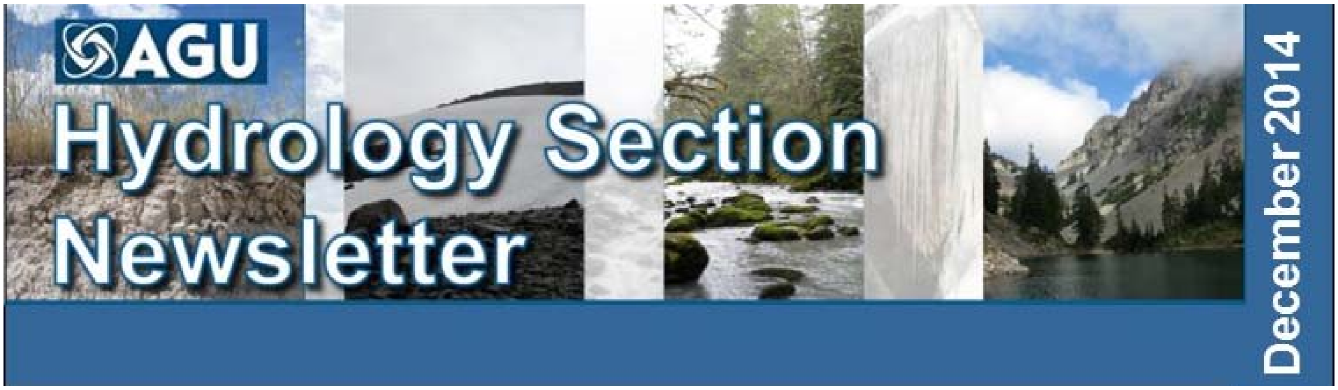
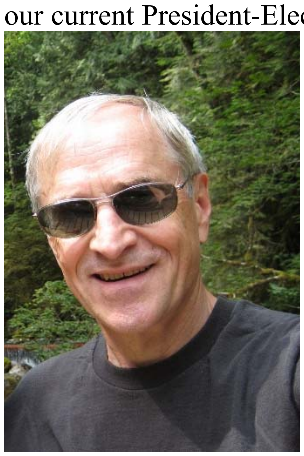


From the Section President

Eric F. Wood (Princeton University)

I want to take this opportunity to congratulate our new Section officers, President-Elect Jeff McDonnell and Section Secretary Terri Hogue. Jeff will serve for two years as the President-Elect and then two years as President. Terri is currently our section Secretary and agreed to stand for re-election, which our by-laws permit. She will serve a new two-year term. Also on January 1, our current President-Elect, Efi Foufoula- Georgiou will become the Section President, and I will step down. Early in the New Year our student representative on the Hydrology Section Executive, Tim H.M. van Emmerik, from Delft University of Technology, will step down as his PhD studies are completed. Below I will say more on the need for the section to find Tim's replacement. As the end of my term draws near, there are many Section members that I'd like to thank – unfortunately far too many to list. Certainly though, the other members of the Section's leadership team, Secretary Terri Hogue, President-Elect Efi Foufoula and Student Representative Tim van Emmerik, merit special mention.



Efi has served the section in many important roles but two really critical contributions have been chairing Section's fellows committee for the last two years, and as a member of the AGU Council Leadership Team. Chairing the section's fellows committee requires a great deal of attention to detail and a broad understanding of hydrologic science. Elsewhere in this newsletter, five of the seven new Fellows from the Section have written

"The Fellows Speak" articles (articles by the other Class of 2014 Fellows should appear in the July 2015 newsletter). The fact that the number of new Fellows from the Section has fairly consistently exceeded the Section's allocation over the recent past speaks both to the care that nominators and supporters have taken in assembling the nominations packages, and the supporting information that Efi and her committee assembled and forwarded to the Union Committee. The AGU Council elects seven members to its Council Leadership Team (CLT), with the charge to conduct the affairs of the Council in between meetings. In reality, since the Council meets approximately four times a year, two virtually, the CLT through their monthly conference calls carries out almost all council business. This is a significant work commitment, but having a section voice on the CLT is very important, and Efi has carried out these duties really well.

We should be highly appreciative of the hard work Terri Hogue has done in coordinating the Outstanding Student Paper Awards (OSPA) process for the section, and making sure it runs smoothly. This requires working with the session liaisons to make sure that each student presentation is assessed by three judges. At the 2013 Fall Meeting 401 student presentations were assessed and the section gave out 15 cash awards. This year we expect to judge 481 presentations – almost a 20% increase – that requires almost 1500 assessments. So I encourage you to sign up to be an OSPA judge for those sessions where you may be presenting or know you'll be attending. Terri has been assisted with an incredibly hard working OSPA committee that includes Kolja Rotzoll (U.S. Geological Survey) Laurel Saito (University of Nevada, Reno) Newsha Ajami (Pacific Institute) and Tara Troy (Lehigh University). Besides coordinating the OSPA judging, Terri (and her committee) is also in charge of evaluating the hydrology section student travel grants that are submitted to AGU. This year, if my memory serves me well, there were approximately 150 requests that were judged.

The section can be proud that our student executive representatives, currently Tim van Emmerik, have led the way within AGU in organizing our student and early career colleagues. Last year, with an energetic group of Hydrology Section students, a "Pop-up session" of TED talks allowed the students to exchange research ideas within a session that is less formal than a regular session. This will be repeated this year (9:30am – 11:30am, Tuesday December 16 at the San Francisco Marriott Marquis - Pacific H). Feel free to attend and feel the energy. Also, more interestingly Tim and colleagues proposed to have a Sunday mini-conference directed towards students and early career scientists (December 14, 9am-5pm, Westin Market Street – Metropolitan Ballroom 1) that AGU essentially jumped on to broaden across AGU. This will be followed by a Hydrology student mixer (5-8pm) at the Thirsty Bear (661 Howard Street). Students can get tickets when they register, and the section helping with financial support. On page 3, there is a call be for a new Student Representative since Tim will have finished his PhD. Interested students should talk with Tim and/or attend the Hydrology Section Student Meeting (Dec 16, 6:45-7:45am, San Francisco Marriott Marquis - Pacific I)

One initiative Tim has been exploring ways to increase interactions among students through social media. AGU is also interested in using social media in general to deliver breaking news that would include journal activities. They've asked WRR editor Alberto Montanari and the section to explore how a Facebook page that covers both the section and WRR could serve us. Currently this is a work in progress, but keeping the section members engaged throughout the year is its primary goal.

Fall Meeting highlights are provided on page 4, with a focus on events and eight Town Hall meetings of interest to the section (apologies if I missed any.). The Hydrology Section sessions this year consist of 113 unique topic sessions (71 with oral slots and 42 poster only sessions). There are 106 oral sessions and 111 sessions with a poster component. This wouldn't be possible without the hard work of the section's Fall Meeting Committee, led this year by Charlie Luce (USFS) with the help of Barbara Bekins (USGS) and Bart Nijssen (U Washington). They've done a fantastic job in organizing our sessions under severe constraints.

Finally, I wish to thanks the almost 200 section members who serve on our Technical Committees. The strength of the section at the FM is due to the work of the technical committees. They help propose and organize sessions that are the foundation of our FM, and provide platforms where we can showcase our work. There is certainly lots for all of us to see, hear and enjoy. For members of technical committees, you can find the time and location of your committee meeting during the FM at http://fallmeeting.agu.org/2014/event/section-focus-group-events/.

I've provided an update on the section's budget (see the box on page 3). I wish to thank the 89 section members who donated this year a total of $7,683. Almost all of our expenditures go to supporting student and early career activities. The challenge to the section is to maintain funding these activities when our donations to the section are falling (and as recently as 2011 we received $10,089.) More discussion on the budget situation was in the November 2013 newsletter. Going forward into 2014, our budgeted expenditures have been reduced to better align with our revenues, but we're still running a budget deficit. I know HQ has been aggressive in soliciting donations for their pet projects, but please put donations to the Hydrology Section high on your list.

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Hydrology Section Budget (10/13 to 12/14)

	10/13 – 6/14	*Projected 10/14-9/15*
Revenue		
Donations	$ 7,683.00	
Sponsorship	$ 500.00	
Total Revenue	**$ 8,183.00**	
Expenses		
Student and Early Career Reception	$ 5,501.00	$ 2,000.00
Student subsidized tickets to Hydrology Business Luncheon	$ 2,500.00	$ 3,000.00
Support for CUASHI reception		$ 500.00
Hydrology Business Luncheon expenses (including expenses related to section awardees)	$ 953.00	$ 2,000.00
FM expenses (Horton Awardees) Horton	$ 1,920.00	$ 0[1]
OSPA winners	$ 2,250.00	$ 2,350.00[2]
Total Expenses	**$13,124.00**	$9,850.00
Net Revenue (Deficit)	$ (4,941.00)	

[1] Expense transferred to Horton Research Grant account starting 2014.

[2] Includes 2 student awards at the July 2014 GEWEX conference

Call for Nominations: Hydrology Executive Student Representative

The Hydrology Section Bylaws (http://hydrology.agu.org/bylaws.html) state the Section's Executive Committee should include one student representative. We are seeking nominations for this position (they can be self-nominations), which provides a unique opportunity for a student AGU member to gain practical experience and insights into the Hydrology Section. Attendance at the Fall Meeting (2015 and on) and attendance at the Executive Committee meeting held there is required. Participation in one or more conference calls per year will be required as well. Nominees should expect to be student members (i.e., not complete their graduate studies) until at least June 30, 2016. Please make nominations to the Section Secretary Terri Hogue (thogue@mines.edu) by January 30, 2015.

From the President-elect

Efi Foufoula-Georgiou (University of Minnesota)

I use this short letter to express my gratitude and sincere thanks to our current president Eric Wood for his immense dedication, vision, leadership, and tireless efforts to promote and secure the interests of our section. The Hydrology section is as vibrant as ever and you will all witness this at the fast coming AGU Fall meeting. The young scientists are rejuvenated hosting their own meeting on the Sunday before AGU, the technical committees are strong and full of ideas, diversity in gender, ranks, and points of view is present in our awards and our decision-making committees, and under the capable hands of our WRR editorial team, the impact of our research is steadily increasing. The past two years have been a time of change for AGU: our journals have transitioned to a commercial publisher, new policies have surfaced on one issue or another, and some of us have felt a different culture in the organization as a whole. Rest assured, that there have been plenty of times that Eric has stood up for what would better serve our science and section and has worked hard on behalf of all of us to attend to small and large issues. He has also made all of us aware of the (slim) budget of our section (see Eric's newsletter of November, 2013) and of how important everyones' donation is in creating opportunities for section social functions that bond us increase our rapport as a community intellectually and socially.

So, if you see Eric at the Fall meeting please stop him and say "Thank you!"

Two small news items:

Are you a Facebook fan? (old-timers, do not worry if you are not) -- Our hydrology section together with *Water Resources Research* will soon be launching an "AGU Water " Facebook page to create an interactive way to engage our community between meetings. The content on the Facebook page will revolve around current research trends, high profile topics on water science and policy, highlight papers published in *WRR*, as well as meetings, workshops, and job announcements. Contribute your voice and join us by 'liking' AGU Water on Facebook! I admit that I am not a Facebook user myself (at least not yet) but I do believe that it offers a self-organizing communication space worth exploring for increasing impact and scale. Stay tuned!

Do you worry about posting your paper on Arxiv.org before publication? -- The current AGU "prior publication policy" considers content on arxiv.org as "prior publication" and the AGU copyright policy excludes posting the accepted version there by the authors. At our last Council Leadership Team (CLT) meeting, an amendment was passed that Arxiv.org postings are excluded and not in violation of the AGU prior publication policy. For those of you posting on Arxiv.org (as myself) please note that you are not illegal anymore!

Looking forward to seeing all of you in San Francisco.

Fall Meeting Highlights (Hydrology Events and Town Hall Meetings)			
Hydrology Section Events			
Date	**Time**	**Event/Function**	**Location**
Sunday Dec. 14	9am – 5pm	Student & Early Career Scientist Conference	Westin Market Street – Metropolitan Ballroom 1
Sunday Dec. 14	5pm – 8pm	Student & Early Career Scientist Conference Mixer	The Thirsty Bear 661 Howard Street, San Francisco, CA 94105
Tuesday Dec. 16	6:45-7:45am	Hydrology Section Student Meeting	San Francisco Marriott Marquis - Pacific I
Tuesday Dec. 16	9:30am - 11:30am	Water Sciences Pop-Up Session	San Francisco Marriott Marquis - Pacific H
Tuesday Dec 16	10:20am - 12:20pm	**H22A: Walter B Langbein Lecture and Hydrology Section Awards**	Mascone West 2022-2024
Tuesday Dec 16	12:30-1:30pm	Hydrology Section Business Meeting and Luncheon	InterContinental San Francisco - Grand Ballroom A-C
Wed. Dec.17	12:30 - 1:30 pm	Hydrology Section Executive Committee	San Francisco Marriott Marquis - Sierra E
Wed. Dec.17	6:00 - 8:00pm	Honors Ceremony	Moscone South - Rooms 103-104
Technical Committee Meetings. Please see the time and locations at http://fallmeeting.agu.org/2014/event/section-focus-group-events/			
Town Hall Meeting of interest to the Hydrology Section Members			
Monday Dec 15	6:15pm - 7:15pm	TH15B. Global Precipitation Measurement (GPM) Mission Town Hall	Moscone West - Room 2006
Monday Dec 15	6:15pm - 7:15pm	TH15D. Advancing Drought Understanding, Monitoring, and Prediction	Moscone West - Room 2003

Monday Dec 15	6:15pm - 7:15pm	TH15G. NASA's Soil Moisture Active Passive (SMAP) Mission Town Hall	Moscone West - Room 2004
Monday Dec 15	6:15pm - 7:15pm	TH15E. DOE Crosscutting Subsurface Initiative: Adaptive Control of Subsurface Fractures and Flow	Moscone West - Room 2005
Wednesday Dec. 17	12:30pm- 1:30pm	TH33F. The BiG CZ Software System for Integration and Analysis of Bio- and Geoscience (BiG) Data in the Critical Zone (CZ)	Moscone West - Room 2007
Thursday Dec. 18	12:30pm – 1:30pm	TH43D. Water Science: Building Research Networks in China	Moscone West - Room 2008
Thursday Dec. 18	6:15 - 7:15pm	TH45F Evaluating the Implementation of the Global Earth Observation System of Systems (GEOSS) and Envisioning the Next Decade	Moscone West - Room 2005
Thursday Dec. 18	6:15 - 7:15pm	TH45A. NASA Earth Science Division Town Hall Session	Moscone West - Room 2002

How are papers submitted to WRR reviewed?

(WRR Editorial Board[1])

The title of the present contribution is taken verbatim from a question that is frequently addressed to the Editors of Water Resources Research (WRR). In fact, although the AGU guidelines for reviewing papers apply across the whole portfolio of AGU Publications, authors actually know that papers submitted to WRR are processed in a slightly different manner compared to other AGU journals. Indeed, some journals have a different aim, which is reflected in unique review procedures, and in any case the individual attitude of the Editor gives a personal imprint to the overall articulation and outcome of the manuscript's assessment. On the one hand this is a positive feature: the Editors and the Associate Editors are not mere executors of procedures, they are scientists whose creativity and constructive cooperation with the authors shape the final product of the editing process, which is the journal itself. On the other hand, in executing such an important responsibility, the editors must maintain a certain level of consistency in reviewing and interpreting research findings presented in manuscripts, keeping in mind the mission of the journal. Therefore, we believe it is interesting to describe the philosophy and experience of the current WRR Editors and Associate Editors after about 18 months of their term.

Indeed, we Editors believe that WRR has an important role in the hydrologic and water resources community. We believe that WRR is "our" top journal. Therefore, it should aim to publish high quality papers and should be able to maintain its correspondingly high reputation in the scientific community. Quality means that manuscripts published in WRR are expected to provide support to the development of new theories and therefore the results should have general validity. We recognize the importance of case studies: hydrology and water resources management have relevant technical implications and therefore case studies are frequently needed to provide support to new findings. However, we consider case studies if, and only if, they are instrumental for providing the above support to broadly relevant and original theories and methods.

A submitted manuscript is rejected without review if the Editor is convinced that it does not meet the quality standards of WRR. Contributions may be rejected without review if they are not original enough, are not well organized and written, and/or if they use verbatim material from other previous publications. We are making an effort to take the responsibility to reject papers without review when appropriate, as we believe that it is beneficial for the authors, who get a rapid response when the manuscript is likely to receive a negative feedback from the reviewers. Rejection without review also saves the referees' time, therefore providing a valuable benefit to the scientific community. Requests to review papers are steadily increasing and therefore an optimal allocation of reviewers' resources is needed to avoid a deterioration of the review process. This is particularly appropriate for WRR, whose reviewers are generally very dedicated and spend a lot of time on each single manuscript. During the year 2014 the rejection without review rate for WRR reached 35%. These rejections are mainly managed by the Editor in Chief, who makes a first screening of all the papers submitted to WRR, sometimes in consultation with other Editors and Associate Editors. The management of the majority of the rejections without review by a single person ensures that the judgment is consistent over all the submitted manuscripts. WRR receives about 1500 submissions each year and therefore the papers rejected without review are about 500.

Papers passing the first screening of the Editor in Chief are forwarded to the relevant Editor. WRR now counts 8 Editors (Editors and Associate Editors are listed in the WRR web site) whose expertise covers the broad spectrum of the hydrological sciences. The relevant Editor makes a second screening of the paper's quality and may still decide to reject the manuscript without review. If the second screening is passed, the paper may be forwarded to an Associate Editor, who organizes and oversees the work of the reviewers. Selecting an Associate Editor is not strictly needed, as the Editor may decide to handle the review process herself/himself. The Associate Editor, if assigned, makes a third screening of the paper and, if the outcome is positive, sends the paper out for review by selecting 3 reviewers. In order to speed the process up it was recently decided by AGU to invite one more reviewer than strictly necessary. We usually look at the lists of the author's suggested reviewers and consider it carefully. A proper selection of the suggested referees is a sign of the author’s effort and dedication to the paper and its contribution to the field. We also look at the list of the reviewers to exclude and we almost always honor the author's request. The average time between paper submission and the first reviewer agreement is about 12 days. Reviewers are allowed 25 days to complete their report. The WRR Staff is in charge of providing reminders to reviewers, to make sure that they deliver on time. The reviewers’ work is enormous: the peer review process is essentially on their shoulders and the success of a journal essentially depends on their dedication. Reviewing papers is a job that is not adequately recognized. We WRR Editors are committed, in cooperation with AGU, to establish procedures for better recognizing the work of the reviewers. Presently, we keep note, together with the AGU Staff, of the referees' performances and take them into account when selecting new Associate Editors and the recipients of the AGU "Editors' Citation for Excellence in Refereeing".

When the reviewers’ reports are received, the most difficult part of the review process begins. Sometimes the reviewers are in agreement, but often they are not. The Associate Editor makes an individual assessment of the paper and a synthesis of the reviewers' reports. The Associate Editor is the key player of the review process. He/she is expert in the paper's specific focus area and looks at the originality of the presented ideas. Finally, the Editor makes a further screening of the overall report and takes the decision. When the paper's subject is deemed to be interesting, but a very major overhaul is needed to address the reviewers' comments, the paper maybe rejected by the Editor with an encouragement to resubmit.

Sometimes reviewers are late and we all know that timeliness is an essential requirement for a successful review process. Editors and Associate Editors of WRR are committed to provide the first decision on a paper within 100 days at most from submission. The average time to get the first decision from WRR has been about 69 days for the year 2014. Only in very rare instances did the time for first decision exceed 100 days .

We try to make the final decision for a paper after at most three review rounds (which means that the papers is revised twice). The effective and constructive cooperation of the authors is fundamental to achieve this target. When a paper is finally accepted, the Editor evaluates whether the contribution deserves to be highlighted. Highlighted contributions are pooled together in a dedicated page of the WRR web site. They may be further selected for a press release, which means that the contribution is also highlighted in EOS. Highlighted papers are selected based on the interest of the findings and the importance of the paper for advancing our knowledge of the water cycle and water resources management at the global level. Papers that have a large scale or global focus and that advance new ideas through new data and new models usually attract our attention.

At the end of the peer review process, the rejection rate of WRR is about 65%. Given that about 35% of the papers are rejected without review, it follows that about 50% of the papers that are sent out for review are finally accepted. They are published in about 230 days from the first submission on average (the above timing also depends on author's timeliness in revising the paper).

Finally, about 8 papers every year are awarded with the Editor's Choice Award (ECA), which is delivered during the Hydrology Luncheon at the AGU Fall Meeting. The list of the past ECA recipients is published at the WRR web site.

Keeping the reputation of a journal high, while providing a good service to the individual authors and the scientific community, is a challenging task. It requires dedication and continuous efforts to stay up to date on new research developments and to monitor the status of the publication market. The success of an Editorial strategy means the success of the journal. We are convinced that an excellent journal is an inestimable benefit for the related scientific community. To maintain the top quality of WRR, a continuous and constructive cooperation among AGU, the Editorial Board and the authors is essential. The Editors of WRR are committed to do their best for improving the journal's quality and we believe firmly that effective dialogues with the community of authors will help us in this process. Please do not hesitate to contact us at wrr@agu.org if you have any suggestions or criticism. We are also available to speak with authors during the AGU Fall Meeting week. Please contact us at wrr@agu.org if you would like to speak with us. We are looking forward to your feedback!

[1]Alberto Montanari (Editor in chief), Jean Bahr, Günter Blöschl, Ximing Cai, D. Scott Mackay, Anna Michalak, Harihar Rajaram, Graham Sander (Editors)

2013 Horton Grant Awardee

Using groundwater age to classify groundwater renewal

Kevin M. Befus (The University of Texas at Austin)
Supervisors: M. Bayani Cardenas and Tom P. Gleeson

Rampant, and for some aquifers severe, groundwater depletion sustains the current rates of water consumption worldwide [*Famiglietti*, 2014]. As the global population grows and water demand increases, how much more water can be pumped without lasting consequences?

This eminent scarcity begs the question: is groundwater a renewable resource? With residence times ranging from weeks to tens of thousands of years and beyond, groundwater systems are clearly not as quickly replenished nor reset as surface water. A renewable resource is one that undergoes a natural cycle of replenishment and restoration, but the definition of renewability does not include a formal timeline over which the cycle operates. Therefore, renewability does not imply sustainability. However, if consumption is limited by the renewal rate, then groundwater use may become more sustainable. Thus, on what timescale(s) is groundwater renewed, and how much groundwater is renewable over various timespans?

Quantifying the sustainability of groundwater use has primarily been undertaken by accounting for the fluxes into and out of aquifers, where a balance of the fluxes could, but predominantly does not, imply sustainability [*Bredehoeft*, 2002]. Complicating this analysis is the fact that groundwater extractions are balanced not only by recharge and changes in storage, but also by diminishing discharge fluxes that sustain baseflow to surface waters [*Theis*, 1940]. Thus, a flux-oriented definition of groundwater renewability requires accurate characterization of vadose zone fluxes, hyporheic fluxes, and/or subterranean groundwater discharges at scales relevant to the groundwater system in question in addition to the rates of precipitation and extraction.

Instead of accounting for all of the fluxes, we have used a storage-based approach for quantifying groundwater renewal, where the total volume of groundwater naturally replaced in an aquifer over a timescale of interest is the storage of renewable groundwater for that timescale. Conceptually, this renewable groundwater is the groundwater storage that is younger than the chosen timescale under steady state conditions. Once groundwater dynamics of the system are introduced, the groundwater age distribution that defines the renewable storage changes, and hydrologic fluxes should be considered to address the sustainability and consequences of groundwater extraction.

Using a pre-pumping, storage-based definition of renewable groundwater has allowed us to quantify the "renewable" storage with steady state models of groundwater flow and age (Figure 1). This was an important simplification in estimating the global volume and distribution of groundwater renewed on timescales relevant for human consumption. We chose a timescale of 50 years for the original analysis, approximating the turnover time of human generations and matching the foresight of some policy decisions. A 50 year timescale also minimizes the effects transient boundary conditions would have on the groundwater ages, filtering out or integrating over most seasonal and inter-annual fluctuations [*Gomez and Wilson*, 2013] while not extending so far into the past to require climatic changes [*Rousseau-Gueutin et al.*, 2013]. Our domain was designed after *Tóth* [1963] to consider only topography-driven flow in two-dimensions, using watershed geometries to define the length scales for the flow systems and multiple global hydrologic datasets. We then used the simulated cumulative residence time distribution to calculate a length scale for the renewable water storage that could then be multiplied by the watershed area to estimate the storage volume.

With the assistance of the Horton Research Grant, I will begin to address the simplification of modeling groundwater age in a two-dimensional rather than a three-dimensional system, include the transport of solutes and density-driven flow, and begin to incorporate more realistic fluxes. Together, these analyses will advance our understanding of hydrologic controls on regional-scale groundwater residence time distributions and quantify the relevant timescales of groundwater flow and transport. Additionally, improvements to the model will better characterize the groundwater systems and residence times that may supply more insight to questions of renewability and sustainability.

Groundwater is a renewable resource, but the timescales of groundwater flow remain poorly constrained and are likely to span longer than typical management plans consider. Numerical modeling together with field studies and geochemical analyses, can begin to deconvolute the spatiotemporal heterogeneity of the timing of groundwater flow to understand the scientifically, environmentally, societally, and economically critical question of how old is groundwater and how much can we responsibly use.

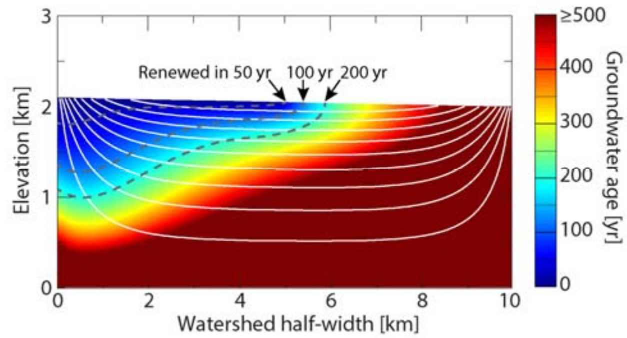

Figure 1. Example two-dimensional groundwater age distribution. Groundwater above the gray dashed lines is renewed over the timescales of interest. White lines show the boundaries of streamtubes, each contributing 10% of the discharge.

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2013 Horton Grant Awardee

The role of bedrock groundwater in headwater catchments: Processes, patterns, storage and transit time

Chris Gabrielli (University of Saskatchewan)
Main Advisor: Jeffrey McDonnell

Headwater, or first order, catchments are the building blocks of the hydrological landscape because of their role in transporting water, nutrients and sediment that sustain the health of ecosystems and humans downstream. They contribute up to half the mean water volume and nitrogen fluxes for fourth -and higher- order rivers in the USA[1]. While much new discovery continues on different components of the headwater catchment water balance[2], catchment storage dynamics have received less attention. Catchment storage is a primary control of both discharge dynamics and subsurface mixing processes[3,4], yet headwater storage changes within bedrock remain poorly characterized[5]. In particular, the contribution of bedrock groundwater to the storage-discharge relationship is difficult to understand and assess, and, as a result, total catchment storage is still largely unknown in most research sites[6]. We are simply unable to predict, a priori, how much water a headwater catchment can store and then release. Baseflow recession analysis[7] and GRACE-based[4] methods have provided insights into catchment scale storage-discharge relationships, however, these black-box approaches fail to resolve internal processes, structures and patterns - information necessary to drive the next generation of catchment scale models[8]. Recent work by Birkel et al. (2011)[9] has highlighted the complexities of catchment storages, identifying both active and passive components that influence differentially, discharge volumes, transit times and solute fluxes. The influence of bedrock as an additional storage volume (beyond the soil mantle) remains the greatest source of uncertainty. A more complete description of the catchment control volume will remain wanting until we have a more complete mechanistic understanding of bedrock groundwater recharge, discharge and storage dynamics.

Bedrock poses a unique challenge to headwater process investigations: the logistical challenges associated with gaining access into bedrock in steep, remote and often roadless terrain combined with complex dual-porosity flow systems have historically thwarted attempts to directly study flowpath dynamics that can contribute considerably to catchment scale mass and energy balances. Geophysical techniques offer a promising way forward, however, interpretation of results are often ambiguous without significant ground truthing. Recent advancements in mobile drilling technology developed specifically for bedrock investigations provides a logistically feasible and economic approach to incorporate direct observation of bedrock groundwater dynamics in headwater catchment investigations. Prior to this work, little access to, or characterization of, bedrock groundwater in the headwaters had been conducted, with previous investigations constrained to the hillslope scale[10,11] or to using bedrock-spring discharge as a proxy for deeper bedrock groundwater dynamics[12,13]. The need still remains for comprehensive catchment scale hydrogeomorphic analysis of the contribution of bedrock groundwater to storage-release and rainfall-runoff processes.

Recent work at the Maimai Experimental Watershed by Graham et al. (2010)[14] and Gabrielli et al. (2012)[15] revealed a currently unsolved inconsistency with respect to catchment storage and bedrock groundwater contributions. Hillslope versus catchment runoff ratios and a bedrock water table response on storm-event time scales suggest that up to 75% of catchment discharge may traverse bedrock flowpaths prior to reaching the stream. Meanwhile the streamwater mean transit time (MTT) is on the order of 4 months - among the youngest streamwater transit times in recorded literature[16]. This is puzzling since the larger storage volume associated with a hydrologically active bedrock formation would presumably lead to longer transit times when streamwater MTT is calculated as storage divided by discharge. Calculation of total catchment storage for the Maimai catchment, based on collected pilot data (and knowing discharge and MTT) is between 500 and 1400 mm, well beyond the storage depth of the thin soil mantle alone. Although these values imply significant stocks of hydrologically active bedrock, preliminary tritium-based groundwater age estimates from bedrock boreholes are close to 3 years, indicating that bedrock storage may be as great as 3000 mm (equal to 25 m of active bedrock using typical porosities for a sandstone based conglomerate). The sharp contrast between tritium-based (3000 mm) and streamwater-based (500 mm to 1400 mm) storage reveals complex catchment scale storage patterns which may provide insights into the driving mechanisms of time-variant streamwater transit time distributions.

The unresolved question of how the Maimai catchment seemingly contains both hydrologically active bedrock *and* short MTTs highlights a lack of understanding as to how bedrock groundwater processes integrate with soil-mantle processes to form the catchment storage-discharge relationship which ultimately drives catchment function. This research aims to unpack the controlling mechanisms of bedrock groundwater recharge, establish how recharge patterns drive discharge patterns and mediate riparian zone biogeochemical and hydrometric dynamics, and ultimately identify how these variable and complex patterns control total catchment storage and transit time distributions.

The first objective of this research aims to identify how landscape structure controls spatial and temporal patterns of bedrock groundwater recharge at multiple scales. Driven by the assumption that patterns of saturation at the soil-bedrock interface control patterns and magnitude of deeper infiltration into bedrock, this work will couple soil and bedrock moisture dynamics with landscape analysis, bedrock formation characteristics and catchment outlet monitoring to quantify patterns and magnitude of bedrock recharge across different geomorphic units and under different catchment wetness conditions. The second objective aims to characterize patterns of bedrock groundwater discharge to understand its influence on riparian hydrometric and geochemical dynamics. Stable isotope (^{2}H and ^{18}O) and geochemical (silica, chloride, and base cations) analysis of hillslope and riparian soil and bedrock water, stream water and precipitation throughfall will be used in an end-member mixing analysis to conduct hydrograph separation and quantify the spatial source patterns of streamflow under both baseflow and stormflow conditions at different points along the stream network. Results will be correlated with upslope recharge dynamics from Objective 1 to provide insight into the controlling mechanisms driving both the timing and magnitude of hydrometric and hydrochemical response within the riparian zone. The third objective leverages the intimate knowledge of catchment form and function gained from the first two objectives with tritium-based soil and bedrock groundwater ageing at different landscape positions within the catchment. This final step will reveal how unique geomorphic features contained within a single catchment differentially store and release their waters and ultimately integrate to create the time-variable transit time distribution through complex storage-release patterns.

The Maimai Experimental Watershed where this research is being conducted boasts a rich 40 year history of headwater investigations and stands as benchmark watershed that has helped shape the disciplines understanding of catchment runoff processes. This unique history offers a valuable platform from which to frame this continued work and provides insights that would otherwise be difficult to obtain in less well-studied sites.

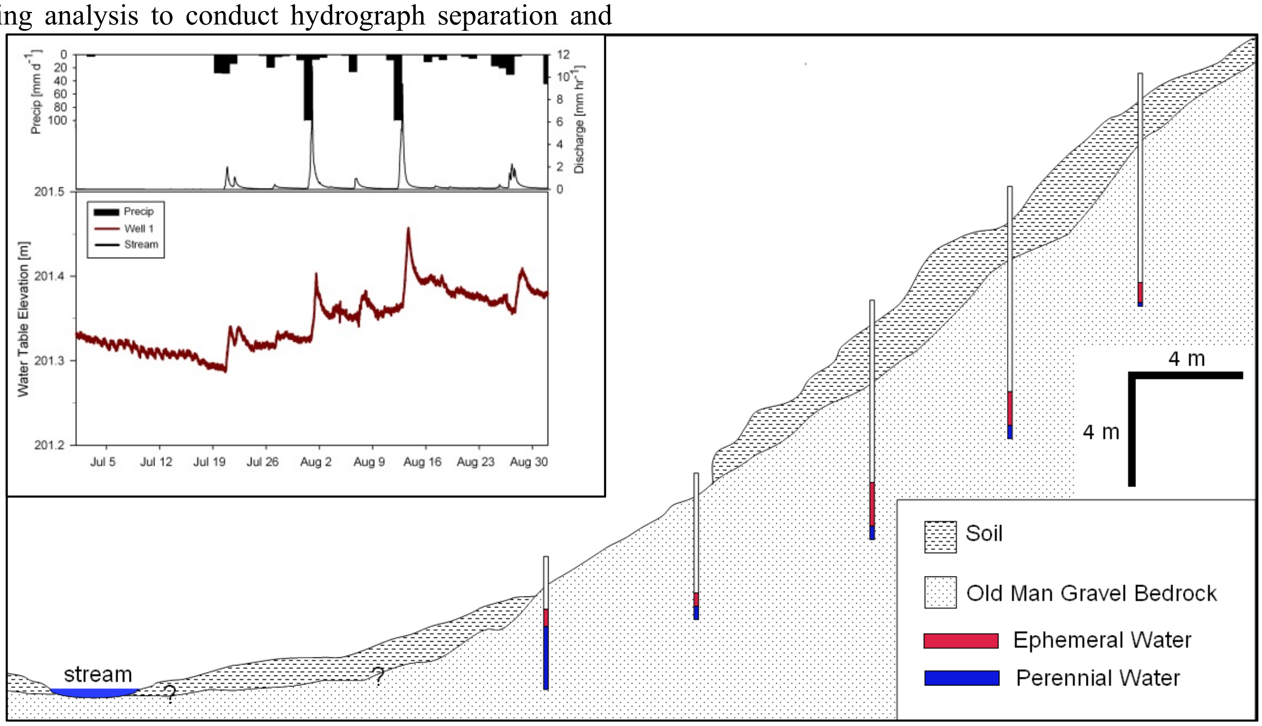

Figure 1. Profile of instrumented M8 hillslope showing well depths, water level dynamics through the duration of the study period and geology. Here perennial water is defined as water that was present in the well through the duration of the monitoring period, while ephemeral water exists only during precipitation events. The inset shows water table dynamics in bedrock well 1, nearest the stream. Note both the diurnal fluctuations during the initial dry period and the highly synchronized dynamics with stream discharge.

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2013 Horton Grant Awardee

Assessing organic carbon storage and carbon dynamics in boreal river floodplains

Katherine Lininger (Colorado State University
Advisor Ellen Wohl

Until recently, rivers were seen as 'neutral passive pipes' within the carbon cycle, carrying carbon from the terrestrial environment to the oceans (Cole et al., 2007). However, recent studies indicate that freshwater systems can store significant carbon and outgas carbon directly to the atmosphere (Battin et al., 2009; Cole et al., 2007), demonstrating that river systems are an aspect of the hydrologic cycle that influences global climate. Organic carbon (OC) enters river systems through soil erosion, riparian inputs of organic matter (e.g., leaf litter, fallen wood), and primary production within rivers. OC leaves channels through sedimentation in floodplains and deltas, uptake by biota, respiration and oxidation, and transfer downstream (Aufdenkampe et al., 2011). The geomorphic and hydrologic characteristics of river-floodplain systems, including grain size, physical complexity, channel-floodplain connectivity and inundation patterns, influence OC dynamics (Noe and Hupp, 2005; Pinay et al., 1992; Wohl et al., 2012). Although research has begun to constrain the amount of OC stored in floodplains and the residence time of these stocks (e.g., Cierjacks et al., 2010; Wohl et al., 2012), studies are few and restricted to the temperate zone.

We are addressing knowledge gaps in floodplain carbon storage by investigating total organic carbon (TOC) storage and residence times in floodplain sediments and downed wood within the Yukon Flats National Wildlife Refuge (YFNWR) in interior Alaska. The YFNWR spans the transition between discontinuous and continuous permafrost and contains large floodplain lowlands of the Yukon River and its tributaries. Climate change is already impacting the hydrology and permafrost distribution in the region (Walvoord and Striegl, 2007). The northern polar regions contain ~50% of the total subsurface carbon stock worldwide (Tarnocai et al., 2009), highlighting the importance of constraining storage and residence times of carbon stocks in boreal and arctic areas. Because the decomposition and oxidation of organic matter within soils is slowed in cold, wet conditions (Davidson and Janssens, 2006), boreal and arctic river floodplains likely contain larger OC stocks relative to floodplains in warmer and drier climates. Although there are some coarse-scale estimates of the depth of the surficial organic layer (e.g., moss and litter layer) within the Yukon River Basin (Pastick et al., 2014) and fine-scale studies of soil OC in upland environments (O'Donnell et al., 2011), organic layers and subsurface mineral soils in boreal lowland floodplains have not been adequately quantified.

Figure 1. One of our camps along the Dall River (top left), an aerial view of Preacher Creek from a float plane (top right), taking floodplain soil samples with an auger in full mosquito protection (bottom left), and portaging boats and gear around logjams through the floodplain brush (bottom right).

Our research questions include: 1) do high-latitude floodplains store more TOC (Mg/ha) in floodplain sediments and downed wood relative to other climatic zones?; 2) how do the geomorphic characteristics of diverse river-floodplain systems within the YFNWR control the storage and residence time of TOC?; and 3) what is a first-order estimate of the floodplain TOC storage within the YFNWR?

We completed our first field season in the summer of 2014, working on the Dall River and Preacher Creek, which represent common river types within the refuge (figure 1). The Dall River is meandering with finer bed and bank material (sands, silts, and clays) and steep, high banks. Preacher Creek is anastomosing with a tendency to braid, transporting larger grains (sands and gravels). We spent approximately two weeks floating down each river, stopping at intervals of tens of kilometers to sample within the floodplain.

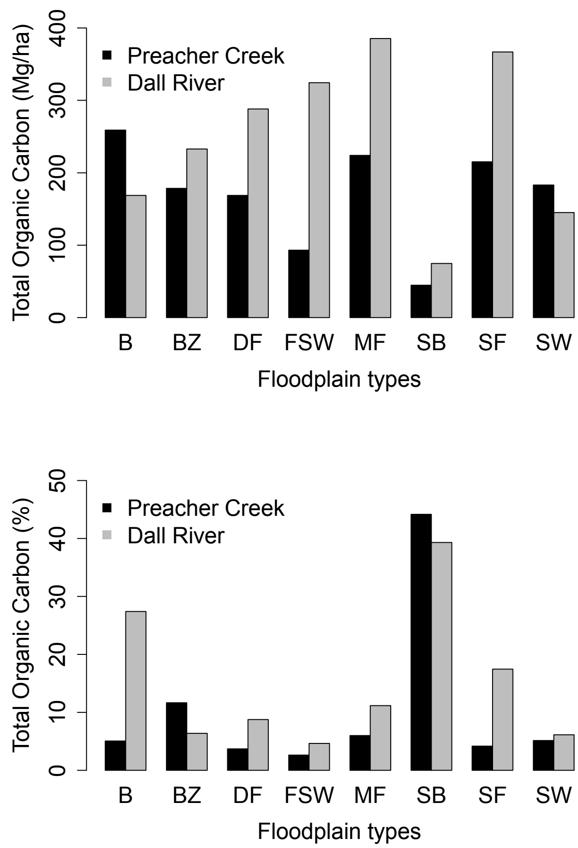

Figure 2. Average values of total organic carbon in Mg/ha (top panel) and percent of total sample by weight (bottom panel). These values include the surficial organic layer and the mineral soil samples. Floodplain vegetation types are: B-bog, BZ-burned zone, DF-deciduous forest, FSW-filled standing water, MF-mixed forest, SB-sphagnum bog, SF-spruce forest, and SW-standing water

We collected sediment samples at 152 locations at regular depth intervals within the active-layer, the top-most seasonally thawed soil layer, using a hand auger, with the organic layer taken as a separate sample. The locations of samples were designed to capture the greatest variability in floodplain environments. Samples have been post-stratified into floodplain types based on vegetation community and geomorphic feature. The proportion of TOC (analyzed by loss-on-ignition for organic layer samples and with a CNH furnace for mineral soil samples) in samples will be converted to TOC in Mg/ha, and all samples will be analyzed for grain-size distribution. Initial results from a portion of our samples demonstrate that the mean values of TOC in Mg/ha and as a percentage of the total sample differ by floodplain type and between rivers (figure 2). These initial results support one of our hypotheses that the Dall River contains more TOC than Preacher Creek, due to slower rates of lateral migration and finer grain sizes. We also surveyed downed wood within the floodplain and cored trees to get minimum ages of the floodplain surface. Buried wood and charcoal taken for radiocarbon dating, along with the tree cores, will provide information on the residence time of OC within floodplain sediments.

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Linking Soil Systems and Critical Zone Processes

Dani Or (ETH Zurich) – SSCZP technical committee co-chair

The Soil Systems and Critical Zone Processes (SSCZP) technical committee was established jointly by the Hydrology and Biogeosciences sections to promote soil and the critical zone as a central biogeochemical-hydrological interface teaming with life and providing ecosystem services critical for life support and for meeting nutritional needs of human population. The integration of soil systems into contemporary cross-disciplinary initiatives and policy panels that address global challenges (climate change, food security, water and land resources and ecosystem health) involves a broad range of activities across scientific communities and disciplines. In addition to increased awareness of soil processes among the AGU community, as illustrated by establishing a *Global Soil SWIRL* (2013 and 2014 Fall meeting programs), members of the SSCZP have been active in organizing several interdisciplinary conferences to engage a range of disciplines including ecology, atmospheric science, biogeochemistry, hydrology, and geological sciences in this outreach challenge. Following the inception of the SSCZP TC (Fall 2012), we organized in 2013 two interdisciplinary conferences; in Monte Verita, Switzerland on *Soil Systems and Critical Zone Processes – Integrating Life Support Functions across Disciplines* (http://www.intersoil2013.ethz.ch/index.php), and an AGU Chapman conference supported by the NAS on *Soil-mediated Drivers of Coupled Biogeochemical and Hydrological Processes Across Scales* (http://chapman.agu.org/soil-mediated/). These activities continued in 2014 with involvement in a conference in Berkeley on *A Path to Improved Understanding of Complex Soil Systems* Supported by SSSA and the Berkeley Lab (http://esd.lbl.gov/research/programs/ERWR/soils_conf erence/), and in the *Sixth International Workshop on Soil and Sedimentary Organic Matter Stabilization and Destabilization* (SOM6 - http://www.som6workshop.org/).

The GEWEX-Soil Communities: The interdisciplinary meetings made it clear that the soil and climate communities need to foster stronger links leading to an ongoing effort to link soil and critical zone with climate modelers through participation in the GEWEX project (temporarily termed the "GEWEX-Soil communities"). The new co-chairs of GEWEX (Sonia Seneviratne and Graeme Stephens) have graciously agreed to identify topics of mutual interest and devise plans for facilitating such involvement. Preliminary topics of joint interest and potential collaboration were presented to several GEWEX panels at a meeting in Den Haag (July 2014) – these included:

a. Leveraging knowledge and operation experiences to integrate critical zone observatories (CZO) and similar eco-hydrological observatories within GEWEX activities (TERENO; ICOS; and potentially CUAHSI in coordination with NSF CZOs http://criticalzone.org/national/)
b. Formation of a global lysimeter network to inventory, standardize, and expand coverage of lysimeter observations (an effort led by Julich)
c. Integration of the ongoing initiative to form an *International Soil Modelling Consortium* (see more below) to improve links between climate, ecology, hydrology and soil modelers concerning available soil processes models, data sets, model repository (effort led by Julich)
d. Expansion of simple and low-cost soil moisture monitoring networks – following the model of *Texas Soil Observation Network* (TxSON - http://www.beg.utexas.edu/soilmoisture/)
e. Incorporation of near surface soil processes in regional and global hydrologic and observational models (surface evaporation and energy balance physics; plants-soil interactions)
f. Global soil map (www.globalsoilmap.net) discussions with Dominque Arrouays and Alex McBratney (leaders) to enhance the GEWEX-Soil initiative

The discussions with the GEWEX panels were positive and supportive, and it was decided to plan a joint workshop in 2015 to identify knowledge gaps and synergies among the communities (dates and venue are not yet available). Information is presently shared with an ad-hoc core group with a range of expertise in the soil-climate interface, with progress in collaboration plans, the interactions will be expanded to facilitate a broader participation (we will post a link on the SSCZP website).

The International Soil Modeling Consortium (ISMC- https://soil-modeling.org/): Traditional soil models have been instrumental in the quantification and prediction of soil processes and related ecosystem services. However, as data collection capabilities and resolution rapidly expand present soil models rooted in the profile or field scale are ill equipped to assimilate and benefit from the new informational capabilities. A new generation of soil models, that integrate physical, mechanical, chemical and biological processes across scales is needed to broaden access of soil processes across disciplines and enhance availability for decision makers. The closing of knowledge gaps and developing new generation soil models is necessary to improve understanding of climate-change–feedback processes, account for ecosystem services, link basic soil science research and management, and facilitate communication among disciplines and with society. A recent international community effort was launched earlier this year to meet these challenges through the formation of an *international soil modeling consortium* (ISMC). The activity is patterned after similar initiatives in systems biology, hydrology, and climate. A preliminary meeting took place during the EGU 2014 spring meeting in Vienna where general objectives and path forward were charted. A multi-author white paper on "Challenges and perspectives in modelling soil processes" is being developed to systematically identify the scope and scientific needs considering the state-of-the art in soil modeling. Additionally, a special session is organized for the 2014 AGU fall meeting (H54E: *Perspectives and Challenges in Modeling Soil Processes*). A formative workshop is planned for March 2016 at UT Austin to solidify the concept, governance and operation of the ISMC.

2015 International Year of Soils: The 68th UN General Assembly declared 2015 the International Year of Soils (IYS) in addition to declaring December 5th as the World Soil Day (WSD). Among the activities for raising awareness for soil, an Intergovernmental Technical Panel on Soils (ITPS) was established at the first Plenary Assembly of the Global Soil Partnership held at FAO in June, 2013. The main function of the ITPS is to provide scientific and technical advice and guidance on global soil issues to the Global Soil Partnership primarily and to specific requests submitted by global or regional institutions. Members of the SSCZP TC are participating in developing a report on the *Status World Soil Resources* to be presented at the upcoming world soil day in December 2014.

The ISMC and a few other initiatives related to the GEWEX-Soil effort are led by Harry Vereecken from Julich research center (Germany) – Harry was elected and approved as the incoming co-chair of the SSCZP TC from the Hydrology section (starting Dec. 2014). I take this opportunity to welcome Harry - he will serve with Kate Lajtha (Oregon State Univ.) the Biogeosciences co-chair.

The Fellow Speaks: Seeing the Forest from the Deep in the Trees

Michael Dettinger (USGS)

We hydrologists often are so focused on the details of the river or reach at hand that everything about it seems special. However, the world's rivers, aquifers, and water resources are tied together in ways that we neglect at our peril. One key tie that binds disparate rivers and streams is shared responses to regional-scale climatic forces. Recognition of these ties is increasingly allowing us to detect and anticipate important parallels between hydrologic fluctuations and trends in seemingly distant river basins and regions. Knowledge of those distant connections (Fig. 1) provides a better scientific basis for prediction of droughts, floods, and water resources from months to years in advance. And, our growing understanding of the shared fluctuations are a scientific foundation for projecting effects of future climate changes on our rivers and resources.

Figure 1: Large-scale climate variations influence the oceans, wind patterns, and storm tracks in the Northern Hemisphere, ultimately driving large-scale fluctuations of rivers and water supplies (e.g., Dettinger and Diaz, J. Hydromet., 2000)

The catch is that the variations of hydroclimatic conditions that determine streamflow and groundwater recharge generally seem erratic and unpredictable. This does not mean, however, that they are strictly random.

My career in hydrology began back in the late 1970s as an MIT student at a time when the new thing was developing ever more devious forms of randomness to represent inflows to water systems. Other approaches incorporated more "upstream" physical process but still represented weather as random. Upon emerging from school to deal with real-world systems, though, I found myself confronting progressively larger geographic scales and hydrologic systems. The larger my "focus" grew, the more the large-scale organization and parallels between atmospheric forcings and responses (e.g., across the Great Basin and western US) that I encountered gave lie to simplifying assumptions about a random hydrology.

Rather, when viewed on time scales and geographic scales close to the atmospheric processes that give rise to them, coherent regional patterns of hydrology were evident. As an example, consider fluctuations of rivers as far apart as the Sierra Nevada, Yellowstone, and the southern Rockies. On a day-to-day basis, my colleagues and I saw that springtime fluctuations are synchronized by essentially simultaneously waxing and waning snowmelts (Fig. 2). Although each river's fluctuations *are* its own, discharge in streams vary in a remarkable lockstep across the western states. This synchronization of snowmelts and streams reflects (mostly) temperature changes from broad weather systems marching across the West every few days. Considered further, this sort of synchronization extends well beyond day-to-day to include seasonal, interannual, and increasingly centuries-long changes.

As another example, viewed across the rivers of western North America—which is roughly the scale of winter-to-winter differences between north-south positions of Pacific storm tracks—El Nino events in the tropical Pacific most often yield recognizable and recurring patterns of precipitation that favor a wetter-than-normal

Southwest and Florida, and drier-than-normal Northwest. The opposite of an El Nino in the tropical Pacific is a "La Nina", and La Ninas very reliably yield a wetter-than-normal Northwest and drier-than-normal Southwest. At these scales, El Ninos, along with other large-scale climatic processes like the Madden-Julian Oscillation, North Pacific decadal variations, and various still more distant climate modes, impose geographic organization on time scales ranging from weeks to decades. Although these climate processes are not as predictable in time as we would like, they yield geographically well-organized patterns of hydrology and water resources.

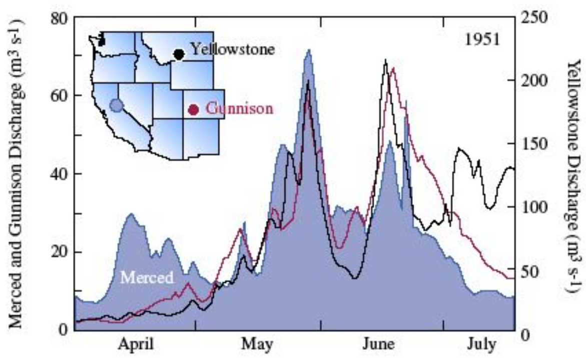

Figure 2: Comparison of streamflows in the Merced, Gunnison, and Yellowstone Rivers during spring 1951 (Peterson et al., JAWRA, 2000).

So a lot of my research has been about untangling the unpredictable from the organized, trying to push back frontiers of what we (for practical purposes) end up treating as "random". Hydrologic implications of climate fluctuations and climate changes have yielded to analysis to a considerable extent in recent years, in terms of providing better understanding of large-area patterns of hydrologic variation. At the same time, short-term weather-driven hydrologic fluctuations are being forecasted with increasing skill. Indeed, the current scientific frontier is the problem of making and using connections between the geographic organization that climate provides and the improving temporal forecastability of weather. In traditional terms, climate is essentially long-term statistics of weather, but increasingly we are recognizing that weather is organized or modulated by a whole other set of conditions and processes that we recognize as climate. An example of the kinds of problems at this climate-weather interface: An accurate 5-day forecast of some weather event that tripped us into a new climatic state would have predictive uses far beyond the weather scale…but only if we recognize how much that weather forecast implies.

One avenue into the weather-climate interface, especially as applies to hydrology, that I have been pursuing--with the help of many indulgent colleagues from Scripps, USGS, NOAA and elsewhere--is through the mechanism and impacts of atmospheric rivers (ARs, Fig. 3). ARs are continually moving and evolving, long, narrow corridors along which many Mississippis-worth of water (vapor) are transported. It has been estimated that >90% of all atmospheric vapor transport outside the tropics is conducted along these "rivers", and when one of them runs aground upon mountains, the amounts of precipitation that they yield is often prodigious. More than 80% of all floods in our Pacific Coast states have been fed directly by the structures and 85% of variance in multiyear wet-dry cycles in California are associated with periods of AR presence or absence. Between conducting >90% of the atmospheric water cycle (surely, a climate-scale role) and their rapid and erratic movements and evolutions (a weather-scale characteristic), I suspect that ARs can provide us access to the weather-climate interface. If we can better understand connections, like these, between climate and weather, we may be able to leverage our understanding of each: our ability to predict long-term patterns of hydrology, if not the temporal details, afforded by growing understanding of climate, and our increasing capacity to forecast temporal variations of weather. One can only hope.

Thus, there is a whole spectrum of levels of organization and predictability of hydroclimates and, consequently, of hydrology once a geographically broader viewpoint is taken. That spectrum ranges from extremely regular and largely predictable variations (like changing seasons) to spatially organized but essentially unpredictable modes. In the midst of this spectrum, and interacting with it, we—of course--now have another form of climate variation, one that is actually becoming more organized and more predictable as time goes on. This "other" mode is long-term anthropogenic climate change in response to increasing greenhouse-gas concentrations in the atmosphere (along with many poorly understood contributions from other human-induced insults to Earth and climate systems). The increasing predictability of the climate changes that we have in store comes both because our understanding of the processes involved is improving *and* because their predictable consequences are themselves rapidly rising above noisy natural climate variations.

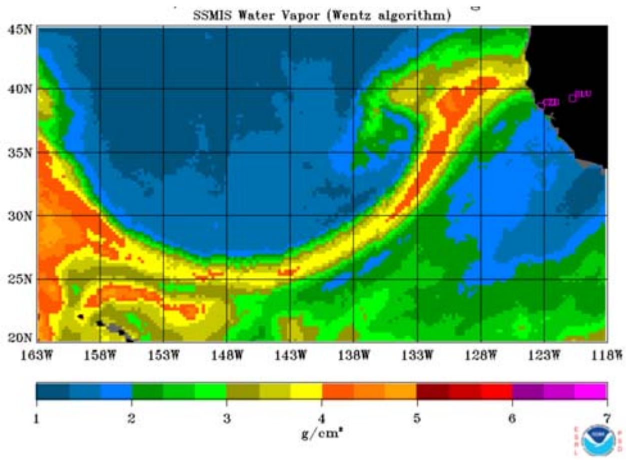

Figure 3: An atmospheric river (AR) making landfall on the coast of the Pacific North Northwest, as visualized from SSM/I vertically integrated water vapor imagery, October 24, 2014 (see Ralph and Dettinger, Eos, 2011, for more AR background).

Admittedly, the large-scale patterns that I have been writing about are often beyond any water managers' control. By learning to recognize and subtract the climatic patterns in streamflow, though, other, more local and more locally managed influences on streamflow can be better understood. Studies of the largest scale fluctuations of water resources thus provide a scientific basis for understanding, predicting, and managing water resources on time scales from days to decades. They advance our ability to protect and integrate resources among basins and across borders, and extend the effectiveness and reliability of water supplies and land-management policies even within basins. Modern hydroclimate and hydrometeorologic research is teaching us to "see the forest from deep in the trees," to step back from views of hydrology that concede too much to randomness. And, as I go forward, I certainly want to keep pushing back on the random.

The Fellow Speaks: Sometimes You Get Only One Chance

Paul Hsieh (U. S. Geological Survey)

I am grateful to AGU for selecting me as one of the five recipient of the 2014 Ambassador Award, which also includes election as a Union Fellow. I thank my colleague Steve Ingebritsen for nominating me. As Steve's citation mentions my work on the Deepwater Horizon oil spill response, I would like to reflect on this experience.

The Deepwater Horizon oil spill is well documented in the report of the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011). *Washington Post* writer John Achenbach's (2011) book gives a behind-the-scene portrayal of the crisis and explains oil drilling technology in layman's terms. A special feature in the *Proceedings of the National Academy of Sciences* (v. 109, no. 50, December 11, 2012) presents 4 perspectives and 11 research articles on "Science Applications in the Deepwater Horizon Oil Spill." Here, I will simply share my personal perspective.

In June of 2010, when I was detailed to the oil spill response effort, a government-led science team had already been in operation for over a month. Headed by then Secretary of Energy, Steven Chu, the team consisted of several prominent scientists, serving as advisors to the Secretary, and a group of staff scientists, comprised of individuals from the Department of Energy National Laboratories and the U.S. Geological Survey. The role of the staff scientists was to analyze the condition of the Macondo well and the operations to contain the spill. Given the crisis setting, these analyses had to be done within a matter of a few hours to a few days. The results would then be presented and discussed at meetings, often with sharp questioning by the Secretary and his advisors. At times, the meetings took on the atmosphere of a dissertation defense. Even seasoned scientists would be mentally transported back to their graduate school days!

When the Macondo well was shut in on the afternoon of July 15, the elation from the cessation of oil flow was subdued by the lower than expected pressure observed in the capping stack. Might this indicate that the well casing was damaged by the explosion that started the spill, and now oil was leaking out of the casing beneath the seafloor? Such a leak could cause an underground blowout, which would not only restart the oil spill, but create a situation much more difficult to control (Hickman et al., 2012). To avert this potential catastrophe, the well would have to be reopened if it was believed to be leaking. According to the protocol developed by the science team, a decision on whether or not to reopen the well would have to be made within 24 hours after shut in.

The immediate path forward lay in analyzing the pressure data collected as the well was shut in. Perhaps this additional information could shed new light on the oil reservoir. As the person providing reservoir modeling support for the science team, I was given the assignment to carry out this analysis. The work would have to be done overnight. There would be no opportunity for revision. A minor oversight could be disastrous. As I worked, I kept thinking of the crash of NASA Mars orbiter because one engineering team used metric units while another used English units. My analysis (Hsieh, 2011) suggested that the low pressure in the capping stack was due to a larger than expected depletion of the reservoir pressure. The well casing appeared to be undamaged.

The prevailing thinking among the government-led science team, however, was that the well should be reopened. It was up to Secretary Chu to make the final call. In my opinion, Secretary Chu's approach exemplified decision making under uncertainty in a crisis situation. The risk of a blowout had to be balanced against the benefit of stopping the spill. If a risk were to be taken to keep the well shut, it should proceed in such a way that recovery would be possible should the decision proved incorrect. To implement this strategy, an intense effort was set in motion to monitor the area around the well. The decision to keep the well closed would be reevaluated every six hours. At the first sign of a leak, the well would be reopened. As each anxious day passed, the monitoring showed no indication of a leak, and the well remained closed. Secretary Chu's strategy worked. The oil spill had stopped for good.

Everyone was in a celebratory mood on August 5. A few days earlier, the static kill operation was successful in filling the well with heavy drilling mud. This was followed by filling the production casing with cement. Although the Macondo well was not yet entirely "dead," the capping stack no longer had to hold thousands of psi of oil pressure. At an informal gathering to celebrate the occasion, the tension between Government and BP personnel eased as everyone enjoyed cake and champagne. However, looming ahead was the lawsuit by the United States against BP for polluting the Gulf of Mexico.

Soon after the start of the oil spill, the Department of Interior issued a document-preservation order to all of its employees. In my office was a large box in which I kept all papers related to the incident. In October 2011, every page was electronically scanned and sent to the Department of Justice (DOJ), along with a copy of my entire computer hard disk, plus every email message for an entire year starting from the day 1 of the spill. The documents and computer files would be available to both the DOJ and BP for use in litigation. Then, in early 2012, the DOJ informed me that I would be called to testify as a witness for the Government. I should start making preparations.

In working with the DOJ attorneys, I learned that the legal process is quite different from the scientific process. Even though debate and disagreements are essential to both processes, the scientific process is essentially cooperative, while the legal process is essentially adversarial. In the scientific arena, the work of one investigator builds on the previous work of others. Authors of scientific papers are expected to acknowledge the strengths and weaknesses of their work, for example, which conclusions are well supported by data, and which conclusions are tenuous and require further research. In litigation, however, each side holds firm to its position and attacks the position of the opposing side. In theory, if both sides do their jobs capably, the truth emerges. However, the adversarial approach could readily frustrate or even infuriate someone unaccustomed to the legal process. An opposing attorney might portray a question in an email as a disagreement. A revision from one draft to the next might be construed as an attempt to fudge results. I had to keep reminding myself: keep cool; don't take it personally.

By the time I testified in Federal Court in New Orleans in October 2013, three years have gone by since the Deepwater Horizon oil spill. Nonetheless, the events were still vivid in my mind. I had reviewed numerous times my participation in the oil spill response: dates and times, meetings, conversations, calculations, data, reports, email messages, etc. All the preparation came to a close as I stepped into the witness box. Based on the testimony that I gave in two and a half hours, a period that seemed both interminable and brief, a Federal Judge would decide on my competence and trustworthiness.

From my Deepwater Horizon oil spill experience, I learned that sometimes you get only one chance. Unlike working on projects with timelines of months or years, when there is ample opportunity for contemplation and revision, sometimes the first cut is the final cut. Hopefully, when faced with such a situation, one is ready to act and make a difference.

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The Fellow Speaks: Role of the Unsaturated Zone in Linking Land Surface Processes and Climate Forcing with Underlying Aquifers

Bridget Scanlon (University of Texas)

I am extremely grateful to the colleagues who nominated me for AGU fellow and would like to thank all the people who have helped me in my career.

Much of our research has focused on the unsaturated zone, which, as Dave Kinniburgh suggested, provides a key to the past, recording subsurface response to climate variability and land use change, and a guide to the future by projecting how water and solute inputs will affect underlying aquifers. Use of unsaturated profiles to evaluate paleohydrology is somewhat akin to the use of ice cores to assess paleoclimate. Our initial work on characterizing unsaturated flow in the Chihuahuan Desert in West Texas showed that these arid regions are generally characterized by upward flow over recent millennia, based on integration of soil physics and chemical and isotopic tracer data. Adaptation of the chloride mass balance approach, previously used in groundwater studies, to unsaturated systems provided a valuable approach for quantifying extremely low fluxes in desert soils with relatively high accuracy (Scanlon, 1991). Nonisothermal flow simulations provided quantitative estimates of liquid and vapor flow consistent with the tracer results, indicating that these desert systems had indeed been drying since the late Pleistocene. Subsequent work showed that there had been no recharge beneath vast areas of natural vegetation throughout the desert Southwest for periods up to 90,000 years (Scanlon et al., 2003), in agreement with the findings of Phillips (1994) from chloride data.

Our early work, focusing on site characterization for radioactive waste disposal, showed the importance of deep rooted perennial vegetation in controlling partitioning of water at the land surface and its effectiveness in precluding deep drainage below the root zone. This work was followed by detailed monitoring of engineered covers for waste containment, which provided a field lab to test different hypotheses with respect to unsaturated zone fluxes. The site was like Swiss cheese given the density of instrumentation including neutron logging holes, time domain reflectometers, heat dissipation probes, and others. Bob Reedy did an incredible job of calibrating and installing these instruments. Collaborations with other researchers at national labs allowed us to compare results from semiarid West Texas with warm desert sites in New Mexico and cold desert sites in Idaho. Detailed monitoring data provided an opportunity to test the ability of different numerical models to simulate unsaturated flow in these systems (Scanlon et al., 2002). Accidental flooding of the engineered covers over a holiday weekend demonstrated the ability of vegetation to respond rapidly to moisture as detailed monitoring revealed no drainage below the capillary barrier (Fig. 1). We extended this work by comparing monitoring data from vegetated and nonvegetated lysimseters at the Nevada Test Site to isolate the importance of vegetation in controlling ecologic responses to climate fluctuations, such as the 1997-1998 El Nino (Scanlon et al., 2005). Results from the lysimeters were expanded regionally using normalized difference vegetation index data from MODIS and were consistent with vegetation responses to climate extremes in other semiarid regions in Africa (Anyamba et al., 2002). The strength of the linkages between precipitation and vegetation response led Gray and Tapley (1985) to refer to vegetation health as nature's climate monitor and use of NDVI as a proxy for precipitation monitoring in Africa because of limited gages (Gray and Tapley, 1985). These studies provided a strong foundation for the emerging field of ecohydrology (Newman et al., 2006).

With increasing recognition of the importance of vegetation in controlling water fluxes in semiarid regions, we turned our attention to what can be considered the largest experiment in terms of vegetation, i.e. conversion of deep rooted perennial native vegetation to shallow rooted annual crops. Initial studies in the southern High Plains of Texas showed that cultivation increased deep percolation below the root zone, indicated by flushing of salts from the unsaturated zone and consistent with rising groundwater tables and increasing groundwater salinities. These results applied to semiarid regions throughout the southwestern U.S. (Scanlon et al., 2005) and globally as described in a synthesis paper on the global impacts of agricultural conversion on water resources in semiarid regions (Scanlon et al., 2007). Similar results were found for West Africa by Favreau et al. (2009) as had also been reported for many regions of Australia (Allison et al., 1990). If land use changes from perennial vegetation to annual crops increased water resources in these semiarid regions, then reversal of these changes with growth of plantations for carbon sequestration led Jackson et al. (2005) to suggest that this process might result in trading water for carbon.

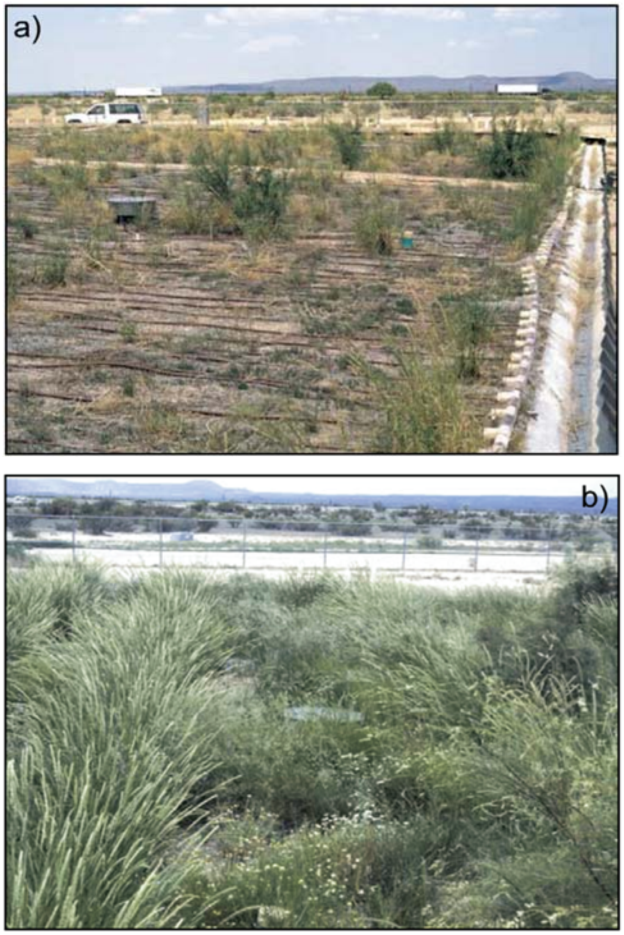

Figure 1. Photos showing importance of vegetation in controlling subsurface flow: a, normal conditions, b, after flooding.

Although conversion to rainfed cropland in semiarid regions generally increased groundwater resources, irrigated agriculture has greatly depleted groundwater in many regions and can be considered the elephant in the room because it consumes an estimated 85% of the global freshwater resource (Siebert et al., 2010). We began to evaluate the impacts of irrigation on water resources in the mid-2000s in the US High Plains. In irrigated regions, increased recharge from cultivation is masked by groundwater depletion from irrigation. The High Plains aquifer is the most intensively monitored aquifer globally, with groundwater levels monitored in up to 9000 wells annually. Comparison of data across the High Plains showed that much greater groundwater depletion in the central and southern High Plains could be explained by lower recharge in these areas, with most groundwater at least thousands of years old (McMahon et al., 2006), relative to higher recharge in the north, e.g. in the Nebraska Sand Hills. Detailed comparisons of groundwater depletion in the High Plains and California's Central Valley provided valuable, if sobering, insight into the controls and dynamics of groundwater depletion (Fig. 2, Faunt, 2009; Scanlon et al., 2012).

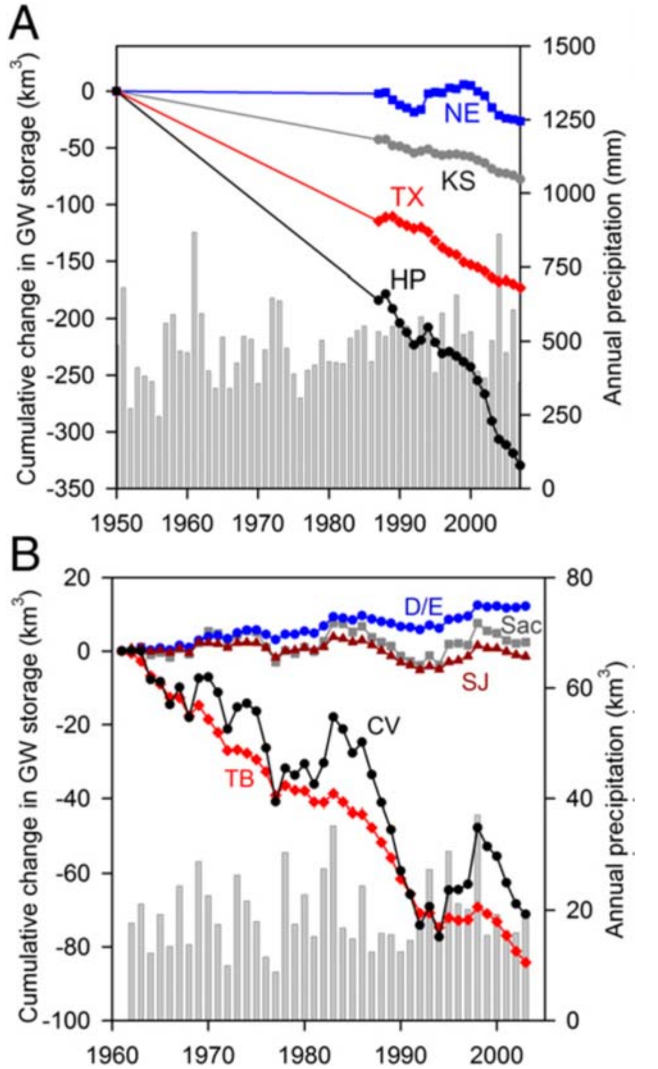

Figure 2. Trends in groundwater depletion in (A) the High Plains (HP) and (B) the Central Valley (CV) aquifers from Scanlon et al. (2012). Depletion is spatially variable and concentrated in the southern regions of both basins, Texas in the HP and Tulare Basin in the CV. The HP data show generally monotonic declines based on water level monitoring in 3,600 wells (1950s) to 9,600 wells (2006). Water level changes in the CV are much more dynamic with declines focused during droughts (1976–1977, 1987–1992, 1998–2003) and recovery at other times. D/E, Delta, Eastside; Sac, Sacramento; SJ, San Joaquin; TB, Tulare Basin.

The advent of the GRACE satellite data in the early 2000s provided another set of eyes to monitor total water storage changes, led by the seminal work of Jay Famiglietti, Matt Rodell and others now at NASA. Although GRACE provides a new set of eyes, they come with cataracts because they are so far away, orbiting ~400 – 450 km above the land surface. Changes in gravity monitored by GRACE at monthly timescales are controlled primarily by changes in the distribution of water, because changes in mass are due, almost entirely, to changes in terrestrial water content. Many studies estimate changes in groundwater storage from GRACE–based changes in total water storage by subtracting other variable components of the water budget, principally soil moisture storage changes. Our work using GRACE satellite gravity measurements provided unequivocal evidence of widespread groundwater depletion from critical U.S. aquifer systems, particularly those underlying the economically vital agricultural regions of the High Plains and California's Central Valley (Strassberg et al., 2007; Longuevergne et al., 2009; Scanlon et al., 2012). More recent applications of GRACE for assessing Texas water resources showed large declines in total water storage in response to drought and difficulties in disaggregating total water storage into soil moisture and groundwater components because of uncertainties in simulated soil moisture from land surface models (Long et al., 2013). These analyses underscore the need for a greatly expanded program in soil moisture monitoring to complement remote sensing of soil moisture in the future.

Though the objectives of our studies varied, many of our research results fed, either directly or indirectly, into groundwater recharge estimates. Knowledge of recharge has become more important than ever if we are to move towards sustainable management, reducing groundwater use to less than recharge and using managed aquifer recharge to store water. We reviewed various approaches for quantifying groundwater recharge in 2002, providing guidance on appropriate techniques for different goals and identifying knowledge gaps for future research (Scanlon et al., 2002). While many of the techniques provided point recharge estimates, a clear need existed for studies linking these estimates to topography, climate, and vegetation to allow upscaling to basin or regional scales. Our understanding of recharge in semiarid settings in the Desert Southwest was described in an AGU monograph that combined results of various studies in different climatic and hydrogeologic settings (Hogan et al., 2004). We reviewed recharge data from semiarid regions globally during an IAEA meeting in Vienna and compiled the findings in a global synthesis (Scanlon et al., 2006). In collaboration with Rick Healy, we provided short courses on recharge, mostly in the U.S., but also in South Africa and other places. His book on estimating recharge rates provides an excellent resource on this topic. Recharge is often estimated as a residual in the water budget approach; however, it is important to recognize that such recharge estimates generally accumulate uncertainties in other components of the water budget, as emphasized by Gee et al. (2002), where 10% uncertainties in water budget inputs can produce up to 200% uncertainties in estimated recharge rates. Because water budgets are widely used to estimate recharge in global models of water resources, it is critical to consider such uncertainties.

In addition to its importance in terms of water quantity, the unsaturated zone plays a critical role in storing and transporting contaminants from the land surface to underlying aquifers. The most widespread contaminants in semiarid regions include salinity and nutrients. Lack of recharge in natural ecosystems has resulted in salt buildups in soil profiles over millennia, including sulfate, fluoride, and perchlorate, along with chloride from atmospheric deposition. Increased recharge under rainfed agriculture flushed some of these salts into underlying aquifers in many regions, including the southwestern U.S. and Australia. However, detailed profiling showed that some salts are retained in soil profiles as a result of sorption, including fluoride (Scanlon et al., 2009). We also found that arsenic sorbed quite strongly onto soils; therefore, arsenical pesticides applied to crops, such as cotton, generally are stored in the shallow subsurface. Thus, fluoride and arsenic in groundwater is likely geologic in origin. Land use conversion to cropland results in direct increased nitrate inputs into the system but was also found to indirectly generate up to 50% of the groundwater nitrate in the southern High Plains due to oxidation of organic matter during initial cultivation, similar to results from western Canada. Focused or preferential flow is a critical issue for contaminant transport because it bypasses much of the buffering capacity of the unsaturated zone. Detailed studies in the High Plains led to the discovery that playas can serve as areas of focused groundwater recharge (Scanlon and Goldsmith, 1997). This work provided the scientific basis for current understanding of these regionally widespread features, overturned the widely held idea of playas as discharge-only features, and contraindicated using playas for the disposal of radioactive wastes. I cannot stress enough the importance of field measurements in developing understanding of water, salt, and nutrient balances.

What does the future look like? With projected growth in population and increasing economic development changing dietary preferences to more water intensive foods, it seems that irrigated agriculture will need to expand to meet rising food demands. It is of vital importance to develop approaches that move towards more sustainable management of water resources. Recent work by Döll et al. (2012) shows the value of conjunctive use of surface water and groundwater for irrigation with recharge from surface water replenishing depleted aquifers. Managed aquifer recharge can be considered an extension of conjunctive use with recharge of excess surface water during wet periods and more reliance on groundwater during dry periods. These approaches are currently being practiced in the Central Valley of California and in Arizona and should expand in the future to adapt to projected climate extremes. While monitoring using satellites and other remote sensing approaches is expanding, I am concerned about a comment from a water manager after attending a recent annual AGU meeting that the advances in remote sensing and modeling reduce the need for ground-based monitoring. I see more and more students from around the world focusing solely on remote sensing and land surface modeling without ground based data to assess the reliability of water resource estimates. There is a danger that we will not build the field measurement and monitoring programs which are essential for ground referencing the remotely sensed data.

I am extremely grateful to my colleagues at the Bureau of Economic Geology, particularly Bob Reedy and JP Nicot who have worked closely with me for over a decade. I am very thankful to our Directors, past and present (Bill Fisher and Scott Tinker) and to the Bureau for providing a wonderful working environment. I really appreciate the generous donation from Mr. Jackson which resulted in the creation of the Jackson School almost a decade ago. I have also benefited tremendously from collaborations with colleagues in other institutions, particularly the U.S. Geological Survey and commend them for their continued emphasis on field data collection, monitoring, and regional modeling.

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The Fellow Speaks: How important is soil information for hydrological modeling?

Hubert H.G. Savenije (Technical University Delft)

Introductory words

It is a great honor having become "fellow of the AGU". I am particularly pleased because my entrance in academics was rather late in life. I started as an operational hydrologist working for the Mozambican government (1978-1985) and subsequently as a water resources expert with an international consultant (1985-1990), for whom I worked mostly in Asia and Africa. So my basis is in 'practical hydrology' in a wide range of climatic and cultural settings. During those years, I always had the ambition to develop and implement my own theories on specific issues I encountered in practice. As a result I developed my own theories on salt intrusion in estuaries and even on atmospheric moisture recycling. I think that working in practice and doing field observations, is an excellent basis for an academic career in later life, although I realize that such a career path is rather exceptional.

This practical experience has been very helpful in the sense that I have the tendency to follow my own ideas, rather than follow in the steps of what is considered the dominant paradigm. Also my practical experience taught me that much can be done even when little information is available. This mind set was particularly useful during the PUB decade. In this short article I present my latest ideas on how we can predict root zone storage capacity of vegetation based on climatic information.

How to determine root zone storage capacity?

Whether we us a lumped, conceptual or distributed, "physically based" model, the storage capacity of the root zone is always a key parameter, determining the partitioning of precipitation between runoff, transpiration and recharge. Being such a crucial hydrological parameter, a lot of attention is given to estimating the root zone storage capacity, particularly for ungauged basins and for global models that simulate land-atmosphere interactions.

A common method for estimating root zone storage capacity is to first derive the plant available moisture (between so-called field capacity and wilting point) from soil maps and then to multiply this by estimates of the rooting depth of the dominant vegetation. The latter follows from land cover maps that besides rooting depth provide information on parameters relevant for the energy balance.

I have always wondered if this was the right way to do it. If I were an ecosystem, living on a certain soil and under a certain climate, how would I then establish my rooting depth? I would have the choice to invest my energy in growth above ground (in competition for light and in maximizing my chances of reproduction) or underground (making sure I have access to water and nutrients). Obviously if I made my foundation too weak, I would wilt during a critical dry period; but conversely, if I put too much energy in my foundation, I would lose opportunities to grow tall and reproduce. Of course this evolutionary way of reasoning is nothing new and rather common among ecologists, I presume. But why then are we using look-up tables to find the rooting depth for a certain land cover type? Surely there is not one single rooting depth for all "evergreen broadleaf" forests, or for all "woody savannah". If I were an individual member of an evergreen broadleaf community, I would definitely adjust my root zone volume to my local conditions. If I happened to stand on a relatively light soil, I would root deeper than if my seed had dropped on a heavier soil. Similarly, I would root deeper if I had to deal with regular dry spells or with more seasonality than if rain falls more regularly.

Until now, I guess, there will be few readers who disagree. In fact one does not have to be a hydrologist or ecologist to follow this reasoning. I remember very well that my mother used to say that if you water a young tree every day it will become 'lazy' and will not develop enough roots to overcome periods of drought. She recommended to water it once per week in the beginning and later once per month, until it had enough roots developed to survive the summer season.

A problem with our models

Is this now just an interesting way to look at root zone storage development, or is it also an issue? Recently I came across a publication in the Dutch hydrological journal "Stromingen" of the Netherlands Hydrological Society, where the authors presented the discrepancy between observed and modeled evaporation using the most advanced physically based distributed model (named NHI) of The Netherlands (Beekman et al., 2014). The observed evaporation was an upscaling of eddy-covariance and lysimeter observations using ETLook (Bastiaanssen et al., 2012).

I have reproduced a part of one of the figures from that article in Figure 1. On the top we see the observed evaporation during two dry months in 2006. Below we see the model results for the same period. In July 2006, the modeled evaporation appeared to be less than half the observed evaporation, on average. But a more striking difference is in the spatial pattern. In the heart of The Netherlands (a bit to the East of its centre) we see a deep blue blot in the modeled evaporation, whereas the same region has a deep red blot in the observed evaporation. Conversely, the polders in the inland IJssel Lake are colored deep red in the model and yellow in the observations. Overall, the patterns are very different. What is happening here?

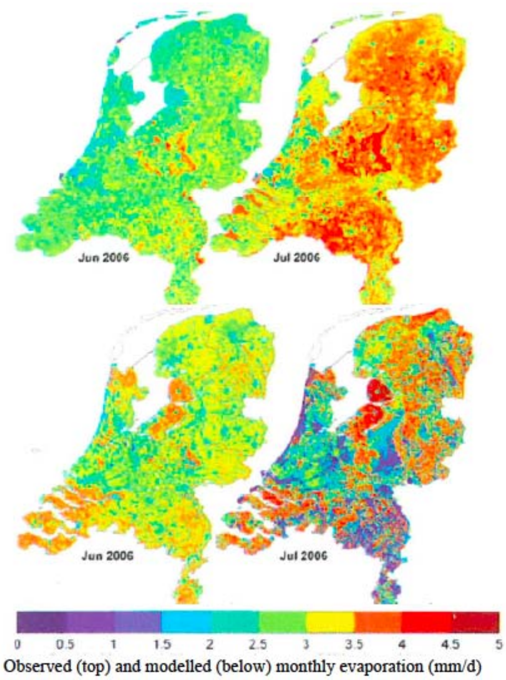

Figure 1 Comparison of observed (top) and modelled (bottom) monthly evaporation

What we essentially see in the lower figures is the spatial variability of the soil characteristics. The dark blue are the sandy soils and the deep red are the heavy soils. The model falsely assumes that the rooting depth of similar vegetation (crops, pasture, forest, etc.) is the same for all soils, causing clay soils in the IJssel Lake polders to evaporate close to potential and the sandy soils to be severely moisture constrained. Although in regular months, where there is no moisture constraint, the model performs well, it clearly provides wrong results in the periods where soil matters.

Although I gave an illustration of The Netherlands, the same happens, and even more prominently, in parts of the world where moisture constraints occur more regularly, particularly in the tropics (due to dry spells) and the sub-tropics (due to seasonality and dry spells). So, I think it is time for a new paradigm.

A new paradigm

As a water resources engineer I am familiar with the way we size reservoirs in response to variable water resources and demands. The traditional method is to use the Mass Curve Technique (MCT), or Ripple diagram (after Ripple, 1883). In the Ripple diagram we plot both the accumulated inflow to a reservoir and the accumulated demand. Using the tangents of the accumulated demand to the accumulated inflow, we can derive the required storage to bridge dry seasons. Plotting the annual storage requirements on extreme values paper (e.g. Gumbel, 1935) allows to estimate the storage requirement for certain return periods.

The similarity with the root zone is that we accumulate the net precipitation (precipitation minus interception) as inflow, and the transpiration of the vegetation as demand. We determine the transpiration in the dry season by scaling the average annual evaporation by the NDVI of dry and average conditions. Even in ungauged basins one can do this on the basis of the Budyko curve.

We tested this method in a large set of well gauged basins, including 6 sub-tropical catchments in Thailand and 323 catchments of the MOPEX data set that were relatively unaffected by snow, and compared the predicted root zone storage capacity with the calibrated capacities using the lumped conceptual model FLEX (Fenicia et al., 2011). The results were surprisingly accurate and are presented in a paper recently accepted in GRL (Gao et al., 2014). Here I shall just reproduce the resulting figure showing the comparison between the root zone storage capacity required to bridge a drought of once in 20 years (S_{R20y}) with the calibrated root zone storage capacity (S_{uMax}). Figure 2 shows the results for 6 eco-region classes based on the classification by Wiken et al. (2011), whereby the 7th class refers to the Thai catchments. In general we found that there is a strong correlation between the S_{R20y} with inter-storm duration and seasonality, showing that vegetation develops more root volume when it has to bridge longer dry spells, or has to deal with seasonality. Applying this globally, this correlation appeared to be strongest for permanent vegetation, such as evergreen broadleaf forest, evergreen needle forest, deciduous forest and woody savannah. The correlation was not good at all for cropland, for which the traditional method based on soil characteristics gives much better results, not surprisingly because the crops are seasonal and strongly rely on the soil.

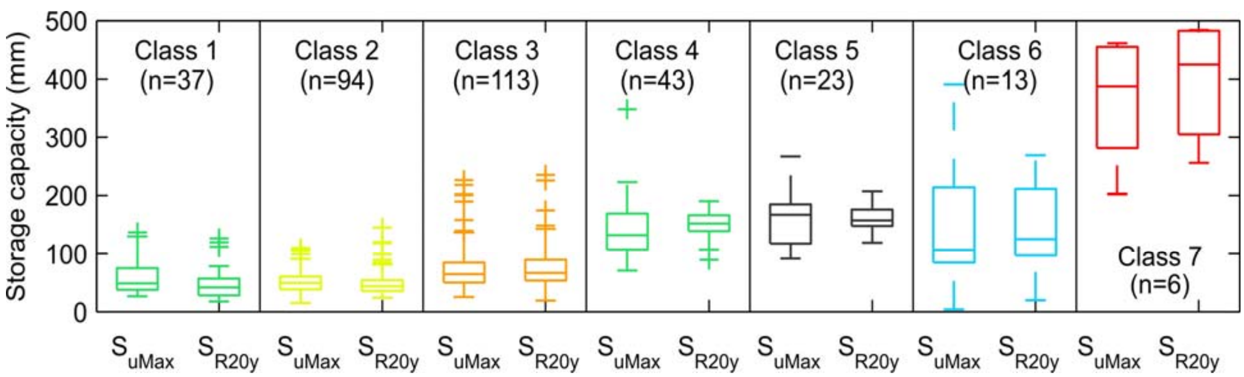

Figure 2 Correspondence between S_{uMax} and S_{R20y} (with their related calibration uncertainty and variability) for different eco-region classes.

Conclusion

So I think we have a very interesting new paradigm here, which could be the beginning of very interesting new research. I think we are over-rating the importance of soil for permanent vegetation, forgetting that vegetation adapts to the climate by creating sufficient root zone storage. Vegetation balances out soil variability by adjusting its rooting depth in a way that the buffer is much more homogenous in space than we classically assume, and in a way that severe moisture stress is much less likely to occur.

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The Fellow Speaks: Future perspectives in terrestrial hydrology research: the role of observations and novel measurement techniques

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I feel honored by the election as AGU fellow and I am grateful to those who supported me. As I look back on my scientific career, I realize that the achievements of the last 25 years have only been possible due to the collaboration and exchange with many outstanding and generous colleagues. I would like to use this opportunity to express my gratitude to all of them.

Many of the ideas and challenges that I see for further developing hydrologic science have been nourished by my earlier research work. During my PhD-work in the eighties, I worked on the development of pedotransfer functions to predict soil hydraulic parameters from simple and readily available soil properties because measurements of soil hydraulic properties were cumbersome and time-consuming. Recent developments in soil physical theory and data fusion methods in combination with improved sensing technologies, such as remote sensing and hydrogeophysical methods, have enabled us to obtain estimates of hydraulic parameters more easily and with a large spatial coverage opening new perspectives to provide highly detailed maps of the distribution of soil hydraulic properties at the field to small catchment scales.

In the nineties, I shifted my focus towards the description and prediction of transport processes in heterogeneous groundwater systems. At that time, tracer experiments combined with pumping tests and groundwater sampling from groundwater wells were the basic tools to derive heterogeneous K-fields using geostatistical and stochastic hydrology theory. However, in most of the well-known test sites, the spatial arrangement of the groundwater wells was not sufficient to resolve small-scale horizontal heterogeneity. Yet, this small-scale variability is clearly decisive in the prediction of transport processes at the field and formation scale. The development of hydrogeophysical measurement techniques combined with improved inversion methods has made it possible to better characterize the subsurface environment and to map heterogeneous K-fields at the sub-meter scale (e.g. Kemna et al. , 2002; Vanderborght et al. 2005). At the beginning of this century, my research interests moved towards studying exchange processes between the land surface, the vegetation and the atmosphere with specific attention to soil as a driver of coupled hydrologic and biogeochemical processes. Recently, a Chapman conference on this subject was organized in Tucson, Arizona (Vereecken et al., 2013). This meeting identified two main challenges relevant for the subject of this article: 1) the development of novel measurement technologies in improving our understanding of soil-plant-atmosphere interactions including hydrologic processes, and 2) the need to establish and provide access to a world-wide network of critical zone observatories footed on a catchment based approach and including hydrologic processes. In the following, I will expand more on the role of measurement technologies in the field of hydrology and its link to the use of mathematical models as I think these are key elements in moving forward are understanding of hydrologic processes.

The development of novel measurement techniques and technologies enabling the continuous monitoring of states and fluxes of the land and subsurface system has been key to many of the research activities in which I have been involved since 2000. In 2008, the TERENO initiative (Bogena et al., 2012, Zacharias et al., 2011) was started in Germany with the aim to observe hydrological and biogeochemical processes at the catchment scale from the groundwater into the atmosphere using a combination of innovative sensing technologies and integrated terrestrial models. This initiative has been instrumental in integrating hydrological and biogeochemical research in Germany. One of the key elements of success was the strategic decision to monitor all relevant states and fluxes of the terrestrial systems with a high spatial and temporal resolution using novel measurement technologies and using the catchment scale as the basic measurement scale. I am convinced that a combination of technological advancement, novel measurement techniques, and high-resolution modelling approaches is essential to improve our understanding of hydrologic processes and to test our hypotheses under the best possible conditions. It will improve our capacity to observe terrestrial hydrological processes and to produce high-quality data that are essential in model-data fusion approaches. Especially, the use and development of data assimilation techniques provide a unique opportunity to predict hydrological processes and at the same integrate different types of data with varying spatial and temporal scales. In the remainder, I will give several examples from recent research efforts to underpin some of the above statements.

Recently, Graf et al. (2014) proposed a data-driven analysis of hydrological fluxes within the Wüstebach catchment within the Eifel/Rur TERENO observatory. Precipitation, evapotranspiration, groundwater levels and runoff were continuously measured during a three-year period (Fig. 1). Novel wireless soil moisture network technology was used to obtain spatially highly resolved soil moisture data at three depths (Fig. 2). This monitoring effort allowed in this case to close the water balance with an accuracy of 3% of the observed rainfall. By using empirical orthogonal functions and cluster analysis, it was shown that the catchment switches between wet and dry states at a critical soil water content value. This critical value was corroborated by runoff measurements that were plotted against the mean soil water content of the catchment (Stockinger et al., 2014). Stockinger et al. (2014) used stable isotope analysis of stream water combined with highly resolved soil moisture measurements to study controls on the transit time distribution of the same catchment. They found that the connection between the hillslopes and the riparian zone was an important factor in understanding why the catchment shifted between two distinct, time-variant hydrological responses governed by seasonal changes of overall catchment wetness.

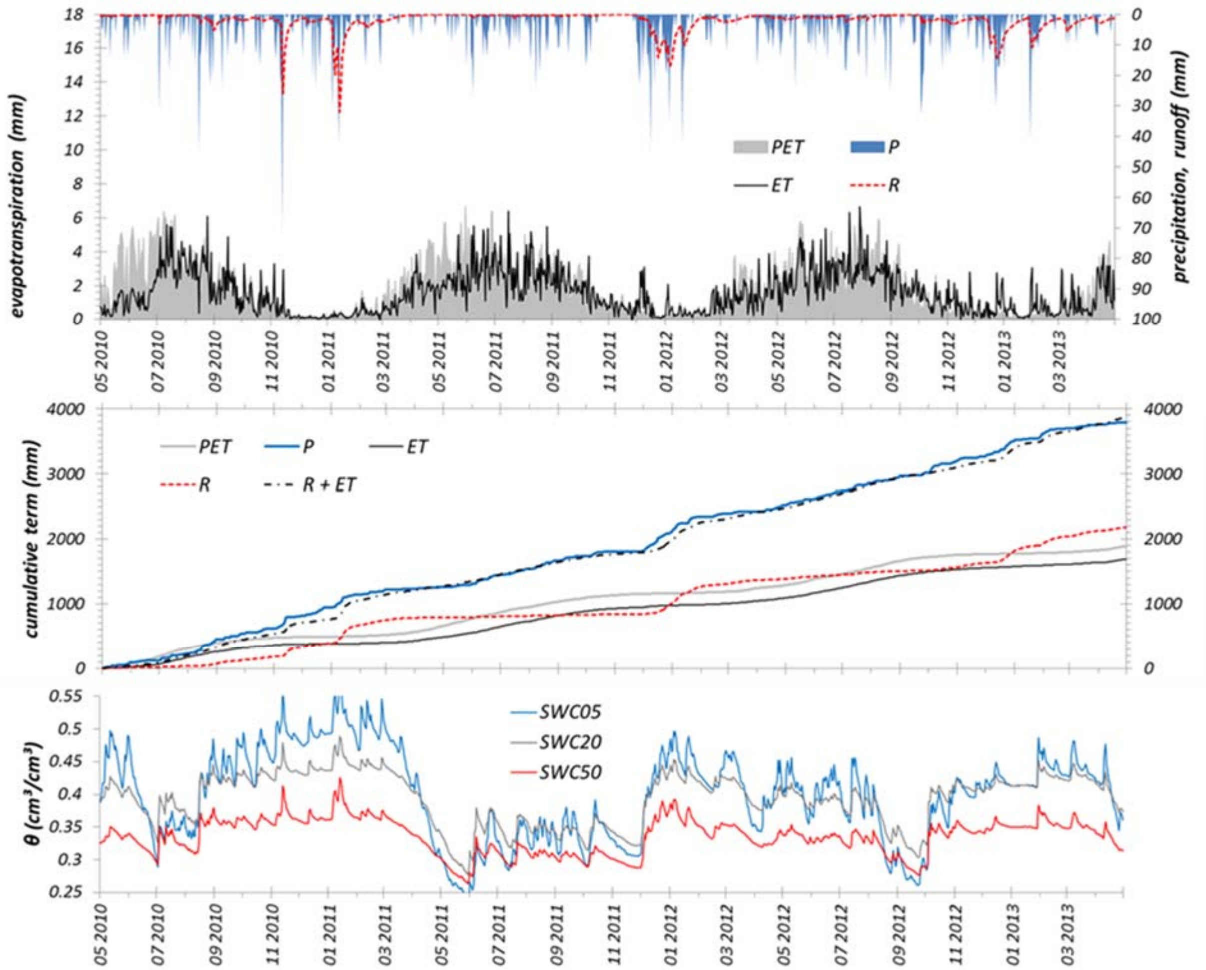

Figure 1. Measurement of the components of the soil water balance at Wüstebach for a three-year period (from Graf et al., 2014). PET=Potential Evapotranspiration (estimated), P=precipitation, ET=actual Evapotranspiration, R=Runoff, SWC= Soil Water Content at depth of 5 cm (05), 20 cm (20) and 50 cm (50).

Cosmic Ray Probes, CRP, (Zreda et al., 2008) have provided new perspectives to measure soil moisture content dynamics at a footprint that matches not only the measurement resolution of many remote sensing platforms but also the scale of micro-meteorologic methods, such as Eddy Covariance techniques. Recently, Bogena et al. (2014) studied the value of using CRP to assess integral daily soil water content dynamics at the Wüstebach catchment. This study strongly benefited from the availability of wireless sensing technology to calibrate CRP measurements and to evaluate the accuracy of soil water content measurements with CRP. Further developments include the use of CRP in data assimilation approaches to better manage irrigation systems and to better predict biogeochemical fluxes by providing high quality and temporally highly resolved soil moisture content measurements at the field and catchment scale, respectively.

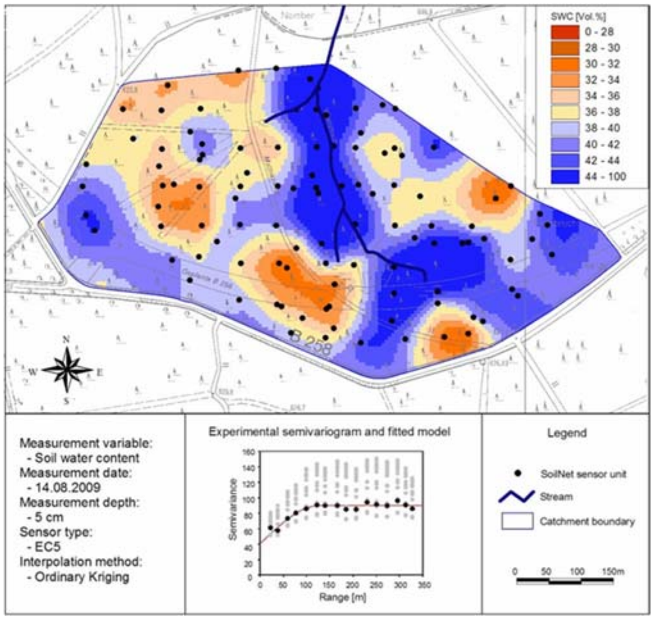

Figure 2: Soil moisture distribution obtained from a wireless soil moisture network at Wüstebach catchment including the corresponding semi-variogram.

Another example that underpins the value of combining new technologies with modelling is the work performed by Busch et al. (2013) on the use of ground penetrating radar to determine soil hydraulic properties. First steps to determine soil hydraulic parameters from GPR data were already undertaken by Lambot et al. (2006) by using off-ground radar systems. By using on-ground GPR, a better handling of soil surface roughness and a deeper GPR signal penetration can be obtained. They used a coupled hydrogeophysical inversion scheme using a forward model of GPR measurements linked to a soil water balance model to inversely estimate soil hydraulic parameters from time-lapse GPR data. This work provides unique opportunities to extent the estimation of soil hydraulic parameters using time-lapse GPR mapping up to the level of small catchments. Using these new developments in observing soil water content and hydrologic fluxes at the scale of catchments, we are now in a position to better integrate and link ground-based measurement technologies with remotely sensed data as we can better match the spatial and temporal scales of measurement.

A final example addresses the value of stable isotope techniques to disentangle the net fluxes of water and carbon dioxide as obtained from Eddy Covariance in their single components. Rothfuss et al. (2013) used on-line measurements of the isotopic composition of soil water obtained using gas-permeable tubing and infrared laser absorption spectroscopy and demonstrated that this approach is capable of monitoring delta H-2 and delta O-18 in soils online with high precision. This will allow the disentangling of soil evaporation and root water uptake processes.

Finally, I strongly believe that we should develop a world-wide network of hydrologic observatories based on well-defined scientific questions and equipped with the best possible measurement technologies in order to provide the hydrologic community with the required high-quality data to falsify our hypotheses. The establishment of science-driven networks is common in other science communities such as meteorology and biogeochemistry (e.g. Fluxnet), ecology (e.g. National Ecological Observatory Network) and geosciences in general (e.g. Integrated Carbon Observation System, ICOS; Critical Zone observatories, CZOs). A similar approach in the field of hydrology would be key to further advance our understanding of hydrologic processes from the field to catchment and continental scales and to further strengthen exchange, cooperation, and synergies in hydrological research.

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