the other hand, seismic reflection for imaging rock intervals at high resolution and interpreting inter-bed character is the most extensively studied and theoretically developed technique, mainly due to its effectiveness in oil exploration. Cost and complexity of the analysis have limited use of reflection to address near-surface hydrologic problems. Recent emergence of multi-channel surface wave techniques has kindled significant interest for potential hydrologic applications. Seismic applications to hydrologic problems have focused on mapping bedrock, delineating confining units, resolving lateral variability in material properties, and distinguishing lithology.

Seismic methods do not lend themselves to distinguishing different types of interstitial liquids. Distinguishing dense non-aqueous phase liquids (DNAPLs) or light non-aqueous phase liquids (LNAPLs) from within a saturated interval is beyond the resolution of the seismic tools; however, interrogation of the subsurface in search of lithologies or structures that might represent traps for contaminants has proven effective.

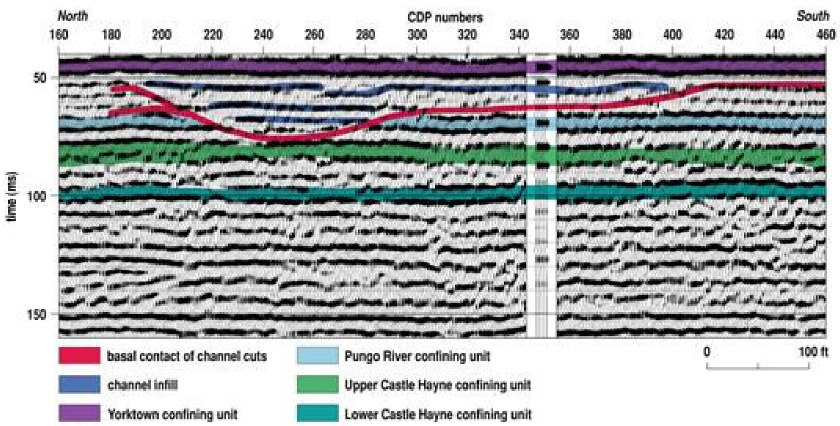

Figure 18. Interpreted high resolution, 12-fold CMP seismic reflection stacked section with inset VSP from Cherry Point, North Carolina. Shallow channels are mapped that penetrate the aquifer's confining layers.

6.2 Uses of Ground-Based Gravimetry for Hydrologic Investigations

Spatial gravity data traditionally have been used effectively to determine the subsurface configuration of structural basins, owing to large density contrasts between basin fill and surrounding bedrock. With only slight modification, this approach can be used successfully to estimate maximum aquifer thickness in basins, which then serves to constrain the base of basin-scale regional ground-water flow models (e.g., Bartolino and Cole, 2002; Langenheim et al., 2005; Pool, 2005). Gravity data can also be used to distinguish carbonate from sandstone aquifers, which is difficult to accomplish using electrical resistivity or magnetic properties.

Gravity data for these applications can be collected using a relative gravimeter and a differential GPS system for accurate vertical location. The gravimeter measures relative differences in the vertical component of the earth's gravitational field based on variations in the extension of an internal spring. The instruments are already widely available at academic and government institutions. Alternatively, they can be purchased for about $80,000 (standard Scintrex meter) or rented for about $1000/week. Instruments are easy for a small crew to operate, but the data require extensive processing and corrections for external effects before they can be modeled. Accuracies for normal field operations are about 20 μGal, decreasing to about 1-5 μGal only with great care

(Nabighian et al., 2005b). On the other hand, gravity data appropriate for basin-scale models are already publically available for much of the conterminous U.S. (http://paces.geo.utep.edu/research/gravmag/gravmag.shtml)

Temporal methods of gravity measurement using absolute gravimeters can be used to measure the total mass of water in a conceptual column and can therefore be used to examine temporal changes in the regional or local mass balance of water. This application is particularly well suited to measurement by microgravity (absolute gravimeters), especially following recent improvements in their portability and durability (Nabighian et al., 2005b). Absolute gravimeters operate by measuring the rate of fall of a control mass. They measure the value of g at a given location to accuracies on the order of 1 μGal (Nabighian et al., 2005b), and do not require comparison to another control location. Accurate corrections for external effects must still be made. These instruments are used less commonly and are relatively expensive. Micro-g Solutions is the only commercial manufacturer of free-fall absolute gravimeters (www.microgsolutions.com). The A-10 model costs around $300,000. The high price reflects the current low demand for this technology.

Most measurements of water content (change) are made at a point scale. Some methods (e.g., ERT) can be applied at large scales, but these methods are rarely used for water content monitoring below the 10 m depth. Gravity has an essentially infinite depth of measurement, making deep water content monitoring possible. Gravity, however, gives only a spatially weighted cumulative measure of the change in water content in the subsurface. As a result, gravity measurements must be used in a coupled hydrologic/instrument response framework to be useful for hydrologic applications. The first example of this application was presented by Pool and Eychaner (1995), they used time-lapse gravity measurements together with water-level measurements made in monitoring wells to infer the specific yield of an aquifer. Implicit in their interpretation was a hydrologic conceptual model of complete drainage throughout the vadose zone and a flat-lying water table. Applications of gravity to more complex conditions are currently being investigated: monitoring infiltration and redistribution beneath ephemeral streams and artificial recharge facilities; and constraining unconfined aquifer pumping tests using gravity. Initial results indicate that gravity methods, when interpreted in the correct modeling framework, can be used to infer hydraulic parameters. This conclusion applies to both relative and absolute gravimeters used either alone or together with other measurements.

6.3 Magnetic Resonance Sounding

Nuclear magnetic resonance shows tantalizing promise for the future, with lab results proving its potential for water content and porosity determination (Hinedi et al., 1997). Field systems have been deployed with application to hydrogeology (Legchenko, et al., 2002; Legchenko and Valla, 2002; Lubczynski and Roy, 2004). At present, the only field system is the NUMIS MRS equipment, which is manufactured in France and is designed to determine water content and porosity to depths of up to 1500 m (IRIS Instruments, Orleans, France). The system requires a knowledgeable user to conduct experiments and interpret the data; currently, users are expected to attend a 2-week training workshop in France to become competent in the equipment usage. The undetermined effect of iron minerals on the MRS signal may limit its utility in some applications.

7. A Synergistic Approach to Geophysical Measurement and Hydrological Modeling

7.1 Geostatistical Approaches to Data Integration

Geostatistics provide a framework for the integration of hydrologic and geophysical data. Methods fall into two categories: estimation and simulation. For a given property of interest, the former yields maps (or volumes) of best estimates, whereas the latter yields multiple realizations, i.e., equally probable maps (or volumes). Both estimation and simulation are readily conditioned to direct measurements, available secondary measurements of a related property (e.g., a seismic or radar tomogram), and a model of spatial variability (e.g., a variogram or spatial covariance). Although estimation methods produce confidence intervals, simulation methods are required to fully explore the uncertainty arising from sparse or incomplete data. For example, a suite of geostatistical simulations of permeability can be input to a hydrologic simulation model to evaluate the probabilistic shape and extent of a pump-and-treat capture zone, given limited permeability and, possibly, geophysical measurements.

Public-domain and commercially available software are used increasingly for hydrologic investigations (e.g., Deutsch and Journel, 1998; Carle, 1999). Indeed, geostatistical tools are now included in several popular graphical user interfaces for ground-water modeling (e.g., GMS), as well as in software for geographic information systems. A growing body of literature documents applications where cokriging, conditional simulation, and Bayesian approaches were used to integrate geophysical and conventional hydrologic data (McKenna and Poeter, 1995; Cassiani et al., 1998; Hubbard et al., 2001); the general conclusion from studies is that geophysics provides cost-effective information between wells, where direct hydrologic measurements are unavailable.

Petrophysics plays a critical role in geostatistical integration of hydrologic and geophysical data. Theoretical, general empirical, or site-specific models are needed to relate the geophysical and hydrologic parameters. For electrical and EM methods, useful empirical models include Archie's Law (Archie, 1942), the CRIM (Birchak et al., 1974), and the Topp Equation (Topp et al., 1980). Applications of petrophysical models to geophysical survey results are commonly based on the assumption of stationarity in the relation between geophysical estimates and hydrologic parameters. For example, given laboratory measurements on cores, the relation between radar velocity and the logarithm of permeability, $\ln(k)$, might be modeled as linear, and the strength of the relation might be quantified with a simple correlation coefficient. Geostatistical simulations of $\ln(k)$ could then be generated conditioned to (1) hard permeability measurements, and (2) a radar velocity tomogram. This approach would assume that the relation derived at the core-scale applied uniformly at the scale of the tomogram. It has long been known that electrical core-scale measurements do not apply at the scale of insitu measurements.

Tomograms, as solutions to underdetermined inverse problems, are commonly blurry and blunted versions of reality. The resolving power of tomography is a longstanding and important topic in the geophysical literature (Backus and Gilbert, 1968; Menke, 1984; Rector and Washbourne, 1994; Schuster, 1996; Alumbaugh and Newman, 2000; Dahlen, 2004). The fact that model resolution posed a potential issue for geostatistics was first recognized by Cassiani et al. (1998), but only recently have the implications for geostatistics been quantified (Day-Lewis and Lane, 2004; Day-Lewis et al., 2005). Inversion regularization, measurement physics, measurement error, spatial variability, and limited survey geometry result in weaker relations between geophysical estimates and hydrologic properties compared to those observed for cores or possibly co-located measurements in boreholes; furthermore, the strength and possibly form of the relation will vary spatially. A positive conclusion of this work is that pixel-scale relations may be predicted and used for field-scale calibration of tomograms. A second positive conclusion is that different electrical resistivity and GPR techniques—both sensitive to electrical conductivity contrasts—may provide complementary information. Whereas GPR provided superior resolution in the middle of the cross section between wells, ERT performed better near boreholes.

To address the issue of spatially variable resolution, Moysey et al. (2005) developed a geostatistical approach that builds field-scale petrophysical relations based on synthetic experiments for numerical analogs of field surveys. The Monte Carlo approach involves (1) geostatistical simulation of correlated random fields of geophysical and hydrologic properties; (2) numerical simulation of the geophysical measurements (and possibly related hydrologic processes); (3) inversion of the geophysical results; and (4) development of pixel-specific calibrations between the inverted tomograms and the underlying hydrologic property. In this way, the effects of survey geometry, measurement physics, spatial variability, and measurement error can be assessed and accounted for in the relation between geophysical estimates and hydrologic properties.

7.2 Linking Hydrologic and Instrument Response Models

Indirect (geophysical) measurement methods offer many advantages for subsurface hydrologic characterization and monitoring including the ability to make rapid, noninvasive or minimally invasive measurements over a range of support volumes and spatial resolutions. Characterization efforts can draw directly on developments in related fields to map and categorize subsurface hydrofacies. The primary challenge in this area is in developing improved petrophysical models to provide quantitative estimations of hydrologic properties from combinations of other medium properties. Similarly, basic subsurface hydrologic characterization can draw on experience in oil field monitoring programs, for example in applying time-lapse methods to characterize changes in fluid saturations with time. There is an opportunity for hydrogeophysics to become a leading discipline in the joint use of characterization and monitoring to infer subsurface properties.

Hydrologists have developed, and routinely use, sophisticated parameter estimation methods. These models (e.g., UCODE, PEST) have seen the widest use in providing automatic calibration of large-scale hydrologic models. In this application, the inverse models provide a rigorous and objective tool for inferring unknown hydraulic parameters from sparse and nonuniformly distributed hydrologic data. These tools and similar inversion algorithms (e.g., SCEM) are now generally available for use in any subsurface hydrologic application. To date, these tools have seen relatively limited use in the interpretation and, ultimately, the design of hydrogeophysical surveys.

Inversion is common in geophysics and many advances in inverse theory have been made by geophysicists; however, most of these inverse methods have been designed for static systems. The optimal combination of characterization and monitoring must rely on measurements of dynamic processes. To make use of these data, inversion routines that rely on "snapshots" of the subsurface must interpolate in time to produce a series of static images for inversion. If this interpolation is performed independently of the hydrologic inversion, much information can be lost. A relatively simple solution to this problem is to directly link hydrologic models and instrument response models. This approach makes use of the hydrologic model being used in the analysis. At each measurement time, the results from the hydrologic model (e.g., water content distribution) are used as input to an instrument response model (e.g., for a time domain reflectometry probe) to calculate the instrument response. No independent geophysical inversion is performed. Rather, the instrument responses are used together with other measurements, with appropriate weighting to reflect expected measurement errors, to constrain a coupled hydrologic-instrument response inverse model. Petrophysical properties can be inverted simultaneously and, in theory, many instrument response models could be used simultaneously to allow for consideration of a diverse data set.

This proposed approach to hydrogeophysical analysis is only subtly different than the standard approach, which relies on independent geophysical and hydrologic inversions. Conceptually, this approach is appealing because it ensures that the same conceptual model of the spatial distributions of medium properties is used in the hydrologic and instrument response models; this is commonly not true when independent geophysical inversions are performed. This approach is also well suited to identifying shortcomings of complex data sets (e.g., correlation of hydrologic and petrophysical parameters). This approach is useful for identifying the most sensitive, and hence, most important independent measurements to make in order to uniquely identify hydrologic parameters. Similarly, this approach can provide a quantitative, objective tool to investigate the added value of any measurement to an existing data set that includes many measurement types. This ability is a prerequisite to developing reliable procedures for designing optimal hydrologic monitoring networks that include indirect methods.

7.3 Integrating Modeling and Measurement Approaches at the Watershed Scale

So far, the link between geophysical measurement and inferring hydrological properties has been considered. This section discusses ways of using hydrogeophysical data as input into watershed-scale hydrological models. A hydrological modeling approach that is gaining momentum within the hillslope and watershed community is that of using a top-down approach or identifying the 'dominant processes' of physical significance within a watershed (Klemes, 1983; Grayson and Bloschl, 2000; Sivapalan et al., 2003; Sivakumar, 2004). This strategy is aimed at identifying the physical controls on hydrological response at different scales. This approach, which often uses measurable parameters (Seibert and McDonnell, 2002) as a way to constrain hydrological models, could provide a synergistic way forward if combined with geophysical measurement.

A combined approach must use model parameters that can be measured using geophysical methods. As an interesting example, Atkinson et al. (2002) showed that the inclusion of subsurface parameters becomes increasingly important in maintaining a high level of model predictability of stream flow as (i) the time scale of interest becomes shorter and (ii) the dryness index becomes large, indicating drier climates (Fig. 19).

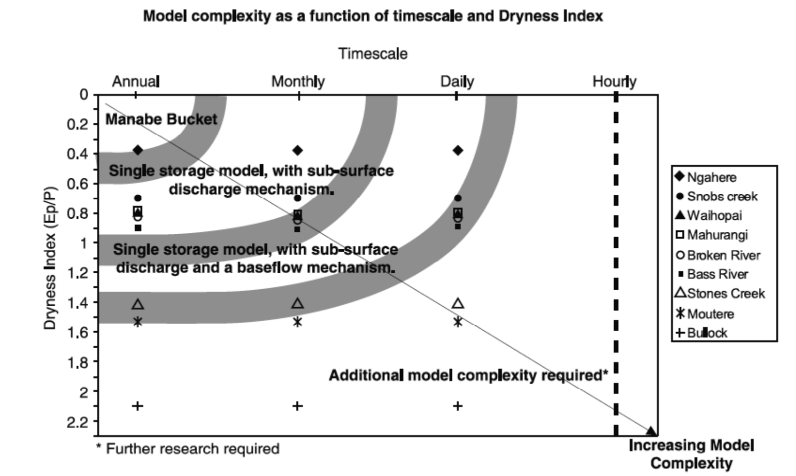

Figure. 19 From Atkinson et al. (2002), Hypothetical relationship between model complexity, timescale and climate characteristics.

One of the variables in the model was soil depth, which provides a first approximation of soil moisture storage. The use of geophysical data from GPR could be used along with limited ground truth to map soil depth across a watershed and hence provide measurement constraint on the parameter values. Other areas of possible synergy include using 'soft' data from EMI surveys to identify flow pathways in the subsurface, indicated by areas of contrasting bulk soil electrical conductivity. Another area in which EMI data could be used is synergistic between geophysics, biogeochemistry and hydrology in locating regional sources and sinks of salinity or other nonpoint-source materials (Corwin et al., 1999). This approach to salinity has been tried in Australia, where it has proven most useful for ground water, but less effective for the near surface where vadose zone water content is needed to interpret the data. Appropriate application of geophysical tools is required in this endeavor and the limitations and constraints must be understood. This approach seeks to develop seamless, cross-scale characterization and quantification of the subsurface, and forms a strategy that could embrace the synthesis of hydrology with geophysics in the most efficient manner, bridging the measurement/modeling disparity.

8. Strategic Plan

8.1 Building Partnerships

In many watershed-scale hydrologic investigations, there is a need for information about the subsurface across a wide range of spatial and temporal scales. While traditional methods of drilling and direct sampling can provide accurate data at specific locations, these methods are inherently limited in terms of the volume and spatial density of the sampling. There is great characterization potential for using complementary geophysical methods as part of a watershed characterization plan to acquire non-invasive, spatially exhaustive data over large volumes of the subsurface, which is the theme outlined in this document.

The use of geophysics as part of a watershed study can be divided into applications that are classified as state-of-the-practice, state-of-the-science, and state-of-the-research. There are some applications for which a geophysical method provides a well-established approach (state-of-the-practice) and can be used in a relatively routine manner. This approach is where contractors could be used who specialize in obtaining high-quality data using routine geophysical methods. Examples of specialist services that might be provided include the gathering of ground penetrating radar transects over a number of line kilometers, field surveys using electromagnetic induction mapping, and airborne surveys such as helicopter transient electromagnetic depth sounding. Some applications have been demonstrated only in controlled experiments, under optimal conditions, and so remain state-of-the-science, thus requiring further research and development; examples include magnetic resonance sounding and microgravity measurements. Then there are state-of-the-research applications where current research is focused on exploring new ways of using geophysics to meet critical measurement needs. This includes a shift in focus for hydrological applications of geophysics, where there is interest in identifying flow pathways and flow networks in the subsurface, in addition to the geological focus of identifying strata. Ways need to be developed to integrate geophysical data from different scales into a seamless image of the subsurface that can be continually upgraded and improved as better data become available. There is a clear need to develop data repositories, which could be worked through the Hydrological Information System component of CUAHSI.

The key to the success of geophysics, for any application, is clarity in defining "success." The best way forward, for advancing the use of geophysics for watershed studies, is to form partnerships between the practitioners or researchers with the interest/expertise in geophysics and the practitioners or researchers with the measurement need. The latter group needs to define the measurement need in a way that includes the required spatial and temporal resolution and extent and the acceptable level of uncertainty in the measurement result. The geophysicists need to be able to quantify all of these parameters, ideally before conducting the field survey, in order to determine the value of the geophysical data. It is important to note that even in state-of-the-practice applications, the needs of a scientific research program are likely to exceed the levels of accuracy currently available, so that what might be assumed to be "state-of-the-practice" needs further research in order to meet the science needs. Many of the reported problems with the use of geophysics for specific applications have arisen due to false expectations.

A partnership is essential at all stages in the use of geophysics as part of a watershed study. While there is a need for workshops and educational programs to introduce students, researchers and practitioners from diverse backgrounds to the potential usefulness of geophysical methods, an experienced geophysicist is essential to ensuring the successful application of geophysics. Data acquisition, processing, inversion, and interpretation (while commonly "sold" as simple off-the-shelf packages), involve layers of complexity. CUAHSI has already demonstrated leadership in developing partnerships such as the CRADA agreement with the U.S.G.S. Hydrologic Instrument Facility. Government agencies, such as U.S.G.S. and U.S.D.A. who are actively involved in watershed studies and/or conduct geophysical research focused on ground-water investigations must be engaged. These agencies should not be engaged simply as a resource but as science partners in this strategic initiative to advance watershed hydrological research.

8.2 A Vision for a Measurement Facility

A vision for a hydrologic measurement facility, HMF, that incorporates geophysics can be developed from the results of the HMF survey (Robinson et al., 2006). This survey was aimed at hydrologists to determine their perceived needs to advance hydrology. Respondents were asked to prioritize their aims for a hydrologic measurement facility given the following options:

The aims of the HMF should be to:	% of total
Conduct research into cutting edge hydrological measurement devices	62.7%
Develop new methodologies	59.1%
Develop new instrumentation for hydrology	57.6%
Provide comparative assessments and ratings of sensor systems	56.0%
Provide a comprehensive handbook of measurement techniques	51.7%
Integrate measurement techniques with modeling approaches	50.8%
Provide high-tech equipment rental	46.1%
Provide technical assistance online	43.0%
Provide high-tech equipment servicing	35.8%
Provide technical assistance in the field	23.6%
Provide standard equipment rental	14.0%
Provide standard equipment servicing	10.5%
Provide a team of technical people that can be hired to set up watershed monitoring	3.9%

The results of the survey clearly indicate that there is strong support for a facility that is involved, not only with providing cutting-edge tools, but that uses this opportunity to advance the science through research into both the tools and methods. The provision of a simple high-tech equipment rental facility was low in the general priorities of respondents. This is perhaps because principle investigators, PI's, feel that the need for supported equipment is beyond the scope of an individual PI and his research group. Considering this fact and the other results from the survey, a community vision can be developed.

The aim of the hydrologic measurement facility (HMF) should be to make available, supported, cutting edge, hydrological research tools to the science community. It should be a single facility incorporating direct hydrological measurement, biogeochemistry and geophysical measurement. The facility would emphasize research and development with cutting-edge hydrological equipment and methods as part of ongoing deployment to watersheds. This approach could take the form of a supported equipment loan portal to access high-tech equipment. HMF would provide scientific training and support, with routine maintenance, insured shipping, and logistical support to move equipment around. Logistical support could be provided for collaborative purchase of major equipment. The facility could work towards facilitating and developing a match-making service / shared pool of equipment as a community resource if insurance/damage concerns can be dealt with. The web presence would be up to date, and list activities, staff, and the equipment / training available. In addition, the staff could provide measurement technique training workshops to fulfill the educational role. The facility would need to be staffed by fully supported scientists and engineers that could assist with trouble shooting in interdisciplinary projects, and/or help with strategic planning for experimental designs within a watershed. The staff would have the capability to design and/or develop methodologies specifically for hydrological application of equipment, and be capable of developing novel applications to address important scientific questions.

In addition to this vision of creating a centralized facility, an exciting concept would be to strongly integrate the user facility into the research community through the use of satellite science nodes. These nodes would consist of scientists within active research groups strategically located around the U.S., who would have a portion of their time funded as a contribution to the HMF, to provide specialist cutting-edge skills to NSF projects. This approach would have the advantage of reducing overhead costs of a central measurement facility, while keeping the scientists in departments exposed to the latest advances in the science. Having a number of such scientists around the country would also reduce travel costs for the HMF. Departments agreeing to support such scientists could obtain a letter of support from HMF and apply through the existing NSF, instruments and facilities panel for technical support and a basic level of equipment. This ensures that NSF, through the peer review process, would support only the nodes offering the highest possible scientific support or scientific instrumentation. One could envision that the scientist would have some basic equipment permanently housed with them such as a GPR, EMI, or ERI. More specialist equipment such as borehole logging tools could be maintained at the central HMF facility and shipped out to these scientists for specific tasks or projects. Developing this type of embedded system would obtain the best community buy in and support, and keep the HMF in touch with grass roots level advances. In addition this approach would lead to a focused, efficient operation that rather than create competition for the community, would genuinely support it, because their in-house specialists would be part of the supported staff collaborative partnership, where its specialist capabilities would come through the development of satellite nodes.

This management concept has been used extensively by the military to provide an efficient and focused way of deploying capabilities where they are most needed. This approach would allow a facility to respond quickly and innovatively to new challenges by attaching, or detaching new or specialist elements to meet with the new challenge. Developing this model within a science context would have the central facility conducting strategic planning, seeking and identifying opportunities in science, and reacting to and promoting scientific advances for the community. This concept provides the greatest level of flexibility, allowing the facility to adapt quickly to new science challenges by embracing new technologies and allowing outdated efforts to easily wind down, without affecting the strength of the facility. This approach would identify new elements, and work with them developing partnerships and encouraging them to obtain funding support through the existing peer review process. As the science moves forward, different satellite nodes would develop to facilitate the transfer of technology into the hands of the community. Our expectation is that these nodes would have a life span of 6-9 years as the technology is transferred across the community. Oversight would be provided by a general independent HMF oversight committee and by specialized independent node oversight committees. The traditional research center concept cannot embrace all of the new technologies, and often becomes inefficient or overgrows if it tries to, thus often becoming bureaucratically inefficient. These centers often become competitors to PI research rather than fulfill the role of support for which they were intended. Our exciting vision of an efficient, flexible, supportive, measurement facility offers a new approach that supports the vision of organizations such as NSF, to keep cutting-edge research at the forefront of the measurement facilities mission.

In particular, geophysics is facing a critical time in advancing the use of geophysical technologies for watershed studies. The “geophysics” part of hydrogeophysics is in need of attention, so that we can better understand, better develop, and better apply geophysical methods. Integrating the HMF with top university geophysics departments would keep the facility at the forefront of science. Our understanding of the applied physics underlying our imaging methods is still in the early stages, and our ability to link our images to subsurface processes, properties, and dynamics is just becoming widely recognized as an important area of basic research. The geophysical community has an opportunity, but also has a responsibility, to become active participants, and partners, in watershed studies to assist in addressing the pressing scientific questions that face us as we attempt to better manage and protect valuable water resources.

Appendix A. Survey logistics

	Field deployment and support requirement	Survey time	Instrument cost	Survey cost	Technological Development stage	Methodological development stage for hydrologic application
Airborne						
Microwave remote sensing	Team	1 week – 1 month		NASA - free	Mature	Developmental/mature
Airborne EM	Team	1 week – 1 month		$100 / line km $50k minimum	Mature	Developmental
Airborne Time Domain Electromagnetic	Team	1 week – 1 month		$100 / line km $75k minimum	Emerging/ mature	Developmental
Aeromagnetic	Team	1 week – 1 month		$15-65 / line km $50k minimum	Mature	Developmental/mature
Ground based						
Time Domain Electromagnetic	1 operator 1 assistant	6-8 stations per day	$60k-85k		Mature	Mature / researchable
Magnetotelluric	1 operator 1 assistant	1-4 stations per day	<50k		Mature	Mature / researchable
Audio Magnetotelluric	1 operator 1 assistant	6-8 stations per day	$60k		Mature	Mature / researchable
Electromagnetic Induction	1 operator 1 assistant	10 line km per day	$20k-30k		Mature	Mature / researchable
Ground penetrating radar	1 operator 1 assistant	10 line km per day	$20k-30k		Mature	Mature / researchable
Electrical resistivity imaging	1 operator 1 assistant		$60k	~$15 k minimum deployment cost	Mature	Mature / researchable
Induced Polarization	1 operator 1 assistant		$60k-100k		Mature	Early developmental
EM Water content sensor system	1 operator	_	$10k		Mature	Mature
Seismic	1 operator 1 assistant		$50k		Mature	Mature / researchable
Gravity	1 operator	10-50 stations per day	$75k-80k		Mature	Mature
Microgravity	1 operator		$300k		Developmental	Developmental
Magnetic	1 operator	10 line km per day	$40k		Mature	Developmental / mature
Magnetic Resonance sounding	Team				Developmental / emerging	Early developmental

A team is considered to consist of 3 or more members. Numbers are 'ball park' estimates and will vary dependent on accessibility and terrain, survey costs vary, depending on length of survey. Under the methodological heading Mature / researchable means that there are standard methods but that there is still work to be done improving and developing new methods.

Appendix B. Hydrologic properties inferred from geophysical measurement

	Dependent physical property	Moisture content	Porosity	Pore fluid electrical conductivity	Hydraulic conductivity	Rock stratification	Lithologic Factors (rock type, grain size or surface area)	Faults and fractures
Airborne								
Microwave remote sensing	Permittivity	P						
Airborne EM	Electrical Resistivity			P			S	
Airborne Time domain Electromagnetic	Electrical Resistivity			P		S	S	
Aeromagnetic	Magnetization						P	P
Ground based								
Time Domain Electromagnetic	Electrical Resistivity			P		P	S	
Magnetotelluric	Electrical resistivity			P		P	S	
Audio Magnetotelluric	Electrical Resistivity			P		P	S	
Electromagnetic Induction	Electrical Resistivity			P		S	S	
Ground penetrating radar	Reflection: Permittivity magnetic permeability Attenuation: resistivity	S				P		S
Electrical resistivity imaging	Electrical Resistivity	P		P		S	S	S
Induced Polarization	Electrical Resistivity/ capacitance				S		P	
EM Water content sensors	Reflection: Permittivity magnetic permeability	P						
	Attenuation: resistivity			P				
Seismic	Elastic moduli; density				S	P	P	
Gravity	Density						P	P
Microgravity	Density	P						
Magnetic	Magnetization						P	P
Magnetic Resonance Sounding	Proton density	P	P		S			

P, indicates primary property inferred, S, indicates secondary properties that might be inferred.

Appendix C. Geophysical/hydrological scale comparison

	Point/profile or transect	Catchment	Sub-watershed	Watershed	Sub-basin	Basin
Airborne						
Microwave remote sensing		--------------	--------------	--------------	--------------	--------------
Airborne EM			--------------	--------------	--------------	--------------
Airborne Time Domain Electromagnetic			--------------	--------------	--------------	--------------
Aeromagnetic			--------------	--------------	--------------	--------------
Ground based						
Time Domain Electromagnetic	--------------	--------------	--------------			
Magnetotelluric	--------------	--------------	--------------	--------------	--------------	--------------
Audio Magnetotelluric	--------------	--------------	--------------			
Electromagnetic Induction	--------------	--------------	--------------			
Ground penetrating radar	--------------	--------------	--------------			
Electrical resistivity imaging	--------------	--------------				
Induced Polarization	--------------	--------------				
EM Water content sensors	--------------					
Seismic	--------------	--------------	--------------	--------------	--------------	--------------
Gravity	--------------	--------------	--------------	--------------	--------------	--------------
Microgravity	--------------	--------------	--------------	--------------		
Magnetic	--------------	--------------	--------------	--------------	--------------	--------------
Magnetic Resonance Sounding	--------------	--------------				

Scales referred to follow, The Center for Watershed Protections (CWP) definitions of watershed management units (watershed vulnerability analysis, 2002), with their approximate corresponding areas; basin (2,500–25,000km^2); sub-basin (250–2,500km^2); watershed (80–250km^2); sub-watershed (1–80km^2); catchment (0.1-1km^2).

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