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Advancing process-based watershed hydrological research using near-surface geophysics: a vision for, and review of, electrical and magnetic geophysical methods

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Abstract:

We want to develop a dialogue between geophysicists and hydrologists interested in synergistically advancing process based watershed research. We identify recent advances in geophysical instrumentation, and provide a vision for the use of electrical and magnetic geophysical instrumentation in watershed scale hydrology. The focus of the paper is to identify instrumentation that could significantly advance this vision for geophysics and hydrology during the next 3–5 years. We acknowledge that this is one of a number of possible ways forward and seek only to offer a relatively narrow and achievable vision. The vision focuses on the measurement of geological structure and identification of flow paths using electrical and magnetic methods. The paper identifies instruments, provides examples of their use, and describes how synergy between measurement and modelling could be achieved. Of specific interest are the airborne systems that can cover large areas and are appropriate for watershed studies. Although airborne geophysics has been around for some time, only in the last few years have systems designed exclusively for hydrological applications begun to emerge. These systems, such as airborne electromagnetic (EM) and transient electromagnetic (TEM), could revolutionize hydrogeological interpretations. Our vision centers on developing nested and cross scale electrical and magnetic measurements that can be used to construct a three-dimensional (3D) electrical or magnetic model of the subsurface in watersheds. The methodological framework assumes a 'top down' approach using airborne methods to identify the large scale, dominant architecture of the subsurface. We recognize that the integration of geophysical measurement methods, and data, into watershed process characterization and modelling can only be achieved through dialogue. Especially, through the development of partnerships between geophysicists and hydrologists, partnerships that explore how the application of geophysics can answer critical hydrological science questions, and conversely provide an understanding of the limitations of geophysical measurements and interpretation.

KEY WORDS geophysics; electromagnetic; watershed; electrical; magnetic; airborne

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INTRODUCTION

For many years hydrogeology has dealt with quantifying and describing the storage and movement of groundwater as an important natural resource (Fetter, 1988; Domenico and Schwartz, 1990). However, there has been less emphasis on the use of geophysics to understand hydrological processes at the watershed scale. Near-surface geophysics (Butler, 2005; Auken *et al.*, 2006) is a strengthening discipline within which hydrogeophysics is emerging, dealing with the application of geophysical methods to investigating hydrological processes (Rubin and Hubbard, 2006). There is a growing recognition that the integration of geophysical measurement into hydrological, process-based watershed studies could significantly advance our understanding of dynamic hydrological processes, especially at intermediate scales, such as in small watersheds to small basins. The application of geophysics to watershed hydrology is not new (Shields and Sopper, 1969; Yamamoto, 1974). However, advances in instrumentation and electronics in the past 20 years have significantly reduced costs and improved

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instrument acquisition rates. Many instruments can now be mobilized and used 'on the fly'. Particularly exciting are the advances that have been made with airborne measurement systems. Airborne mounted non-invasive, electromagnetic induction (EMI), transient electromagnetic (TEM) and magnetic methods stand to revolutionize the way we see into the earth, and increase the spatial area over which we can observe. Spatially exhaustive airborne data, collected over large areas, can be used to identify geological architecture and act as a guide to further, more expensive, ground based studies. A hierarchical approach to subsurface measurement could be developed that begins with the identification of dominant geological structure and flow path identification and reduces in scale to focus on areas of interest. This 'top down' approach offers an efficient way of characterizing the subsurface over large spatial scales.

The development of the CUAHSI Hydrologic Measurement Facility (HMF) has been developed by engaging the community through a survey (Selker, 2005) that was conducted between November 2005 and January 2006. Findings from the survey gave a clear mandate for improving and implementing subsurface science as a key aspect for advancing hydrologic sciences (Robinson *et al*., 2006). The need for characterizing and quantifying subsurface properties 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 surprise, having been outlined in two recent National Research Council (NRC) reports as a priority area for research (NRC, 2000, 2001). This paper reviews the literature pertinent to watershed studies and develops a vision for improving the integration of geophysics into hydrology at the national level in the US. In particular it focuses on the understanding of processes and dynamics in a changing system at the watershed scale. 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' (CUAHSI, 2002). Within this core objective, three intertwined themes are identified, (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 (e.g. aquifer storage), fluxes (e.g. hydraulic conductivity), and transformations (e.g. contaminant plume migration) in the subsurface. Also for identifying structural hydrological controls on flow and for determining the stocks of water available for ecosystems (e.g. soil moisture). 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 programmes such as NEON (National Ecological Observatory Network) (Mervis and Kaiser, 2003).

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 Centre for Watershed Protections (CWPs) definitions of watershed management units (Zielinski, 2002), with their approximate corresponding areas; basin (2500–25000 km^2); subbasin (250–2500 km^2); watershed (80–250 km^2); subwatershed (1–80 km^2); catchment (0·1–1 km^2). Though these delineations are subjective, they guide you in relating geophysical measurements to hydrological scales of interest.

Scaling is a fundamental concept to hydrology. Commonly we measure or study properties at the point or sample scale and try to determine patterns or processes at larger scales. Many of the instruments we use measure at the point or sample scale, such as soil moisture probes and tensiometers, whilst others, such as satellite remote sensing, determine regional patterns but are limited in the depth of penetration into the subsurface. This often leaves us with a lack of spatially dense, relevant data at intermediate scales (e.g. catchment or sub-watershed). This is often termed the, 'intermediate or meso-scale gap phenomenon', where data are sparse at the sub-watershed level and we try to upscale or downscale to infer processes of interest at those level scales. This is perhaps where geophysical methods can make the most impact, obtaining data at a range of spatial scales across watersheds (Table I).

We can often measure with high temporal resolution at a point, but as spatial scale increases, so we lose our ability to maintain this high temporal resolution. This is important because systems theory often predicts that the behaviour of the system is not simply the sum of its parts. If we seek to understand the patterns and emergent behaviour of a watershed, greater spatial data coverage will be required to identify dominant architecture. Whilst we agree with the need for improved understanding of spatial patterns (McDonnell *et al*., 2007), we also believe that improved spatial measurement can help reduce the over parameterization of physical models. Whilst there is a need to develop new watershed modelling approaches, physical hydrological models are important. Not only do they provide mechanistic understanding, but they can be used to better understand and interpret geophysical measurement response. Rather than the hydrologist viewing geophysics as providing a service to further hydrological model testing, a new style of science is required, one that can merge geophysical and hydrological data and use each to learn about the response of the other and so advance our understanding. Physical, mechanistic modelling is important for these ends, so that we can

Table I. A comparison of the suitability of a measurement method for obtaining data to infer processes at the desired watershed scale

	Point/profile or transect	Catchment	Sub-watershed	Watershed	Sub-basin	Basin
Airborne						
Microwave remote sensing		—	—	—	—	—
Airborne electromagnetic			—	—	—	—
Airborne time domain electromagnetic			—	—	—	—
Aeromagnetic			—	—	—	—
Ground based						
Time domain electromagnetic	—	—	—			
Magnetotelluric	—	—	—	—	—	—
Audio magnetotelluric	—	—	—			
Electromagnetic induction	—	—	—			
Ground penetrating radar	—	—	—			
Electrical resistivity imaging	—	—				
Induced polarization	—	—				
Electromagnetic water content sensors	—					
Seismic	—	—	—	—	—	—
Gravity	—	—	—	—	—	—
Microgravity	—	—	—	—		
Magnetic	—					
Magnetic resonance sounding	—	—				

Note: scales referred to follow, the Centre for Watershed Protections (CWPs) definitions of watershed management units (watershed vulnerability analysis, 2002), with their approximate corresponding areas; basin (2500–25000 km^2); sub-basin (250–2500 km^2); watershed (80–250 km^2); sub-watershed (1–80 km^2); catchment (0·1–1 km^2) (Zielinski, 2002).

understand how geophysical instrument response might be impacted by hydrological variation, especially in the vadose zone.

Figure 1 presents a conceptual diagram indicating where we can currently measure (grey shaded area), and the space time scales at which we would like to be able to measure, indicated by the light grey arrows. As we want to measure bigger areas it takes longer using point sensors. Remote sensing methods do not return soon enough to capture the temporal dynamics. We are therefore generally constrained to temporal and spatial measurement scales in the shaded area below the black arrows (Figure 1). We desire measurements at spatial and temporal scales along the grey arrows. These arrows offer the trajectories where cutting edge measurement science must go to allow us to observe processes of interest. The pioneering efforts must, therefore, push along these trajectories to obtain measurements at the intermediate-scale, while still maintaining high temporal resolution. It is therefore no surprise that CUAHSI initially defined areas ranging from 10–10000 km^2 as being the watershed scale of interest, with associated modelling 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 these large spatial scales. In this paper 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. In addition we review a range of ground based measurement methods and see how they can be applied to issues like sediment characterization in rivers.

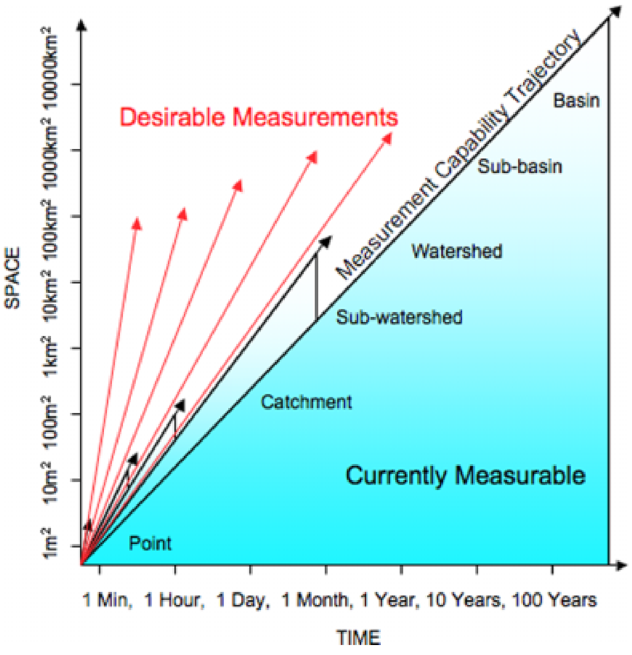

Figure 1. Conceptual diagram of spatial and temporal resolution scales

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 fundamental to understanding hydrological processes and dynamics in the subsurface. This is the focus of much of environmental geophysics (Nobes, 1996; Pellerin, 2002). Geophysical methods measure a range of physical properties from which hydrological variables can be determined (Table II). Subsurface architecture controls the flow of water through the subsurface. Therefore, imaging the structure and hydraulic properties should help us to understand how water moves through 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, has 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, partially saturated materials, 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 single technique can provide information on all the subtleties involved. Instead, a multi-method, cross-scale geophysical approach is necessary that integrates information from geology, physics, chemistry, biology, and hydrology.

An example of a conceptual model focused on electromagnetic (EM) geophysical techniques (Figure 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 three-dimensional (3D) geo-electrical image of the subsurface over the entire watershed. In the vadose (unsaturated) and groundwater (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 and magnetic properties.

Realizing such a cross-scale conceptual model can be achieved through a top-down approach, utilizing satellite information or more especially 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 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 18000 km^2 with a spacing of between 200 and 400 m 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 EMI methods can provide spatial patterns of ground conductivity with depths of up to 100 m 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. TEM sounding methods can generally sense the subsurface architecture to depths of 100 m, which makes these methods suitable for identifying aquifers, aquitards, and depth to clay layers. A combination of the collected data can 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, as a fundamental interface between the atmosphere and subsurface. They affect the partitioning of precipitation between infiltration and runoff and subsequently the pattern of streamflow response, especially when observed at shorter time scales in drier regions (Atkinson *et al.*, 2002). A number of soil properties and characteristics are of major interest in hydrology, the location of flow paths in soils, soil thickness or depth, which is a first approximation of soil-water storage and the nature of the boundary between the soil and the deeper vadose zone or bedrock. For instance, thin soils over bedrock, or an impermeable layer, may lead to 'fill-and-spill' processes along the soil/bedrock boundary (Tromp-van Meerveld and McDonnell, 2006). Where as a deep permeable vadose zone may lead to groundwater recharge. Geophysics can be used to improve the quantification of these aspects of soils.

Ground-based EMI can be used to map soil texture where strong electrical contrasts exist between areas of conductive clay and non-conductive 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 image of the subsurface.

REGIONAL, SUB-WATERSHED TO BASIN-SCALE REMOTE SENSING AND AIRBORNE SURVEY

Measurement at regional scales can be used to interpret 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.

Table II. Hydrologic properties inferred from geophysical measurement methods

	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 electromagnetic	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	S				P		S
	Magnetic permeability							
	Attenuation: resistivity							
Electrical resistivity imaging	Electrical resistivity	P		P		S	S	S
Induced polarization	Electrical resistivity/capacitance				S		P	
Electromagnetic water content sensors	Reflection: permittivity	P						
	Magnetic permeability							
	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			

Note: this table serves as a guide and is not definitive, new methods are continually being developed. P, indicates primary property inferred, S, indicates secondary properties that might be inferred.

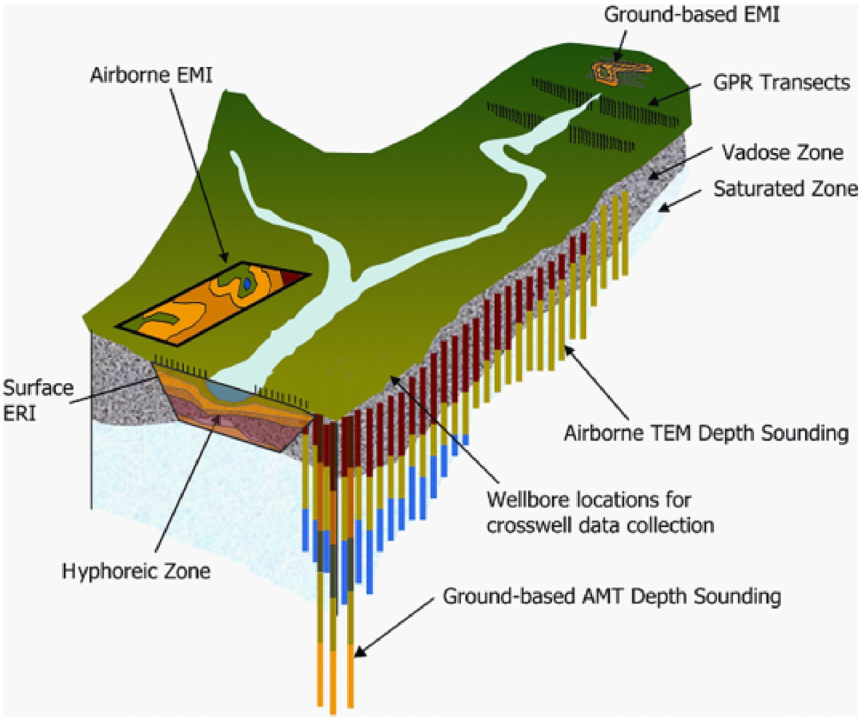

Figure 2. Example conceptual model of how EM geophysical measurements could be used at multiple scales to characterize a watershed

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, and offers all weather, day and night viewing capability. The technique relies on the high contrast between the dielectric constant of dry soil (∼3) and water (∼80). A four-component (solid, air, water and bound water), dielectric mixing model is often used to evaluate the dielectric constant of the soil–water mixture. The soil dielectric constant depends largely on soil moisture, texture, bulk density, specific surface area, and frequency of the instrument (Dobson *et al*., 1985). Remotely sensed surface brightness temperatures and radar backscattering coefficients for the target are obtained from passive and active sensors, and are 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 EM 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 estimation to be performed with lower ancillary data requirements under bare to moderately vegetated conditions. Current methods for soil moisture estimation from radar data work for bare soil surfaces only. Radar, however, provides much higher spatial resolution than passive microwave 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 estimation, and at this frequency an average soil penetration depth of 0·05 m is achieved (Jackson *et al*., 1996). With currently available sensors, airborne surveying techniques can use even lower frequencies to achieve better penetration through dense canopies 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 further exploration with ground-based geophysical techniques. The temporal spacing 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 days) 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, 1or 2–35 days). Space-borne estimates of soil moisture from passive remote sensing have a spatial resolution on the order of tens of kilometres. By combining with active microwave data these estimates can be improved in spatial resolution (Narayan *et al.*, 2006). Simultaneously obtained active and passive data are needed for such research and are not available from currently operational satellite instruments. Microwave remote sensing provides an estimate of near-surface soil moisture. Data assimilation techniques, an interpretation method, can be used to retrieve a soil moisture profile, to a depth of a few metres, 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 earlier-mentioned areas because 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 is scheduled to be launched by ESA in 2007, and 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.

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 with 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 related to rock type, porosity, and the ionic strength of the pore fluids. EM techniques excite the earths subsurface inductively and the resulting magnetic field is measured. Apparent resistivity maps, resistivity depth imaging, or inverted models are computed from the field measurements. 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 groundwater. Distinguishing between the unsaturated and saturated zone is difficult because of potential overprint of stratigraphic and structural uncertainties, but useful information about the resistivity structure and the quality of the aquifer can be gained. The low resistivity of saline water makes it an excellent target for EM detection. The Florida Everglades is an example where high rates of groundwater extraction altered groundwater flow and led to intrusion of seawater (Fitterman and Deszcz-Pan, 1998). Repeated AEM monitored variation of the intrusion with time.

Distortion of EM measurements of the earth is caused by cultural noise sources and AEM methods are no exception. In general, data are affected 100–200 m from two-dimensional (2D) linear features such as powerlines and pipelines. The distance is smaller for noise from 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. Ground based reconnaissance can test the appropriateness of methodologies, and then used to design an airborne survey that can guide subsequent more intensive ground surveys if needed. These ground based surveys can provide more detailed and deeper exploration of identified areas of interest. Airborne surveys are typically contracted; raw data along with various maps and profiles are then delivered for geologic interpretation.

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 metres to roughly 100 m. Transmitter and receiver coil configurations include both horizontal coplanar (HCP) and vertical co-axial (VCA) as shown in Figure 3. The HPC is best for mapping horizontal features, such as a groundwater interface, where as the VCA is best 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.

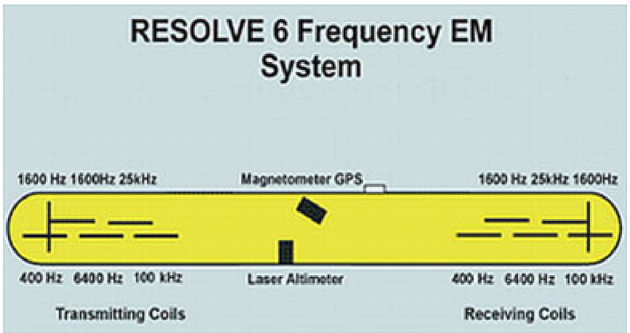

Figure 3. Array configuration for the Fugro airborne RESOLVE frequency-domain EM system

Table III. This table provides a summary of survey logistics, costs and technological stage of development as a guide to the non expert

	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
Helicopter EM	Team	1 week – 1 month		$100 / line km $50k minimum	Mature	Developmental
Helicopter Time Domain Electromagnetic	Team	1 week – 1 month		$100 / line km $75k minimum	Emerging/ mature	Developmental
Fixed wing Aeromagnetic	Team	1 week – 1 month		$15-30 / line km $75k minimum	Mature	Developmental/mature
Helicopter Aeromagnetic	Team	1 week – 1 month		$50-75 / line km $75k 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	$15k-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

Note: a team is considered to consist of three or more members. Numbers are 'ball park' estimates and will vary dependent on accessibility and terrain, survey costs vary, depending on length of survey. 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.

Typically, interpretation involves apparent resistivity maps for each frequency and coil configuration. Although research continues in multi-dimensional inversion, because of the relatively sparse temporal sampling, one-dimensional (1D) inversion is more stable. With the dense spatial density of 1D measurements (e.g. every 100 m), the data can be used to recover an approximate 3D distribution (Sengpiel and Siemon, 1998; Farquharson *et al.*, 2003). Survey pricing is based on several variables such as location, area, terrain, line spacing, final products, and rough estimates for hydrological surveys are presented in Table III where they are compared with other measurement methods.

Time-domain fixed-wing electromagnetic (FWEM)

Fixed-wing surveys (Figure 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. The receiver typically measures the three orthogonal components of the secondary EM field. The FWEM method can have depths of investigation greater than 200 m, depending on the resistivity of the near-surface materials. FWEM is more cost effective than HEM methods, but lacks resolution of the near surface and the ability to work in rugged terrain. 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).

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 was designed specifically for hydrogeophysical and environmental investigations (Sørensen and Auken, 2004). (The use of firm, trade, and

Figure 4. The Fugro airborne GEOTEM time-domain FWEM system

brand names in this report is for identification purposes only and does not constitute endorsement by the US Government. All prices are given in USD amounts.) 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.

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 target resistivity is low. 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 one 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 four 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 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 low resistivity 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 (~200 m) resistive rock outcrop.

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 was 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 groundwater systems, and are much less sensitive to powerline 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.

Figure 5. The SkyTEM HTEM system

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.

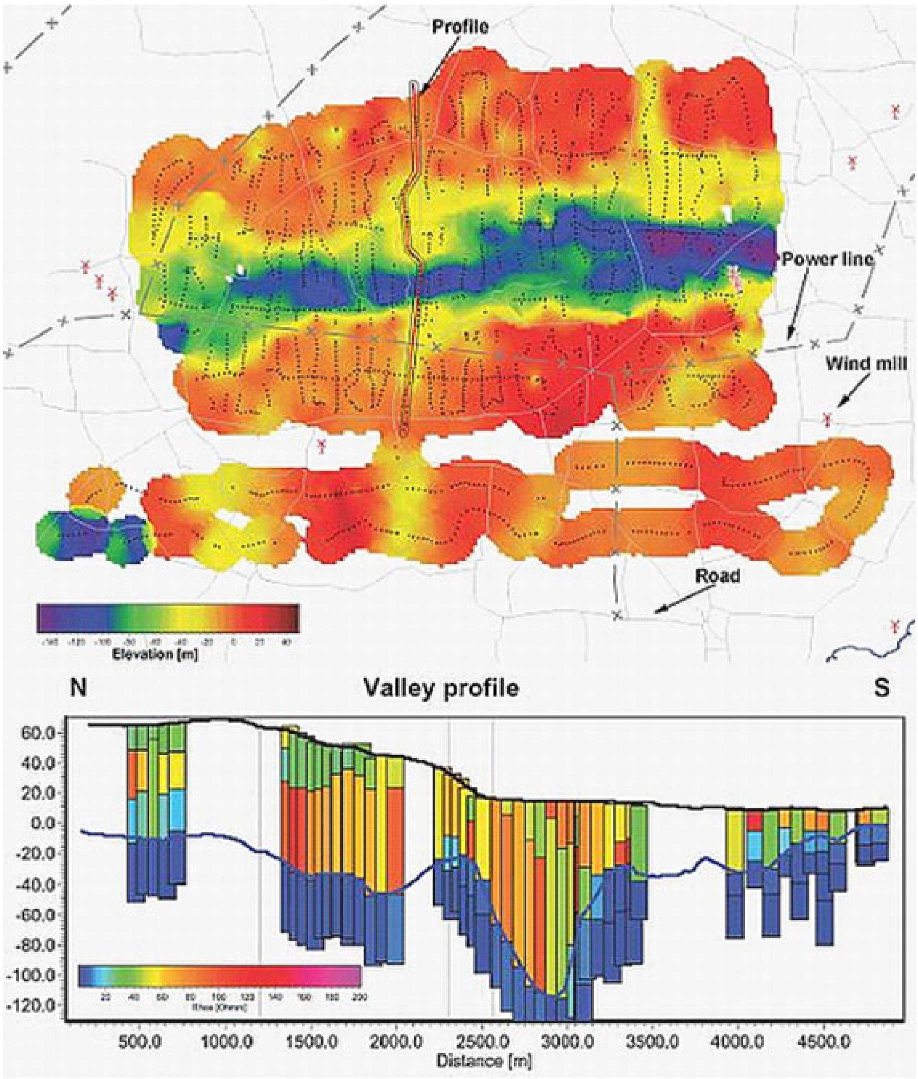

Figure 6. Thematic map showing elevation of low resistivity tertiary clay and delineation of a buried valley (from Auken *et al*., 2006)

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 (Figure 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 across these faults show that magnetic properties can be generally characterized relative to certain geologic characteristics, such as sediment provenance, depositional history, and grain size (Hudson *et al*., 1999; Hudson *et al*., 2007). In particular, a general correlation between coarser grain size and stronger magnetization indicates that aeromagnetic data can provide clues about the extent to which low-permeability fine-grained sediments are juxtaposed against high-permeability coarse-grained sediments at faults (Grauch and Hudson, 2007).

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. Magnetometers are commonly added to towed-bird AEM configurations at little to no additional cost.

LOCAL, CATCHMENT TO SUB-WATERSHED-SCALE ELECTRICAL AND MAGNETIC 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 measurements are generally more cost effective. Some ground-based measurements should be made as the

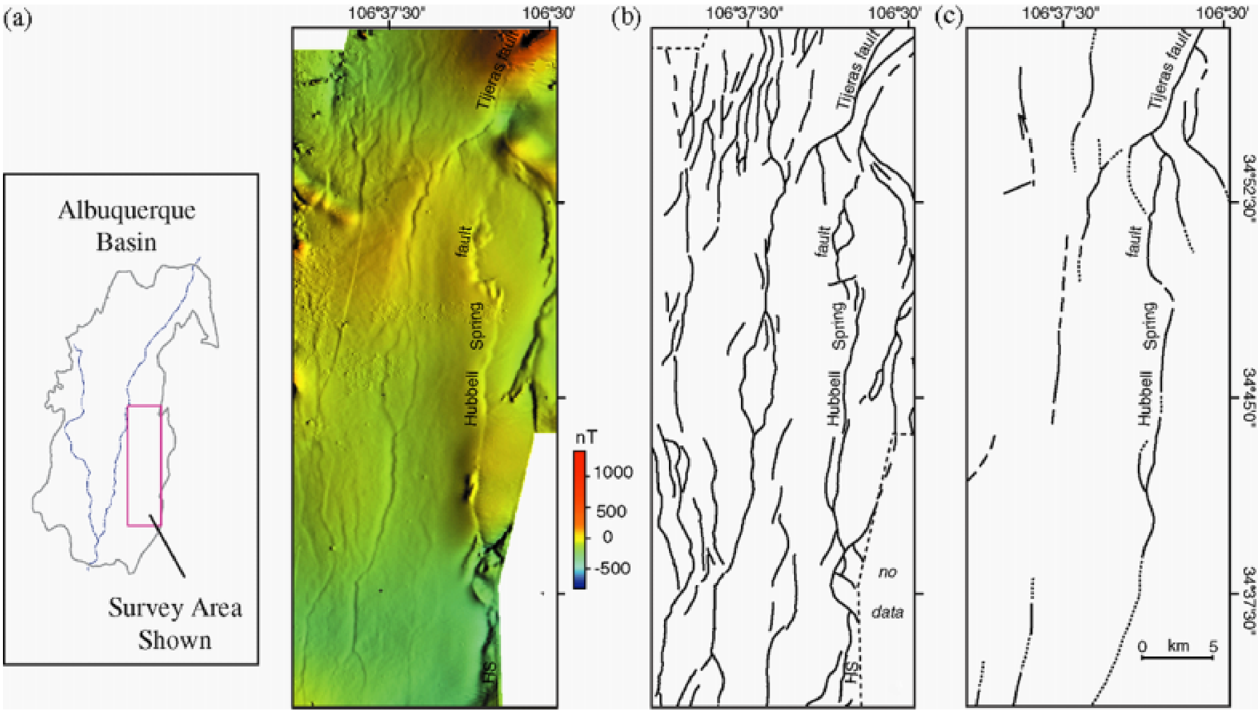

Figure 7. Mapping intrasedimentary faults with aeromagnetic data in the Albuquerque Basin, Rio Grande rift (Grauch *et al*., 2001). The semi-linear, generally northerly-striking anomalies (typically 5–15 nT amplitude) in the high-resolution aeromagnetic image (a) are primarily due to faults that offset 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)

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.

Electromagnetic sounding methods

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

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.

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 high resistivity range. Clay and salt-water intrusion constitute low resistivity 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 groundwater resources and hydraulic properties (Danielsen *et al*., 2003). The survey area of approximately 40 km^2 covered the equivalent of 1600 (40 × 40) central-loop TEM soundings. There were no topographic, geomorphologic or geological data to indicate the presence of a buried valley system; this was revealed solely by the TEM survey (Figure 8). The map of the elevation of the low resistivity tertiary clay defines the basal layer with resistivity below 15 ohm m as derived from parameterized 1D inversion (Effersø *et al*., 1999). Two main features are apparent: one striking north–south and the other south-east–north-west. The steep part of the buried valley descends from approximately 35 m above sea level (pale grey colours) to approximately 50 m below sea level (grey colours) over a few hundred metres. A variety of systems are available with varying capabilities,

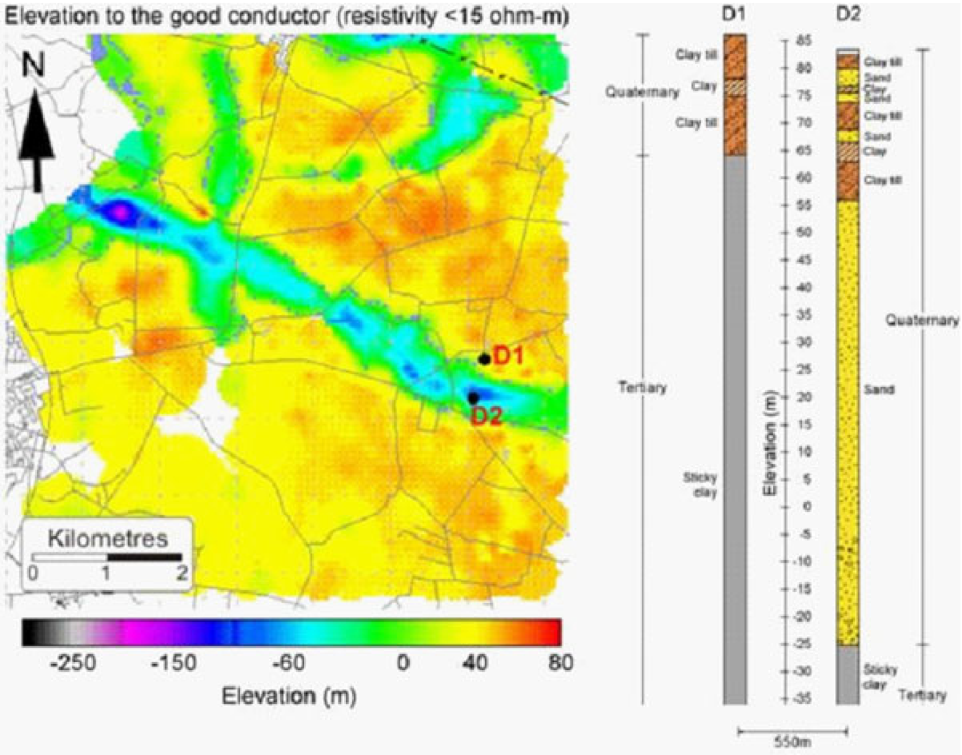

Figure 8. Map showing depth to good conductor map derived from 1D inversion models of TEM data (from Auken *et al*., 2006)

including the Geonics EM-37, 47, 57, Protem and Protem D (Geonics, Inc., Mississauga, Ontario, Canada), Zonge engineering GDP 12, 16 and 32 Systems (Zonge Engineering, Tucson, Arizona), Phoenix Geophysics V-5 System (Toronto, Ontario, Canada). Cost of a TEM system ranges from $60000 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 $15000 to $25000 more (Table III).

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 kilometres), 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 (Figure 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 modelling capabilities are well developed from the crustal studies community, and are directly applicable to the watershed problem. Presently, there are several 2D inversion codes

Figure 9. The StrataGem® AMT system (photograph courtesy of Geometrics, Inc.)

(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 collecting a data set that justifies 3D inversion or 3D forward modelling is time consuming and expensive. 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 inferred from the electrical resistivity, e.g. the presence of soluble salts (Deszcz-Pan *et al*., 2001). A StrataGem® system costs approximately $60000, and an Electromagnetic Instruments MT24LF or MT24HF system is about $50000.

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). EMI is a highly adaptable non-invasive geophysical technique originally developed for borehole logging (Keller and Frischknecht, 1966). The instrument measures the apparent bulk electrical conductivity of the ground (ECa) (the inverse of resistivity), 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 (all other factors being equal). 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 EM dipole configuration, and 1·5 times the spacing for a vertical dipole. The EM-38 has a loop spacing of 1 m, and the EM-31 a spacing of 3·66 m, 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 around $20000, the electronic stability of the instrument, however, has been questioned (Sudduth *et al*., 2001), especially in hot sunny climates like the south-western US. Work by Robinson *et al*. (2003a) indicated that unstable readings occur when instrument temperatures rise above 40 °C, and discussion with other instrument makers suggests that this is a problem common to this type of instrument.

A new generation of EMI sensors has been developed by DUALEM (Milton, Ontario, Canada); their range of EMI instruments are reported to be less temperature sensitive (Abdu *et al*., 2007). The instrument is housed in a tough yellow casing and has internal, automatic calibration (Figure 10), making it easy to use. The instrument is available with dual dipole and 1·1-m coil spacing at a cost of around $15000; 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 easily linked to field computers and GPS to give real-time measurements 'on the fly'. Another emerging instrument is the EMP-400 (GSSI, Raleigh, North Carolina), which

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

offers multi-frequency operation between 1 and 16 kHz. Making its debut on the market in 2007, the user can select up to three frequencies at a recording frequency of 1-Hz to provide three effective depths of penetration. The instrument coil spacing is 1·25 m and the length of the instrument is 1·4 m.

The technology to collect (geo-referenced) and process data has greatly progressed in the last few years. Tough field computers such as the Trimble Recon (Trimble Navigation Limited, Sunnyvale, California) and Juniper Systems Allegro (Juniper Systems Inc., Logan, Utah) provide the opportunity to synchronize data collection from different instruments. GPS technology is becoming more accurate and more compact for 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 can then be calibrated to provide information on ion concentration and soil texture and wetness. Soil salinity mapping is common in agriculture (Lesch *et al*., 2005) and directed sampling using the ECa response surface to calibrate (Lesch *et al*., 1995a,b) has been used to reduce invasive soil sampling; 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 dark grey areas indicate zones of higher electrical conductivity and deeper soils.

Ground penetrating radar

GPR is an EM method that utilizes the transmission and reflection of high frequency (1 MHz to 1GHz) EM waves within the subsurface; typically sub-metre to tens of metres 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). Sedimentological applications are reviewed by Neal (2004) and an overview of its use for environmental applications is given in Knight (2001), where as soil water determination can be found 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.

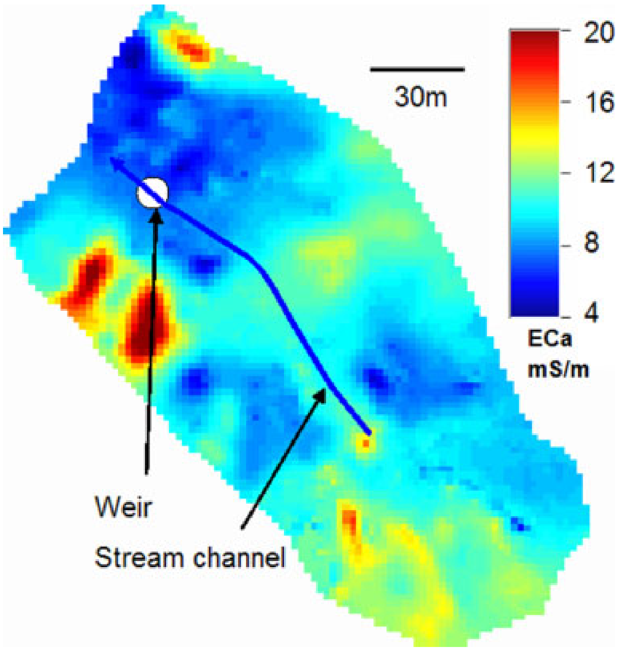

Figure 11. Bulk electrical conductivity of a catchment, zones of higher conductivity indicating locations of greater soil development

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 ($\kappa' = 80$) and that of air ($\kappa' = 1$) and minerals ($\kappa' \sim 5$), GPR data contain information about the subsurface variation in water content. This sensitivity to water content, or water-filled porosity, 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 (kilometres or more) or at a specific test site (a few metres 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.

The use of GPR data has generated much interest in obtaining estimates of subsurface properties such as water content in the vadose or unsaturated zone, and porosity in the saturated zone. 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 metres 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 metres to tens of metres. 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. A means of quantifying the heterogeneity that exists in the sampled regions is required, if radar-based dielectric measurements are to be used to provide accurate estimates of hydrogeologic 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 four-dimensional (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 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.

A wide variety of GPR instruments are now available commercially including mobile platforms (Figure 12). 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 price ranges indicated in Table III.

Figure 12. Noggin smart cart GPR (courtesy of Sensors and Software Inc.)

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 (in practice a 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. During field measurement, a series of electrodes are attached to the resistivity meter for data collection. A voltage gradient is established between two source electrodes and the resultant potential distribution is measured at two or more receiving electrodes, the resistivity is determined from this data. 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 of the ground between the electrodes is a weighted average of the electrical properties of the mineral grains, liquid and air (Keller and Frischknecht, 1966). After data inversion, ERI can provide a series of 2D or 3D tomograms, where each tomogram shows the distribution of electrical resistivity in the subsurface. Electrical imaging is possible at the sub-metre- to tens-of-metres 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 pure water 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, 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 has disadvantages: (1) direct contact with the subsurface is needed (which is problematic in areas with impenetrable ground cover, such as highways, permafrost, etc.); (2) electrode array coverage of an area can be labour 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 metre below ground surface down a few tens of metres, and cross-well studies commonly have boreholes spaced on a similar scale.

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 if the water is conductive, 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 groundwater (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 advancement is the ability of new equipment to measure multiple channels simultaneously (thus increasing data acquisition speed over single channel instruments). Several ERI multi-electrode instruments are available, a number of which have multi-channel capability. Systems typically consist of a single control unit with personal computer connection and multi-electrode cable connection (Figure 13). Some systems offer ‘smart’ electrode capability. Such systems allow a reduction of the number of electrical wires in the multi-wire 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 multi-channel operation. A number of these units offering multi-channel capability 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 $60000. 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 groundwater/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 groundwater/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), deciding where to deploy monitoring equipment, or how to interpolate between point measurements, is difficult. 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 (Figure 14). The continuous measurements can potentially be used to guide the placement of seepage monitoring equipment and to interpolate between point measurements.

Induced polarization instruments

Recent research advances in 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

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

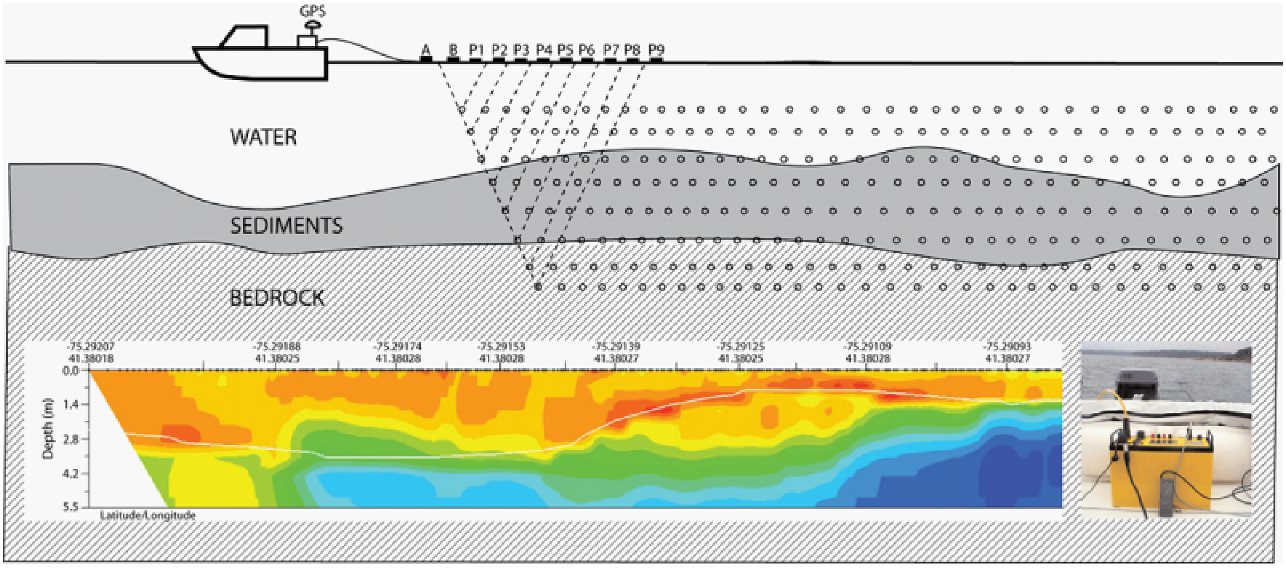

Figure 14. Multi-electrode cable towed by boat with GPS positioning and example resistivity profile (left); the resistivity instrument is shown on the right

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 measured over some specified frequency range. Exploration depths for IP in hydrogeophysical surveys have been found to range from less than a metre to a few tens of metres.

The magnitude of the polarization and the frequency dependence of the polarization dispersion are closely related to the pore-scale properties of a porous medium that in part determine hydraulic conductivity [see Slater (2007) for a review]. Induced polarization measurements could therefore make a significant contribution to the characterization of the hydraulic conductivity structure at the watershed scale. 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 groundwater, 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 yielding 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 groundwater 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 modelled 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. In a recent paper a strong direct empirical relation between τ and hydraulic conductivity was reported (Figure 15b), leading the authors to suggest that the length scale of the polarization is directly related to the hydraulic length scale determining groundwater flow (Binley *et al.*, 2005). Empirical relations between τ and pore/pore throat size have been reported (Binley *et al.*, 2005; Scott and Barker, 2005).

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 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

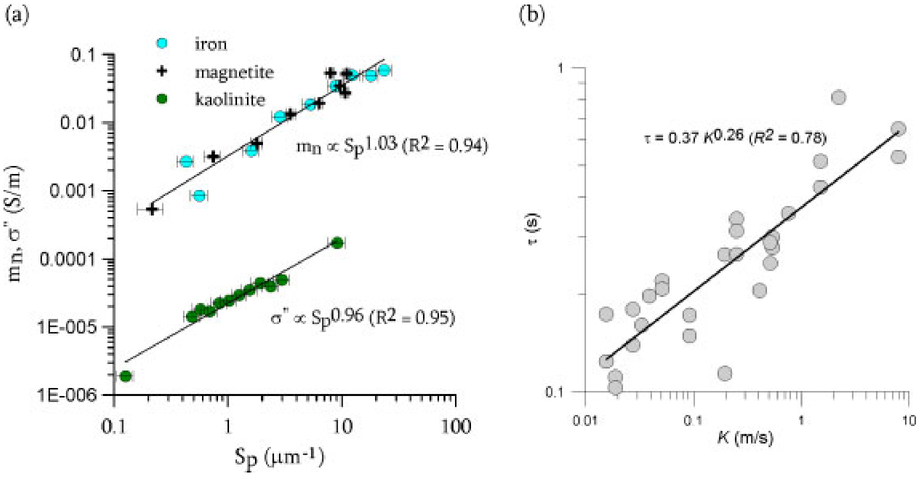

Figure 15. (a) IP parameters (m_n, σ'') as a function of surface area to pore volume (S_p) for a range of three artificial soils (data from Slater *et al*., 2006), (b) Cole-Cole relaxation time constant (τ) as a function of vertical hydraulic conductivity (K) for sandstone samples (data from Binley *et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

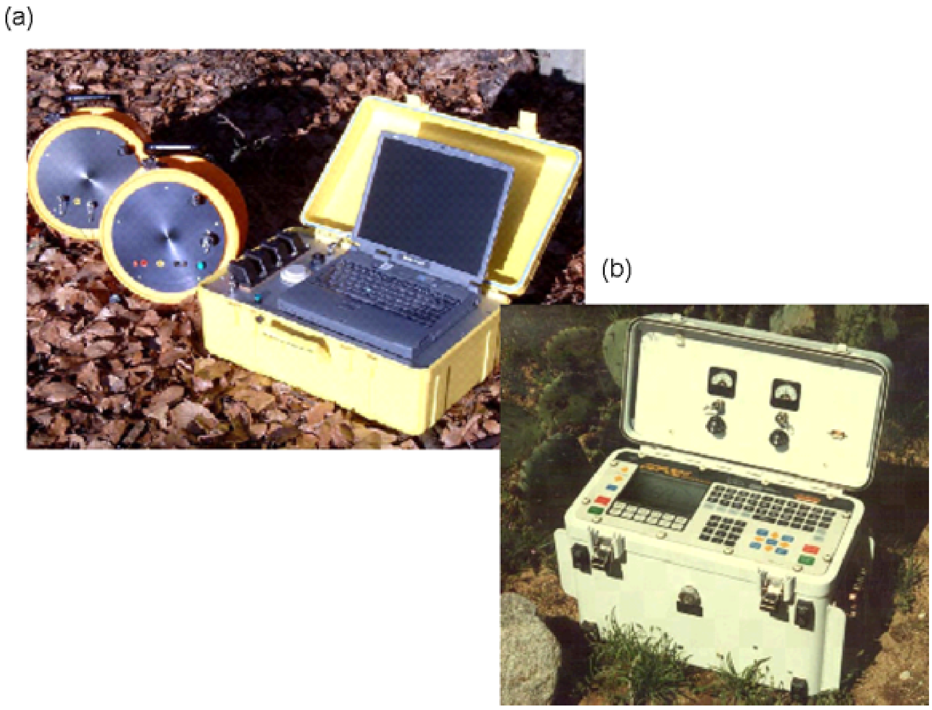

Figure 16. Examples of frequency domain SIP instruments: (a) SIP Fuchs II base unit and fiber optic cable reels; (b) Zonge GDP32 receiver

scale studies (Figure 16). The Zonge GDP32, manufactured by Zonge Engineering (USA), 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 EM 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 uses a 'remote unit concept', whereby voltage and current wires are as short as possible, to minimize EM and capacitive-coupling effects, with data transfer done via optical cables (avoiding cross-coupling). Both instruments also utilize data processing techniques to estimate and remove coupling effects from the data after acquisition. Obtaining reliable IP at high frequencies remains challenging [the experience of the author (L.S.) is that measurements above 50–100 Hz are challenging]. However, the SIP Fuchs II has built in software to estimate the effects of EM coupling based on electrode and cable configuration that may permit field IP measurements up to the kilohertz range. 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. 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 \$30000 for a two-channel system, and around \$73000 for a system allowing multiplexer control of 20 electrodes (SIP256). In contrast a Zonge GDP32 system would be in the range of \$80000–\$100000, but it is worth noting that it is capable of collecting other time and frequency domain EM data. Because IP/SIP is an emerging technology, the current availability of data interpretation 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 nonexistent.

Ground based magnetic measurements

The general principles behind the technique are identical to those set out in the aeromagnetic section (or see Hansen *et al*., 2005). For ground based surveys the magnetometer, along with the associated electronics, data logger and display package, can be carried by an operator or mounted on an all terrain vehicle. In many cases the main objectives of this surveying remain similar to those in the aeromagnetic case. Indeed in numerous cases the ground based surveys will be in response to the need for higher resolution studies of certain anomalies in the aeromagnetic data in order to provide a more constrained interpretation (Blakely *et al*., 2005). Ground based magnetic profiling has been highly successful in detecting and modelling faults and fractures in sediments (La Femina *et al*., 2002) and bedrock (Gibson *et al*., 1996, Dutta *et al*., 2006), features where secondary hydraulic permeability can often enhance groundwater flow. Geological bodies, such as igneous dykes, can exert controls on groundwater flow directions where they cut across aquifers. Magnetic profiling can reveal the location, extent, and strike of these magnetic bodies (Gibson *et al*., 1996). In cases where a magnetic contrast exists between the underlying basement and infilling sediments aquifer thickness can be modelled through magnetic mapping (Birch, 1984).

The increasing sensitivity of magnetometers and gradiometers (two magnetometer sensors are mounted vertically with separations of the order $\sim 1{\cdot}5$ m) has led to more applications in the very near-surface. This includes mapping the position and orientations of field drainage to improve understanding of solute transport and hydrological models (Rogers *et al*., 2005). Mathé and Lévêque (2003) have shown that mapping of magnetic properties may help us better understand formation, genesis, and types of soil, as well as soil drainage.

Remediation of contaminated soils and sediments is another major environmental priority in watersheds. Typically the pre-remediation situation is poorly understood due to limitations on sampling, in many cases the contaminants are often closely associated with magnetic minerals, such as Fe-oxides, and hence high resolution magnetic surveying could provide a detailed characterization of a contaminated area. Pozza *et al.* (2004) used a water-deployed magnetometer system to survey the total field magnetic anomaly within Hamilton Harbour, in western Lake Ontario. A number of positive magnetic anomalies were identified relating to discrete point source inputs of urban and industrial effluents identified in previous coring work.

Several different types of magnetometers are available. These include the proton-precession, fluxgate, and optically pumped (cesium- and potassium-vapour) magnetometers. The main difference between these instruments, excluding the actual mechanisms by which the magnetic field is measured, is the sensitivity of their measurements. Typically the proton-precession magnetometers have a sensitivity of 0·1 nT, whilst the cesium-vapour magnetometers can achieve an order of magnitude increase at 0·01 nT. The potassium-vapour magnetometers are more sensitive at 0·0025 nT. This variation in sensitivity is reflected in the cost of the systems. For example Geometrics (San Jose, California) produces the G-856AX proton-precession magnetometer at a cost of around \$5000. The G-858 cesium-vapor magnetometer costs around \$18,500. Both of these instruments can be used in the magnetometer and gradiometer configurations (the latter requiring the purchase of an additional sensor in each case, at a cost of around \$2000 and \$8000, respectively).

HIGH TEMPORAL RESOLUTION MEASURMENTS AT POINT TO CATCHMENT SCALES

Borehole Methods GPR/ERT

Borehole radar methods measure differences in the travel time and amplitude attenuation of EM 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 a fixed distance apart. Radar waves transmitted into the material surrounding the borehole travel through the material until they arrive at an interface with different EM properties. At this interface, some of the radar energy is reflected back toward the receiver and some radar energy continues farther into the ground. Because borehole radar methods are based on the transmission of EM waves, they depend on differences in the EM properties of the medium through which they travel. Borehole radar data collection is 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 antennas used (frequencies usually range between 10 and 1000 MHz) and the EM properties of the surrounding material 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, 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 plastic borehole wall as well as features in the surrounding earth material. 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 another, so that 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 groundwater 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 *et 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 receiver location is fixed in one borehole, and readings are taken at regular intervals as the transmitter is moved down the length of the second borehole. The intervals are kept short to avoid under-sampling. The receiver 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)—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 groundwater investigations, the water column in an open (or slotted) well provides the contact between electrode and formation and thus electrode arrays may be retrieved after the survey is completed. However, care must be taken, when interpreting or processing later, 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). Another further problem is that artefacts get mapped into the inversion if the 3D effect of the borehole is not accounted for.

Dielectric soil 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 modelling 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 (hours rather than weeks), 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.

Improvements in electrical components in the 1960s and 1970s revolutionized soil water content determination, 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 1980s, 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, California) are rugged field portable instruments and can be attached to probes varying in length using a waveguide connector (Figure 17). For *in situ* monitoring, Campbell Scientific (CS Inc, Logan, Utah) produces the TDR 100 that is compatible with their 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 illite or montmorillonite clay minerals, soil-specific calibration is required. All EM water content sensors perform poorly in saline soils. Several particularly promising devices are commercially available and could advance hydrological research in the next 3–5 years, particularly if they form part of distributed or wireless sensor networks.

The Acclima, Time Domain Transmission (TDT) sensor is a new instrument to emerge in the irrigation market (Blonquist *et al.*, 2005a). This sensor uses cutting-edge, cell phone technology incorporated on a computer-chip mounted in the head of the sensor (Figure 17). In TDT the

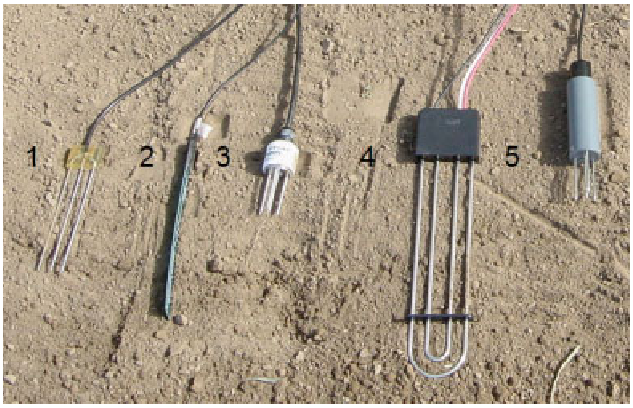

Figure 17. Soil moisture sensors: (1) TDR, (2) ECHO probe, (3) Hydra probe, (4) Acclima TDT sensor, (5) Theta probe. As a scale the TDR rods are 0·15 m long

signal propagates around a sensor loop rather than being reflected from the end of the sensor electrodes, as in TDR. Evaluation of the sensor demonstrates that it has a rise time comparable with a $12000 Tektronix TDR (Blonquist *et al*., 2005a). The manufacturer' specification sheet indicates that the sensor can resolve time differences of 25 ps, which relates to differences in water content of 0·2%. The voltage that the sensor works at is about 1 V, 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 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. The sensor measurement data is sent by conventional twin-wire cable to a data logger after being processed by the computer-chip. The processing by the computer-chip and the signal conversion to an analogue voltage signal 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. Presently the TDT sensor retails for about $300, making multiple installation affordable. The manufacturer is now developing the Acclima Junior that can link to a conventional analogue data logger through a digital/analogue converter. One of the constraints with the current design is the use of a loop instead of two rods, which can make installation in the soil more difficult; 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.

Impedance probes tend to be short (<0·1 m) fixed-frequency devices, operating at lower frequencies than TDR, usually between 50–100 MHz, 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 niche for calibrating remote-sensing data because they measure approximately the top 0·05 m 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 direct current voltage output that can be linked to a data logger or a handheld device purchased with the instrument. An alternative sensor gaining in popularity is the Hydra probe (Stevens-Vitel, Beaverton, Oregon). Although the Hydra probe operates at 50 MHz, it has circuitry that can determine the bulk soil electrical conductivity 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 electrical conductivity; in addition the sensor can measure soil temperature.

ADVANCES IN OTHER GEOPHYSICAL TECHNIQUES

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 al*., 1989; Steeples and Miller, 1990; Pullan and Hunter, 1990; Pelton, 2005; Steeples, 2005). Exploration depths range from a few metres to a few hundred kilometres. Seismic methods are sensitive to the speed of propagation of various types of elastic waves. Elastic properties and mass density of the medium in which the waves travel control the velocity of the elastic waves, and can be used to infer earth properties. 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 (Figure 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 generally they 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 many closely spaced seismic sensors in shallow surveys. Mapping bedrock with seismic refraction has probably been the most common approach used for hydrology studies. However, seismic reflection for imaging rock strata

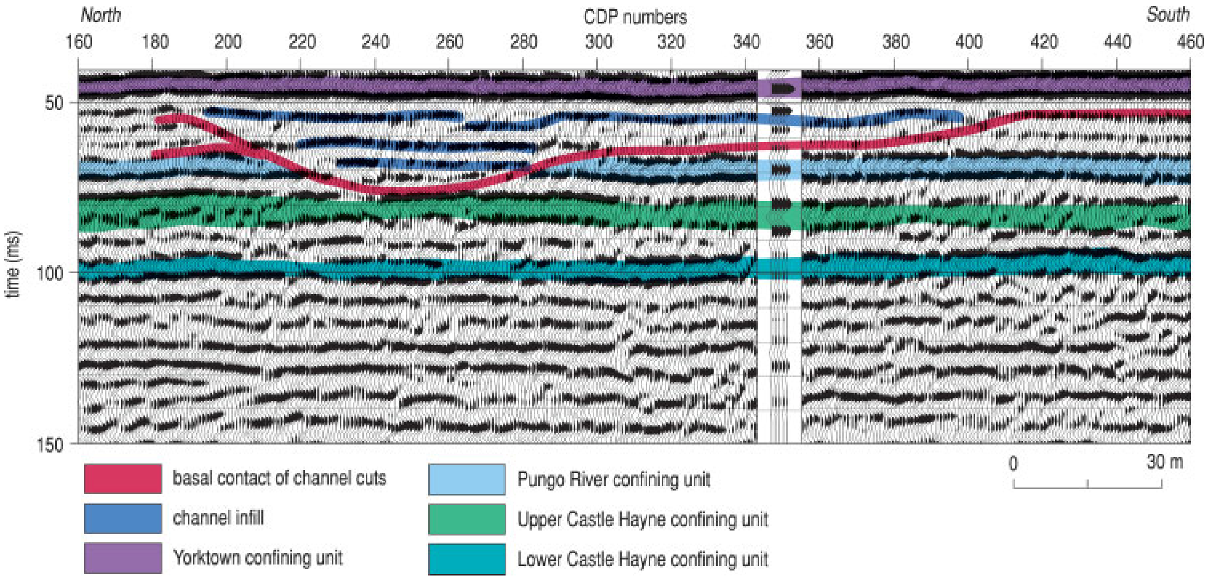

Figure 18. Interpreted high resolution, 12-fold CMP seismic reflection stacked section with inset VSP from Cherry Point, North Carolina. Shallow channels are mapped that penetrate the aquifer's confining layers

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 prevented the wide adoption of reflection for addressing near-surface hydrologic problems. Recent emergence of multi-channel surface wave techniques has kindled significant interest in applying seismic methods to 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 the different types of interstitial liquids commonly of concern in hydrologic applications. 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.

Uses of ground-based gravimetry for hydrologic investigations

Spatial gravity data traditionally have been used effectively to determine the subsurface configuration of structural basins, because of 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 groundwater 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 relative 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 widely available at academic and government institutions. Alternatively, they can be purchased for about \$80000 (standard Scintrex meter) or rented for about \$1000 per week. The instruments are easy for two or three people to operate, but the data require extensive processing and corrections for external effects before they can be modelled. Accuracies for normal field operations are about 20 µgal, decreasing to about 1–5µgal only with great care (Nabighian *et al*., 2005b). However, gravity data appropriate for basin-scale models are already publically available for much of the conterminous US (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 of the earth and can therefore be used to examine temporal changes in the regional or local mass balance of water. The measurement of changes in water content 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 \$300000. 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 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 modelling framework, hold promise for inferring hydraulic parameters. This conclusion applies to both relative and absolute gravimeters used either alone or together with other measurements.

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 and Valla, 2002; Legchenko, *et al.*, 2002; Lubczynski and Roy, 2004). At present, the only field system is the NUMIS MRS equipment for surface measurements, 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.

A SYNERGISTIC APPROACH TO GEOPHYSICAL MEASUREMENT AND HYDROLOGICAL MODELLING

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 groundwater modelling (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 these 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 complex refractive index model, 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 modelled 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 implicitly assume that the relation derived at the core-scale applied uniformly at the scale of the tomogram; however, the resolution or support volumes of geophysical and hydrologic measurements may differ or vary in space.

As solutions to ill-conditioned or ill-posed inverse problems, tomograms are commonly blurry versions of reality, lacking sharpness in detail. The resolving power of tomography is a long-standing 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).

Day-Lewis *et al.* (2005) demonstrated that 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 the form of the relation will vary spatially. A positive conclusion of Day-Lewis *et al.* (2005) was 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 analogues 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 simulated geophysical results; (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.

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, non-invasive 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 programmes, for example in applying time-lapse methods to characterize changes in fluid saturation with time. Hydrogeophysics has the opportunity to become a leading discipline in the joint use of characterization and monitoring to infer subsurface hydrological 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 non-uniformly 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 TDR 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 distribution 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, to investigate added value, is a prerequisite to developing reliable procedures for designing optimal hydrologic monitoring networks that include indirect methods.

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 hydrologic models. A hydrological modelling 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). A variety of methods and approaches are described in McDonnell *et al.* (2007) that consider exploiting hydrological patterns to infer processes. The 'dominant processes' strategy is aimed at identifying important controls, or indicators of controls, on hydrological response at different scales. The dominant processes approach tries to use a reduced number of measurable parameters (Seibert and McDonnell, 2002) as a way to constrain hydrological models. As geophysical methods are good for collecting spatial data across a range of scales (Table I) they lend themselves to integration with modelling approaches that use spatial patterns to understand hydrological connectivity. However, the combination of geophysical methods with physical models is of fundamental importance if improved geophysical and hydrological understanding is to be gained, as discussed in the previous section.

A combined approach must use model parameters that can be measured using geophysical methods. As an 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 (Figure 19). 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.

Geophysics has provided the backbone of groundwater hydrogeological exploration for many years (Fetter, 1988; Domenico and Schwartz, 1990). In Denmark it has been incorporated into National Policy for creating groundwater protection zones (Thomsen *et al.*, 2004). However, other applications of geophysics for understanding watershed hydrology are emerging, with near surface geophysics now being incorporated into watershed research (Wheater *et al.*, 2007). The emergence of airborne technologies opens up new ways to characterize watersheds including the identifation of subsurface features, e.g. fractures, voids, flow paths, and groundwater discharge locations (Ackman, 2004). Moreover, the improvement, especially in data acquisition times, with more established ground based methods opens up new avenues of research as considered in this section.

GPR and ERI have both been used in rivers to understand sediment dynamics. Froese *et al.* (2005) characterized a long reach of the Middle Yukon River in Alaska. The aim was to draw inferences about the historical fluvial behaviour of the river over millennia. GPR was used extensively to measure gravel thickness. The hyphoeric zone in rivers plays a critical role in biogeochemical cycling and its extent is often ill-defined. Often the physical extent and hydrological connectivity of the sediment in rivers is not well understood and geophysical methods can help to image the sediment structure (Birkhead *et al.*, 1996; Baines, 2002; Cardenas and Zlotnik, 2003; Gourry *et al.*, 2003). This commonly requires a strong interdisciplinary effort that combines the geophysics, hydrology and biogeochemistry. One such study by Bendjoudi *et al.*

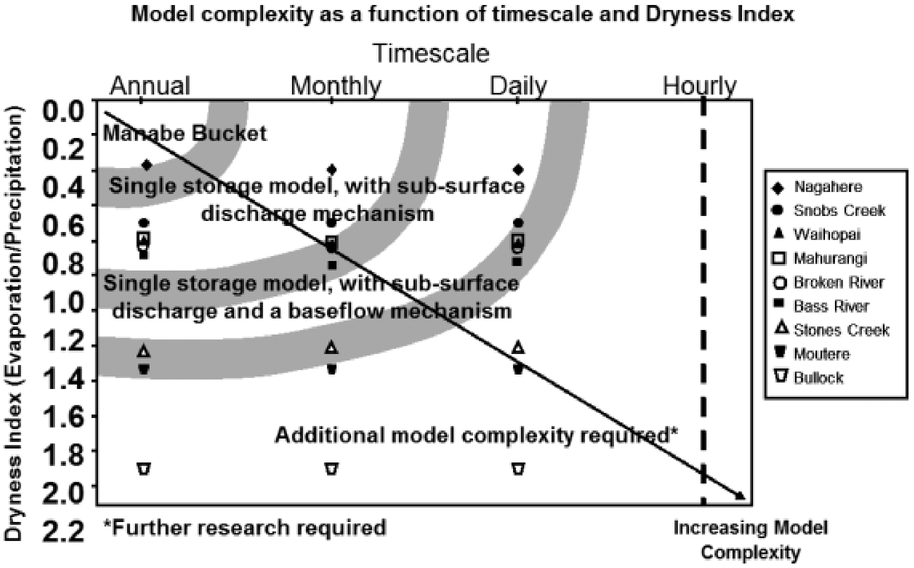

Figure 19. Hypothetical relationship between model complexity, timescale and climate characteristics (from Atkinson *et al.*, 2002)

(2002) reported the use of geophysics to determine clay layer thickness during a study of the Seine River in France that investigated the functioning of the riparian wetlands. Development of surface-water based resistivity sounding methods means that studies are emerging using these methods to examine river (Maillet *et al.*, 2005) and lake-bottom structure (Baumgartner, 1996: Yang *et al.*, 2002).

In marsh and lacustrine depositional environments the use of near surface geophysical methods is helping to unravel historic sedimentation (Hinschberger *et al.*, 2006). In peatlands geophysical methods are also providing insight into vegetation community structure related to peat stratigraphy. Slater and Reeve (2002) found a correlation between confining layer thickness and the dominant vegetation type, developing an ecohydrological angle to the use of geophysics. More recently the geophysical methods have been used to study biogenic gas and its distribution in peatlands (Comas *et al.*, 2005).

Karst environments are particularly challenging in terms of understanding hydrological processes. The complexity of the substructure and its connectivity is mostly unknown in watersheds. Geophysics has been proposed as one suite of tools that could help identify large scale patterns and flow paths, especially high permeability locations (McGrath *et al.*, 2002). Kruse *et al.* (2006) have used GPR and resisitivity methods to map sinkholes and identify preferential flow conduits. They found that the resolution of the GPR proved more valuable in resolving hydrologically important structure. A combination of geophysical methods and tracer tests could improve our understanding of processes in these complex environments.

Coastal watersheds are particularly vulnerable to sea water intrusion and aquifer salinization. The strong contrast between freshwater and seawater lends itself to imaging using electrical geophysical methods (Fitterman and Deszcz-Pan, 1998). Kruse *et al.* (2006) presented a study in which they used electrical geophysical methods to map the extent of seawater intrusion from a seawater canal in Florida, demonstrating a mixing zone extending 150–200 m from the canal boundaries inland. EMI data collected on the ground, or in the air, is helpful for integrating geophysics, biogeochemistry and hydrology to study processes linked to the development of regional sources and sinks of salinity (Corwin *et al.*, 1999; Paine, 2003; Dent, 2007). This approach to measuring salinity has been tried in Australia, where it has proven most useful for groundwater, but less effective for the near surface where vadose zone water content is needed to interpret the data (Lane *et al.*, 2000). This problem highlights the limitation of the geophysical technique as a stand alone method of interpreting earth/hydrological properties. Improvements in the interpretation of the geophysical information in the unsaturated zone could perhaps be improved by integrating the geophysical data and physically based hydrological models. In this combination both the interpretation of the geophysical signal and the hydrological response might be improved. Appropriate application of geophysical tools is required in this endeavour 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/modelling disparity.

STRATEGIC PLAN AND THE WAY FORWARD

Building Partnerships

In many watershed-scale hydrologic investigations, information is needed 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 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, with the result of identifying subsurface spatial patterns and connectivity.

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. In this approach contractors who specialize in obtaining high-quality data using routine geophysical methods could be used. Examples of specialist services that might be provided include the gathering of ground penetrating radar transects over a number of line-kilometres, field surveys using EMI mapping, and airborne surveys such as HTEM 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 in which 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, traditionally associated with groundwater evaluation, to where there is interest in identifying flow pathways, patterns and flow networks in the subsurface, in addition to the geological focus of identifying strata. Subsurface pattern identification could be exceptionally helpful in developing and testing new styles of hydrological network models as proposed by McDonnell *et al.* (2007). 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 implemented 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. However, even in state-of-the-practice applications, the needs of a scientific research programme 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 a need for workshops and educational programmes exists, 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 USGS Hydrologic Instrument Facility. Government agencies, such as USGS and USDA who are actively involved in watershed studies and/or conduct geophysical research focused on groundwater 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.

A Vision for a measurement facility

A vision for a 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. From a list of options respondents were asked to prioritize their goals for a hydrologic measurement facility. Their response is summarized in Table IV.

The results of the survey clearly indicate strong support for a facility that, not only provides cutting-edge tools, but 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 (PIs), 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.

Table IV. Prioritized goals for a hydrologic measurement facility

The aims of the HMF should be to:	Percentage 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 modelling 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 aim of the 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 or shared pool of equipment as a community resource if insurance and or 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 fulfil 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 integrate the user facility into the research community through the use of satellite science nodes. These nodes would provide the supported instrumentation and consist of scientists within active research groups strategically located around the US, who would have a portion of their time funded as a contribution to the HMF, to provide specialist cutting-edge equipment and skills to hydrology projects. This approach would have the advantage of reducing overhead costs of a central measurement facility, while keeping the scientists running the node 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 National Science Foundation (NSF), instruments and facilities panel for technical support and a basic level of equipment. This ensures that the 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 in the context of geophysics. More specialist equipment such as borehole logging tools could be maintained at the central HMF facility and shipped 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.

Groups that need to respond to local events within a large coverage area use this type of management concept extensively; it provides an efficient and focused way of deploying assets 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 science 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 those elements to develop partnerships and encourage these partnerships 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. An independent HMF oversight committee would be created as well as a more specialized independent committee to oversee the nodes. The traditional research centre concept cannot embrace all of the new technologies. They can easily become inefficient or overgrown, becoming bureaucratically inefficient. These centres often become competitors to PI research rather than fulfil 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, develop, apply and interpret geophysical methods and information. 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 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.

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