Boise State University
ScholarWorks

CGISS Publications and Presentations

Center for Geophysical Investigation of the Shallow Subsurface (CGISS)

3-20-2008

A View Toward the Future of Subsurface Characterization: CAT Scanning Groundwater Basins

Warren Barrash
Boise State University

Copyright 2008 by the American Geophysical Union. DOI: 10.1029/2007WR006375

WATER RESOURCES RESEARCH, VOL. 44, W03301, doi:10.1029/2007WR006375, 2008

A view toward the future of subsurface characterization: CAT scanning groundwater basins

Tian-Chyi Jim Yeh,[1] Cheng-Haw Lee,[2] Kuo-Chin Hsu,[2] Walter A. Illman,[3]
Warren Barrash,[4] Xing Cai,[5] Jeffrey Daniels,[6] Ed Sudicky,[3] Li Wan,[7]
Guomin Li,[8] and C. L. Winter[9]

Received 24 July 2007; revised 18 November 2007; accepted 28 December 2007; published 20 March 2008.

[1] In this opinion paper we contend that high-resolution characterization, monitoring, and prediction are the key elements to advancing and reducing uncertainty in our understanding and prediction of subsurface processes at basin scales. First, we advocate that recently developed tomographic surveying is an effective and high-resolution approach for characterizing the field-scale subsurface. Fusion of different types of tomographic surveys further enhances the characterization. A basin is an appropriate scale for many water resources management purposes. We thereby propose the expansion of the tomographic surveying and data fusion concept to basin-scale characterization. In order to facilitate basin-scale tomographic surveys, different types of passive, basin-scale, CAT scan technologies are suggested that exploit recurrent natural stimuli (e.g., lightning, earthquakes, storm events, barometric variations, river-stage variations, etc.) as sources of excitations, along with implementation of sensor networks that provide long-term and spatially distributed monitoring of excitation as well as response signals on the land surface and in the subsurface. This vision for basin-scale subsurface characterization faces many significant technological challenges and requires interdisciplinary collaborations (e.g., surface and subsurface hydrology, geophysics, geology, geochemistry, information and sensor technology, applied mathematics, atmospheric science, etc.). We nevertheless contend that this should be a future direction for subsurface science research.

Citation: Yeh, T.-C. J., et al. (2008), A view toward the future of subsurface characterization: CAT scanning groundwater basins, *Water Resour. Res.*, *44*, W03301, doi:10.1029/2007WR006375.

1. Introduction

[2] A basin is the appropriate geologic and geographic delimiter for water resources management. Spatial and temporal variations of subsurface hydrologic and other processes within a basin are the rule rather than the exception. Groundwater inflow (infiltration, recharge, river seepage, regional inflows, etc.) and outflow (evapotranspiration, spring discharge, regional groundwater flows, etc.) are sporadic and localized, with temporal and spatial variations controlled in part by the characteristics of basins that are heterogeneous at many scales. Proper management of groundwater resources requires accurate knowledge of the water balance (i.e., storage, inflow, and outflow) and spatial and temporal distributions of water bodies with different chemistries (e.g., contaminants or salinity). As a result, three-dimensional (3-D) subsurface information (high-resolution in space and time for basin scale) is needed about key hydrologic and geological stratigraphy, structure, and properties and state distributions in a basin.

[3] Existing monitoring and characterization technologies can cover only a small fraction of the subsurface. The collected information is not sufficient to support effective management of increasing and competing demands for water, current and future drought, and other water-related problems that occur at the basin scale. Subsurface science needs breakthrough technologies to greatly expand and deepen our ability to “see into the groundwater basin.” As its key scientific focus, this paper promotes a vision and ambition to develop capabilities for subsurface imaging at basin scales. Here, field scale refers to areas of tens to thousands of square meters, and areas over several to tens of thousands of square kilometers or more are considered to be basin scale (e.g., a groundwater basin).

2. Data Fusion for Field-Scale Problems

[4] Acquiring data that satisfy the sufficient and necessary conditions for a groundwater inverse problem to be well posed [see *Yeh et al.*, 2007] is generally intractable for

---

[1] Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA.

[2] Department of Resources Engineering, National Cheng-Kung University, Tainan, Taiwan.

[3] Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario, Canada.

[4] Center for Geophysical Investigation of the Shallow Subsurface, Department of Geosciences, Boise State University, Boise, Idaho, USA.

[5] Simula Research Laboratory, Lysaker, Norway.

[6] School of Earth Sciences, Ohio State University, Columbus, Ohio, USA.

[7] China University of Geosciences, Beijing, China.

[8] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.

[9] National Center for Atmospheric Research, Boulder, Colorado, USA.

Copyright 2008 by the American Geophysical Union.
0043-1397/08/2007WR006375$09.00

field-scale problems. Viable alternatives have emerged recently, though, in which data from direct characterization and monitoring methods are supplemented with coverage of greater density from indirect, less invasive hydrologic and geophysical tomographic surveys. More specifically, tomographic surveys have emerged as a key component of in situ analysis at the field scale [see *Vereecken et al.*, 2006]. The concepts behind these tomographic surveys are analogous to that of computerized axial tomography (CAT) scan technology that yields a 3-D image of an object that is more detailed than a standard X ray. Unlike traditional hydrologic tests and geophysical surveys or traditional inverse modeling (i.e., model calibration), active tomographic surveys sequentially excite the subsurface using well-characterized artificial stimuli (e.g., injection of water, air, tracers, electricity, electromagnetic wave, etc.) at different locations. During each excitation, responses of the subsurface at a large number of locations are collected (i.e., collect the same type of information from many different perspectives). An inverse model then synthesizes all the responses (fusion of the same type of information) to generate a 3-D model of the distribution of hydraulic or geophysical parameters in the subsurface. These active tomographic surveys provide multiple sets of nonredundant information that constrain the parameter search space and cross-validate parameter estimates during the inverse modeling process. The tomographic surveys thereby reveal more detailed and reliable information about the subsurface than traditional model calibration efforts.

[5] Although the tomography concept is straightforward, its applications to hydrologic and geophysical characterization of the subsurface at field scales have only emerged over the last 20 years due to the large scale and characteristics of the subsurface. In hydrology, hydraulic, pneumatic, and tracer tomographic surveys have been developed recently [e.g., *Gottlieb and Dietrich*, 1995; *Vasco et al.*, 2000; *Yeh and Liu*, 2000; *Vesselinov et al.*, 2001; *Bohling et al.*, 2002; *Brauchler et al.*, 2003; *Zhu and Yeh*, 2005, 2006; *Yeh and Zhu*, 2007], while seismic, acoustic, electromagnetic (EM) and other tomography surveys have emerged in geophysics over the last few decades [e.g., *Romero et al.*, 1997; *Vereecken et al.*, 2006]. Robustness of these hydrologic and geophysical tomographic surveys as well as the fusion of hydrologic and geophysical tomographic surveys including fusion with other types of supporting or proxy information (geochemical, temperature, etc.) has been widely reported (see compendiums by *Hyndman et al.* [2007] and see also *Liu et al.* [2002], *Liu et al.* [2007], *Illman et al.* [2007, 2008], *Bohling et al.* [2007], *Straface et al.* [2007], *Yeh and Zhu* [2007], *Hao et al.* [2008], *Li et al.* [2007], and others).

3. Data Fusion for Basin-Scale Problems

[6] Traditional approaches of mapping the subsurface with surface geophysics or the recently emerging field-scale data fusion and tomographic approaches are either too expensive for basin coverage or provide information that does not directly address issues related to groundwater. Reflection seismology is an ideal tool for mapping stratigraphy, and magnetotellurics, gravity, and magnetometry surveys are excellent methods for characterizing the basement morphology and volcanogenic occurrences in a basin, but they cannot be used on a routine basis to measure temporal and spatial variations of hydrologic properties and states [*National Research Council*, 2000]. New characterization techniques must be developed that can be applied at the basin scale.

[7] Although data fusion technologies are still evolving [see *Hyndman et al.*, 2007], the tomographic survey, in particular, is potentially a key to future basin-scale subsurface characterization. In order to apply the tomographic approach to imaging the subsurface at the basin scale, strong and spatially varying hydrologic and geophysical excitations with wide area coverage and/or significant depth penetration are necessary, as are long-term and spatially distributed monitoring of signals on the land surface and in the subsurface. Naturally recurrent stimuli (e.g., lightning, earthquakes, storm events, barometric variations, precipitation loading, etc.) with frequent and spatially varying occurrences are readily available energy sources for "illuminating" the subsurface throughout a basin, providing the opportunity for progressive and perennial passive 3-D tomographic surveys of the basin as long as the sources are characterized.

[8] Below, we first present several numerical examples to illustrate and discuss the feasibility of exploiting naturally recurrent stimuli for a passive groundwater basin "CAT scan." In contrast to traditional long-term monitoring and model calibration efforts, these passive basin-wide tomography techniques advocate the characterization of spatially and temporally varying natural sources, monitoring of corresponding subsurface responses, and effective fusion of the information collected from different perspectives. Subsequently, fusion of different types of information at different scales is discussed to complement the basin-scale "CAT scan." Challenges associated with our vision are presented, and strategies to take on these challenges are then suggested.

3.1. Fusion of the Same Types of Information

[9] In this category of data fusion for basin-scale characterization, for the sake of stimulating discussion, we will focus on the possibility of taking advantage of river stage fluctuations, cloud-to-ground lightning strikes, earthquakes, and large-scale barometric variations as potential energy sources for basin-scale tomographic surveys.

3.1.1. River-Stage Tomography

[10] The example given below illustrates the potential of using river stage fluctuations for basin-scale tomographic surveys. The influence of stage fluctuation of rivers on the groundwater table and piezometric surfaces has been recognized for decades, as has been the exploitation of the relation between the temporal fluctuation of a river stage and that of the well hydrograph to estimate hydraulic properties of aquifers as an alternative to aquifer tests [e.g., *Duffy*, 1978; *Nevulis et al.*, 1989]. However, these conventional analyses of the relation between river stage and the well hydrograph have relied on the assumption of aquifer homogeneity. The potential of using temporal and spatial variations in the river stage as an excitation source for basin-scale aquifer characterization was not recognized until the development of hydraulic tomography. *Yeh et al.* [2004] postulated that when a flood wave migrates downstream at any given time, it creates a set of pressure responses at wells located at different locations along the river. As the flood wave moves downstream, it produces

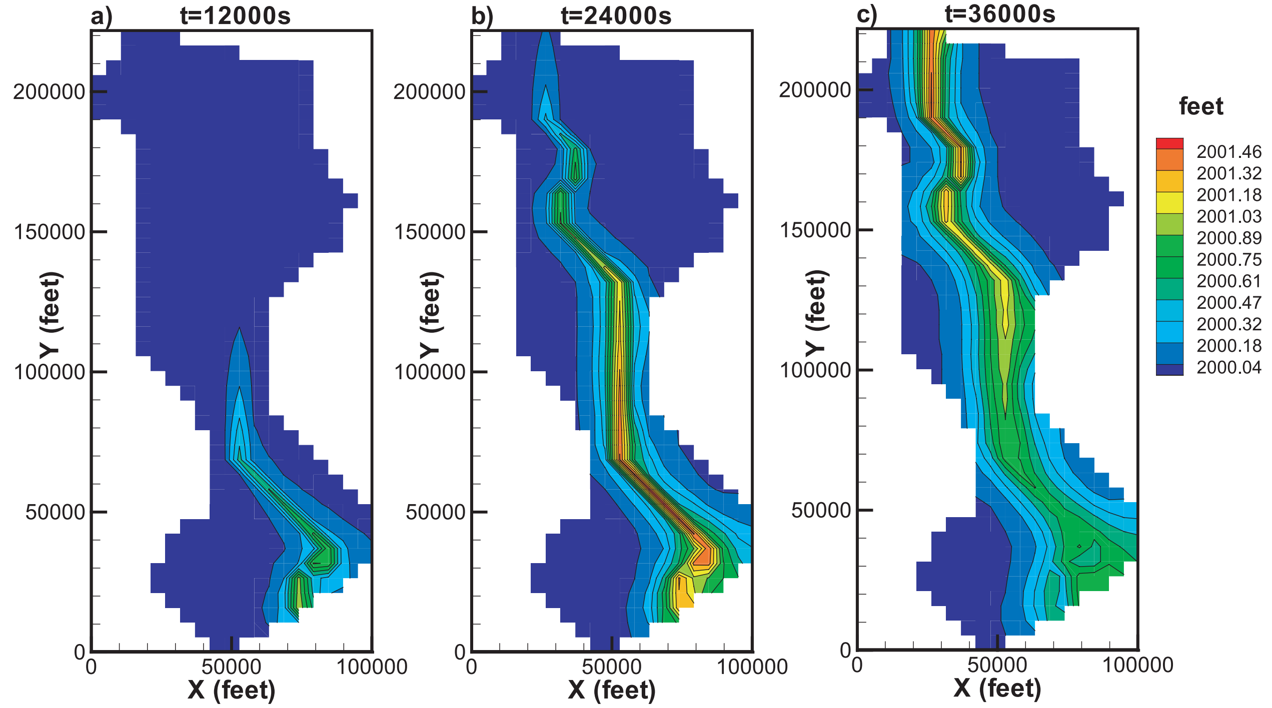

Figure 1. Hydraulic head distributions in the hypothetical confined aquifer basin at (a) 12,000 s, (b) 24,000 s, and (c) 36,000 s.

other sets of well hydrographs at the observation wells along the stream. These hydrographs are equivalent to snapshots of the aquifer at different perspectives. Synthesis of these hydrographs to map the aquifer thus constitutes a naturally occurring, large-scale hydraulic tomographic survey.

[11] Following this concept, *Xiang and Yeh* [2005] conducted numerical experiments to test the river stage tomography concept for characterizing large-scale aquifers. Figures 1a, 1b, and 1c show simulated hydraulic head distributions in a 2-D synthetic groundwater basin at times 12,000, 24,000, and 36,000 s, respectively, after the introduction of a triangular flood wave upstream of a river in the basin. These figures show the high head values occuring at river locations and gradually decreasing from the river to the boundaries on the east and west sides of the basin. Well hydrographs from 25 locations distributed throughout the basin are used to estimate transmissivity (T) and storage coefficient (S) distributions for the basin. Figures 2a and 2b are the plots of the true and the estimated T fields, while Figures 3a and 3b show the true and the estimated S fields using time-varying hydrographs from the 25 wells. Evaluation of these figures suggests that the concept of river-stage tomography can be used to map the general patterns of T and S in a groundwater basin. Detailed distributions of these properties, however, could not be obtained due to the insufficient number of the wells and sparse temporal sampling. Nevertheless, the results of this pilot study demonstrate the potential of river stage tomography for characterizing large-scale groundwater basins.

[12] While the river stage tomography concept appears to be valid, its implementation has encountered difficulties. Our attempt to apply the proposed approach to groundwater basins in Taiwan [*Yeh et al.*, 2004] has revealed that well hydrographs sampled on an hourly basis do not record an aquifer's response to rapid flood migration in basins, suggesting that more accurate and frequent sampling of river stage variations and well hydrographs must be implemented in order to record these short-period signals from flood surges.

3.1.2. Lightning Tomography

[13] Cloud-to-ground (CG) lightning strikes are a potential energy source for basin-scale EM tomographic surveys. When lightning EM waves propagate through the subsurface, they will be modified by subsurface heterogeneity at various scales. By measuring these signals at different locations and depths, and then performing 3-D inverse modeling, we can estimate electrical resistivity and dielectric constant fields of the subsurface, which are reflections of geologic structure, hydrologic heterogeneity, and chemical distributions in the subsurface. Collecting the signals from lightning strikes at many different locations is equivalent to conducting large-scale EM tomographic surveys, if the amplitude and location of each strike are known.

[14] The exploitation of lightning for tomographic imaging is different from the conventional magnetotelluric methods (MT). Electromagnetic waves for MT arise from lightning (above ~1 Hz), and electric currents flow in the ionosphere in prodigious rings around the magnetic poles (below ~1 Hz). Because of its low frequency, MT has been used to explore the Earth and geologic basins at great depth, but at low resolution. The suggested lightning tomography takes advantage of the U.S. National Lightning Detection Network (NLDN) that can pinpoint the location of each CG strike and provide its peak amplitude with accuracy [*Cummins et al.*, 1998a, 1998b]. Lightning tomography also takes advantage of the fact that CG lightning produces extremely large EM transients (source powers of 10^9 to

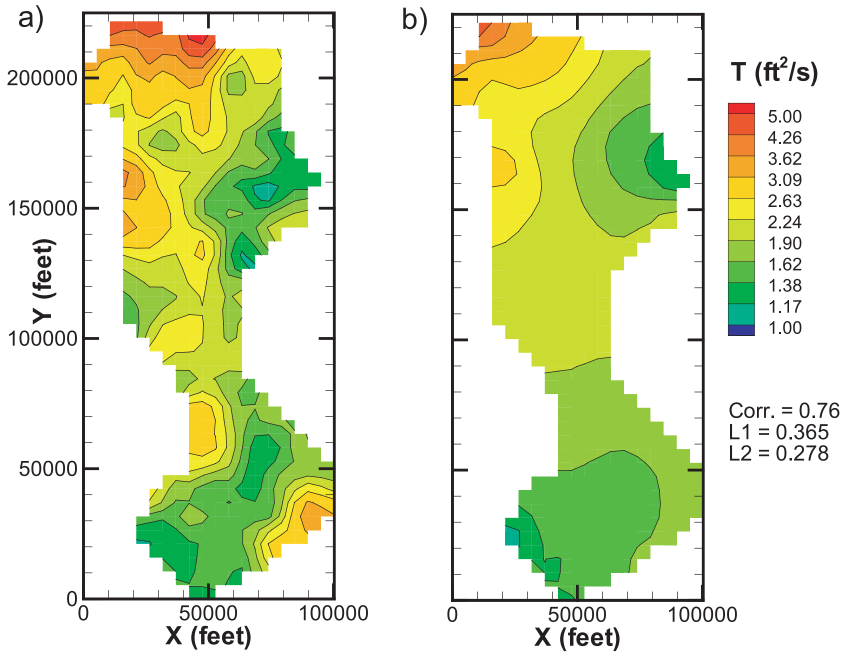

Figure 2. (a) True and (b) estimated T fields of the hypothetical groundwater basin based on the river stage tomography, and the correlation between the two fields and L1 and L2 norms of the estimated field.

10^{10} W) [*Krider*, 1992] over a broad frequency range (<1 to 10^7 Hz). The great power of a broad frequency range implies that it is possible to image the subsurface at various scales over great areas and depths. More important, locations of CG strikes vary across basins, and the strikes are abundant seasonally, and recur annually. These facts support the possibility of using lightning strikes for EM tomographic surveys of groundwater basins.

3.1.3. Earthquake Hydrogeologic Tomography

[15] Earthquakes provide another type of natural stimulus source that may be valuable for both conventional seismic tomography and large-scale hydrologic tomography. Seismologists have been using information from earthquakes to generate tomographic images of the subsurface for many years [e.g., *Aki et al.*, 1977; *Nolet*, 1987; *Iyer and Hirahara*, 1993]. Effects of earthquakes on groundwater levels or

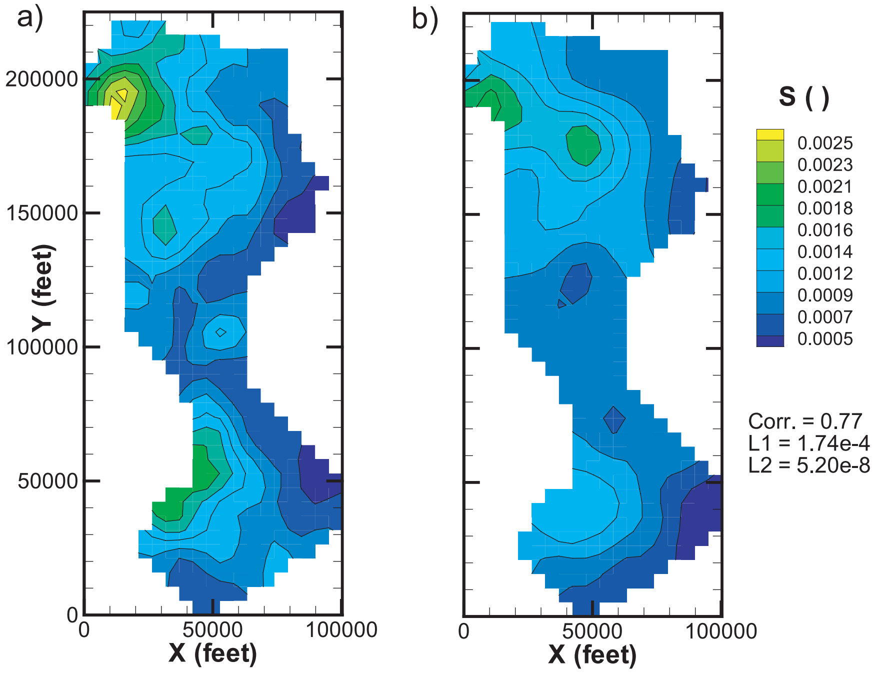

Figure 3. (a) True and (b) estimated S fields of the hypothetical groundwater basin based on the river-stage tomography, and the correlation between the two fields and L1 and L2 norms of the estimated field.

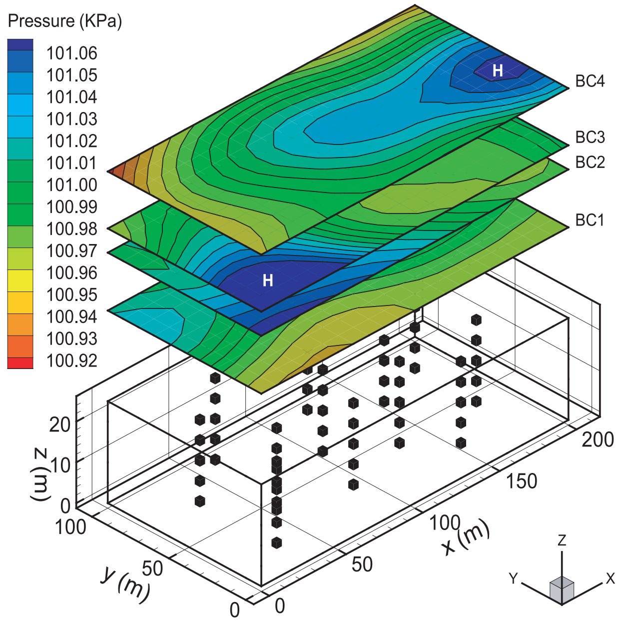

Figure 4. Illustration of spatial distributions of barometric pressure at four different times (BC1, BC2, BC3, and BC4), which were used to estimate the intrinsic permeability and porosity of an unsaturated geologic formation. Circles are the locations where air pressures were measured.

pressures have been investigated in the past as possible precursors for earthquakes [*King et al.*, 2000]. Few investigators, however, have explored the relation between groundwater fluctuations due to earthquakes and geologic heterogeneity, or exploited the phenomenon for imaging 3-D hydrologic property heterogeneity in a basin. A recent study by *Lin et al.* [2004], using pore-elastic and viscoelastic models and field data during the Chi-Chi earthquakes in Taiwan during 1999, showed that the propagation of groundwater pressure waves induced by earthquakes is indeed influenced by geologic structures and hydrologic heterogeneity. They demonstrated that hydrologic properties of aquifers can be estimated using changes in groundwater levels before and after earthquakes. As a result, an earthquake of sufficient magnitude in a groundwater basin is analogous to an artificially induced excitation to an aquifer during an aquifer test, and the occurrence of successive earthquakes originating from different epicenters is similar to the sequential excitations at different positions in the aquifer during a hydraulic tomography survey.

3.1.4. Exploiting Barometric Variations as the Energy Source

[16] The possibility of exploiting temporal and spatial barometric variations as energy sources for CAT scanning the vadose zone was recently investigated by *Ni et al.* [2006] using numerical experiments. Atmospheric pressure variations are known to vary from seconds to weeks on temporal scales and from meters to thousands of kilometers in space. Usually, the air pressure values are recorded hourly at weather stations, but during special events such as storms, hurricanes, or typhoons, they may be recorded more frequently to obtain detailed information. Since their study was aimed at exploring feasibility of using temporal and spatial variations of air pressures to estimate spatial variation in hydraulic parameters in geologic media, a relatively small (200 m × 100 m × 25 m) geologic medium under the residual water content condition was considered. Unlike extreme events (the highest recorded atmospheric pressure was 108.6 kPa and the lowest recorded nontornadic atmospheric pressure was 87.0 kPa at sea level [*Burt*, 2004]), a mild variation of the air pressure distribution of around 0.1 kPa was considered. Four snapshots of the pressure distribution with 1000-s intervals (BC1, BC2, BC3, and BC4 in Figure 4) were assumed to be measured on the ground surface. There were 12 monitoring boreholes; each borehole had five ports along the vertical direction to measure pressure changes in the geologic medium. Using the simulation time step of 5 s, when the top boundary was changed, air pressures in the medium were recorded at the 60 monitoring ports at 5, 10, 15, 20, 50, 100, 200, 400, 600, and 1000 s, resulting in a total of 2400 observations.

[17] These observed pressure changes along with known initial and boundary conditions were then used to estimate the intrinsic permeability and porosity distribution of the geologic medium. Estimated and true intrinsic permeability fields are plotted in Figure 5, while estimated and true porosity distributions are shown in Figure 6. These figures indicate good agreement between the estimated and the true fields. It must be noted that many simplifying assumptions (e.g., initial and boundary conditions are known and no movement of moisture content in the medium) were used in their example although real-world scenarios are more complex. Nevertheless, this example illustrates the potential of using spatiotemporal variations in the barometric pressure to "CAT scan" geologic media at the basin scale.

3.1.5. Groundwater Responses to Other Natural Stimuli

[18] Also in this context, it should be noted that storms, tidal waves, and other types of naturally occurring aquifer loadings take place frequently at different locations in groundwater basins. For each event, groundwater levels respond differently at different well locations [see *Jacob*, 1939; *DeWiest*, 1965] (also see *Desmarais and Rojstaczer* [2002], *Jan et al.* [2007], and *Sophocleous et al.* [2006] for groundwater level fluctuations induced due to precipitation loading). Again, information about such disturbances and associated responses of aquifers in a basin is equivalent to a set of data collected during a large-scale hydrologic test. Numerous occurrences of these disturbances originating at different locations, along with corresponding responses of the aquifers, thus constitute a naturally occurring hydraulic tomography survey.

[19] Of course, a well hydrograph can be simultaneously influenced by a variety of factors (e.g., Earth tides, external loadings, barometric pressure variations, precipitation, even a passing train). Influences of each source on the hydrograph generally bear the source signature and characteristics (i.e., frequencies and amplitudes). These different influencing components can be identified and sorted from a hydrograph if the source characteristics are known. Despite these complications, water level fluctuations caused by pumping, barometric pressure variation, Earth tides, etc., have been widely used to estimate aquifer properties in the past [e.g., *Nevulis et al.*, 1989; *Ritzi et al.*, 1991; *Desbarats et al.*, 1999]. Last, while the basic principle of these basin-scale tomographic surveys is identical to commonly employed

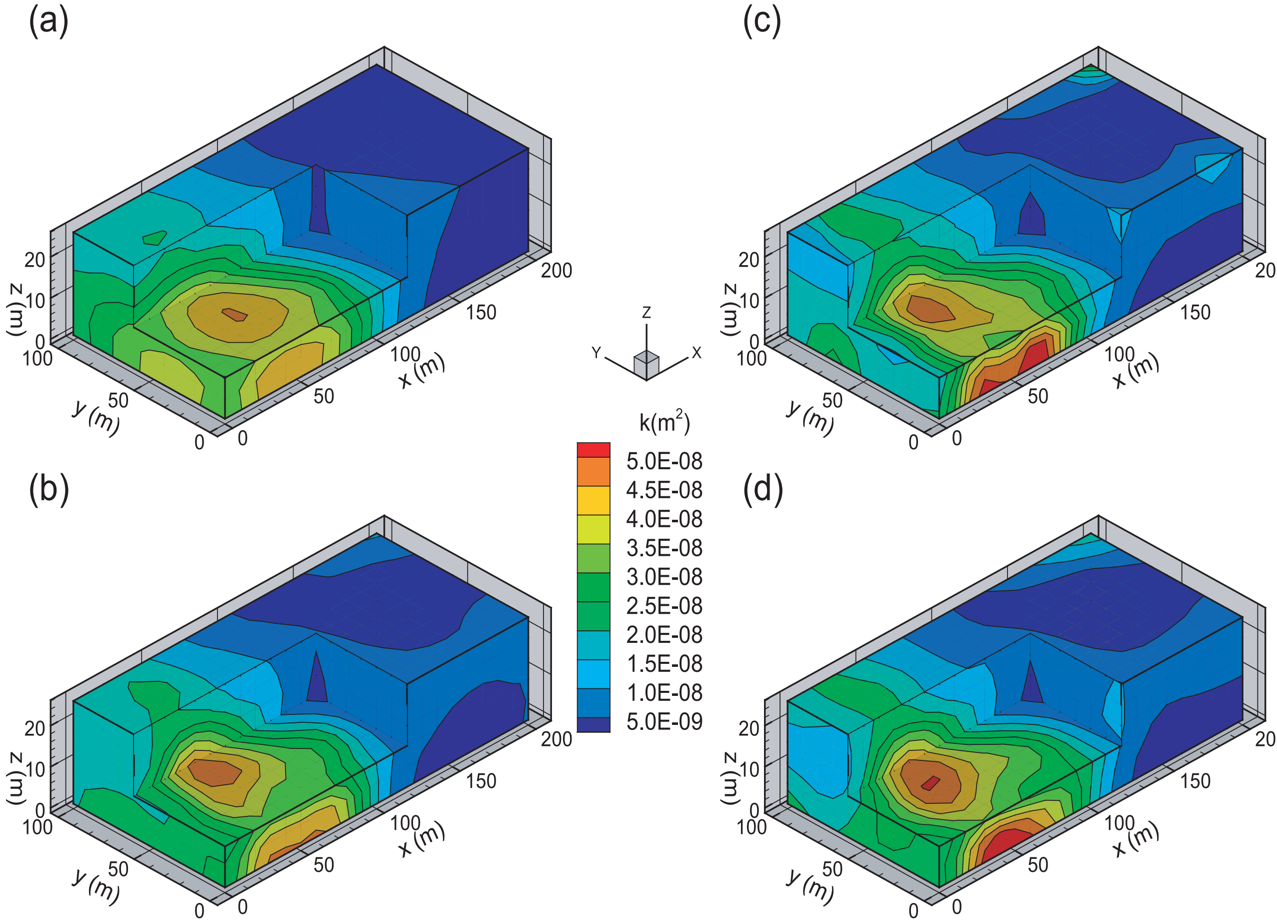

Figure 5. Estimated permeability fields (Figures 5a, 5b, and 5c) corresponding to the sequential inclusion of the information of barometric fields (BC2, BC3, and BC4). The true permeability field is shown in Figure 5d.

aquifer model calibrations, these natural stimuli tomography surveys expand the traditional approaches to a new level by recognizing the benefits of fusing the same type but nonoverlapping information. As a matter of fact, seismologists for decades have been using this rather intuitive concept to pinpoint earthquake epicenters and to image the deep subsurface.

3.2. Fusion of Different Types of Information at Different Scales

[20] Mapping basin-scale hydrogeologic structures and the distributions of hydrogeologic parameters and system states is the main objective of exploiting natural stimuli for basin-scale tomography. A basin-scale tomographic survey using only one type of natural stimulus will not likely yield a high-resolution map of major structures, or processes in the subsurface. Integration of surveys that use different types of natural stimuli is needed, as is the integration of geologic knowledge, field-scale active tomographic surveys, and available point measurements of hydraulic and geologic information in addition to our knowledge of relations between various hydrogeological, geophysical, and geochemical attributes. Recurrence of natural stimuli and adaptive fusion of these different types and scales of information thereby can provide the opportunity for a progressive, and integrative 3-D tomographic survey of a basin. As a result, we should be able to “see” into a basin at higher resolution than currently possible.

4. New Challenges and Strategies

[21] Mapping groundwater basins by fusing active and passive tomographic surveys is an unexplored science and technology. Despite great potential in this new approach, a number of barriers exist. Such barriers, largely methodological in nature, include a lack of (1) effective and robust stochastic approaches for fusion of different types of information at various scales, for data screening and discrimination, and for providing statistically best unbiased estimate and associated uncertainty; (2) more-efficient computational capabilities (e.g., data/knowledge-driven adaptive parallel computing technology for processing the massive information [e.g., *Parashar and Browne*, 2000; *Zeigler et al.*, 2002; *Jamshidi et al.*, 2003]); and (3) economical smart sensor networks that can characterize the locations and energies of natural stimuli and collect responses of the subsurface, and which are driven by results of the stochastic information fusion and data to collect appropriate types of data at the right time, place, and frequency to minimize the likelihood of information overload.

[22] Specifically, we suggest dynamically collecting information about natural stimuli and groundwater and

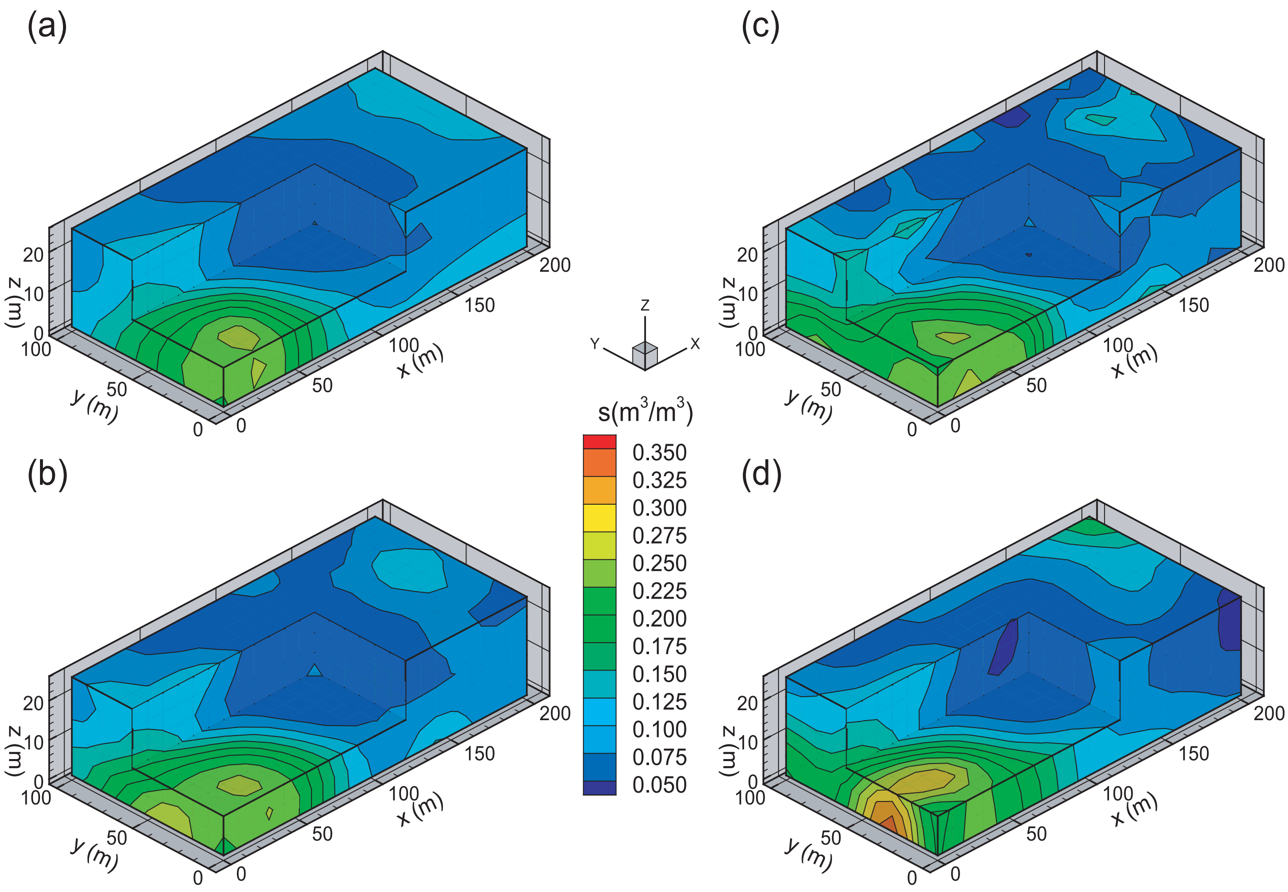

Figure 6. Estimated porosity fields (Figures 6a, 6b, and 6c) corresponding to the sequential inclusion of the information of barometric fields (BC2, BC3, and BC4). The true porosity field is shown in Figure 6d.

subsurface responses, and then taking advantage of autonomic and grid computing [e.g., *Dong et al.*, 2003] to conduct stochastic information fusion on these data sets. This fusion technology can subsequently produce at near-real time the best unbiased estimates of the properties and processes of aquifers, and the uncertainty associated with the estimates. The uncertainty distribution thereafter forms the basis for deployment of a sensor network in terms of where, when, and what to sample, or whether to perform a direct dynamic injection of available additional data sets. Besides, the sensor network and inclusion of new data sets are dynamically driven by occurrence of natural events. That is, smart sensors are activated and included in analyses (modeling) only from regions where activities are occurring [e.g., *Parashar and Browne*, 2000; *Zeigler et al.*, 2002; *Jamshidi et al.*, 2003]. Such a dynamic sampling and analysis (modeling) strategy avoids information overload and reduces the computational complexity. A dynamically data driven simulation strategy and management of heterogeneous grid computing resources are also essential. Specifically, on the basis of the knowledge of physical processes, one can dynamically refine the simulation domain and select solution algorithms for each region and configure these algorithms (e.g., fine or coarse resolution) as required by the activity of events associated with each region [e.g., *Boyett et al.*, 1992; *Diaz et al.*, 1992; *Keyes et al.*, 1995; *Smith et al.*, 1996; *Toselli and Widlund*, 2005]. Simulation tasks can then be allocated according to the computational demands of the tasks and capability of different clusters in order to significantly reduce their computational complexity and required resources.

[23] Developing dynamic fusion technologies is challenging, but rapid advances in electronics, sensor technologies, information technology, computer engineering, and smart parallel network computing technologies will synergistically support the evolution of this concept if we recognize its importance and focus research efforts to significantly advance subsurface sciences.

5. Conclusion

[24] Exploration of naturally recurring stimuli for basin-scale tomographic surveys is a novel concept that can significantly advance our capabilities to characterize the subsurface at management scales and to understand processes in subsurface sciences as a whole. Development of this technology will provide a quantum leap in hydrologic and geophysical technologies for effective near-real-time monitoring, characterization, and prediction of properties and states in the subsurface from laboratory to basin scales. This breakthrough will profoundly improve our understanding of, and predictive capability for, subsurface (not only hydrologic) processes, which are fundamental to issues related to public health and safety, basic science, civil infrastructure, and resources extraction. In addition, this direction of hydrologic research will initiate further advan-

ces in modeling and simulation methodologies and networked information technology to meet the needs of these and other computationally intensive and network-centric applications. The complete development of a near-real-time, self-updating, basin-scale tomographic survey system perhaps may not be realized in a short period of time, but initiation of development of this technology will ultimately yield a quantum leap in our capabilities for 3-D monitoring, characterization, and prediction of subsurface processes in lab-, field-, and basin-scale problems. Finally, we have a dream: Before the next century, the ‘‘seeing into the groundwater basin’’ technology will be widely deployed over groundwater basins to significantly improve management of scarce groundwater resources on the Earth. In achieving this dream, we must have a beginning.

[25] **Acknowledgments.** The first author would like to acknowledge supports from National Cheng-Kung University during his visit in 2006 and 2007. Support from the Strategic Environmental Research and Development Program (SERDP) as well as by funding from the National Science Foundation (NSF) through grants EAR-0229713, EAR-0229717, IIS-0431069, IIS-0431079, EAR-0450336, and EAR-0450388 are acknowledged. Many of the ideas presented here were initially developed as part of an NSF STC proposal in 2004, and so we acknowledge here Computer Science and Engineering team members from that proposal: B. Zeigler, S. Hariri, M. Jamshidi, N. al-Holou, H. Sarjoughian, M. Parashar, L. Yilmaz, G. Wainer, and others. We also express our sincere gratitude to Geoff Bohling for his constructive comments and suggestions during the first stage of this manuscript. Comments and suggestions from six anonymous reviewers, the Associate Editor, and the Editor are greatly appreciated.

References

Aki, K., A. Christoffersson, and E. S. Huesbye (1977), Determination of the three-dimensional structure of the lithosphere, *J. Geophys. Res.*, *82*, 277–296.

Bohling, G. C., X. Zhan, J. J. Butler Jr., and L. Zheng (2002), Steady shape analysis of tomographic pumping tests for characterization of aquifer heterogeneities, *Water Resour. Res.*, *38*(12), 1324, doi:10.1029/2001WR001176.

Bohling, G. C., J. J. Butler, X. Zhan, and M. D. Knoll (2007), A field assessment of the value of steady shape hydraulic tomography for characterization of aquifer heterogeneities, *Water Resour. Res.*, *43*, W05430, doi:10.1029/2006WR004932.

Boyett, B. A., M. S. El-Mandouh, and R. E. Ewing (1992), Local grid refinement for reservoir simulation, in *Computational Methods in Geosciences*, edited by W. E. Fitzgibbon and M. F. Wheeler, pp. 15–28, Soc. for Ind. and Appl. Math., Philadelphia, Pa.

Brauchler, R., R. Liedl, and P. Dietrich (2003), A travel time based hydraulic tomographic approach, *Water Resour. Res.*, *39*(12), 1370, doi:10.1029/2003WR002262.

Burt, C. C. (2004), *Extreme Weather: A Guide and Record Book*, Norton, New York.

Cummins, K. L., E. P. Krider, and M. D. Malone (1998a), The U.S. National Lightning Detection Network and applications of cloud-to-ground lightning data by electric power utilities, *IEEE Trans. Electromagn. Compat.*, *40*(4), 465–480.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. P. Pyle, and A. E. Pifer (1998b), A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res.*, *103*, 9035–9044.

Desbarats, A. J., D. R. Boyle, M. Stapinsky, and M. J. L. Robin (1999), A dual-porosity model for water level response to atmospheric loading in wells tapping fractured rock aquifers, *Water Resour. Res.*, *35*(5), 1495–1506.

Desmarais, K., and S. Rojstaczer (2002), Inferring source waters from measurements of carbonate spring response to storms, *J. Hydrol.*, *260*, 118–134.

DeWiest, R. J. M. (1965), *Geohydrology*, John Wiley, Hoboken, N. J.

Diaz, J. C., C. G. Macedo Jr., and R. E. Ewing (1992), Indicator evaluation for self-adaptive grid methods, in *Computational Methods in Geosciences*, edited by W. E. Fitzgibbon and M. F. Wheeler, pp. 44–53, Soc. for Ind. and Appl. Math., Philadelphia, Pa.

Dong, X., S. Hariri, L. Xue, H. Chen, M. Zhang, and S. Rao, (2003), AUTONOMIA: An Autonomic Computing Environment, in *Proceedings of the IEEE International Performance, Computing, and Communications Conference*, pp. 61–68, Inst. of Electr. and Electron. Eng., New York.

Duffy, C. (1978), Recharge and groundwater conditions in the western region of the Roswell Basin, New Mexico, *Rep. TR100*, N. M. Water Resour. Res. Inst., Las Cruces.

Gottlieb, J., and P. Dietrich (1995), Identification of the permeability distribution in soil by hydraulic tomography, *Inverse Probl.*, *11*, 353–360.

Hao, Y., T.-C. J. Yeh, J. Xiang, W. A. Illman, K. Ando, and K.-C. Hsu (2008), Hydraulic tomography for detecting fracture connectivity, *Ground Water*, in press.

Hyndman, D. W., F. D. Day-Lewis, and K. Singha (Eds.) (2007), *Subsurface Hydrology: Data Integration for Properties and Processes*, *Geophys. Monogr. Ser.*, vol. 171, 253 pp., AGU, Washington, D. C.

Illman, W. A., X. Liu, and A. Craig (2007), Steady-state hydraulic tomography in a laboratory aquifer with deterministic heterogeneity: Multi-method and multiscale validation of hydraulic conductivity tomograms, *J. Hydrol.*, *341*(3–4), 222–234.

Illman, W. A., A. J. Craig, and X. Liu (2008), Practical issues in imaging hydraulic conductivity through hydraulic tomography, *Ground Water*, *46*(1), 120–132.

Iyer, H. M., and K. Hirahara (Eds.) (1993), *Seismic Tomography: Theory and Practice*, pp. 227–247, Chapman and Hall, London.

Jacob, C. E. (1939), Fluctuations in artesian pressure produced by passing railroad trains as shown in a well on Long Island, New York, *Eos Trans. AGU*, *20*, 666–674.

Jamshidi, M., et al. (2003), V-Lab: A distributed intelligent discrete-event environment for autonomous agents simulation, *Intell. Automat. Soft Comput.*, *9*(3), 241–274.

Jan, C.-D., T.-H. Chen, and W.-C. Lo (2007), Effect of rainfall intensity and distribution on groundwater level fluctuations, *J. Hydrol.*, *332*, 348–360.

Keyes, D. E., Y. Saad, and D. G. Truhlar (Eds.) (1995), *Domain-Based Parallelism and Problem Decomposition Methods in Computational Science and Engineering*, Soc. for Ind. and Appl. Math., Philadelphia, Pa.

King, C.-Y., S. Azuma, M. Ohno, Y. Asai, P. He, Y. Kitagawa, G. Igarashi, and H. Wakita (2000), In search of earthquake precursors in the water-level data of 16 closely clustered wells at Tono, Japan, *Geophys J. Int.*, *143*(2), 469–477.

Krider, E. P. (1992), On the electromagnetic fields, Poynting vector, and peak power radiated by lightning return strokes, *J. Geophys. Res.*, *97*(D14), 15,913–15,917.

Li, W., A. Englert, O. A. Cirpka, J. Vanderborght, and H. Vereecken (2007), Two-dimensional characterization of hydraulic heterogeneity by multiple pumping tests, *Water Resour. Res.*, *43*, W04433, doi:10.1029/2006WR005333.

Lin, Y. B., Y.-C. Tan, T.-C. J. Yeh, C.-W. Liu, and C.-H. Chen (2004), A viscoelastic model for groundwater level changes in the Cho-Shui River alluvial fan after the Chi-Chi earthquake in Taiwan, *Water Resour. Res.*, *40*, W04213, doi:10.1029/2003WR002412.

Liu, S., T.-C. J. Yeh, and R. Gardiner (2002), Effectiveness of hydraulic tomography: Sandbox experiments, *Water Resour. Res.*, *38*(4), 1034, doi:10.1029/2001WR000338.

Liu, X., W. A. Illman, A. J. Craig, J. Zhu, and T.-C. J. Yeh (2007), Laboratory sandbox validation of transient hydraulic tomography, *Water Resour. Res.*, *43*, W05404, doi:10.1029/2006WR005144.

National Research Council (2000), *Seeing Into the Earth: Noninvasive Characterization of the Shallow Subsurface for Environmental and Engineering Application*, Natl. Acad. Press, Washington, D. C.

Nevulis, R. H., D. R. Davis, and S. Sorooshian (1989), Analysis of natural groundwater level variations for hydrogeologic conceptualization, Hanford Site, Washington, *Water Resour. Res.*, *25*(7), 1519–1529.

Ni, C., T. J. Yeh, and J. Xiang (2006), Detecting fracture connectivity with hydraulic/pneumatic tomography surveys, *Eos Trans. AGU*, *87*(52), Fall Meet. Suppl., Abstract H42A-05.

Nolet, G. (Ed.) (1987), *Seismic Tomography: With Applications in Global Seismology and Exploration Geophysics*, 386 pp., D. Reidel, Dordrecht, Netherlands.

Parashar, M., and J. C. Browne (2000), System engineering for high performance computing software: The HDDA/DAGH infrastructure for implementation of parallel structured adaptive mesh refinement, in *IMA: Structured Adaptive Mesh Refinement (SAMR) Grid Methods*, edited by S. B. Baden et al., pp. 1–18, Springer, New York.

Ritzi, R. W., S. Sorooshian, and P. A. Hsieh (1991), The estimation of fluid flow properties from the response of water levels in wells to the combined atmospheric and Earth tide forces, *Water Resour. Res.*, *27*(5), 883–893.

Romero, A. E., Jr., T. V. McEvilly, and E. L. Majer (1997), 3-D microearthquake attenuation tomography at the Northwest Geysers geothermal region, California, *Geophysics*, *62*, 149–167.

Smith, B., P. Bjoerstad, and W. Gropp (1996), *Domain Decomposition*, Cambridge Univ. Press, New York.

Sophocleous, M., E. Bardsley, and J. Healey (2006), A rainfall loading response recorded at 300 meters depth: Implications for geological weighing lysimeters, *J. Hydrol.*, *319*(1–4), 237–244.

Straface, S., T.-C. J. Yeh, J. Zhu, S. Troisi, and C. H. Lee (2007), Sequential aquifer tests at a well field, Montalto Uffugo Scalo, Italy, *Water Resour. Res.*, *43*, W07432, doi:10.1029/2006WR005287.

Toselli, A., and O. Widlund (2005), *Domain Decomposition Methods: Algorithms and Theory*, Springer, New York.

Vasco, D. W., H. Keers, and K. Karasaki (2000), Estimation of reservoir properties using transient pressure data: An asymptotic approach, *Water Resour. Res.*, *36*(12), 3447–3465.

Vereecken, H., A. Binley, G. Cassiani, A. Revil, and K. Titov (2006), Applied hydrogeophysics, *NATO Sci. Ser., IV*, *71*, 383 pp.

Vesselinov, V. V., S. P. Neuman, and W. A. Illman (2001), Three-dimensional numerical inversion of pneumatic cross-hole tests in unsaturated fractured tuff: 1. Methodology and borehole effects, *Water Resour. Res.*, *37*(12), 3001–3018.

Xiang, J., and T.-C. J. Yeh (2005), Numerical simulation of river stage tomography, *Eos Trans. AGU*, *86*(52), Fall Meet. Suppl., Abstract H41E-0463.

Yeh, T.-C. J., and S. Liu (2000), Hydraulic tomography: Development of a new aquifer test method, *Water Resour. Res.*, *36*(8), 2095–2105.

Yeh, T.-C. J., and J. Zhu (2007), Hydraulic/partitioning tracer tomography for characterization of dense nonaqueous phase liquid source zones, *Water Resour. Res.*, *43*, W06435, doi:10.1029/2006WR004877.

Yeh, T.-C. J., K. Hsu, C. Lee, J. Wen, and C. Ting (2004), On the possibility of using river stage tomography to characterize the aquifer properties of the Choshuishi Alluvial Fan, Taiwan, *Eos Trans. AGU*, *85*(47), Fall Meet. Suppl., Abstract H11D-0329.

Yeh, T.-C. J., C. H. Lee, K.-C. Hsu, and Y.-C. Tan (2007), Fusion of active and passive hydrologic and geophysical tomographic surveys: The future of subsurface characterization, in *Subsurface Hydrology: Data Integration for Properties and Processes*, *Geophys. Monogr. Ser.*, vol. 171, edited by D. W. Hyndman et al., p. 109, AGU, Washington, D. C.

Zeigler, B. P., et al. (2002), Quantization based filtering in distributed discrete event simulation, *J. Parallel Distrib. Comput.*, *62*(11), 1629–1647.

Zhu, J., and T.-C. J. Yeh (2005), Characterization of aquifer heterogeneity using transient hydraulic tomography, *Water Resour. Res.*, *41*, W07028, doi:10.1029/2004WR003790.

Zhu, J., and T.-C. J. Yeh (2006), Analysis of hydraulic tomography using temporal moments of drawdown recovery data, *Water Resour. Res.*, *42*, W02403, doi:10.1029/2005WR004309.

W. Barrash, Center for Geophysical Investigation of the Shallow Subsurface, Department of Geosciences, Boise State University, Boise, ID 83725, USA. (wbarrash@cgiss.boisestate.edu)

X. Cai, Simula Research Laboratory, P.O. Box 134, N-1325 Lysaker, Norway. (xingca@simula.no)

J. Daniels, School of Earth Sciences, Ohio State University, 125 S. Oval Mall, Columbus, OH 43210, USA. (daniels.9@osu.edu)

K.-C. Hsu and C.-H. Lee (corresponding author), Department of Resources Engineering, National Cheng-Kung University, No. 1, University Road, Tainan City 701, Taiwan. (kchu@mail.ncku.edu.tw; leech@mail.ncku.edu.tw)

W. A. Illman and E. Sudicky, Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1. (willman@uwaterloo.ca; sudicky@sciborg.uwaterloo.ca)

G. Li, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825 Beijing 100029, China. (guominli@mail.iggcas.ac.cn)

L. Wan, China University of Geosciences, Xueyuan Road, No. 29, Beijing, China. (wanli@cugb.edu.cn)

C. L. Winter, National Center for Atmospheric Research, 1850 W. Table Mesa, Boulder, CO 80305, USA. (lwinter@ucar.edu)

T.-C. J. Yeh, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, 85721, USA. (yeh@hwr.arizona.edu)