

## From the Section President

*Efi Foufoula-Georgiou (University of Minnesota)*

Dear colleagues, dear friends,

I am happy to report that 2015 has been a great year for our section. Our collective goals of: (1) promoting and rewarding excellence, (2) building community and increasing the scope and visibility of our section, and (3) mentoring our next generation, are advancing with renewed energy and commitment.



The old African proverb says “it takes a village to raise a child”. Well, it is safe to say that it takes approximately 500 committed volunteers to run our section -- from the elected officers, to the Fall Meeting program committee, to our award committees, to the members of our 12 technical committees, to OSPA judges, to student committees, to nominators, to letter writers, to much more. And “running a section” is vastly different than “leading change” -- *Our Hydrology section is indeed leading change.*

(1) We perceived the lack of mechanisms within our section to reward our mid-career excellence and established the first mid-career (10-20 years since PhD) award of our section. The inaugural *Mid-career Paul Witherspoon Lecture award* will start in 2016 (see the article in this newsletter and the newly-formed committee posted in our Hydrology web site <http://hydrology.agu.org>). AGU has recently recognized the lack of mid career awards at the Union level and a process is starting to establish such an award by 2017.

From the Section President.....	1
Hydrology Section Budget Update.....	3
Fall Meeting Highlights .....	4
From the Section President-Elect.....	6
From the Section Secretary.....	7
From the Section Student Chair.....	7
From the WRR Editorial Board.....	8
Paul Witherspoon’s Legacy: A Tribute to a Brilliant Scientist and Inspiring Teacher, and an Introduction to AGU’s “Paul A. Witherspoon Mid-Career Lecturer in Hydrologic Sciences” Award.....	10
2014 Hydrologic Sciences Awardee <i>Diane McKnight</i> .....	13
A Fellow Speaks: <i>Larry Band</i> .....	14
A Fellow Speaks: <i>Paul Bates</i> .....	17
A Fellow Speaks: <i>Georgia Destouni</i> .....	20
A Fellow Speaks: <i>Praveen Kumar</i> .....	22
A Fellow Speaks: <i>Peter A. Troch</i> .....	24
Horton Research Grant Recipient <i>Laura Stevens</i> .....	27
Horton Research Grant Recipient <i>Emily Voytek</i> .....	29
Horton Research Grant Recipient <i>Adam Wlostowski</i> .....	31

(2) Our *young hydrologists* perceived the need to foster connections inwards and outwards and established the first pre-AGU Early Career (EC) Conference in 2014. This idea has now spread to the Union level, as have some other initiatives of our young hydrology leaders: the Water Sciences Pop-ups are becoming popular across AGU and the new 2015 “Hydrologist Bingo” idea sounds like fun. Learn more about these activities in the article by the Hydrology Section Student Subcommittee – H3S – in this newsletter. Also, please visit a newly established link in our section web site dedicated to student activities <http://hydrology.agu.org/student/h3s-activities/>.

**Congratulations:** Once more, congratulations to the 10 elected Fellows in 2015 from our Hydrology section: Lawrence Band, Paul Bates, Georgia Destouni, Praveen Kumar, Peter Troch, Olaf Cirpka, Michael

Roderick, Barbara Sherwood Lollar, Laurence Smith, and Scott Tyler. Please read the fascinating perspective articles of five fellows contributed to this newsletter – exciting scientific advances at the forefront of hydrology and related sciences – and anticipate another five exciting articles in our July 2016 newsletter. Please also read the article by Diane McKnight, our 2014 Hydrological Sciences Awardee. Congratulations also to our Horton Research Grant student awardees Laura Stevens, Emily Voytek, and Adam Wlostowski, whose awards will be presented at the Hydrology Luncheon on Tuesday Dec. 15. We look forward to excellent science and leadership from you in the years to come!

I take the opportunity to congratulate once more our 2015 Hydrologic Sciences Awardee -- Dara Entekhabi; Early Career Hydrologic Sciences awardee -- Tom Gleeson; and the Langbein Lecture awardee -- Tissa Illangasekare. Please attend the Langbein lecture and award ceremony on Tuesday December 15 at 10:20 am (H22A –MW2022-2024) where the presentation of these awards will take place followed by the Langbein lecture.

Finally, please join me in congratulating our Union 2015 awardees Günter Blöschl (Horton Medal) and Wilf Brutsaert (Bowie Medal). Honors greatly deserved.

**Thank you:** I start by thanking our vibrant community of graduate students for crafting an exciting path forward of engagement and learning and for leading new ways for the whole Union. I thank Tim van Emmerik, Evan Kipnis, Natasha Krell, Kevin Roche, Sheila Saia, Frank Sedlar, and Adam Wlostowski for their leadership and dedication to our section. Please read their article in this newsletter and sense their vibrant spirit of science-networking across continents.

A dedicated cadre of award committee members have done an excellent job in propelling forward our deserving colleagues for awards and recognitions. Rotating members of all committees “exit quietly” (their names just disappear from our web site!) but we are working on a process to deliver a more appropriate Thank you! Thank yous go to the following committee members whose terms expire on December 31, 2015: Fellows committee -- Witold Krajewski; Hydrologic Sciences award committee – Mike Gooseff; Horton Research Grant Committee – Tissa Illangasekare and Jasmeet Judge; Langbein Lecture award committee – Jim Shuttleworth; Fall meeting program committee –

Newsha Ajami and Tara Troy. Many members of the Technical Committees are also rotating off and are too many to mention here by name. I will only say *Thank you! Your dedication, hard work and perspective has been invaluable to the section.*

**Fall Meeting organization:** Barbara Bekins (chair of the 2015 FM Hydrology Program Committee) has done an excellent job in leading our section’s FM program and steering so politely the heated exchanges when sessions are merged or not selected for orals. To achieve a better coordination of sessions before the program committee meets in DC, we have proposed a new process that involves the Technical Committees (TCs) early on in terms of proposing integrating sessions and suggesting mergers. Please find the recommendations of the Ad-hoc committee on improving the FM at the July 2015 newsletter <http://hydrology.agu.org/agu-hydrology-section-newsletter/>.

Thank you FM program committee: Barbara Bekins (chair), Bart Nijssen (co-chair), Casey Brown, Terri Hogue, Megan Smith, Newsha Ajami and Tara Troy, for your incredible work in putting together an exciting program for our Hydrology section. Please see also the article of our section secretary Terri Hogue for more details.

**Finances:** New initiatives need resources to be established and sustained. As our past president Eric Wood kept reporting, we barely break even year after year – in short, our expenses exceed our income for the past several years. I believe that many of us can afford to contribute a bit more if we know that our money is well spent.

I provided a detailed account of the causes we need the resources for and these relate to supporting the events of the young hydrologists, and the main event of our section – the hydrology luncheon. I also reported in the past newsletter that AGU is listening and has been generous in providing more support starting in 2015: \$5,000 for support of student activities and \$50/attendee of our luncheon. I remind you that the decision was made to spend this money as follows: increase the Hydrology OSPA winners from 15 to 20 and award each \$150 towards their FM expenses; use \$1,000 for a networking event of our Young Hydrologists, and use \$1000 for partial Fall meeting expenses of the chair and co-chair (\$500 each) of the Hydrology Section Student Subcommittee. I believe

this money is well spent and a small token of appreciation to our students and future leaders.

**Donating to our section:** Based on comments from many of you, we have made some progress in facilitating the process of donating directly to our section. A direct link in our Hydrology web site has been created which takes you to a more manageable selection process (go to <http://hydrology.agu.org> and then click the “Support” button). *Thank you for contributing – your donations, small or large, matter greatly in sustaining and enlarging the scope of our community-building events and promoting our young scientists.*

**50<sup>th</sup> WRR Anniversary special volume:** Please read the article of the WRR Editorial team. I am personally very proud and thankful for their hard work in putting this volume together. It is a milestone in our scientific trajectory and speaks for what has been accomplished and what still lies ahead as our field of water science become more and more central to sister geosciences and societal issues related to sustainability. A special volume has been produced which will be made available open access in digital format on the WRR web site. The volume will be released on December 15 at 1:30 pm following the Hydrology Section luncheon. Please join me in thanking our WRR editorial team for their excellent vision and hard work in making this anniversary volume a reality.

#### ***Need OSPA (Outstanding Student Paper Awards)***

**Judges:** Please read the article of our section secretary Terri Hogue. We have excellent participation from our students for the OSPA competition and we need more judges. Post-doctoral associates and Early Career scientists are welcomed and encouraged to register as OSPA judges. Please send a message to Terri Hogue [thogue@mines.edu](mailto:thogue@mines.edu)

**Highlights for the 2015 Fall Meeting:** The 2015 FM has many inspiring sessions and some highlights, Union events, and townhall meetings are listed below. Our section luncheon meeting (Tuesday Dec. 15 following the Langbein lecture; San Francisco Marriot, Salon 7) promises to be larger than ever (400 attendees including 150 student members) – tickets sold very quickly so sorry if you were not able to get one. I think I got the last ticket myself. We will present awards, hear from the WRR Editorship Team, and review the section business and future aspirations.

Thinking out of the box is a good thing, and our section is doing a lot of this with spirit and enthusiasm creating a stronger and renewed fabric of pride and support within our community. *Thanks to all for contributing in small and bigger ways towards a vibrant Hydrology section.*

Best regards to all,  
Efi

P.S. Special thanks go to Anthony Longjas whose help in coordinating this newsletter is invaluable.

<b>Hydrology Section Budget (1/14 to 12/15)</b>			
	<i>1/14-12/14</i>	<i>1/15-10/15</i>	<i>Projected 11/15 – 12/15</i>
<b>Revenue</b>			
Donations	\$8,495	\$11,182	\$11,182
Sponsorship	\$1,802	\$0	\$0
<b>Total Revenue</b>	<b>\$10,297</b>	<b>\$11,182</b>	<b>\$11,182</b>
<b>Expenses</b>			
Student and Early Career Reception	\$4,000	\$0	\$4,000
Support for CUAHSI reception	\$500	\$0	\$500
Hydrology Business Luncheon (including expenses on section awardees and student ticket subsidy)	\$2,000	\$0	\$3,000
Hydrology Technical Committee Meetings	\$7,000		\$8,000
OSPA winners	\$3,250	\$0	\$3,000
AGU Subsidies of OSPA winners	\$0	\$0	(\$3,000)
<b>Total Expenses</b>	<b>\$16,750</b>	<b>\$0</b>	<b>\$15,500</b>
<b>Net Revenue (Deficit)</b>	<b>(\$6,453)</b>	<b>\$11,182</b>	<b>(\$4,318)</b>

<b>Fall Meeting Highlights</b> <b>(Hydrology Section Events, Union Lectures of Interest, and Town Hall Meetings)</b>			
<b>Hydrology Section Events</b>			
<b>Date</b>	<b>Time</b>	<b>Event/Function</b>	<b>Location</b>
Sunday Dec. 13	8:15 A.M. – 5:45 P.M.	<b>Student and Early Career Scientist Conference</b>	San Francisco Marriott Marquis, Golden Gate B
Sunday Dec. 13	5:00–8:00 P.M.	Student and Early Career Scientist Mixer Conference	ThirstyBear Brewing Company, 661 Howard St., San Francisco
Monday Dec. 14	4:00–6:00 P.M.	<b>Water Sciences Pop-Ups Session</b>	Moscone South 101
Tuesday Dec. 15	10:20 A.M. – 12:20 P.M.	<b>H22A Walter B. Langbein Lecture and Hydrology Section Awards</b>	Moscone West 2022–2024
Tuesday Dec. 15	12:30–1:30 P.M.	<b>Hydrology Section Business Meeting and Luncheon</b>	San Francisco Marriott Marquis, Salon 7
Tuesday Dec. 15	4:00–6:00 P.M.	Social Dimensions in Geosciences Pop-Ups	Moscone South 101
Tuesday Dec. 15	6:00–8:00 P.M.	<b>CUAHSI Reception</b>	Jillian's San Francisco
Wednesday Dec. 16	6:45–8:15 A.M.	Hydrology Technical Committee Chairs Meeting	San Francisco Marriott Marquis, Salon 6
Wednesday Dec. 16	12:30–1:30 P.M.	Hydrology Section Executive Committee Meeting	San Francisco Marriott Marquis, Salon 6
Wednesday Dec. 16	6–8 P.M.	<b>AGU Honors Ceremony</b>	Moscone North – Rooms 134–135
Thursday Dec. 17	6:45–7:30 A.M.	Meet H3S (Hydrology Section Student Subcommittee)	Marriott Room Sierra
<b>Union Lectures of Interest</b>			
Tuesday Dec. 15	12:30–1:30 P.M.	Union Agency Lecture: France A. Cordova (Director, NSF)	Moscone North Hall E
Thursday Dec. 17	12:30–1:30 P.M.	Frontiers of Geophysics Lecture: Gordon McBean (President, ICSU)	Moscone North Hall E
<b>Technical Committee Meetings. Please see time and locations at:</b> <a href="http://fallmeeting.agu.org/2015/calendar/">http://fallmeeting.agu.org/2015/calendar/</a>			
<b>Town Hall Meetings of interest to Hydrology Section Members:</b> <a href="https://agu.confex.com/agu/fm15/meetingapp.cgi/Program/1126">https://agu.confex.com/agu/fm15/meetingapp.cgi/Program/1126</a>			
Monday Dec. 14	12:30–1:30 P.M.	<b>TH13F</b> The Energy-Water Nexus - Ongoing Science Activities and Future Opportunities with the Department of Energy	Moscone West 2008
		<b>TH13H</b> USDA Town Hall on Climate Change, Global Food Security and the U.S. Food System Report	Moscone West 2004
		<b>TH13I</b> The 2017–2027 National Academies' Decadal Survey for Earth Science and Applications from Space	Moscone West 2005
		<b>TH15D</b> EarthCube Science Drivers and Implementation Roadmap - Seeking Community Guidance	Moscone West 2011
Monday Dec. 14	6:15–7:15 P.M.	<b>TH15A</b> Challenges and Opportunities for Research in Earth Surface and Interior at NASA	Moscone West 2010
		<b>TH15B</b> A Conversation With DJ Patil, Chief Data Scientist of the United States	Moscone South 104

		<b>TH15C</b> DOE Scientific Successes as Part of the International Land Model Benchmarking (ILAMB) Project	Moscone West 2006
		<b>TH15H</b> NOAA's Research And Development Enterprise	Moscone West 2002
		<b>TH23H</b> The Hydrologic Model Synthesis Project	Moscone West 2011
Tuesday Dec. 15	12:30–1:30 P.M.	<b>TH23F</b> Decadal USGCRP Science Assessment of the Carbon Cycle in the US and North America: The 2nd State of the Carbon Cycle Report (SOCCR-2)	Moscone West 2007
		<b>TH23I</b> DOE's Trait-Based Modeling Approach for Next Generation Ecosystem Experiments (NGEE)	Moscone West 2003
Tuesday Dec. 15	6:15–7:15 P.M.	<b>TH25D</b> A Town Hall for the Network of Critical Zone Observatories	Moscone West 2010
		<b>TH25E</b> Building Science Knowledge and Meeting Climate Change Challenges: U.S. Global Change Research Program and the National Climate Assessment	Moscone West 2016
		<b>TH25F</b> Earth Observations and Global Water Security	Moscone West 2006
		<b>TH25H</b> NASA Mission Applications and the Early Adopter Program	Moscone West 2009
		<b>TH25I</b> Revolutionizing Utilization of the Earth's Subsurface for America's Energy Future: The DOE Subsurface Crosscut Initiative (SubTER)	Moscone West 2004
		<b>TH25K</b> U.S. Group on Earth Observations (USGEO) Town Hall	Moscone West 2007
Wednesday Dec. 16	12:30–1:30 P.M.	<b>TH33B</b> e-Infrastructure and Data Management for Global Change Research	Moscone West 2002
		<b>TH33D</b> NASA Earth Science Division Town Hall	Moscone West 2003
		<b>TH33G</b> NWS Model Development Forum	Moscone West 2007
Thursday Dec. 17	12:30–1:30 P.M.	<b>TH43D</b> Future Earth – Research for Global Sustainability: Latest Developments and Opportunities	Moscone West 2009
		<b>TH43E</b> NASA Sea Level Change Team Town Hall	Moscone West 2010
		<b>TH43H</b> The AmeriFlux Network: Celebrating Its 20th Anniversary	Moscone West 2004
		<b>TH43J</b> What Is New in NSF Geosciences?	Moscone West 2003

## From the Section President-Elect

*Jeff McDonnell (University of Saskatchewan)*



***This past year:*** It has been almost a year since my installation as President-Elect of the Hydrology Section (HS). My duties this year have included chairing both the HS Fellows selection committee and the ad hoc committee for Fall Meeting, as reported in the July 2015 newsletter. I'm delighted to celebrate the slate of HS Fellows this year, which includes Larry Band, Paul Bates, Olaf Cirpka, Gia Destouni, Praveen Kumar, Mike Roderick, Barbara Sherwood Lollar, Laurence Smith, Peter Troch, and Scott Tyler, and I appreciate the very hard work by the selection committee (Witold Krajewski, Hoshin Gupta, Bridget Scanlon, and Harry Vereecken). The selection of AGU fellows is a rigorous two-stage process: first, at the HS section level, where a ranked long list is assembled, and second, at the Union level, where a Fellows selection committee chooses the final short list of successful candidates from that long list. AGU is always striving to improve the selection process. This year, a Union-level task force submitted guidelines for improving the Fellow selection criteria: <https://eos.org/agu-news/task-force-recommends-ways-to-improve-agu-fellows-program-2>. The new criteria for evaluating scientific eminence are focused on the following areas:

- breakthrough or discovery
- innovation in disciplinary science, cross-disciplinary science, instrument development, or methods development and/or
- sustained scientific impact

Within HS, we're already focusing on these areas—but we welcome and value feedback from section members and, of course, nominations (!) for next year.

***Looking ahead:*** As President-Elect, I am happy to serve the Union that has been such a major force in my scientific life over the years. The President-Elect duties are pretty much summed up in the AGU HS Bylaws. I must admit that, until this year, I had never read them. The Bylaws outline the roles of our elected Executive Committee in general and shed light on our various awards and special recognitions

(<http://hydrology.agu.org/bylaws-of-the-agu-hydrology-section/>). There, you will see our HS Objectives, which are “to promote the aims and activities of the American Geophysical Union within the field of hydrology and water resources” and specifically:

1. To promote the scientific study of hydrology and water resources and to make the results of such studies available to the public by
  - a. scientific discussion, publication, and other dissemination of information, and
  - b. by sponsorship of scientific and technical symposia, colloquia, and meetings.
2. To initiate and participate in hydrologic and water resource research programs including those which depend upon international cooperation.
3. To promote cooperation among those scientific organizations whose objectives include furtherance of knowledge in the hydrologic and water resource disciplines.

Objective 1 is the one that I intuitively understood and believe is well in hand at the section level. I am committed to spending a good part of 2016 working to address Objectives 2 and 3 and exploring how HS can initiate and participate in international hydrologic and water resource research programs. I am also going to work with my counterparts in IAHS, EGU, SSSA, GSA, and AMS to explore and promote better cooperation among our scientific organizations. One tool for facilitating this communication and for improving communication within HS for technical session development and curation is a HS Listserve. I hope to launch this in early 2016 and to have it become a useful vehicle for sharing information. I welcome comments, ideas, and suggestions for improving on this and all matters arising for the HS. Before I close, I want to thank each and every volunteer within HS—those who have served on awards committees or performed editorial duties for WRR. Your unselfish cooperation in research and service is much appreciated by all.

## From the Section Secretary

*Terri Hogue (Colorado School of Mines)*



The Hydrology Section Outstanding Student Paper Awards (OSPA) committee is in full swing organizing the Fall Meeting student judging. Your OSPA committee includes Kolja Rotzoll (U.S. Geological Survey), Laurel Saito (University of Nevada, Reno), Newsha Ajami (Stanford University), Tara Troy (Lehigh University), and myself as chair. This year, we have 424 hydrology student presentations to judge at Fall Meeting, which will require 1272 assessments by our attending members (we are down ~60 students from last fall's meeting). Please take the time to provide feedback to our students by signing up to be an OSPA judge at Fall Meeting. We especially encourage postdocs and early career scientists to engage in OSPA. In addition to numerical scores, winning students must also have outstanding comments specific to their presentation. These comments are weighed heavily, so please take a few minutes to add comments reflective of your scores and what stood out during the presentation. The OSPA committee will see a change at the end of this year, as Newsha Ajami and Tara Troy will complete their terms. We are excited to have Rolf Hut (Delft University) and Alicia Kinoshita (San Diego State University) join the team this January. I am extremely grateful for the commitment and hard work that Newsha and Tara have given to OSPA over the last several years. Please thank them for their service when you see them at Fall Meeting.

A new role for the section secretary this year has been participation in the fall program planning process. As

Fall Meeting expands its social and media presence, and with increasing abstract submissions, the committee's workload is ever increasing. This year, I was able to help with development of the virtual program and SWIRLS sessions, and also assist in session and speaker planning. Please encourage colleagues and students unable to attend Fall Meeting to access the Fall Meeting virtual program—AGU On-Demand

(<http://fallmeeting.agu.org/2015/virtual-options/>).

Nearly all special lectures as well as select topics are available for viewing.

As you are likely aware, there is ongoing discussion on how to improve the Fall Meeting experience for our members. An ad hoc committee, led by President-Elect Jeff McDonnell, developed recommendations for going forward and better engaging the technical committees in the planning process (see the July 2015 newsletter). We will use the technical chairs and executive committee meetings in San Francisco to further discuss these recommendations and the Fall Meeting planning process in general. If you have input or feedback, please get in touch with your Technical committee chairs, the Fall program committee or the Executive leadership team (<http://hydrology.agu.org>). We all want to make the planning process smoother and the Fall Meeting experience more integrative. However, we also need to ensure some autonomy and efficiency for the fall program committee. It's a tough job organizing hundreds of presentations with significant constraints and fast turnaround times. Finally, thanks for all you do in ensuring that Fall Meeting and the section's OSPA are once again a success.

## Hydrology Section Student Subcommittee (H3S) First Year at a Glance

*Tim van Emmerik (chair), Evan Kipnis (co-chair), Natasha Krell, Kevin Roche, Sheila Saia, Frank Sedlar, Adam Wlostowski*



This year has been a great year for the student body of the AGU Hydrology section. At the beginning of 2015, the AGU Hydrology Section Student Subcommittee (H3S) was installed. H3S consists of seven

student and early career scientists and is chaired by the section's student representative. Every year, half of the committee is replaced by new members, who are appointed for a 2-year period.

Various new initiatives were launched in 2015. During this spring's Joint Assembly, the first Early Career

Hydrology Night was organized. Around 40 early career hydrologists joined for a “Meet the Expert” session, discussing the future of hydrological sciences with John Pomeroy, Bill Quinton, and Maria Strack. Second, H3S started to increase the visibility of early career hydrologists online. H3S contributes to hydrology-related blogs (e.g., youngHS.com, GEWEX), launched its twitter account (@AGU\_H3S), and initiated the Early Career Hydrologist Profile series on the AGU Tumblr website.

However, most activities are organized around AGU Fall Meeting. H3S has been actively involved in designing the program for the 2nd Early Career Scientist Conference, which will take place on Sunday, 13 December. This year, 250 students and early career scientists have registered for either the general program or the interdisciplinary water sciences track. During the latter, participants have the opportunity to get to know each other and connect to experts from the field. In the morning, there will be interactive workshops on Remote Sensing in Geosciences, Fieldwork (Headache, Blessing, or Both?), and how to make the best presentation in your session. The afternoon will revolve around a new edition of the Meet the Expert session, in which participants and experts (Anne van Loon, Peter Gleick, and Jay Famiglietti) will discuss the California Drought.

Second, based on the success of last year’s Water Sciences Pop-Up session, H3S is organizing two pop-up sessions this year, (1) Innovations in Water Sciences and (2) Social Dimensions in Geosciences. They are scheduled for Monday, 14 December, and Tuesday, 15 December, 4:00–6:00 P.M., in Moscone South, Room 101.

Last, but not least, H3S will organize the first-ever “Hydrologist Bingo.” Early career scientists can collect

(or print) a bingo card, which will have  $5 \times 5$  pictures and names of eminent hydrologists. To stimulate interaction between generations, participants can “collect” signatures of the hydrologists on their card by having a short conversation. The purpose is to share experiences about networking, career development, and views on gender issues in our field. When a participant has a bingo, (s)he can send a picture to the H3S twitter account (#HydroBingo). Every day, prizes will be distributed among those who sent pictures.

All members of H3S will attend this year’s Fall Meeting, and we are very eager to meet you. Whether you want to join activities, have ideas for new ones, or want to be actively involved, feel free to approach us. For 2016, we are looking for at least three new committee members. If you are interested, or know someone who is, don’t hesitate to contact us.

See you in San Francisco!

### Important dates:

1. Early Career Scientist Conference: 13 Dec., San Francisco Marriott Marquis, Golden Gate B.
2. Water Sciences Pop-Ups: 14 Dec., 4:00–6:00 P.M., Moscone South 101.
3. Social Dimensions in Geosciences Pop-Ups: 15 Dec., 4:00–6:00 P.M., Moscone South 101.
4. Meet H3S: 17 Dec., 6:45–7:30 A.M., Marriott Room Sierra.
5. Hydrologist Bingo: 14–18 Dec.; get your card at the Student Lounge.

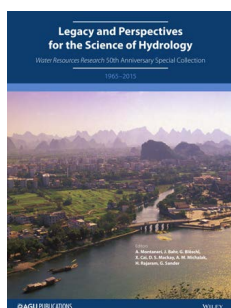
### Further links:

[@AGU\\_H3S](#)  
[H3S web page](#)

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## Happy Anniversary, *WRR*!

*Alberto Montanari (Editor in Chief), Jean Bahr, Günter Blöschl, Ximing Cai, D. Scott Mackay, Anna Michalak, Harihar Rajaram, and Xavier Sanchez-Vila (Editors)*



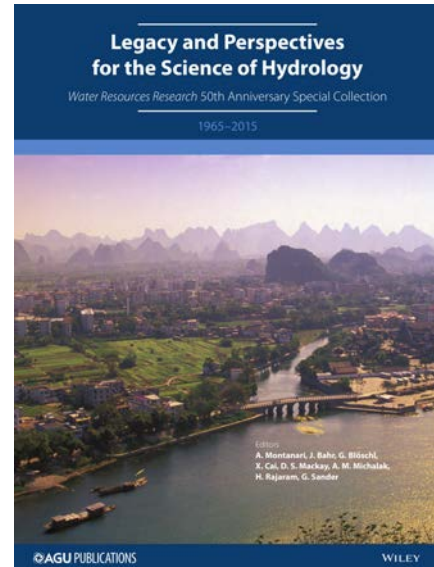
*Water Resources Research* (WRR) just entered its fifties! In fact, WRR was first issued in March 1965. Since then, about 14,000 papers have been published in the journal, and these have collected more than

22,000 citations. Looking back at these past 50 years, one realizes that the 50th anniversary of WRR is excellent food for thought. The journal has witnessed the development of hydrology as an independent science during a period characterized by the continuous increase of environmental monitoring capabilities, the advent of the computer era, and the consequent

dramatic developments of modeling techniques. Throughout the past 50 years, *WRR* always played a leadership role. To publish a paper in *WRR* has been, and still is, a milestone achievement for generations of hydrologists and a dream for students and researchers. The rigorous review process of *WRR* has always been considered an outstanding test for groundbreaking contributions.

To celebrate the 50th anniversary of *WRR*, the international community of hydrologists promoted a special collection of the journal, titled “Legacy and perspectives for the science of hydrology.” It includes a total of 57 papers, divided into three chapters and eight subjects, for a total of more than 1200 pages! The special collection is already available on the *WRR* website under the menu item “Collections” that is visible on the *WRR* home page. The resulting set of contributions is an ideal successor to the special issue “Trends and directions in hydrology” that was edited by Steven Burges in 1986 to celebrate the 20th anniversary of the journal [Burges, 1986]. The *WRR* editors are convinced that “Legacy and perspectives for the science of hydrology” is the excellent result of a collective endeavor of the hydrologic community that will provide a long-lasting benchmark and inspiration for future generations. These distinguished papers clearly bring forward the emerging topics and challenges in water science. In particular, the contributions emphasize the exciting opportunities offered by **(1) new monitoring techniques, which are providing innovative tools for observing hydrological processes across a wide range of spatial and temporal scales, (2) global-scale modeling, offering new ways forward to resolve global water problems, (3) the study of the coevolution of water systems within natural environments and societal settings, and, finally, (4) the characterization of heterogeneity at several spatial and temporal scales.** A comprehensive summary of the content of the papers is offered by the introduction to the special collection, authored by the *WRR* editors, which highlights the emerging perspectives. The introduction concludes with the aspiration that “... **water science may evolve at the global level, to minimize inequalities between genders, across the continents and across the ethnic groups. Water is a unifying element, and water science will be vital to ensure that humans and our planet co-evolve sustainably**” [Montanari *et al.*, 2015].

**To make the content of the special collection more effectively available to the hydrologic community, AGU, in cooperation with Wiley, has compiled a digital book collecting all the papers, along with a preface by AGU Hydrology section President Efi Foufoula-Georgiou. The book will be made available via open access, in digital format, on the *WRR* website (see Figure 1).**



**Figure 1.** The cover of the *WRR* 50th anniversary special collection.

AGU Fall Meeting will offer plenty of opportunities for hearing, directly from the editors, a report on the preparation and finalization of the special collection. On Tuesday, 15 December, at 1:30 P.M., the editors will present the special collection at the AGU booth in the exposition area. The presentation will focus on the history of the journal, which is excellently summarized by one of the papers [Rajaram *et al.*, 2015], and the development of the ideas underlying the conception of the special collection. After the presentation, there will be a Q&A session with the audience. In addition, the Editor in Chief of *WRR*, Alberto Montanari, will be available for individual discussions at the AGU Publication Booth on Tuesday, 15 December, 9:00–10:00 A.M. Finally, the *WRR* editors are available during the whole week for face-to-face meetings in the Editors’ Lounge. Please contact us by email if you wish to schedule a personal appointment. We are willing to discuss any item related to *WRR*. We are particularly pleased to meet young scientists to get their advice and vision on the journal and their publishing experiences.

From the perspective of the editors, putting the special collection together has been a demanding but very rewarding experience. We had the opportunity to meet and speak with many amazing colleagues, including prospective authors, reviewers (about 250, for this special collection only), editorial board members, past editors and associate editors, and many other interested colleagues. It has been exciting to see ideas mature, and it is now stimulating to receive comments on the published papers and see the number of citations to these papers rapidly growing. We highly appreciate receiving the feedback of the community. Therefore, please email us if you have any question on the special collection dedicated to the *WRR* 50th anniversary.

When compiling the special collection, it was unavoidable that we make an attempt to look at the future and imagine how *WRR* and the field of hydrology will evolve in the next 50 years. It is unlikely that any of us will be able to witness the changes over that long time span, but many of our young colleagues will. It is our hope that these colleagues may still remember the huge effort that the hydrologic community wanted to make in 2015. Our prediction is that *WRR* will still exist, but hydrologic science and practice will be markedly different. The future will guide us to resolve relevant current challenges, but new and important problems are certain

to arise, together with unimaginable opportunities. Water will become more and more the regulator of social dynamics, including economy, politics, immigration, and social tensions. Virtual connections (including water sharing) around the world will increase, and will make global analyses more and more important. Water will play a fundamental role in ensuring a peaceful future for humanity, provided scientists are proactive enough to effectively advise politicians toward equity in water security and solving the water-food-energy nexus. It is our duty to make such a peaceful future happen.

Happy anniversary, *WRR*!

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## Paul Witherspoon's Legacy: A Tribute to a Brilliant Scientist and Inspiring Teacher, and an Introduction to AGU's Paul A. Witherspoon Mid-Career Lecturer in Hydrologic Sciences Award

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In his long life and career within the Earth Sciences community, Paul A. Witherspoon (1919–2012) left a legacy as one of the world's leading hydrogeologists [Duncan and Voss, 2013; Freeze et al., 2015a, 2015b]. Paul's influence on advancing our science and

empowering the next generation of hydrogeologists runs much deeper than we can know. Working with Paul was a life-enhancing experience for his many graduate students and colleagues. He was supportive, available, optimistic, and fun. His students and colleagues fondly recall the many dinner parties and events that Paul and his late wife Elizabeth hosted at their home, and the lively, wide-ranging and stimulating discussions that marked those occasions.

Paul was a role model in his ability to foster a research environment of cooperation, excitement, and friendship. His students who stayed in academia inevitably attempted to create a similar setting. In the contemporary scientific world, Witherspoon is still widely acknowledged as having possessed an unusual gift for identifying really important problems, finding the resources to work on them, communicating clearly, and making friends and trusted colleagues across disciplinary and geographic boundaries.

Moreover, Paul had a seminal influence on the development of ideas and methodologies related to the hydrogeology of fractured rock. His interest in the topic originated from his early studies on caprock integrity for underground gas storage, grew through his mid-career emphasis on the role of aquitards in hydrogeological systems, and then flourished in his later work on thermohydrologic and hydromechanical couplings in geothermal systems and nuclear waste isolation. Never one to shy away from difficult topics, Paul tackled the seemingly most intractable and difficult research problems and inspired his colleagues to do the same.

As just one example, Paul and several of his students wrote an acclaimed article on the cubic law, entitled “Validity of cubic law for fluid flow in a deformable rock fracture” [Witherspoon *et al.*, 1980]. Arguably, this has been the most influential paper on the topic of fluid flow in a single rock fracture, with over 1000 citations to date (Google Scholar, 21 November, 2015).

Paul was widely honored for his work. He was awarded the Horton Medal from the American Geophysical Union and both the Meinzer Award and the Distinguished Service Award from the Geological Society of America. In 1989, he was elected to the U.S. National Academy of Engineering for “pioneering work in geothermal energy, underground storage, hydrogeology, and the flow of fluids in fractured and porous rocks.” In 1992, Paul initiated a collaboration between U.S. and Ukrainian scientists to develop a program of hydrological studies on contaminant transport at Chernobyl and its surroundings; subsequently, he was elected as a Foreign Member to the National Academy of Sciences of Ukraine. In 2001, he was elected Fellow of the World Innovation Foundation.

Paul’s greatest legacy is his many students and colleagues, who benefited from his generous mentorship and lifelong friendship. Not surprisingly,

Paul’s former students became key scientists throughout the world, including many outstanding hydrogeologists in the United States, Canada, UK, and other countries. To show their appreciation, they honored him over the years with several memorable research conferences and symposia at Lawrence Berkeley National Laboratory (LBNL), on the occasions of his 60th, 70th, 80th, and 85th birthdays [Narasimhan, 1982; Faybishenko, 1999; Faybishenko and Witherspoon, 2004]. Two monographs stemming from these events were published by the American Geophysical Union [Faybishenko *et al.*, 2000, 2005]. The monograph resulting from the presentations given in the fall 2012 AGU session devoted to the memory of Paul was recently published by AGU and Wiley [Faybishenko *et al.*, 2015].

Paul always reveled in his international coterie. He knew a few words in more languages than anyone you will ever meet, and always relished greeting people in their native language. He also developed close ties with scientists and organizations in China, Russia, France, Sweden, Ukraine, and many other countries, and traveled widely to give talks and courses.

Paul had a most attractive quality: the ability to explain, to anyone of any age or social group or background, difficult scientific problems in very simple terms. As an example, one of his colleagues recalled how he succinctly explained the problem of water movement at Yucca Mountain to a taxi driver in Nevada. He clearly had the knack of raising scientific questions and explaining difficult scientific topics to anybody. His goal, always, was to make students and colleagues feel at ease in his interactions with them. For this reason, he was never short of appreciative comments. Paul knew the secrets of effective conversation, had the skill of asking questions that promoted conversation, and encouraged innovative research. He also knew how to listen and to put others at ease, so that they would be inspired to express their ideas. His presence, encouragement, words of wisdom, and feedback really motivated his students and colleagues to excel and perform at their best.

In 1977, working from his faculty position at the University of California, Berkeley, Paul initiated and organized the Earth Sciences Division (ESD), and was the first Director of this new division at LBNL. Since then, ESD has developed into one of the most prestigious and respected Earth sciences institutes in the world. This division has recently been expanded to become the Earth and Environmental Sciences Area

(<http://eesa.lbl.gov>). This expansion is intended to position Berkeley Lab's programs so that they will have an even greater impact on environmental sciences, climate sciences, and subsurface energy resources worldwide. This vision all started with Paul. He would have been delighted and proud.

In 2015, AGU established the Paul A. Witherspoon Mid-Career Lecturer in Hydrologic Sciences. The award is intended to promote and reward excellence and outstanding achievements by a mid-career scientist (within 10 to 20 years postdoctoral) in advancing the field of hydrologic sciences. As the scientific community enlarges the scope of hydrological science, not only on the fundamental disciplinary level but also by including more interfaces with other disciplines and society at large, this award is very much needed. While obviously honoring its recipients, the Paul A. Witherspoon award will also honor Paul's great accomplishments—in advancing the science of hydrology, its application to socially important problems, and Paul's inspired and dedicated mentoring of young hydrologists. Some of his former students and colleagues recall that Paul himself very much valued mid-career professionals, who often developed significant expertise in one or more areas, and who were ambitious and constantly looking for new research challenges and directions.

As one of Paul's former students said, "Paul's notes for Mineral Engineering 282 formed the starting point of my own course notes. Over the years, about half of my research has involved fluid flow in porous or fractured media. All of this work owes a great debt, in many direct and indirect ways, to Paul Witherspoon—a brilliant scientist and inspiring teacher."

To learn first-hand about Paul Witherspoon's perspective in research and community building, view the videotaped interview that he gave in 2007, posted on the website of the International Association of Hydrogeologists (IAH) ([timecapsule.iah.org](http://timecapsule.iah.org)). A biographical article based on the interview was also published by IAH [Freeze and Javandel, 2008]. As expressed in his obituary [Freeze et al., 2012], "to enter Paul's orbit was to experience a stimulating mix of high intelligence, deep curiosity, and love of life."

\*Witherspoon's biography at the LBNL EESA website  
<http://esd.lbl.gov/profiles/paul-a-witherspoon/>.

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## Taking the Pulse of River Networks: A Monitoring Approach for Understanding Hydrologic Change?

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I appreciate the opportunity to provide a research perspective on understanding hydrologic change, and have chosen to focus on monitoring, a topic that is sometimes not viewed as “research”. Certainly, there is general agreement that a great value of hydrologic monitoring is documentation

of long-term change in the characteristics of the hydrologic regime and associated water quality parameters. Knowledge of these characteristics is important for providing resources and protection for communities and ecosystems. Keeping track has intrinsic merit for water resource management at the present time, when it is well recognized that “stationarity is dead” [Milly *et al.*, 2008].

Planning and design are key aspects of a successful monitoring program. At the start of my career with the U.S. Geological Survey, I was privileged to be involved in the initial design of the ecological aspects of the National Water Quality Assessment Program (NAWQA). I remember vigorous discussions of potential approaches and the implications of the River Continuum Concept [Vannote *et al.*, 1980] for the design of the program. The NAWQA program was launched in 1991, after several pilot programs, and, since then, has contributed greatly to understanding of underlying processes driving changes in water quality across the country. Planning activities are now underway for the third decade of the NAWQA program (<http://water.usgs.gov/nawqa/about.html>).

Monitoring programs can be also designed to test scientific hypotheses. In the Long-Term Ecological Research (LTER) program supported by the National Science Foundation (NSF), interdisciplinary teams of investigators explore hypotheses for ecosystem function and strive to design monitoring programs that not only will address five core areas (primary production, population dynamics, cycling of organic matter, nutrient cycling, and patterns of disturbance) that are studied across the LTER program but also will provide data for testing the specific hypotheses that the

team has put forward. These hypotheses are continually refined and built upon as research progresses. For both the McMurdo Dry Valleys LTER site in Antarctica and the Niwot Ridge LTER site in the Colorado Front Range, monitoring of streamflow and water quality is included to address core areas and test hypotheses (Figure 1).



**Fig. 1.** The weir at low flow of the Onyx River in Wright Valley at the gauging station near Lake Vanda. The 45-year flow record from this gauge is the longest environmental record in the McMurdo Dry Valleys and has been the highest priority to be maintained by the MCMLTER project.

It is not uncommon for monitoring results to reveal trends and interactions that were not anticipated. These discoveries may be equally important outcomes of monitoring programs as achieving the initial design objectives. The science-based approach used in NAWQA and the LTER program provides enough ancillary information to support interpretation of unexpected results in the context of underlying processes. In my opinion, discovering what we do not understand about the environment is as important a step toward advancing and improving predictions for water resources as developing more complex and finer-scale climate models. However, a change in pattern can be slow to emerge, as we analyze interannual variation looking for changes that are statistically significant. Sometimes, it can seem that the environment is changing too fast for our statistically rigorous approaches to keep up.

As the planning process is underway for NAWQA and other monitoring programs are being developed by NSF, we can consider how to design, redesign, and upgrade hydrologic monitoring programs to more effectively make such discoveries of unanticipated interactions. Fortunately, our ability to collect and process data in real time at high frequency and the development of new in situ sensors are both advancing rapidly. In this context, I argue that we can also take advantage of the day/night cycle as a driver of detectable temporal change in river networks in redesigning monitoring programs. For example, for streams and rivers, in addition to measuring temporal variation in discharge, temperature, and electrical conductivity, we can measure carbon dioxide and dissolved oxygen as measures of groundwater fluxes, hyporheic exchange, and biogeochemical processes.

As these capabilities advance, we will be able to detect directional change not only as a change in one parameter but also as a change in the day/night synchronicity of a selected set of continuously monitored parameters. This approach can be characterized as “taking the pulse” of a river network. This approach could also be taken to a larger, continental scale. Instead of just tuning into a weather report on the news, maybe, in the future, we will

commonly also get a report on daily evapotranspiration or snowmelt infiltration relative to runoff.

To take advantage of these advances in this way, continuing scientific advances are needed. For example, choices of what to measure can be made within a science-based framework. This approach may result in inclusion of parameters that do not have a direct application for documenting a water resource, and thus would need strong scientific support. In addition, continuing development of robust models will need to be an aspect of a successful monitoring program. These models will be needed to interpret the temporally resolved signals and compare observations across regions in time for the next day’s weather report.

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## A Fellow Speaks: Ecosystem Processes at the Watershed Scale

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I am grateful to my colleagues for nominating and electing me as an AGU Fellow. I have had the very good fortune to work collaboratively with a set of leading scientists in different fields and excellent graduate and postdoctoral students (not all of whom can be named here). I have found that the most interesting and challenging questions are at the junction of disciplinary domains, and in the feedbacks and coevolution of natural and human components of Earth systems. Like many of our colleagues, my research career has been guided by equal parts long-term strategy, opportunity, and chance.

While my first publication was on crop photosynthesis [Band *et al.*, 1981], the focus of my dissertation at University of California, Los Angeles, was in geomorphology, working on small, unvegetated hillslopes developing on weathered phyllite in the base of an abandoned hydraulic gold mine (The Malakoff Diggins, photographed by G. K. Gilbert and presented in his 1909 paper) in the Sierra Nevada. Direct measurement of runoff and sediment transport to determine transport equations, estimated boundary, and initial conditions from historic photographs, and the availability of more than a century of rainfall records, provided a simplified system to develop and test the equation sets governing hillslope evolution [Band, 1985]. However, something nagged at me as I sampled runoff and transport on the slopes during rainstorms, while watching snowfall on the second growth ponderosa pine forests on the ridge above the mine. It

convinced me that I needed to build in better plumbing than needed on my bare, miniature hillslopes, a dynamic ecosystem, and develop the ability to represent terrain complexity over large areas if I wanted to study real watersheds.

While finishing my dissertation, I taught a set of courses at San Francisco State University, including computer cartography (later called GIS), when the U. S. Geological Survey released its first Digital Elevation Model of San Bruno Mountain. Taking the train twice a day past San Bruno Mountain from Menlo Park to San Francisco, I wondered how I could build a digital terrain model of the essential components of a drainage basin: stream and valley network, ridge networks, and hillslopes. By chance, I used to pick grapes in the fall at Ridge Wine in the Santa Cruz Mountains, coowned by old family friends, with a core of people from the Stanford Research Institute Artificial Intelligence Lab, and our conversations while picking zinfandel and cabernet naturally turned to pattern recognition of terrain. A good example of the chance encounters in the innovation center of the early Silicon Valley, it sparked new approaches that I used my computer cartography course to initially explore. The long-term plan, conceived in the vineyard and on the Caltrain commuter line, was to work on the coevolution of watersheds, combining spatially distributed models of photosynthesis, hydrology, hillslope geomorphology, and the terrain analytical methods that were emerging.

My graduate experience imprinted a set of principles that helped shape my research. The first was the long-term transience of geomorphic systems, and, by extension, the coevolution of hydrologic and ecological systems that mantle the landscape. Steady-state assumptions in these long memory systems under shifting boundary conditions may be useful simplifications but may miss key legacy influences. The second was that as we develop models of these environmental systems, the equation sets, initial and boundary conditions, and predictions should be viewed as hypotheses, requiring sufficient observational or experimental measurement to allow testing and refinement. Otherwise, our models are in danger of being confused with video games. The third was that coupling the dynamics of two or more “disciplinary” models can fundamentally change their behavior, and this further requires measurements across these areas. Finding good colleagues in the different disciplines, and gaining sufficient understanding to make sense of their interactions, was a prerequisite for me.

My first tenure-track position, at Hunter College in New York, was in a department with no lab facilities but with good image processing facilities, which favored further development of the pattern recognition methods to extract and build a watershed data structure from digital terrain data [Band, 1986]. Long train commutes again provided the time and opportunity to learn a new field and think through new approaches. During this time, I met and worked with Eric Wood and Siva Sivapalan across the river in Princeton. We exchanged visits to merge the terrain analysis with TOPMODEL, and visualize dynamics using the banks of SGI machines at Princeton (with the reverse visits sampling the pastrami on rye in the various delis on the upper east side of New York City around Hunter College). This collaboration resulted in publications [e.g., Wood *et al.*, 1988] on variable source area dynamics and dominant length and area scales in watershed behavior. Two summers at NASA Ames Research Center developed other collaborations with ecology and remote sensing scientists. While I was interested in building better canopy photosynthesis and water use models into the distributed hydrologic models, Steve Running at the University of Montana was interested in adding the hydrology and terrain analysis required to distribute his forest water and carbon-cycling models, while Dave Peterson at NASA-Ames provided the remote sensing of forest canopy properties. This was a spontaneous fit and very productive collaboration that resulted in early versions of our distributed water, carbon, energy, and nutrient cycling models [Running *et al.*, 1989; Band *et al.*, 1993]. NASA provided an infrastructure that was organized around Earth system problems rather than disciplines. Major outcomes that emerged included how the spatial distribution of canopy cover and physiology, soil, and terrain conditions at hillslope scales influence emergent landscape-level water, carbon and nutrient cycling, the resilience of land surface processes to dry-down and wet-up periods [Band *et al.*, 1993; Creed *et al.*, 1996], land surface energy partitioning, and the interaction with atmospheric boundary layer development [Walko *et al.*, 2000].

I have had excellent graduate and postdoctoral students at the University of Toronto and the University of North Carolina who now have another generation of excellent graduate students in the United States, Canada, and China. With the interdisciplinary focus of our research, my students arrived with a set of diverse backgrounds including geography, biology, engineering, planning, and computer and systems

science, all with the interest of integrating across the component areas of watershed systems. Expanding our early focus on western North American forests to multiple climates and land uses, including urban watersheds, required adding to the set of endogenized processes for models and related measurements for testing and refinement. Working in the Loess Plateau of China with a visiting scientist with Chinese Academy of Science and in Australia with CSIRO and the Bureau of Meteorology provided that expansion of environments, measurements, and models, with fruitful and long-term collaboration.

At the Coweeta and Baltimore Long-Term Ecological Research sites, the detailed, interdisciplinary, long-term observations, measurements, and experiments (in Coweeta, dating to 1934) provide the empirical base to develop, test, and refine our concepts and models, and generate new ecohydrological principles. These include the adjustment of downslope to upslope ecosystems through a resource subsidy, and the emergence of “optimal” canopy patterns at the hillslope and catchment scale in terms of system water and carbon exchange [Hwang *et al.*, 2009, 2012]. One of our current challenges working in Baltimore is that most of our theory and observations on ecohydrologic dynamics are derived from sites like Coweeta, a high-biodiversity ecosystem with long-term control and experimental catchments. Testing and translating principles to benefit design and operation of urban green infrastructure [Miles and Band, 2015] within urban flowpaths, or riparian and stream restoration, is still in a nascent form (perhaps analogous to the trial and error medieval cathedral building) but is in strong demand, as municipal governments commit billions of dollars to retrofit existing urban forms and infrastructures.

As we shift our interest to the Anthropocene and “sociohydrology,” a major challenge is the integration of individual, community, and institutional behavior and governance as a coupled dynamic to watershed science. When we started the Baltimore LTER in 1998, the mix of colleagues working in hydrology, ecology, and climatology expanded to include community social and governance issues. We spent about 2 years learning what questions each group was asking, why they were important, and how our interests and skills interfaced. Some of my most interesting projects have been with community sociologists and planners, in which individual and group behavior have been the primary dynamic controlling the dynamics of urban stormwater ecohydrological and biogeochemical processes [Law *et*

*al.*, 2004; Groffman *et al.*, 2003; Fraser *et al.*, 2013]. Another new project integrating forest ecology, land use, and climate change with the management of water scarcity and environmental financial risk, with Greg Characklis at University of North Carolina and others, involves decision making and learning environments of water utility managers. Our research methods and paradigms in watershed ecohydrology and water resources are necessary, but not sufficient, for this integration.

This all means more time with new colleagues at the white board.

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## A Fellow Speaks: A Revolution in Flood Modeling

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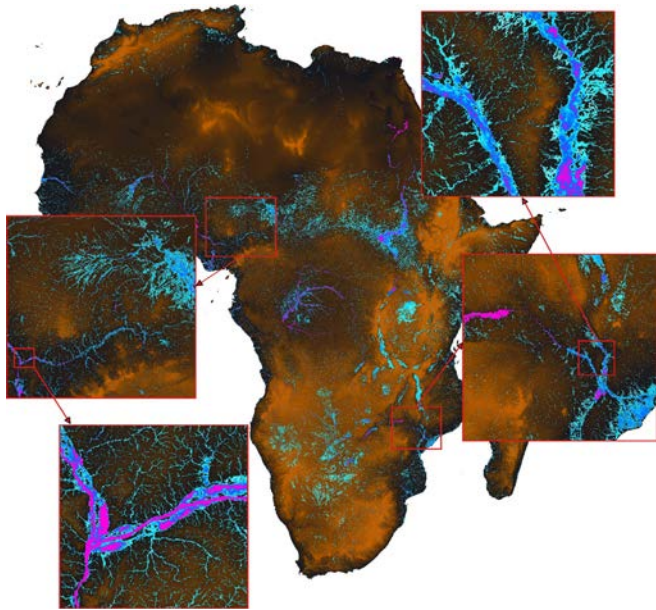
It is an enormous honour to have been elected a Fellow of AGU, and I'd like to thank those people kind enough to write and nominate me and also all the outstanding and truly inspirational colleagues with whom I have worked over the years. This has actually been quite some time, as hydrology,

for me, started early: When I was a child, the garden of our family house led down to a small stream, and from the moment I was able to wear wellington boots and get down into the water, I have been playing in rivers. I have never stopped, and it has been a privilege to spend my career doing the thing I love.

Most days, as a child, I played in the river, and, with time, I began to notice that things were not always the same. In winter, after heavy rain, the level would rise and brown flood water would cover the lower part of our garden. I became fascinated by just how high the water could get, and marked the water's edge with twigs stuck into the ground to see if the latest flood would be the "record." I would watch out of the window to see if my last marker was getting submerged or whether it had been left high and dry (in my defense, this was the 1970s, and there wasn't an awful lot else to do). When the flood receded, I tried to work out how high above normal levels the river had risen, with the tape measure from my dad's toolbox. I was amazed that a clear stream just a couple of meters wide that I could paddle in during the summer could rise several meters and become a raging muddy torrent after heavy rain, sweeping away vegetation and leaving sediment behind.

Without even realizing it, I was becoming a hydrologist, and, perhaps even more improbably, I was already specializing in floods. As a result, when, after my Bachelor's degree, I was offered the chance to do a Ph.D. on modeling floods using two-dimensional hydraulic models, I didn't even think twice before accepting. Serendipitously, this turned out to be a smart move: Over the last 25 years, the economic, health, and social consequences of severe flooding have become increasingly recognized, while, at the same time, new measurement and modeling techniques have enabled significant progress to be made both in the science of flooding and in producing new tools for better managing flood risk.

Floods are the costliest and most deadly class of natural disaster each year. According to the UN's EM-DAT database [Guha-Sapir et al., 2015], out of 324 reported natural disasters in 2014, floods and landslides caused by hydrological events affected 42.3 million people globally, killed ~4600 people (~58% of the annual total), and caused ~\$37 billion of damages (~38% of the total). Shocking though these figures are, it is worth noting that 2014 had the third lowest number of reported disasters out of the preceding decade, and the total number of disasters was below the annual average observed from 2004 to 2013. The patterns observed in 2014 are repeated annually, and high-profile flood events (e.g., Australia and Thailand in 2011, Central Europe in 2013, and India and Pakistan in 2014) are an all too regular occurrence. As a result, there has been, and continues to be, sustained public, commercial, political, and scientific interest in flood risk.



**Fig. 1.** The 1 in 100 year flood depths at 1/1200 arcsec spatial resolution ( $\sim 90$  m at the equator) created using a global hydrodynamic model [Sampson *et al.*, 2015].

However, flood risk is really only well understood in a very small number of territories worldwide (the Netherlands, the UK, Germany, Japan the United States, and a handful of others), and the rest of the planet has, until quite recently, been largely unmodeled. Lack of skill in global flood models is due to poor or nonexistent monitoring of river networks in many regions [Fekete *et al.*, 2002], the low suitability of global terrain data sets for flood modeling [Sanders, 2007], the restricted spatiotemporal coverage of suitable remotely sensed data sets used to map flood extent [Bates *et al.*, 2014; Prigent *et al.*, 2007], and the limited spatial resolution and process representation that can be achieved in global flood models due to computational constraints [Bell *et al.*, 2007]. Like politics<sup>1</sup>, all flooding is local, and, in addition, flood extent is determined by complex and nonlinear processes. For example, correct representation of the physics of flood waves (i.e., hydrodynamics) is often required to determine whether a flood defense overtops or not, and this can result in huge differences in predicted flooded area. As a result, low-resolution and nonhydrodynamic models may significantly misestimate exceedance probability curves because they do not have sufficient local skill in to produce correct results, even when aggregated to coarser spatial scales, because the overprediction and underprediction errors do not cancel out. Despite “bottom-up” modeling

being exceptionally difficult, “top-down” approaches are likely to be even less able to anticipate the consequence of previously unobserved events.

Looking to the future, the continued expansion of cities located on river floodplains and coastal deltas because of population growth and migration will inevitably produce a significant increase in flood risk. Economic losses will also inevitably increase as people are lifted out of poverty, living standards rise, and a global middle class with western consumption patterns emerges. If current trends continue, then populations will grow, age, become more affluent, and migrate to zones of higher flood risk. Recent modeling studies [e.g., chapter 2 in Mace *et al.*, 2014] have also shown that exposure to flooding over the forthcoming decades will increase most in exactly those regions (Africa, less-developed parts of Southeast Asia) where we currently have the most-limited risk information.

There are therefore very strong economic and humanitarian drivers to improve our understanding of flood risk for the  $\sim 90\%$  of the globe that is currently unmodeled. As a result, the last 2–3 years has seen a significant push to develop and test the first global hydrodynamic flood hazard and risk models. This work is still very much in its infancy, yet there is already evidence for levels of model skill that would have been considered surprising (if not actually impossible) only 5 years ago. In hydrology, global models with approximately kilometer grid scales have been termed “hyperresolution” by Wood *et al.* [2011] and are seen as a “Grand Challenge” for the forthcoming decade. In hydrodynamics, the use of true physically based equations derived strictly from Newtonian physics means that this is potentially even more of a computational challenge, yet this is exactly what recent models have been able to do. As Hall [2014] noted “in flood modelling, a revolution has been taking place.”

Figure 1 gives an example of the output of one such model [Sampson *et al.*, 2015]. This shows the 1 in 100 year flood depths for the whole of the African continent at a 1/1200 arcsec spatial resolution ( $\sim 90$  m at the equator), and represents just one part of a data set covering the whole terrestrial land surface between  $60^\circ\text{N}$  and  $54^\circ\text{S}$ . This model solves the local inertial form of the shallow water equations and is clearly hyperresolved and truly hydrodynamic. The hydraulic engine is a clone of the LISFLOOD-FP model described in detail by Bates *et al.* [2010] using the sub-grid scale approach to river channels outlined by Neal *et al.* [2012]. Boundary conditions for the flood extent calculations are derived from the regional flood

<sup>1</sup> “All politics is local” is a maxim widely attributed to the former Speaker of the U.S. House of Representatives Tip O’Neil.

frequency approach for global applications developed by *Smith et al.* [2015], which gives the magnitude of extreme return period river flows and rainfall anywhere on the globe. Digital elevation data for the model come from a bespoke version of the SRTM data set specifically adapted for flood inundation using some of the techniques outlined by *Baugh et al.* [2013] but extended to also identify and remove building artifacts using nighttime light intensity data to identify built-up areas. River widths are estimated using a hybrid geomorphological/web survey technique in which river widths along major rivers within a domain are measured and recorded along with their corresponding upstream accumulating areas. By assuming a bankfull discharge return period of approximately 1 - 2 years, the flow generation algorithm of *Smith et al.* [2015] is used to generate an estimate of bankfull discharge. By combining bankfull discharge, channel width, and an estimate of slope calculated from the DEM, it is then possible to produce an estimate of channel depth using Manning's equation. The model operates on 10° by 10° tiles, and the results are stitched together to form the water depth map shown in Figure 1.

Data such as those shown in Figure 1 are unprecedented; however, we have now realized that hydrodynamic modeling at global scales is conceptually no different than the reach-scale engineering-grade modeling I undertook my for Ph.D. Global models are therefore built on a rich heritage of algorithm and data set development in hydraulic modeling over the last 20 years. We are entering a hugely exciting era in flood modeling, and I have been exceptionally lucky to work in this scientific field during such a period of dramatic change. Moreover, the pace of development shows no sign of abating: Watch this space!

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## A Fellow Speaks: What Drives Global Change in Hydrology and Human Freshwater Consumption?

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I am honored and grateful to have been elected AGU Fellow and thank everyone who has supported me in this election. I also thank all friends and colleagues who have worked with me over the years on the research leading to this recognition. An overarching goal of my research has been to

link our understanding of water flow and waterborne transport at multiple scales and through various water bodies into a coherent view and representation of the continuous, ever-flowing hydrological system on Earth.

Water and waterborne material fluxes along various pathways connect the world's rivers, lakes, wetlands, and aquifers into a coupled hydrological system (schematized in Figure 1A), which is organized in catchments and drainage basins of different scales that, together, cover Earth's land surface (Figure 1B). Through some water fluxes and flux pathways, the basin-wise organized hydrological system also interacts closely with other major Earth system segments, including the anthroposphere (through the engineered water systems and water impacts of society) and other surface and subsurface features of the landscape, as well as with the atmosphere and the coastal and marine waters. Overall, the coupled water fluxes within and into/from each hydrological basin thus propagate hydrological and environmental change from different change drivers, including regional-global forces of atmospheric climate change as well as landscape-internal change drivers (see main driver types and examples schematized in Figure 1C).

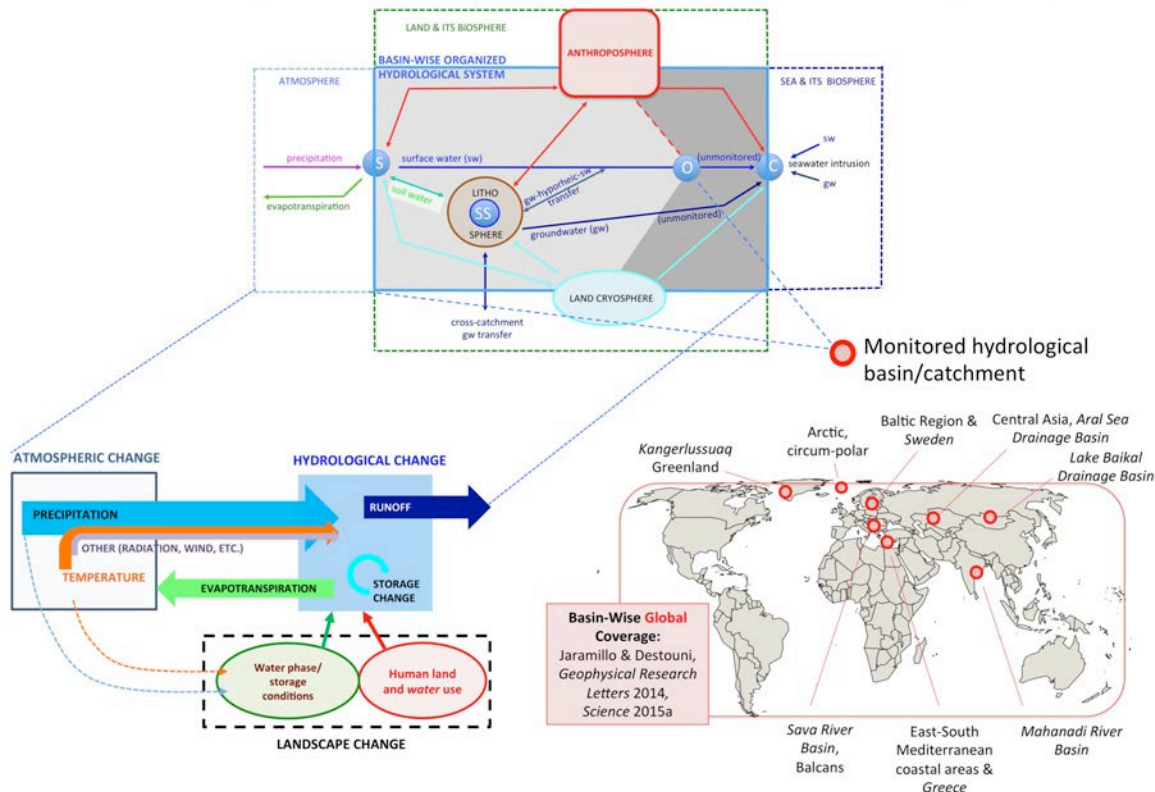
For regional hydrological basins in different parts of the world, recent research has shown landscape-internal drivers as dominant for main hydrological shifts occurring over the past century (see, e.g., the Swedish, Aral Sea, and Mahanadi River basins among those exemplified in Figure 1B [Destouni et al., 2015]). Specifically, the key landscape drivers in these regional basins were human land use and water use changes, including agricultural extension/intensification, and

developments of irrigation schemes and hydropower-related flow regulation. These drivers were all found to increase actual evapotranspiration (ET) relative to precipitation (P). In addition, the flow regulation developments decreased the temporal short-term variability of runoff (R), indicating this as a useful effect for distinguishing ET/P increase driven by flow regulation from that by other landscape-internal or atmospheric climate drivers.

Follow-up studies of hydrological change in many basins/catchments of different scales and with total land area coverage and spreading representative of the global scale have further supported the regional findings of dominant landscape-internal drivers [Jaramillo and Destouni, 2014, 2015a]. Specifically, in at least 74% of 462 investigated hydrological basins over the world, dominant landscape-internal change drivers of various types (Figure 1C) were needed to explain ET changes occurring in the basins during the period 1901–2008, in addition to the ET change explanation provided by the observed surface temperature and P change drivers in the basins [Jaramillo and Destouni, 2014]. Furthermore, consistent and dominant effects of increased ET/P were found also globally for both flow regulation and irrigation developments, accompanied by decreased temporal R variability for flow regulation developments [Jaramillo and Destouni, 2015a].

In total, the global ET increase driven by local flow regulation and irrigation developments over the past century implies an increase in the long-term average human consumption of freshwater by around 3563 km<sup>3</sup>/yr from 1901–1954 to 1955–2008, with an uncertainty range of  $\pm 979$  km<sup>3</sup>/yr around this mean quantification [Jaramillo and Destouni, 2015a]. This increase in global freshwater consumption then accounts for the total increase in freshwater loss from the landscape to the atmosphere due to the total ET increase driven by these local human activities. This global increase also raises a previous estimate [Hoekstra and Mekonnen, 2012] of the global water footprint of humanity by 18% to around 10,688 km<sup>3</sup>/yr.

## A. Basin-wise organized hydrological system - coupled by water fluxes &amp; pathways



## C. Drivers of hydrological system change

## B. Basin-wise studied global hydrological system

**Fig. 1.** (A) Schematic representation of the basin-wise organized coupled hydrological system (redrawn and simplified from a similar schematization by *Destouni et al.* [2014]). (B) Examples of hydrological basins around the world that have been in focus for my research on hydroclimatic change and its drivers, and references to some recent papers of multiple basins with total area coverage and spreading that are representative of the global scale [*Jaramillo and Destouni*, 2014, 2015a]. (C) Schematic outline and examples of atmospheric and landscape-internal drivers of hydrological change (redrawn from *Jaramillo and Destouni* [2014]). Fig. 1A shows the pathways of water flow and waterborne transport (arrows) that physically couple the hydrological system and are organized in two types of catchments or basin parts: convergent into an observation point (light gray) and divergent and commonly unmonitored coastal catchment areas draining their water through an extended shoreline (dark gray). The water pathways interact and are partitioned in four main zones of hydrological change, schematized in Figure 1A as blue filled circles, marked with: S, surface; SS, subsurface; C, coast; and O, observation.

Moreover, the found global ET increase by local flow regulation and irrigation developments supports previous regionally based estimations [*Destouni et al.*, 2015; *Jaramillo and Destouni*, 2015b] of the total global human water consumption being well above (rather than well below, as suggested in connection with) a proposed planetary boundary of 4000 km<sup>3</sup>/yr [*Steffen et al.*, 2015]. Specifically, adding this global ET increase effect to previous estimates of global human freshwater consumption by various other sectors (807 km<sup>3</sup>/yr in net total for nonirrigated agriculture, deforestation, industry, and municipalities [*Jaramillo and Destouni*, 2015b]) yields a total global freshwater consumption of 4370 ± 979 km<sup>3</sup>/yr.

Regarding total hydroclimatic change on land over the past century, landscape-driven and climate-driven changes in ET have tended to counteract each other globally and in most continents [*Jaramillo and Destouni*, 2014]. This counteraction may have dampened the net total water change so far, compared to only climate-driven or only landscape-driven components of global water change. However, estimates of large-scale change effects are also shown to be highly uncertain for both human-driven [*Jaramillo and Destouni*, 2015a] and climate-driven water changes on land, with the latter considering the relevant hydrological output from the latest generation of Earth system models (ESMs) [*Bring et al.*, 2015]. Common for these recent studies of global and regional water changes on land is their use of a wide range of

long-term climatic and hydrological observations, combined with worldwide land use and water use data [Jaramillo and Destouni, 2015a], or directly compared with hydrological ESM output data [Bring *et al.*, 2015]. In combination, these data-based results show that worldwide observation data can and should be more widely used to constrain quantifications of long-term global hydrological and freshwater changes, in addition to only attempting to model such changes.

The data-based results have thus expanded both the likely magnitude and the uncertainty range of the global human consumption of freshwater, and should raise awareness of and guide new efforts for reducing both. These results and the direct comparison between observation and ESM output data also stress the importance of considering local water use and hydrological system conditions and constraints (Figure 1A) in addition to larger-scale atmospheric and land use considerations in Earth system studies and modeling that should be of relevance for water resources and their changes on land.

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## A Fellow Speaks: Emerging Role of Algorithms in HydroComplexity

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Digital water cycle, a characterization of processes participating in Earth's water cycle through widespread measurements and their digital representation, is becoming increasingly more realistic. On the one hand, we have large-scale representation of terrestrial, atmospheric, and

oceanic attributes from regular monitoring using satellites, and, on the other hand, emerging low-cost sensing through in situ instruments and UAVs (unmanned autonomous vehicles) promises to provide a pervasive knowledge of the state of our environments almost everywhere and almost all the time. Long-term place-based studies such as LTER (<https://www.lternet.edu/>), NEON (<http://www.neoninc.org/>), Fluxnet (<http://fluxnet.ornl.gov/>), and Critical Zone Observatories (<http://criticalzone.org/national/>) are creating rich databases that allow exploration of deep linkages. Deeply intertwined in this milieu are the data

associated with anthropogenic participation in the water cycle, albeit often fragmented and difficult to obtain, which is impacting the water cycle from the local to global scale with potential to create emergent risks [Kumar, 2015]. Such data are complex in that they encompass a heterogeneous collection with many dimensions, local coordinate systems, scales, variables, nomenclature, providers, users, and scientific contexts. Due to the rapidly increasing volume of such data, we have to think of new ways of representing the information such that their complex interdependencies and hierarchies are retrievable. In this regard, the representation and ease of access of information about the data become just as important as the data. This is because the sheer volume and heterogeneity of the data makes direct human consumption difficult, requiring that most of the data be directly consumed by sophisticated tools for analysis, visualization, modeling, decision support, etc., through APIs (application program interfaces).

Emerging semantic web technologies are making such representation and data use a reality. They support

representation of information in ways that computers, or more precisely the algorithms implemented for such purpose, can understand their meaning and context, and enable sophisticated reasoning and computation across these resources. These algorithms allow us to provide direct interface of data with models, and analytical and visualization tools. In other words, it will be possible to take humans out of the loop in integration of digital resources such as data, models, etc. To support such integration, the notion of “web service” is becoming an increasingly important enabler. Web services provide access to resources over the web through well-defined protocols, thus enabling structured unambiguous communication between agents (devices, computers, things, algorithms, people, etc.). They shield the details of the structure and organization of the resources. This allows flexibility in the use of technologies that are appropriately suited for the requirements and consistent with institutional practices related to such tasks, yet supports access through a rich set of queries. This is leading to the emergence of data as a service (DaaS), software as a service (SaaS), and, more recently, model as a service (MaaS), so that it is now possible to create a network of interacting algorithms that are distributed across the Internet and use resources across the web automatically. Model-data integration accomplished locally on a machine or a local network through considerable human effort will soon be a practice of the past. New paradigms for information distribution and their use are emerging that are taking prediction, analysis, and decision support to a new framework where the “Internet is the computer,” allowing a democratic participation of scientists, institutions, and nonscientists in data collection, analyses, interpretations, and decision making about the use and management of our precious natural resources and infrastructure.

In a provocative 2011 Ted Talk, “How algorithms shape our world,” Kevin Slavin ([www.ted.com/talks/kevin\\_slavin\\_how\\_algorithms\\_shape\\_our\\_world](http://www.ted.com/talks/kevin_slavin_how_algorithms_shape_our_world)) argued that “we live in a world run by algorithms, computer programs that make decision or solve problems for us.” Algorithms are widely prevalent in our daily lives, from GPS solutions to communication between smart devices. Algorithmic solutions now go beyond conversion of mathematical formulations to computer code for fast solutions. Indeed, we may consider algorithms in the same vein as mathematics—linked but independent. Much as computer codes in the traditional scientific context enable solutions to otherwise unsolvable systems of equations, algorithms can be regarded as methods in

their own right in that they provide solutions that we would not be able to arrive at otherwise. The value of algorithms as a novel way to seek solutions is amply exemplified in the “blockchain” technology that underlies the peer-to-peer transactions based on Bitcoin, a decentralized digital currency. This blockchain technology has many potential applications, such as enabling tamper-proof ledgers of property and goods [*Economist*, 2015], a hitherto unsolved problem.

Algorithms can sift through large complex data to seek deeper relationships between data elements. Examples include study of gene sequences through their expression and possible relationship to diseases; or between metadata, such as identifying that variables encoded with either “stage” or “discharge” may refer to the same physical phenomenon of stream flow; or between units encoded in different standards for different data elements to provide conversions on the fly; or identifying complex patterns such as atmospheric rivers from large and dynamic atmospheric moisture flux data, etc. The algorithmic approach is already pervasive in data mining techniques where methods such as decision tree provide valuable categorization in large volumes of data. In recent years, we have seen the emergence of formal data models for a broad suite of environmental data (<https://github.com/ODM2/ODM2>), ontologies (<https://marinemetadata.org/conventions/ontologies-thesauri>), and semantic platforms (<http://earthcube.org/group/geosemantics>), which are rapidly making such systems a reality by encoding information such that algorithms can be developed to explore relationships and dependencies. Interacting algorithms that exploit such technologies may evolve as complex adaptive systems [*Holland*, 2014] by participating in hitherto unforeseen couplings, and presenting us with insights that we wouldn’t otherwise seek or predictions that may exhibit no historical precedence. They may range from novel solutions to warnings about emergent risks [*Kumar*, 2015, and references therein]. With the expanding data sizes and their heterogeneity, increasing resolution, model complexity, cross-disciplinary linkages, and algorithms for direct and “intelligent” communication between them, we are presented with an unprecedented opportunity to provide solution for present and emerging societal problems that go significantly beyond present approaches.

Such approaches are not without risks, however. Without suitable checks and balances of verification and validation of information that may sit behind

boundaries of web services across numerous institutions, the risks are high that outcomes of assessment and prediction may be flawed. Blending of incompatible or erroneous data, models, and other resources can lead to outcomes that have deep consequences. Transparency, open system approaches, and technologies for verifying the reproducibility of results have to go hand in hand with the emerging advances. Deeper discourse is needed to support best practices that will enable such advances. How can we exploit such emerging systems to better understand, predict, use, and manage the water cycle in the Anthropocene? How do we ensure that outcomes from such autonomous systems are reliable, and how do we validate them? These are some of the Big Data challenges that are likely to shape water cycle studies in the near future.

I appreciate the opportunity to provide my thoughts through this forum. It is a tremendous honor to be

elected a Fellow of AGU. But it is not a singular achievement. I would like to recognize my former and present students and postdocs for their contributions. I also would like to acknowledge the support and contributions of my mentors and colleagues who continue to encourage and inspire me. Special thanks go to my colleagues who have spent tremendous time and effort for the nomination and writing the support letters.

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## A Fellow Speaks: Fascinating New Laser Spectroscopy Facility for Real-Time Isotope Hydrology

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The University of Arizona just completed construction of the Landscape Evolution Observatory (LEO). LEO is the world's largest Earth systems science experiment and consists of three large hillslopes under the glass of Biosphere 2 (Figure 1). Each hillslope is 30 m long and 11 m wide and contains 1 m of crushed

basalt. In and above the soil, a network of more than 2000 sensors and samplers allows for observing water content, carbon concentration, and energy fluxes in real time. But what makes the LEO unique from a hydrological perspective is its laser spectroscopy capabilities.

Stable isotope analysis can provide valuable information about the origin, pathways, and physicochemical reaction processes of H<sub>2</sub>O and CO<sub>2</sub> throughout the landscape. While natural fluxes and/or transformation processes of water and CO<sub>2</sub> may be

highly variable in time and space, technical constraints have usually limited the temporal and spatial frequency at which water and air samples could be collected and isotopically analyzed in field studies. The stable isotope laboratory of LEO allows overcoming such limitations by utilizing an extensive network of sample intake points along with state-of-the-art techniques for continual direct monitoring of specific isotope abundances in H<sub>2</sub>O and/or CO<sub>2</sub> in soil, atmosphere, and seepage outflow. This capacity can specifically be used to track isotopically labeled rainfall applications or atmospheric gas injections through the model landscapes.

The isotope monitoring system currently comprises two isotope analyzers based on laser absorption spectroscopy (LAS). Both are housed in a custom on-site laboratory located below the central LEO hillslope (Figure 2). The laboratory is equipped with air conditioning and UPS power supply for stable and uninterrupted operation of the analyzers.



**Fig. 1.** (left) Wide-angle photograph of the three climate-controlled bays at Biosphere 2 within which LEO was built. (right) Converging surface of the landscape, showing aboveground instrumentation.

The first LAS instrument is a near-infrared gas analyzer based on off-axis integrated cavity output spectroscopy (OA-ICOS; IWA-35EP, Los Gatos Research Inc., Mountain View, Calif.) for measurement of the hydrogen ( $\delta^2\text{H-H}_2\text{O}$ ) and oxygen ( $\delta^{18}\text{O-H}_2\text{O}$ ) stable isotopic composition in liquid water and water vapor. Measurement precision is  $<0.05\%$  for  $\delta^{18}\text{O}$  and  $<0.2\%$  for  $\delta^2\text{H}$  (100-s integrations), and flow response time ( $1/e$ ) is  $<6$  s with an external vacuum pump. The second LAS instrument is a dual trace gas analyzer based on quantum cascade laser absorption spectroscopy (QCLAS; TILDAS-D, Aerodyne Research Inc., Billerica, Mass.), which measures  $\delta^2\text{H-H}_2\text{O}$  and  $\delta^{18}\text{O-H}_2\text{O}$  with one laser and the carbon ( $\delta^{13}\text{C-CO}_2$ ) and oxygen ( $\delta^{18}\text{O-CO}_2$ ) isotopic composition of  $\text{CO}_2$  with the second laser at maximally 10 Hz. Measurement precision is  $0.03\%$  for  $\delta^{18}\text{O}$  and  $0.1\%$  for  $\delta^2\text{H}$  (120-s integration), and gas exchange time constant ( $1/e$ ) is  $0.3$  s with a  $60\text{-L min}^{-1}$  vacuum pump (David Nelson, personal communication). Detailed descriptions of the respective technologies can be found elsewhere [Baer *et al.*, 2002; Nelson *et al.*, 2008; McManus *et al.*, 2015].

The OA-ICOS instrument will be used mainly for automated high-frequency sampling and analysis of seepage water outflow from the three LEO hillslopes. It will therefore be paired with a multiport liquid

sampling system (Los Gatos Research, Inc.) as described by Pangle *et al.* [2013] (Figure 3). The sampling system uses a four-channel peristaltic pump to continuously deliver liquid water from a given source to one of four ports of a stainless steel sampling manifold that is mounted on the tray holder of an autosampler (LC PAL, CTC Analytics AG, Zwingen, Switzerland) for liquid injection into the isotopic

analyzer. This setup will facilitate isotopic analysis of outflow from the three LEO hillslopes at intervals of approximately 30 min.



**Fig. 2.** (A) View of the airconditioned shed build under one of the LEO hillslopes; (B) View of the inside of the shed with workbenches for housing the laser spectrometers.

The QCLAS instrument will be used mainly for continual direct monitoring of the isotopic composition of soil air  $\text{CO}_2$  ( $\delta^{13}\text{C-CO}_2$  and  $\delta^{18}\text{O-CO}_2$ ) and water vapor ( $\delta^2\text{H-H}_2\text{O}$  and  $\delta^{18}\text{O-H}_2\text{O}$ ). In addition, since soil temperatures are measured throughout the LEO soils, inference of liquid soil water isotopic composition is possible based on the vapor-phase measurements [Volkman and Weiler, 2014] due to the mainly temperature-dependent isotopic liquid-vapor equilibrium in soils [Mathieu and Bariac, 1996]. To obtain air samples from the subsurface, the QCLAS analyzer will be linked to arrays of 144 (out of 151 available) custom soil gas sampling probes installed within each of the model landscapes at LEO. The probes are constructed from microporous and hydrophobic Teflon tubing (pore sizes  $10\text{--}35\text{ }\mu\text{m}$ , total porosity  $50\%$ , length  $0.3$  m, diameter  $0.0064$  m; Zeus Industrial Products, Orangeburg, S. C.) sealed at both ends to gas transport lines (diameter  $0.0032$  m; Parker, Cleveland, Ohio) with epoxy and heat shrink tubing. A

multivalve control system will be set up to sample automatically from the various probe locations. The system will comprise 27 trapping stream selectors with 16 positions each (ST16MWE, VICI Valco Instruments Inc., Houston, Texas) and 2 dead-ended stream selector valves with 28 positions each (C25G-24528, VICI Valco Instruments, Inc.) to accommodate the extensive probe arrays. Based on this system, soil gas sampling for isotope analysis will be accomplished using a closed flow-through loop approach. In this configuration, sample gas is continuously circulated through a selected porous probe and the QCLAS instrument to attain and stably measure sample gas in isotopic equilibrium with soil air. The anticipated sampling interval is <5 min per probe location, accounting for the time required for equilibration, transport of the sample gas, cavity gas exchange, and signal stabilization. The system thus allows for approximately one complete measurement cycle per day. Depending on the dynamic state of the LEO slopes and/or the timescale of specific processes of interest, a subset of the available soil gas probes can be selected into the sampling scheme to attain much higher temporal resolution.



**Fig. 3.** Stainless steel sampling manifold mounted on the tray holder of an autosampler for liquid injection into the isotopic analyzer.

Finally, both LAS instruments will be used for isotope analysis of air samples from the LEO atmospheres. In each LEO bay, 24 air intake lines (diameter 0.0064 m; Series 1300 composite tubing, Goodrich Sales Inc., Geneva, Ill.) are available, with sheltered inlets at four to five different heights (0.25, 1, 3, 6, and 9–10 m) along each of five masts distributed over the slope surface [Pangle *et al.*, 2015]. Subsequent sampling of the intake lines will be facilitated by three dead-ended stream selector valves with 28 positions (VICI Valco Instruments, Inc.) located at the on-site isotope laboratory (Figure 4), with flow driven by a downstream vacuum pump (UN815KNE, KNF

Neuberger Inc., Trenton, N. J.; flow capacity of  $16 \text{ L min}^{-1}$ ). The valve outlets will be connectable to either of the LAS instruments to allow automated isotope analysis in programmed sequences. To reduce the time delay associated with gas transport from air inlet to analyzer, the intake lines upstream of the valves will be constantly purged with fresh atmospheric air using branch-off lines connected to a purge pump via manifold unions.



**Fig. 4.** Soil and atmosphere air of LEO will be sampled by three dead-ended stream selector valves with 28 positions, located at the on-site isotope laboratory, with flow driven by a downstream vacuum pump.

This research facility is unique in the world and provides unique opportunities for Earth scientists representing a wide range of disciplines (from hydrology to geochemistry to microbiology and ecology) to work in an interdisciplinary setting and address fundamental questions about the coevolution of hydrologic, biogeochemical, and ecological processes and their interactions. The LEO experiment is scheduled to start in 2016, when, initially, the evolution of the unvegetated landscapes will be observed under identical treatment regarding climate forcing. This initial phase is estimated to last for about 2–3 years, after which vascular plants will be introduced to the slopes, in order to study how complex ecosystems alter the cycling of resources through these slopes and how they affect the evolutionary trajectory of the landscapes. This second phase is scheduled to last for another 2–3 years. Finally, after identical treatment of all three slopes, the slopes can be set on different climate trajectories, to observe how identical ecosystems will further evolve in different climatic settings. The data collected during this 10-year-long experiment and the knowledge gained from it will

allow us to develop coupled systems models that are better capable of predicting how landscape in the real world might change under climate change, providing urgently needed tools to study the fate of real ecosystems in the 21st century.

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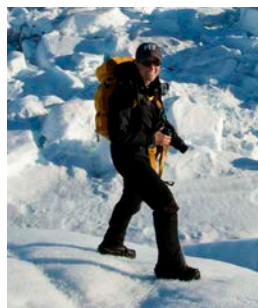
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## Subglacial Hydrology Following Greenland Ice Sheet Supraglacial Lake Drainages

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Large areas of the Greenland Ice Sheet speed up significantly during the summer months in response to surface meltwater reaching and lubricating the ice sheet bed [Joughin et al., 2008, 2013]. Ice flow observations over the past decade have revealed rapid velocity

variations indicative of a more complicated, highly nonlinear relationship between ice sheet speed and meltwater at the bed [Joughin et al., 2013; Das et al., 2008; Hoffman et al., 2011]. Understanding these hydrologically driven processes impacting Greenland Ice Sheet flow dynamics is crucial for determining the ice sheet's dynamic response to increased mass loss, which has quadrupled over the last 2 decades, contributing an estimated  $7.4 \pm 1.8$  mm to global sea level rise from 1992 through 2011 [Shepherd et al., 2012]. We still lack a comprehensive understanding of the physical processes relating ice sheet hydrology (most notably variability in surface meltwater abundance and timing) to ice speed in the ablation zone [Joughin et al., 2013; Andrews et al., 2014; Schoof, 2010; Hewitt, 2013]. Critically, the region of the ice sheet surface that experiences melt is projected to expand in a warming climate [Parizek and Alley, 2004]. Insufficient knowledge on both current and

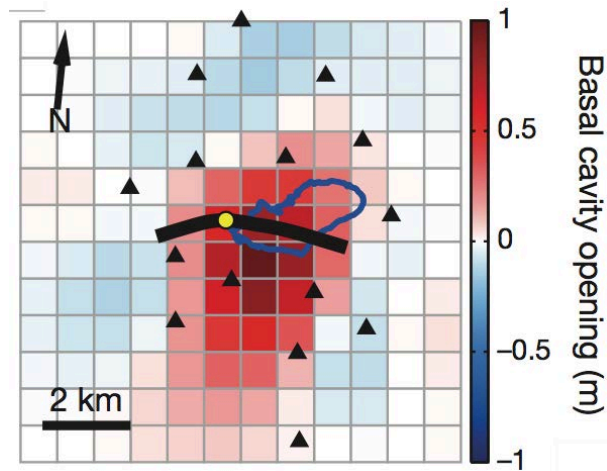
future processes that transport surface meltwater to the bed limit predictions of future ice sheet contributions to sea level rise [Intergovernmental Panel on Climate Change, 2007].



**Fig. 1.** Installing a GPS station near a supraglacial lake on the Greenland Ice Sheet (photo by author).

We are addressing one area of knowledge gap on the role supraglacial lakes play for Greenland Ice Sheet dynamics (Figure 1). Rapid supraglacial lake drainages provide an incredible natural experiment that enables us to probe the upper limits of meltwater's influence on ice flow. Water-driven fracture propagation beneath supraglacial lakes rapidly transports large volumes of meltwater to the base of the Greenland Ice Sheet over a few hours [Das et al., 2008]. These drainage events

cause transient, hydraulically driven ice sheet acceleration and establish conduits for additional surface-to-bed meltwater transport for the remainder of the melt season [Joughin *et al.*, 2013; Das *et al.*, 2008]. While hydrofracture processes through glacial ice are well known [van der Veen, 2007; Krawczynski *et al.*, 2009], a trigger mechanism for initiating hydrofractures in an otherwise compressive supraglacial lake basin was only recently identified [Stevens *et al.*, 2015].



**Fig. 2.** Basal cavity opening at the ice sheet–bed interface beneath a supraglacial lake at the time of maximum hydrofracture opening [Stevens *et al.*, 2015]. GPS stations, supraglacial lake margin, hydrofracture scarp, and a prominent moulin are shown with black triangles, blue line, black line, and yellow circle, respectively.

To determine a trigger mechanism for rapid supraglacial lake drainage, we investigated hydrofracture initiation during three rapid drainages of a single West Greenland supraglacial lake, combining ice flow measurements from spatially dense array of 16 GPS stations positioned around the lake [Stevens *et al.*, 2015] with a time-dependent geodetic inversion [Segall and Matthews, 1997]. We modeled the GPS time series of drainage-related motion as the summation of three deformation sources: (1) hydrofracture opening, (2) basal cavity opening (due to the rapid injection of meltwater) (Figure 2), and (3) extra basal slip above the background rate (due to enhanced basal lubrication). We found that each drainage event is preceded by a 6- to 12-hour period of ice sheet uplift and/or enhanced basal slip, indicative of the presence of an increased volume of meltwater reaching the bed, hours before hydrofracture initiation. The geodetic inversion results allow us to determine the distribution of meltwater at the ice sheet bed before the three drainages, each of which generates tensile stresses that promote hydrofracture beneath the lake. Thus, we hypothesize

that these precursors are associated with the introduction of meltwater to the bed through neighboring moulin (surface-to-bed vertical conduits) systems. Our results imply that as lakes form in less crevassed, interior regions of the ice sheet [Howat *et al.*, 2013], where water at the bed is currently less pervasive [Doyle *et al.*, 2014], the creation of new surface-to-bed conduits caused by lake-draining hydrofractures may be limited.

With a supraglacial lake drainage trigger mechanism identified, the question that follows is how meltwater from the drainage event is routed through subglacial drainage networks and affects ice flow. Subglacial drainage networks comprise a morphologically complicated assemblage of linked cavities and/or subglacial channels at the ice sheet bed [Flowers, 2015], whose characteristics are controlled by the abundance and timing of meltwater inputs [Schoof, 2010]. The injection of large volumes of meltwater into the subglacial environment over a period of a few hours during lake drainages results in localized hydraulic jacking of the ice sheet where basal water pressures exceed ice overburden pressure [Tsai and Rice, 2010; Pimentel and Flowers, 2010], and significantly alters or obliterates any preexisting subglacial hydrologic network. Analysis on the evolution of this drainage network must be combined with spatially dense surface ice observations to better constrain the largely unobservable subglacial environment. Understanding how subglacial drainage networks alter to accommodate the rapid influx of meltwater during lake drainage events will advance our understanding of how meltwater inputs into this subglacial drainage network affect ice flow.

Coupling our GPS observations with numerical models, we are investigating subglacial hydraulic networks beneath the lake to understand how subglacial drainage networks are formed and altered when forced to accommodate a large influx of meltwater during a lake drainage event. Using the postdrainage basal cavity volume and geometry results (Figure 2) as initial conditions for a numerical model of subglacial drainage systems following Hewitt [2013], we are investigating (1) the response of the subglacial drainage system to rapid lake drainage and (2) how subglacial drainage system characteristics translate to local surface ice flow following lake drainage. Notably, the unprecedented surface ice motion observations and inversion results allow us to carry out these numerical experiments at a level of temporal-spatial detail far exceeding previous work. The Horton grant was

instrumental for supporting new collaborations with Ian Hewitt (Oxford University). By investigating both the subglacial drainage system's morphology and its effect on local ice flow following lake drainages, we will be able to place these large injections of meltwater in the context of seasonal meltwater variability and ice flow. Our results will advance our understanding of both the subglacial drainage network and how meltwater inputs into this network affect ice flow, both of which are critical variables for accurate predictions of future ice sheet contributions to sea level rise.

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## Mapping Shallow Groundwater Flow Patterns With the Self-Potential Method

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Looking out at the horizon, it was clear we were not in Colorado anymore. Several things were different. The nearest tree was 100 miles south of us, and, despite my reading 7 P.M. on my watch, the Sun showed no intention of setting any time soon. The moment we stepped

out of the truck at the Toolik Field Station on Alaska's North Slope, a thick cloud of mosquitoes swarmed us. Their obnoxious buzz would not cease for the next 3 weeks of fieldwork on the tundra.

Last summer, my advisor, Kamini Singha, and I were invited by Sarah Godsey of Idaho State University to enhance ongoing investigations in her National Science Foundation-funded project. Our goals were to

determine variability in flow direction and rate through-water tracks—hillslope drainage features in permafrost regions—over entire hillslopes with geophysical tools. Water tracks have a surface depression relative to surrounding areas, but lack consistent overland flow. The presence of shallow permafrost and seasonal freeze-up restricts soil erosion and formation of defined channels, resulting in features that are somewhere between groundwater flow in a hillslope and a first-order stream. These shallow hillslope drainage features make up roughly 30% of the area of the Kuparuk River Basin of the North Slope.

Just like the landscape around us, conducting fieldwork in Alaska is different than work in more quotidian locations. Any equipment that we intended to use had to be shipped from Golden, Colorado, to Fairbanks, Alaska, where it was loaded on a truck for the twice-weekly 10-hour drive up the Dalton Highway to the field station and finally transported to field sites in backpacks or by helicopter. These constraints required a fine balance when selecting equipment. Transport was expensive and space was limited, but obtaining a replacement of anything broken or forgotten was not an option given the limited timeframe. In preparation for the trip, I spent weeks determining exactly what we would need, finding any way to reduce the size or weight of each piece of equipment, and preparing to troubleshoot anything that could possibly go wrong.



**Fig. 1.** Emily Voytek and Kamini Singha collecting self-potential data and attempting to evade mosquitoes under bug nets.

In contrast to our gear limitations, daylight during Alaskan summers is nearly unlimited. During our near round-the-clock data collection, we collected a series

of electrical resistivity tomography (ERT) transects and self-potential measurements (SP) to map shallow subsurface flowpaths in and around water tracks (Figure 1). ERT measurements helped us delineate thawed zones in the subsurface, while SP was sensitive to groundwater flow. Unlike other geophysical methods that rely on empirical relationships to transform measurements of physical quantities back to hydraulic parameters (e.g., Archie's law to convert electrical resistivity to water content), SP measurements are directly related to flow. The data are simply voltages created by the small currents generated as water moves through soils; these voltages allowed us to estimate heterogeneous patterns of groundwater flow at high spatial resolution [Voytek *et al.*, 2015]. As enlightening as these data were for determining the flow patterns through an arctic hillslope at maximum thaw, they only covered a single snapshot in time.

The Horton Research Grant allows me to build on this work through the purchase of a digital multiplexer. This instrument can continually measure voltages between electrodes, resulting in data with much higher temporal resolution than I am currently able to collect manually. As a result, I will be able to explore important, time-varying hydrologic processes; I plan to use high-frequency SP data to evaluate seasonal changes in source water to vegetation. Brooks *et al.* [2010] analyzed the isotopic signatures of tree and soil water and determined that they came from the same source; however, the two isotopic compositions were different from the nearby stream water. To explain their findings, Brooks *et al.* [2010] developed a conceptual model showing a periodic disconnect between shallow soil water and deeper groundwater. SP measurements will help to test this hypothesis by mapping daily changes in flow patterns, which are important when quantifying transpiration and nutrient uptake rates across a watershed. Building on our work in Alaska, the SP method provides an additional data set from which to analyze patterns of groundwater movement; these data will be collected in conjunction with an ongoing isotopic study at the H.J. Andrews Experimental Forest.

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## Moving Beyond a Snapshot: Towards a Time-Continuous Understanding of Hyporheic Exchange

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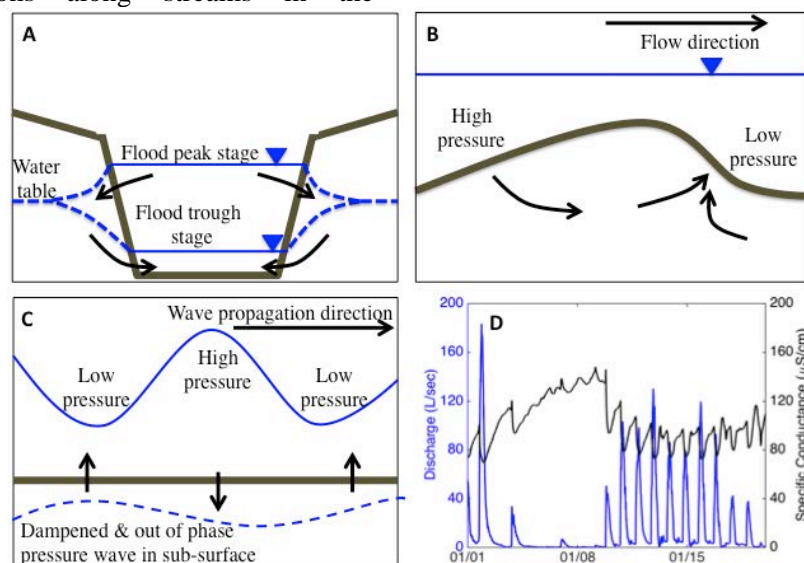
Advisor: Michael N. Gooseff



Hyporheic zones (HZs) and hyporheic exchange (HE) are critical to the hydrologic and ecological functionality of stream networks [Boulton *et al.*, 1998]. Our current understanding of HE is largely based on experimental tracer evidence collected over relatively short timescales, on the order of hours to days, and during steady discharge conditions [Stream Solute Workshop, 1990; González-Pinzón *et al.*, 2015]. Analysis of experimental tracer data can help quantify hyporheic fluxes and residence times prevailing over a short duration of time [Harvey *et al.*, 1996]. However, it remains difficult to quantify the time-continuous influence of HZs over annual or interannual timescales. A broader temporal perspective of HE is necessary to understand how HZ function will change as hydrologic regimes are altered by human activity and global climate change [Wagner *et al.*, 2010]. My proposed Horton Research Project seeks to (1) quantify how unsteady streamflow controls HE and (2) develop a predictive understanding of how HZ function will respond to climate change. To address these goals, I will monitor and model surface water–groundwater interactions along streams in the

McMurdo Dry Valleys (MDVs) of Antarctica. The MDVs system is simplified by a complete lack of vascular vegetation (i.e., transpiration) and no deep groundwater interactions. Hence the MDVs provide something of an outdoor laboratory field setting.

The hydraulic behavior of HZs in temperate rainfall runoff-dominated catchments is controlled by two variable head boundary conditions: stream stage and hillslope groundwater level. Dynamic hillslope groundwater levels alter riparian hydraulic gradients and exert boundary condition controls on HE [Voltz *et al.*, 2013; Ward *et al.*, 2012; White, 1993]. Unsteady streamflows control HE through bank storage [Chen and Chen, 2003] (Figure 1A), bedform-induced pumping [Boano *et al.*, 2007] (Figure 1B), and wave pumping [Precht and Huettel, 2003] (Figure 1C). It becomes difficult to understand how unsteady streamflow controls HE in temperate catchments, because we must first accurately characterize spatial and temporal dynamics of hillslope storage. However, in the natural hydrologic laboratory of the MDVs, unsteady streamflow is the only forcing on HE, and time-continuous stream solute loads are a manifestation of streamflow-driven HE (Figure 1D).



**Fig. 1.** Bank storage (A), bedform induced pumping (B), and wave pumping (C) are unsteady flow-driven processes controlling HE in the MDV's. Seasonal variations in stream solute loads on a Dry Valley Stream (D) are a manifestation of the cooccurrence of these processes (A–C). Figures 1A–1C are modified from Precht and Huettel [2003].



**Fig. 2.** A map of the greater MDVs region highlighting the location of the Taylor Valley, where our proposed research will take place (left). A field technician collects samples from the riparian zone of a stream within the Taylor Valley, Green Creek (right). Cartographic credit: Brad Herried, Polar Geospatial Center, University of Minnesota.

The MDVs (Figure 2) are characterized by an extremely cold and dry climate. The long-term mean annual temperature and relative humidity as measured at Lake Hoare in the Taylor Valley are  $-17.7^{\circ}\text{C}$  and 66%, respectively [Doran *et al.*, 2002]. Precipitation falls only as snow, and total annual snowfall rarely exceeds 100 mm weq. Streamflow is almost entirely generated by daily pulses of glacial melt, and interannual variability in streamflow is directly related to interannual variability in glacier

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