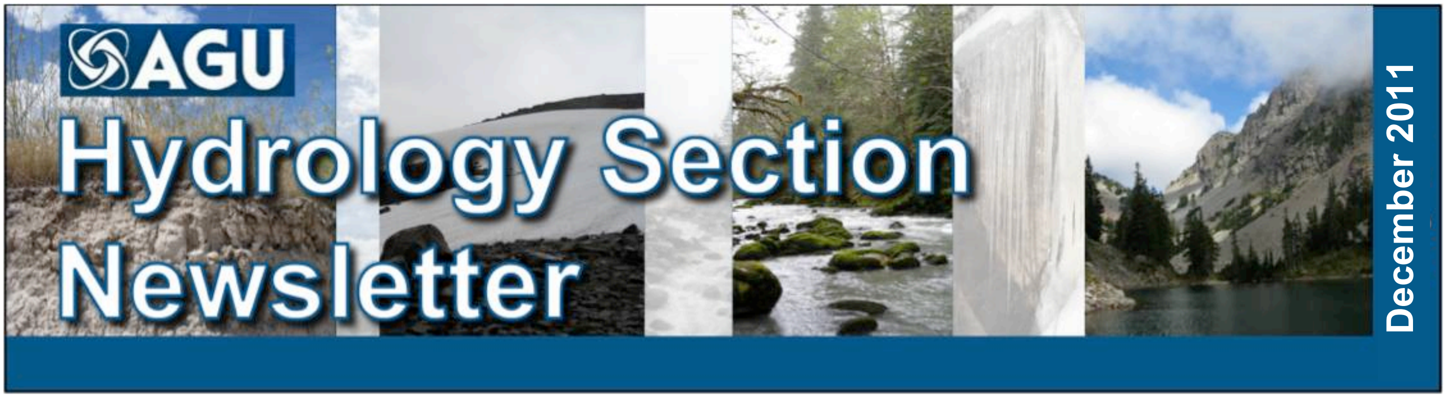

From the Section President

Dennis P. Lettenmaier (University of Washington)

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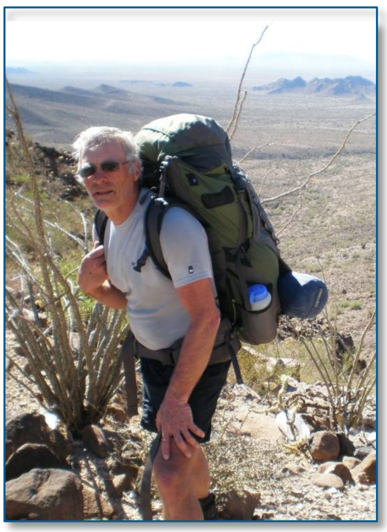
By the time you receive this, many of you will be well into the last minute pre-AGU scramble – preparing presentations, going through "dry runs" of student talks, reviewing posters, and so on. This year's meeting will be the largest ever, with over 2500 oral and poster presentations in Hydrology alone. For an idea of what's involved in putting together a meeting of this size, see Matt Rodell's article on p. 15 – and if you see Matt and the other two members of the Section's Fall Meeting Committee, Mike Cosh and Stefan Kollet, please thank them for their extraordinary effort on behalf of the Section.



On p. 2, you'll find a summary of meeting highlights for the Section. One thing to note – we are making a change in the presentation of the Hydrologic Sciences Early Career Award and the Hydrologic Sciences Award, which will be just before the start of the Langbein Lecture on Tuesday AM. This is an idea we took from the Cryospheric Sciences Focus Group – they used a similar format prior to their Nye Lecture last year, and it seemed to work well. It's not quite as rushed as doing the presentations at the Section luncheon. Please arrive promptly at 10:20 on Tuesday for the presentations and the Langbein Lecture.

Also new at this year's Fall Meeting will be presentations of *WRR* Editor's Choice Awards (see Praveen Kumar's article on p. 4). Editor's choice awards are given to a maximum of one percent of articles published each year. The presentations will be made at the Section luncheon. Congratulations to the authors of the five papers that were selected from among those published in calendar year 2010.

On the meeting highlights list on p. 2 are the dates, times, and locations of all of the Section's Technical Committee meetings (if you can't find your copy of this newsletter, there is also a link to the schedule from the Section web site, hydrology.agu.org). I want to emphasize that as always, the TC meetings are open to all who are interested. I especially encourage students and other young members to attend – the TCs are somewhat unique to Hydrology, and are effectively an entry point into the organization for those who are interested in participating. Please come, and introduce yourselves and your interests to your colleagues. I especially want to note two new TCs – Water and Society (see Casey Brown's article in the July Newsletter) and Soil Systems and Critical Zone Processes (joint with the Biogeosciences Section; see article by Dani Or and Yakov Pachepsky on p. 22) which will be meeting for the first time.

I want to make a few comments on ongoing reorganization at AGU. So long as the journals are published, and the annual meeting continues to grow, much of this probably doesn't make a lot of difference to many members.

Fall Meeting Highlights

Event	Date	Start Time	End Time	Location	Room
Early Career and Hydrologic Sciences Award presentations	12/6/11	10:20 AM	12:20 PM	Moscone West	2022-2024
Langbein Lecture (W. James Shuttleworth)	12/6/11	10:20 AM	12:20 PM	Moscone West	2022-2024
Section Luncheon	12/6/12	12:30 PM	1:30 PM	Intercontinental Hotel	Grand Ballroom A-C
Ecohydrology Technical Committee Meeting	12/6/11	6:45 AM	7:45 AM	Moscone North	Room 122
Ground Water Technical Committee Meeting	12/6/11	6:45 AM	7:45 AM	Moscone North	Room 120
Hydrogeophysics Technical Committee Meeting	12/6/11	6:45 AM	7:45 AM	Moscone North	Room 112
Large-Scale Field Experimentation Technical Committee Meeting	12/6/11	6:45 AM	7:45 AM	Moscone North	Room 113
Precipitation Technical Committee Meeting	12/6/11	6:45 AM	7:45 AM	Moscone North	Room 114
Water and Society Technical Committee Meeting	12/6/11	6:45 AM	7:45 AM	Marriott Marquis Hotel	Sierra B
Soil Systems and Critical Zone Processes Technical Committee	12/6/11	12:30 PM	1:30 PM	Moscone North	Room 114
Remote Sensing Technical Committee Meeting	12/7/11	12:30 PM	1:30 PM	Moscone North	Room 120
Surface Water Technical Committee Meeting	12/7/11	12:30 PM	1:30 PM	Moscone North	Room 122
Unsaturated Zone Technical Committee Meeting	12/7/11	12:30 PM	1:30 PM	Moscone North	Room 123
Water Quality Technical Committee Meeting	12/7/11	12:30 PM	1:30 PM	Marriott Marquis Hotel	Sierra A
Technical Committee Chairs Meeting	12/8/11	6:45 AM	7:45 AM	Moscone North	Room 112
Section Executive Committee Meeting	12/8/11	12:30 PM	1:30 PM	Moscone North	Room 111
Section and FG Student Representatives Meeting	12/4/11	4:30 PM	5:30 PM	Moscone North	Room 120
Student Breakfast	12/6/11	6:45 AM	7:45 AM	Marriott Marquis Hotel	Salon 7

Governance at the Union level is nonetheless important to the interests of the Section, and AGU is the primary affiliation for many of the Section's members. One change that is being made at the Union level, which I applaud, is that the Fellows Committee will now report to the Honors and Recognition Committee. While seemingly an obscure detail, this means that the Fellows Committee can focus on the selection process, and criteria for selection will be the responsibility of H&R, and (we hope) will be somewhat more stable over time. If you are considering making a Fellows nomination (and I encourage you to do so – the deadline will likely be sometime in the summer) please read the article "How to assemble a compelling Fellows nomination package" by Andrew Barry and Eric Wood in the July issue (http://hydrology.agu.org/pdf/AGUHydro-201107.pdf). Andrew and Eric discuss some of the implications of an ongoing discussion on the role of "discovery" versus "eminence" as a criterion for Fellows selection. This is an issue that has persisted for many years, and has, until now, been somewhat at the discretion of the Fellows Committee. Responsibility for such criteria will now pass to H&R.

One other substantive change that you will notice (if only because you'll be seeing the same faces at the head table at the Section Luncheon a year from now) is that the terms of all Union and Section and Focus Group officers have been extended by six months, to end December 31, 2012 (rather than June 30). The reason for the change is that the old July 1 – June 30 terms date back many years when the now-defunct Spring Meeting was the major meeting of the year (the Fall Meeting at that time was a regional meeting). Many of the activities of the Section, including the awards nomination and selection processes, now straddle the July 1 date, making for an awkward transition, so the change makes sense. It also means that elections for new officers, whose terms will start January 1, 2013, have been set back. Announcement of candidates will occur in the spring time frame, with publication of position statements in EOS in late spring. The elections will be held in late summer, with an announcement of results in the fall. Specific dates will be announced soon. I believe that the timing is such that we should be able to print some information, and perhaps expansions of the position statements that will appear in *EOS*, in the July newsletter. In the meantime – the Section nominating committee is chaired by our past President, John Wilson. If you have suggestions for his committee (the members of which are Mary Anderson, Kelly Caylor, Ana Barros, and Peter Troch,) please contact either John or other members of the committee.

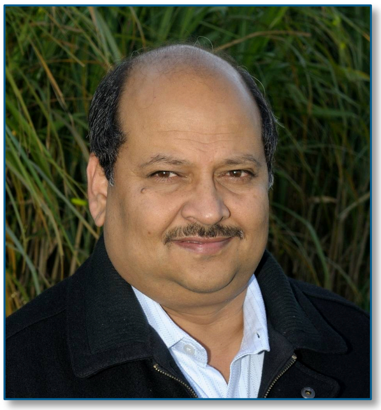
Before closing, I want to comment on Outstanding Student Paper Awards (OSPA). This year, we have almost 800 student oral and poster presentations that are eligible for awards. Our Section Secretary, Martha Conklin, assisted by a committee that includes Kolja Rotzell, Laurel Saito, Glenn Toutle, and Yong Zhang, is charged with identifying three judges for each presentation. To do so, Martha and I convinced AGU staff to require that each session proposer for this year's meeting identify an OSPA liaison, who would be responsible for identifying the judges for the student presentations in their session. This reduces the challenge of Martha's committee from identifying over 2000 individual judges (nearly impossible!) to assuring that the 100+ liaisons identify the judges for their sessions (challenging, but presumably not impossible). This remains a work in progress, and I am hearing that some of the liaisons may not have been entirely aware of their responsibility (so just to be clear – if you were listed as an OSPA liaison, you are responsible for seeing that there are three judges for each of the student papers in your session, and that their reports are filed). For next year's meeting, we are trying to convince AGU to require, at the time of session proposal submission, that there be a positive acknowledgment by each liaison of their responsibilities. All of this may seem a bit bureaucratic, but I can tell you from experience that it is a huge boost to the students to receive these awards, and we owe it to them to be as thorough and methodical as possible in the judging process – that really is what this is all about.

I look forward to seeing you next week in San Francisco.

From the Water Resources Research Editor-in-Chief

Praveen Kumar (University of Illinois)

With the approval of the AGU Hydrology Section Executive Committee, *WRR* has instituted an *Editors' Choice Award* to be given to (about) the top one percent of published articles in any calendar year. Our goal is to provide professional recognition to scientists and students for their outstanding work. The selection is made by the *WRR* Editors based on technical significance, novelty, originality, presentation, and broader implications of the publication. Awards made in a given year are for the previous calendar year. We are pleased to announce that the following contributions are being recognized for 2010 award year (all appeared in print in *WRR* in 2010). The awards will be presented at the Section Luncheon at the 2011 Fall Meeting (Tuesday, Dec. 6):



- Julien J. Harou, Josué Medellín-Azuara, Tingju Zhu, Stacy K. Tanaka, Jay R. Lund, Scott Stine, Marcelo A. Olivares, and Marion W. Jenkins, "Economic consequences of optimized water management for a prolonged, severe drought in California" (doi:10.1029/2008WR007681).
- Luis Samaniego, Rohini Kumar, and Sabine Attinger, "Multiscale parameter regionalization of a grid-based hydrologic model at the mesoscale" (doi:10.1029/2008WR007327).
- Elizabeth H. Keating, John Doherty, Jasper A. Vrugt, and Qinjun Kang, "Optimization and uncertainty assessment of strongly nonlinear groundwater models with high parameter dimensionality" (doi:10.1029/2009WR008584).
- Dmitri Kavetski and Martyn P. Clark, "Ancient numerical daemons of conceptual hydrological modeling: 2. Impact of time stepping schemes on model analysis and prediction" (doi:10.1029/2009WR008896).
- Lance F. W. Lesack and Philip Marsh, "River‑to‑lake connectivities, water renewal, and aquatic habitat diversity in the Mackenzie River Delta" (doi:10.1029/2010WR009607).

While *WRR* attracts manuscripts that lead the innovations in the field, the editors are sometimes confronted with situations that pose significant challenges for the editorial process. These generally deal with violations of acceptable standards of publication and/or communication, and impose a burden on the time and effort of all involved. These violations often relate to attribution, responsibility, and respect. For example, the choice of who to include or exclude as co-author reflects a deliberate decision, the responsibility for which rests with the corresponding author (a definition of "authorship" as used by AGU is available at http://www.agu.org/pubs/pdf/AGU_Authorship_Clarified.pdf). Authorship is not just an acknowledgment of contribution but also an acceptance of responsibility for the content. That is, all authors are responsible for the veracity of the results and the conclusions, and will also share the criticisms, if they arise. The corresponding author, as the guarantor of the work, assumes the responsibility of ensuring that appropriate norms for research and its communication have been followed; and accepts the responsibility of having included as authors all persons who meet the criteria for authorship and none who do not, and also attests that all living coauthors have seen the final version of the article, agree with the major conclusions, and have agreed to its submission (or resubmission) for publication. Exclusion of a person who claims intellectual contribution to the content also poses a serious challenge and can lead to an intervention or investigation. It is in everyone's best interest that submitted manuscripts should be clear of any such disputes. Any resource that is used in the research, such as data or experimental facility, should also be appropriately attributed. It is best that authors familiarize themselves early on with the policies for such use and conform to acceptable norms during publication. Inappropriate attribution concerning the use of previously published material from one's own work or those of others poses another challenging scenario. Strict adherence to best practices is required, and I have written about this in a previous article (http://hydrology.agu.org/pdf/AGUHydro-201012.pdf). Authors are sometimes disappointed with the outcome of the review and may feel that the process or the decision hasn't been fair. We are always open to discussing further what modifications to the content would possibly result in a more favorable review and outcome. However, we all accomplish more through a professional and cordial approach after careful thought to the comments and evaluation since we do our best to ensure that reviews are fair and substantive.

The Fellows Speak: The need for reliable data in hydrologic investigations

Mary Jo Baedecker (U.S. Geological Survey, Scientist Emeritus)

As more decisions in water management are made on the basis of modeling results, it needs to be remembered that models are only as good as the data on which they are based. Reliable physical, chemical, and biological data are needed to meet the environmental challenges associated with: water distribution and use, impacts of climate change, disturbances caused by changes in land use, and the impacts of contamination. Looking at funding sources for science and the topics of those engaged in hydrologic investigations, it would appear that the collection of reliable long-term data is not as compelling as modeling. Following are some comments on the value of long-term databases, characterization of groundwater flow systems, and use of physico-chemical data.

Cutbacks in biological databases were reported by Merali and Giles in 2005, who noted that "...a lack of stable funding is threatening biology's core databases." The argument for the need of long-term datasets for detecting and understanding environmental change in ecosystems is made by Parr et al. (2003). Many agencies that have traditionally funded the collection of hydrologic data are finding it is difficult to maintain these programs. NOAA found its funding for the Climate Reference Network cut in 2005 (Mervis, 2005). The USGS has been striving to federally fund a system of stream gages, but at this time only 500 out of 4758 stream gages in the National Streamflow Information Program are fully federally funded. Measurements from Federal stream gages meet critical needs for forecasting, the requirements of compacts, monitoring border areas, and accounting for water quantity and quality in major basins. Stream gages funded partially or fully by State agency cooperators can be discontinued as funding sources become scarce and priorities change. A recent paper on stationarity and water management makes the point that relying on the idea that natural systems fluctuate within an unchanging envelope of variability and can be used as end-members for short-term predictions, such as annual peak flood, can no longer be assumed (Milly et al., 2008). The assumption of stationarity has been compromised by human disturbances in river basins and changes in the Earth's climate (Milly et al., 2008). This means that different kinds of data must be used along with long-term records to make future predictions. As suggested by Hirsch (2011), research related to climate change and water resources should follow two paths: 1) climate modeling, and 2) exploring trends in the long-term hydrologic record. Although "monitoring for the sake of monitoring" is usually not a good expenditure of funds, long-term databases are essential to understanding environmental change now and forecasting into the future. Adaptive monitoring as suggested by Lindenmayer and Likens (2009) for management of ecosystems and natural resources enables monitoring programs to evolve as new information and questions change.

Of interest are two data-sharing endeavors established recently. The first is the National Phenology Network, which although officially started in 2007 in its present form, is based on an idea initiated in 1956 with phenological records of lilac blooms by Joseph M. Caprio (http://www.usanpn.org). The goal of the network is to encourage citizens to observe phenological events like leaf out, flowering, migrations, and egg laying and provide a place for people to enter, store and share their observations. This very successful network, funded by the USGS, NPS, NSF, and the University of Arizona, provides valuable information related to biological responses to environmental change. Although much of the data needed for hydrologic investigations cannot be collected by non-scientists, we should remember that many citizens have a genuine interest in science and might be willing to participate in data collection. The second example is the efforts of the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. – Hydrologic Information System (CUAHSI-HIS). This organization initiated the development of data transmission standards so that hydrologic data will be in a consistent format and a larger volume of data can be made available. Currently, 76 separate services from government and university sources are registered with CUAHSI-HIS, and over 23 million time-series are cataloged, including the USGS National Water Information System databases and the EPA STORET system. CUAHSI maintains a catalog of metadata that permits searching across these different services, but the data resides with the original source. The current prototype system can be explored at http://his.cuahsi.org; a data facility to maintain these services after the pilot project ends is being proposed to NSF.

The reliability of data is frequently not addressed in the characterization of *groundwater-flow systems*. Because it is a hidden resource, groundwater's movement and status is difficult to ascertain (Reilly et al., 2008). The availability of groundwater, a topic of major concern for many parts of the world, depends on the quantity and quality of the water and the recharge rate and withdrawal rate of an aquifer. The geologic framework, hydraulic properties, recharge amount and distribution, biogeochemical environment, and concentrations of constituents contribute to uncertainty in groundwater solute-transport models. Aquifer heterogeneity is a critical factor that is determined mostly using data from wells, cores, geophysics and geostatistics, yet it is impossible to cover the entire aquifer. The hydraulic properties of rocks or sediments can be measured in-situ or in the laboratory on core samples. These laboratory measurements might be biased when they fail to incorporate large-scale features. In terms of water quality data, concentrations of inorganic constituents and nutrients are generally reliable, whereas data for organic compounds are less so. Organic chemical data are very dependent on the sample collection process, method of preservation, and method of analysis. Organic chemical concentrations determined in one laboratory may not be consistent with measurements made by another laboratory. The most unreliable data are for rates of biodegradation, which occurs under different environmental conditions (light, temperature, humidity, pH, etc.), varying availability of electron acceptors (such as nitrate, sulfate, iron, and carbon dioxide), and a consortium of microbes. It is clear that one rate of biodegradation for a mixture of compounds, such as crude oil, creosote, fuel oil is inadequate. Moreover, laboratory-determined degradation rates cannot be assumed to be representative of field rates, and biodegradation rates from field studies vary with recharge and the availability of nutrients. Thus, modeling results are more reliable when a realistic range of uncertainty for the data is considered and the corresponding uncertainty of model output is assessed.

The robustness of *physico-chemical data* is seldom critically evaluated and published values are often repeated from paper to paper without accurate source identification. In an assessment of K_{ow} and aqueous solubilities for DDT and its degradation product DDE, Pontolillo and Eganhouse (2001) reviewed 700 publications from 1944-2001 and found 4 orders of magnitude variation in these properties with no convergence over time (Figure 1).

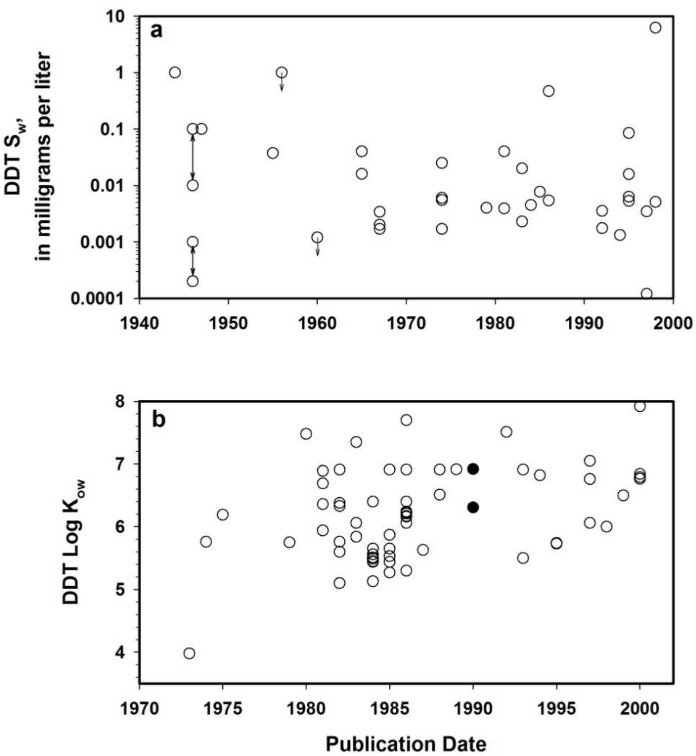


Figure 1: Published original data for DDT as a function of publication date; (a) solubility data (S_w) is over 55 years; (b) log octanol-water partition coefficient data (log K_{ow}) is over 27 years. In both plots, the data span 4 orders of magnitude or more. The most reliable K_{ow} data are in solid circles. The large variation of values demonstrates the difficulty in finding the best data to cite. Figure modified from Pontolillo and Eganhouse (2001).

In some cases an error in one paper was perpetuated in subsequent papers. The publication of these results led to a range of opinions in the environmental chemistry and modeling communities. Some believe that the best numbers can be recognized by researchers. Others suggest that incorrect environmental risk assessments may result from using incorrect published data (Renner, 2002). I agree that having erroneous data appearing in the literature only perpetuates the problem. As new scientists begin their research and analyses, determining which data are reliable becomes an onerous task that seldom will be undertaken. In a review paper on multimedia models of global transport and fate of persistent organic pollutants (e.g. polychlorinated biphenyls and DDT), Scheringer and Wania (2003) noted that along with other factors, incomplete or uncertain data on physical-chemical properties and degradation rate constants contribute to significant uncertainty associated with model results. For another example, years ago, research to calculate themodynamic data in simple solutions was undertaken by many research groups. Recently, this type of research has seen a great decline, yet the environments to which these data are being applied are more complicated and contain solutes, such as organics or brines, that have not been considered in experimental conditions to determine thermodynamic constants. As we examine more complicated systems, a critical evaluation of published physico-chemical data needs to be undertaken.

As we examine more complicated environmental problems and a wider variety of constituents, I believe that the basic data that are used in reaching conclusions and in modeling should be more carefully evaluated. Users need to understand how data are collected and how samples are analyzed. Research should follow multiple paths and different types of analysis to examine a problem, so that a range of results can provide a strong foundation for examining hydrologic change. Finally, there should be a greater appreciation for publishing well-documented data in the literature.

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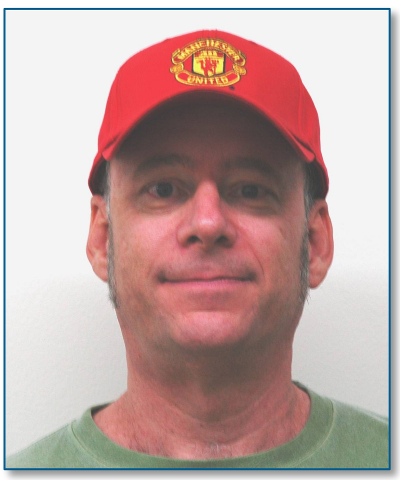
The Fellows Speak: Field work at a hazardous waste site: Challenges, rewards, and unexpected outcomes

Mark L. Brusseau (University of Arizona)

With great appreciation for the tremendous honor of being selected an AGU Fellow, I would like to briefly discuss field work in contaminant hydrology. Field-based investigations have certainly been a key aspect of hydrologic research from its inception. Such investigations have a rich history in contaminant hydrology; in fact, there are several well-known research facilities that have been developed over the years to support field-based investigations. My research group has had the great fortune to have access to an operating hazardous waste site in Tucson, at which we have conducted research for the past 18 years. I will not present a detailed discussion of the results of our research endeavors. Rather, I intend to provide an overview of some of the challenges inherent to conducting research at an operating hazardous waste site, as well as some of the unexpected outcomes and rewards.



Our site is the Tucson International Airport Area (TIAA) federal Superfund site. The TIAA site was placed on the U.S. National Priorities List in August 1983 in response to the detection of trichloroethene in groundwater pumped from several potable water supply wells. A large, multiple-source plume of trichloroethene, 1,1-dichloroethene, and 1,4-dioxane exists in the upper portion of the regional aquifer (Figure 1), which is the primary source of potable water for the Tucson metropolitan area. Several responsible parties have been identified, and multiple contaminant sources are distributed throughout the site. Past exposure associated with use of the contaminated groundwater by local communities has been a significant concern and has been the subject of multiple toxic-tort lawsuits.

Characterization and remediation of the groundwater contamination was initiated in the early 1980's and is still ongoing. Pump and treat is being used to contain and treat the contaminant plume. Two large and three smaller pump-and-treat operations are in place. The first system was started in 1987, and the other systems were initiated in the 1990's. The systems combined have pumped more than 230 million cubic meters of groundwater to date and have removed more than 15,000 kg of solvent mass. Soil vapor extraction and in-situ chemical oxidation have been used to address source-zone contamination.

Throughout the years, we have conducted multiple field activities, supplemented by laboratory and mathematical-modeling efforts, to characterize the site, to test innovative technologies, and to assess remediation performance. Our initial activities at the site were focused on a facility in the south section, owned by the U.S. Air Force and

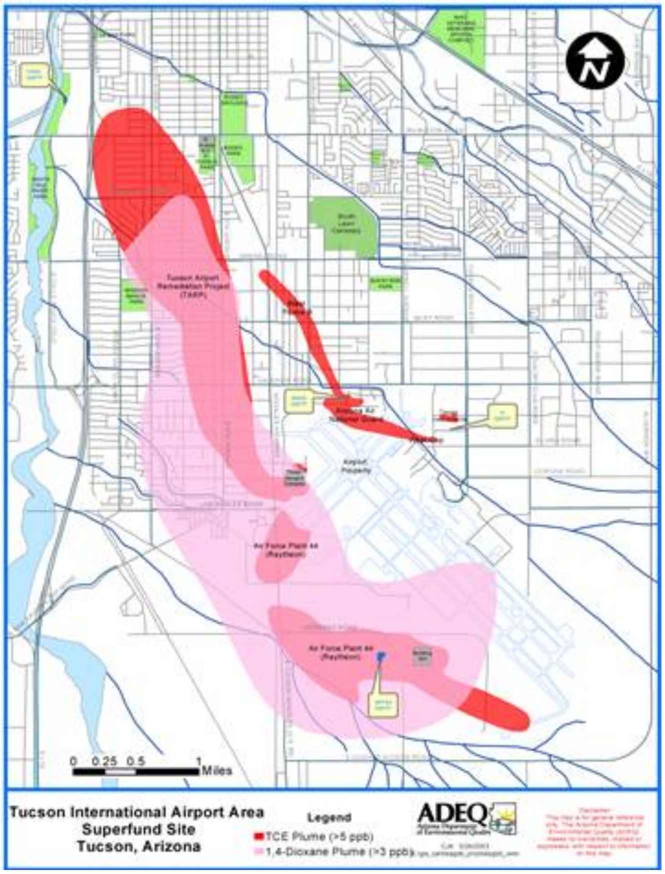


Figure 1: Tucson International Airport Authority (TIAA) Superfund site

operated by Hughes Missile Systems (later purchased by Raytheon). I had become aware of the TIAA site shortly after my arrival at the University of Arizona (UA) in 1990, and was interested in pursuing possible interactions. Fortuitously, an analytical chemist in the Hughes environmental laboratory at the site had decided to obtain an M.S. degree in our program, and contacted me in 1991. Through this initial contact, I met the director and associate director of the environmental services office for Hughes, which was responsible for conducting the remediation efforts at the site. We held a series of meetings over the next two years, discussing possible collaborative projects.

The Environmental Protection Agency (EPA) released a request for proposals in 1993, soliciting research on the application of pump and treat for groundwater remediation. We developed a proposal to conduct research at the site in collaboration with Hughes and Air Force personnel. Unfortunately, the proposal was not funded by the EPA; the primary concern voiced by the reviewers was whether the proposed research would be relevant beyond the target site. This question of broader-scale relevance or applicability is a critical issue that needs to be addressed to obtain funding from sources beyond site owners for research efforts targeted to a specific site. While the project was not funded by the EPA, the Air Force project managers considered the project of sufficient merit to provide funding of their own, which was approved in 1994. This funding allowed us to generate an initial set of data that were used to help package the site as a real-world test case for examining issues specifically related to chlorinated-solvent sites. Over the intervening years, we have been successful in leveraging the initial funding provided by the Air Force to obtain support from several federal programs. We have also obtained funding from other responsible parties (site owners) to conduct research at other portions of the site.

The receipt of funding initiated a bevy of activities, many of which were not directly related to planning of the actual field investigations. It is these other activities that are of particular interest for this story, and that are of paramount concern for implementing field work at hazardous waste sites. The first activity involved interactions with representatives of the relevant regulatory agencies, in this case the EPA, the Arizona Department of Environmental Quality, and the Arizona Department of Water Resources. The EPA project manager was supportive of the proposed project, but voiced some concern over the potential reactions of the local community. This is one area in which research projects conducted at hazardous waste sites typically differ from standard field projects- the involvement of and interactions with local communities. Gaining their trust and support is critical to a successful project.

Once we received the support of the regulatory groups, the second activity involved meeting with the Unified Community Advisory Committee (an official community action committee) to discuss the proposed project. The members of the committee were generally receptive, and pleased to have the UA involved with the site. The third activity involved development of a fact sheet that was released to the public. Developing this material required a significantly different approach compared to writing scholarly articles and was certainly a learning experience.

The activities noted above were my first real exposure to what today we call research translation and outreach, and were positive experiences. The interaction with the public, in particular, provided another perspective through which to view our project, and helped me better understand the role and import of academic research efforts within the broader framework of addressing environmental issues. This unexpected outcome helped inform the development of a formal environmental research translation and outreach program, which we have since implemented at the UA through the NIEHS Superfund Research Program. Through this program, we have conducted numerous translation and outreach activities targeted to communities affected by chlorinated-solvent contaminated sites, including developing public-education informational materials about TCE and dioxane, providing training to Promotoras (local community health advocates), and holding workshops for K-12 teachers.

The fourth activity was not such a positive experience but eventually led to another unexpected outcome. After public release of information, I was interviewed by a reporter from the local newspaper. I was excited at the prospect of the story illustrating the role of the UA in helping resolve local issues. Unfortunately, the reporter was more interested in generating controversy, presented the work in a somewhat negative context, and included erroneous and misleading information in their story. For example, we were proposing to use bromide as a standard non-reactive tracer, at aqueous concentrations of less than 1000 mg/L. Rather than placing this in context, the reporter presented the toxicity information for ingestion of the calcium bromide solid. Needless to say, I was dismayed at this turn of events and have since become more circumspect in my interactions with the press. This experience was a motivating factor in the recent implementation of a Dual-Degree M.S. program in Journalism and Environmental Science that I helped to develop at the UA, the goal of which is to provide a strong science base for journalists interested in environmental issues.

A primary goal of research conducted at operating hazardous waste sites is to improve characterization and remediation efforts for the site—namely successful technology transfer. We believe that our research efforts have been of direct benefit to remediation operations at the site. For example, our results led to modification of the conceptual site model, and some of the technologies that we tested at the site have since been implemented for full-scale operation. We also participate in the annual technology exchange meeting for the site, wherein we present the results of our research to the various site managers and associated environmental consultants.

Another outcome of our activities at the TIAA site is that they have provided my students opportunities to obtain field experience at an actual hazardous waste site. A number of graduate students have mentioned that that experience was one factor in their successful employment. This is true for those that were employed as an environmental consultant, as a government scientist (e.g., USGS, DOE), and in academia. Another related benefit for employment was that we provided the students with the specialized training required to work at hazardous waste sites (known as Hazwoper). The prospective employers were pleased that they would not have to pay for the new employee to receive such training. This latter point is another example of the many unexpected outcomes that can accrue to projects such as this.

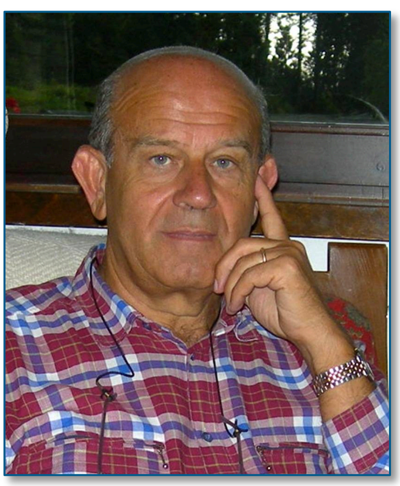
It is important to note that our efforts would not have been possible without the initial support of the Hughes and Air Force personnel. They showed what I view as great foresight in their willingness to collaborate with the UA. The level of support, interest, and openness they provided is rare to this day for an operating hazardous waste site. The continuing support of these and other collaborators (Tucson Airport Authority, AECOM, CRA), of the regulatory agencies, and of the UCAB has been instrumental in the long-term success of this effort. Establishing and maintaining positive relationships with the various stakeholders is essential for long-term success of field projects conducted at contaminated sites.

In summary, long-term access to this site has been of significant benefit to our research program, and has allowed us to amass a large body of research and associated publications related to the transport and fate, characterization, and remediation of chlorinated solvents in heterogeneous environments. We trust that this research has benefitted efforts at other chlorinated-solvent sites and contributed to the field of contaminant hydrology in general. Beyond this, however, our experiences at the TIAA site have resulted in a number of other positive outcomes, some unexpected, such as enhancing remediation operations at the site, student training, and experience in research translation and outreach. The rewards have certainly out-weighed the many days spent at the site in 100-degree temperatures (it always seemed no matter what that our field work occurred in the summer) and run-ins with the odd snake, scorpion, or reporter.

The Fellows Speak: Earth "breathing" in response to underground gas storage as revealed by InSAR measurements and a transversally isotropic geomechanical model

Giuseppe Gambolati (University of Padova, Italy)

Underground gas storage in depleted gas fields, and more recently in saline aquifers as well, is becoming a common practice to cope with the growing cold-season energy demand in many parts of the world. In response to summer gas injection and winter gas withdrawal, the reservoir expands and contracts almost elastically, namely it breaks like a living creature, and the overlying land moves accordingly. A few upper kilometres of the earth's crust are locally subject to three-dimensional (3D) movements with cyclic motion of the ground surface being both vertical and horizontal. The magnitude and distribution of such movements depend on a number of factors including: 1) burial depth, thickness and areal extent of the porous volume affected by the storage operation; 2) cyclic pore pressure variation generated by gas injection and extraction in both the reservoir and the surrounding aquifer; and 3) hydrological and geomechanical properties of the reservoir rock, the lateral aquifer and the overburden. Land motion in its full entity can be accurately revealed by InSAR measurements from space (Galloway and Hoffmann, 2007).



A geostatistical analysis was performed over the 5-year period 2003-2007 to remove the regional trend and the nugget effect from the satellite interferometric data over a gas reservoir in Northern Italy. This reservoir is used to store methane from April to October and to pump it out from November to March each year. The aim of the analysis was to identify and model the vertical and horizontal components of the ground motion that are strictly related to the cyclic gas storage. In particular, the horizontal displacements are hard to measure and have been so far inferred mainly from theory. This note is concerned with the prediction of seasonal earth movements up and down, as well as to and from the injection/withdrawal wells. The land displacements measured with the aid of persistent scatterer interferometry (PSI) are simulated by an advanced numerical geomechanical model that is capable of accounting for the geophysical processes controlling the expansion and contraction of a storage reservoir seated at a depth of 1050-1350 m, and of its overburden in the Po River plain.

The aforementioned model is transversally isotropic and requires the definition of five geomechanical parameters, namely the elastic Young moduli E_v and E_h and the Poisson ratios ν_v and ν_h in the vertical and horizontal plane, respectively, plus the shear modulus G_v in the vertical plane. The medium deformation is primarily sensitive to E_v and E_h and much less to ν_v and ν_h, which vary over a plausible, quite restricted interval and play a relatively minor role. Another important factor is the recompression index, i.e. the ratio between I and II cycle vertical rock compressibility at the load inversion. This has been assumed to be equal to four, consistent with the formation expansion measured in the depleted/repressurized gas fields of the Northern Adriatic Sea (Baù et al., 2002; Ferronato et al., 2003). The other parameter values are: $E_h/E_v = 3$, $G_v = E_h/2(1+\nu_h)$, $\nu_v = 0.25$ and $\nu_h = 0.15$. The vertical rock compressibility, from which E_v is derived, is a stress, and is, therefore, depth-dependent (see Baù et al., 2002).

Essential information for the geomechanical model includes the fluctuating gas pore pressure. Within the field, this is a known variable (Figure 1a) and represents a source strength in the form of a spatial pressure gradient. Since the reservoir is connected to a lateral aquifer (called "waterdrive" in petroleum engineering) a groundwater flow model is also needed to predict the water pore-pressure variation within the waterdrive as the result of the pressure variation in the reservoir (Teatini et al., 2011). As a major consequence, the porous medium volume where there is a non-zero pore pressure gradient, is larger than the gas field itself with the pore pressure unevenly distributed in both space and time. The geomechanical model was calibrated against the interferometric measurements over a five-year period, i.e. 2003-2007. Figures 1b and 1c show the excellent agreement between the simulated and the observed vertical and horizontal displacement, respectively, at two representative points over and close to the reservoir. Note the good correspondence between pressure (Figure 1a) and land displacements (Figures 1b and 1c) in connection with the injection and the withdrawal phases. To provide an idea of the complex spatial pattern of land motion and the model's ability to capture the occurrence over a complete injection/extraction cycle, Figures 2a and 2b show the computed land uplift and horizontal movement from April 2006 to November 2006 as compared with the satellite measurements. Considering the very small values recorded (on the order of a few mm) and the inevitable role of local disturbances, it may be concluded that the transversally isotropic model overall matches the geomechanical process very successfully.

It may be interesting to evaluate how much gas can be stored if the gas pore pressure is pushed beyond the original in situ pressure, p_i, prior to the field development and the corresponding earth breathing. A prediction has been made with a maximum overpressure equal to $1.2p_i$. It is worth noting that starting from the lowest pressure of $0.75p_i$, i.e. the pore pressure experienced by the wells at the wells' shutdown, the $1.2p_i$ case allows for the methane stored per cycle to be increased by approximately three times as much as the quantity disposed of at 100% p_i. Such a large increase of the working gas volume is due mainly to the

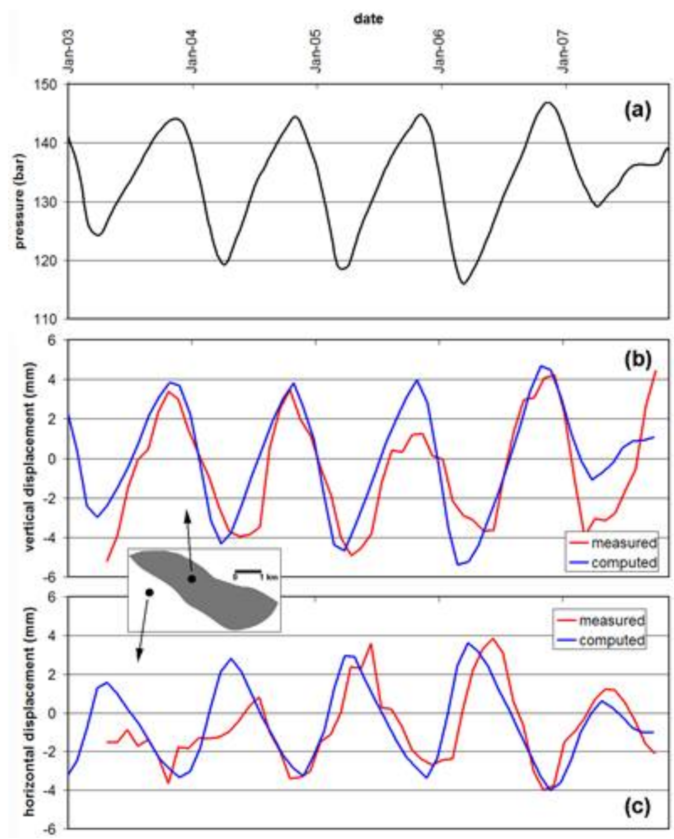


Figure 1: a) Seasonal behaviour of the average gas pore pressure within the storage reservoir over the 5 year period 2003-2007; b) vertical land displacement (uplift and settlement) and c) West-East horizontal land displacement as measured by the satellite interferometry and predicted by the geomechanical model over the same period.

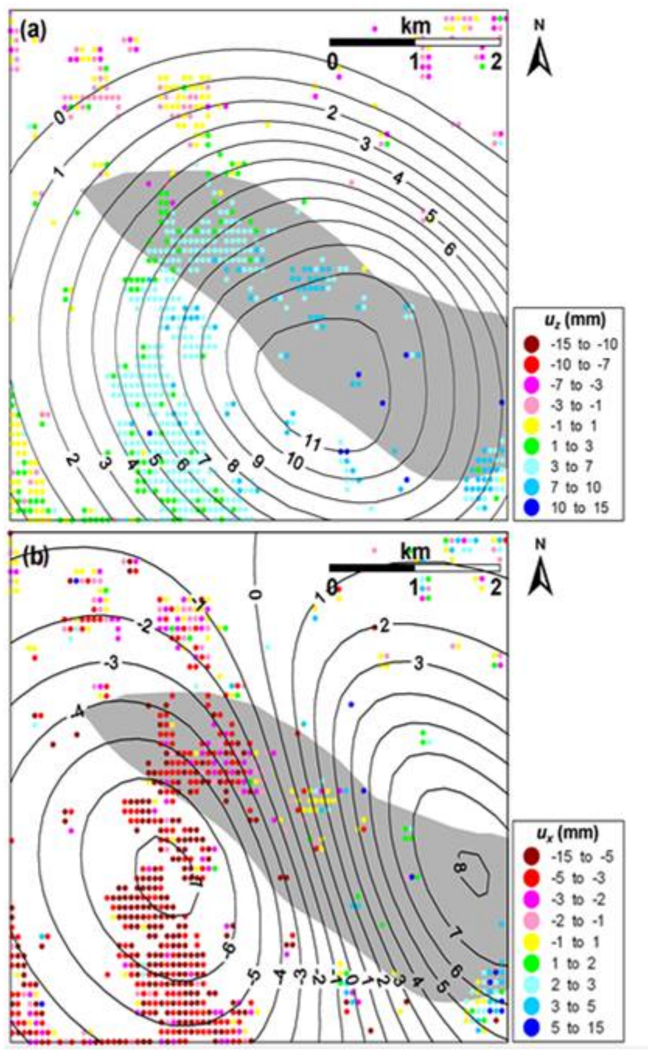


Figure 2: a) Spatial land uplift and b) west-east horizontal land displacement from April 2006 to November 2006 as predicted (solid lines) with the aid of the geomechanical model and compared with the PSI results (colored dots).

groundwater displacement in the waterdrive (accounting for 60-65%) and, secondarily, the methane compression caused by the maximum overpressure (30-35%) and finally the elastic reservoir expansion (1-2%). The latter migrates to the surface giving rise to a vertical land excursion equal to 27 mm while the largest horizontal land oscillation close to the field border is 23 mm (Teatini et al., 2011). So the earth "breathes" as gas is seasonally stored into and extracted from a depleted gas field with the largest vertical and horizontal motion on the order of few cm overall (at least for gas reservoirs of the Po River plain). The land moves elastically up and down and west-east and vice versa during each annual cycle. However, only a very small fraction of the gas injected and released is controlled by the contraction and expansion of the reservoir.

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The Horton Research Grants – Nearly thirty years of rewarding excellence

Jud Harvey (U.S. Geological Survey)

Robert E. Horton's scientific achievements in the early twentieth century were central in establishing hydrology as the key discipline of geophysics and environmental science that we recognize today. In addition to Horton's many scientific contributions was his tireless advancement of the role of hydrology in government service and in scientific societies, including the successful campaign to establish the Hydrology Section of AGU in 1930. Fittingly, Robert Horton is honored by several AGU awards aimed at early as well as career-long contributions. The first Horton Research Grant (HRG) was awarded to Ph.D. student Jane L. Stockman of Stanford University in 1983. Nearly thirty years later the annual call for HRG applications typically attracts nearly one hundred applications, and honors the Horton legacy by affirming the vision and creativity of the next generation of professionals. Over its lifetime, fifty-five grants have been made, with recipients typically receiving $10,000 in research expenses, in addition to travel expenses to accept their award in San Francisco at the fall AGU meeting.

An informal survey of past recipients produced warm and varied remembrances attesting to the award's personal impact on young scientists, including:

"the honor of being added to a list of graduate students many of whom are now recognized leaders… it brought attention to my faculty applications and research at the right time" – Audrey Sawyer, University of Delaware, 2009 recipient

"recognition that the research I was pursuing was at the forefront of hydrology" – Brian McGlynn, Montana State University, 2001 recipient

"first time to completely manage my own grant…some of the equipment purchased is still used by my graduate students today" – Joe Wheaton, Utah State University, 2005 recipient

"confirmation that my ideas were interesting…and money to get my first field season underway… campground fees, gas for old Subaru, Ramen noodles, sampling equipment" – Martin Doyle, Duke University, 2000 recipient

"really helpful in getting me to pursue original ideas that launched my career" – Bayani Cardenas, University of Texas, 2005 recipient

"instantly catapulted me into discussions with the key people…a game changer and job getter" – Jeff McDonnell, Oregon State University, 1987 recipient

With the growth of AGU, the popularity of the HRG has increased along with the number and the quality of applications. Each summer the HRG committee spends about five weeks judging applications using NSF-style criteria to evaluate originality and creativity, clarity of objectives and access to needed resources, likelihood that outcomes will be influential and overall qualifications of the applicant. Applicants benefit by using a short proposal format that makes every word and graphic count, and also by emphasizing their growing record of professional achievement. The committee typically judges 15% or more of the proposals to be highly competitive and 5% to be truly outstanding; however the award ratio has dipped as low as 2% in some years due to funding limitations. The difficulty in selecting awardees from a growing pool of outstanding finalists has suggested the need to pursue supplementary sources to support additional grants (see President-elect Eric Wood's article in the July 2011 Hydrology Section Newsletter). The hope is to support one or two additional awards each cycle, which will guarantee the continuation of HRG's important role in AGU for the next thirty years and beyond.

Diary of a Fall Program Chair

Matt Rodell (NASA/Goddard Space Flight Center)
2011 Chair, Hydrology Section
Fall Meeting Committee

Generating the Hydrology Fall Meeting program consists of conveners submitting sessions in the spring, presenters submitting abstracts in the summer, and AGU printing the program in the fall, right? Like making sausage, there's more to the process than you may want to know. This past year, while serving as chair of the Section's Fall Meeting Committee, I kept notes, and now I'm going to pull back the curtain...

February 16 - I've been co-chair for the past two years, and this year I'm ready to take the lead. Last year's chair, Roseanna Neupauer, has rotated off, and Dennis Lettenmaier has asked Stefan Kollet to join Mike Cosh and me on the Fall Meeting Committee. Noting that we had 111 sessions proposed last year with many that were duplicative, we recommend on the section website that those who propose sessions first check to make sure that what they are proposing is unique. We also remind folks that the Union has moved the program schedule forward by a month, and that conveners are responsible for advertising their sessions and attracting enough abstract submissions.

April 21 - Session proposals are in, and the number has increased by 22% to 135. Many are redundant. Does anyone read the section web site?

May 5 - Spring planning meeting at AGU headquarters. The deadlines for each phase of program development have already been set (to our chagrin, without input from the section committees or officers). Once again, the oral slot allotment and session finalization period is much too short - only 5 days including a weekend. We argue with AGU staff, to no avail (not only that, but the GRACE Science Team meeting is scheduled for the exact same dates. C'est la vie!)

May 6 - We identify 56 sessions for mergers, transfers to other sections, or withdrawals, and begin contacting conveners. Also, we're guinea pigs for the new ScholarOne/AbstractCentral software system in which the program will be created. The work is to be done under a tab called "Session *Beta*". I don't have a good feeling about this.

May 20 - The first round of session mergers is complete. Thirty-one sessions merged, 3 were withdrawn, 5 moved to other sections, and 17 remained unchanged. Some conveners were understanding, others recalcitrant. We now have 112 sessions plus the Langbein Lecture and General Contributions. Not as much progress as I'd hoped, but it's a start.

June 8 - The abstract submission site is open. AGU receives two abstracts on the first day. Vying for the coveted abstract ID #0000001?

June 22 - After an hour of copying and weeding out duplicates from AGU's master spreadsheet of session proposals, I have a comma-delimited list of nearly 400 conveners' email addresses. Good times. To the conveners I send a schedule and list of duties that is much too long to expect anyone to read.

August 4 - Yesterday's abstract deadline was final - doesn't anybody read their AGU emails? Yes, it's unfortunate that the eminent Prof. Albert Rainstein wasn't aware that invited authors must submit abstracts, but there's nothing I can do about it, nor IMHO should the policy change. Without a hard deadline hundreds of late abstracts would pour in.

August 5 - I keep my schedule open to work on session mergers, but the abstract distribution and oral slot allotment information doesn't arrive until 6:12 PM eastern. I guess it will be a working weekend! How did we go from 2099 to 2537 abstracts in one year? Hydrology, the king of the AGU jungle. Accordingly, we are given 110 oral slots, up from 86 last year. That makes it difficult to try to keep the number of uniquely-named oral sessions near 70, as directed by Dennis. Stefan will be in charge of distributing general contribution abstracts to sessions and moving misplaced abstracts, and Mike and I will manage mergers. Thank goodness for my co-chairs, this job is too big for one person!

August 7 - I've sent another mass email to conveners with instructions for the coming days. They are much more agreeable to our merger suggestions this time, with oral slots on the line. Stefan is on his way to sending over 100 messages related to abstract moves. I'm off to Austin for the GRACE meeting.

August 8 - Yes, I'm glad the ten of you are converging towards a merged title and set of conveners. No, I don't need to be copied on every email along the way.

August 9 - I've set the thresholds for 1, 2, 3, and 4 oral slots. "Please let me have one more - we're so close to the cutoff!" That's the thing about a threshold - someone is going to be under it.

August 10 - Our final set of sessions and oral slot assignments has been completed and sent to AGU, on schedule. Time for a Shiner Bock.

August 12 - Ha! Other sections missed the deadline - sections smaller than ours! Unfortunately, that pushes back the opening of the abstract scheduling tool to within days of the Fall Planning Meeting.

August 23 - AbstractCentral still has unresolved issues the day before the planning meeting. This is the worst I've ever seen it. Many mergers have not yet been imported into AbstractCentral, and for those that have, the conveners can only administer the abstracts from their original sessions. Some conveners apparently think I wrote the AbstractCentral software. I feel your pain, but until you call ScholarOne, your problem will not be resolved!

August 24 - Fall Program Planning Meeting, AGU headquarters. One to three committee members from each of 27 sections and focus groups sit around tables, laptops open. The long back wall is lined by 15 poster boards covered with index cards color coded by section; room number on the x-axis, meeting day and time on the y-axis. How did Hydrology get stuck with one of the small rooms at the Moscone Center? After introductions, the day begins with room trading, as sections plan around their named lectures. Representatives from ScholarOne are here to fix their software on the fly. They are going to be busy. Despite arriving from Germany the night before, Stefan works tirelessly. Mike's draft schedule, prepared in advance of the meeting, is in good shape. The key is to strike the right balance between grouping Hydrology sub-disciplines into the early, middle, or end of the week and avoiding overlap of closely related sessions. Again, thank goodness for co-chairs. The group dinner at Restaurant Nora is excellent. That's one perk of serving on the program committee - AGU feeds you well.

August 25 - I've distributed the few extra oral slots I'd saved to desirous session conveners, and the Hydrology schedule has been revised. Entering it into AbstractCentral proves to be tedious. We learn the hard way that if you don't give the system a chance to refresh after each input, sessions end up on the wrong day. The schedule must be replicated by hand, pinning index cards for each oral and poster session to the poster boards, as a backup for the electronic method. Other tasks include confirming cross-sectional mergers and abstract transfers, tweaking the program based on scheduling requests, recreating one session that completely disappeared from AbstractCentral, and crafting a new, detailed program listing for the Langbein Lecture.

August 26 - AbstractCentral searches for conflicts (speakers and conveners scheduled to be in two places at once) and, miraculously, we only have a few. Mike shuffles some sessions and our schedule is complete. Before we can leave we must work through a checklist that includes items like ensuring that Hydrology sessions have not listed Hydrology as a co-sponsor. You'd be surprised. By early afternoon, after a decadent lunch, we're home free.

October 27 - All that remains is to wear the "Program Chair" ribbon at the Fall Meeting, which could be a badge of honor or a bull's-eye, depending on members' satisfaction with the program. In hindsight I have no regrets about volunteering for the program committee. It is a good alternative to editorship as a community service, with work that is focused in a few intense periods per year. The Section's Fall Meeting Committee has a good system, with a three-year rotation that provides each chair with two years of experience before taking the lead, and specific roles for the first and second year co-chairs. Looking ahead to next year, I expect that many of the kinks in the new software will be ironed out, which will reduce the stress level. One of the biggest complaints this year was that the abstract deadline was moved forward by a month, as was the fall planning meeting moved into the Euro-vacation month of August, while the session merger finalization period remained too short. AGU leadership has agreed to solicit the program committee's input on the schedule before finalizing it next year, but they are not going to shift the abstract deadline back to September. In closing, thanks to Mike and Stefan, and good luck in 2012!

Hydrological Sciences within the European Geosciences Union

Gerrit H. de Rooij (Helmholtz Centre for Environmental Research, Halle, Germany)
President, European Geosciences Union Division on Hydrological Sciences

Hydrology has its major outlet in Europe in the Hydrological Sciences Division (HS) of the European Geoscience Union *EGU). HS is currently the largest division within EGU. HS has two main responsibilities: 1) organizing a vigorous hydrology program at the annual General Assembly of EGU in April, and 2) running its dedicated journal: *Hydrology and Earth System Sciences* (*HESS*). In addition, HS has an awards and medals program that recognizes young as well as established scientists. HS also organizes small, topical conferences known as Leonardo Conferences, typically in the autumn.

In total, the General Assembly attracts about 10,000 attendees and includes around 8000 oral and poster presentations. Roughly 15-20% of the attendees are associated with HS. The HS attendees come from all continents, with the top 3 nationalities being German, British, and American (2010 data). The total HS program comprises 80 to 90 sessions that host on the order of 1800 presentations. Dedicated time slots for poster viewing (no simultaneous talks) are scheduled at end of the day from Monday through Thursday.

In order to cover all aspects of hydrology in the program, the HS division is divided into 10 subdivisions, each of which has an open committee headed by a subdivision chair, who serves a four-year term. Their main job is to organize their subdivision's part of the HS program at the General Assembly. HS (and EGU in general) try to work in a bottom-up mode as much as possible. The subdivisions hold business meetings, open to all, to invite feedback and receive input for next year's program. The planning process then proceeds through an on-line call for additional sessions (July-September), the finalization of the session program, and the on-line call for papers (November-January).

HESS publishes articles on a wide array of hydrological subjects (e.g., catchment hydrology, hydrology and climate, unsaturated zone, groundwater, experimental and theoretical innovations, and many more) as reflected in its broad editorial board. The journal's 2010 impact factor is 2.4, placing it firmly among the top hydrological journals. *HESS* is an on-line journal with open access (no subscription fee). A signature EGU feature is the public on-line discussion phase of the first submitted version of each manuscript in the discussion forum of the journal (designated *HESSD*), during which an exchange with the authors can take place. The formal reviews are part of this discussion, and thus are freely accessible as well, either as anonymous or signed reviews, at the discretion of the reviewer. After this discussion phase, revised and accepted papers are published as peer-reviewed full papers in *HESS*.

Many AGU Hydrology Section members attend the General Assembly and publish in *HESS*, and we want to encourage and expand this involvement. If you want to like to get involved, the easiest way is to join a committee (membership is open as indicated above) or to volunteer to convene a session – you can do so by contacting the subdivision chair of your choice at the HS link below.

Useful links:
EGU: www.egu.eu
HS: http://www.egu.eu/inside-egu/divisions-and-present-officers/division-hydrological-sciences/home.html
HESS: http://www.hydrology-and-earth-system-sciences.net/

Water diplomacy

Shafiqul ("Shafik") Islam (Tufts University)

Water Problems are Complex. Science, Policy, and Politics of water are interdependent.

There are over six billion humans competing for roughly the same amount of water that was available during the time of the dinosaurs. But we now find ourselves concerned about an incredibly complex array of water problems that cross multiple boundaries: Is water a property or a human right? Is maximization of economic utility more important than environmental sustainability? Do fish have more rights to water than corn? How can we reconcile competing cultural and religious values associated with water? How much water do people actually need? Should we adjust our ways of living to reduce the overall demand?

Over-utilization of natural resources is already creating constraints on our planet. We can debate the nature and implications of those constraints and how they are manifested – for example, in water, energy, food, climate change, and nano-, bio-, and info- domains – but these constraints are certainly going to create an uncertain and ambiguous future. A key question for us now is: *How can we use the water diplomacy framework to design an innovative and creative approach to ascertain water as a global common good for our uncertain future?* As we undertake this design experiment, we must be fully cognizant of the fact that the exact nature of the challenges in this experiment is open to multiple interpretations. It is not the ideas or strategy of execution, but rather the filtering process that links the two, and separates the wheat from the chaff.

To address emerging realities of our globalized world and related water issues, we no longer can afford to rely on the 20th Century paradigm: Scientists innovate; politicians make policies; and people adopt. Our 21st Century approach to water management needs to emphasize interaction of interdependent variables and processes, pervasive nature and surprise elements in natural (think of the intricacies and uncertainties of climate change) and societal (think of the impact of Facebook) systems, connectivity and instantaneous nature of information flow, and diminished influence of hierarchical governance structure.

For our era, water problems are shaped by the interactions of natural, societal, and political variables and processes. Together, interactions and feedbacks among these variables and processes create water networks. As population growth, economic development and climate change create pressure on water resources, management of these networks becomes critically important. Science alone is not sufficient, nor will policy-making without science yield sustainable solutions. These can only come from diplomacy that takes science, policy, and politics into account within networks. We now describe our "work-in-progress" exhibition of creating approaches for effective intervention and resolution of emerging water problems (*Islam et al., 2010, 2011; Islam and Susskind, 2012).*

In our assessment, there are three types of water problems: simple, complicated, and complex. Simple problems are characterized by being easily knowable, while complicated problems are not simple yet are knowable and predictable. Complex problems, on the other hand, are not easily knowable and usually are unpredictable. The design of a water-efficient flushing toilet is an example of a simple water problem. Getting water from the Quabbin reservoir (the largest inland body of water in the Commonwealth of Massachusetts, built between 1930 and 1939) to allow a resident to take a morning shower on the 16th floor of an apartment building in Boston is a complicated problem. Indeed, piping of a water distribution network from the reservoir to an apartment building is inevitably complicated. Figuring out how water flows, where every pipe goes, how many pumps and other control fixtures are required, and what type of chemicals are needed to keep water potable takes significant engineering ingenuity and creativity. Still, with careful study we can know with (near) certainty what each component of this distribution network does and how to control it. In other words, a complicated system is knowable, predictable, and controllable. Now, think about the complete inundation of four towns, which was required to create the Quabbin reservoir, or the task of balancing the competing demands on water for fish and farm or urban development and ecological sustainability. Suddenly, we go from a complicated to a complex water problem. One could study each of these variables and processes in minute detail without ever being certain how they will interact. No matter how much effort one puts into studying all the elements, or how deeply one digs down into all of those elements, one will never gain the certainty inherent in simple and complicated problems. Complex problems are never fully knowable because there are too many variables and because they feature numerous interaction and feedback loops *(Kauffmann, 1993; Bar Yam, 2004; Miller and Page, 2007).* Consequently, complex problems are not easily predictable or controllable.

Water problems are complex because they arise when natural, societal, and political variables and processes interact. They are also complex because they involve numerous stakeholders (e.g., farmers, industrial users, urban developers, environmental activists) competing for a limited and common resource, and they cross multiple boundaries and scales (e.g., physical, disciplinary, jurisdictional).

For centuries, we have taken nature apart and analyzed its components in ever-increasing detail. Now we realize that this process of "reductionism" can provide only so much insight. We recognize that a system is more than the sum of its parts and that "systems thinking" only works well when systems are bounded and cause-effect dynamics are known. For purposeful systems – like water resources management – where system boundaries are ill-defined and cause-effect relationships are ambiguous, an indiscriminate use of the systems approach can provide little insight *(Kauffmann, 1993; Barabasi, 2003; Miller and Page, 2007).* A key difference between predictable systems (simple and complicated systems) and complex systems is our approach to understanding and managing them. We can understand and optimize simple and complicated systems by taking them apart and analyzing the details; however, we cannot understand and manage complex systems by applying the same strategy of reductionism. A failure to appreciate this difference could cause us to apply exactly the wrong approach to the right water problem or the right approach to the wrong problem. In general, continued efforts to refine existing tools like cost-benefit analysis and optimization algorithms to address complex problems have not worked (e.g., *Ackoff, 1979; Bennis et al., 2010; Stiglitz et al., 2010*). We need a different approach to address complex water problems.

Many of our water management difficulties stem from our fragmented view of water resources management as a "natural object" or as a "societal issue" or as a "political construct". As a complex system, the components of a water resources management puzzle can fit in so many different ways that it is practically impossible for us to put the components together using "reductionist" or traditional "systems engineering" methodologies in a way that is functional and actionable. The 2008 Bihar flood (Figure 1) was one of the most disastrous floods in the history of Bihar; a primary cause for this flood was not excessive rainfall, but a breach in the Koshi embankment near the Indo-Nepal border. Thus, a very reliable rainfall forecast would have very limited value to deal with the uncertainty related to whether or not a breach would

Figure 1: 2007 Flood in Bihar, India: Is this System Open or Closed? Simple or Complex? Fixed or Flexible ? (photo courtesy Flood Management Information System Cell, Patna, Bihar, India).

form in the embankment, the subsequent emergency it created, and the relief and rehabilitation efforts it required. The flood killed over 250 people, forced nearly three million people from their homes, and damaged over 800,000 acres of crops. The Prime Minister of India declared a national calamity and earmarked US$230 million in aid. To effectively address similar problems, we need an approach that is adaptive with actionable ideas and execution strategies regardless of the specific components (in this case, sudden breach of the embankment) that create and exacerbate the complexity of the problem.

One of the most powerful tools to represent functional relationships among large numbers of interconnected components that cross multiple boundaries and scales is network analysis. A network (or graph) is a collection of nodes (vertices) and links (edges) between nodes. The links can be directed or undirected, and weighted or un-weighted. A water network can be described as an interconnected set of nodes representing variables from natural, societal and political variables and processes. The flow of information among these variables through these links is what enables the nodes to update their states and make them dynamic. The challenge is to identify the mechanisms that define the flow of information among the nodes. It is in the context of networks that we propose a new water management approach - called Water Diplomacy Framework - rooted in ideas of complexity theory and non-zero sum negotiation; this approach seeks to synthesize scientific objectivity with contextual understanding to manage complex water problems within a political reality.

The Water Diplomacy Framework posits that water problems might be more effectively managed by viewing water as a flexible resource and invoking three key propositions about water networks: (i) they are open and continuously changing because of interactions among natural, societal and political variables and processes; (ii) water network management must account for nonlinearity, uncertainty, interactions and feedbacks; and (iii) the management of water networks needs to be adaptive and negotiated using a "non-zero sum" approach.

Many water management problems stem from interaction and feedback among **N**atural and **S**ocietal processes within a **P**olitical **D**omain (NSPD; Figure 2). Within the natural domain, the interplay among three variables— water quantity (Q), water quality (P), and the ecosystems (E) —can lead to conflict. Within the societal domain, there are equally complex interdependencies and feedbacks among social values and cultural norms

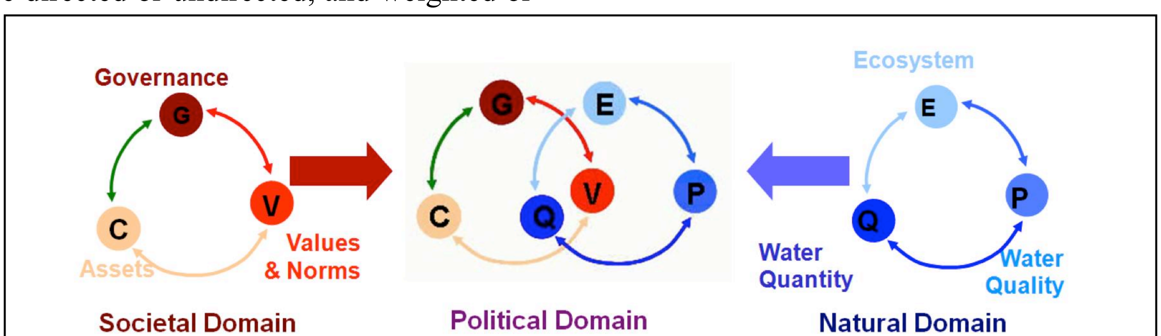

Figure 2: A schematic of NSPD (**N**atural and **S**ocietal processes within a **P**olitical **D**omain)

(V), assets including economic and human resources (C), and governance and institutions (G) (*Islam et al., 2010; Islam and Susskind, 2012)*.

A key is to identify and prioritize interactions and feedbacks in NSPDs by examining a large number of real world water disputes, both within and beyond national borders. Ideas from decomposability of complex subsystems and nested conceptual maps will be used to identify secondary variables, critical feedbacks and interactions of NSPDs. Preliminary results of examining several water case studies suggest that certain functional patterns are identifiable (*Islam et al., 2010*). A key question we will examine is: How can we integrate heterogeneous knowledge from natural, societal, and political domains within a useable framework, where both qualitative and quantitative findings are relevant? More specifically: Why do certain adaptive management interventions work in one setting but not in another? What can be learned by studying the effectiveness of particular adaptive management strategies across different settings?

These case studies are now available in AquaPedia (http://aquapedia.tufts.edu), which is a growing virtual world of reliable, relevant, and readily accessible water information and wisdom collected and synthesized by users and producers of explicit (scientific information) and tacit (contextual information) knowledge. This web-based, wiki-style, self-learning repository of interactive and extractable water disputes from around the world - AquaPedia - will connect the global community of water scholars, policy makers, practitioners, educators, and users to synthesize theory and practice of effective water management. In AquaPedia, which is in its Beta state, case studies are categorized within the framework of NSPD, water network, and natural and societal variables with a discussion forum allowing feedback and comments for each case study.

The Water Diplomacy initiative is currently supported by two five-year grants from NSF that are intended to educate the next generation of water professionals (NSF IGERT Program) and create a global network of reflective water professionals (NSF SESS-RCN) who will share research and field-based experience by actively participating in water diplomacy and the AquaPedia forum. We welcome you to be a part of this growing network of water professionals through http://waterdiplomacy.org, http://waterdiplomacy.tufts.edu and http://aquapedia.tufts.edu.

In closing, I note that this article draws from several publications, including *Islam et al. (2010, 2011)* and *Islam and Susskind (2012)*. It has benefitted from discussions with and comments from water diplomacy partners, including A. Akanda, E. Choudhury, A. Jutla, P. Mollinga, W. Moomaw, K. Portney, M. Reed, D. Small, L. Susskind, and R. Vogel, to whom I am grateful.

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Linking hydrology and biogeosciences towards better understanding of soil and critical zone processes

Dani Or (ETH Zurich) and Yakov Pachepsky, (USDA-Agricultural Research Service)

The growing recognition of the centrality of soil and the critical zone (SCZ) as a key biogeochemical-hydrological compartment of the biosphere and as a scientific arena is driven by pressing global challenges that range from climate change to food security and from energy and water resources to understanding of ecosystem functioning. The evolving SCZ community is expanding beyond traditional links with agriculture and pedogenic processes. The importance of strengthening ties across disciplines including atmospheric sciences; biogeosciences; ecology; hydrology; and geochemistry are not only critical for the relevance of the SCZ community, but are mandated by the scientific challenges such as water quality and quantity, carbon cycling, and nutrient availability. A more strongly interdisciplinary community will offer numerous advantages for the professional preparation of broadly-trained current and future students, and will undoubtedly contribute to the flourishing of a vibrant SCZ discipline.

The US National Academy of Sciences (2001) defined the critical zone as the Earth's outer layer from vegetation canopy to the soil and groundwater that sustains life on earth. The evolving and broader context of soil science is derived from the array of functions and critical services provided by soils that both include and transcend food production (Figure 1):

- Soil within the critical zone is probably the most biologically active compartment of the biosphere, hosting the largest pool of biodiversity on Earth;
- Soil functions as Earths' life support body, a thin film of life covering much of the terrestrial surface;
- Soil is a giant recycling system, providing most of our needs for food, feed, fiber, and increasingly for renewable energy production through biofuels.
- Soil supports global biogeochemical cycles (C, N, P), representing the largest terrestrial stock of organic carbon;
- Soil provides important ecosystem services essential for human primary needs including drinking water and food provision, and carbon storage and flood regulation;
- Soil is a functioning complex natural body with unique characteristics and emergent behaviors that cannot be deduced from a collection of its constituents or individual processes; soil is an integrator of the Earth processes for which it is intrinsically linked.

Translating these general ideas into a coherent plan of action requires formulation of SCZ-relevant science questions that frame grand challenges to the community. Questions such as the following will provide more specific context for the evolution of the field:

a. How will improved understanding of SCZ processes lead to a more complete description of land surface-climate interactions in the context of climate modeling and assessment of changing climate impacts? For example, how can surface soil moisture dynamics and remotely-sensed fluxes be better linked? How is soil water storage manifested in hydro-climatic memory, or in mediating precipitation patterns and extreme heat waves? How can the contribution of SCZ better constrain estimates of carbon storage and greenhouse gas emissions?

b. What are the gaps in fundamental understanding of SCZ processes that must be addressed to sustain and increase food production with limited natural resources (land, water) and in a changing climate? How can we leverage SCZ knowledge to refine crop selection and improve agricultural production? How can modern theories of hydro-mechanical process be implemented to support sustainable land use under increasingly intensive practices? How do land use patterns vary with climatic and SCZ processes? What are the ramification of climate change trends on SCZ process and land use?

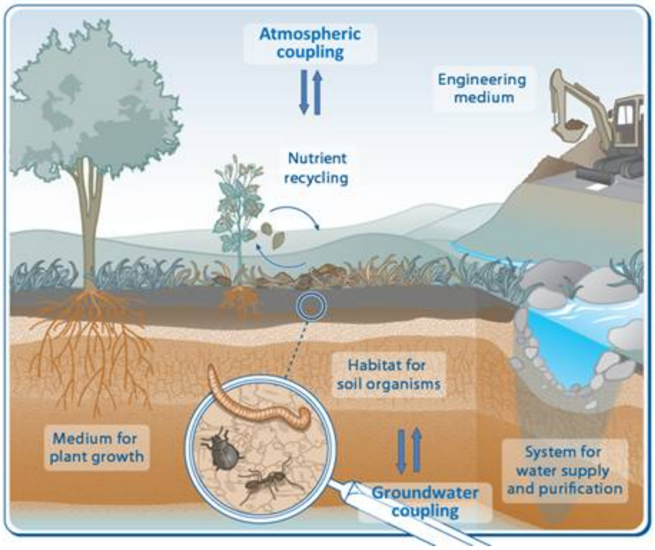

Figure 1: An overview of some of key ecological functions and services provided by soil and the critical zone (visual courtesy D. Or, ETH Zurich).

c. Considering the central role of soil as the most biologically active part of the Earth's terrestrial biosphere, how can SCZ processes be managed to assure sustainability of ecosystem functions of natural and man-made (agro) ecosystems? How do SCZ conditions affect global biogeochemical cycles? What are the most pressing gaps in understanding of plant-soil interactions? What are relationships between structure and function in soils? How do we define and assess soil quality and functionality to detect trends and thus mitigate degradation processes?
d. Can the potential of remote and terrestrial land observing systems (targeting primarily soil surfaces) be better exploited to understand connections between observable above land surface SCZ elements (vegetation, atmosphere) and unobservable elements (groundwater, deep vadose zone)?How can observations of hydrological, climatic and ecological elements of the critical zone be acquired and linked for synergistic assessment of processes and state of ecosystems? How can SCZ information best be communicated to decision makers and the public?

These are only few examples of overarching issues facing the SCZ community. Most of them point to intricate connections between many disciplines, most prominent of which in the context of AGU are links between hydrology and biogeosciences. The newly-formed Technical Committee on Soil Systems and Critical Zone Processes creates a natural bridge between the Biogeosciences and Hydrology Sections of AGU, and provides the SCZ community with opportunities to strengthen links with the Soil Science Society of America (SSSA), the Ecological Society of America (ESA), and others. We hope that the TC will promote the scientific study of soil and critical zone by increasing visibility of soil and critical zone processes at AGU meetings, engaging in joint activities with other societies, and fostering publication on these topics in AGU journals.

Among the short-term goals for the TC will be to solicit reviews and/or position papers on some of the cross-cutting research questions above. The new TC will also be developing ideas for sessions at AGU meetings that will capitalize on natural SCZ links in the context of AGU Earth System Science. It may also organize Chapman or Gordon Research Conferences, and other topical conferences on the role of SCZ in some of the themes listed above. We expect that an important, but less specific role of the TC will be to promote teaching of SCZ science, and to encourage young scientists in the area. We have launched a new web page for the SCZ TC (http://www.soils-agu.ethz.ch/index.php) where such initiatives can be announced, and we encourage members to contact us as co-chairs of the TC regarding proposals and promotion of new ideas. An inaugural TC meeting will be held during the AGU Fall 2011 meeting (*12/7/2011; 6:45-7:45AM at Moscone North, Room 114*) and will be devoted to establishing activities and operating rules for the TC. We encourage you to become involved, express your views and share your ideas for future activities!

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Characterization and monitoring of subsurface processes using parallel computing and electrical resistivity imaging

Tim Johnson, Mike Truex, and Dawn Wellman
(Pacific Northwest National Laboratory)
Justin Marble (U.S. Department of Energy)

Electrical resistivity tomography (ERT) is a method of imaging the electrical resistivity distribution of the subsurface. An ERT data collection system consists of an array of electrodes, deployed on the ground surface or within boreholes, that are connected to a control unit which can access each electrode independently (Figure 1). A single measurement is collected by injecting current across a pair of current injection electrodes (source and sink), and measuring the resulting potential generated across a pair of potential measurement electrodes (positive and negative). An ERT data set is generated by collecting many such measurements using strategically selected current and potential electrode pairs. This data set is then processed using an inversion algorithm, which reconstructs an estimate (or image) of the electrical conductivity (i.e. the inverse of resistivity) distribution that gave rise to the measured data.

Electrical conductivity is useful because it is governed by many of the physical and geochemical properties that are important for understanding subsurface processes (Lesmes and Friedman, 2005). ERT has been used, for instance, to infer spatial variations in water content (Daily et al., 1992), hydraulic properties (Slater and Lesmes, 2002), and even the hydrothermal structure internal to volcanoes (Revil et al., 2010). Time-lapse ERT has also been used to monitor the spatial and temporal evolution of subsurface processes, such as solute transport (Kemna et al., 2002), steam injection (Ramirez et al., 1993), groundwater discharge (Henderson et al., 2010), infiltration rates, (Pidlisecky et al., 2011), and bioremediation (Johnson et al., 2010). The advantages of using ERT to characterize the subsurface and monitor subsurface processes are that the measurements are autonomously collected, inexpensive, and sensitive to the subsurface conductivity away from electrode locations, making it possible to image in two dimensions (2D) and three dimensions (3D). This renders ERT a powerful tool for understanding the subsurface when spatial and temporal changes in conductivity can be interpreted in terms of properties and processes of hydrogeological and geochemical interest.

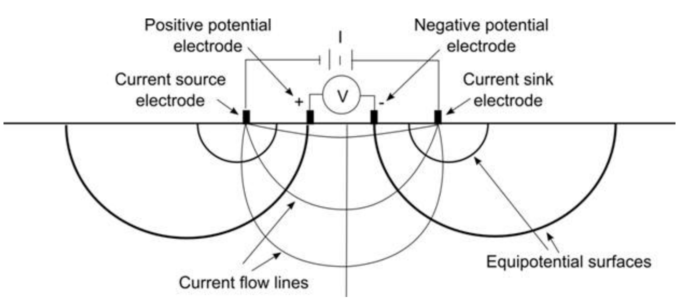

Figure 1: Basic ERT system requirements and example measurement configuration for a single measurement. Current is injected across a current source and sink electrode, and the resulting potential is measured across the positive and negative potential electrodes. Measurements are collected using many strategically chosen source-potential pairs to produce an ERT data set.

The first ERT systems used a DC current source, an amp meter, and a volt meter. Operators manually moved current and potential electrodes along the ground surface, taking one measurement at a time to complete a survey. Modern ERT arrays commonly consist of many hundreds to thousands of electrodes permanently installed along the ground surface and within boreholes. State of the art multi-electrode ERT systems can access each electrode for either a current injection or a potential measurement, providing an enormous number of possible configurations. Modern systems are also multi-channel, meaning that many potential measurements can be collected simultaneously during a given current injection event. Furthermore, data collection can be completely customized by the operator and automated for a single survey, or for repeated surveys when collecting time-lapse data.

Autonomous multi-electrode and multi-channel ERT systems are capable of collecting many hundreds of measurements per minute, thereby providing rich data sets with high resolution in both space and time. Extracting the information available in these data sets requires an inversion procedure, whereby a numerical model describing subsurface current flow is used to estimate the subsurface conductivity distribution, giving rise to the observed ERT data. The direct-current potential at position $\mathbf{r}$ induced by a point source of current I injected at position $\mathbf{r_0}$ within a medium of electrical conductivity $\boldsymbol{\sigma}$ is given by

$$\nabla \cdot (\sigma(\boldsymbol{r})\nabla\phi(\boldsymbol{r})) = -I(\boldsymbol{r} - \boldsymbol{r_0}) \qquad (1)$$

where $\phi(\mathbf{r})$ is the electrical potential at position $\mathbf{r}$. This equation is used to model the potential measured in the field for a given current injection episode. The objective of the inversion procedure is to numerically invert equation 1 in order to estimate the conductivity distribution, giving rise to the measurements (Sasaki, 1994). Because measurements cannot be collected everywhere, the inverse problem is ill-posed, and many different conductivity distributions exist which can reproduce the observed data. Therefore, it is necessary to provide constraining information, typically through a process called regularization (Tikhonov and Arsenin, 1977), which forces the inversion to provide a smooth conductivity distribution and add only that heterogeneity which is required to honor the observed data. This leads to images that are generally somewhat smoothed, or less resolved, than reality.

ERT inversion is a computationally demanding problem both in terms of memory requirements and processing time. For a single data set, the demanding nature of ERT inversion makes it difficult or impossible to fully extract the information that can be provided by arrays with hundreds of electrodes on current desktop systems, particularly for 3D imaging applications. This problem is exacerbated for time-lapse imaging when many data-sets must be inverted.

Time-lapse ERT inversion refers to the process of analyzing a chronological sequence of data sets to investigate changes in conductivity with time arising from some process of interest. This can be done after the fact, or as the process occurs in the case of real-time imaging. During real-time imaging, 'snap shots' of the bulk conductivity distribution are generated by collecting and inverting a sequence of ERT surveys as the subsurface process occurs. Note that 'real-time' is a relative term that depends upon that rate at which the process of interest evolves compared to the time required to collect and invert a single ERT data set. It may be possible to do real-time imaging for a slowly evolving process, but not for a faster one. We use the term 'near real-time' to emphasize the fact that some finite amount of time is required to collect and process each ERT snap shot. In any case, the ability to effectively execute near real-time ERT imaging requires two conditions:

1) The time required to invert the data must be less than the time required to collect measurements;
2) The time required to collect measurements is small compared to the time required for the process of interest to evolve.

Given the capabilities of modern ERT systems to collect large amounts of data quickly and the demands of processing that data, condition one, above, may be difficult to satisfy, leading to the need for parallel ERT modeling and inversion capabilities.

3D real-time ERT imaging has been used to monitor changes in electrical conductivity associated with soil desiccation at the Hanford BC-Cribs area. From 1956 to 1995, approximately 118 x 10^3 m^3 of liquid wasted containing mobile contaminants including nitrate, technetium, and uranium were deposited in the BC-Cribs (Ward et al., 2004). The nitrate and technetium penetrated deep into the approximately 100-m-thick vadose zone and present a potential future risk to the groundwater resource. Site cleanup contractors are investigating the potential of desiccating portions of the vadose zone to reduce moisture content and thereby reduce contaminant flux downward to the water table. A field-scale treatability test was conducted in the vadose zone adjacent to some of the former disposal cribs. Some of the disposed water and associated contaminants spread laterally from these cribs such that moisture and contamination are elevated at the test site. During the test, dry nitrogen was injected into a well targeting a 7.5 m-thick (25 ft) portion of the vadose zone, 8.5-16 m (28-53 ft) below ground surface.

Soil gas was extracted from a well approximately 12 m (40 ft) away to direct gas flow through a subsurface monitoring network. In addition to temperature and matric potential probes located at multiple discrete vertical points at each monitoring location, borehole ERT electrodes were installed to monitor desiccation progress in terms of changes in conductivity. The test ran for approximately 4 months, and two full time-lapse ERT data sets were collected per day, including full reciprocal data sets for noise analysis. Each data set consisted of approximately 9,000 ERT measurements taken from 99 electrodes, and was used to estimate approximately 350,000 bulk conductivity parameters (one for each element in the computational mesh) using the parallel regularized inversion approach described by Johnson et al. (2010). Inversions were executed on parallel computing resources housed at the Pacific Northwest National Laboratory.

The pre-desiccation 3D ERT inversion results at the Hanford BC-Cribs area are shown in Figure 2, along with the locations of ERT electrodes, and injection and extraction wells. The baseline characterization reveals electrical conductivity variations spanning nearly three orders of magnitude. The high conductivity lenses identified are contaminated finer-grained zones with elevated moisture content and/or pore fluid ionic strength, both of which increase electrical conductivity. Zones with lower conductivity are diagnostic of coarser, drier, more permeable materials through which gas will preferentially flow. The pre-desiccation ERT characterization alone locates the contaminated regions in 3D, and gives some indication concerning how the system might behave. That is, gas will flow, and desiccation will occur primarily between the injection and extraction well, above and below the fine grained unit identified.

In resistive granular materials such as those found in the Hanford BC-Cribs area vadose zone, electrical current travels primarily through the pore fluid. As water content decreases during desiccation, current flow paths are eliminated and/or become more tortuous, resulting in a corresponding decrease in electrical conductivity. Therefore, changes in electrical conductivity as determined via 3D ERT monitoring serve as a proxy indicator of corresponding changes in water content during desiccation.

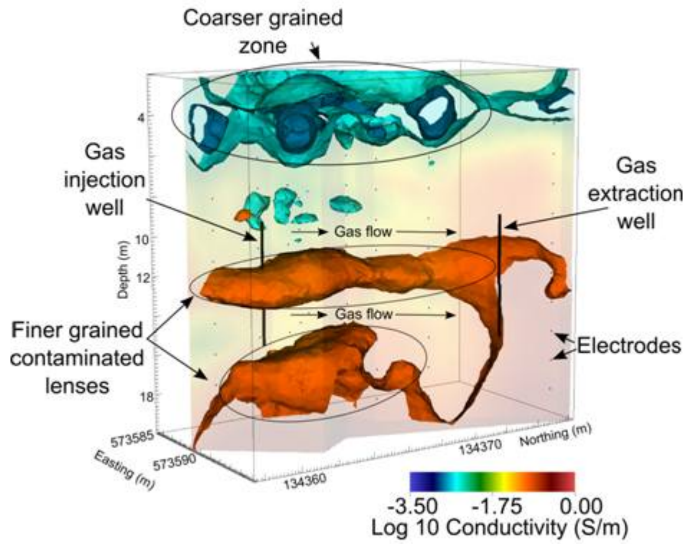

Figure 2: Isosurfaces of 3D pre-desiccation electrical conductivity at the desiccation treatability test site within the Hanford BC-Cribs area, November, 2010. Dry gas is injected from the injection well to the extraction well to desiccate the region between wells. Pre-desiccation ERT results show a contaminated finer-grained lens with elevated electrical conductivity bisecting gas wells. Gas flows primarily in the less electrically conductive (coarser grained) zones above and below this lens.

The desiccation treatability test operated from January to July, 2012. A subset of the time-lapse ERT desiccation-monitoring results are shown in Figure 3 in terms of change in log10 bulk conductivity from the baseline condition shown in Figure 2. The time lapse images show the primary zone of desiccation (and gas flow) occurring just below the fine-grained lens identified in the ERT characterization image (Figure 2). The region desiccated by nitrogen flow is shown as propagating from the injection well and moving toward the extraction well with time as expected, moving predominantly along the presumed high permeability pathways. These results reveal that the fine-grained unit provides an upper boundary to gas injected in the lower portion of the injection well. The 3D nature of the monitoring provides a level of process understanding that is difficult to achieve with point sensors alone. However, because electrical conductivity is sensitive to many properties that can be influenced by desiccation (saturation, ionic strength, and temperature), joint interpretation of 3D ERT and point sensor data is critical for correctly interpreting monitoring results in terms of the dominant processes and the subsurface properties that are changing.

There are multiple opportunities for improving time lapse geophysical monitoring; a few of these are described below. The utility of electrical geophysical methods in hydrological applications is based in the sensitivity of electrical properties to a variety of hydrogeological and geochemical properties. This sensitivity is also the basis for one of the primary drawbacks of using electrical methods to understand hydrogeological and geochemical processes. In general, the specific properties or processes influencing electrical properties cannot be determined without some supporting data or processes understanding. Thus, additional efforts to help correlate changes in hydrogeological and geochemical properties to electrical responses are of value. For use of ERT in field-scale applications, efforts are needed to improve impacts of limited inversion resolution (e.g., smoothing effects) on quantitative interpretation of data sets. Techniques to address time varying noise levels between time lapse data sets also need to be improved to enhance the use of ERT for time-lapse imaging.

In spite of these limitations, modern ERT systems are capable producing large amounts of data describing subsurface properties and processes with high resolution in both space and time. Fully leveraging this data through time lapse inversion is a demanding computational problem which can be addressed through the use of high performance computing resources.

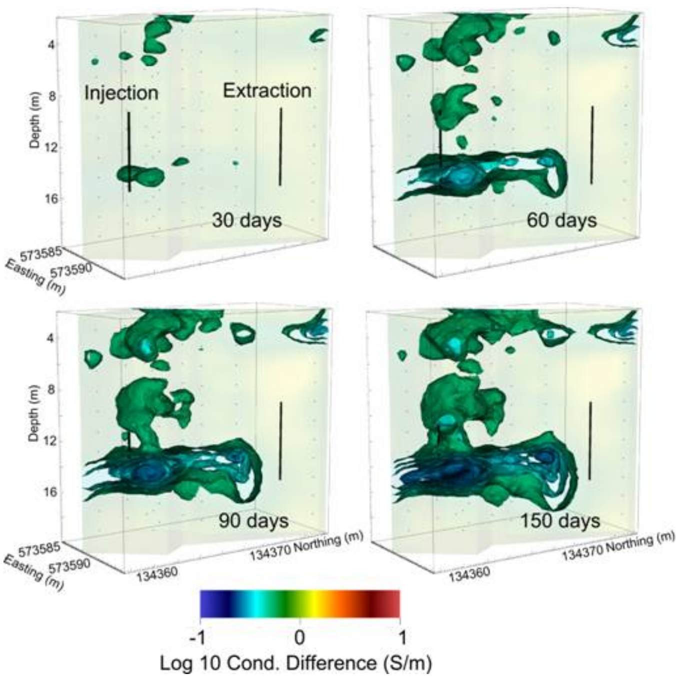

Figure 3: 3D time lapse changes in electrical conductivity from pre-desiccation baseline conductivity (see Figure 2). Zones of negative electrical conductivity difference indicate where desiccation is occurring or has occured. Time-lapse imaging reveals desiccation advancing from the injection to the extraction well along preferred gas flow paths. The primary zone of desiccation (and presumably gas flow), occurs just below the fine grained lens shown in the baseline image (Figure 2).

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Think globally, act locally: Targeting the rhizosphere to control soil fertility and improve water quality

Jane E. Hill and Courtney D. Giles (University of Vermont)

This past month the world's population reached a landmark seven billion. As the population continues its exponential ascent, demand for food, and hence food production, will also grow. And yet, we still do not have a sustainable agricultural paradigm for the limiting crop nutrient phosphorus (P). Sources of rock phosphate are predicted to peak in approximately 25 years (Cordell et al*.,* 2009), but much of the phosphate applied to crops is wasted: nearly half is lost to surface runoff and percolation processes (Elser and Bennett, 2011). The downstream accumulation of agricultural nutrients leads to an unintended fertilization of lakes and oceans, and ultimately, deteriorating water quality. The development of algal blooms in freshwater systems, spurred by high concentrations of phosphate, is directly linked to dissolved oxygen consumption and surface water eutrophication. Several components of agricultural management have been the focus of nutrient mitigation efforts (e.g., livestock diet, manure treatment, fertilization rates and timing, vegetative buffer strips).

The development of P-efficient cropping systems is another approach to minimizing nutrient losses, and hence reducing fertilizer application requirements. For over two decades scientists and engineers have been developing and testing ways to enhance the utilization of native soil phosphorus by crop plants (Gaxiola et al., 2011; Richardson and Simpson, 2011). This commentary provides an introduction and update on the status of this effort with respect to improving crop phosphorus utilization, a key step in a sustainable approach to phosphorus resource management and water quality protection.

There is quite a lot of phosphorus in soil, but crop plants have difficulty accessing the nutrient (Figure 1). Native soil P includes both inorganic and organic (~20-50%) phosphorus (Turner et al., 2004). P-containing compounds are typically insoluble and, thus, not bioavailable to facilitate plant growth. The bioavailability of orthophosphate and phytate (the two dominant sources of phosphorus in soils) is limited in alkaline soils due to precipitation with metals (e.g., calcium, magnesium) and in acid soils, through sorption to metal-hydroxide minerals (e.g. goethite). The end-goal of any strategy targeting bioavailable P enhancement is the production of orthophosphate. The challenge is to generate and keep that orthophosphate in the root-zone of crop plants (the *rhizosphere*) and not have it migrate offsite to waterways.

Phosphate availability to crop plants can be enhanced through mechanisms that decrease soil pH and/or chelate metal ions (Oburger et al., 2011). Phosphate liberation in the rhizosphere can be achieved by plants alone or in conjunction with their root-associated microbiota, specifically through:

1. pH reduction
2. anion production
3. phytase production (to utilize organic phosphorus).

Crop plants have been genetically engineered to increase phosphate solubility in soils by a) decreasing rhizosphere pH, and b) increasing root exudation of organic anions. Increasing the acidity in the rhizosphere, for example, has been tested in tomatoes expressing mustard H^+-PPase growing under phosphate-deficient conditions. Greater growth (~80%; dry weight) and higher plant P content (~30%) resulted (Gaxiola et al., 2011). In addition to improved P nutrition, plants expressing these H^+-PPases were more salt tolerant and drought resistant, leading to improvements in plant productivity, particularly in nutrient poor and arid agricultural soils. Greater detail on transgenic approaches to rhizosphere acidification can be found in recently published reviews on the topic (Ryan et al., 2011; Gaxiola et al., 2011). Crop plants have also been engineered for greater root exudation of organic anions, primarily, using two transgenic approaches. The first of these approaches targets over-expression of genes that regulate the production of organic acids in the plant cytosol, while the second increases organic acid efflux directly, through increased expression of plasma-membrane transport proteins that facilitate root organic acid export. These transporters were originally expressed in plants (e.g., wheat, tobacco, barley, rice, mustard) to improve Al^{3+}- tolerance via organic anion chelation, but are now also being studied with respect to P utilization efficiency (Ryan et al., 2011).

Rhizosphere microorganisms can also decrease root-zone pH and produce organic acids. There are two primary strategies microorganisms can employ to decrease root zone pH: inorganic and organic acid production. Studies have shown that pH decline alone does not account for the solubilization of precipitated phosphates (e.g., Oburger et al., 2011); hence, the primary research emphasis has focused on organic acid production. Several soil microorganisms have been characterized for their native ability to produce organic acids and improve plant P acquisition (Richardson and Simpson, 2011). Phosphate-solubilizing bacteria (PSB; e.g., *Pseudomonas, Burkholderia, Citrobacter, Erwinia* spp.) produce a variety of organic acids in response to P-limitation (e.g., gluconate, 2-ketogluconate, acetate, pyruvate, citrate, and ascorbate; Buch et al., 2008), and many examples have been published which demonstrate plant growth promotion following the incorporation of PSBs into P-limited plant systems, though examples in soils are limited. For a full review of how soil microorganisms mediate plant access to insoluble phosphate, see Richardson and Simpson (2011).

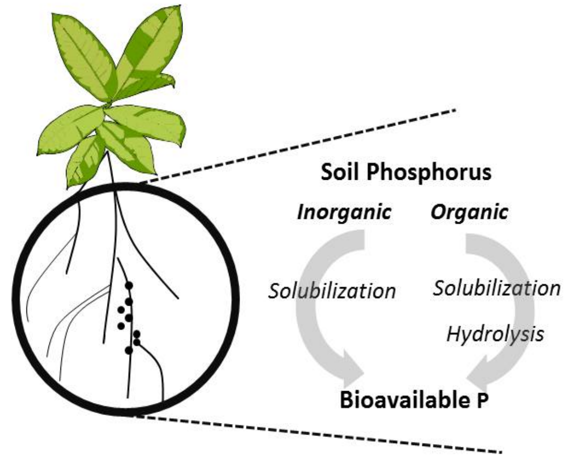

Figure 1: In the rhizosphere, plant access to inorganic phosphorus requires solubilization of phosphates. Organic phosphorus compounds in the rhizosphere, like phytate, require solubilization, as well as a hydrolysis step, to liberate bioavailable P.

Phytate hydrolysis is a necessary step for crop plant utilization of the dominant organic phosphorus compound, phytate (*myo*-inositol hexa*kis*phosphate). Phytate is abundant in soils (~20-80% total organic P) but must be hydrolyzed to orthophosphate by specific phytase enzymes before plant uptake can occur. Phytase activity and solubility is diminished by the presence of soil metals, but can be overcome when chelating organic anions are present in the rhizosphere. Phytase concentrations in plant systems have been augmented by a) increasing the production and extracellular translocation of recombinant phytases in plant roots and b) through rhizosphere inoculation with native or engineered rhizobiota that produce extracellular phytases. Fungal phytase enzymes (e.g. *Aspergillus* spp. *phyA*) expressed in the roots of crop plants such as tobacco (*Nicotiana tabacum*), clover (*Trifolium subterraneum*), and wheat (*Triticum* spp.) have resulted in root phytase activities greater than in the roots of wild-type plants (George et al., 2007). Thus far, genetically engineered plants have shown a greater accumulation of P in plant material than their non-engineered counterparts. Most of the engineered plant systems tested thus far have been in model media and not soils; however, some studies show solid results in soil. For example, tobacco expressing the *A. niger phyA* gene accumulated as much as 52% more P than wild-type plants when grown in phytate-amended top soils (George et al., 2005). Inoculation of the rhizosphere with bacteria overexpressing phytase is also a promising approach (e.g., *Pseudomonas*, *Pantoea*; *appA*, *Citrobacter* sp.; Patel et al., 2010). However, whether plants or the microbiota are targeted for phytase production, without employing processes to improve phytate solubility and phytase activity, many of these plant- and microbe-focused studies show little impact on plant growth in metal and mineral-rich soil environments (Lung and Lim, 2006).

While there are more strategies to employ to manage phosphorus on agricultural land, there is an elegant synergy in the sustainable approach outlined here. Holistic research objectives now employ strategies that simultaneously address pH, organic anion, and phytase considerations, leading to a local liberation of phosphate right where plants need it, and in doing so, limiting the migration of labile phosphate offsite. More field trials are needed to show the broader utility of this approach. An added benefit is that the traditional agriculture versus water quality tension within communities might decline with this sustainable, targeted approach to phosphorus management.

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