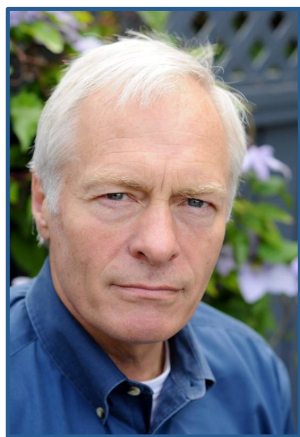


From the Section President

Dennis P. Lettenmaier (University of Washington)

I'd like to open by congratulating the Fellows Class of 2011 who are affiliated with the Section. These include Mary Jo Baedeker (U.S. Geological Survey), Mark Brusseu (University of Arizona), Ed Cook (Lamont-Doherty Earth Observatory), Giuseppe Gambolati (University of Padova), John Melack (University of California, Santa Barbara), and Jeff Richey (University of Washington). You'll



find articles in *The Fellows Speak* section of this issue by Cook, Melack, and Richey, and I'm sure you'll find their perspectives intriguing. Articles by Baedeker, Brusseu, and Gambolati will appear in the December issue. Thanks are due to all of those who wrote nominating or supporting letters last year, and I encourage

you to participate in this year's process. The deadline for nominations for the Class of 2012 will rapidly be upon us (July 15). If you are thinking of making a Fellows nomination, I'm sure that you'll find the article in this issue by Andrew Barry and Eric Wood insightful and useful.

I also want to congratulate the recipients of Outstanding Student Paper Awards (OSPA) from the Fall 2010 Annual Meeting (FM10). The 30 award recipients were selected from well over 500 student oral and poster presentations at FM10. A great deal of credit goes to our Section Secretary,

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Martha Conklin, who has helped to reform the Union's judging process for these presentations. Martha and AGU staff have designed and implemented a process that is now standard across the Union, initial aspects of which were in place for FM10. These new procedures have helped to increase greatly the number of student presentations that are judged. Those of you who have submitted proposals for sessions at this year's Fall Meeting (FM11) may have noticed one aspect of the new procedures that Martha has helped to set in motion – convenors are now required to designate a judges' liaison, who will have overall responsibility for assuring that student presentations in their session are judged. We expect that this will help to increase further the number of judged student presentations.

Speaking of FM11 -- Most of you are probably aware that the deadline for abstract submissions has been moved forward to August 4 (2400 GMT, to be

specific; see the AGU web site for details). This change has had a number of ripple effects. Among these are that there is a tight window, immediately following the abstract submission deadline, during which the Section's Fall Meeting Committee (chaired by Matt Rodell, assisted by Mike Cosh and Stefan Kollet) has to organize the program. The problem they face is that the number of hydrology session proposals has exploded over the last few years – from 94 in 2009 to 111 last year to 137 this year! Matt and his committee have already reduced the number from 137 to 115 by “encouraging” aggregation of similar sessions. However, during the period August 6-10, they'll be required to further reduce the number from 115 to (probably) around 80. The exact number is dictated by the number of poster-only sessions and the availability of rooms for oral sessions, and is complicated by joint sessions, but it's been capped at about the same number for at least the last three years. For comparison purposes, at FM10 there were 62 sessions that used the 86 quarter-day oral time slots (some had two or three). What this means is that Matt and his team will be faced with consolidating sessions, probably reducing the number by at least 30-40 (depending on the number of poster-only sessions) over the period August 6-10 (note that this includes a weekend). Those of you who are convening sessions should have already been notified that either you, or a designee, will need to be available by phone during the period August 6-10. Please keep in mind that it is a huge job that Matt, Mike, and Stefan face, and there simply won't be time for negotiation with all 115 convenors. Please recognize the constraints, and do your best to work within them. For instance, it may be possible to sequence talks in combined sessions with similar, but not identical topics, in such a way that there's a

progression of subtopics throughout the session. In your discussions, please try to extrapolate whatever complications you face with your session by a factor of 100+, and ask yourself whether “special handling” is really feasible. I'm sure that the FM11 program will be the best ever, but we do need to work together to make it happen.

Finally, I want to note the formation of two new technical committees. The Soil Systems and Critical Zone Processes Committee is joint between the Biogeosciences and Hydrology Sections, and is co-chaired by Dani Or (ETH Zurich) and Yakov Pachepsky (USDA/ARS). They will hold their first meeting at FM11, and like all Hydrology technical committee meetings, theirs will be open to all. The Water and Society technical committee is joint with the Societal Impacts and Policy Sciences Focus Group. The chair is Casey Brown (University of Massachusetts), with a co-chair to be named. Casey's article in this issue describes some of the underlying issues that motivate formation of this committee, which will also meet for the first time at FM11.

In concluding, I want to thank all of you who participated in the guided group discussions at FM10 and who participated in the member survey. Those activities have provided critical input to AGU's ongoing Mission Alignment Project (see my article in the December 2010 issue), results of which will be known later this year. The guided group discussion and survey results (to be released soon) clearly show that hydrologists were well represented, which is certainly in our best interests.

I wish all of you the best for the summer. I hope that you will be able to clear away the administrative clutter that seems to engulf us during the rest of the year, and think science!

From the Water Resources Research Editor-in-Chief

Praveen Kumar (University of Illinois)

Water Resources Research is the premier journal in hydrology because of the time and commitment of the reviewers who not only provide detailed and thoughtful comments to the authors but also share insights that spawn new ideas. They serve dual roles in both evaluating the manuscripts entrusted to them



and in promoting the journal. We are thankful to the entire community for this valuable contribution in the service of science. During the past couple of years the reviewing community has also responded to our request to reduce the

turnaround time, and we have made considerable progress in this respect. For 2011, the average time from submission to first decision was about 60 days. We urge the community to continue its support for WRR by accepting the requests for review and submitting high quality reviews in a timely fashion. Increasingly, rapid turnaround is a key consideration for authors in choosing an outlet for their work and is essential to the competitiveness of the journal.

Although fast turnaround is often viewed as a review issue, authors can play an important role as well by ensuring that all submissions are well prepared, and are not submitted with the notion of “let’s see what the reviewers say.” Well-prepared submissions are concise yet comprehensive. Their language has been edited for grammar and readability (for a list of language editing services see <http://www.agu.org/pubs/authors>). The problem addressed by the paper and its goals are clearly stated in the context of existing literature, particularly taking recent publications into account. The results and analyses are complete and support the conclusions; the illustrations are well prepared; and the bibliography is accurate. The paper is written so as to draw out the novel and significant

elements and highlights the broader implications of the research findings. Improving the readability and comprehensibility makes reading the manuscript enjoyable for the reviewers and motivates them to provide constructive and timely comments. We all know the impression we get from a first scan of a paper we’ve been sent to review – if it’s “this looks interesting”, we’re more likely to put it at the top of our to-do list.

A few factoids about WRR: Did you know that:

- WRR is now accepting submissions for journal cover images. Cover images can be figures from a paper published in that issue, or images or photographs from research related to the paper. They should be in color and have a resolution of at least 300 dpi. If you would like to submit an image for consideration, please send it along with a short caption to wrr@agu.org. We expect the cover to go through a significant redesign next year to be more attractive.
- Over 5000 people subscribe to e-alerts, an e-mail service that delivers a list of articles published in the past 7 days. This is an excellent way to keep abreast with the research findings, and frame the novelty, uniqueness, and significance of the research contribution for your next submission in light of the recent literature. It is also an excellent way for the students to take advantage of rapidly evolving research ideas. You can sign up at http://www.agu.org/e_alert.
- WRR identified about 25 ‘featured articles’ in 2009. These were highlighted in the Research Spotlight published by Eos to reach a broad audience thereby providing a wider dissemination of ideas. For a link to all of the WRR papers that have appeared in the Research Spotlight, see <http://www.agu.org/journals/wr/featured.shtml>.
- AGU’s GeoSpace Blog features newsworthy WRR articles among others. Check out <http://blogs.agu.org/geospace>.

Please feel free to drop me a note with constructive suggestions and ideas. It is in all of our interests to ensure that WRR remains the

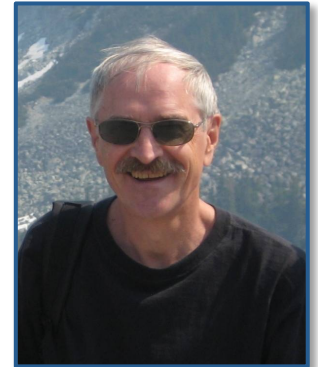
premier journal in the field and a pride of the community.

How to assemble a compelling Fellows nomination package

*D. Andrew Barry (EPFL Lausanne)
Eric F. Wood (Princeton University)*

Editor's note: Fellowship is awarded each year to not more than 0.1 percent of the Union membership, for "acknowledged eminence in the geophysical sciences". The selection process consists of two steps. A Section committee, chaired by the President-Elect, screens nominations, which are ranked and forwarded to the Union Fellows Committee, which considers all nominations and makes the final selections. The first author serves on the Union Fellows Committee, the second author chairs the Section Fellows Committee, and has also served on, and chaired, the Union committee. In this article, they reflect on the key elements of successful nominations packages.

Each year the Section receives 20 to 30 nominations for evaluation by the Section's Fellows Committee. A sub-set is forwarded to the Union Fellows Committee, which makes final decisions. The number that goes forward is determined by a formula based on the number of section members. The total number of new fellows is restricted by AGU bylaws to 0.1% of the membership, and the total number that goes forward from the Section is about 0.2% of Section membership -- thus, on average, about half of the nominations that go forward are successful (in fact, the actual situation is somewhat more complicated as the nomination process allows for designation of more than one section or focus group to review an application). From these numbers, it is clear that election to Fellow (at present about 60 per year across the Union) is a significant honor, the selection criteria for which are the most stringent of all major scientific societies. We are often asked: "What does it take to put together a compelling nomination



package?" In this article, we offer our insights, based on our combined experience on both the Section and Union committees.

The Fellow's package is based on the nominee's 2-page CV and publication summary. Then, the first major supporting element of a nomination package is the nomination letter. The starting point needs to be evidence in the nominee's record that his or her scientific contributions are among the top 1-2% (integrating 0.1 percent per year) of the field. Given that nominations must be evaluated across all areas of Earth and Space sciences (which is reflected in the membership of the Union Fellows Committee), it is hardly surprising that an individual's eminence in one branch of the earth sciences might not be readily apparent outside that branch, and this is, in fact, the challenge that faces the Union (and to a lesser extent the Section) committee in its task of electing new fellows. So, how can a nominator prepare a package that will make a compelling argument given this backdrop?

The key phrases that a nomination must address are "acknowledged eminence" (from the Union Bylaws) and "major breakthrough/discovery and paradigm shift" (from the AGU web site, under Fellows selection). Although "breakthrough/discovery" is difficult in hydrology (arguably, progress in hydrologic science is more a result of sustained contributions that collectively results in better understanding of how very complicated systems function), "paradigm shift", or evidence of how thinking in an area of science has

changed as a result of the nominee's contributions, can and should be targeted. Just how the nominee has had that impact is what must be the key element of the nomination, and the nomination letter in particular. The nomination letter must provide a digestible (not easy in some scientific specialties!) overview of the context for the nominee's achievements, explain the major contributions, and identify the implications for his/her sub-discipline. Successful nominees in hydrology typically have sustained contributions throughout their professional careers, not a singular breakthrough, and the nature and extent of those should be part of the nomination (on the other hand, where there are specific papers that have had singular impacts, those should be highlighted). Nominations that rely mainly on recent scientific breakthroughs, for which the ramifications are not yet apparent, are less likely to succeed. Use of jargon should be limited in order to convey clearly the contribution to the diverse scientific backgrounds represented on the Union Fellows Committee.

The second major supporting element is the set of (preferably) five supporting letters. Strong packages include well-written, insightful letters by leaders in the field. Regardless of their own eminence, writers must avoid short, clichéd letters containing unsupported statements, which tend to be dismissed. Supporting letters should not just repeat the nomination material. Rather, the letters should support and elaborate the research contributions and impacts identified in the nomination letter. Their role is to provide deeper insights into specific contributions and their impact on the discipline. Supporting letter writers who can write knowledgeably about the nominee's contributions and their impacts are critical to the success of the case. It is useful for supporting letter writers to have in hand at least a draft of the nomination letter. Letter writers who are AGU Fellows should so indicate that under their signature. Nominations are required to include the individual's citation index (often referred to as the *h*-index), usually at the top of the 2-page summary bibliography. In addition to the *h*-index, the nomination can draw attention to well cited papers as a means to demonstrate the impact of the nominee's work. Extreme cases, such as ISI

"Highly Cited", should be highlighted. Major awards from other societies or winning other major research awards benefit the nomination. In disciplines where large research groups are the norm, the scientific contributions of the individual should be identifiable, or identified. While statistics, such as the *h*-index, are considered by both the Section and Union Committees, the reliance on these statistics has diminished in recent years with the recognition that citation patterns vary strongly across disciplines and suitable normalizations are not commonly agreed. Hence, where these statistics provide strong support for a case, they should be emphasized, and where not, other evidence of eminence should be stressed.

AGU Fellows are not elected primarily for service, leadership, mentoring or similar activities, important and beneficial as they are to scientific progress. Nonetheless, such information can and should be included (albeit briefly) as it underlines the nominee's contributions and supports one of the AGU's core values of "unselfish cooperation in research."

Hydrology is a discipline with a rich history of incorporating disparate theories, methods and techniques from other disciplines and using these to gain new hydrological insights. Despite the significant achievement involved in successfully "translating" (for want of a better word) mathematical tools, experimental methods, etc. from another field, that *per se* is usually insufficient to gain fellowship. Instead, the nomination should expound upon the new insights and impact on the field of hydrology that the nominee developed in his or her research.

In summary, a strong nomination should address each of these elements:

- Provide cogent statements into the nominee's novel/insightful/creative contributions with an emphasis on resulting paradigm shift, avoiding (particularly in the nomination letter) the use of jargon in so doing;
- Concentrate on the scientific contributions in the body of the letters (avoid listing major grants, and leave service, leadership and/or mentoring to short statements near the end);

- Enunciate the impact of the nominee's work on the field, including highly cited papers where the nominee had a key role;
- Where there could be questions (i.e., in large research groups, or where many papers are co-authored with exceptionally well-known scientists), identify the nominee's contribution;
- Mention major awards from other societies;
- Ensure that supporting letters expand on and clarify the nominee's contributions and impacts as identified in the nominating letter.

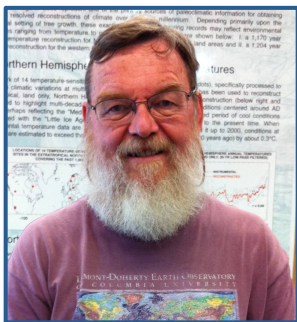
It is clear that a successful nomination requires time and effort, so starting early helps. Historically,

the Hydrology Section has been very successful in facilitating the selection as Fellows of our members who have made significant contributions to the field. We are grateful to the nominators and supporters for the effort they have made in assembling Fellows nominations, and we are proud of those who have been elected. We hope that this article has helped clarify the process, and motivates the nomination of worthy candidates. Please feel free to contact either one of us (Andrew Barry: andrew.barry@epfl.ch or Eric Wood: efwood@princeton.edu) if you have questions. The nomination deadline for 2012 Fellows is July 15, 2011; detailed information is available on the AGU web site.

The Fellows Speak: The role of paleo-drought atlases in modeling the causes of hydroclimatic variability

Edward R. Cook (Lamont-Doherty Earth Observatory of Columbia University)

Climate model projections of future hydroclimatic change associated with increasing atmospheric greenhouse gas concentrations are sobering and, depending on where you live, even alarming. For example, southwestern North America is projected to enter into a long-term



drying trend in the subtropics to mid-latitudes, and this trend in increasing aridity may have already begun (Seager et al., 2007a). Independent of whether or not the projected radiatively forced drying is already happening,

there is abundant evidence now for the occurrence of past 'megadroughts' in various regions of North America that dwarf any periods of drought seen in the instrumental climate record over the past century. The occurrence of unprecedented past

megadroughts harkens back to the discovery of the "Great Drouth" from AD 1276 to 1299 that was famously documented in 1929 by A. E. Douglass when he developed the first archaeological tree-ring chronology for Chaco Canyon, Mesa Verde, and other major prehistoric occupations across the Colorado Plateau. More recent papers by Stine (1994) and Woodhouse and Overpeck (1998) have also documented the occurrence of other megadroughts scattered across the western and central United States. A detailed spatio-temporal history of past megadroughts over the past millennium was not fully realized, however, until the development of the North American Drought Atlas (NADA; Cook et al., 2004).

The NADA is a 286-point grid of Palmer Drought Severity Index (PDSI) reconstructions from a large network of centuries-to-millennia long annual tree-ring chronologies distributed across much of North America (Fig. 1). It provides, for the first time, an annually resolved record of past drought in full spatio-temporal detail that extends in some regions back through medieval times over 1,000 years ago. In so doing, the NADA has revealed an exceptional period of elevated aridity in western North America during medieval and into post-medieval times that lasted several decades to a century or more depending on the location. Given that these megadroughts all occurred well before any meaningful buildup of greenhouse gas

concentrations in the atmosphere, they show how extreme natural hydroclimatic variability can be even in the absence of anthropogenic forcing. The causes of this natural variability and the degree to which it might occur in the future in combination with greenhouse gas forcing are critical scientific questions.

To answer these questions, we must rely on climate models that accurately reflect the underlying forced and unforced variability of the coupled ocean-atmosphere climate system. This is where paleo-drought atlases make an especially valuable contribution to global climate change research because they provide the target fields 1) for testing the degree to which climate models can faithfully reproduce hydroclimatic variability of the recent past (e.g., Seager et al., 2005) and 2) for testing hypothesized causes of past megadroughts (e.g., Seager et al., 2007b). The results of this research have clearly demonstrated the importance of tropical Pacific sea surface temperatures (SSTs) in influencing hydroclimatic variability over large parts of North America (Seager et al., 2005). Thus, when eastern equatorial Pacific SSTs are in a cool (La Niña-like) state, conditions over western North America tend to be drier than average. This is not the whole story, however, because other oceans have at times undoubtedly contributed to large-scale drought conditions over North America as well (e.g., Kushnir et al., 2010). What still remains to be fully explained is what caused these extraordinary medieval megadroughts in North America to last so long. SST forcing appears to have played a major role (e.g., Seager et al., 2007b), but how those and other drought-inducing forcings persisted for so long is still an unresolved scientific question.

One way to improve our understanding of the causes of past megadroughts is through the development of more paleo-drought atlases elsewhere in the world. Doing so would allow much larger-scale climate analyses to be conducted, which should lead to additional hypothesis testing and resulting deeper insights into the causes of past megadroughts. A recently developed paleo-drought atlas for Asian monsoon regions, the Monsoon Asia



Figure 1: Paleo-drought atlases from long tree-ring records developed to date (NADA and MADA) and under construction (OWDA). The borders of the atlases are approximate. For more details on the NADA and MADA, see Cook et al. (2004, 2010).

Drought Atlas (MADA; Cook et al., 2010) is a step in that direction.

The MADA is a grid of 534 PDSI reconstructions over southern Asia developed from long tree-ring records (Fig. 1). It was developed in the same way as the NADA to provide a much needed long-term understanding of Asian monsoon variability and change over the past millennium. The results obtained from the MADA include the discovery of several pre-20th century megadroughts in full spatial detail (Cook et al., 2010). Two of these megadroughts occurred in the 12th and 13th centuries and are associated with the demise of the Khmer civilization at Angkor in present-day Cambodia (Buckley et al., 2010). Others are associated with the fall of the Ming Dynasty in the 17th century and a recently documented mid-18th century period of large-scale cultural upheaval in Asia.

A reduced-space analysis of the MADA back to AD 1300 also supports the long-term importance of tropical Pacific SSTs in influencing the development of drought and wetness over southern Asia (Cook et al., 2010). Thus, the MADA and NADA are linked by a common climatic bridge - tropical Pacific SSTs - but in the opposite way. Cool (warm) SSTs lead to drier (wetter) conditions in western North America and wetter (drier) conditions in southern Asia. This provides a unique opportunity to examine how drought and wetness forced by SSTs co-vary over the past millennium between two completely independent regions separated at synoptic scales. Detailed analyses are still in progress, but comparisons of the NADA and MADA for two exceptional El Niño events (1876-

78 and 1918-19) indicate that the patterns of drought and wetness over Asia and North America vary in both expected and unexpected ways (Cook et al., 2010). Thus, when used jointly the NADA and MADA will provide a new set of target fields for testing climate models and hypotheses of forcing and change.

The teleconnection between tropical Pacific SSTs and hydroclimatic variability over the MADA domain has also allowed for testing the impact of explosive volcanism on the Asian monsoon because climate model experiments commonly indicate that the radiative impact of explosive volcanism in the tropics should lead to the development of warm (El Niño-like) SSTs in the eastern tropical Pacific. This state should result in a weaker monsoon and the development of drier conditions over southern Asia (e.g., Schneider et al. 2009), and the MADA should reflect this condition if true. Yet, when Anchukaitis et al. (2010) compared composited patterns of reconstructed PDSI from the MADA against composited moisture patterns produced by climate models using the same published lists of volcanic eruption years, they found just the opposite. Explosive volcanism resulted in wetter-than-average conditions over southern Asia. While the cause for this stark difference between data and models is not yet well understood, it is highly likely that the results from the MADA are correct because the trees were there to experience what actually happened.

The research value of paleo-drought atlases is well established now and will undoubtedly grow as their geographic coverage increases. An Old World Drought Atlas (OWDA; Fig. 1) is now under development. It will cover another large area of the Northern Hemisphere and allow for more detailed comparisons of long-term hydroclimatic variability at synoptic scales. The ultimate goal is near-complete drought atlas coverage of Northern Hemisphere land areas for full synoptic scale analyses and the development of Southern

Hemisphere drought atlases based on identical techniques to ensure comparability.

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The Fellows Speak: The River-to-Ocean Continuum

Jeffrey E. Richey (University of Washington)

Near and dear to the heart of hydrologists is understanding how water moves across the landscape. And, for some hydrologists, who incorporate biogeochemistry into their work, understanding how that water mobilizes and transports dissolved and particulate materials from



the landscape to the sea is an additional – if complex – motivation. While water availability is clearly a crucial determinant of terrestrial primary production, the immediate role of freshwaters in broader biogeochemical cycles has been considered to be

relatively minor. The classic perspective is that the role of freshwaters is defined as the global export of riverine organic matter to the world's oceans, where long-term preservation of this terrestrially derived organic matter occurs largely from sediments that accumulate along continental margins. But, as summarized by Melack (2011), lakes and rivers appear to play a much broader role than historically thought. Through outgassing to the atmosphere (freshwaters are frequently supersaturated in CO₂ and CH₄) and burial of carbon in lake and reservoir sediments, freshwater systems are not passive conduits but rather dynamic process-rich systems that themselves influence global geochemical balances in both ocean and atmospheric environments.

In the spirit of following water downstream, I will extend the Melack thesis from lakes and rivers to the lower reaches of large rivers, and to their potential direct influences in the ocean. I will emphasize tropical systems, given their high discharge and sediment loads. As with many of the simplifying calculations made in global budgets, broad-brush portrayals of the export of organic carbon from rivers to the sea as “0.5 to 1.0 Gt/y”

(Degens et al., 1991, as an early example) do not accurately represent the dynamics of the underlying processes, especially with respect to the coupling of hydrologic and biogeochemical cycles.

Most, if not all, characterizations of the mass flux of material from rivers have been performed at the downstream-most gauging station on that river. Such stations are typically located a considerable distance from the actual confluence of the river with the sea, at a convenient site for gauging, usually above tidal influences. Just outside the mouth, in the “river impacted ocean margin” (McKee et al., 2004), the river continuum transforms. Typically the river slows, deposits a great deal of sediment, and then the water is clear enough for primary production to dominate over respiration in the surface layer. Scientists (and their funding agencies) have mostly ignored this critical transition region, creating a severe gap in our knowledge of material transfer on Earth.

In the case of the Amazon River, for example, the defining gauge is located at Óbidos, some 900 km from the sea. In the reach below Óbidos, three major tributaries (Tapajós, Xingú, and Tocantins/Araguaia), plus many smaller tributaries and local flood plain drainages, add ~40,000 m³/s, or an additional 20% to the river's total annual discharge (about two Mississippi Rivers' worth). It takes ~7 transit days from Óbidos before the Amazon meets the sea. These tributaries all have large, estuarine-like “mouthbays,” which modify upstream chemical signals and yield water with high primary production. It is a region of extensive varzéas (floodplain lakes), with high production, and high rates of outgassing of CO₂ and CH₄. Hence these additional waters have very different chemical and biological signatures from the sediment-rich main stem, likely with the potential to alter the metabolism of the waters flowing to the sea. To make life even more complicated, the primary discharge of the Amazon is to the north of Marajó Island, but the water discharged to the south of it is likely constituted primarily of water from the Tocantins and the Xingú, such that the actual marine delivery from the southern arm of the Amazon will be quite different from the northern branch, with unknown consequences for the sea.

Further, the physical dynamics of the lower river are extremely complex. A comparison of fluxes between Óbidos and offshore sediment accumulation by Nittrouer et al. (1995) suggested that roughly a third of the sediment from upstream is captured somewhere in the tidal river. The recent development of acoustic measurement techniques (ADCP) that permit rapid discharge measurements provides insights into the dynamics of these lower reaches (by making continuous cross-channel transects for 13 hours covering the tidal cycle). Tides induce significant, local semi-diurnal discharge fluctuations. Kosuth et al. (2009) reported differences of 30,000 m³/s to 130,000 m³/s at Almeirim (nearly 500 km upstream) and tidal wave propagation as far as Óbidos, during a low water period. Large flow reversals are observed closer to the sea (M.S. da Silva, pers. comm). Such extreme fluctuations will clearly have a large impact on any attempts to measure material flux.

The next part of the River-Ocean Continuum occurs in the river plume itself. The Amazon River generates an offshore plume (Fig. 1) that covers ~2 million km² (about a third the area of the entire Amazon basin) of the western tropical North Atlantic Ocean (WTNA) each summer with a thin (5–10 m) layer of low-inorganic-carbon, and low-salinity (mesohaline) water (Cooley et al., 2007). The tropical North Atlantic Ocean is generally considered a net source of ~30 Tg Cy⁻¹ to the atmosphere (Takahashi et al., 2002). But the results from more recent direct measurements (Subramaniam et al., 2008) indicated a biologically

mediated C sink of about 15 Tg/y in the mesohaline region. They believe this resulted from excess riverine phosphorus (P), silica (Si), and iron (Fe) input and N₂-fixation within the Amazon plume (by diatom-diazotroph symbiotic associations, DDAs). Combined with a sink of about 8 Tg/y in the inner plume, from direct river N, new production in the plume driven by river nutrients, appears to reverse the normal tropical surface ocean condition and leads to CO₂ uptake and sequestration in areas that would otherwise be outgassing. But the calculation of the plume drawdown is dependent on an accurate knowledge of the river end member's total alkalinity and dissolved inorganic carbon (DIC), but these are currently poorly quantified (Cooley et al., 2007).

To put these values into perspective, Richey et al. (1990) reported that the annual flux of total organic carbon at Óbidos was 36 Tg/y (*cf.* to direct outgassing to the atmosphere from the river system of about 500 Tg/y; Richey et al., 2002). That is, the river export of organic carbon to the sea is roughly equivalent to the river-supported new production in the plume. Therefore, inclusion of the terrestrial-driven marine fixation would essentially double the “effective” impact of the river on the plume. It could be argued that the carbon budget of the Amazon should be extended to include the oceanic component.

How relevant are these results to other large tropical rivers? Sediment trapping has been observed in, for example, the Ganges-Brahmaputra, by Goodbred and Kuehl (1999). Although the Amazon represents the largest riverine input to the tropical ocean, there are numerous other tropical rivers that deliver large volumes of water with “excess” P and Si, with the presence of DDAs and other N₂-fixing symbionts, (Subramaniam et al., 2008). Hence carbon sequestration by DDAs associated with excess nutrients supplied by tropical river plumes may be a globally significant phenomenon, and tropical mesohaline waters are a potentially important interface between terrestrial and oceanic realms.

A discussion of this type would not be complete without consideration of how the

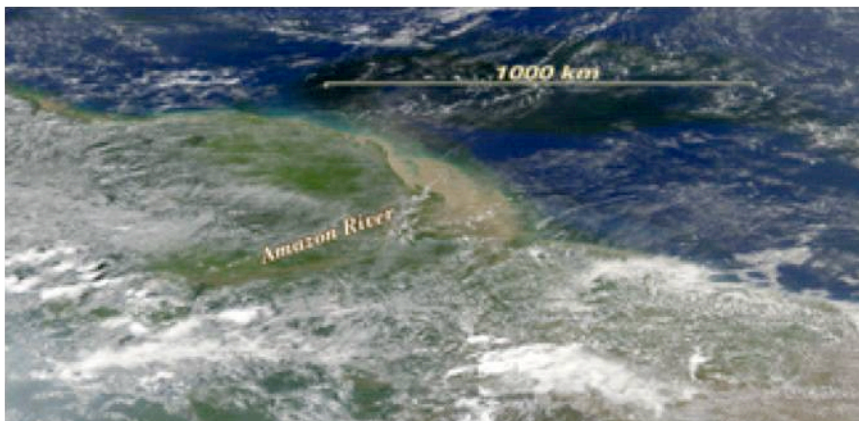


Figure 1: True-color image of the Amazon River sediment outflow (light brown), and the formation of the Amazon plume (dark green) into the Atlantic Ocean (modified from Subramaniam et al., 2008).

tropical river-ocean continuum will fare in the Anthropocene (*sensu* Syvitski and Kettner, 2011). The impact of dams is well-documented in global riverine literature, but many of the high-sediment rivers of the tropics have escaped damming in the past. But there is currently a “hydropower renaissance” in the world. Emerging global dynamics (developing regions, re-visiting carbon- and nuclear based energy) are contributing to an expansion, or desire for expansion of hydropower. This is especially true in the tropics. New dams are under development in the Amazon (on the Madeira and Xingú Rivers, with others planned). A series of dams is being planned for the lower Mekong, including in Cambodia, as well as multiple dams on tributaries in Laos (Grumbine and Xu, 2011). The obvious question is: what will the effect of these new dams be on the river-ocean continuum in these regions? Not to mention on riverine ecosystems and the human ecosystems that depend on the rivers for food, potable water, waste disposal and transportation? Adding to the dam considerations are changes in flow regimes from land use and climate change.

In summary, a more thorough consideration of the river-ocean continuum poses a series of interesting, and important, questions.

- What is the interplay of hydrodynamics and biogeochemistry in lower river basins (below the “last” gauge), and how does that interplay impact the actual delivery of dissolved and particulate materials to the sea and to the atmosphere?
- How much does river-supplied P, Fe, and Si (either dissolved or particulate) fuel a significant plume CO₂ drawdown by diazotrophs offshore, and how universal is this phenomenon?
- How will new dams and shifts in temperature, precipitation, and land use alter biogeochemical cycling across the river-ocean continuum?
- And what are the economic, ecological and climatic impacts of these phenomenon?

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The Fellows Speak: Inland waters and the carbon cycle in a global perspective

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Over the last decade the roles of inland waters in continental and global scale carbon fluxes has become recognized as more significant than previously thought, based on new measurements and synthetic analyses complemented by applications of remote sensing. As these efforts have combined information about lakes, reservoirs, rivers, streams and wetlands, the high rates of biogeochemical processes common in inland waters in conjunction with greater areal coverage than earlier estimates have increased their importance relative to oceans and land. In parallel with these results, a field of global limnology is emerging (Downing, 2009).

Historically, limnologists have tended to focus on individual lakes, streams or wetlands or groups of neighboring waters. Beginning in the 1970s and 1980s, as part of evaluations of impacts of nutrient inputs and of acidic atmospheric deposition, national surveys in Europe and North America began to provide comprehensive regional data. With the availability of remotely sensed imagery in the last couple of decades, regional analyses in much of the world have become feasible. Remote sensing techniques applicable to examination of inland waters include synthetic aperture radars, radar altimeters, visible, infrared, thermal and microwave radiometers, and, more recently, gravity anomaly detection systems and lidars (Melack, 2004).

As an outgrowth of a working group on the integration of the terrestrial and aquatic carbon cycles at the National Center for Ecological Analysis and Synthesis, a Chapman Conference ‘Lakes and Reservoirs as Sentinels, Integrators, and

Regulators of Climate Change’, and various publications, the global significance of inland waters has become increasingly apparent. We now have mounting evidence that the flux of carbon delivered by rivers to oceans is only a fraction of that entering inland waters from the atmosphere and land, and that most carbon the moves in rivers ultimately outgases as carbon dioxide or is stored in sediments of lakes, wetlands, and reservoirs (Cole et al., 2007; Tranvik et al., 2009; Aufdenkampe et al., 2011). Nonetheless, assessments of the global carbon cycle and its climatic implications seldom explicitly incorporate the roles of inland waters other than as fluvial transport pathways from land to oceans.

Inland waters are generally supersaturated in carbon dioxide and receive subsidies of organic and inorganic carbon from their watersheds. As a result, inland waters can be both net emitters of carbon to the atmosphere and net sinks of carbon in their sediments. Furthermore, the evasion of carbon dioxide and much of the bicarbonate transported in rivers could be considered a component of terrestrial respiration not measured on land. It therefore may lead to an overestimate of terrestrial net ecosystem production by approaches that do not consider lateral transport.

Tranvik et al.’s revision of Cole et al.’s ‘active pipe’ hypothesis for transport and processing of carbon through river systems estimates that annually 2.9 Pg C enters inland waters (not including wetlands) from land, of which, 0.6 Pg C sediments in them, 1.4 Pg C vents to the atmosphere, and 0.9 Pg C passes to oceans (Figure 1). These estimates derive from recent upward revisions of the areal extent of lakes and reservoirs and the significance of the small, but very numerous, water bodies. Downing et al. (2006) calculated that there are 304 million natural lakes covering 4.2 million km², nearly twice previous estimates, and when combined with constructed water bodies, this estimate results in global coverage of about 3% of the land area. If the areas of wetlands, rivers and streams, which often vary considerably in area and are less well inventoried than lakes and reservoirs, are included, the area of inland waters reaches up to 15% of the global land area, excluding Antarctica and Greenland.

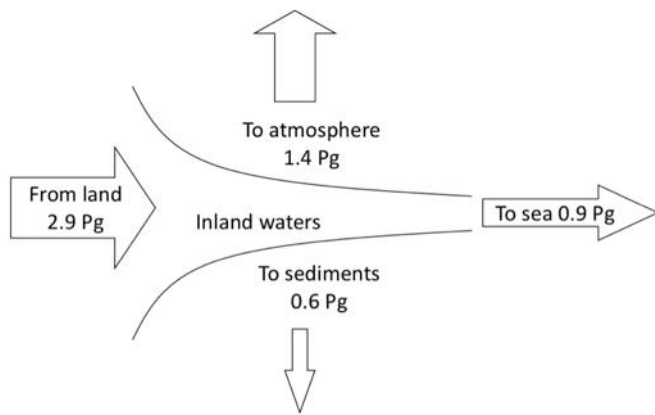


Figure 1: Revision by Tranvik et al. (2009) of ‘active pipe’ model proposed by Cole et al. (2007). Values are Pg carbon per year. Copyright (2009) by the American Society of Limnology and Oceanography, Inc.; reprinted by permission.

As important, and perhaps more surprising than the large amount of evasion of carbon dioxide, is the amount of carbon deposited in lake and reservoir sediments. Recent extrapolations by Downing et al. (2008) suggest that impoundments may sequester four times as much carbon as is buried in the ocean and that farm ponds alone may bury more organic carbon than the oceans. These rates reflect the very high rates of burial calculated for farm ponds and the large number of these small impoundments. Furthermore, construction of these ponds continues, and, when combined with planned additions of larger reservoirs, is projected to about double the area of impounded waters in the next few decades. These actions will further increase burial of carbon derived from erosion and organic carbon photosynthetically produced in inland waters as well as lengthening the residence time of runoff on the continents and providing more opportunity for biogeochemical processing of the carbon.

Within the humid tropics, high rates of productivity and extensive inland waters indicate that this region is of particular interest, yet is not well understood. Studies in the Amazon basin have benefitted from coordinated, international efforts, such as the Large-scale Biosphere-Atmosphere experiment in Amazonia, and provide the most complete information for the humid tropics. Floodplains and associated lakes and wetlands are the dominant aquatic habitat in the Amazon and are important on other tropical continents. Deciphering

the complex interactions among the hydrology, ecology and biogeochemistry of these systems has benefitted from intensive studies and extensive surveys and remote sensing (Melack et al., 2009). Evasion of CO₂ from rivers and wetlands of the Amazon basin is of similar magnitude to net uptake by the forest and is an order of magnitude greater than fluvial export of organic carbon (Richey et al., 2002); the greenhouse warming potential of the methane emitted is about 40% that of the carbon dioxide (Melack et al., 2004). As hydroelectric reservoirs are built and flood tropical forests in the Amazon and elsewhere, methane produced in the organic-rich anoxic environments created can be released as the water exits the turbines and as bubbles in the reservoir and therefore avoid oxidation. The likelihood of a growing number of tropical impoundments suggests that this source will increase.

Overall, it appears that inland waters emit about as much carbon dioxide globally as is taken up by the oceans and bury more organic carbon than the oceans. As construction of impoundments leads to additional carbon sequestration and possibly enhanced release of methane, at least in tropical regions, the role of inland waters in the global carbon cycle is likely to be augmented. Regional variations in water balances, as the climate changes, are likely to increase or decrease the extent of lakes and wetlands with ramifications for carbon cycling. In any case, given that inland waters are disproportionately biogeochemically active relative to their area, inland waters have an important role in global carbon dynamics.

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River restoration: Evolution and perspectives

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“Rivers are perhaps the most impacted ecosystem on the planet as they have been the focus for human settlement, and are heavily exploited for water supply, irrigation, electricity generation and waste disposal” (Malmqvist and Rundle, 2002, pg.134). Constanza et al. (1997) assessed the annual value of river and lake ecosystem services and estuarine systems (usually fed by rivers) at \$9 trillion, 27 percent of the \$33 trillion estimated for all global ecosystem services (in 1994 USD). At the time, the global gross national product was around \$18 trillion. Notwithstanding questions as to the basis for such estimates, it is clear that the value we derive from riverine ecosystem services is profound. Rivers are linear in dimension, but their functions can be viewed as a continuum of fluid flow, energy and sediment transport and biological adaptation (Vannote et al., 1980). Human activities such as flow control, levee-building, withdrawals, and channel modifications disrupt the energy and biological continuum and reduce the natural variability of river flow. The consequences of such disruptions come in the form of severely degraded ecosystems, plummeting biodiversity, unhealthy water quality and sometimes the complete cessation

of flow. Over the last two decades or so, a movement to return rivers to a healthy state has developed into an entirely new field: river restoration. The purpose of this article is to offer a brief overview of the field, an understanding of the inherent complexities, and suggestions from some experts as to what the future holds.

Possibly the one human activity that has had the most devastating and far reaching impact on river ecosystems is dam construction. There are estimated to be more than 45,000 large dams (>15 meters in height) globally with a combined storage capacity in excess of 6,500 km³ or about 15% of estimated global annual freshwater discharge to the oceans (Nilsson et al., 2005). There is no global figure for the number of existing smaller dams and reservoirs, but extrapolations suggest they are in the millions; Renwick et al. (2005) estimated that for the U.S. alone several million small dams have been built. Dam operations have caused global-scale ecological changes in aquatic and riparian ecosystems (Nilsson and Berggren, 2000), but dams are not the only instream structures that can impact river functions. As numerous as dams are, they are far outnumbered by the structures (culverts and bridges) built where streams and transportation routes intersect, generically referred to as stream crossings. Unlike dams, which tend to be built in the lower river reaches, stream crossings are ubiquitous in the upper reaches, fragmenting headwater ecosystems and blocking passage for

many aquatic organisms. In addition, stream crossings can affect water quality and temperature, and consequently impact the suitability of rivers for many native species. Figure 1 shows the location of (mostly small) dams and stream crossings in the Chicopee River basin, a rural watershed in central Massachusetts. Considered individually, the 195 dams and 2,230 stream crossings in this one river basin are each potential sites for fragmentation or destruction of aquatic habitat, alteration of hydrologic and geomorphic stream processes and disruption of aquatic life cycles. Viewed in combination and over a multitude of watersheds, these structures have changed the very nature of stream and river systems and the distribution of biological organisms that depend on them.

Hydrologists have been measuring river flow and geomorphologists have been studying how water transforms landscapes since at least the late 19th century. However, it was the work of Luna

Leopold, Reds Wolman, Arthur Strahler, John Miller and others in the middle 20th century that defined the field of fluvial geomorphology and transformed it into a largely quantitative science. It was upon this quantitative foundation that modern river restoration approaches and tools were developed. A conservative estimate of the total cost of river restoration projects in the continental U.S. from 1990 through 2005 is \$14 to \$15 billion (Bernhardt et al., 2005). Geomorphic restoration approaches have developed mainly along two lines of reasoning, one based on an empirical classification scheme that attempts to identify a stable channel geometry for a river and the other based on a mechanistic approach that attempts to quantify the dynamic fluvial processes at work within a river. Dave Rosgen's empirically-based scheme, "natural channel design (NCD)", has gained an enormous following in the U.S and has become synonymous with the term "river

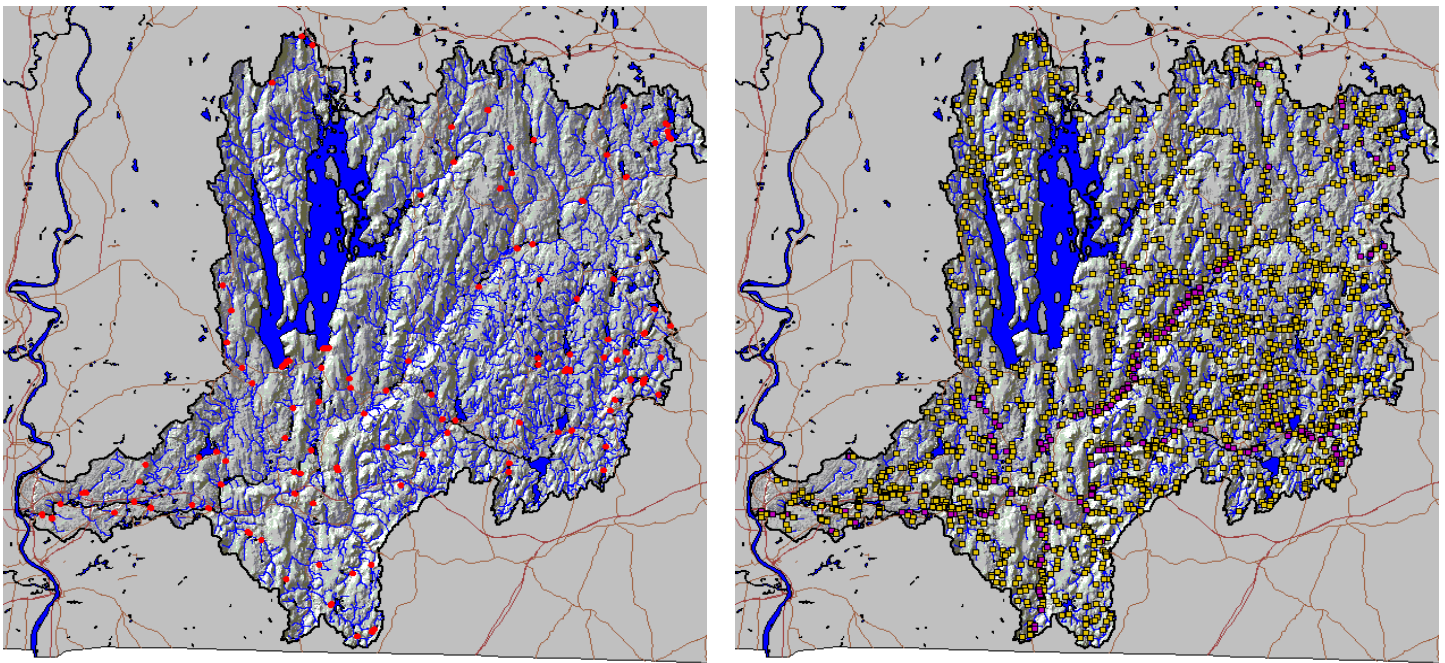


Figure 1: Location of a) dams (red) and b) stream crossings (yellow and purple) in the Chicopee River basin, a tributary of the Connecticut River in central Massachusetts. The Chicopee basin has a drainage area of 1,867 km² with approximately 3,462 km of roads and 417 km of railroad tracks. Small-scale industrialization in the late 19th and early 20th century resulted in construction of at least 195 dams on the mainstem and tributaries of the Chicopee River. The intersection of stream and transportation networks has resulted in approximately 2,230 stream crossings. Undersized and poorly maintained culverts and bridge openings can impede flow and sediment transport, interrupt ecosystem continuity and block the movement of aquatic species. (Source: Scott D. Jackson, UMass Extension, University of Massachusetts Amherst)

restoration”, much to the chagrin of many in the field. The geomorphic simplifications and hierarchical approach inherent in NCD are both the reason for its broad adoption by practitioners and some state and federal agencies and for its failure when applied in the wrong setting or by those with little or no geomorphic background. Despite the (sometimes heated) debate between proponents of NCD and the mechanistic approach, Wilcock (2011) argues that the two are actually intertwined because each approach requires elements of the other in order to be successful.

The field of stream and river restoration actually encompasses a wide variety of activities at different scales that may or may not support the restoration of hydrologic and ecological function. “There is a difference between river engineering and river restoration,” says Tim Beechie of the NOAA Northwest Fisheries Science Center. In some cases, projects are limited to the stabilization of river banks within a reach to halt the erosion of valuable riparian property or the revegetation of riparian areas to improve water quality. “I can think of many small-scale examples of riparian fencing and replanting to protect stream banks and water quality, examples of riffle construction to enhance fish passage, and constructed large woody debris jams to stabilize banks and provide fish habitat. In each case, the methods to undertake these projects are well proven and – if success is measured by local-scale benefits – then by all accounts these can be shown to work well,” states Stuart Bunn, Director of the Australian Rivers Institute at Griffith University in Queensland. In other cases, projects encompass the transformation of a subwatershed that has been completely altered by human activities. “Our biggest benefit-to-cost ratios have come from the larger headwater stream projects where we have seen improvement not only in the stream but across the entire watershed,” says Marty Melchior of Interfluve, Inc., a river restoration design firm. The keys to success are a holistic view of the project site within the context of the watershed and a fundamental understanding of the geomorphic processes that drive the fluvial system.

One of the pervasive questions that plagues those who want to restore rivers is: just what do we restore the river to? In many areas, human activities

have been dominant for centuries and it is difficult, if not impossible, to determine just what the natural state of a river is. In a 2008 *Science* article, Walter and Merritts called into question the very nature of a “natural stream channel”. Instead of a single thread, meandering stream with coarse-grained channel and fine-grained riparian floodplains, the archetype of the NCD approach, their investigation found that prior to the emplacement of colonial mill dams, many streams in the mid-Atlantic region of the U.S. were multi-thread within expansive wetlands that stored much more carbon than sediment. Mathias Collins of the NOAA Restoration Center has noted a related phenomenon in some valleys in the northeastern U.S. Upstream of dam sites, it is not uncommon to find landforms that look like floodplains but are actually impoundment accretions that have become well vegetated in a comparatively short period of time—sometimes with very large trees. These impoundment accretions can be verified by historical maps and/or aerial photographs or sediment cores. “I have been amazed at how human structures like dams can modify a valley very profoundly and in ways that become quickly unknown to the people who traverse those areas,” says Collins. Hence, one of the big challenges in river restoration is specifying restoration objectives that are “possible, practical and desirable” notes Gordon Grant of the U.S. Forest Service in Corvallis, Oregon. “We think that when we tear down a dam, we are allowing the river to do what it wants to do, but in fact, the river itself doesn’t care. The river simply adjusts to the latest perturbation.”

The need for restoration seems almost infinite while the funding for such projects is limited, hence restoration planning needs to be strategic, targeted and long-term. Small-scale projects, such as culvert replacements, can be part of a basin-wide or regional restoration plan. “When you consider how many linear miles of small headwater streams there really are, and how far upstream fish swim, you realize just how much impact stream crossings can have on the functioning of an entire river,” says Scott Jackson, Director of the Natural Resources and Environmental Conservation Extension Program, University of Massachusetts Amherst. Jackson and colleagues have partnered with The

Nature Conservancy to develop *Critical Linkages*, a program for proactive transportation and land protection planning in Massachusetts, which helps to prioritize the rehabilitation of stream crossings. Dam removal has become the preferred approach by some organizations because it turns the “river back into a river” without relying on more expensive interventions. “Our philosophy is to get the structures out and let the river restore itself,” says Brian Graber, Director of River Restoration for the Northeast Region of American Rivers. Simply removing the dam is not enough, however; there are issues related to infrastructure, abutting property and downstream impacts that need to be addressed and managed as a result. Establishing and maintaining environmental flows (defined as the flow required for aquatic ecosystem function) is necessary for sustaining river health. “Recognizing that the environment is a legitimate user of water is essential,” says Stuart Bunn. Bunn adds, “...investing in protection of streams/ivers and riparian zones in good condition is probably far more cost effective (by orders of magnitude) than reclaiming land and compensating land holders, and undertaking expensive restoration and maintenance.”

The first step in any successful restoration project should be to determine why the river is degrading and then develop a strategy to address the root causes (Beechie et al., 2010). However, success is difficult to demonstrate if clear goals and performance criteria are not established before construction begins. Often, if restoration monitoring is done at all, it is done in a haphazard way. “What we need is better translation of monitoring results, turning the lessons learned into modifications and improvements of the restoration methods for future projects,” adds Brian Graber. In order to learn from both successes and failures, many agree that river restoration projects should be viewed as applied experiments with well-defined project objectives, appropriate project design, and a monitoring plan for evaluating project performance. “The most exciting thing about river restoration is that with each attempt, we get to learn how the river responds,” notes Gordon Grant.

River restoration is still a very young field, both as a science and as a practice, and as such, the

arguments and the “lessons learned” can be viewed as a necessary part of the growing process. Wilcock (2011) outlines a number of research challenges that must be addressed in order for the science of river restoration to continue to improve. These challenges include developing better ways to estimate sediment continuity and capacity, incorporating uncertainty into design, using multi-dimensional hydromorphological models to create reliable design charts, and involving decision science in goal setting and decision-making throughout the process. Wilcock is working with the U. S. Army Corps of Engineers to incorporate the results of such research into the permitting process. Restoration practice needs to move forward as well. In the literature, at least, there appears to be a movement away from the expectation of a stable river channel and towards restoring the dynamics of fluvial processes (flow, sediment transport, erosion and deposition) that allow for the self-healing complexity of a natural stream system. Given the constraints of human infrastructure and societal priorities, this is not always possible, hence Kondolf (in press) presents a framework for establishing when “self-healing” is plausible and when other, more engineered approaches must be considered. The most amazing thing we have learned is that, given the chance, rivers and biological systems are incredibly resilient, and quickly recover even after decades of human assault. The field of river restoration must be resilient, too, and move beyond contention toward effective communication and collaboration between scientists, engineers and stakeholders, all of whom place a high value on rivers running free.

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Research in karst: A model for future directions in hydrologic science?

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Interdisciplinary research on the hydrology of karst aquifers has long been practiced and is perhaps of even greater value today as a model for future directions in hydrologic science in general. Challenges to achieving a deep understanding of karst systems span the full range of current problems in hydrology. Questions in karst encompass general hydrological problems, such as conceptualizing flow heterogeneity and connectivity, transferring detailed time series of flow and geochemistry into predictive relationships, modeling multi-phase and density-driven flow, and understanding the interactions between geological history, climate, geomorphology, biological systems, geochemistry, and hydrology. Heterogeneities in subsurface flow and hydrogeologic processes that generate flow networks are central to conceptual frameworks in modern hydrology, and are exemplified by karst systems. Insights gained through the approaches used to study karst aquifers can be applied to a wide spectrum of hydrologic systems, from surficial

alluvial aquifers to deep confined fractured bedrock aquifers.

Karst and analogous hydrologic systems are present in every state of the United States, either at the surface or at depth. Approximately 15% of the exposed or shallowly-buried bedrock of the United States alone has the potential for hosting karst features such as caves, sinkholes, sinking streams, and subsurface conduits (Weary and Doctor, 2011; Figure 1). This number greatly understates the extent of aquifers that have karst, paleokarst, and pseudokarst features at depth. The common perception that karst phenomena are limited to the shallow subsurface is false, and certain karst aquifers have circulation up to several kilometers depth.

Nearly one quarter (23%) of all fresh groundwater withdrawn from principal aquifers in the U.S. was from bedrock aquifers in the year 2000, and of this amount, slightly more than half (52%) was from carbonate and mixed sandstone and carbonate rocks; if basaltic rock aquifers are included in this latter percentage, it increases to 83% (Maupin and Barber, 2005). Thus, karst and volcanic pseudokarst aquifers are the most productive bedrock aquifers in the United States (Table 1). Withdrawals from the Floridan aquifer alone accounted for 26% of total bedrock aquifer withdrawals, and more groundwater is withdrawn from the Floridan aquifer than from all other U.S. carbonate aquifers combined. Stresses such as climate change, pollution, groundwater extraction,

and saltwater intrusion threaten the sustainability of karst systems and warrant further integrated scientific investigation.

Given these facts, it is noteworthy that karst processes have historically received less attention in North America than in Europe or Asia (Florea et al., 2007). However, the attention is steadily growing. The number of publications on karst-related subjects has increased greatly since 1990. Yet, the AGU journal *Water Resources Research* has lagged behind the trend. For example, a search of the ISI Web of Knowledge shows 208 articles published in *Journal of Hydrology* since 1990 with the topic of “karst,” whereas only 48 were published in *Water Resources Research* during that same time period. These numbers are 3.16% and 0.64%, respectively, of all papers published in these journals since 1990, suggesting nearly a 5-fold difference.

Despite inherent difficulties, researchers have made advances toward numerical characterization of karst systems. For example, the MODFLOW conduit-flow process (Shoemaker et al., 2008) incorporates a discrete conduit network coupled with the traditional continuum solution and also

employs high-conductivity, continuum flow layers in which flow can transition between laminar and turbulent. Ongoing research is focused on unsteady and non-uniform flow within partially-filled conduits and description of turbulent flows with nonlinear gradient functions. While MODFLOW conduit-flow process is currently limited to the flow solution, future versions will incorporate additional processes, such as buoyancy forcing, solute transport, and heat exchange.

Representing permeability structure remains a major challenge to deterministic modeling of karst systems. Because conduit and fracture geometries can rarely be measured directly, new indirect techniques are needed to deduce the influence of permeability structure on system response to external stress. Inverse modeling of permeability structure using deterministic models is likely to be difficult, due to the large number of descriptive parameters required. Additional research is needed to determine the type and amount of data required to constrain representations of permeability. Stochastic methods and fractal concepts will likely play a key role (e.g., Hergarten and Birk, 2007).

Model uncertainty and sensitivity are largely a function of data quality and data density; however, in most karst settings, even dense well data may not overcome uncertainty associated with aquifer permeability structure. Significant effort has been expended to develop lumped-parameter and grey-box models of karst systems (e.g., Fleury et al. 2007). These models can allow prediction of discharge and geochemistry, within observed ranges, without quantifying conduit properties. Future research that expands upon the groundwork of lumped parameterizations of karst conduit networks is needed.

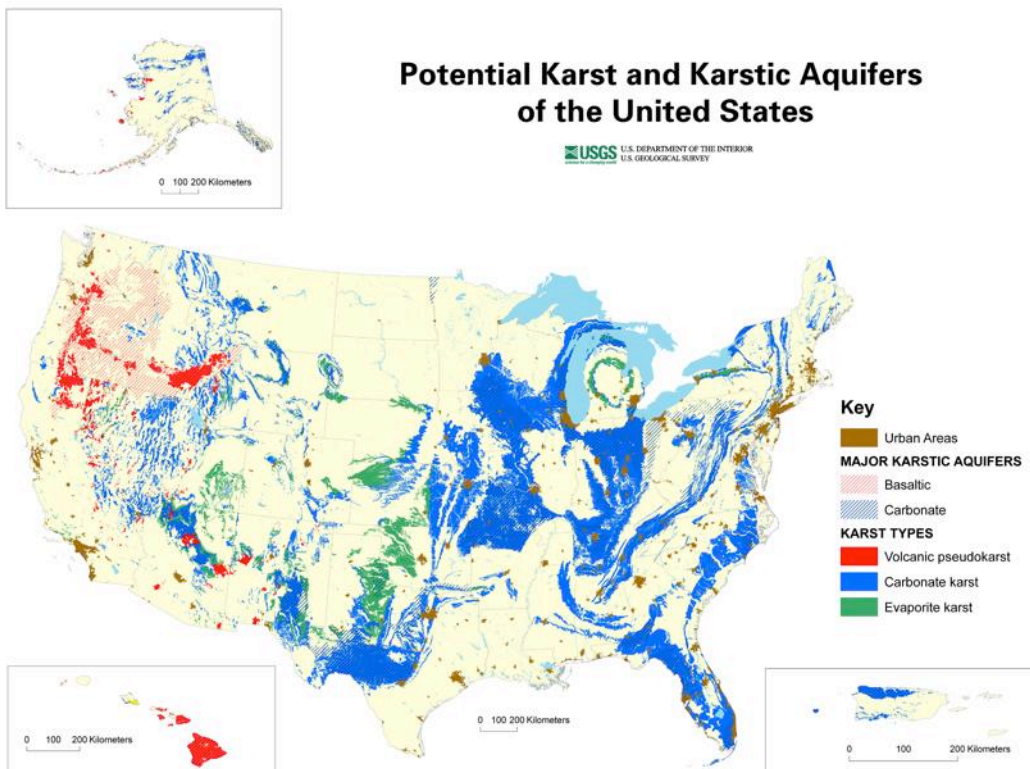


Figure 1: Map of potential karst and karstic principal aquifers of the United States (unpublished USGS data).

The continuous measurement of flow, geochemistry, and temperature is often applied in karst, and is becoming standard practice in other hydrologic systems as technologies become less expensive and more user-friendly. Despite long-held views to the contrary, a theoretical analysis has suggested that spring hydrographs carry little information about conduit system geometry (Covington et al., 2009). Other signals, such as temperature and geochemistry provide more promise. A study by Luhmann et al. (2011) of thermal patterns at 25 springs in Minnesota suggested that temperature signals carry significant information about permeability structure and recharge mechanisms. High-frequency geochemical sampling at springs has shown utility for elucidating the dynamics of mixing between

different components of a karst aquifer (e.g., Doctor et al., 2006). Dye tracing and analysis of tracer breakthrough curves remain important tools in karst hydrology and an area of continuing research with particular focus on multi-tracer approaches.

Groundwater age, or mean residence time (MRT), is an important quantity to estimate in hydrologic studies, as it provides insight into system dynamics and has implications for resource sustainability and quality. Measurement of environmental tracers with known atmospheric concentrations provides a quantitative estimate of water age; however, in most cases, the age of a single sample reflects a mixture of waters with widely disparate residence times. In karst aquifers, residence times may range across several orders of magnitude, and residence time distributions may be

Table 1: Year 2000 U.S. groundwater withdrawal from carbonate karst aquifers, mixed sandstone and carbonate karst aquifers, and volcanic pseudokarst aquifers in million cubic meters per day (Maupin and Barber, 2005).

AQUIFER	Groundwater withdrawal $\text{m}^3 \text{ day}^{-1}$ [$\times 10^6$]
CARBONATE KARST AQUIFERS	
Floridan aquifer system	13.8
Biscayne aquifer	3.1
Roswell Basin aquifer system	1.5
Valley and Ridge carbonate-rock aquifers	1.0
Silurian-Devonian aquifers	0.9
Ozark Plateaus aquifer system	0.6
Basin and Range carbonate-rock aquifers	0.3
North Coast Limestone aquifer system (Puerto Rico)	0.2
New York and New England carbonate-rock aquifers	0.2
Blaine aquifer	0.2
Castle Hayne aquifer	0.1
MIXED SANDSTONE AND CARBONATE KARST AQUIFERS	
Edwards-Trinity aquifer system	2.8
Intermediate aquifer system (Florida)	1.3
Mississippian aquifers	1.1
Valley and Ridge aquifers	0.4
Paleozoic aquifers	0.1
VOLCANIC PSEUDOKARST AQUIFERS	
Snake River Plain basaltic-rock aquifers	9.9
Columbia Plateau basaltic-rock aquifers	3.5
Pacific Northwest basaltic-rock aquifers	1.8
Volcanic-rock aquifers (Hawaii)	1.6

non-stationary and multi-peaked. For modeling groundwater age, two approaches are common: 1) direct measurement of environmental tracers of groundwater age in a water sample (e.g., ^3H , ^{14}C , CFCs, SF_6) ; and 2) indirect estimation of MRT based upon convolution or weighting functions of input-output environmental tracer data, such as water stable isotope values ($\delta^{18}\text{O}$ and δD) (Plummer et al., 2003). Estimation of groundwater MRT using the convolution integral approach can provide an independent estimate of ground water age, but is highly dependent upon input and output data obtained at high frequency, and the transit time distribution applied in the model. Technological advances in continuous measurement of isotopic and chemical parameters will make estimation of MRT less expensive and facilitate wider use of the method. Great potential lies in the application of field-deployable laser-based isotope analyzers for continuous measurement of water stable isotopes at springs (Berman et al, 2009).

Karst systems provide opportunities to test new hydrogeophysical technologies. Electrical resistivity surveys have proven very effective for site-specific investigations in karst, but the limited scope of individual electrode arrays generally make them impractical for regional studies. Advances in airborne electromagnetic surveying (Smith et al., 2005) and audio-magneto tellurics (AMT) hold great promise for future regional karst aquifer characterization.

Many avenues of inquiry remain open concerning the relationships and feedback among karst ecosystems, hydrology, and geomorphology. With the absence of light, karst ecosystems have no primary production. Thus, karst ecosystems are truncated (Gibert and DeHarveng, 2002) and dependent on externally derived organic matter or on autogenically generated organic matter. Within karst aquifers, transformation of detritus into usable organic matter is driven by microorganisms frequently with the generation of carbonic acid that can drive additional dissolution and subsequent flowpath changes. Given the importance of microorganisms in the ecology of subterranean and phreatic ecosystems, more research is needed in karst areas to try to understand how nutrients and organic carbon are delivered to, processed in, and

removed from aquifers. High-resolution time series of ecologically important geochemical constituents, such as carbon, nitrogen, sulfur, trace metals and their stable isotopes will advance knowledge of mixing between near-surface and deeper aquifer components, and will provide insight into the role karst aquifers play in global biogeochemical cycles.

On longer time scales, karst hydrology can provide a framework within which ecologists can interpret the life history of stygobionts (obligate groundwater-dwelling species). For instance, how have the episodic changes in discharge, temperature, sediment load, and water chemistry shaped life histories? As karst basins are subjected to anthropogenic stress, will these stygobionts adapt? As the global climate changes, the ability of these animals to migrate with the changing climate is non-existent. How do we attempt to conserve these ecosystems? How much change in conditions can the stygobionts accommodate? Addressing these questions will require collaboration between hydrologists and biologists.

Hydrological boundary conditions, geologic stratigraphy, geomorphological forces, and landscape history control karst aquifer structure. Knowledge of the processes of cave formation are crucial to conceptualizing and quantifying karst aquifer structure, and for informing management strategies for preserving water quality. Advances continue to be made in the quantification of geomorphological processes in karst, and often systems display signatures from multiple hydrological or climatic regimes. For example, Gulley et al. (2011) show that episodic flow reversals of Suwannee River springs force conduit growth in the Floridan aquifer, thus highlighting the long-term history of surface water-groundwater interaction in this important karst aquifer.

Solving the remaining conundrums that karst presents requires addressing many of the open questions in the field of hydrology at large. Given the great importance of karst aquifers as water resources, the American community of hydrologic scientists can no longer afford to largely ignore these complex hydrologic systems. Clearly, the future of hydrologic science will benefit from additional research in karst.

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Creating a research space for Water and Society

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Editor's Note: The Hydrology Section has recently formed a Water and Society Technical Committee, jointly with AGU's Societal Impacts and Policy Sciences Focus Group. The author is a co-Chair of the committee (the second co-Chair will be named soon). This article describes the motivation for the committee, which will meet for the first time in San Francisco. It also describes a session (H61, "The Evolution of Water Management Paradigms," sponsored by the TC, to be held in San Francisco.

The subject of water and society is at the heart of the study of water as a resource. Water is essential to human activities and to ecosystems. It is a vital input to food and energy production, and, yet, is

also a destructive hazard. The hydrologic cycle is an integral element of Earth's climate system, but the fact that it is modulated by human alteration of the land surface and atmosphere is a fact that is often ignored in the climate context, notwithstanding that anthropogenic manipulations have severely altered the land surface hydrologic cycle in many respects. Society demands, withdraws, competes, uses and wastes the resource in dynamic counterpart.

The science of water management emerges from this field at the nexus of engineering and geoscience, with substantial influence from economics and other social sciences. The spatial scales of analysis range from a single smallholder farm, in the case of a rainwater harvesting system, to the entire Earth, in the case of global flow of water in agricultural production. Within this purview are some of the most pressing environmental questions of our time, such as

adaptation to climate change, direct and indirect connections between water and energy policy, the continuing dependence of agriculture on depleting aquifers, the conservation or preservation of ecosystems within increasingly human-influenced river systems, and food security and poverty reduction for the Earth's poorest inhabitants.

Why now? Simply put, there is a need for a focus on the basic science of water management. At present, the research is as scattered as the funding sources that the academic community pieces together to create something resembling a research program. As Lettenmaier (2008) describes, there is no funding program for research in the basic science of water management. It was not always so. While research on hydrology and water management has been documented to at least Roman times, the publication of Maas et al. (1962) marked the formalization (by the Harvard Water Program) of much of the knowledge that had preceded it and launched a scientific field of water management.

Maas et al.'s landmark book included chapters on economic analysis of water systems, the first formalized methods for computer-based simulation and optimization analysis of water systems, and stochastic streamflow analysis. These remain central to the field. Water resources research flourished throughout the 60's and 70's (it is not a coincidence that the premier journal in the field

carries the title *Water Resources Research*) and the planning and management of water systems throughout the world relied on the insights produced. However, progress waned due to limitations in the effectiveness of the top-down, objective-planning approach that dominated, especially in light of political realities, and the general distrust of federal water planning during the Reagan era (Reuss, 2003). Meanwhile, when Hydrologic Science made a "great leap forward" with the NRC "Eagleson report" (NRC, 1991) and the ensuing establishment of a Hydrologic Sciences program under the Geoscience Directorate at NSF, water management was left behind.

As a result, there is a gap in the U.S. research community on the subject of water management (Lettenmaier, 2008). Those who do the research are often required to pursue "problem-driven" funding from state and local agencies or utilities in lieu of federal funding. This does have the benefit of producing research that is highly relevant to society. However, in addition to being significantly less copious and prestigious than other sources, a major drawback is the absence of support for basic, hypothesis-driven scientific research in the field of water management. Consequently, there is limited production of basic science needed to address the pressing issues that society faces.

One of the most prominent areas of need is adaptation to climate change and nonstationarity.

The foundational assumption underlying water resources planning and management methods is publicly questioned. The need for basic research for adaptation is made clear in the NRC report on adaptation to climate change (NRC, 2010), which cites a lack of basic understanding of adaptation options as a primary impediment to action. Gleick's hypothesis (Gleick, 2003) that "soft paths" can provide many of the services of traditional infrastructure remains untested in any formal and generalizable way. Society's ability to manage hydrologic extremes such as droughts and floods may be decreasing just as societal exposure to these events increases.

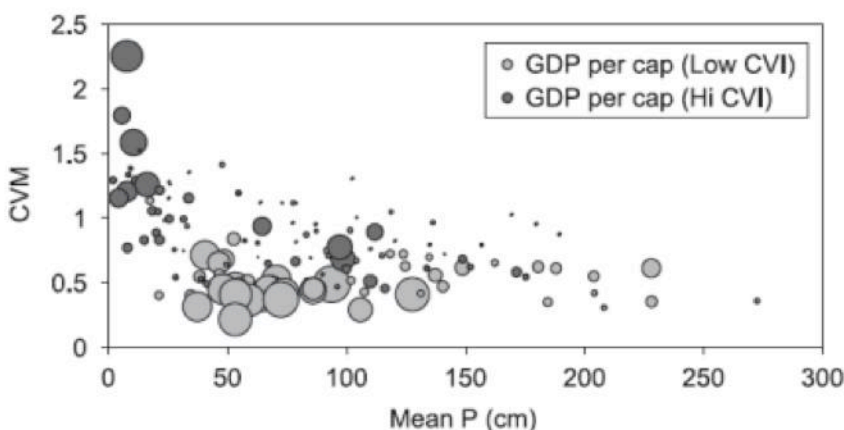


Figure 1: The relationship between precipitation mean and variability and per capita GDP for the nations of the world. Circle size is proportional to per capita GDP. The x-axis is mean annual precipitation, the y-axis is coefficient of variation of monthly precipitation, and color indicates high or low coefficient of variation of interannual precipitation (CVI). From Brown and Lall (2006).

At the same time, the age old concerns related to the management of competing objectives for water uses are only intensifying. Conflicts involving the use of water for energy production are paramount, including cooling for thermoelectric plants, the water demand of biofuels, and hydroelectricity production. In many cases the water for these purposes is drawn from resources that provide irrigation for food production or that sustain ecosystems.

Water is connected to some of the great challenges of our time, including the feeding the world's poorest. The ability or inability to manage hydrologic variability has a demonstrable effect on economic development throughout the world (Figure 1), and especially in Africa (Brown et al., 2011). Yet, there remains little consensus on the best means of achieving so-called water security in developing countries and in the U.S.

This is a small sampling of the pressing issues that call for renewed research in the science of water resources management. They are global in scale or in their implications. They require basic understanding of human and water *interactions*. And they require knowledge of the human systems and institutions within which decisions are made and policies enacted.

For some, the case may have to be made that water management research constitutes science. Perhaps for others, there may be fear that hypothesis-driven investigation may lose its credibility with the world of practice. It's true that, to remain vital, the links to the world of practitioners must remain strong. But neither concern should be an impediment to strong basic science in this field. The science of water management may be best understood as neither applied nor basic but rather a "use-inspired basic research," (see Stokes, 1997, cited in Clark, 2007). It is fundamentally a "sustainability science," which as Clark (2007) states,

"... seeks to facilitate what the National Research Council has called a 'transition toward sustainability,' improving society's capacity to use the earth['s water resources] in ways that simultaneously 'meet the needs of a much larger but stabilizing human population, ... sustain the

life support systems of the planet, and ... substantially reduce hunger and poverty'."

The Water and Society Technical Committee hopes to provide a forum for the advancement of the sustainability science of water management. The goal is to create a space for discussion of research and education in this field, provide ground for the establishment of a common research agenda and ultimately, grow our science. I strongly encourage authors interested in this endeavor to submit to session "H61: The Evolution of Water Management Paradigms" (for details, see sites.agu.org/fallmeeting/scientific-program/session-search; search for convenor Casey Brown) and to attend the TC's first meeting (see the December Section newsletter for time and location; TC meetings are open).

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Integrating information from multiple sources for improved precipitation products

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Despite its critical importance in a wide range of scientific and societal applications, accurate estimation of precipitation at high temporal and spatial resolutions remains a challenging task. Sources of information about the spatial pattern and temporal variations of precipitation include gauge measurements, weather radar observations, estimates derived from satellite observations in the infrared (IR) and microwave (MW) channels, and analyses and reanalyses from numerical weather prediction models. In general, the quality of precipitation data derived from the above-mentioned sources is limited by a combination of factors including a) coverage and/or sampling errors; b) bias; and c) random errors. The bias and random error inherent in precipitation estimates result from inaccurate measurements, imperfect retrieval and estimation algorithms, and insufficient samplings.

Gauge measurements and gridded analyses derived from interpolated gauge observations have been the mainstay of precipitation products over land and are widely used in model predictions and diagnoses. The accuracy of such products is limited, however, by the station network density and other shortcomings. Integrating information from gauge, radar, satellite and other observation-based sources has been pursued as a means to improve the resolution and accuracy of precipitation products for both real-time monitoring of weather and hydrological events and their retrospective analysis since about 1998 when high-resolution, high-quality radar and satellite data became widely available.

The notion of combining information from multiple platforms was first adopted by hydrologists in constructing merged analyses of gauges and radar in the mid-1980s (Krajewski, 1987). Since then, research in the field has yielded an improved understanding and refined quantification of the input gauge measurement and radar precipitation

error structure. Following this line of research, several algorithms have been developed that optimize the information from gauges and radar. While these algorithms differ in their statistical bases, they are designed to perform two functions: to remove radar rainfall estimation bias through comparisons with gauge observations (e.g. Seo and Breidenbach, 2002), and to reduce the random error by combining bias-corrected radar estimates with gauge data (e.g. Seo, 1998). Several gauge-radar systems that generate high-resolution merged precipitation maps over regional domains have been constructed and implemented operationally. One well-known gauge-radar combined analysis is the NOAA National Centers for Environmental Prediction (NCEP) Stage IV product (Lin and Mitchell 2005). Hourly 4-km resolution radar precipitation maps over the Continental United States (CONUS) are produced at NCEP through a procedure that mosaics Stage III bias-corrected radar precipitation products generated at individual NOAA River Forecast Centers (RFC). A project is currently underway to construct gauge-radar multisensor precipitation reanalysis over the CONUS through the combination of information from quality controlled inputs (Nelson et al. 2010). Another example is the Japan Meteorological Agency (JMA) hourly 5-km resolution radar-gauge composite precipitation estimation product over Japan (Makihara, 2000). Amitai et al. (2011) describe an ongoing project at NOAA's National Severe Storm Laboratory (NSSL) that focuses on the development of a very fine 1-km resolution 5-minute gauge-radar merged National Mosaic Quantitative Precipitation Estimation (NMQ) over CONUS (Figure 1).

Such high space-time resolution Quantitative Precipitation Estimation QPE, with quantified uncertainty derived from the input error estimation and error growth model, will enable the prediction of the timing and stages of river discharges ranging from common flows to extreme. Since accurate rainfall forcing data is of paramount importance for streamflow simulation, small-scale events (i.e. flash floods) are also a subject of particular interest within the context of uncertainty quantification in hydrologic modeling (see e.g., Villarini et al., 2010). Recent efforts have been invested in the

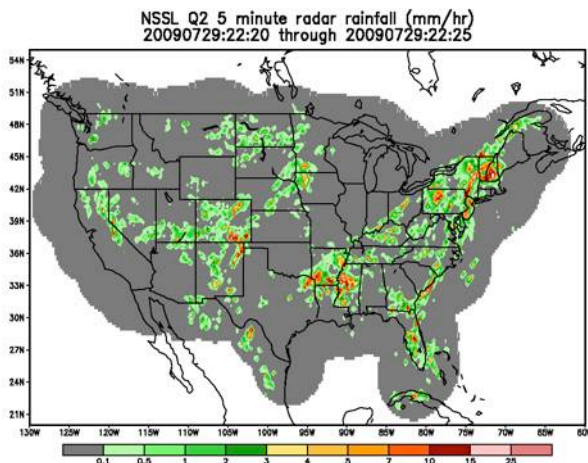


Figure 1: Distribution of 5-min 1-km precipitation (mm/hr) for 22:25GMT, July 29, 2009, derived from NSSL Q2 radar estimates (Source: <http://nmq.ou.edu>).

implementation of a CONUS-wide Ensemble Framework for Flash Flood Forecasting system (http://eos.ou.edu/USA_Flood.html) by combining the NMQ and distributed hydrological models (e.g., Wang et al., 2011).

Early efforts in the development of gauge-satellite merging algorithms were largely made in association with the Global Precipitation Climatology Project (GPCP), which aims at the construction of relatively coarse time/space resolution global precipitation analyses. Huffman et al. (1997) devised a procedure utilized in the GPCP products that adjusts precipitation estimates derived from frequently sampled geostationary satellite infrared (IR) observations with relatively (more) accurate passive microwave (PMW) rainfall estimates from less frequent low earth orbit platform observations. At higher latitudes the microwave and sounding-based estimates are used. The combined satellite estimates are further calibrated against co-located monthly GPCC gauge analysis. The final merged global monthly precipitation analysis, used by the GPCP as its official precipitation product, is computed as a weighted mean of the GPCC gauge analysis and the calibrated combined satellite estimates, with the weights inversely proportional to the estimated random error variances.

The Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), in the meantime, was developed taking a slightly different approach (Xie and Arkin, 1997). Satellite estimates derived from several IR and PMW observations are first combined through the maximum likelihood estimation (MLE) method, in which weighting coefficients are inversely proportional to the individual error variances computed through comparisons with concurrent gauge analysis. Combined satellite estimates are then blended with gauge data; in this process, the satellite and gauge data are used to determine the ‘shape’ and magnitude of the precipitation fields, respectively. The GPCP and CMAP merged analyses have been constructed for both monthly and pentad time resolution on a global 2.5° lat/lon grid for a 32-year period from 1979 to the present. Finally, the GPCP computes a daily 1° product from late 1996 to the present; in this product, the IR is calibrated to the monthly GPCP amount, PMW frequency of precipitation over 40°N-S, and sounding-based data at higher latitudes. All of these merged analyses have been utilized in a wide range of applications including weather/climate monitoring, climate analysis, numerical model verifications, and hydrological studies.

With the advent of the Tropical Rainfall Measurement Mission (TRMM, Kummerow et al., 1998) and the development of upcoming Global Precipitation Measurement (GPM) project (Hou et al., 2011), substantial progress has been made in the past decade or so to develop advanced techniques to generate precipitation estimates of higher spatial and temporal resolution (3-hourly, 0.25° lat/lon or finer) through the combined use of IR and PMW observations from multiple satellite platforms. Hsu et al. (1997) developed a sophisticated system to convert IR brightness temperatures observed by geostationary satellites into instantaneous rain rates through an artificial neural network by carefully training concurrent IR and PMW-based precipitation estimates. Called Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN), this technique is further improved by including additional information on cloud type (Hong et al., 2007). Recently developed algorithms (e.g.,

Huffman et al., 2007) derive IR-based precipitation estimates by first matching the probability density function (PDF) of geostationary IR data with co-located PMW-derived precipitation intensities and then combining these IR-based estimates with PMW data to form maps of high spatial/temporal resolution. Joyce et al. (2004), meanwhile, took a very different approach. They defined precipitation analyses at 30-min intervals and on an 8-km grid over the globe through the propagation of precipitating cloud clusters, observed by the instantaneous PMW, along advection vectors computed from consecutive geostationary IR images. A recent modification of the original CMORPH algorithm resulted in substantial improvements in integrated satellite estimation over temporal gaps between PMW observations by including IR-based precipitation estimates (Joyce and Xie, 2011).

Integrating information from multi-sensor observations aboard multiple geostationary and low earth orbiting platforms enabled the construction of high-resolution precipitation estimates of improved quality over a quasi-global domain (up to 60°S-60°N). These integrated satellite estimates, however, contain biases and random error of substantial magnitude. One way to improve the quality of high-resolution satellite-based precipitation is to incorporate information from additional sources of information. For example, Xie and Xiong (2011) proposed a conceptual model to remove CMORPH estimation bias through PDF matching against a daily gauge analysis, and by combining the bias-corrected CMORPH with gauge analysis through the optimal interpolation (OI) technique. The final gauge-satellite merged analysis is dominated by the gauge observations over densely gauged regions, while it is close to the satellite estimates over gauge-sparse areas (Figure 2).

As a result of continuous efforts over recent decades by meteorologists and hydrologists, the accuracy of land precipitation analyses have improved substantially, especially for warm season

precipitation over regions covered by dense gauge stations and weather radar networks. Deficiencies, however, remain in the current generation land precipitation analyses, especially for cold seasons, over mountainous regions, and in terms of long-term analysis homogeneity.

The ability of the current generation precipitation analyses to detect and quantify snowfall is hampered by under-catch problems, which can be severe with most operational gauges, and by the relatively poor accuracy of the radar and satellite-based estimates of solid precipitation. The precipitation analysis problem over mountainous regions is a combined effect of sparse gauge network, blocked radar coverage, and complicated orographic enhancements in precipitation. Long-term homogeneity of precipitation, critical to many climate and hydrometeorological applications is compromised by changes in the input observations over the data record period (e.g. gauge network, radar/satellite instruments/algorithms).

Improving observations from individual sources (gauge, radar, and satellite) is fundamental to the quality of precipitation analyses. Optimal

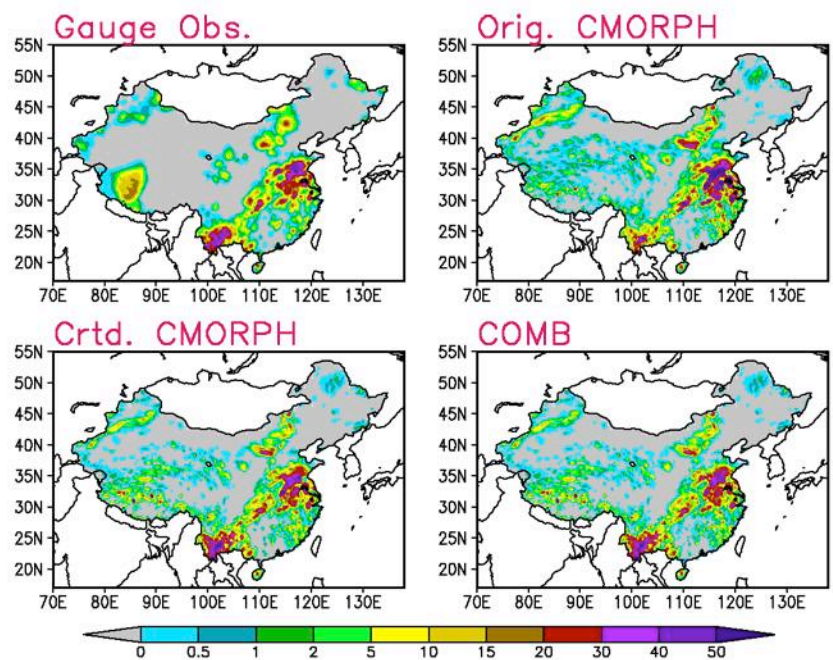


Figure 2: Distribution of daily precipitation for August 2, 2007, derived from (top-left) gauge-based analysis, (top-right) CMORPH satellite estimates, (bottom-left) bias-corrected CMORPH, and (bottom-right) combination of gauge analysis and bias-corrected CMORPH.

integration of information from multiple sources, meanwhile, leads to precipitation analyses of refined quality through the reduction of error and uncertainties in the existing individual observations. Efforts toward integrating information from multiple sources have been largely divided into two groups: those that combine gauge data with radar observations and those that merge gauge analysis with satellite estimates. Little work has been done to take advantage of information from numerical model simulations and forecasts, notwithstanding recent work by Ebert et al. (2007) that illustrated consistent superior performance of precipitation fields produced by the current generation operational numerical models over extra-tropical areas during cold seasons

To better serve hydrological, hydrometeorological, weather, and climate applications, future development of objective algorithms for precipitation analyses need to incorporate information from all available sources, including gauge measurements, radar observations, satellite estimates and model analysis fields. The National Mosaic and QPE (NMQ) system, which is being developed as a community project led by NSSL, is an example of such multi-source integration (Vasiloff et al. 2007). An effective integration algorithm may take different statistical frameworks but will benefit from prior research findings, including:

- Gauge snowfall under-catch adjustment requires wind, air temperature, and humidity information available from model-generated fields;
- Coverage gaps of radar observations may be filled in by high-resolution satellite estimates;
- Bias in the radar and satellite estimates can be adjusted through comparison against gauge observations;
- Range-dependent bias in radar precipitation estimation may be corrected using information from precipitation radar aboard TRMM and GPM satellites and from integrated satellite estimates;

- Orographic enhancements in precipitation need to be quantified using wind and humidity data from numerical models;
- Precipitation fields generated by numerical model provide important cold season precipitation information over extra-tropical areas; and
- Impacts of including/withdrawing input observations need to be examined in order to achieve the best balance between homogeneity in the long-term time series and the quantitative accuracy in the individual time steps.

As proposed by Vasiloff et al. (2007), a community-wide integrated approach is needed to achieve the final goal of constructing improved quality precipitation analyses that better satisfy the requirements for various applications. This will require collaboration between algorithm developers from both hydrology and meteorology, and between the developers and users of precipitation data sets.

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Platforms for change: The increasing importance of sustained satellite observation for global hydrologic change monitoring

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The global water cycle is one of the primary Earth systems being impacted by climate change (Trenberth et al., 2007). On a global scale, this change is frequently described as an “intensification” of the hydrological cycle, a trend that has potentially tremendous implications for a range of societal and geopolitical issues as diverse as water supply, flood control, food security, and epidemiology. But the nature of hydrological

change and its impacts is quite complex, involving interacting forcings and feedbacks that vary over space and time. For this reason, long-term global observations, such as those from remote-sensing, are essential in order to monitor local, regional, and global changes in the water and energy cycles, and to inform theory and models that are used to project future change.

Certain fundamentals of the interaction between increased tropospheric temperatures and the water cycle are well understood. More water vapor in the atmosphere should result in more precipitation globally, although changes in precipitation intensity, frequency, and duration may vary significantly locally (Trenberth et al., 2003). Enhanced evaporation due to warming is also expected to increase precipitation, due to mass and energy balance in the lower atmosphere (Held and Soden, 2006).

Still, complex and often competing processes complicate these fundamentals. For example,

changes in precipitation have a significant impact on evaporation in water-limited environments, while changes in humidity can influence evaporative demand. Furthermore, complexities related to changes in cloud cover, precipitation extremes, and transport and convective processes all play a role. All of these complexities can be approached with basic physical theory but demand detailed observational studies—and, in many cases, the intellectual commitment to understand contradictory or counter-intuitive observations such as the “pan evaporation paradox” (e.g., Brutsaert and Parlange, 1998; Hobbins et al., 2004). As a result of these complexities, there remains considerable uncertainty as to how intensification of the hydrologic cycle will manifest itself.

In a comprehensive review of studies on hydrologic cycle intensification, Huntington (2005) found support throughout the literature for trends in essential hydroclimatic variables like precipitation, soil moisture, and evapotranspiration (ET). Huntington cautions that there exist substantial uncertainties in the magnitude and even direction of the trends that are partly attributable to large gaps in spatial coverage of data and serial completeness of records. Recent studies suggest, however, that the use of sustained satellite observation of Earth for detection of hydrologic cycle intensification driven by climate change is beginning to bear fruit.

Among the most recent and far-reaching of these studies is the work of Jung et al. (2010). They used data from more than 250 eddy covariance stations throughout the world to obtain estimates of monthly ET at each station. Estimates of monthly ET and other meteorological observations from these flux sites were then used in combination with 2-km resolution global data for fraction of photosynthetically active radiation (FPAR) from the sea-viewing wide field-of-view sensor (SeaWiFS) to train a model tree ensemble estimate of global mean monthly ET at a 0.5° spatial resolution for 1982–2008 (Figure 1). They estimate that global land ET increased from the early 1980s to the late 1990s at a rate of approximately 7 mm/year. Between 1998 and 2008 their approach

suggests a decrease in land ET at a rate of approximately 8 mm/year, consistent with the outputs of nine land surface models over the same period. Introducing soil moisture data retrieved from the Tropical Rainfall Measurement Mission (TRMM) microwave imager, the authors tested the hypothesis that the decline in ET during 1998–2008 was associated with a corresponding decadal change in soil moisture. Over this time period and in regions where soil moisture control on ET is expected, they found a high correspondence between their estimate of ET and soil moisture observations derived from TRMM (Figure 2). In particular, a predicted decrease in ET during 1998–2008 over large parts of Australia, East Africa, and South America was associated with a corresponding decrease in soil moisture over that same period. The authors point out that while their study finds a coherent relationship between soil moisture and ET over the period 1998–2008, it remains to be seen whether the observed trends in soil moisture and ET represent natural variations in climate or a more fundamental shift from historical conditions. This caveat underscores the need for continuity of satellite observations in the coming decades.

Beyond intensification of the hydrologic cycle associated with increasing concentrations of atmospheric greenhouse gases, satellite data have proven invaluable in assessing the impact of land cover-related modifications to the hydrologic cycle. In a sequence of studies, Chagnon et al. (2004) and Wang et al. (2009) investigate the role of

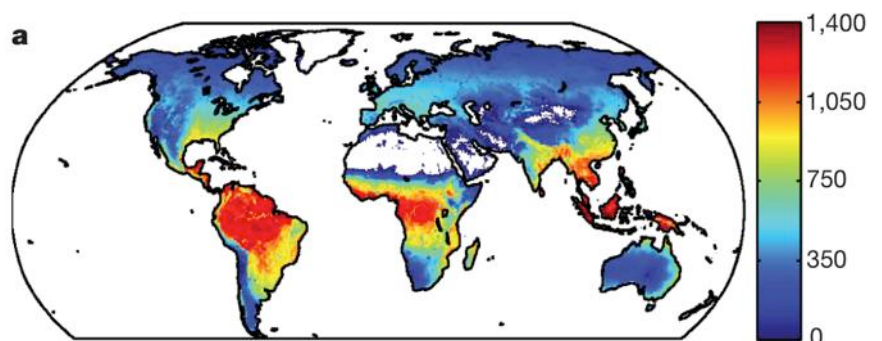


Figure 1: Estimated mean annual land ET in mm/year from 1982–2008 as derived through a combination of data from a global network of flux measurements and satellite measurements of FAPAR derived from SeaWiFS. Reprinted by permission from Macmillan Publishers Ltd: *Nature* (Jung et al. 2010), copyright 2010 (<http://www.nature.com>).

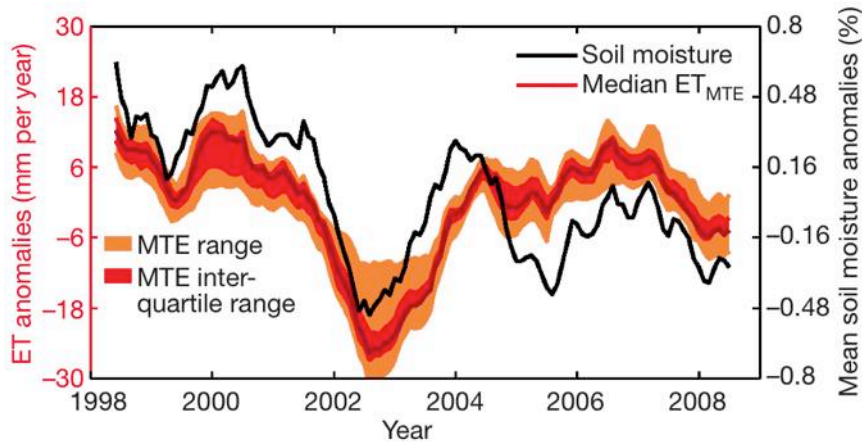


Figure 2: Estimated mean land ET anomalies (left ordinate) and TRMM soil moisture anomalies (right ordinate) from 1998-2008 in areas with a valid TRMM soil moisture retrieval. In each case the seasonal cycle has been subtracted and the data filtered with an 11-month running mean. Reprinted by permission from Macmillan Publishers Ltd: *Nature* (Jung et al. 2010), copyright 2010 (<http://www.nature.com>).

deforestation in the formation of clouds and regional circulation. Chagnon et al. (2004) performed a Bayesian analysis of cloud cover observations using Geostationary Operational Environmental Observational Satellites (GOES) data and concluded that shallow cumulus clouds were significantly more likely to be observed over deforested areas in the Rondonia region of the Amazon basin. Wang et al. (2009) extended the work of Chagnon et al. (2004) to determine whether corresponding trends in the occurrence of deep clouds over deforested regions of Rondonia were observed. From the GOES satellite data they concluded that deep clouds were statistically more likely over forested regions during the dry season in which frontal storms are less common. Ground-based atmospheric sounding data over a two-week period showed that convective available potential energy (CAPE) was favorable for the development of deep clouds over a forested site, but that deep clouds occurred only once during this period. The authors conclude that while atmospheric conditions were favorable for the development of deep clouds over the forested site, the lack of a lifting mechanism inhibited their development. This study illustrates the importance of sustained satellite observation of the land surface and atmosphere for

understanding land-atmosphere coupling as land cover modification continues.

These primarily data-driven studies demonstrate the value of remote sensing as a tool in hydrology and climate science. They highlight the critical need for continued support for land hydrology missions and raise two important issues:

First, the length of existing satellite data records remains short compared with some of the longer period forcings of the global water cycle. For instance, it has been almost 40 years since the Landsat satellites began continuously observing Earth's land surface in 1972. However, this period represents a little more than one half-period of the Pacific Decadal Oscillation, an ocean climate index that is associated with hydroclimate anomalies in western North America. Thus, sustained

and continuous satellite observations of variables like soil moisture, precipitation, and snow extent and water content are essential to ensure that hydrologic trends may be definitively attributed to climate change or natural climate oscillations.

Second, global networks of in situ measurements are critical both to validate retrievals of hydrologic variables from satellite observations and because they often yield rich and detailed databases of continuous and complementary measurements. New and forthcoming satellite missions like the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) and Cold Region High-resolution Hydrologic Observatory (CoReH2O) missions, NASA's Soil Moisture Active-Passive (SMAP) and Global Precipitation Measurement (GPM), and the joint NASA/CNES (French Space Agency) Surface Water and Ocean Topography (SWOT) missions will offer an unprecedented view of global hydrological processes. But, supporting in-situ networks are essential to relate the hydrological variables of interest to those quantities measured by the satellite instruments and to validate the data products. Jung et al. (2010) demonstrated the added value of complementary in-situ data through their combination of mean monthly measurements of ET derived from a global network of flux measurement

sites with a global dataset of FPAR derived from satellite data.

Quantifying and understanding the intensification of the hydrologic cycle in response to climate change is a critical challenge for the hydrology community in the coming decades. The studies discussed here are prototypical of how satellite and in-situ observations and models will be synergistically combined to investigate the hydrological cycle. Furthermore, they highlight the pivotal role of remote sensing in rising to meet this challenge.

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Ecohydrology and the challenges of coming decades

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In this second decade of the 21st century, we look back with satisfaction at tremendous advancements in ecohydrology during the first decade, as highlighted by Vivoni and others in a previous issue of this newsletter (Vivoni et al., 2010). As we look forward, we foresee new scientific and societal challenges as well as outstanding opportunities for our field. There are many issues of urgency to humanity where ecohydrologists can make important contributions in the coming decade. In this article, we outline what we view as some of the most prominent challenges and opportunities.

Food and Water Security: The Food and Agriculture Organization of the United Nations (FAO) predicts that by 2050 the world's water resources will have to support agricultural systems to feed an additional 2.7 billion people. Ecohydrology, by definition, deals with issues related to both water scarcity (hydrology) and food security (ecology) and their interactions and feedbacks with the ecosystem. Thus we foresee that in the future, ecohydrologists will be increasingly called upon to use their scientific knowledge to address questions regarding vegetation water use and/or ways to enhance food production under threatened human water security (Figure 1). We expect that the science of ecohydrology will be at the forefront of many of the seemingly intractable issues facing humanity – in particular the grand challenge of providing for human needs while sustaining our natural resources and coping with

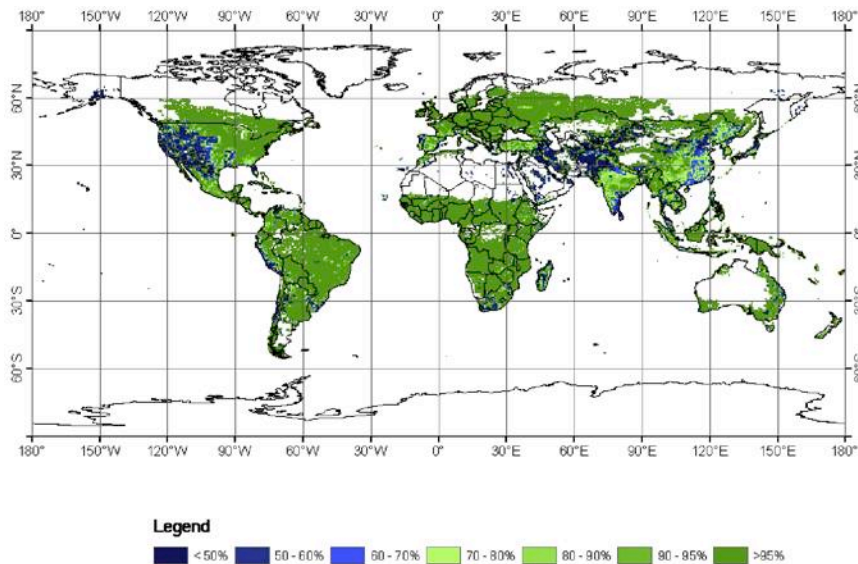


Figure 1: Proportion of water used for crop production that comes from precipitation. By 2050 the world's water resources will have to support agricultural systems to feed an additional 2.7 billion people. From Liu et al. (2009).

global alterations in temperature or precipitation (e.g., Wilcox et al., 2011).

Ecosystem responses to climate-related natural disasters: Unfortunately, we do not need to look hard for examples of climate-related natural disasters. In just the last few years we have witnessed devastating droughts in Russia, China, and the United States. During the last 12 months alone, large-scale flooding has occurred from Pakistan to Thailand to Colombia to the Mississippi and Missouri River Valleys in the U.S., with disastrous socio-economic as well as ecological consequences. In the Western U.S., an unprecedented infestation of Mountain Pine Beetle (MPB) is rapidly killing high-elevation forests with consequences that are yet to be determined. Climate-related disasters such as these are recurring stressors of ecosystem services, and we can expect that these and other stressors will continue in the future as the climate changes. Ecohydrology will continue to provide critical understanding of these natural disasters as well as ways of mitigating and adapting to them. For example, Webster et al. (2011) demonstrated that the 2010 precipitation rates in Pakistan were only modestly higher than the average for July and August; however, heavy rainfall pulses on steep valleys that were severely

affected by deforestation resulted in the increased runoff that led to the devastating floods. In the headwaters of the Colorado River in the Western U.S., Pugh and Small (2011) quantified the effects of MPB-induced tree mortality on snow dynamics and reported that tree mortality resulted in higher snow accumulation and earlier snow depletion, with potentially significant implications for streamflow and summer water resources for this part of the country.

Transformational landscape changes: While climate-related changes abound, human-induced landscape changes are equally severe. Many ecosystems have endured relentless degradation, water exploitation, low-productivity farming practices, and rapid population growth. Intentional forms of land use are often the primary drivers of change, such as

agricultural conversion, overgrazing, and wood harvesting (Asner et al., 2004). The interaction of all of these agents is exceedingly complex, and the end result is often a highly transformed and little-understood landscape. An imperative for ecohydrology in the 21st century is to better understand the effects of such changes on water resources, from groundwater recharge (Brauman et al., 2011) to the coupling of ecological and hydrological processes across scales (Vose et al., 2011).

Understanding ecohydrological connectivity: Ecohydrological connectivity is a system-level property that results from the linkages in the networks of water transport through ecosystems, by which feedbacks and other emergent system behavior may be generated (Miller et al., in press). The challenge of modeling ecohydrological connectivity lies in the poor understanding of cross-scale interdependencies of the processes from the soil to the plant to the atmosphere or the stream. Wang et al. (2011) developed a conceptual framework for upscaling ecohydrological and biogeochemical processes using electrical circuit analogies and Thévenin's theorem, highlighting its utility to represent concomitant processes at both small and large spatial scales. Riveros-Iregui et al.

(2011) demonstrated that the lateral redistribution of soil water imprints a spatiotemporal ‘signature’ to soil biological activity at the catchment scale in mountainous regions. By coupling hydrological and biogeochemical models across a watershed, these researchers simulated the spatial variability of soil C processes and provided independent corroboration of flux tower fluxes of CO₂ measured over the canopy. Notwithstanding, representing and synthesizing ecohydrological connectivity, from the point to the landscape scale, will require enhanced knowledge of connections between hydrology, climate, vegetation activity, soil processes, and landscape morphology.

It is well recognized that a single discipline cannot summarize the complexity of ecosystem responses to climate change. In this note we have presented a few examples of outstanding challenges and opportunities that will gain urgency in the coming decades. Water is fundamental for biological processes responsible for ecosystem function and food production, and for abiotic processes on and below the land surface and in the atmosphere. The field of ecohydrology conveys unique, interdisciplinary knowledge that can be adapted to address these challenges. Despite the important contributions that our field has made to science and society to date, we are only about to witness the real potential that our field will offer in tackling the challenges of a changing world.

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2010 Outstanding Student Paper Award Winners

Awardee	Paper Title	Institution	Advisor
Pasha Ameli	Micromechanical modeling of the normal deformation of rough-walled fractures: The influence of local damage events on macroscopic properties	University of California, Irvine	Scott Detwiler
Bhavna Arora	Hydrological perturbations drive biogeochemical processes in experimental soil columns from the Norman Landfill site	Texas A&M University	Binayak P. Mohanty
Michel Baraer	Proglacial hydrology in the Cordillera Blanca, Peru	McGill University	Jeff McKenzie
Edward Bulliner	Measuring and modeling stream temperature in a forested Ozark border stream: An energy balance approach	University of Missouri	Jason Hubbart
Francesco Ciocca	Heated optical fiber to measure soil moisture	EPF Lausanne	Marc Parlange
James Cullis	A conceptual model for the growth, persistence, and blooming behavior of the benthic mat-forming diatom <i>Didymosphenia geminata</i> (invited)	University of Colorado	Diane McKnight
David Hisz	Characterization of fractured rock during well tests using Tilt-X, a portable tiltmeter and extensometer for multi-component deformation measurements	Clemson University	Larry Murdoch
Syewoon Hwang	Development of spatiotemporal bias-correction techniques for downscaling GCM predictions	University of Florida	Wendy D. Graham
Kelsey Jencso	Linking catchment structure to hydrologic function: Implications of catchment topography for patterns of landscape hydrologic connectivity and stream flow dynamics	Montana State University	Brian L. McGlynn
Birendra Jha	Fluid mixing from viscous fingering	MIT	Ruben Juanes
Peter Kang	Effective transport in lattice fracture networks with uncorrelated and correlated velocity field	MIT	Ruben Juanes
Gregory Karlovits	Monte Carlo simulation to characterize stormwater runoff uncertainty in a changing climate	Washington State University	Jennifer C. Adam
Dimitrios Karvounis	Modeling of flow and transport in enhanced geothermal systems (invited)	ETH Zurich	Patrick Jenny
Colin Kikuchi	Coordinated use of physical measurements and environmental tracers to characterize stream-aquifer interactions along two small, groundwater-connected streams	University of Arizona	Ty Ferre
Jongho Kim	Effects of climate change and hydrological signals on streamflow characteristics	University of Michigan, Ann Arbor	Valeriy Ivanov
Magdalena Krol	Effect of gas bubble mobilization on contaminant transport during thermal remediation	University of Toronto	Brent Sleep
Sanjiv Kumar	Future water resource scenarios for USA: Effects of land use/cover change, climate change and human disturbance	Purdue University	Venkatesh Merwade

2010 Outstanding Student Paper Award Winners

Awardee	Paper Title	Institution	Advisor
Anna Liljedahl	Hyper-resolution hydrological modeling of polygonal ground	University of Alaska, Fairbanks	Larry Hinzman
Huidong Liu	Lake level simulations using a land surface model and satellite altimetry data	University of California, Irvine	James Famiglietti
Christopher MacMinn	Spreading and dissolution of CO ₂ in horizontal aquifers: Theory and experiments	MIT	Ruben Juanes
John Mallard	The role of stream network complexity in hydrologic turnover, nutrient retention, and watershed outlet signatures	Montana State University	Brian McGlynn
Corey Markfort	Wind sheltering of lakes and wetlands: the effect of stability on turbulent canopy wakes and evaporation	University of Minnesota	Fernando Porté-Agel and Heinz Stefan
Nicole Rudolph	Combining fluorescence imaging and neutron radiography to simultaneously record dynamics of oxygen and water content in the root zone	University of Potsdam	Sascha Oswald
Eugenio F. Santillan	Mineralogy and microbial survival during carbon sequestration	University of Texas, Austin	Phil Bennett
Audrey Sawyer	Quantifying hyporheic zones formed by large woody debris: Synthesis of numerical, laboratory flume, and field experiments	University of Texas-Austin	Bayani Cardenas
Zachary Schuster	Using damage functions and total risk to quantify the impacts of climate change on extreme precipitation	University of Wisconsin-Madison	Ken Potter
Tyler Smith	A Bayesian toolkit for modeling perennial and ephemeral catchments	Montana State University	Lucy Marshall
Tobias Vogt	Heat transport upon river-water infiltration investigated by fiber-optic high-resolution temperature profiling	Swiss Federal Institute of Aquatic Science and Technology	Olaf Cirpka
June Yeung	Sensitivity of WRF-simulated water and energy budget to land-surface parameterization over a heterogeneous landscape in the Northeastern U.S.	Princeton University	James A. Smith
Xiaochi Zhou	A tree-shrub-grass competition model and its evaluation in a semiarid savanna landscape with complex morphology	University of Washington	Erkan Istanbuluoglu

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