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Fusion of hydrologic and geophysical tomographic surveys

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ABSTRACT: In this paper, we argue the need for high-resolution characterization of the subsurface and discuss difficulties of traditional characterization approaches to meet this need. Necessary and sufficient conditions are then presented for well-posedness of groundwater inverse problems associated with identifying spatially distributed parameters. Non-uniqueness and large uncertainty in model calibration are subsequently attributed to difficulties in collecting information to meet these conditions. Using an example, we show that a tomographic survey can make problems of identification of spatially distributed parameters better posed. We subsequently present some recent advances in hydrologic/geophysical characterization of the subsurface using information fusion based on tomographic survey concepts. This paper includes hydraulic and electrical resistivity tomographic surveys as well as fusion of hydraulic and resistivity tomography and fusion of hydraulic and tracer tomography.

Key words: inverse modeling, well-posedness, hydraulic/geophysical tomographic surveys, data fusion

1. INTRODUCTION

Spatial and temporal variations of subsurface processes are the rule rather than the exception. For instance, inflow (infiltration, recharge, seepage, regional inflows, etc.) and outflow (evaporation, seepage, regional outflows, etc.) are known to be sporadic and highly localized. The variability is controlled in part by the characteristics of basins, which are also heterogeneous at various scales. Currently, we lack the capability to economically obtain three-dimensional (3-D) subsurface information that portrays detailed distributions of water and related properties, as well as the variable spatial and temporal processes. Such 3-D information is necessary to improve our ability to understand and manage groundwater resources that are fundamental to the quality and viability of human life on Earth.

Existing subsurface characterization technologies can cover only a small fraction of the subsurface, and sometimes their results are dubious. As a consequence, the characterization information cannot be used to reliably evaluate current and future drought and other water-related conditions. Subsurface sciences need a breakthrough approach or "instrument" to greatly expand and deepen our ability to "see into the Earth." As its key scientific focus, this paper will present recent successes of data fusion technologies for characterizing and monitoring the subsurface.

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2. DIFFICULTIES OF CLASSIC APPROACHES

Quantitative analysis and prediction of subsurface fluid flow and solute transport requires the use of mathematical models. These models generally rely on partial differential equations (PDE) that express hydrologic, physical, and chemical principles of natural phenomena in the subsurface, extended over space and time. A forward problem (i.e., prediction) generally refers to solving PDE's for the system states in space and time, with known properties and given initial and boundary conditions. An inverse problem (i.e., characterization, parameter identification or estimation) refers to determining values of the system's properties from information about excitations to the subsurface and observations (monitoring) of responses of state variables to those excitations.

Therefore, high-resolution, quantitative prediction demands high-resolution information about the system's properties and initial and boundary conditions. Similarly, high-resolution inverse modeling requires detailed information about excitations to and responses of the system, as well as any pre-existing information on system properties and states. The inherent spatial variation or 3-D heterogeneity of properties at various scales (e.g., pores, lenses, strata, formations, and basins) greatly compounds the difficulties of site characterization and prediction. Traditional in-situ borehole characterization and monitoring methods (i.e., core samples, slug tests, flow meter tests, aquifer tests, multi-level samplers, wells, etc. see Domenico and Schwartz, 1990) are invasive and too costly to emplace in large numbers and significant depths throughout an aquifer. More critically, "representativeness" of the properties estimated from these methods has recently been questioned by Beckie and Harvey (2002), Wu et al. (2005), and others.

Likewise, traditional inverse modeling of groundwater models with distributed parameters based on sparsely observed responses (or inverse modeling for short) also fails to provide reliable information about the aquifer characteristics. Difficulties in obtaining necessary and sufficient information that makes the inverse problem well posed are the cause of the failure. To understand these difficulties, let us first consider the governing PDE for forward modeling groundwater flow in aquifers (Bear, 1972):

$$\nabla \cdot [K(\mathbf{x})\nabla h(\mathbf{x},t)] = S_s(\mathbf{x})\frac{\partial h(\mathbf{x},t)}{\partial t} \tag{1}$$

where $h(\mathbf{x}, t)$ is the hydraulic head which is a function of the position vector, $\mathbf{x}$, and time, t; $K(\mathbf{x})$ is the spatially varying hydraulic conductivity field; $S_s(\mathbf{x})$ is the spatially varying specific storage field of the aquifer. As mentioned previously, a forward model solves the equation with known hydraulic conductivity and specific storage property fields for the hydraulic head in time and space, given initial and boundary conditions. A lack of complete information of the property fields, and initial and boundary conditions (i.e., the necessary and sufficient information) makes the forward problem ill posed; many possible solutions exist, implying that the predictions of groundwater state are uncertain.

Equation (1) can be rewritten as a corresponding inverse PDE:

$$K(\mathbf{x})\nabla h(\mathbf{x},t) + \nabla K(\mathbf{x}) \cdot \nabla h(\mathbf{x},t) = S_s(\mathbf{x})\frac{\partial h(\mathbf{x},t)}{\partial t} \tag{2}$$

Unknowns in equation (2) are the hydraulic conductivity and the specific storage field, as opposed to the unknown hydraulic head field in equation (1) for the forward problem. The aim of inverse modeling therefore is to solve equation (2) for these hydraulic property fields.

Prerequisites for a unique solution to equation (2) are: (i) the hydraulic heads everywhere in the solution domain for at least at two time levels, t and t'; and (ii) boundary K values. Once they are given, we have a system of equations for $K(\mathbf{x})$ and $S_s(\mathbf{x})$:

$$\begin{aligned}
[\nabla h(\mathbf{x},t)]\nabla K(\mathbf{x}) + [\nabla^2 h(\mathbf{x},t)]K(\mathbf{x}) &= \left[\frac{\partial h(\mathbf{x},t)}{\partial t}\right]S_s(\mathbf{x}) \\
[\nabla h(\mathbf{x},t')]\nabla K(\mathbf{x}) + [\nabla^2 h(\mathbf{x},t')]K(\mathbf{x}) &= \left[\frac{\partial h(\mathbf{x},t')}{\partial t}\right]S_s(\mathbf{x})
\end{aligned} \tag{3}$$

According to the system of equations (3), the specific storage can be estimated only if the net inflow to a given volume of the medium and the head change over time at the volume are known. Therefore, estimation of S_s at a given location, $\mathbf{x}$, requires an observable temporal change in the hydraulic head at the location. These requirements are thus called necessary and sufficient conditions for the inversion of equation (2) (Yeh and Šimůnek, 2002). If these conditions are specified, the inverse problem is mathematically well posed; it has a unique solution, and the aquifer can be fully characterized. Otherwise, the problem is ill posed and characterization of the aquifer is uncertain.

Specification of these necessary and sufficient conditions is possible in well-controlled laboratory and field experiments, but unlikely in any field-scale problem. Without fully specifying these conditions, current inverse modeling efforts of field-scale aquifers have become so called model calibration or history matching exercises that aim at fitting limited observed system responses. History matching, however, does not assure parameter correctness, and it thereby often yields highly subjective aquifer characterizations. Because of this uncertainty in aquifer characterization, as well as our inability to determine temporally and spatially varying boundary conditions (e.g., inflow and outflow) of the aquifers, many grossly misleading predictions of groundwater flow and contaminant migration have been made. Our ability to validate a subsurface model as such has been seriously questioned (see Konikow and Bredehoeft, 1992; Oreskes et al., 1994; Bredehoeft, 2003), as has our ability to predict flow and solute migration in aquifers. Groundwater resources management virtually becomes a matter of political debate without much scientific basis.

3. DATA FUSION

Recently, viable alternatives to the traditional in-situ borehole characterization and inverse modeling approaches have emerged, in which data from the traditional characterization methods are supplemented with other types of information, for example, indirect, minimally-invasive hydrologic and geophysical surveys. These alternatives are basically the so-called data fusion approaches. The rationale behind the data fusion approaches is straight forward: making the best interpretation by taking advantage of many pieces of available information (or collecting and analyzing data intelligently). In the following discussions, the concept and technologies of 1) fusion of the same type of information and 2) fusion of different types of information are presented.

3.1. Fusion of the Same Types of Information

Tomographic surveys belong to fusion of the same types of information. These surveys excite the subsurface using well-characterized, anthropogenic stimuli (e.g., injection of electricity; water, air, tracers, etc.) at different locations in the subsurface and simultaneously monitor responses at a large number of other locations. These surveys thereby yield many pieces of non-fully "overlapped" information, which are used to constrain interpretation of data collected from each excitation. As a result, the final result is less uncertain. These tomographic surveys are analogous to CAT scan technology which produces a 3-D picture of an object that is more detailed than a standard X-ray, and which has been widely used in medical sciences to “see” into human bodies non-invasively.

To illustrate the concept and principle of the tomographic survey, consider a composite geologic medium that consists of two layers; each layer has a different hydraulic conductivity value, K_1 and K_2, and the same thickness. Suppose the hydraulic conductivity values of the two layers are the unknowns to be determined. If a steady-state flow experiment is conducted in which water flows in the direction parallel to the layering and if the boundary heads and the total flux are measured, an effective hydraulic conductivity of the composite medium can be determined. It is an arithmetic mean of an infinite number of possible pairs of K_1 and K_2 values (i.e., $K_a = 0.5\times(K_1+K_2)$). If the flow experiment is repeated again but allows the flow to enter perpendicular to bedding, the effective hydraulic conductivity becomes the harmonic mean of an infinite number of possible pairs of K_1 and K_2 values (i.e., $K_h = K_1K_2/(K_1+K_2)$). If now we integrate or “fuse” the information from these two experiments (i.e., solve the arithmetic mean and the harmonic mean equations, simultaneously), the number of possible pairs of K_1 and K_2 values becomes only two. This rudimentary example manifests that a tomographic survey -- which collects data intelligently and analyzes data smartly -- indeed provides additional information for an inverse problem being better posed, and hence reduces the number of possible solutions to the problem.

In the following sections, we will discuss the tomographic survey concept applied to hydrologic and geophysical characterization of the subsurface. These tomographic surveys rely on anthropogenic stimuli (e.g., pumping or injection of water or air, injection of electric current, etc.) which can be well-characterized but have limited area coverage. In hydrology, hydraulic, pneumatic as well as tracer tomography surveys have been developed recently. Likewise, seismic, acoustic, electromagnetic (EM) and other tomography surveys have emerged in geophysics. Our discussion, however, will focus on hydraulic tomography and electrical resistivity tomography only, and then a discussion will follow regarding the strengths and weaknesses of general hydrologic and geophysical tomography.

3.1.1. Hydraulic tomography (HT)

Gottlieb and Dietrich (1995); Vasco et al. (2000), Yeh and Liu, (2000); Bohling et al. (2002); Brauchler et al. (2003); Zhu and Yeh (2005 and 2006); and others have developed new methods for aquifer characterization, i.e., hydraulic tomography. A simple example of HT involves the installation of at least two wells in an aquifer. Using packers, each well is then partitioned into several intervals along its depth. A sequential aquifer test is subsequently undertaken. During this test, water is injected or withdrawn (a pressure excitation) at a selected interval in a given well, and pressure responses of the subsurface are then monitored at other intervals at this well and the other well(s). This test thus produces a set of pressure excitation/response data of the subsurface. Afterward, the pump is moved to another interval and the test is repeated to collect another set of data. This test is applied to all of the intervals at all of the wells. The data sets from all the tests are then processed by an inverse model to estimate the spatial distribution of hydraulic properties of the aquifer. In other words, a set of pressure excitation/response data in HT is tantamount to an image of subsurface heterogeneity due to light emitting from a given location. Repetition of the test at different intervals merely takes many of these snapshots of the heterogeneity in the aquifer from different angles and directions. Synthesizing all of the snapshots thus maps a 3-D hydraulic property distribution of the tested volume.

Using laboratory sandbox experiments and the HT algorithm by Yeh and Liu (2000), Liu et al. (2002) and Illman et al. (2006) demonstrated that steady-state HT is an effective technique for depicting an aquifer’s heterogeneity with a limited number of invasive observations. Recently, Zhu and Yeh (2005) extended the analysis algorithm for steady-state HT to transient HT, and thus both hydraulic conductivity and specific storage fields of aquifers can be estimated. Since great computational resources are required for analyzing data from transient HT, Zhu and Yeh (2006) adapted a temporal moment approach (Harvey and Gorelick, 1995a; Li et. al., 2005) to expedite the analysis.

Although the capabilities of transient HT remains to be fully assessed in the field, results from sand box experiments by Liu et al. (2007) are encouraging. Not only did tomography identify the pattern of the hydraulic conductivity heterogeneity, but also the variation of specific storage values in the sandbox. More importantly, they showed that using the identified spatially varying hydraulic conductivity and specific storage fields, they can predict temporal and spatial evolutions of the drawdown induced by independent hydraulic tests. Likewise, a recent application of HT to a well field at Montalto Uffugo Scalo, Italy, produced an estimated transimssivity field that is deemed consistent with the geology of the site (Straface et al., 2006).

HT can be used to image fracture connectivity in fractured aquifers as well. Figure 1 depicts a synthetic fractured aquifer in which two slanted boreholes intercept two orthogonal fractures. The hydraulic conductivity along the two boreholes was assumed to have been measured prior to a HT survey. Five separate pumping operations were then initiated at specified locations (see Fig. 1) to reach five corresponding steady flow fields. During each flow field, pressures along the boreholes were monitored. Using these pressure data and the hydraulic conductivity measurements, the hydraulic conductivity distribution in the entire aquifer (Fig. 2) was estimated with the HT algorithm by Zhu and Yeh (2005). A comparison of Figures 1 and 2 suggests that HT is poten-

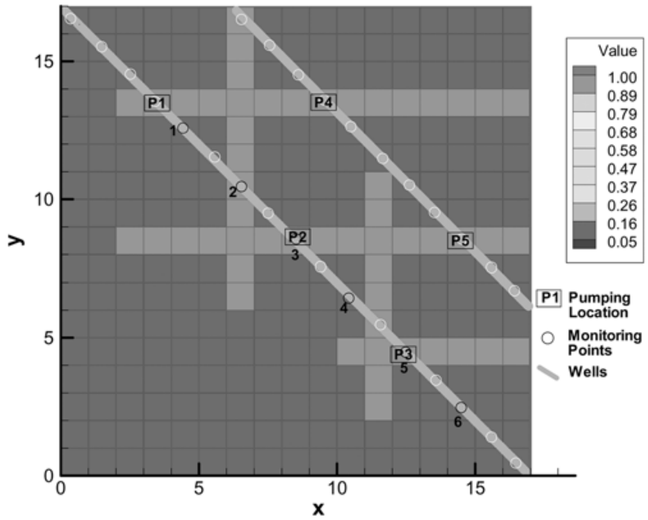

Fig. 1. The orthogonal fracture pattern and location of slanted pumping wells used in the numerical experiment. The hydraulic conductivity of the fracture (red) and that of the rock matrix (blue) are 1m/s and 0.05 m/s, respectively.

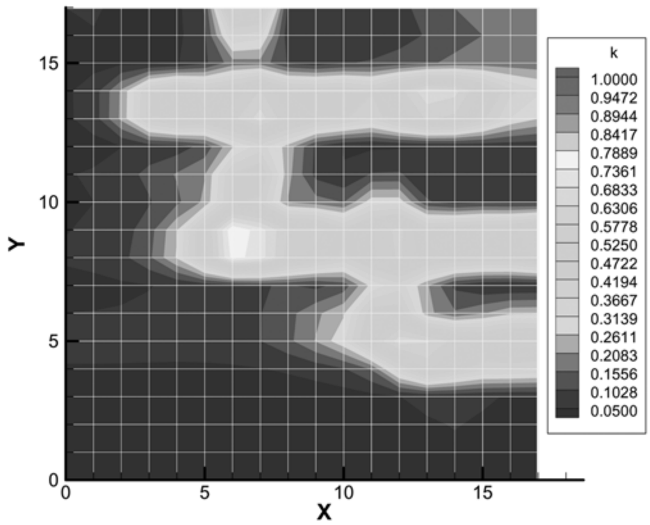

Fig. 2. The detected hydraulic conductivity field reflecting fracture pattern, based on the steady hydraulic tomography.

tially a promising technology for mapping connectivity of fractures in aquifers.

3.1.2. Electrical resistivity tomography (ERT)

Over the past few decades, the dc resistivity survey has been an inexpensive and widely used technique for the investigation of near-surface resistivity anomalies. It recently has become popular for the investigation of subsurface pollution problems (NRC, 2000). The classic analysis of a resistivity survey relies on analytical formulas that assume a homogeneous earth to derive apparent resistivity. Generally speaking, the electric potential observed at a point in space is influenced by resistivity anomalies over the entire electric potential field created by a survey. In particular, resistivity anomalies near the transmitting and the receiving electrodes have greater influence. But a significant geologic anomaly anywhere within the entire electric current field can also have the same impact. Thus, the apparent resistivity can be highly misleading when derived from a potential measurement using the classical analysis. Similar findings were found in a recent study of traditional analyses of aquifer tests (Wu et al., 2005), which is analogous to the analysis of the apparent resistivity. Indeed, the conventional resistivity survey has been found virtually ineffective for environmental applications, where electrical resistivity anomalies are subtle, complex, and of a multiplicity of scales.

Meanwhile, a contemporary electrical resistivity survey (i.e., ERT) has been designed to collect extensive electric potential data sets in multi-dimensions in a tomograhic survey fashion. The resistivity field is then estimated by inversion of the data sets using a model without the assumption of a homogeneous earth, and using a regularized optimization approach (e.g., Daily et al., 1992; Ellis and Oldenburg, 1994; Li and Oldenburg, 1994; and Zhang et al., 1995).

The general consensus for inverse modeling of resistivity and hydrologic property fields is that prior information about geological structure, and some point measurements of parameters to be estimated, are essential to constrain the solution to the inverse problem (Oldenburg and Li, 1999; Li and Oldenburg 2000; Kitanidis, 1995, McLaughin, and Townley, 1996).

Recently, Yeh et al. (2002) developed a geostatistically-based inverse approach for ERT that includes prior information, i.e., spatial statistics of the resistivity distribution of geologic media and point measurements of resistivity. Applications of this approach to field situations as well as laboratory and numerical experiments have proven its robustness (Yeh et al., 2006). In particular, Englert et al. (2005) show that, when only scarce potential measurements are available, the geostatistically-based approach yields better estimates than those using the classical regularization method. Accordingly, ERT is an appealing technology for imaging subsurface electrical resistivity anomalies. The resolution of the image nevertheless depends on the design of data collection network. For example, a surface electrode array detects only anomalies near the surface; a down-hole array provides more accurate mapping of the anomalies at great depths. Higher-resolution images can only be obtained if a spatially high-resolution electric potential field is collected using a combination of densely distributed surface and down-hole arrays.

3.1.3. Strengths and weakness of fusion of the same types of information

Geophysical tomography (e.g., ERT) generally produces subsurface images at higher resolution than hydraulic or tracer tomography. This is attributed to relative inexpensiveness of geophysical sensors compared to hydrologic sensors. Hence a greater number of geophysical sensors can be deployed to cover a given field site during a tomographic survey to collect more responses and in turn, the survey yields more detailed images. Geophysical sensors can also be easily implemented on the land surface with little invasive operation, whereas hydrologic sensors must be installed in boreholes. Such invasive borehole drilling operations prohibit any dense deployment of hydrologic sensors.

In spite of its shortcomings, hydrologic tomography has its advantages over geophysical tomography for characterization of flow and solute transport processes and properties of geologic formations. Analysis of hydrologic tomography directly yields hydrologic properties. On the other hand, analysis of geophysical surveys yields electrical resistivity or permittivity, which has to be translated into hydrologic properties via some constitutive relation. This relation is often empirical, site specific, scale-dependent, and perhaps ambiguous (Day-Lewis et al., 2005, Moysey et al., 2005, Day-Lewis, and Lane, 2004, etc.) and the translated hydrologic properties, as such, could be misleading. Spatial variability of the relation, as noticed by Yeh et al. (2002), further complicates this translation.

3.2. Fusion of Different Types of Information

Both HT and ERT are typical examples of fusion of the same type of information. They are most appealing because only a small number of invasive operations are needed to obtain a comparable resolution of other conventional characterization methods. However, neither hydrologic nor geophysical tomography alone provides perfect characterization of the subsurface. A tomographic survey merely makes the inverse problem better posed and reduces uncertainty associated with the traditional inverse modeling approaches. Taking advantage of the strength of a particular type of tomographic survey to compensate for the deficiencies of the other becomes a possible means to enhance the resolution of a tomographic survey. This thinking thus promotes fusion of different types of hydrologic information, fusion of hydrologic and geophysical information, and fusion of hydraulic and tracer tomography to enhance our subsurface characterization, as discussed below.

3.2.1. Fusion of different types of hydrologic information

For decades, hydrologists have integrated different types of hydrologic information to obtain better hydrologic characterization of the subsurface. For example, Harvey and Gorelick (1995b) estimated a hydraulic conductivity field using sparse measurements of hydraulic conductivity, heads and solute arrival time. They found that arrival time and head data yielded different estimates. Li and Yeh (1999) estimated the hydraulic conductivity field of variable saturated media conditioned on three types of measurements (i.e., pressure head, solute transport, and solute arrival time). They reported that steady state head measurements are most effective among the three types of measurements, while additional solute concentration data can enhance the estimates based on head measurements alone. Cirpka and Kitanidis (2001) used the first two temporal moments of solute data to estimate the hydraulic conductivity field. They recommended that the use of both head and tracer data could lead to better estimations of the hydraulic conductivity field.

For vadose zone problems, a study by Harter and Yeh (1996) suggested that conditioning the solution transport simulation using pressure head information improves prediction of plume migration. Yeh and Zhang (1996) reported that pressure data can benefit estimation of the saturated hydraulic conductivity field, while moisture content data enhance estimation of the pore-size distribution parameter of the unsaturated hydraulic conductivity curve of the vadose zone. Finally, the use of both pressure and moisture data can result in better characterization of the vadose zone than using either one of them alone.

Clearly, the worth of a type of data rests upon the type of property to be estimated. As an example, information of the hydraulic head gradient and specific discharge is critical to estimating hydraulic conductivity, because these data, along with Darcy's law, define the hydraulic conductivity. By the same token, tracer data are most useful for estimating chemical properties, porosity, and dispersivities. Tracer data alone are, however, less informative about the hydraulic conductivity. The reason is rather straightforward: movement of tracers is governed by the velocity field if the dispersion process is omitted. Velocity is a function of the hydraulic conductivity, but also of the hydraulic gradient and the porosity. Without knowledge of all these controlling factors, estimation of the hydraulic conductivity can be highly uncertain when based on tracer data alone.

On the other hand, propagation of a pressure excitation is a diffusion process which generally smoothes out the effects of heterogeneity (analogous to an electric potential field). The migration of tracers is mainly controlled by advection, which is highly sensitive to variation in hydraulic conductivity. Tracers are thus generally more sensitive to preferential flow paths even at small scales (not identical but similar to high-frequency EM waves, such as ground penetrating radar) than the hydraulic head. Inclusion of tracer data, therefore, can enhance the estimate of the hydraulic conductivity based on the hydraulic head information alone.

3.2.2. Fusion of hydrologic and geophysical information

Near-surface geophysics has become increasingly popular and has played an important role in groundwater investigations over the past few years (NRC, 2000, Rubin and Hubbard, 2005; Vereecken et al., 2006). While geophysical surveys may not be suitable for mapping hydraulic properties, they are desirable tools for detecting changes in the hydrologic state of geologic media. For instance, Binley et al. (1996) demonstrated that ERT can be used to monitor the breakthrough of chloride tracers in column experiments; Kemna et al. (2002), and Singha and Gorelick (2005) used ERT to monitor the migration of a tracer plume in porous media. Day-Lewis et al. (2003, 2004) used time-lapse radar tomography to monitor tracer migration in fractured rock. Ground penetrating radar (GPR) and self potential measurements were used by Endres et al. (2000), Bevan et al. (2003), Bevan et al. (2005), and Rizzo et al. (2004) to monitor water table responses during aquifer tests; ERT and GPR have been widely used to detect movement of moisture in the vadose zone (e.g., Daily et al., 1992 and Binley et al., 2001). Caution, however, was raised by Yeh et al. (2002) about using ERT to determine changes in moisture content in the vadose zone due to the inherent variability of the relation between moisture content and resistivity (i.e., parameters of Archie's law). Nonetheless, Liu and Yeh (2004) develop a data fusion approach to overcome this difficulty, which includes in-situ measurements of moisture content, resistivity, and parameters of Archie's law.

Success of these applications suggest that ERT, GPR, and other geophysical surveys may serve as cost-effective tools for obtaining a large number of hydrologic responses of the subsurface over large areas. Spatially dense information of hydrologic responses is a prerequisite for a better hydrologic inversion. To achieve a better hydrologic inversion, it is therefore a logical step to couple geophysical surveys, for the purpose of monitoring states of the subsurface, with hydrologic inversion.

This information fusion idea was demonstrated by Yeh and Šimůnek (2002) for vadose zone monitoring and characterization. Specifically, they used ERT to monitor moisture evolution in the vadose zone during infiltration events. Electrical potentials from ERT surveys were then analyzed for the moisture content distribution. During the analysis, point measurements of moisture content by neutron probes, core samples, and others were included, as well as their prior knowledge of the spatial statistics of the moisture distribution. Inclusions of point measurements and the spatial statistics not only ensured a correct interpretation of the ERT results in terms of hydrologic and geologic contexts, but also expanded our knowledge about the true distribution of the moisture plume beyond the point measurement locations (e.g., Liu and Yeh, 2004). As a result, this spatially-extensive moisture information makes a hydrologic inversion better posed, and the estimates of hydrologic properties approach representative values.

Better characterization of geologic media leads to a more accurate prediction of the migration of moisture and in turn, more accurate constraints for the ERT inversion during the monitoring of advancing moisture plumes. Using this iterative information fusion procedure and numerical examples, Yeh and Šimůnek (2002) demonstrated the feasibility of developing a cost-effective monitoring, characterization, and prediction protocol for the vadose zone process.

3.2.3. Fusion of hydraulic and tracer tomography

The potential of fusion of different types of tomography surveys for mapping residual DNAPL distribution was recently studied by Zhu and Yeh (2005). Figure 3a shows the DNAPL distribution in a synthetic aquifer with four wells, and each well is partitioned into several injection or sampling ports (square and circle, respectively). A hydraulic and partitioning tracer tomography involves injection of water into the aquifer at one of the injection ports to establish a forced gradient flow field. Once a steady flow field is reached, a partitioning tracer is introduced into the aquifer at the same port. Steady flow pressure and the tracer breakthroughs are subsequently collected at the sampling ports of all wells. Afterward, the water and tracer injection operation is moved to another injection port and steady pressure and breakthroughs at all sampling ports are collected again. This operation is repeated until all the selected injection ports are used. Note that a different partitioning tracer is used for each tracer test. After the tests are completed, the pressure data collected during all the injection tests are first used to determine the hydraulic property distribution in the aquifer. This estimated hydraulic property field is subsequently used in the analysis of the partitioning tracer breakthrough data to map the distribution of the DNAPL in the aquifer. This is called hydraulic/partitioning tracer tomography (HPTT).

Figure 3b shows the estimated DNAPL field using conventional direct measurements of DNAPL from the four wells and the kriging method. Using a traditional partitioning tracer test (injection of water and the tracer at only one port and monitoring the breakthroughs at the other ports), and analysis of the tracer breakthroughs assuming aquifer homogeneity and without taking advantage of head information lead to an estimated DNAPL distribution shown in Figure 3c. Figure 3d illustrates an estimated DNAPL distribution, using the partitioning tracer tomography (PTT) without any knowledge of the hydraulic heterogeneity of the aquifer or taking advantage of the hydraulic head information. Lastly, the DNAPL distribution resulting from the hydraulic/tracer tomography is plotted in Figure 3e.

Among the approaches used to derive the results shown in Figures 3b, c, d and e, the direct sampling approach (Fig. 3b) yields the worst estimate. It detects DNAPL near sampling locations and extrapolates the sample values to its vicinity via the correlation structure, but fails to capture high DNAPL saturation areas between observation wells. A comparison of Figures 3c and d demonstrates the benefit of tracer tomography: tomographic surveys yield many pieces of "partially-overlapped information" such that more detailed DNAPL distribution is identified. A comparison of Figures 3d and e manifests the advantage of fusion of hydraulic and tracer tomography. That is, PTT alone can lead to erroneous

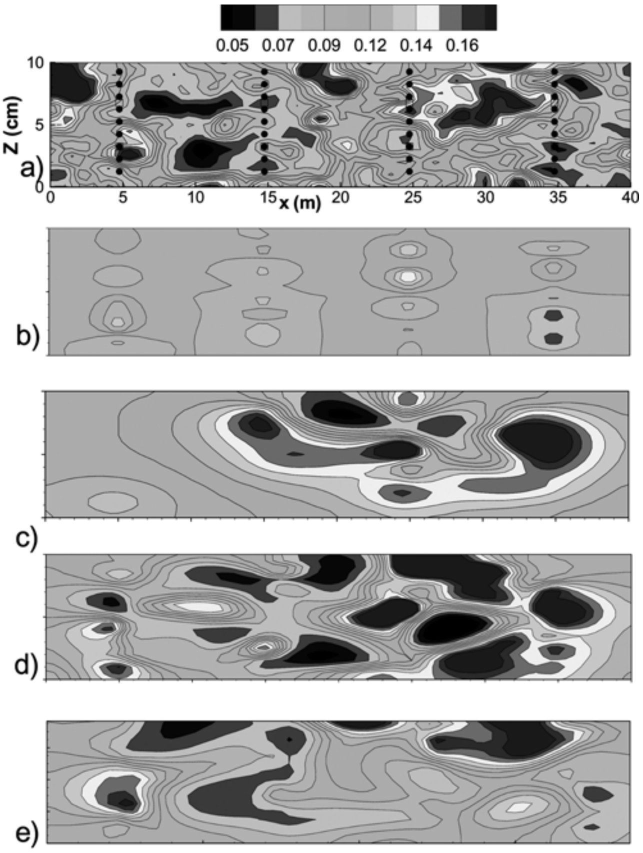

Fig. 3. An illustration of the benefit of hydraulic/tracer tomography: a) a synthetic true DNAPL distribution and samples and injection ports of the hydraulic/tracer tomography survey; b) estimated DNAPL distribution based on in-situ borehole samples and geostatistics; c) the estimated distribution using the traditional single injection partitioning tracer test, without taking advantage of hydraulic head information; d) the estimated distribution based on partitioning tracer tomography alone without using the hydraulic head information; e) the estimated field using the hydraulic/tracer tomography.

estimates of the DNAPL field, which is attributed to the fact the tracer data from one injection test provide only an estimate of the specific discharge (Darcian velocity) field for the given flow scenario. This field is only weakly related to the hydraulic conductivity field unless the hydraulic head field or gradient is specified. While PTT produces many sets of the estimated velocity field, each velocity estimate (in turn, each DNAPL estimate) is independent from one another. Without conditioning each estimate using the available head information during each injection, each DNAPL estimate therefore can be inconsistent with the other. Thus, the final DNAPL estimate deteriorates. A conjunctive use of HT and PTT (i.e., HPTT) is thereby a superior approach for better DNAPL characterization.

4. CONCLUSIONS

It is our belief that mapping the subsurface in detail is a necessary step to advance our understanding and prediction of processes in the subsurface. Collecting data intelligently and analyzing data smartly are required to accomplish this step. Tomographic surveys are examples of collecting data intelligently and analyzing data smartly under constraints. Fusion of different tomographic surveys maximizes our ability to obtain high-resolution images of the subsurface.

We firmly believe that recent success of the information fusion approach is a major milestone of the subsurface characterization technology although obstacles remain. These obstacles include skepticisms about the usefulness of this new technology because of its higher operational cost than those of traditional low-resolution technologies. However, we recall that decades ago similar critics were raised about the benefits of similar high-resolution but now life-saving medical technologies such as CATsan, MRI, etc. in medical science and technology.

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