December 2019

Newsletter

Hydrology Section

AGU 100 ADVANCING EARTH AND SPACE SCIENCE

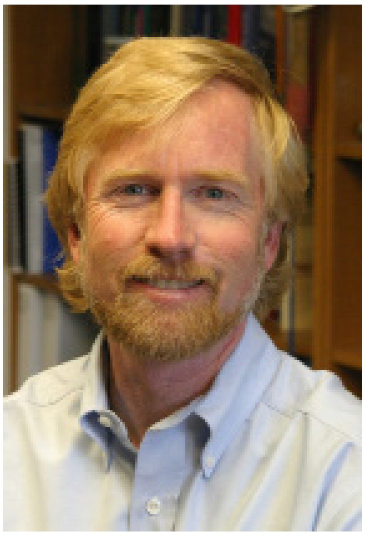
FALL MEETING

San Francisco, CA | 9–13 December 2019

In this Issue:

From the Section President

Scott Tyler (University of Nevada, Reno)



On behalf of the leadership of the AGU's Hydrology Section, it is my pleasure to report to you on the state of the Section. In this newsletter, we focus on activities over the past year, remind you of activities at the upcoming 2019 Fall meeting in San Francisco, celebrate some of our award winners as well as hear from our recently elected class of Hydrology Fellows.

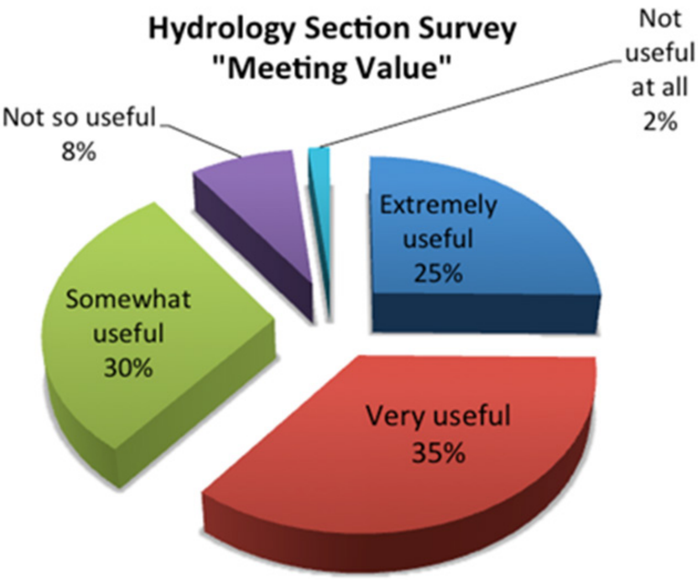
It has been a very busy and successful fall for the section leadership and volunteers. Laura Bowling and her Fall Meeting Planning Committee, along with our 12 Technical Committees and Hydrology Section Student Subcommittee have put together an outstanding program, and one of the largest in the Section's history. I'll highlight a few sessions in my lead off, and I'll let Laura provide even greater details. As you have probably also noticed, this is the Centennial anniversary of AGU's founding, and the Fall Meeting has a significant component of Centennial sessions as well as an entire day (Tuesday, December 10th) of sessions focusing on the future organized by our "Earth Covering" neighborhood. These events will be held in Centennial Central and prominently feature hydrology and water resource talks, particularly in the morning sessions.

We will also be hosting a series of town halls and events, including a Town Hall in collaboration with the GeoHealth, Society and Policy and Biogeosciences Sections to organize AGU's first "cross-sectional" Technical Committee on Monday evening as well as a special student event across several of our sections on Thursday evening.

Hydrology-Focused Meeting: I am very excited to announce that the AGU Board of Directors has formally approved our proposal for a Hydrology-focused biennial meeting slated for kick-off in the spring/summer of 2022. I am also pleased to announce that we will be formally partnering with the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) to jointly sponsor the meeting. My personal thanks to the Section's Task Force on Meetings, chaired by Sally Thompson and Julia Guimond, whose team did an outstanding effort designing and completing its survey report. I am very excited that so much of our community is enthused and recognized the value in developing a more focused meeting venue; one in which we can experiment to improve our information transfer, collaboration and setting of long-term objectives in hydrology. As you will see below and on page 9, the survey shows broad support for developing the meeting, and provides critical insights into how to best develop the meeting.

"... the AGU (...) formally approved our proposal for a Hydrology-focused biennial meeting slated for kick-off in the spring/summer of 2022..."

In the first year of meeting planning (2020), it is important to develop an inclusive structure to attain the goals set out above. Engagement of the hydrology community, both formal and informal, will be key to building the meeting. There is also the need to build a strong institutional structure and a task-oriented team to execute the meeting details in 2021 leading up to the meeting. To meet these objectives for 2022, I am proposing to launch two new organizing committees, the first to serve as an executive meeting group comprised of the leadership of AGU, CUAHSI and the section to formalize agreements and duties. This group will meet routinely to insure that logistical and organization side of the meeting proceeds smoothly. The *Hydrologic Sciences Program Advisory Committee*, formed from within the Hydrology Section and the CUAHSI membership, will serve as the heart of the meeting planning, developing the scope of the meeting at first, followed by a general meeting layout and lastly, a complete meeting program. I envision this committee to be made up of volunteers from our Technical Committees, our student and early career section (H3S) and from both the Section and CUAHSI membership in its first year, and then morphing to a smaller Program Committee in late 2020 to be begin the formal meeting program development. While the meeting will take place after my term as Section President, I have assured incoming President Ana Barros that I will continue to work with the committee, AGU and CUAHSI to make the meeting a success. **If you are interested in working on this exciting new project, please let me know and we will find a place for you!**



~90% Responded Positively

Survey results: Hydrology-focused Meeting

Open Access Model Evaluation for WRR Open Access Model Evaluation: I also want to report on the section's *Task Force on Open Access Model Evaluation for Water Resources Research*. The Task Force was formed to address the rapid changes in publishing, particularly the press for full and open access, and to assess how WRR can adapt in this world. Martyn Clark, editor in chief of WRR is heading that task force, and the group has been meeting through the fall. I have also reached out to the leadership of sections who also contribute to WRR to keep them informed of the process and to gather input. I believe it is critical that the WRR community address the challenges of the new world of publishing straight on, and that AGU gets the input from the section to make decisions that are best for our science, authors and readers.

To this end, the Task Force will be hosting an information exchange Town Hall, "Planning for the Future at Water Resources Research" on Thursday, December 12 from 12:30-1:30 in Moscone West Room 3004. This will be directly across the hall from our annual WRR Highlights Session (H42F) and food will be available. This is an important opportunity for the community to learn about alternative publishing models, and to provide feedback to us on how you want your journal to work in the next decade.

"... The (Open Access Model Evaluation for WRR)Task Force will be hosting an information exchange Town Hall, "Planning for the Future at Water Resources Research" on Thursday, December 12 from 12:30-1:30 in Moscone West Room 3004..."

Awards and Updates: It is my pleasure to recognize our Section's Union award winners in this newsletter after having announced our section awardees in the July 2019 Newsletter. These awards will be presented on Wednesday, December 11th at the Union Awards Ceremony and I encourage you to attend to congratulate our colleagues on their successes. The 2019 Class of AGU Fellows includes seven Hydrology Section affiliated researchers across the breadth of hydrology: Barbara Bekins, U.S. Geological Survey; Ximing Cai; University of Illinois, Reed Maxwell; Colorado School of Mines; Tom Painter University of California, Los Angeles; Beth Parker, Guelph University; Carl Steefel, Lawrence Berkeley National Laboratory; and Chunmiao Zheng Southern University of Science and Technology, Schenzen. I have asked our 2019 Class of Fellows to contribute their stories and reflections in this issue and I hope that you will enjoy their insights. It is also with great pleasure to announce that Robert E. Horton Medal to Majid Hassanizadeh of Utrecht University for his seminal work on porous media and porous media transport. I had the pleasure of visiting Majid just before the award was announced, and while I thought I knew his work well, I was amazed at the breadth of his contributions, which reach far beyond traditional hydrologic sciences.

I also want to recognize Amir AghaKouchak from the University of California, Irvine for his receipt of the prestigious James B. Macelwane award for his contributions, depth and breadth of research, impact, creativity as well as service, outreach, and diversity, and Constance Millar from the U.S. Forest Service for her recognition of service and contribution as an AGU Ambassador.

I have asked all of our award winners to share their thoughts and life lessons in the Newsletter, and for those presenting lectures at the Fall Meeting, to give us a warm up to their lectures. It is a busy time and we may not have all the articles in by the newsletter deadline, so I will be including any of the late entries in the Summer 2020 newsletter.

And finally, but not the least, we recognize our Section's Horton Research Awards to: David Litwin, of The Johns Hopkins University, Lorenzo Rosa from the University of California Berkeley and Megali Nehemy from the University of Saskatchewan. These awards include financial support of research and as you read their short articles in this newsletter, you will be amazed at the places they have come from, and the contribution they are going to make!

Also please note the 2020 Union and Section Awards nomination process has opened at AGU. The Hydrology Section follows a two-step process with the first deadline set for February 15, 2020. The Union follows a different trajectory, with due date for full nominations on March 15, 2020. Please go to the Section Website for complete details and instructions for our awards!

Volunteers Needed: As you register for the Fall Meeting, I want to encourage you to volunteer for the Section and AGU if you can to help with our student activities. With a $1 million matching donation from Jamie Austin, we have the opportunity to significantly increase our funding for student travel grants. We are close to halfway to the matching goal, and AGU has offered a giving incentive program to the sections. We are embarked on a 100 member drive from the sections: if 100 members of section each donate $100, the section will receive an additional $3000 to their 2020 budgets for their discretionary use. There are additional levels of support for the section, and you will be hearing more about this in coming month.

Each year, our section members volunteer their time during the Fall Meeting to support of our students through the Outstanding Student Presentation Award judging. It is a great way to meet our student members, and to give them the credit they deserve. Please volunteer though https://ospa.agu.org/2019/ospa/ or contact our Section Secretary, Charlie Luce for more information.

Scott Tyler
University of Nevada, Reno

Important Section Activities/meetings at the 2019 Fall Meeting

Monday December 9:
PA11C: Joint Section Catchment Collaboration: Hydrology and Public Affairs: The Catchments behind the data and Processes Behind the Catchments- Posters. 8:00-12:00 Moscone South.

PA13B: Joint Section Catchment Collaboration: Hydrology and Public Affairs: The Catchments behind the data and Processes Behind the Catchments- Posters. 13:40-18:00 Moscone South.

TH15L: Joint Section Town Hall: Hydrology, GeoHealth, GEC and SIPS: Water in the Coupled Earth-Human System: Leveraging Convergence to Move Science to Action to Support a Healthy Environment and Safe Water System. 18:15 - 19:15, Moscone West, Room: 3002, L3: Building

Tuesday December 10:
H24A Walter B. Langbein Lecture: The challenge of rainfall estimation and prediction across scales: learning from patterns; Efi Foufoula-Georgiou , 16:00 - 18:00 Moscone West - 2022-2024, L2

Hydrology Section Business Meeting and Reception: Co-sponsored by CUAHSI
18:30-20:00 Marriott Marquis, Salon 9 Lower B2

Wednesday December 11:
Hydrology Section Executive Committee Meeting
12:30-13:30: Marriott Marquis, Nob Hill D Lower B2

Union Awards Ceremony
18:00-20:00: Moscone North LL Hall E

Thursday December 12
Water Resources Research Town Hall: The Future of WRR
12:30-13:30 Moscone West - 3004

H43D Paul A. Witherspoon Lecture: Patrick Reed, Conflict, Coordination & Control in Water Resources Systems Confronting Change
13:40 - 14:40 Moscone West - 2022-2024, L2

Hydrology Student Subcommittee Early Career Mixer Cosponsored with GeoHealth, SIPS and GEC) Ticketed Event, 18:30-20:00: Marriott Marquis, Salon 13-15 Lower B2

From the Section Secretary

Charlie Luce (United States Forest Service, Boise)

Here we are again in the month leading to the Fall Meeting. A busy month, with poster, presentation, feast, and holiday preparations. For many students around the world, it may be one of the most productive months for science! The field data are finally cleaned up enough to start the plotting and comparison with the models and calculations, and initial disappointments are turning into ah-ha's … or at least they will shortly. It is yet another record year for student presentations, with 564 presentations available for judging. This is an increase of 13% over last year's student contributions. Please go to ospa.agu.org/2019/ and sign up to be a judge. Feel free to stop reading now and sign up!!

Later this month, people in the U.S. will be celebrating Thanksgiving. Since gratitude is one of the most profoundly healthy emotions to cultivate, I'd like to offer a few. There are quite a few volunteers involved in helping the Fall Meeting be a great experience for students. There are the student travel grant award judges; the coordinators for the Outstanding Student Presentation Awards; and, of course, the many judges for the Outstanding Student Presentation Awards. This year, Jasper Vrugt, Sebastian Uhlemann, Matt Cohen, Salli Dymond, Theodore Lim, Antonia Hadjimichael, Marios Anagnostou, Veljko Petkovic, and Colin Gleason helped evaluate around 70 travel grants and scholarships. Reading about each student's interests and background is one of the most fun support activities for AGU. If you would like to help with this in future years, let me or any of the Technical Committee Chairs know of your interest!

If you would like to help with this in future years, let me or any of the Technical Committee Chairs know of your interest!

I'd like to offer some huge thankyous to Alicia Kinoshita (San Diego State University) and Rolf Hut (Delft University), who are rotating off of the Outstanding Student Presentation Award Committee. Coordinating liaisons and sorting through the comments and scores at the end is a big lift between November and January, and they did it for four years! On a more personal note, they helped me learn how to do this work and have been great supports. Matthew Weingarten (San Diego State University) and Heidi Asbjornsen (University of New Hampshire) are continuing for their 3rd year. They are becoming quite practiced at wrangling session liaisons into getting judges signed up. This year, Di Long (Tsinghua University, and one of this year's Hydrologic Science Early Career Award Winners!) and Anne Jefferson (Kent State University) will be joining the team, welcome. Thank you all!

Offering my thanks to the hundreds of judges helping with OSPA can seem a little impersonal, yet theirs is the fundamentally important task. The act of listening and giving your full attention to someone in the midst of a huge gathering is a tremendous gift. So, I'll close with a "listening" challenge because like many giving activities, it is often easier to give thanks than to receive. For all of the coordinators on the committee, to all the judges who have found words of heart and wisdom to share with emerging scientists, and indeed to any and all of the scientists who have gone to listen to students speak or visit student posters, here are the thanks of the recipients of last years Outstanding Student Presentation Awards. I am glad that these responses from the students can be heard, and listened to, and received with grace.

"Thank you for taking the time to put together the student presentation competition. It was really helpful to receive feedback on my work and presentation from people outside my university and with multiple perspectives."

"Thank you so much for your time and comments. It is always helpful to receive feedback on your work but as a student and early career scientist, it is even more appreciated. I was grateful for the opportunity to share my work with you and the other AGU attendees."

"Dear Judges, I am very excited to have won the OSPA award for this year and truly appreciate your positive feedback. Thank you very much for providing feedback to the graduate students on their presentation skills. Your feedback over the years has helped me improve my presentations. "

"Dear Coordinators and Judges, Thank you for taking time out of your AGU schedules to support OSPA! Delivering my poster was a great experience, and it means so much to me to get feedback of my work through your judging. Thank you so much! "

"Thank you for the opportunity to present with an alternative media platform to an international audience. I enjoyed exploring the capabilities of the digital poster while still having the ability for discussions afterwards. I appreciate the comments from the judges. Thank you for your time during a very busy conference! "

"Thank you for taking time out of your busy conference schedules to organize the contest and assess us! I sincerely appreciate the comments from judges and will use them to improve future presentations as I strive to best communicate my work. "

"Thank you so much for the kind comments! I feel honored to receive this award, and thank you for taking the time to come listen to me rave about how much I love streambeds for five minutes. I would like to thank my judges and coordinators for the useful feedback and support. "

"Dear committee, I am extremely grateful and proud to have been selected as an OSPA winner. I would like to thank my supervisors, without whom I would have never been able to investigate thoroughly my topic and prepare a successful presentation; the OSPA judges, whose feedback is especially useful and constructive; and the AGU board for the valuable effort in organizing an excellent initiative such as OSPA. Thank you again. "

"As a non-native English speaker, I've had lots of difficulties trying to express myself during this first and a half year in the US. Therefore, getting this award is probably the best compliment that I could receive. I want to thank all the judges for spending some of their time and attention on this activity. As a second-year Ph.D. student, I am aware that there is still much to learn and improve. Thus, all the comments of my judges are more than appreciated and taken into consideration for future presentations. I would also like to thank all the coordinators who allow this activity to be carried out without problems every year, improving, not only my, communication skills but also of many other students. I am looking forward to keeping participating in the program, now as a student, and in the future as a judge. Thanks a lot. "

"Thank you to everyone involved in coordinating the sessions at AGU and to all those who participated in OSPA as judges. The opportunity to present research and receive constructive feedback really is an invaluable part of becoming a more effective communicator and advocate for the sciences. "

"Thank you for your comments. I am very pleased to receive this award. I hope the discussions I had during the AGU meeting will lead to scientific collaborations. "

"I greatly appreciate all the anonymous judges for their positive feedback and valuable comments. This prize means a lot to me. I would like to express my sincere gratitude to my adviser for his supports and encouragements. "

"Thank you so much for taking the time to come view my poster, talk to me about my research, and give me feedback on my work and my presentation. I am honored to receive an OSPA award and hope that I can effectively put your feedback into practice in the future. Thanks also to the session coordinators. I really enjoyed getting to share my science in your session. "

"Hello all, I wanted to thank everyone for taking the time out of your busy AGU schedules to visit and judge the student posters. Your feedback and comments are invaluable to the development of both our presentation and communication skills as developing scientists. As a first time AGU attendee, the poster hall is overwhelming at first glance. However, it provided me with opportunities to speak with a wide variety of individuals and groups within and outside of my field, which allowed me to consider the scope of my work on a greater scale. This conference was a great experience and I really enjoyed the opportunity to work with you all. "

"Thank you so much! I'm very excited and particularly grateful for the detailed comments the judges provided. Hands down the most constructive feedback I've received from presentation judges. I'll be thinking carefully about these suggestions and comments as I work on publishing my results. Thanks again! "

"I would like to thank all of the judges who attended my presentation and gave both critical comments and positive words. I got great feedback both from the judges' comments and from the individuals who stopped by my poster. This is invaluable for the continuation of my research and

From the Section Secretary (continued)

for future presentations. I would also like to thank the coordinators who allow all of this to be possible. This was a fantastic experience and I hope to be able to give my time in the future as well. Thank you! "

"Thank you so much to the coordinators for the opportunity to share my research! Thank you to the judges for all your feedback and supportive comments! "

"I would like to thank my judges for spending time on listening and reviewing my presentation. Your responses improve the quality of my work and encourage me to become an even better scientist. I look forward to many more years of presenting my research at AGU! Thank you so much! "

"Many thanks for the arrangement of the OSPA and all helpful comments! "

"Thank you for your constructive feedback and taking the time to attend the presentation. I appreciate it! "

"I'd like to sincerely thank the judges for their time and constructive comments. It is an honor to be presented with this award and I'm incredibly grateful to be selected. I'd also like to thank the program coordinators and session conveners for creating such a valuable platform for scientific discussion. "

"Dear OSPA coordinators and judges, I am honored for receiving this highly coveted award, it represents an invaluable source of encouragement for me in my future research and career. Thank you for investing your time to attend my talk and for providing valuable feedback on my presentation skills. I also want to thank my academic supervisor for his input and guidance as well as my coauthors and group colleagues for their support and contributions. "

From the Section Student Subcommittee Chair

Caitlyn Hall (Arizona State University)

First off - the Hydrology Section Student and Early Career Scientist Subcommittee (H3S) is super excited for Fall Meeting and the events that we've organized for all participants. We will be hosting a week-long scavenger hunt, which can be found at http://bit.ly/AGU19Scavenger (note that capitalization matters for the link!). Below are all of our events and sessions that we had a hand in. We started compiling some tips for surviving Fall Meeting on Twitter, share yours on the thread here: https://twitter.com/AGU_H3S/status/1184486104533065728?s=20! But, check back on our twitter @AGU_H3S leading up to everyone meeting up in San Francisco, as we'll be sharing top tips!

We kept busy this fall! We teamed up with CUAHSI to bring early career and students our Fall seminar series on Beyond Grad School: a Guide to Landing Your Dream Job. Where we brought panelists from academia, industry, government, and more to talk about 1) the pre-application phase (when and how to start) 2) the application phase (materials and interviews) 3) the post-application negotiations and 4) the job transition. Recordings can be found here: https://www.cuahsi.org/education/cyberseminars/cuahsi-agu-h3s-cyberseminar-series

AGU 100 FALL MEETING
San Francisco, CA | 9–13 December 2019

Join the AGU Hydrology Section Student Subcommittee (H3S) at the following events during the AGU Fall Meeting 2019!

Week long #AGU19Scavenger hunt on Twitter and Instagram! Go to http://bit.ly/AGU19Scavenger!

Day	Time	Event	Location
Sun., 12/8	8:00 - 17:00	Student and Early Career Conference	Parc 55
Mon., 12/9	12:30 - 13:30	Town Hall: Building Momentum: Developing Sustainable Cross-Disciplinary Collaborations *How can we build our AGU connections to be collaborations?*	Moscone West, Room:2016, L2
Tues., 12/10	10:00 - 12:15	Hydrology Coding Help Desk and Demo	Student Lounge
	18:30 - 20:30	Hydrology Meeting and Reception *Register to attend when registering for AGU!*	Marriott Marquis, Salon 9, Lower B2
Wed., 12/11	10:00- 12:15	Hydrology Coding Help Desk and Demo	Student Lounge
Thurs., 12/12	10:00- 12:15	Hydrology Coding Help Desk and Demo	Student Lounge
	12:30 - 13:30	Town Hall: Centennial Early-Career Scientist Forum *We want your feedback on what you are looking for from us and AGU!*	Moscone West, Room:3005, L3
	18:30 - 20:00	Team Trivia with Hydrology, GEC, GeoHealth, and SIPS! *All career levels are welcome! Register to attend when registering for AGU!*	Marriott Marquis, Salons 13-15, Lower B2
Fri., 12/13	8:00 - 12:00	Science to Action: Transformative Partnerships to Advance Decision-Relevant Science	Moscone South Poster Hall, PA51E
	13:40 - 15:40	Science to Action: Transformative Partnerships to Advance Decision-Relevant Science	Moscone South, 301-302, L3
	16:00 - 18:00	Science to Action: Transformative Partnerships to Advance Decision-Relevant Science eLightning	Moscone South, eLightning Theater II

From Water Resources Research Editorial Board

Martyn Clark (Editor-in-Chief), Jean Bahr, Marc Bierkens, Jim Hall, Stefan Kollet, Charles Luce, Jessica Lundquist, Scott Mackay, Ilja van Meerveld, Xavier Sanchez-Vila, Peter Troch, and Ellen Wohl (Editors)

The discipline of hydrology is certainly thriving, and WRR continues to publish many excellent articles across a broad range of subjects. A highlight for 2019 is the publication of the first set of the Grand Challenge papers in the Centennial Collection. Key papers published so far in 2019 include those by Giuliano Di Baldassarre et al., "Sociohydrology: Scientific challenges in addressing the sustainable development goals (doi: 10.1029/2018WR023901), Ying Fan et al., "Hillslope hydrology in global change research and Earth System modeling" (doi: 10.1029/2018WR023903), and Ellen Wohl, "Forgotten legacies: Understanding and mitigating historical human alterations of river corridors" (doi: 10.1029/2018WR024433). These papers are all excellent and we encourage you to explore them in full.

We look forward to seeing you at the WRR Town Hall meeting:

"Planning for the Future at Water Resources Research",
Thursday, 12 December 2019
12:30 - 13:30,
Moscone West, Room 3004

Open Access Task Force at the Fall Meeting. The Centennial celebrations coincide with a major change in the openness of our science. We're seeing the entire science community dive headlong into open science – with open data, open models, and, yes, open access journals. Many authors are now required (or at least strongly encouraged) to publish in open access journals, and many authors would like to see their papers to be more freely available. It is now clear that we are in the midst of a community transition to open access journals – the question is no longer a matter of "if" we transition to open access, but rather, when and how. The Hydrology Section's open access task force has been meeting to address these issues. The task force has reviewed the current status of open access publishing; in particular, the alternative publishing models that are used across different journals and societies. The task force has also looked at changes in the publishing landscape; in particular, how changing institutional constraints affect the capabilities and incentives for our community to publish in open access journals. The next step for the task force is to obtain your input on changing constraints and preferences for open access publishing (the WRR Town Hall meeting, "Planning for the Future at Water Resources Research", Thursday, 12 December 2019: 12:30 - 13:30, Moscone West, Room 3004). Based on this information, the task force will provide a summary of findings to the Hydrology Section in February 2020, including community preferences for open access publishing models, tradeoffs among alternative publishing models, and innovative ways to enable more inclusiveness in pay-to-play publishing models. We look forward to seeing you at the WRR Town Hall meeting where you will have an opportunity to make yourself heard.

More on Fall Meeting. Also at the AGU Fall Meeting, on Thursday morning, we will hold our third annual WRR Session on "Recent advances in the hydrological sciences" (Thursday, 12 December 2019: 10:20 - 12:20, Moscone West, Room 3014). In this session a mid-career scientist will provide a broad perspective on the evolution of hydrological science, and editor-author pairs will provide a synthesis of innovations published in WRR across different subfields of hydrology. For 2019, the synthesis talk will be from Yoshihide Wada, and the editor-author pairs are Xavi Sanchez-Vila and Zhilin Guo (groundwater modelling), Ellen Wohl and Isabella Schalko (fluvial geomorphology), and Martyn Clark and Nico Wanders (continental-domain hydrological modelling).

In the past two years we have held this session in an overflowing room, where we had a vigorous interdisciplinary discussion of research challenges across different sub-fields in the hydrological sciences. We look forward to another exciting session this year.

WRR Editors' Choice Award. We are also very excited to announce the 2018 recipients of the WRR Editors' Choice Award. These papers represent an excellent cross-section of the major advances across the different sub-fields in hydrology:

- Erfani, Tohid, Kevis Pachos, and Julien J. Harou. **"Real-Options Water Supply Planning: Multistage Scenario Trees for Adaptive and Flexible Capacity Expansion Under Probabilistic Climate Change Uncertainty."** Water Resources Research 54, no. 7 (2018): 5069-5087.

- Hawkins, Adam J., Matthew W. Becker, and Jefferson W. Tester. **"Inert and Adsorptive Tracer Tests for Field Measurement of Flow-Wetted Surface Area."** Water Resources Research 54, no. 8 (2018): 5341-5358.

- Hedrick, Andrew R., Danny Marks, Scott Havens, Mark Robertson, Micah Johnson, Micah Sandusky, Hans-Peter Marshall, Patrick R. Kormos, Kat J. Bormann, and Thomas H. Painter. **"Direct insertion of NASA Airborne Snow Observatory-derived snow depth time series into the iSnobal energy balance snow model."** Water Resources Research 54, no. 10 (2018): 8045-8063.

- Hwang, Taehee, Katherine L. Martin, James M. Vose, David Wear, Brian Miles, Yuri Kim, and Lawrence E. Band. **"Nonstationary Hydrological Behavior in Forested Watersheds Is Mediated by Climate-Induced Changes in Growing Season Length and Subsequent Vegetation Growth."** Water Resources Research 54, no. 8 (2018): 5359-5375.

- Kiang, Julie E., Chris Gazoorian, Hilary McMillan, Gemma Coxon, Jérôme Le Coz, Ida K. Westerberg, Arnaud Belleville et al. **"A comparison of methods for streamflow uncertainty estimation."** Water Resources Research 54, no. 10 (2018): 7149-7176.

- Klaus, Julian, and C. Rhett Jackson. **"Interflow is not binary: A continuous shallow perched layer does not imply continuous connectivity."** Water Resources Research 54, no. 9 (2018): 5921-5932.

- Lovill, S. M., W. J. Hahm, and W. E. Dietrich. **"Drainage from the critical zone: Lithologic controls on the persistence and spatial extent of wetted channels during the summer dry season."** Water Resources Research 54, no. 8 (2018): 5702-5726.

- O'Keeffe, Jimmy, Simon Moulds, Emma Bergin, Nick Brozović, Ana Mijic, and Wouter Buytaert. **"Including farmer irrigation behavior in a sociohydrological modeling framework with application in North India."** Water Resources Research 54, no. 7 (2018): 4849-4866.

- Roche, K. R., G. Blois, James Leonard Best, K. T. Christensen, A. F. Aubeneau, and A. I. Packman. **"Turbulence links momentum and solute exchange in coarse-grained streambeds."** Water Resources Research 54, no. 5 (2018): 3225-3242.

- Sörensson, Anna A., and Romina C. Ruscica. **"Intercomparison and uncertainty assessment of nine evapotranspiration estimates over South America."** Water Resources Research 54, no. 4 (2018): 2891-2908.

- Tarasova, L., S. Basso, C. Poncelet, and R. Merz. **"Exploring controls on rainfall-runoff events: 2. Regional patterns and spatial controls of event characteristics in Germany."** Water Resources Research 54, no. 10 (2018): 7688-7710.

In addition to a number of well-established researchers, authors of the "Editors' Choice" papers include a number of early career scientists and engineers. This bodes well for the future of hydrological sciences. Please look for these authors at the AGU Fall meeting and congratulate them for their outstanding work.

We're all looking forward to seeing you during the AGU Fall Meeting and learning more about your recent science discoveries. In particular, we look forward to seeing you at the WRR Town Hall meeting at AGU (Thursday Dec 12 at 1230p) to hear your opinions on how WRR should evolve in this rapidly changing publishing landscape. We're also looking forward to seeing you at the WRR science session (Thursday Dec 12 at 1020a) to discuss recent advances in the hydrological sciences. As always, please feel free to share your ideas, your opinions, your concerns, and your experiences, so that we can improve the extent that WRR advances hydrological science.

AGU Hydrologic Sciences Meeting Survey Report

Scott Tyler, Jerad Bales, Gordon Grant, Julia Guimond, Christa Kelleher, Sheila Saia, Megan Smith, Sally Thompson

In May 2019 the AGU Hydrology Section disseminated a survey asking members of the section to provide feedback on the concept of a joint, biennial Hydrologic Sciences meeting. Nearly 650 people responded to the survey, 20% of whom were undergraduate, graduate students, or postdoctoral researchers; 5% research associates, 20% assistant professors/early-career scientists, 20% associate professors/mid-career scientists, and 35% full professors/senior scientists. Almost all respondents (~85%) were from North America, with the remainder from Europe, the Asia-Pacific, South Asia, and South America.

Survey results convey positive but not overwhelmingly enthusiastic responses toward the concept of a stand-alone biennial Hydrologic Sciences meeting. Of the 650 respondents, 61% indicated that a Hydrologic Sciences meeting would be “extremely” or “very” useful to them. Almost all (97%) of respondents said they would attend such meetings, although 20% said they would attend most meetings, 45% said they would attend regularly (i.e., half of the meetings), and 32% said they would attend occasionally (i.e. about a fourth of the meetings). A similar attendance distribution applied for supervisors who would be sending students. Most respondents (77%) indicated that a meeting of this nature would be different from those already offered. Respondents were attracted to the smaller meeting size (85% positive), the potential to avoid overlapping poster and oral sessions (76% positive) or concurrent sessions (74% positive), and to a focus on networking (74% positive).

A new Hydrologic Sciences meeting presents an exciting opportunity to formulate, implement and test innovative approaches (...) to develop more advanced capacities for virtual attendance, extended focused presentations, and other events identified by the community.

The most common concern about a stand-alone Hydrologic Sciences meeting was the addition of another conference to the already overcrowded calendar of meetings. Respondents considered that a new meeting would conflict (25%) or had the potential to conflict (40%) with existing meetings. This potential conflict between the proposed Hydrologic Sciences meeting and existing meetings was also a common topic raised in written comments.

Based on the following two criteria, the task force **recommends moving forward with development of a biennial AGU Hydrologic Sciences meeting**:

1. *A majority of the survey respondents indicate that a section meeting would be extremely useful or useful.* The survey results indicated that 61 percent of the respondents met this criterion.

2. A majority of the respondents indicate that they would attend every or most (at least half) meetings. Sixty-five percent of the respondents indicated that they would attend half or more of the Hydrologic Sciences meetings.

A new Hydrologic Sciences meeting presents an exciting opportunity to formulate, implement and test innovative approaches to conference design including leveraging collaborations among AGU, CUAHSI, and IAHS to develop more advanced capacities for virtual attendance, extended focused presentations, and other events identified by the community. Members of the task force and broader hydrology community (as indicated by survey comments) believe that there is an increasingly urgent need to rethink traditional scientific conference formats in the interests of (i) reducing our carbon footprints, (ii) creating more equitable and accessible conference experiences, (iii) providing more opportunities for students and early-career members, and (iv) improving networking opportunities.

Thus, we strongly recommend that any conference planning committee formed subsequent to **our recommendation act to create an innovative,**

inclusive, and carbon neutral conference. To achieve this, we have several specific recommendations:

1. The meeting design should incorporate, at a minimum, all "attractive" features identified by a majority of the survey respondents and attempt to incorporate other features identified by respondents as being "attractive" such as the potential to avoid overlapping poster and oral sessions or concurrent sessions, a focus on networking, and incorporation of non-traditional sessions (panels, Q&A, round tables).

2. The meeting design should be informed by further analysis of the survey responses, in particular to identify whether respondents in under-represented demographic groups within the Hydrologic Sciences (including early-career respondents) identified any needs and wants that are distinct from those of the majority. In the interests of equity, these needs and wants should be given close consideration in meeting design.

3. AGU Hydrology Section should provide the planning committee with training in best practices to ensure diversity, equity and inclusion in conference design, such as the resources listed in Appendix A.

4. Affordability represents a major barrier to achieving diversity, equity and inclusion in conferences. The meeting should be designed so that it is affordable to all section members at all career stages and on all career paths.

5. The meeting design should attempt to minimize the carbon footprint associated with the conference. Meeting planning should take a broad and experimental approach to addressing this problem. Options to consider include the creation of satellite meetings at regional nodes, expanded virtual options, purchase of carbon offsets, and other creative approaches to reducing the carbon footprint of the meeting.

The task force appreciates the opportunity given to us by AGU to explore the possibility of a Hydrologic Sciences meeting, and we are excited about the opportunities such a new meeting can provide for the community.

Appendix: Resources for Organizing Equitable and Inclusive Conferences

Equitable and Inclusive Conference Organizing Guides

- Guide developed by 500 Women Scientists (in collaboration with the Earth Science Women's Network): https://500womenscientists.org/inclusive-scientific-meetings
- Guide for improving conference accessibility for disabled people: https://blog.ucsusa.org/science-blogger/how-to-make-professional-conferences-more-accessible-for-disabled-people-guidance-from-actual-disabled-scientists
- Guide for improving inclusion of parents from PNAS: https://www.pnas.org/content/115/12/2845.abstract
- Guide for improving inclusion of LGBTQ+ people from the Creating Change Conference: https://www.creatingchange.org/creating-a-positive-environment/
- General conference inclusion guidelines from the American Society of Association Executives: https://www.asaecenter.org/resources/articles/an_magazine/2015/september-october/make-your-conference-more-inclusive
- General conference inclusion guidelines from Physics World/IOP Publishing: https://physicsworld.com/a/fifteen-tips-to-make-scientific-conferences-more-welcoming-for-everyone/

Other Notes on Conference Equity and Inclusion

- Ensure the conference facilities are accessible (including handicap accessible) to everyone and can accommodate the number of participants.
- As it relates to LGBTQ+ identities, keep in mind that not every person will have disclosed their identity publicly. If pictures are taken at any point during the conference, it would be helpful to have a system in place for participants to sign a release form and have the ability to indicate whether or not they want their

picture taken. For example, check the box that says "yes" if you want your picture taken or check "no" if you do not wish to have your picture taken. This may be further facilitated by color coding name tags (e.g., neon or brightly colored name tags indicate the participant does not want their picture taken white name tags indicate that the participant is ok with having their picture taken).

- Include a way for attendees to disclose their pronouns, whether that's through the use of pronoun stickers, pronoun buttons, or just writing pronouns down on their name tags.
- Panelists should reflect diverse backgrounds, cultures, sexualities, genders, races, etc. If the panel is diverse there is a higher chance that they can share experiences that relate to audience members of diverse backgrounds.
- Have gender inclusive or single use restrooms, if possible.

Special thanks to Dr. Erika Martin Spiotta, Beverly Williams, and Chris Moore for helping compile this information.

"I'd like to do that, but not right now"

Why to make time to be a rotator at the National Science Foundation.

Holly R. Barnard (University of Colorado, Boulder)

I recently returned to my faculty position at the University of Colorado – Boulder after spending 19 months as a Program Officer for the Hydrologic Sciences (HS) Program at the National Science Foundation (NSF). When I started my term, the question I got from my academic colleagues more than any other was: Why would you do that? My response at the time and still remains: Why wouldn't I? (And no, I have not given up my research.) Being a Program Officer at the NSF was one of the most rewarding experiences of my career, perhaps only second to seeing my students succeed. Here, I'll outline the key reasons you should (and should not) consider making time in your career to serve as a Program Officer, and also try to debunk some myths.

The Pros:

1)There is tremendous opportunity to make an impact on our science community. An effective and trustworthy Program Officer leaves their personal agendas behind when starting at NSF. The position isn't about you, it's about supporting the larger research community and moving science forward especially during this time when science is frequently under attack. My work ranged from engaging new PIs in the review process to making sure the HS community was represented during the formation of new solicitations to participating in interagency discussions on the future of water research in the United States. In my conversations with PIs, there was a common misconception that the HS program would prioritize funding research topics that were closely aligned with the personal research of Program Officers. This was not the culture of the HS program or the norm for the foundation. Great effort was put into balancing and diversifying the funding portfolio across all sub-disciplines that fall under the solicitation.

2)You will get a view of the research landscape that is like no other. While you manage a wide diversity of proposals within the HS program, there is also tremendous exposure to the scientific enterprise as a whole. In my observations, the most effective Program Officers spent more time listening than talking, and put in the effort to get to know other Program Officers across the foundation and how other programs functioned. The misconception that

I most frequently heard was that the rotator was simply a 'paper pusher' silo-ed in their own program, shepherding proposals through the review process. While the responsible handling of program proposals is the core of the job, nearly all Program Officers serve on working groups across their division, their directorate, and across the foundation. These working groups make decisions about what solicitation priorities should be for the future. You learn what topics are generating excitement and attention from the perspectives ranging from individual PIs to the White House Office of Science and Technology Policy.

3) It is really fun see others succeed and to have played some role in that success. One of the best parts of the job was letting PIs know that their proposal was being recommended for an award. Even though my time at NSF has ended, I still look forward to seeing the results of the projects that were funded during my time of service. Seeing new science get its start is exciting—plain and simple.

Being a rotator isn't all roses; there are some downsides. **The Cons:**

1) Time away from your home and your home institution can be challenging. I enjoyed many parts of my life in the D.C. area. There is great culture, food, and plenty of things to do. Colleagues were frequently visiting D.C., so I got to network regularly. That being said, many rotators, like me, are not in a position to bring their families with them. Relationships via the phone or video get old and it can be lonely. On the flip side, I know other rotators who were able to relocate with their families and embraced the change. Staying connected with your graduate students can also be challenging. Monthly visits home help, but it is not the same as your students being able to walk into your office when they have questions.

2) Federal government rules and culture can be frustrating. The federal government is much more hierarchical than most research institutions. Although the government system creates some barriers to getting things done efficiently, it rarely prevented me from being able to support our community once I learned the ropes. The most effective Program Officers are astute of the federal rules and know how to get things done within (or despite) the system. One problem is that the bureaucratic system does little to acknowledge merit or to differentiate effective from ineffective workers. You must get your validation from doing your work well.

3) Don't expect a lot of recognition for your work. The position isn't about you; it is about supporting the community. In a recent commentary on ScienceMag.org (doi:10.1126/science.caredit.aaz3879), Dr. Gisèle Muller-Parker highlighted the reasons she chose to become a permanent Program Officer at the NSF and the personal pride she gained from the experience. However, she also notes what I have learned to be a common experience for rotators: few community members will recognize the effort you put into the program and few universities recognize or capitalize on the knowledge and skills rotators gain. Once you leave NSF and return to your home institution, there will be nothing at the NSF to indicate you were ever a Program Officer. Your name is removed from the NSF website and from all public documents. This means you need to value what you have done for your community more than you value public recognition. This isn't easy for everyone. Rotators who come to the NSF to promote themselves more than their community are not effective.

Approximately 30% of the NSF is comprised of rotators. Effective community-focused rotators are critical to the function of the foundation. They are important positions and the Hydrologic Science community needs capable individuals in these positions. If there is no possible way for you to serve as a rotating Program Officer, then you can (and should!) help in other ways: agree to review proposals and do so in a timely manner (don't forget that 8-12 colleagues were likely involved in the review of your proposal), review proposals with the same care that you'd want your own proposal to be reviewed, and serve on panels.

The HS program doesn't function without the community and the program is only as good as the individuals who agree to serve. As a colleague once clearly surmised: if the hydrology community doesn't step up to NSF service, then we may not like the HS program we get, but we will get the HS program we deserve.

"The HS program doesn't function without the community and the program is only as good as the individuals who agree to serve."

A Fellow Speaks: Keeping Geology in the Forefront of Hydrogeology

Barbara Bekins, U.S. Geological Survey

My deeply felt thanks to the colleagues and letter writers who nominated me, and to the Hydrology and Tectonophysics Sections for this great honor. For the benefit of those who think their path must be straight, their progress faster, or their interests constrained, here is the briefest of narratives of my nontraditional path to hydrogeology research. Growing up with abundant camping trips in California, always near water, instilled in me a love of geology, water and environmental preservation. My circuitous post-secondary education teetered between earth science and math for over two decades. Freshman year geology field trips to both Yosemite and the Grand Canyon with Glendale Community College left me hungry for more geology. Starting out as a geology major at University of California, Los Angeles, I learned to respect mineralogy and love structural geology, but ultimately migrated to math with its closed-system allure. A job in computer support for the U.S. Geological Survey (USGS) Seismology Branch provided fascinating proximity to the world of earth science research and enough grumbling computer users to fuel greater aspirations. Meanwhile, spending evenings at San Jose State University pursuing an M.S. in math, I grew fond of applied math and developed confidence as a researcher in their student industrial research program. Being accepted at age 34 to a Ph.D. program in hydrogeology with Professor Shirley Dreiss at U.C. Santa Cruz provided the perfect opportunity at last to combine math, geology and environmental research. I was in the final cohort of Shirley's students before her untimely death in a 1993 car accident. For a summary of her many contributions to hydrogeology see the introduction to the special section of Water Resources Research in her honor (Hornberger and Anderson 1995). Shirley was especially valuable to me for her hydrogeologic insights and enthusiastic, supportive mentoring style. Hornberger and Anderson (1995) stated: "In her own distinctive way Shirley was a catalyst as well as an active agent for promulgating research in hydrogeology, work that kept the 'geology' in 'hydrogeology' at the forefront". One example is her pioneering work on subduction zone hydrology, which I had the good fortune to join in 1988

> "Being accepted at age 34 to a Ph.D. program in hydrogeology with Professor Shirley Dreiss at U.C. Santa Cruz provided the perfect opportunity at last to combine math, geology and environmental research."

In the 1980s the discovery of seafloor cold seeps and excess pore pressures in subduction zones created a demand for hydrogeologic models to understand the causes and estimate the effects of pore pressure on fault strength. Shirley, a hydrogeologist, was recruited by her structural geologist colleague, Casey Moore, to create a groundwater model of the northern Barbados subduction zone. This new research effort combining hydrology and tectonophysics led to large-scale models of pore pressure in subduction zones. The model constraints came from Ocean Drilling Program (ODP) cores, seismic imaging and heat flow measurements. The core data were limited to the first 20 km and 1 km depth in a model cross section 120 km wide and 8 km deep, but the system inputs (plate convergence rate and sediment properties) and resulting geometry of the accretionary prism were well known. These constraints allowed for surprisingly useful insights based on conservation of mass of sediment solids and pore water (Bekins and Dreiss 1992). Shirley convinced the ODP of the importance of hydrogeology and was the first hydrologist to serve on one of their proposal review committees, followed by Jean Bahr and later me. The many research topics and questions on hydrogeology below the seafloor were summarized by Ge et al. (2003). The most recent **plans for post 2023** include numerous questions requiring participation by hydrologists, such as how microbes interact with seafloor fluids and rocks, evolution of rainfall and aridity patterns and their causes, fresh water under the ocean floor, and physical processes controlling slip behavior at the subduction interface.

During my PhD studies, John Bredehoeft offered me an opportunity to work with the **USGS Toxic Substance Hydrology Program**. This program funds interdisciplinary teams from USGS and universities to conduct field investigations, laboratory studies and modeling of contaminant sources, fate, and exposure pathways in the environment. One of the program's research goals is to understand the environmental fate of crude oil in the subsurface using the long-term **USGS study** near Bemidji, Minnesota, as a natural laboratory. Early work at the site established the efficacy of anaerobic biodegradation of the most mobile and toxic compounds dissolving from the oil into the groundwater: benzene, toluene, ethylbenzene and xylene (BTEX). Because of the Bemidji results and other studies, natural biodegradation forms at least part of the solution for many of the >500,000 fuel spills in the Nation, and in the late 1990s most of the contaminant research community moved on to other problems. The continuing commitment to long-term studies by the USGS then provided a singular opportunity to study the progression and ultimate timeframe for biodegradation.

"The continuing commitment to long-term studies by the USGS then provided a singular opportunity to study the progression and ultimate timeframe for biodegradation."

The progression of hydrocarbon biodegradation at the Bemidji site is controlled by the geology. The oxidation of the hydrocarbons is coupled to reduction of iron-oxide coatings formed on the glacial outwash sediments during the Holocene. The iron oxides are depleted first in the higher permeability, coarse-grained intervals, because they host a higher flux of hydrocarbons and have lower surface areas (Bekins et al. 2001). The largest organic carbon fraction in the plume consists of partial transformation products of hydrocarbons (Eganhouse et al. 1993). This fraction is not being measured in the current regulatory framework (Bekins et al. 2016) and the plume is advancing as the iron oxides are depleted (Cozzarelli et al. 2001; Ng et al. 2015). We also know that the source and plume, already 40 years old, will continue to evolve for many decades to come (Baedecker et al. 2018). I am immensely grateful to the Bemidji site research team for their outstanding scientific contributions, professionalism and friendship, and especially to my USGS colleagues Isabelle Cozzarelli and Ean Warren. Geology will continue to be important in future contaminant hydrology research. Although contaminants from manufactured chemicals often capture our attention (U.S. EPA 2016 **Chemical Data Reporting** listed 8,707 chemicals in amounts of 25,000 lbs or more), recent studies have shown that the most common contaminants in groundwater are geogenic. For example, in a summary of the Nation's groundwater quality, DeSimone et al. (2016) wrote: "More than one in five wells contained at least one constituent greater than the EPA Maximum Contaminant Level. Most of these contaminants were from geologic sources—for example, arsenic, manganese, radon, and uranium". Research incorporating geology and hydrology to predict geogenic sources continues to be needed, especially in countries with populations affected by severe arsenic toxicity.

During 2008-2013 a new research question, requiring an interdisciplinary team of hydrogeologists and seismologists, emerged from the increased rate of seismicity in the central and eastern continental U.S.. The biggest concentration of earthquakes was in Oklahoma, which contributed 45% of the increase in magnitude 3 and larger earthquakes (Keranen et al. 2014). Although increased wastewater disposal by the oil and gas industry was implicated, a groundwater model had not yet been used to establish a connection. Our research collaboration on induced seismicity began with a 2012 proposal by Shemin Ge and others to the USGS John Wesley Powell Center for Analysis and Synthesis. The **Powell Center** supports synthesis projects with university, government, and other scientists to accelerate scientific understanding and influence management practices. The hydrogeologists on the project tested a hypothesis that a swarm of earthquakes near Jones, OK, could have been induced by four high-rate injection wells located 15-20 km from the swarm. Using a MODFLOW model of a homogeneous, isotropic half-space aquifer with wastewater injected at the recorded rates into four high-rate wells and 69 lower-rate wells, we demonstrated that the migration of the pore pressure front matched the migration of earthquake locations from 2009 to 2012. The four high-rate wells contributed 85% of the pressure and the remaining 69 lower-rate wells just 15% (Keranen et al. 2014). Understanding the role of hydrogeology in induced seismicity will continue to be important in a post-hydrocarbon world. Today the most detailed and data-rich studies are in areas of enhanced geothermal energy production.

Progress in each research activity described above required the synthesis of hydrology and geology. The USGS actively encourages interdisciplinary, long-term research in the geosciences. I am proud to work in an organization that shares my values and happy that many of my collaborators and co-workers have become life-long friends.

"Progress in each research activity described above required the synthesis of hydrology and geology. The USGS actively encourages interdisciplinary, long-term research in the geosciences. I am proud to work in an organization that shares my values and happy that many of my collaborators and co-workers have become life-long friends."

I encourage new researchers to remember the geology in hydrogeology and identify interesting relevant questions with interdisciplinary collaborators.

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A Fellow Speaks

Ximing Cai, University of Illinois

I am deeply honored and humbled to be elected as a 2019 AGU Fellow. I am deeply grateful for my nominator Professor William W-G Yeh and support letter writers. My thanks are extended to my advisors, mentors, colleagues, and students. munity moved on to other problems.

I have been lucky to receive many opportunities and valuable mentoring along my educational and career path. I grew up in a poor village in Central China, and my parents had hardly received any schooling. In 1985, I was admitted to Tsinghua University, one of the top universities in China, to study water resources engineering.

"After finishing my degree (...) UNDP hired several international consultants to help Chinese researchers conduct the project. The two groups could not communicate well initially because the international consultants were water economists and Chinese domestic researchers were engineers. I did not have much experience in either area. I just learned from both, and eventually, I became a “bridge” between the engineers and the economists."

After finishing my degree, I had intended to find a job as an engineer in training, but an unexpected project changed my whole life. The project, funded by the United Nation Development Programme (UNDP), was to study water resources management in North China. UNDP hired several international consultants to help Chinese researchers conduct the project. The two groups could not communicate well initially because the international consultants were water economists and Chinese domestic researchers were engineers. I did not have much experience in either area. I just learned from both, and eventually, I became a “bridge” between the engineers and the economists. Through this unique experience, I observed that complex water resources management problems should be addressed using an interdisciplinary approach. I was encouraged to undertake an integrated engineering-economics framework for my graduate study by my advisor Professor Wenbin Weng at Tsinghua University and international consultants Dr. Ronald North (Professor emeritus of University of Georgia) and Dr. Ari Michelson (late Professor of Texas A&M University and former President of American Water Resources Association). Drs. North and Michelson have been my long-term mentors. They have greatly impacted my career, and without meeting them in China, my career would be different. By the way, half a year before he passed away, Dr. Michelson talked to me by phone for nearly one hour about the importance of the work we did together in China!

In 1995, Dr. Daene McKinney welcomed me into his research group at the University of Texas at Austin (UT-Austin) and gave me the opportunity to continue integrated engineering-economics research. Furthermore, Daene and Dr. Peter Loucks (Professor emeritus, Cornell University, Daene’s PhD advisor) introduced me to the topic of sustainable water resources management, which motivated me to conduct integrated hydrologic-agronomic-economic modeling exercises at the river basin scale. In my thesis, I applied the concept of sustainability and interdisciplinary modeling to address multiple interconnected issues of the Aral Sea Basin in Central Asia, including hydropower generation, irrigation, and ecosystem restoration (Cai et al., 2002; Cai et al. 2003). Among my PhD committee members at UT-Austin, Professor Leon Lasdon (a world leader of nonlinear optimization), along with Daene, guided me to solve large-scale nonconvex nonlinear optimization models with over ten thousand variables, which resulted in several papers on solving large-scale nonlinear optimization models (Cai et al., 2001a; Cai et al. 2001b).

At an international conference on Aral Sea restoration, Daene presented our work. Dr. Mark Rosegrant at the International Food Policy Research Institute (IFPRI, a think tank serving major international organizations), approached Daene and offered Daene a collaboration project. This offer opened the door for me to work with IFPRI. After I finished my PhD thesis in 1999, Mark created a position for me at IFPRI. At that time, I was the only IFPRI employee with an engineering background. I worked as a postdoc-in-training for six months before becoming an IFPRI postdoc (a formal research position at IFPRI). Later on, to my own surprise, my economics and policy colleagues found hydrology and engineering useful for their work; while I learned so much from them. Mark asked me to develop a water component for his IMPACT model (International Model for Policy Analysis of Agricultural Commodities and Trade, a flagship model for international food policy analysis).

The task was challenging since there was not much work on global hydrologic modeling at the time, and water availability and water use data at the global scale were not yet available for such modeling analysis. Eventually finding WaterGAP (first led by J. Alcamo, and then P. Döll, the only global hydrologic model I could find in 1999), we created a new model called IMPACT-WATER in 2002 (Rosegrant et al., 2002), which has been updated since then and widely used for global water and food policy analysis. I must say that in the early 2000's not many people in the academic arena felt comfortable about global water modeling (understandable). However, Dr. Upmanu Lall at Columbia University, a visionary researcher, was an exception. I felt so encouraged by his positive words about IMPACT-WATER when I first met Manu at a conference. Also, to my surprise, over the past 20 years, global hydrologic modeling has received much attention from the hydrologic community; the new topic of water and global food trade has even begun receiving growing attention from researchers.

After working with IFPRI for four and half years, I started seeking an academic position. To be honest, I had never dreamed to join the Civil Engineering faculty of the University of Illinois at Urban-Champaign (UIUC). "Your adventure just started" – a fortune cookie message from a Chinese restaurant in Champaign told me right before I started my job at UIUC. I was thrilled and of course nervous too! I have been so lucky to have such wonderful colleagues in the Ven Te Chow Hydrosystems Laboratory at UIUC. With their support and mentoring, I have had a smooth and enjoyable journey.

"To be honest, I had never dreamed to join the Civil Engineering faculty of the University of Illinois at Urban-Champaign (UIUC). "Your adventure just started" – a fortune cookie message from a Chinese restaurant in Champaign told me right before I started my job at UIUC.I was thrilled and of course nervous too!"

After several years of work on policy analysis, **I came to the academic position with the following two questions,** stimulated by the need of better scientific support for policy analysis:

1) How can we make water management decision models more based on sciences (particularly hydrology and economics) and realistic institutional settings (beyond simplified, top-down approaches adopted in the models from my work before that time)?

2) Given that human interferences can drive hydrologic process changes and that the changes in turn affect water use decisions over a long-term horizon (e.g., the case of the Aral Sea), how can we model the co-evolution of coupled hydrologic-human systems? These questions led to:

1) Analyzing hedging rules for reservoir operation based on hydrologic uncertainty and microeconomic principles (You and Cai, 2008a, b). This work follows that of Draper and Lund (2004). Although some colleagues do not understand why it is needed to move away from traditional numerical models to simplified theoretical analysis, Professor Jay Lund (UC Davis) and I share the common idea that the theoretical work provides insights on reservoir operation and eventually guidelines to update and solve complex numerical models. In addition, I have joined Jay and Professor Richard Howitt (UC Davis) to prompt hydro-economic modeling, an effort starting from the Harvard Water Program in the 1950's, and new and strong inputs seem needed more than ever.

2) Conducting uncertainty analysis with hydrologic forecasts (Zhao et al., 2012; Zhao and Cai, 2019) and developing algorithms for more effective use of forecasts, for example, for irrigation scheduling and reservoir operation. In general, hydrologic forecasts and predictions are useful but not many of those are used for water resources planning and management due to the barriers of uncertainty, as well as user's perception and institutional factors (Cai et al. 2017).

"Water resources management problems have never been as complex as what we face today"

3) Identifying the impact of human interferences on hydrologic processes and updating existing hydrologic relationships that previously ignored this impact. For example, the work of my group shows that the traditional log-linear streamflow recession relationship originally developed for watersheds without significant human interferences (Brutsaert and Nieber, 1977) breaks down when human-induced flow is a major fraction of total streamflow (Wang and Cai, 2010); we also re-derived the equation for ET variance analysis of Koster and Suarez (1999) by considering human-induced terrestrial watershed storage change (Zeng and Cai, 2015). The incorporation of the human dimension in my work has been encouraged by Professor Richard Vogel at Tufts University and recognized in his vision of hydrology (Vogel et al., 2015). Rich's enthusiasm for creativity, devotion to research, and generous mentoring have truly influenced my career.

"Moreover, emerging technology in sensing and monitoring, Big Data, and artificial intelligence are filling the data gaps, and cyber-physical systems techniques are enabling more powerful tools for understanding and predictions."

4) Discovering human water use behaviors using advanced data mining techniques (Hejazi and Cai, 2011; Hu et al. 2017) and uncovering hidden relationships between hydrologic processes and ecosystem functions (Yang et al. 2008). Theories and empirical knowledge have enabled us to use equations to describe hydrologic processes and water resources systems. However, our progress has also been limited due to inexact or unknown equations especially for the human dimension. I'm optimistic that growing data and emerging data techniques will facilitate groundbreaking advances in water resources research.

5) Developing models to simulate the coupled dynamics of both human and natural systems. Specifically, my group has been developing and testing agent-based models (ABMs) to simulate "distributed decision making" considering the heterogeneity of stakeholders' behaviors, and coupling the ABMs with distributed hydrological models to understand the feedbacks between water management decisions and hydrological conditions (e.g., Noel and Cai 2017). Several years ago there were debates on the feasibility of applying an ABM in water resources research, and today it seems that more people have accepted it as a tool. It is great to see many prominent hydrologists have joined this effort, such as Professors Steve Gorelick at Stanford and George Hornberger at Vanderbilt. It can be expected that growing sensing and monitoring and social media will enable us to model agent's behaviors in a more reliable way. My vision of the next generation of watershed or river basin models are those that are scientifically sound, institutionally realistic, and computationally tractable. These models should be one model, rather than separate models for science and management, that will be used for both scientific understanding and sustainable water management solution development in a common context.

Water resources management problems have never been as complex as what we face today (e.g., Housh et al. 2015 for systems of system complexity, Marston and Cai, 2016 on water reallocations; Cai et al. 2018 on food-energy-water nexus;). However, hydrology communities also seem ripe for developing innovations in water resources management for the sake of sustainable development goals (SDGs). Our communities have a broader vision about hydrology, and researchers highlight societal needs for water solutions more than ever before (**see the special issue of the 50th Anniversary of *Water Resources Research (WRR)* and the special issue on socio-hydrology recently published in WRR**). Moreover, emerging technology in sensing and monitoring, Big Data, and artificial intelligence are filling the data gaps, and cyber-physical systems techniques are enabling more powerful tools for understanding and predictions. In particular, new methods for time series analysis may provide information to help explain the human dimension of water resources systems in ways existing theories have not;

meanwhile diagnostic hypotheses can be developed and tested with respect to observation, model, and theory congruence to advance hydrology knowledge (Zeng and Cai, 2018). Hydrologic communities must not miss these opportunities to better serve society.

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A Fellow Speaks: Gratitude

Reed Maxwell, Colorado School of Mines

I am beyond grateful for being elected AGU fellow. This is like a lifetime-achievement award half-way through my career, and I feel super humbled. I am thankful for the obvious people: those who nominated and wrote letters in support of my application, my PhD and postdoctoral advisors who trained me, the faculty from whom I first took classes in hydrology and in groundwater inspiring me to be interested in the hydrologic sciences. I'm also grateful to my parents: my mom who bought her 12 year old son a book on Z80 assembly language, even though we didn't have much money, providing appreciation for the value of learning; for my dad who moved us all to Toronto while he went to graduate school, giving me empathy for the many challenges in getting an education. I'm of course thankful to my junior-high science teacher, who organized and fund-raised for a science contest where I won my second computer. Also, to my calculus teacher who not only taught me calculus, but also FORTRAN, and arranged for the IBM PCs to be donated to my high school so we had something to actually run it on. I am grateful for my undergraduate engineering professor who pulled me aside after class to say he was impressed with my work and that I should think about graduate school. I am thankful to have met a partner who was willing to move twice to support that goal. I'm also incredibly lucky to have had such great colleagues, collaborators, students and postdocs. I often can't believe how fortunate I've been for the students who have walked into my office wanting to work with me, or the postdocs and staff who put up with my tireless enthusiasm for utterly crazy ideas. A colleague who while walking along the Rhine helped hash out a continental-scale science plan, and a PhD student who was willing to help take it on as a hobby until we got it funded. A program officer who was willing to roll the dice and fund this plan.

I also feel compelled to give thanks to the less-obvious people. Reviewer 2, who made an impassioned plea to the editor that yes, this work did belong in a brand-new journal called Nature Geoscience. The anonymous review panel that recommended a crazy WSC proposal on bark beetles, or a multi-campus IGERT that proposed a complicated distance learning strategy that many would never have though would work. Those two proposals completely changed my career, funding some of my best students and pushing my work in new directions. Most of all I'm so thankful for my family and friends, who love and support me unconditionally, especially when I let the frustrations of this lifestyle job get the better of me.

> "I hope that I will be able to repay at least some of what I have received in the next half of my career. In the obvious ways, by being a good mentor, reviewer, colleague, husband and father; and in the less obvious ways, giving back to those who pay for this work we all do."

As I reflect on all that I have to be grateful for, I hope that I will be able to repay at least some of what I have received in the next half of my career. In the obvious ways, by being a good mentor, reviewer, colleague, husband and father; and in the less obvious ways, giving back to those who pay for this work we all do. I think that education and outreach is one way to accomplish this. Teaching others also helps us understand our own work better, to solidify what we know and communicate it. We owe it to share our work, not just to each other, but more broadly, and I am grateful to have the opportunity to do this every day. I am proud to be a hydrologists and work on problems that are relevant to the future of our planet. I don't know what the future of hydrology should look like, but I hope that you all share in this pride and gratitude for what we get to do.

A Fellow Speaks: Snow, Sun, Schmutz, and Water

Tom Painter, University of California, Los Angeles

To be elected Fellow of the American Geophysical Union is for me among my life's greatest joys and honors. The richness and opportunities that AGU has brought my life can never be repaid but I have done and will continue to do my best to do so. My deep appreciation to Dennis Lettenmaier and the letter-writing team, as well as my parents and brother, my wife and sons, and my advisors and friends Jeff Dozier, David Schimel, and Koni Steffen.

The mountains and education were omnipresent in my life, climbing mountains and skiing, following my dad around his ski coaching duties for Colorado State University and his career as a mathematics professor, and my parents' consistent devotion to education. For some reason, my greatest peace came when looking at sun reflecting off of sparkling snow on the shoulders of the Front Range of Colorado. To this day, looking out the window at the early snows here in the Sierra Nevada, that peaceful feeling spills over me but now with a sense of obligation to those landscapes.

"I was on track to become a mathematics professor (...) The afternoon before the final symphonic concert of my senior year, I managed to sprint headlong into a cinder block, tennis practice wall while chasing down a crosscourt shot from my friend. Smashing my forehead into the wall, I was knocked out. In the coming weeks, the clarity of my path ahead in mathematics was lost and thus began a tortuous search for my new path.

In my last few years of high school, I was on track to become a mathematics professor (not knowing that a career in snow and mountains was a possibility), with a great love of linear and abstract algebra. The afternoon before the final symphonic concert of my senior year, I managed to sprint headlong into a cinder block, tennis practice wall while chasing down a crosscourt shot from my friend. Smashing my forehead into the wall, I was knocked out. In the coming weeks, the clarity of my path ahead in mathematics was lost and thus began a tortuous search for my new path. Still, I completed my BS in Math after dropping out of college twice in order to attend to my love of snow and climbing.

A few years later, while working as a programmer on the Climate System Modeling Program at NCAR, I had the fortune of meeting Jeff Dozier (1992 AGU Fellow), who came to dinner at the house in Boulder, CO where I was living and renting from Dave Schimel (2010 AGU Fellow). The three of us, being obsessed with mountains, talked about climbing and skiing all evening and spoke nothing of science. The following morning, Dave looked at me and declared, "You're going to do your PhD with Jeff! That's what you need to do!" Dave then emailed the UCSB Geography department and requested an application packet for me. I had little idea at that moment that Dave was absolutely right, though a couple of years would pass before I would start on that path.

While at NCAR, I started studying remote sensing in the course series taught by the spectroscopy and instrumentation pioneer Alex Goetz, who had moved from the NASA Jet Propulsion Laboratory to CU-Boulder. His quantitative and physically-based approach resonated with my linear algebra background. And to this day, I recall and use the remote sensing background that was cemented in the lectures and discussions with Alex.

In 1994, I commenced my Masters and PhD program at UCSB in the Department of Geography with Jeff Dozier as my advisor. In the first few weeks, I realized that this was the path for my life. I loved the intensity of thinking, the depth and breadth of Earth science and remote sensing that I was so lucky to be studying, and the vision and charisma of exploration embodied in the faculties of UCSB Geography and the Bren School of Environmental Science and Management. Much of my cohort was funded by NASA Earth Observation System projects and we found ourselves in an orchard of low-hanging, ripe fruit of growing remote sensing technologies, increasing computational capacity, and the drive to more comprehensively constrained physically-based modeling of the Earth System – for us, in particular the mountain snowpack.

My tool of choice was the VSWIR imaging spectrometer. In those days there was just the NASA/JPL Airborne Visible/Infrared Imaging Spectrometer, preceded by the Airborne Imaging Spectrometer by Gregg Vane. I explored how best to squeeze the spectrum for understanding properties of the mountain snowpack, springboarding off of the work of Roger Clark, Ted Roush, Joe Boardman, Warren Wiscombe, Steve Warren, Anne Nolin, Dar Roberts, and of course Jeff Dozier. Among the results, (1) we were able to quantify fractional snow cover while simultaneously determining the grain size and albedo of that partial cover of snow, (2) determine the concentration in snow of the extremophile C. nivalis (aka snow algae) (setting the stage for my eventual move to JPL), and (3) properly toward the goal of the NASA EOS project constraining with Noah Molotch a distributed snow model with the spatially distributed snow albedo measurements. This last effort set the stage for coming efforts with the NASA Surface Biology and Geology mission (we prefer to call it Snow Biology and Geology given the driving science questions) and with the NASA Airborne Snow Observatory.

During this time, I was also fascinated by the directional reflectance of snow and set forth on the path toward better measurements and better understanding of the implications of incomplete knowledge of directional reflectance on imaging spectroscopy retrievals of snow properties. My insistence on pursuing steep learning curves then led me to work with the UCSB Mechanical Engineering department to build an automated spherical robot goniometer. This goniometer guided a VSWIR field spectrometer through the repeatable, angular sampling of snow's directional reflectance. Now with the flock of spaceborne imaging spectrometers arising (NASA EMIT, NASA SBG, DLR EnMAP, ESA CHIME, METI HISUI) and the focus of these on snow albedo and the controls on albedo, this importance of this understanding of directional reflectance will come into focus.

During field campaigns in the Sierra Nevada, murky light had me cleaning my prescription sunglasses thinking they must be layered with sweat and sunscreen but the layer was never as thick as suspected. One day on Mammoth Mountain, I kicked at the snow surface with my ski boot and magically the murky light was gone and the sparkle of snow returned. I dropped to my knees to see that a layer of schmutz was accumulated just at the surface, hiding Disney-quality, sparkly (cleaner!) snow underneath. Schmutz is probably the best word for it because we now know it to be a mix of black carbon, brown carbon, dust, and other organic materials. This triggered my investigations into the impacts of light absorbing particles on snowmelt, runoff, and regional climate.

"One day on Mammoth Mountain, I kicked at the snow surface with my ski boot and magically the murky light was gone and the sparkle of snow returned. I dropped to my knees to see that a layer of schmutz was accumulated just at the surface, hiding Disney-quality, sparkly (cleaner!) snow underneath(...). This triggered my investigations into the impacts of light absorbing particles on snowmelt, runoff, and regional climate."

On a climb of South Maroon Peak in the Elk Range of Colorado, I showed off to my father and brother my newly found understanding of dirty snow. Early in the ascent, before sunrise, I scraped with my ice axe a 30 cm x 30 cm area free of the schmutz layer, exposing the clean snow. During the descent later in the afternoon, we could see a strange sight of clean snow appearing to be extruded from the dirty snow layer. With some modest extrapolation, I realized that the clean snow was melting more slowly and that the hydrologic implications of this impact across the landscape were enormous.

With funding from the NSF Atmospheric Dynamics program and Terrestrial Hydrology program, Chris Landry (Center for Snow and Avalanche Studies) and I instrumented the Senator Beck Basin in Colorado toward understanding radiative and hydrologic impacts of dust in snow. We performed field, modeling, and remote sensing studies of the accumulation of desert dust in snow there and the radiative and hydrologic implications of the accelerated snowmelt.

Among the important results from this work are (1) that we understand now that snowpack disappears 1-2 months earlier due to increased dust loading (Painter et al 2007; Skiles et al 2012), (2) that the interannual variability in steepness of the rising limb of the hydrograph in dust-influenced basins is controlled by the variability in dust radiative forcing and not winter or spring air temperature (Painter et al 2018), (3) that dust loading in the Colorado River Basin has increased 5-7 fold since the major anglo settlement in the mid 19th century (Neff et al 2008), and (4) that this increase in dust loading and the associated accelerated melt have likely caused annual runoff at Lee's Ferry to drop by ~5% (Painter et al 2010). This work involved many colleagues, most prominently McKenzie Skiles, Jeff Deems, Greg Okin, Jason Neff, and Annie Bryant.

"With scanning lidar, we could finally pluck the "holy grail" of hydrology – distributed snow depth and snow water equivalent – while having coincident snow albedo measurements from the spectrometer, thus constraining models with the most critical compo- nents in understanding magnitude and timing of snowmelt runoff."

The experience with dust and radiative forcing in the western US led us to look elsewhere on Earth. I became most obsessed with understanding the paradox of the glacial end of the Little Ice Age in the European Alps – the paradox coming from the glaciers abrupt retreat in the mid to later 19th century to lengths outside of and away from the envelope they'd experienced in the previous several hundred years, while precipitation remained largely unchanged and air temperatures declined to a nadir not until the early 20th century. Ice cores in the Alps however indicated that black carbon concentrations increased during the Industrial Revolution on the continent with positive 2nd derivative coincident with the increased glacier retreat. Through radiative transfer modeling constrained by the BC concentrations and timing and the associated glacier mass balance modeling, we concluded that such a forcing very likely drove this end of the glacial Little Ice Age before the end of the climatic LIA (Painter et al 2013) and thus provided the first physically-based explanation for the apparent paradox.

I've also been exploring the impacts of dust and BC radiative forcing in High Mountain Asia (HMA) in collaboration with Yun Qian's mesoscale modeling group at PNNL. Through the physically-based, radiative transfer-enabled modeling constrained by our MODIS remote sensing retrievals (along with Kat Bormann and Karl Rittger), we have the capacity to now explore the impacts of warming, BC deposition, and dust deposition on snowmelt and glacier mass balance. Most recently, our results have indicated that surface radiative forcing by dust and BC in snow in the HMA is markedly more potent in accelerating melt (Sarangi et al 2018) than that of atmospheric heating, despite previous suggestions from coarser modeling.

In 2010, I was recruited from the University of Utah to the NASA Jet Propulsion Laboratory to ramp up the water resources, cryosphere remote sensing, and applications program. The primary focus of these was to attack all three with the advent of the Airborne Snow Observatory, a program I envisioned a year before when listening to Greg Asner talk about his innovative Carnegie Airborne Observatory coupling of scanning lidar and imaging spectrometer for tropical ecological applications. With scanning lidar, we could finally pluck the "holy grail" of hydrology – distributed snow depth and snow water equivalent – while having coincident snow albedo measurements from the spectrometer, thus constraining models with the most critical components in understanding magnitude and timing of snowmelt runoff.

With the investment by JPL and NASA Terrestrial Hydrology (many thanks to Jared Entin for trusting us), I saw this as my opportunity to provide my hydrology and cryosphere communities with a measurement and modeling breakthrough that we had long been yearning. From the beginning of ASO (a large team too numerous to list here), we partnered with the California Department of Water Resources to develop the water management path of the program, while also addressing the pure water cycle research angle. Ultimately, ASO has become operational critical in California and likewise grown into operations in the State of Colorado, and campaigns in Washington, Oregon, Idaho, and Switzerland. In the basins where we've operated, seasonal streamflow forecasting has improved to high 90s percent accuracies, flood spillage over dams has been averted in water years 2017 and 2019, and water has been optimally retained in service districts. Likewise, the ASO data have allowed science investigations into mountain hydrology, mountain ecology, and glaciology that had not been previously accessible with such reduced uncertainties (Lettenmaier, 2017; Henn et al, 2018; Wahrhaftig et al, 2019).

Moving forward

Ahead of us lies great promise to understand the Earth system and likewise reduce vulnerabilities and stresses on our freshwater supplies globally. The updates in process understanding of the last decades have suggested paths forward for remote sensing needs – to understand where we stand with partial derivatives in energy and mass balance across the global land surfaces. The Airborne Snow Observatory program is now on track toward implementation in the mountains of the globe through a tech transfer from JPL/Caltech. On the horizon are also the visible-shortwave infrared imaging spectrometers (EnMAP, HISUI, EMIT, SBG) that will give us far more accurate understanding of the spatio-temporal variability in snow albedo, grain size, and light absorbing particles, as well as pushing other discipline of the Earth system science to far greater understanding.

"The updates in process understanding of the last decades have suggested paths forward for remote sensing needs – to understand where we stand with partial derivatives in energy and mass balance across the global land surfaces. "

While I feel enormously fortunate to be paid to pursue this career in science and technology, I also carry some sadness that we have removed some of the mystery of the mountain snow and ice. What used to hold magic is now seen from behind the curtain. That we find ourselves however at the transition from linear to nonlinear impacts of climate forcings lays bare our obligation to continue to improve our understanding of the Earth system as well as find mitigation and adaptation solutions.

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A Fellow Speaks: Perspectives Gained Across Boundaries

Industry Experience Driving Fundamental Research in Hydrogeology

Beth L. Parker, University of Guelph

It is an honor to be selected as an AGU Fellow and join such an esteemed group of colleagues and I appreciate the nomination and support. I feel privileged to have been taught and mentored by so many smart and capable people at all ages and stages of my life. This is a great opportunity to reflect and review some highlights in my past that most strongly impacted where I am today.

If I trace my career path to its headwaters, it takes me back to Allegheny College, a small liberal arts college in northwestern Pennsylvania. I liked the sciences and math, but picking a degree program overwhelmed me until I stumbled into an evening lecture about two novel interdisciplinary environmental science programs: one was natural science-based and the other a mix of natural and social sciences. Environmental and interdisciplinary programs are common today, but not so in the 1970's, when I went to college. An environmental science program focused on water resonated with me given that I grew up on a dairy and cash-crop farm where we were always mindful of water and soil quality for growing crops and milking cows. As kids on the farm, we were aware of the weather, the amount of water in the cistern or the position of the water table in our well and cognizant of the operation of our septic system and waste streams. My advisor and mentor, Dr. Samuel Harrison, was a hydrogeologist, and I was hooked on groundwater after I took his geomorphology course. He took us out to the field to pound piezometers along a point bar in a local creek so we could understand hydraulic head and how ground- and surface waters are linked. I learned the importance of field-based teaching and appreciated different perspectives coming from varied disciplines like biology versus chemistry, geology, or economics. I also learned the benefits of interdisciplinary degree programs that provide distinct perspectives and insights that come from integrating these fields. Another critical piece of advice from Dr. Harrison was to "take as much math as I could possibly stand!" My minor in math most likely opened the door for me to get a master's degree in Engineering, which I pursued at Duke University immediately after getting my undergraduate degree.

My supervisor at Duke University, the late Dr. Aarne Vesilind, was also a pioneer in his field. He was an expert in water and wastewater treatment and promoted a modern view of environmental engineering as a distinct discipline from other classical engineering programs and wrote several textbooks in this diverse field. Dr. Vesilind and his colleagues cared little whether you were coming from a natural science or engineering undergraduate program because they viewed the environmental engineering profession as necessarily interdisciplinary. I benefitted from this enlightened view, as did other students in the program. We took core undergraduate engineering courses upon our arrival, but were also expected to learn the engineering principles and terminology along with the advanced subject material in our graduate courses and research. As many experience in graduate school, my student cohort became my most important teachers as we bounced ideas off of one another to solve problems with experimental design or data analysis. We were a small cohort of 12 environmental engineering graduate students from different regions of the country, different size universities and various undergraduate disciplines, which greatly enhanced our abilities as a team. After this experience, although excited to pursue a PhD, I found my interests still too numerous and decided to obtain some 'real world' work experience to gain insights and a personal perspective.

"...although excited to pursue a PhD, I found my interests still too numerous and decided to obtain some 'real world' work experience to gain insights and a personal perspective."

Most jobs in the environmental profession are with the consulting service industry or within regulatory agencies. I did discover, however, that large corporations often manage their own waste streams and employed scientists and engineers within their corporate structure. This was the nature of my first permanent job in the Health, Safety and Environmental Division at Eastman Kodak Company from 1985 to 1991. Eastman Kodak was a chemical-based manufacturing company in operation since 1878. Compliance with the then new environmental regulations such as RCRA (1976) and Superfund (1980) were beginning to influence the amount of work focused on groundwater monitoring, which was the area that interested me most.

During my first week at work I met the consultant advising the company on groundwater monitoring and he wondered if I had heard the term “DNAPL” before? I had not! He explained that many of the chemicals used at Kodak were Dense, Non-Aqueous Phase Liquids, requiring wells to be drilled deeper than the water table and might change the size of the contaminant plumes currently mapped at the site. This was presented to my management and changed the nature of my job overnight. The groundwater contamination issues at the > 2,000 acre facility were complex because these chemicals could sink deep below the water table through fractures in the sedimentary rock.

"During my first week at work I met the consultant advising the company on groundwater monitoring and he wondered if I had heard the term “DNAPL” before?"

Over the more than 110 years of plant operations, there were many areas on-site, adjacent to residential neighborhoods within an urban area, where inadvertent leaks and spills created contamination requiring investigation and remediation. It was a time when the hydrogeology profession had little experience with these contaminants, especially in fractured rock. The regulations were new and not tailored for the nature of the contamination issues being discovered. At Kodak, I was mentored by Dr. Richard Poduska, who was committed to identifying the nature of the problem and developing logical and reasonable solutions that were science-based. This was a time of extreme uncertainty and we all learned fast, working across various disciplines from manufacturing to environmental compliance, legal to corporate communications and community relations. I was now working with an even more diverse, multi-generational team including folks with different amounts of experience, which sometimes helped and other times hindered our progress.

As an environmentalist, I was empowered by the corporate commitment to do the job properly, seeking both short term and long-term solutions that were not readily available. My job was focused on the science and I hired advisors that were the best experts in the profession. Dr. Robert Mutch introduced me to the importance of chemical diffusion as contaminants travel through fractures in clays and rocks presented in the modern textbook Groundwater by Freeze & Cherry (1979), although with no mention of chlorinated solvents. We installed wells to multiple depths in rock, innovated sampling methods to show these organic solvent contaminants were stored in the low-permeability rock matrix, and worked with the in-house environmental chemistry lab to develop better analytical procedures for the site-specific contaminants; all to try and understand the evolution of concentrations in wells after drilling or reported spills. We learned many things but still had more questions than answers. Eventually, I left Kodak to pursue my PhD at the University of Waterloo, motivated to find answers to numerous questions about organic solvent contaminant behavior, noting that some of the complexities were due in part to the characteristics of fractured rock.

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At Waterloo, I was encouraged by my supervisors, Drs. John Cherry and Robert Gillham to work in clays as an analog to sedimentary rock. As I prepared for the field release experiments in fractured clay, my diffusion calculations showed that the typical-sized fractures in clays would dissolve the DNAPL volume quickly, causing its disappearance, consistent with observations at Kodak. The implications were substantial and led to new insights about the future of these contaminated zones. We set out to show mathematically and prove with field evidence, starting with controlled release experiments, how diffusive transport controls contaminant behavior. We then sought to address this as evidence for flux as well as transport,

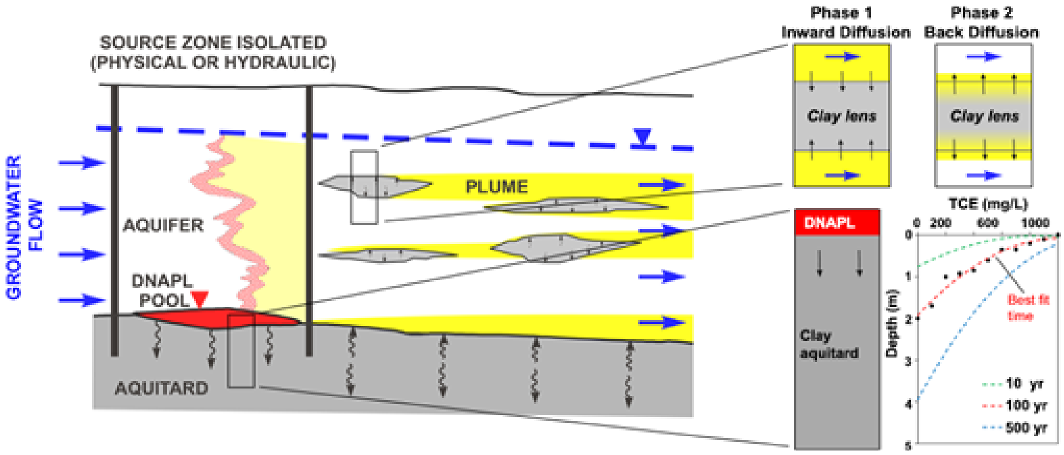

Figure 1. Persistent plume after complete source zone isolation due to back diffusion from clay lenses and aquitard. Profiles from cores inform source zone age and diffusion rates.

combining the engineering and hydrogeology frameworks. This insight became evident when the groundwater remediation industry was just getting used to the idea that DNAPL was going to persist forever and most of the remediation technologies were geared for DNAPL removal. The concept of source zone evolution was published in 1994 and 1997 as part of my PhD research, along with evidence for diffusion in water-saturated, low permeability natural clays (Figure 1). Diffusion haloes in clays were measurable over a few to 10's of centimeters to accurately measure mass transfer over periods of weeks to years. Collection of diffusion dominated profiles allowed quantitation of the mass transport by diffusion and both mass storage and flux enhanced by sorption, and were used forensically to identify DNAPL migration pathways in the Borden aquitard (Parker, 1996) and in a large column experiment with fractured clay (O'Hara et al., 2000).

"We set out to show mathematically and prove with field evidence, starting with controlled release experiments, how diffusive transport controls contaminant behavior."

My next 12 years at the University of Waterloo as a research faculty member provided opportunities for me and my students to adapt these ideas to real-field sites with scenarios similar to those depicted in **Figure 1**, seeking direct field evidence of contaminant distributions in both low and high permeability zones and using diffusion haloes forensically to inform timescales since contamination began (Parker and Cherry, 1995; Parker et al., 2004) and quantitation of processes for predicting remediation time-scales prolonged by back diffusion (Parker and McWhorter, 1994; Chapman and Parker, 2005; Parker et al., 2008). Furthermore, I also recognized that chlorinated solvents are ideal tracers of the flow system and contaminant migration pathways where the combined effects of specific processes provide fundamental insights. This is because they are mobile, relatively persistent, can be analyzed over six or more orders of magnitude, have distinct and known decay products, entered the groundwater system at many sites decades ago, and traveled under natural-gradient conditions.

"Furthermore, I also recognized that chlorinated solvents are ideal tracers of the flow system and contaminant migration pathways where the combined effects of specific processes provide fundamental insights."

What was essential in this approach was the importance of selecting industrial sites with both the appropriate hydrogeologic and contaminant conditions and sufficient simplicity to allow understanding of processes quantitatively; for example, sharp interfaces between lithologies with higher and lower permeabilities like the clayey aquitard and overlying sandy aquifer with DNAPL accumulation shown in Figure 1. Continuous cores with good recovery and retention of pore fluids were essential for measuring contaminant profiles over the diffusion transport distances (Parker, 1996; Parker et al., 2004) and identified the critical processes controlling contaminated site evolution, where it was evident that diffusion in and out of the low permeability zones was important over multiple decade time-scales (Chapman and Parker, 2005; Parker et al., 2008, 2010). Not all field sites are well suited for advancing fundamental concepts; sites were carefully selected, often complementing each other with distinct geologic and contaminant conditions (e.g. Parker et al., 2003; Guilbeault et al., 2005; Parker et al., 2008; Meyer et al., 2014).

I also found ways to transfer my experience with chlorinated solvent behavior in fractured clay to sedimentary rock, as answers to my questions from my Kodak

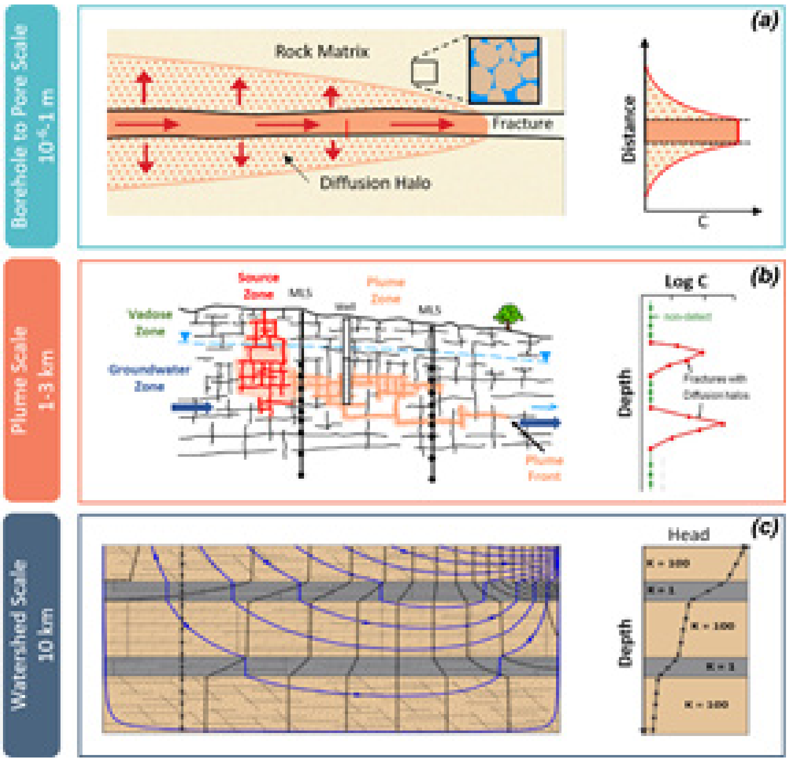

Figure 2 Site complexity requires field data at multiple scales to inform processes and constrain uncertainty.

days remained elusive and approaches for resolution of these questions more expensive. Given that controlled release experiments in bedrock were unlikely to be approved by any site manager or jurisdiction, I continued my pursuit for industrial sites with a certain style of contaminant and hydrogeologic condition to be suitable as 'field laboratories'. I adapted the use of contaminant concentration profiles to identify diffusion haloes in clays to the scale appropriate for haloes in fractured sedimentary rock, complemented with depth-discrete hydraulic data informing the flow system (Figure 2).

The rock matrix porewater method we used at Kodak to show diffusion was too tedious to use at the resolution needed to assess the occurrence of haloes away from many visible fractures in core. I worked collaboratively with my chemistry colleague Dr. Tadeusz Gorecki to advance the extraction of aqueous and sorbed mass from low-permeability clay and rock to be efficient and robust (Dincutoiu et al., 2003, 2006) to identify preferential advection pathways by their diffusion haloes into the lower permeability matrix used by O'Hara et al. (2001) in a fractured clay column experiment and Sterling et al. (2005) for TCE in sedimentary rock. It became readily apparent from these rock core TCE concentration profiles (**Figure 2b**) that there were many more hydraulically active fractures participating in the flow of DNAPL and transport of contaminants than deduced from open hole flow meter measurements of fractures (Sterling et al., 2005; Goldstein et al., 2004; Parker et al., 2018) and how vertical flow typical in open bedrock boreholes skew our measurements of hydraulic head and concentrations, leading to poor interpretations due to cross-connection (Sterling et al., 2005; Pehme et al., 2013; Meyer et al., 2014).

This showed me the need for better field methods. I had begun working with Carl Keller with Water FLUTeTM multilevel systems in the late 1990's. Conversations with Carl also lead to sealing boreholes with blank liners (water FLUTes without ports) in 2000 at one of my research sites, and many important permutations of ideas and data sets from our collaborations occurred (e.g. Cherry et al., 2007; Keller et al., 2014; Keller, 2017). Temporary borehole seals lead to temperature logging in sealed boreholes with and without added heat (Pehme et al., 2007; 2010; 2013) which provides insights about the position of hydraulically active fractures under natural gradient flow conditions. The insights form these high-resolution profile data sets complemented the rock core information from the same boreholes. Options for measurements in these boreholes continued to expand with temporary deployment of sensors and samplers behind liners (Pehme et al., 2014) and deployment of fiber optic cables in bedrock boreholes for active distributed temperature sensing for identifying flow and quantifying groundwater fluxes (Coleman et al., 2015; Maldaner et al., 2019) and improved coupling for distributed acoustic sensing vertical seismic profiles (Munn et al., 2017).

Field measurements at select contaminated industrial sites provided opportunity for fundamental research by pursuing multiple depth-discrete, high-resolution sampling methods. These were initially focused on continuous cores (**Figure 2**), where the creation of measurable diffusion-haloes in sedimentary rock (**Figure 2a**) show contaminant storage and identify, which fractures are hydraulically connected and important in the system for migration or remediation. This sampling strategy shows mass distributions along the full length of the borehole that can be aligned with fractures and lithology (**Figure 2b**). Multiple lines of evidence also bring transmissivity and groundwater flow profiles from various field methods discussed previously together to determine advection versus diffusion controls on

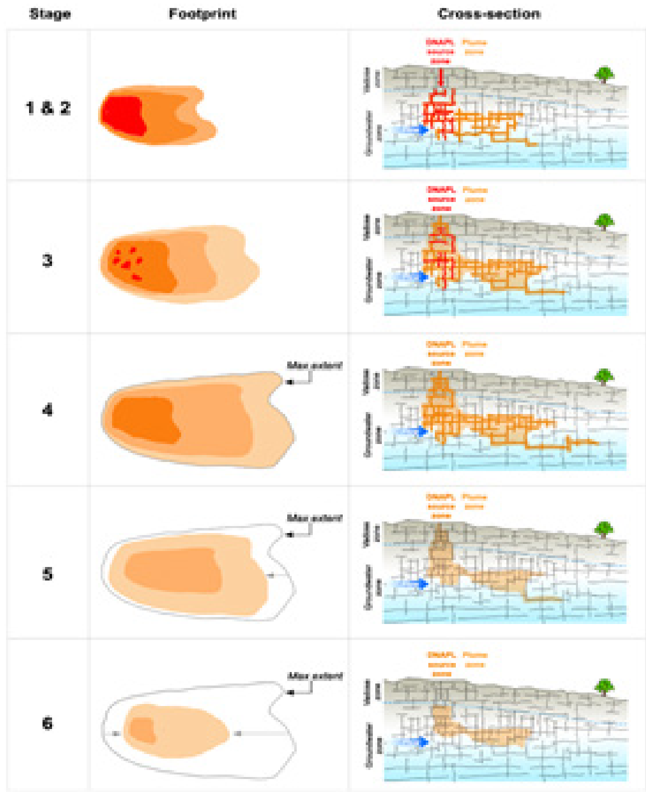

Figure 3 General conceptual model of source zone and plume evolution in fractured sedimentary rock. Stage 1-2: DNAPL quickly migrates through interconnected fractures, partially dissolves and is transported by advection in fractures and diffusion into the matrix. Stage 3: DNAPL in fractures has partially dissolved and contaminants diffuse into the rock matrix and the plume advances in direction of groundwater flow. Stage 4: DNAPL phase has completely dissolved away and plume front reaches the maximum downgradient extent. Stage 5: Diffusion with slow degradation causes plume front to retreat back toward the source. Stage 6: Diffusion with established degradation causes plume front to retreat

migration rates, including DNA extractions on rock core samples (Lima et al., 2012), hydrochemistry, and isotopes through collaborations with Dr. Ramon Aravena providing supporting evidence for attenuating reactions (Pierce et al., 2018). These interpretations, however, are highly dependent on the direction and magnitude of groundwater flow, which can be complex. Ultimately, the flow system must be understood at a scale larger than the contaminated zone to produce reliable predictions of transport and fate. High resolution depth-discrete hydraulic head data provide 1-D profiles showing head loss over lower vertical hydraulic conductivity zones (Figure 2c) identifying the position, thickness and lateral continuity of aquitards that inform the 3-D groundwater flow system. Monitoring wells can then be constructed within this hydraulically-calibrated geologic framework with less cross-connection. These concepts of vertical head profiles as a direct measure of aquitard positions in sedimentary rocks was advanced by Meyer et al. (2008, 2014, 2016), with insights regarding thin aquitard layers or surfaces due to fracture terminations influencing flow system conditions. Once a geologic system has been informed hydraulically, the newly informed hydrogeologic framework and calibrated tools (e.g. geophysical datasets) can help to design future monitoring systems across the 3-D system with better precision, accuracy and lower cost.

Studying these sedimentary rock systems for a sufficient amount of time allowed me to observe at many sites, the complete (or nearly complete) DNAPL dissolution in the subsurface source zone (Figure 3, stages 1 through 4), with diffusion having caused substantial mass transfer from the many well-connected fractures into the lower permeability rock matrix between fractures (where the mass resides in the dissolved and sorbed phases) over a few decades. Moreover, each of the plumes has evolved to a near-stationary position ("quasi-steady state" plumes) shown in stage 4 (Figure 3), primarily due to the combined influences of advection and diffusion enhanced by sorption throughout the source zone and plume. In advanced stages 5 and 6 (Figure 3), these plumes are shown to retreat toward the source zones, rather than flushing toward the receptor, based on evidence for very slow abiotic and biological degradation rates in the matrix. These similarities, found at all sites despite their different hydrogeologic, climatic, and contaminant conditions, form the basis of the general conceptual model (GCM) for chlorinated solvent source zones and their plumes in fractured sedimentary rock, as they evolve over a few to several decades. The GCM summarized in Figure 3 represents typical plume characteristics and behavior for most sedimentary rock sites where initial DNAPL conditions have caused persistent bedrock contamination. This GCM and a field-based methodology for site characterization, referred to as the Discrete Fracture Network – Matrix (DFN-M) Approach, provides a fundamental framework to inform conceptual site models used to forecast future conditions and inform site remediation decisions (Parker et al., 2012).

In summary, my quest to better understand organic contaminant behaviour in various types of geology, I have used large columns of fractured natural clay for lab experiments and performed controlled DNAPL release experiments in field settings, but the essence of my work has been the study of organic contaminant distributions at actual contaminated industrial sites where the contaminants have been in the groundwater zone for decades. Time is a key factor that cannot be practically represented in the laboratory for the long periods that are relevant. I have found the key to progress is using high resolution measurement methods to discern diffusion patterns archived in the low permeability parts of whatever system is being studied. Fick's law of diffusion, like Darcy's law for flow, has been known since the mid-1800's. Like flow, diffusion manifests in complex groundwater systems with many facets. What I find so intriguing is the many relevant and important ways these two laws combine to govern the transport and fate of contaminants beyond what our initial intuition suggests.

> My field research (...) would not have been possible without being extremely relevant to the contaminated site owners with obligations to stringent environmental regulations making this fundamental research highly relevant, justifying a significant funding commitment.

I was trained to pursue excellence and this was honed by both industry and academia. This allowed me to pursue fundamental research at industrial sites where the aged contamination in relevant hydrogeologic settings was not contrived. The contaminant mass distributions were controlled by natural processes over the time and distance scales of relevance. I only needed to convince a few site owners (manufacturing companies) that the research might provide useful insights that would help them manage their subsurface contamination more cost-effectively. The idea was to pursue fundamental research that was also practically relevant. The stage was set with robust regulations for mandatory cleanup with a "one size fits all" approach, written before the professional experience was advanced. Industry was caught in a bind, and they needed the effective solutions our profession could not deliver without experimentation.

I have been able to balance perspectives between industry and academia, providing fundamental process understanding that altered the professional practice along the way. My field research at these sites with complex hydrogeologic conditions would not have been possible without being extremely relevant to the contaminated site owners with obligations to stringent environmental regulations making this fundamental research highly relevant, justifying a significant funding commitment. I am grateful for the corporate donations that generated federal matching funds from the Government of Canada. The conceptual model for source zone evolution of chlorinated solvents in fractured porous clays and rock proposed in 1994 as part of my PhD has advanced to a six-stage model for the source and down-gradient plume to achieve a maximum extent within a few decades before attenuating and retreating back toward the source zone position (Figure 3), which is now being validated at several sites around the globe in different hydrologic systems.

The past 35 years has been an exciting era, with an interdisciplinary and highly collaborative approach to field-focused research aimed at testing conceptual models that engages students in hands-on training. I continue to pursue this work with numerous collaborative partners, colleagues and students of all ages, across many disciplines and cultures, combining insights from working with both industry and academia. The long-term nature of the problem has also spanned a few generations, and this has also enriched the experience, speaking to another element of team diversity. However, you will notice my career lacked many professional women mentors, a condition I hope changes in the future. **I would be remiss if I didn't acknowledge that there were numerous women role-models that I emulated regardless of their presence inside or outside my professional world; and many others, including my family, not mentioned by name.**

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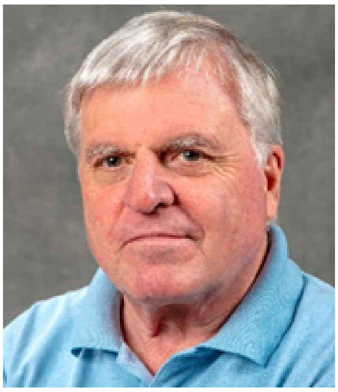
A Fellow Speaks: A Reactive Transport Odyssey

Carl Steefel, Lawrence Berkeley National Laboratory



It is a great honor for me to be selected as an AGU Fellow. I thank the members of the committee, past and present, who put so much time and effort into nominating me for this prestigious award. I am indebted to my advisors and mentors who have supported and inspired me over the years, including Bill Atkinson, Tony Lasaga, Bob Berner, Peter Lichtner, John Zachara, Bill Glassley, Sue Brantley, Bo Bodvarsson, Don DePaolo, and Susan Hubbard. Directly or indirectly, I think all of these contributed to the emergence of reactive transport as a recognized discipline, so I share the honor with them.

"But how did I get from literature into the earth and environmental sciences then? By an unusual path (...) literally through physical immersion in the mine tunnel with the ore body around me."

I suspect that I am not the best person to be offering a role model to the younger generation, since my path to where I am now is far from a conventional one. Following perhaps on the model set by my father and mother, I began at the university as an English and French Literature major, writing short papers of extended abstract length every two weeks until I graduated. Despite the fact that many think of poets, novelists, and literature majors as guilty of florid and wordy prose, in fact I am convinced that in literature one focuses on and thus learns conciseness and economy of expression, maybe even beyond what one learns in the sciences. Maybe there is also some overlap between the arts and the hydrological/geochemical sciences insofar as we consider how coupled processes play out in space and time in the Earth's surface and subsurface—it is a veritable symphony of processes and effects.

But how did I get from literature into the earth and environmental sciences then? By an unusual path again, this time by working in several metal mines in Colorado after graduation, literally through physical immersion in the mine tunnel with the ore body around me. And through my study of ore geology with Professor Bill Atkinson at the University of Colorado, I first developed an appreciation for the important role of coupled processes in the earth sciences, with hydrologic and thermal processes in parts of the system affecting geochemical phenomena elsewhere.

After 5 years as a hard-core field geologist in the wind and rain-swept hills and forests of Alaska searching for gold and silver, the demise of the minerals industry helped push me back to school at Yale University. There I found the most fertile and supportive intellectual environment I had yet experienced, even more than was the case in Alaska. Yale at the time had the leading lights in quantitative geochemistry, and now I began to see ways to describe and investigate more rigorously the coupled processes I saw taking place in water-rock systems. Despite being categorized as a "geochemist" at Yale, the curriculum there was always such that one took an integrative approach to the Earth Sciences—any processes that came into play had to be dealt with, whether physics or chemistry. Within short order, I found myself deriving Darcy's Law and the Einstein diffusion equation as part of my Ph.D. comprehensive examination. My natural interest in geological system evolution and coupled processes that I had developed in my mineral deposit investigations predisposed me to say "Yes" when my advisor Tony Lasaga suggested to tackle reactive transport modeling. The inspiration also came from Bob Berner's course in early diagenesis, where I saw for the first time how one could develop a powerful and yet concise description of system behavior through partial differential equations. For me, analytical approaches, with all of their assumptions and restrictions, could not compete with numerical approaches that seemed to resonate more naturally with my field geologist background. Still, it was a tough haul in the early days at Yale—I went in search of the classic book by Jacob Bear "Dynamics of Fluids in Porous Media" and could not find a single copy on campus. Then in the early stages of exploring numerical modeling of transport, I naively implemented a central difference approximation for solute advection, since I had been told that it was second order accurate and thus preferred to less accurate first order representations. Those troublesome oscillations near the front were unexplained until I jumped further into the literature, leading me eventually to sign up for Mike Celia's short course at Princeton University so as to get a handle on the problem.

As I got further into reactive transport modeling and kinetic theory, I found again that I was drawn to the coupled problems that seemed to be amenable only to numerical analysis. My first paper in reactive transport modeling dealt with the difficult problem of kinetically controlled dissolution leading to "wormholing" via the reactive infiltration instability (Steefel and Lasaga, 1990). This was also the first time I explored the use of non-dimensional analysis in a study, an approach that proved to be very powerful because of the ability to generalize results. The analysis would suggest that, given the right length and time scales, it should be possible to develop karst topography even in silicate rocks, a conclusion that is perhaps borne out by the observation of such features in ancient landscapes like the Tepuis in Venezuela.

My second modeling paper co-authored with my colleague Philippe Van Cappellen tackled the problem of chemical weathering by including secondary mineral formation via nucleation and Ostwald ripening (Steefel and Van Cappellen, 1990). The third paper (Steefel and Lasaga, 1994) attempted to describe the evolution of a hydrothermal system subject to both mineral dissolution and precipitation in fractures. The numerical study suggested that mineral precipitation provided a negative feedback, in contrast to the positive feedback associated with mineral dissolution and wormholing, that could nonetheless modify the character of hydrothermal convection cells over time.

After finishing my Ph.D. work, it was on to the cobblestone streets and clock towers of Bern, Switzerland to work with Peter Lichtner on cement-water alteration and other topics in reactive transport. Lichtner's papers, although taking some time to fully digest, finally convinced me that mathematical descriptions of hydrological and geochemical phenomena were far more concise and rigorous than was possible with conventional prose descriptions. With him, I prepared three manuscripts related to reactive transport in cement-water systems. The first focused on kinetic reaction and diffusion perpendicular to a fracture (Steefel and Lichtner, 1994), predicting the isolation of the fracture from the adjacent rock matrix (subsequently confirmed by isotopic studies). Two others (Steefel and Lichtner, 1998a and 1998b) examined reactive transport in a single discrete fracture.

Leaving the ghost of Einstein behind in Bern, I returned to the USA to work at Pacific Northwest National Laboratory, where I immersed myself in contaminant transport, a topic that was considered important to the Department of Energy at the time. Working with Steve Yabusaki at PNNL, we developed the first massively parallel reactive transport simulator (Yabusaki, Steefel, and Wood, 1998). Then at the University of South Florida in Tampa, when not teaching classes in introductory geochemistry, environmental geology, and reactive transport, I co-edited with Peter Lichtner and Eric Oelkers the first Mineralogical Society in America volume that went beyond classical mineralogy and geochemistry (Lichtner, Steefel, & Oelkers, 1996). With a capacity crowd of 100 on hand, we felt like we overcame at least temporarily the sociological barriers to reactive transport as a discipline that arise apparently because it falls between the classical fields of hydrology and geochemistry.

Back in the National Lab environment at Livermore Lab, I had the good fortune to work with Emily Giambalvo and Andy Fisher at UC Santa Cruz on a fascinating study of upwelling hydrothermal fluids in an off-axis system in the Pacific (Giambalvo et al, 2002). Here was a very tricky system to capture, but also one in which it became apparent that Fick's Law (diagonal diffusion only) was not going to work and the Nernst-Planck (multicomponent diffusion) equation was required. I was drawn into work on the legacy contamination of U.S. Department of Energy sites, spurred by the apparent failure of classical Kd approaches to describe expedited cesium transport at the Hanford site. Working with Susan Carroll and John Zachara, we were able to show that the enhanced migration of 137Cs could be explained using classical ion exchange theory (Steefel et al, 2003). Then another collaboration, this time with Kate Maher and Don DePaolo on deep sea sediments in the Mid-Atlantic associated with α-recoil isotopic effects in the uranium isotope system (Maher et al, 2006). This study provided support for the idea that slow clay precipitation, first suggested by Zhu et al (2004), combined with nonlinear mineral dissolution could help to explain the oft-discussed laboratory-field rate discrepancy. The suggestion in this study turned into a "smoking gun" in the Maher et al (2009) study of weathering in the Santa Cruz chronosequence, where it was possible capture both present day solute concentration profiles and 226 ka mineral profiles with a single reactive transport simulation using laboratory rates. Maybe the so-called laboratory-field rate discrepancy was not a discrepancy at all. In 2005 we tried to summarize how reactive transport could be used as a new paradigm for organizing research in the earth and environmental sciences (Steefel, DePaolo, and Lichtner, 2005).

"The road to establishing a new discipline is long and winding, and the pathways are unpredictable."

As I saw the clear signs that Livermore Lab would jettison the University of California as their manager, I headed for Berkeley Lab in 2004. Here the environment for collaboration dramatically increased my scientific productivity. I was able to collaborate with Alexis Navarre-Sitchler and Sue Brantley on a study of chemical weathering-enhanced diffusion rates (Navarre-Sitchler et al, 2009; 2011). This turned out to be another fascinating study where the rate controlling step for chemical weathering is apparently the rate at which porosity (and resulting diffusivity) increases. The model also explains how two separate mineral fronts, one for plagioclase and one for pyroxene, could evolve at the same rate over hundreds of thousands of years despite the difference in their rate coefficients. Other collaborations developed, including pore scale reactive transport modeling with Li Li (Li et al, 2008) and later Sergi Molins, Dave Trebotich, and Hang Deng using both high performance and reduced order computing (Molins et al., 2012; 2014; Deng et al, 2016), and biogeochemical reactive transport modeling with Li Li (Li et al, 2009) and Jenny Druhan (Druhan et al, 2014) at the Rifle, Colorado uranium site. Considerable effort also went into organizing a series of workshops on reactive transport model benchmarking around the globe, leading eventually to a high impact special issue in Computational Geosciences (Steefel et al, 2015). While benchmarking is often considered as a prosaic even mundane activity, in fact there seems to be no other way to develop confidence in the numerical approaches for reactive transport modeling, whether the application is to contaminant transport or to chemical weathering or to carbon sequestration.

Following a separate line with of set computational routines that gradually took on a trajectory of their own, I began investigating electrostatic effects in porous media using the CrunchFlow software developed over more than 20 years. Following the pioneering work of Tony Appelo (Appelo and Wersin, 2007), the objective was to use the Nernst-Planck equation within two linked continua in the porous medium: 1) bulk water (electrically neutral), and 2) the electrical double layer (or EDL), where charge within the aqueous phase is balanced by the charge of the mineral surface (normally clay). Leading eventually to an entirely separate branch of the code, I worked closely with Christophe Tournassat of the BRGM in France, the best collaborator imaginable, to develop CrunchClay (Tournassat and Steefel, 2019). With this software, it became possible in a single simulation to capture both anions and cations in clay-rock and to simulate apparent uphill diffusion of ions (Tournassat and Steefel, 2015). Other collaborations, particularly those associated with an Energy Frontier Research Center at Berkeley Lab, proved profitable as well. Studying the interaction of CO2 saturated fluids with heterolithic sediments in the Nagaoka, Japan carbon sequestration test site, detailed microscopic imaging and chemical characterization combined with reactive transport modeling made it possible to demonstrate the effect of different reactive minerals on sediment reactivity (Beckingham et al, 2016; 2017). The study also quantified the contribution of the "porous medium effect" to reactivity, showing that rates in the unconsolidated sediment were about 10x lower in flowthrough column experiments than they were in well-stirred batch kinetic experiments.

Whatever is in my reactive transport portfolio from the past, I spend most of my time these days thinking about the new frontiers (Steefel, 2019). These include watershed biogeochemical function, a beautiful problem full of the most exquisite feedbacks that I am investigating with Berkeley Lab collaborators Bhavna Arora and Dipankar Dwivedi, chemo-mechanical subsurface processes, a topic yielding rich emergent behavior under investigation with collaborators Mengsu Hu and Jonny Rutqvist, and the frontier topic of nanoscale transport in clays with Ben Gilbert and Christophe Tournassat. But to identify the threads running through my personal history that would be valuable to early career scientists, it would probably require the most advanced Machine Learning tool available today. The road to establishing a new discipline is long and winding, and the pathways are unpredictable. All I can say is that I never really thought about the "impact" of this or that study I undertook, I only thought of how I could venture into uncharted territory, whether reading a new novel that connected me to new states of being, or trekking over the next ridge in search of that undiscovered gold deposit, or the next reactive transport modeling frontier that somehow nobody had got to.

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A Fellow Speaks: The winding road of a hydrogeologist

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When I learned of my election to the 2019 class of AGU Fellows, I was thrilled and humbled by this incredible honor. I was immensely grateful to my colleagues and friends who took the time and effort to nominate and support me. As I look back on my 30-year career, I see a winding road with many twists and turns, but my passion for groundwater has remained a constant.

I am a product of Chinese and American educational systems with contrasting philosophies. I graduated from Chengdu College of Geology (now Chengdu University of Technology) in 1983 with a narrowly focused undergraduate degree in "hydrogeology". Afterwards, I received a government study abroad scholarship which would take me to the University of Wisconsin-Madison to broaden my perspective. I arrived in Madison in December 1984 and started my Ph.D. program with Professor Mary Anderson who would become my life-long mentor and dear friend.

Mary got me to work with Ken Bradbury, one of Mary's former Ph.D. students and a hydrogeologist at Wisconsin Geological and Natural History Survey during that time, for my Ph.D. project in groundwater modeling. The project was to assess how interceptor ditches, a common feature in Wisconsin's Central Sand Plain, affected the movement of agricultural chemicals. My work was able to demonstrate that these interceptor ditches act as sinks for agricultural chemicals and form an effective barrier for spread of these contaminants in the shallow aquifer. The very first two scientific papers of my career, as a result of the Ph.D. project (Zheng et al., 1988a, b), were accepted 'as is' and with a single word change, respectively, by Journal of Hydrology and Ground Water. Obviously, I had no inkling that my career, in terms of trying to get papers accepted by good journals, would only go downhill from there.

At that time, I started to recognize the need for developing solute transport modeling tools. I wanted to quantify and visualize the transient, three-dimensional flow pattern beneath an interceptor ditch, but I just could not find a suitable tool to do that, so I would spend several precious months developing a particle tracking code called PATH3D (Zheng, 1988), which, along with the MODPATH code by the U.S. Geological Survey, would be widely used for computing flow paths and approximating solute movement assuming only the advection process.

I went on to work for S.S. Papadopulos & Associates, Inc. after receiving my Ph.D. from UW-Madison in the summer of 1988. I was able to obtain a small grant from the U.S. Environmental Protection Agency to develop a three-dimensional solute transport model, named MT3D, as an extension to PATH3D. The first version of MT3D (Zheng, 1990) was released as an open-source code to the public domain in 1990. Looking back, I think the success of MT3D was a confluence of several factors. First, I made multiple transport solution options available in a single code which could be selected to minimize numerical dispersion. Second, I adopted the same modular structure used by MODFLOW for MT3D and made the two models work seamlessly together. Third, I devoted much time to writing a well-documented and easy-to-understand user's guide. During the development of MT3D, I received great support from Charlie Andrews, Gordon Bennett, and Stavros Papadopulos. Also, my experimentation with solute transport techniques was inspired by the USGS MOC code (Konikow and Bredehoeft, 1978).

A few years later, after I started at the University of Alabama in 1993, I obtained more funding support from the environmental program of the US Department of Defense for further model development. With help from two mathematician colleagues, Patrick Wang and T.-Z. Mai, at Alabama, I expanded MT3D into a multi-component transport simulator referred to as MT3DMS (Zheng and Wang, 1999). I continued to improve MT3DMS until 2010 (Zheng, 2010), including new options to simulate groundwater age and heat transport. More recently, the U.S. Geological Survey has developed newer versions of MT3DMS (MT3D-USGS) and taken over the distribution and maintenance of the software freely available on the internet.

Over the years, MT3D/MT3DMS has become a foundation on which other transport modeling tools with more advanced functionalities are built, affording me the opportunities to work with a large number of collaborators around the world. They include: Henning Prommer for the coupled geochemical-transport model PHT3D, Prabhakar Clement for the biological-transport model RT3D, Christian Langevin and Weixing Guo for the seawater intrusion model SEAWAT, as well as Rui Ma, Guoliang Cao and Mary Hill for heat transport and groundwater age simulation capabilities. The popularity of MT3D/MT3DMS has also been helped by the book that I co-authored with Gordon Bennett, Applied Contaminant Transport Modeling, which features MT3DMS and related tools in discussion of modeling theories and

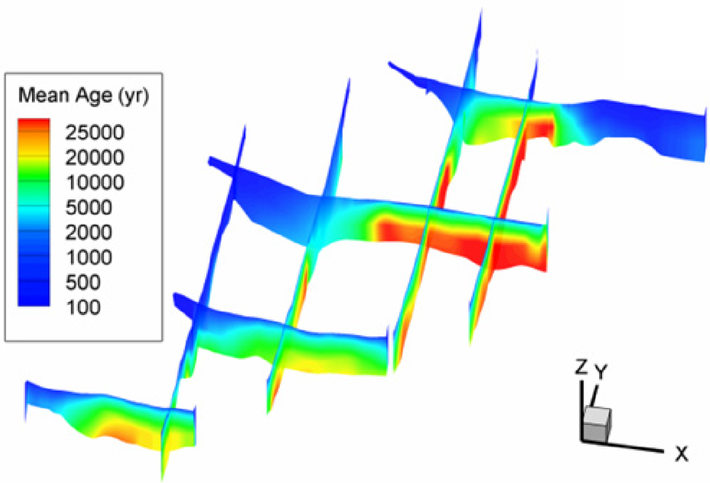

Figure 1. Simulated mean groundwater age distribution in the North China Plain using the solute transport model MT3DMS (Zheng et al., 2012).

field applications (Zheng and Bennett, 1995, 2002). My early career as a model developer took a significant turn when I embarked on a field-based research program at the MADE site in the Columbus Air Force Base, Mississippi. The MADE site, where MADE is an acronym for 'Macro-Dispersion Experiment', is one of the three best-known, intensively instrumented tracer field research research sites in the world, along with the Borden site in Canada and the Cape Cod site in Massachusetts. The fluvial deposits at the MADE site are at least one order of magnitude more heterogenous than sandy aquifers at the Borden and Cape Cod sites. The classical advection-dispersion equation based on Fickian and macro-dispersion concepts has served as the basis for solute transport modeling since the 1960s and has been shown to work well in the mostly homogeneous aquifers at the Borden and Cape Cod sites. However, I was dismayed by its failure to reproduce the observed tracer plumes when applied to the MADE site, although there were over 2000 hydraulic conductivity data points within a domain of approximately 300 m by 150 m by 10 m, and the model grid was already down to 2 m in the horizontal and 1 m in the vertical direction.

Our subsequent analysis was able to demonstrate that the failure was due to the existence of decimeter-scale preferential flow paths embedded in a low-permeability matrix which could not be explicitly represented by the model grid in the meter scale (Feehley, Zheng and Molz, 2000). To overcome this difficulty, we incorporated the dual-domain mass transport approach (DDMT) into MT3DMS, making it possible to implicitly represent such small-scale preferential flow paths (as the mobile domain) and the low-permeability matrix (as the immobile domain). The DDMT approach significantly improved the match between the model simulation results and field observations. Similar conclusions were reached by other researchers such as Charles Harvey and Steve Gorelick at Stanford around the same time. That mutual interest at the MADE site led to a long and fruitful period of collaborative research with Steve Gorelick. Our groups at Alabama and Stanford worked together to develop the theoretical basis and parameterization methods for using the DDMT approach to represent non-Gaussian transport controlled by decimeter or smaller scale preferential flow paths (Zheng and Gorelick, 2003; Liu et al., 2004, 2007, 2010; Gorelick et al., 2005; Ronayne et al., 2010; Bianchi et al., 2011; Zheng et al., 2011).

While the DDMT approach is effective in representing transport in highly heterogeneous aquifers such as the MADE site, model calibration is generally needed to define the porosities of the mobile and immobile domains as well as the mass transfer rate coefficient between the two domains, which is nonunique and lacks predictive capability. To address this dilemma, my student and I developed a lithofacies-based approach that relied on a small number of boreholes to construct a 3D network of lithofacies (Bianchi and Zheng, 2016). The most permeable facies was shown to dominate the transport process and result in the preferential flow paths that caused the non-Gaussian transport at the MADE site. With the lithofacies approach, the classical advection-dispersion model can be applied to the MADE site without the need to estimate the effective parameters required by the DDMT approach. Thus, the lithofacies approach appears to significantly enhance the predictive capability of transport modeling.

So, the story of the classical advection-dispersion model has come full cycle. Yes, it works beautifully (as at the relatively homogeneous Borden and Cape Cod sites). No, it does not work (due to strong heterogeneity as encountered at the MADE site). Yes, it works, if the preferential flow paths arising from the heterogeneity are properly conceptualized and represented with appropriate model grid resolution. If anything, the 35 years of research at the MADE site since the beginning illuminate the power of persistence and never ever giving up in pursuit of fundamental understanding of natural processes that seem to defy a conventional explanation.

I would probably be plugging along with my research and development in contaminant transport modeling, had I not started to work in China in the late 2000s, leading to another major shift in my research direction. As a country with about 7 percent of the planet's water resources to nourish a fifth of the global population, China faces severe water shortage in many parts of the country, exacerbated by changing climate and intensified human activities. So, I started several studies on groundwater sustainability issues using the North China Plain (NCP) as a compelling case where the confluence of population growth, economic development and climate change has made it one of the most water scarce regions in the world. For example, in a collaborative effort with Bridget Scanlon, my research team at Peking University developed the first comprehensive regional groundwater model for the entire NCP and evaluated the options for more sustainable management under different scenarios (Cao et al. 2013). Qin et al. (2013) coupled system dynamics (SD) and integrated hydrologic modeling to inform sustainable management. Hyndman et al. (2017) developed integrated models that coupled climate, land use, surface water, and groundwater components to explore more sustainable water management strategies for Beijing, the megacity in the NCP. Yao et al. (2019) presented an integrated framework and policy-making procedure for the groundwater pumping control policy as part of China's South-to-North Water Transfer Project. Together, these studies addressed some of the most pressing groundwater problems in the world.

From 2010-2018, I played a leadership role in a major ecohydrological research program "An Integrated Study of Ecological and Hydrological Processes in the Heihe River Basin" sponsored by the National Natural Science Foundation of China (NSFC). The "Heihe" program was a concerted effort to understand multiscale ecohydrological processes in a large endorheic watershed (over 100,000 km2) in arid-semiarid northwest China and to provide stronger scientific underpinning for integrated water management in water-limited ecosystems. As the only groundwater hydrologist in the steering committee, I was responsible for the overall design of projects that involve groundwater-surface water interactions and groundwater dependence of ecosystems. In addition, I led a synthesis effort that integrates the field data and research findings from all related projects for the middle basin (irrigated agriculture) and lower basin (Gobi desert) to investigate basin-scale system behaviors and regu-

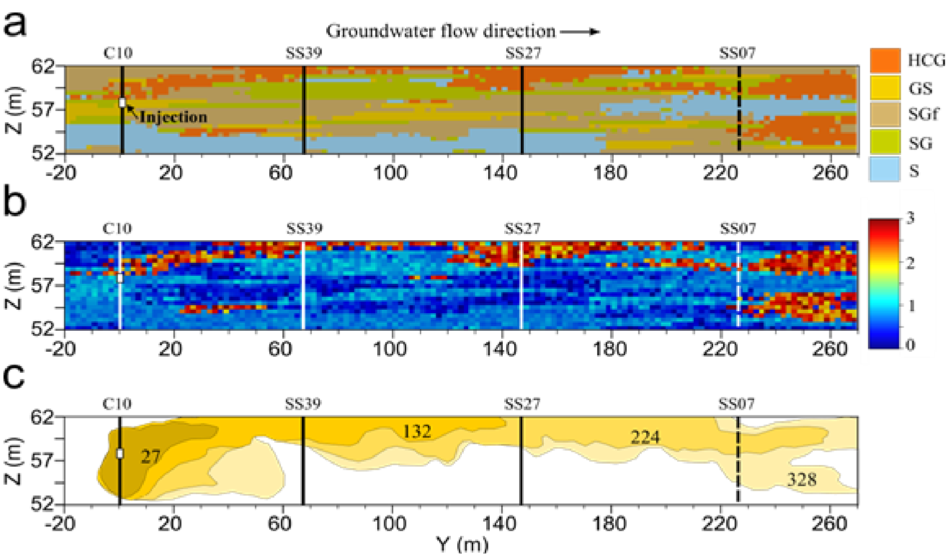

Figure 2. Illustration of a lithofacies-based solute transport modeling approach for the MADE site (after Bianchi and Zheng, 2016): (a) One realization of the lithofacies distribution in a cross section parallel to the general flow direction; (b) Corresponding log10(K) hydraulic conductivity field based on the lithofacies; and (c) Simulated evolution of the tracer plume that agrees well with field observations.

lation mechanisms (e.g., Yao et al., 2015, 1017, 2018; Tian et al., 2015; Hu et al., 2016; Sun et al., 2018).

Then in 2015, I moved from Peking University to Southern University of Science and Technology in Shenzhen, China, where I have started yet another new line of research aimed at understanding emerging contaminants and associated ecological and health risks in the watersheds of Shenzhen, which rose from a fishing village 40 years ago to become a burgeoning international metropolis with a population of over 20 million today. With rapid economic growth and urbanization, most of the over 300 small streams and tributaries in Shenzhen have been severely polluted by organic and heavy metal contaminants. The work of my research group has focused on antibiotics, an emerging contaminant whose occurrence, fate and transport has rarely been investigated but nevertheless poses potentially high risks to human health, as the extensive use of antibiotics has led to the rapid spread of antibiotic resistance (e.g., Ben et al., 2019; Qiu et al., 2019).

Figure 3. An image from the upper Heihe River Basin showing Qilian Mountains in the Northern Qinghai-Tibet Plateau with glaciers in the distance sustaining an intermittent stream (the cover image of Water Resources Research as discussed in Yao et al., 2017).

So, I have taken quite a winding road in my 30-year career to date, from a "bona fide" hydrogeologist working on classical groundwater contamination and remediation problems, to a "broadly defined" hydrologic scientist exploring the impacts of global changes and emerging contaminants on the sustainability of water resources. And the journey continues. I was fortunate to arrive in the United States as an anxious, young graduate student at the dawn of a golden era of hydrogeology when every earth science department in the U.S. universities seemed to be adding a hydrogeologist faculty member and there was plentiful funding for groundwater research, especially related to groundwater contamination and remediation. As the funding sources declined for contaminant hydrogeology, there was concern that the field of hydrogeology would be entering a mature and aging phase (Schwartz and Ibaraki, 2001). However, as my career path has illustrated, many new problems have emerged where groundwater plays a central role. As I remarked at the end of my 2009 Birdsall-Dreiss lecture tour sponsored by the Geological Society of America that took me to 70 institutions in four continents, "a clear trend I have seen from my visits is that more and more hydrogeologists are working with natural and social scientists from other disciplines to tackle difficult problems that are intrinsically complex and multidisciplinary in nature, such as global change, sustainable development, and ecohydrology." That was true in 2009 and even more so today (Gorelick and Zheng, 2015). While the research activities on contaminant hydrogeology in developed countries such as the U.S. have significantly declined since the 1980s (Schwartz et al., 2019), groundwater science has evolved to become a vibrant and indispensable component of ever more multidisciplinary earth and environmental science.

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Hydrologic Sciences Early Career Award:

Megan Konar, University of Illinois at Urbana-Champaign

I am deeply honored to receive the Early Career Award in Hydrologic Sciences. This award is particularly meaningful to me because my research is interdisciplinary, yet I have always felt welcomed and encouraged by the AGU hydrology community. Thank you to my mentors and colleagues who nominated me for this award. I am especially indebted to my amazing students and collaborators, with whom I share this award. I am also grateful to my many amazing colleagues in the hydrology community who make it such a great community.

The goal of my research is to better understand how to achieve water resources sustainability while simultaneously enabling supply chains to promote food security. In my research, I seek to understand the implications of water resources for supply chains, as well as how supply chains, in turn, impact water resources. I conceive of water hazards and unsustainable water use as a risk facing supply chains. In the process of working to understand the impact of supply chains on water resources I have come to realize that social sciences has much to offer on how to think about coupled human and natural systems, including how to determine the impact of social drivers on resource use. I think the hydrologic sciences community (particularly those of us working on water use, or other topics with explicit human interactions) could take cues from social scientists, who have been thinking rigorously about how to handle observational data related to humans for many decades.

I have come to realize that determining the impact of supply chains (or trade) on water resources is a question of causality. This is why I have started to incorporate modern econometric techniques to better understand the causal impact of trade on water resources in recent work. Going forward, I intend to continue to focus on using causal inference methods to understand the drivers in complex human-water systems. Empirical research at the interface of societal water use could benefit from modern econometric methods. I would like to use this article as an opportunity to explain what these methods are and how research on water and society can benefit from the use of these tools.

"I have come to realize that determining the impact of supply chains (or trade) on water resources is a question of causality. This is why I have started to incorporate modern econometric techniques to better understand the causal impact of trade on water resources in recent work."

What is econometrics? When we deal with human-water systems, we have to be particularly wary of "selection bias". Selection bias occurs when people have the ability to opt-in to a "treatment" of interest (e.g. policy, management decision, etc). The main example I like to give is for determining the impact of hospital (a treatment) on health. If we were to look at health outcome for people who went to hospitals compared with those who do not, we would see that health outcomes are worse for the group that goes to hospital. However, the people that go to hospital are different to those that don't go (i.e. they are sicker to begin with), so the difference in means between these groups would not reveal the causal impact of hospitalization due to this selection bias.

In the water resources context, we may be interested in the impact of crop insurance (a treatment) on water use. In this case, we would have to recognize that the farmers who choose to receive crop insurance are inherently different to farmers who do not purchase crop insurance. This inherent difference between these groups of farmers is selection bias. These differences may drive their water usage rather than the crop insurance. For this reason, looking at the relationship between crop insurance and water use in the data would not indicate the causal impact of crop insurance. The same is true of trade (also a treatment), because nations decide how much they are going to trade, which means they select into levels of the treatment.

What can we do? Ideally, in order to determine the impact of any treatment, including crop insurance and trade, we would randomly assign the treatment to the study groups. In other words, we want to pretend that we are a pharmaceutical drug company running a drug trial. To determine the efficacy of the drug, the pharmaceutical company needs to randomly give pills with the medication and placebo pills to patients. The random assignment of the medication enables the pharmaceutical efficacy to be determined. The same is true of any other social intervention – such as a policy, infrastructural improvement, etc. Ideally, we would like to randomly distribute the treatment in order to properly assess its impact on an outcome that we care about. Here, the experimental ideal would be random assignment of crop insurance to farmers or random assignment of trade to world nations.

It is often impossible, infeasible, or unethical to randomly assign treatment. We will never be able to witness a counterfactual world in which we randomly assign countries to trade or not to trade with one another. For this reason, econometricians have developed a wide array of methods to use naturally occurring (i.e. non-experimental) data in clever ways to tease out causal relationships. The main obstacle that these methods seek to overcome is selection bias. Econometric methods are very careful to form the appropriate control group for comparison in order to assess the impact of the treatment of interest. They do this through several core approaches, including instrumental variables and differences-in-differences. Although econometrics often relies on standard statistical techniques (including regression analysis) the main technical contribution is in the interpretation of the coefficient of interest: the goal is to move beyond correlational understanding between two variables and pin down the causal relationship.

Going forward, I think there are many exciting opportunities to apply the tools of modern econometrics to water resources research. Identifying causality in complex human and water systems is of core interest to both science and policy. The field of economics has spent several decades developing the theory and empirical tools of identification of causality of a treatment in human systems. We can now benefit from the fruits of their labor and glean new insights into human-water systems.

Hydrologic Sciences Early Career Award:

Kaveh Madani, Yale University

I am delighted and thankful for being selected as one of the recipients of the Hydrologic Sciences Early Career Award in 2019. I owe this incredible recognition to my inspiring mentors, collaborators and students. I sincerely thank my supportive colleagues for kindly nominating me for this award.

Choosing water as my field of expertise was not unexpected. My parents both worked in the water sector. I was their only child and spent a lot of my childhood with them when visiting water infrastructure around my home country, Iran. Discussions on water management were common at our home and developing passion for water was natural for me. My parents were both on the planning side of water management, but I decided to become a civil engineer during Iran's dam construction boom.

During undergraduate studies, I served as the head of the civil engineering students club at the University of Tabriz and an executive member of the national civil engineering students club. This was my first exposure to operations in real world where I learned that financial restrictions, legal barriers, conflicts of self-interests, and power competitions can kill good intentions and block positive movements.

I moved to Sweden at the age of 22 to get my master's in water resources at Lund University. After taking a system dynamics course, I ended up developing my first model of coupled water-human system in my M.Sc. research. My modeling results were interesting, counter-intuitive, and controversial. I had found that water transfer to meet the increasing water demand in central Iran could exacerbate water shortage. The main reason for this finding was coupling my traditional hydrologic sub-system with a social sub-system that helped me internalize some variables that are normally treated as exogenous variables (e.g. water demand and population growth) in water resources modeling.

My numerical water-human system dynamics model was highly speculative but got me interested in exploring unintended consequences and unexpected behaviors in managing water later in my career. The encouraging feedback I received from Pete Loucks, Rolf Larsson, the late Jonathan Bulkley, and the late Miguel Mariño motivated me to continue this line of research later in career.

I spent one semester as a Ph.D. student in systems design engineering at the University of Waterloo under the supervision of Keith Hipel. In Waterloo, I got into game theory, water resources allocation, and trans-boundary conflict resolution. I also had an admission for doing a PhD in civil and environmental engineering with Jay Lund at UC Davis. Being an expert in conflict resolution and finding win-win solutions, Keith kindly agreed to serve on my Ph.D. committee and let me continue my studies in Davis.

Working with Jay Lund on hydro-economic modeling and optimization was another priceless opportunity for me. Jay encouraged me to take courses in law, economics, and political science in addition to my engineering courses. He continuously reminded me that to be successful in the field, I need to develop my own niche of research and independence. My work with him was on exploring the impacts of climate change on the hydropower operations and market in California. But he gave me the freedom and courage of integrating my work with game theory to take advantage of what I had learned earlier at Waterloo.

The first draft of my most cited publication ("Game Theory and Water Resources") was written as a term paper when I took one of Jay's graduate classes. His encouraging feedback motivated me to publish it after graduation in 2009. This paper questioned the inherent assumption about the perfect cooperation of stakeholders in water management. I had learned well from my parents' discussions and own observations in running student clubs that perfect cooperation among stakeholders is very far from reality. Using some simple game theory examples, in this paper, I tried to highlight the significance of this incorrect assumption that makes many of our modeling solutions impractical.

I started my post-doctoral research at UC Riverside with a well-known water economist, Ariel Dinar. Ariel gave me the freedom of doing what I liked in environmental economics and policy. Our different backgrounds, terminologies, and solution approaches were occasionally making things challenging, but these differences helped me be a better listener and communicator when interacting with people of other disciplines. The slope of learning curve was very steep for me during my one year in Riverside. Together, we worked on developing mechanisms and intervention tools for sustainable management of common pool resources (e.g. groundwater).

In January 2011, I started my career as an assistant professor in the Department of Civil, Environmental, and Construction Engineering at the University of Central Florida and three years later, I moved to the Centre for Environmental Policy of Imperial College London.

The work I have been doing with my students and collaborators at these universities is mainly focused on analysing complex, coupled human-nature systems under global change at the interface of science/engineering, policy and society. Most of our work involves developing and applying a range of systems analysis, mathematical, economic, operations research, social science, decision/behaviour modeling, and game theory methods to coupled human-nature systems problems, involving water, energy, food, climate and the environment, to advise policy. We identify trade-offs in management, explore the unintended consequences of engineering and policy solutions, discover the behavioral motives of stakeholders in complex situations, and explain why our theoretical solutions that are based on simplifying assumptions can make our solutions infeasible. Our research helps us understand the good reasons behind the bad decisions made in the past and design tools and mechanisms to avoid unexpected impacts and behavior in the future.

"The work I have been doing with my students and collaborators at these universities is mainly focused on analysing complex, coupled human-nature systems under global change at the interface of science/engineering, policy and society."

We have worked on practical interdisciplinary problems such as water management/governance, environmental policy and diplomacy, energy systems, food security, climate change impacts and adaptation, infrastructure design and operations, governance institutions, group decision-making, stakeholders behavior analysis, serious games, international development, and empowerment, sustainable development, and transboundary-conflicts and negotiations in different parts of the world.

Our work involves active interactions with stakeholders, societal outreach, and knowledge dissemination through media. Although challenging, the latter motivates us to improve our communication skills for making an impact. Over the years, we have learned that what matters is not our modeling result. What makes an impact is, indeed, the answer to the "so what?" question that policy makers and the general public ask when they see our results. Trying to answer the "so what?" question reminds us that sometimes (if not often) our problem formulation is inaccurate, our solution is useless/impractical, or we are solving a wrong problem!

"Trying to answer the "so what?" question reminds us that sometimes (if not often) our problem formulation is inaccurate, our solution is not useless/impractical, or we are solving a wrong problem!"

In 2017, at the invitation of Iran's Government I took a leave from academia to serve as the Deputy Head of Iran's Department of Environment. Serving as a high-level decision maker is not usual for most academics. Given the policy-orientation of my research, I was not naive to politics, but still faced many surprises that help me better define my research questions today to be more practical. My life in politics was not too long because of the complexities that Iran is experiencing these days. If you have not heard about it already, you can find many stories about my tragic experience in Iran online. That chapter has fortunately ended safely and now I can claim that I have had the best sabbatical I could wish for.

I have had the experience of working in both engineering and natural science departments before politics. But now, I am affiliated with the political science department at Yale University. This is another interesting chapter of my life in which I am trying to highlight the significance of the dynamic interactions of nature and humans in complex systems that we often very naively model in our mathematical exercises.

Reminding the natural scientists and engineers about the socio-political reality of managing water and environmental resources is as challenging as convincing the social scientists about the inadequacy of social and economic models in developing practical solutions to today's unsustainable development problems. Yet, I have not lost hope. I will keep talking about the need for understanding the reality on the ground as I am convinced that we might be good in publishing highly cited publications but we need to do way more if we want to go beyond citations and make an impact on the lives of millions of people around the world who need our help.

Hydrologic Sciences Award:

William P. Kustas, Agricultural Research Service, U.S. Department of Agriculture

The Hydrologic Sciences Award, known as the Robert E. Horton Award from 1956 to 1998, was established in 1956 and is granted by the Section for outstanding contributions to the Science of Hydrology over a career, with an emphasis on the past five years.

I am both honored and humbled to be selected to receive this year's Hydrologic Sciences Award, especially given the class of past recipients. I would like to thank my nominator Marc Parlange and the supporting letter writers, as well as the awards committee members for my selection.

My interest in hydrology and remote sensing started at SUNY Environmental Science Forestry where I received my BS degree in 1981. Then, starting with my PhD work in 1982 at Cornell, under the guidance of Wilfried Brutsaert, my research career has focused on conducting hydrometeorological and remote sensing field experiments to develop and evaluate theories and models of land-atmosphere exchange processes with a primary goal on estimating regional evaporation. Based on radiosonde observations from the Rietholzbach watershed (Figure 1) in the per-Alpine region in Switzerland together with lysimeter and hydrologic data, I was able to contribute important advances in the development of techniques, based on atmospheric boundary layer similarity theory and heat and water vapor conservation equations, for computing surface fluxes of latent and sensible heat at regional scales over complex terrain (Brutsaert and Kustas, 1987; Kustas and Brutsaert, 1987). This

Figure 1. Professor Wilfried Brutsaert with balloon and radiosonde in hand preparing for a launch (top); the Rietholzbach watershed (bottom); me (red shirt) and a graduate student from University of Zurich releasing a radiosonde (right).

experience in using data from field experiments to further develop models and theories of land-atmosphere flux exchange with a focus on evaporation set me on a research path that has defined my career.

In 1986, I joined the USDA-Agricultural Research Service (ARS) Hydrology Laboratory to begin a research career on developing physically-based modeling tools for estimating crop water use in agroecosystems, which encompass not only irrigated and rain fed crops, but rangelands, pastures, forests, riparian systems, and virtually all ecosystems that are impacted by agriculture or provide water resources to agriculture.

I was encouraged early on by Ted Engman in the lab to visit ARS locations conducting remote sensing research. The U.S. Water Conservation Lab in Phoenix, Arizona had a tremendous impact on my early career in the late 80s. This laboratory was where the observational and theoretical underpinnings of the Crop Water Stress Index (CWSI) was first developed and led by the late Ray Jackson (Jackson et al., 1988). This was my first exposure to the application of thermal-infrared remote sensing as a tool for evaluating crop water use and stress. They had a project in Owens Valley California mapping rangeland ET using optical and thermal-infrared imagery over shrublands/phreatophytes. Using standard aerodynamic resistance formulations with the derived land surface temperature they were not matching their heat flux measurements and so I began the first part of my career participating in remote sensing field experiments where surface fluxes and land surface temperature data were collected in the hopes of revising current theory on momentum and heat transport from complex surfaces. Ray invited me to participate in field experiments conducted in Maricopa, Arizona (the MAC experiments) over irrigated agriculture, which in most cases contained a mixture of wet cool and hot dry bare soils together with transpiring row crops. Maricopa was very hot in the summer reaching 40o C or higher and if you were in an irrigated field the dew point temperatures could produce a heat index in the 50o C range (over 120o F!). Ray was an inspiration working under such conditions and is seen below preparing data loggers for making measurements during aircraft and satellite overpasses (**Figure 2**).

These experiments in Maricopa led to my involvement in the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) conducted in the Konza Prairie outside of Manhattan, Kansas. With encouragement of Tom Schmugge, a member of the FIFE project planning team, who recently transferred from NASA over to the USDA-ARS Hydrology Lab, I became part of the surface flux group collecting energy balance data at multiple locations within the FIFE study domain. In 1987, the eddy correlation or eddy covariance approach for estimating sensible and latent heat fluxes were mainly using data from one-dimensional sonic anemometers for measuring high frequency (~10 Hz) vertical velocity fluctuations, along with fine

Figure 2. Ray Jackson programming data loggers for upcoming field measurements during a MAC field campaign.

wire thermocouples and hygrometers for measuring the temperature and water vapor fluctuations. The other technique frequently used was the Bowen ratio energy balance approach, which assumes similarity in flux-gradient-eddy diffusivity relationship for water vapor and temperature. I deployed a such system (Figure 3) during the FIFE field studies in 1987 and contributed to the FIFE Special Issue.

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Figure 3. Here I am with dark hair and a mustache, just starting my research career at USDA-ARS testing the Campbell Scientific Bowen ratio/energy balance system in preparation for the FIFE 1987 field campaign.

Hz) vertical velocity fluctuations, along with fine wire thermocouples and hygrometers for measuring the temperature and water vapor fluctuations. The other technique frequently used was the Bowen ratio energy balance approach, which assumes similarity in flux-gradient-eddy diffusivity relationship for water vapor and temperature. I deployed a such system (Figure 3) during the FIFE field studies in 1987 and contributed to the FIFE Special Issue.

After FIFE, I was fortunate enough to receive funding on a NASA proposal to evaluate the utility of remote sensing data from the visible through microwave wavelengths for mapping surface states and fluxes over shrub and grass rangeland sites in southern Arizona outside of the famous town of Tombstone in the USDA-ARS Walnut Gulch watershed. The project was called MONSOON '90, since this region of the

Figure 4. An international team of scientists preparing to collect multispectral data over prescribed areas for validating aircraft and satellite sensor retrievals (left); there I am checking data logger from one of the micrometeorological towers prior to an oncoming storm (top right); and the NASA C-130 which flew a push broom microwave radiometer and multispectral and thermal-IR sensor package for testing microwave soil moisture retrieval and for modeling land surface fluxes over the Walnut Gulch watershed. Photos courtesy of USDA-ARS AgResearch Magazine https://agresearchmag.ars.usda.gov/archive

semiarid southwest typically experiences a wet or "monsoon" season in July and August. In addition to airborne and satellite remote sensing, we had atmospheric boundary layer radiosonde observations and ground-based remote sensing and hydrometeorological measurements across the watershed for validating water and energy balance models using remote sensing retrievals of land surface temperature, vegetation cover and soil moisture (**Figure 4**).

While analyzing data from MONSOON '90, which produced a special section in Water Resources Research (Kustas and Goodrich, 1994), out of the FIFE Special Issue a seminal paper was published (Hall et al., 1992) that concluded remotely sensed surface temperature for land surface modeling of heat fluxes was not a viable approach. Specifically, they stated the following: "Unfortunately from our research we also found that remote estimation of surface temperature to useful accuracies is problematic; consequently, the use of thermal infrared measurements to infer sensible heat flux is probably not feasible to acceptable accuracies." This led to a small but influential community of international scientists to organize a workshop on thermal infrared remote sensing to review its utility in conjunction with other sensor data for estimating land surface fluxes and states. I was fortunate enough to take part in this workshop, which had a tremendous impact on my career.

At the meeting, what started out as a contentious debate on how to best use land surface temperature for estimating heat fluxes came a paradigm shift on how to model the radiative and convective heat exchange across the land surface-atmosphere interface. A well-known saying attributed to Albert Einstein is "everything should be made as simple as possible, but not simpler." This profound statement is relevant to many scientific endeavors, being a version of Occam's Razor. The application of land surface temperature to estimate surface fluxes is no exception and algorithms at every conceivable level of complexity have been proposed over the years. However, the key challenge is to find methods that are robust, generally applicable, and as simple as possible without being too simple.

John Norman from the University of Wisconsin proposed a more robust method of applying land surface temperature for flux estimation using a two-source energy balance modeling framework, which explicitly treats the difference in radiative and aerodynamic exchange from the canopy and soil. The conceptual framework for this modeling approach illustrated in the notes from John at the meeting (Figure 5), had its origins in the modification of the Penman-Monteith model of evaporation for partially vegetated covered surfaces proposed by Shuttleworth and Wallace (1985) and Shuttleworth and Gurney (1990). I was convinced this was the right approach, so John and I collaborated to convert the two-source parameterizations into computer code and evaluate the output with field data from MONSOON '90. The landmark paper that developed and tested this new and robust modeling scheme (Norman et al. 1995; my 2nd most cited paper) and others in the proceedings from this workshop were published in a Special Issue of Agricultural and Forest Meteorology entitled "Thermal Remote Sensing of the Energy and Water Balance over Vegetation" (Moran, 1995). This paper and others in the special issue reestablished the utility of land surface temperature for modeling ET over complex surfaces.

The Norman et al. (1995) model originally coined TSM for 'two-source model' and with the original title of the paper 'Source Approach for Estimating Soil and Vegetation Energy Fluxes in Observations of Directional Radiometric Surface Temperature' was changed to TSEB-Two-Source Energy Balance model and with the intended title 'A Two-Source Approach for Estimating Soil And Vegetation Energy Fluxes from Observations of Directional Radiometric Surface Temperature'. The TSEB model was specifically designed to address the key factors affecting the aerodynamic–radiometric temperature relationship that had plagued many prior applications of one-source or single-source modeling schemes, resulting in poor performance when applied to partial canopy cover and heterogeneous landscapes unless the roughness length for heat

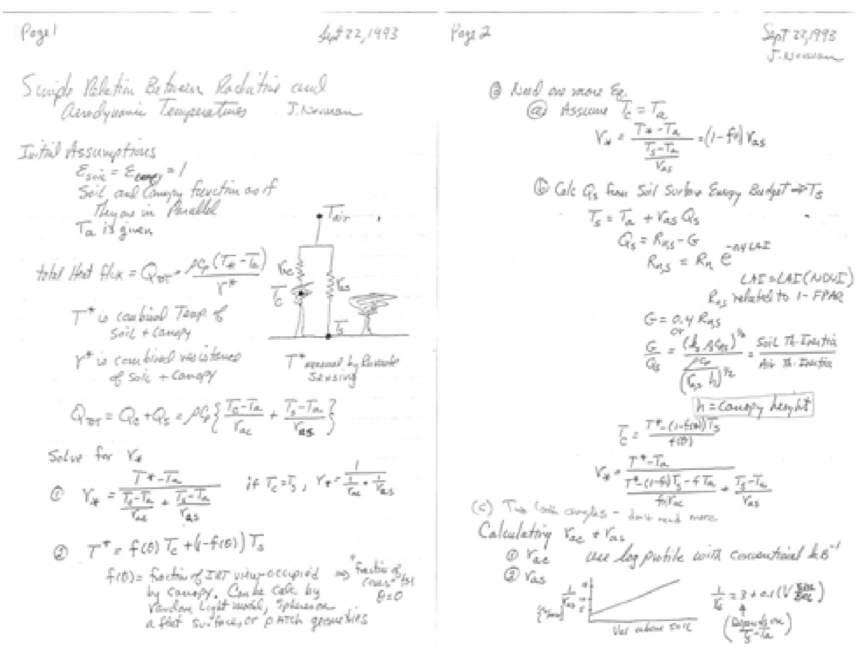


Figure 5. John Norman's notes from the "Workshop on Thermal Remote Sensing of the Surface Energy and Water Balance over Vegetation in Conjunction with Other Sensors", which took place in La Londe Les Maures France, 20-23 September, 1993.

was calibrated using local observations. My work with the late John Stewart from the Institute of Hydrology in Wallingford, UK and others (Stewart et al., 1994) highlighted this issue with single-source approaches.

I continued in my career path of participating and in some cases leading large scale remote sensing field experiments. There were several conducted in the Southern Great Plains, one at the USDA-ARS Little Washita watershed in Oklahoma near the town of Chickasha (Washita '92). This was followed with another field experiment having a focused study site in grasslands and winter wheat fields surrounding El Reno, Oklahoma (SGP '97) where John Norman and I designed a multi-view angle thermal-IR radiometer tower involving the use of Slinkies (**Figure 6**).

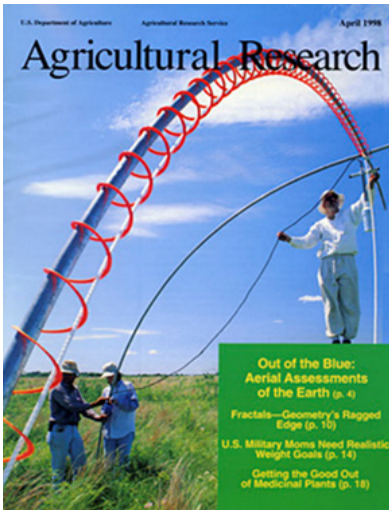


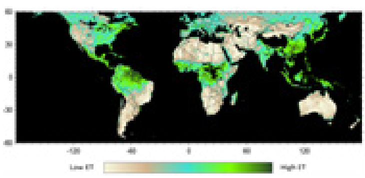
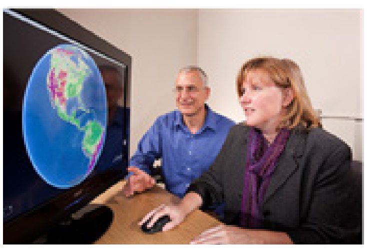
Figure 6. Deployment of a thermal-infrared radiometer tower for supporting multiple sensors at different viewing angles over a grassland site at SGP'97. Photos courtesy of USDA-ARS AgResearch Magazine https://agresearchmag.ars.usda.gov/archive

There was an additional set of field campaigns in 1999 (SGP '99). Out of these experiments came the development of a TSEB model version using microwave soil moisture (Kustas et al., 2001) and two seminal papers, one jointly led by John Norman and Martha Anderson on a disaggregation (Dis) methodology for the regional scale TSEB model called the Atmosphere Land Exchange Inverse (ALEXI) or DisALEXI (Norman et al., 2003) and a paper (my most cited) on energy balance closure of eddy covariance measurements by Twine et al (2000); note that both the senior author Tracy Twine and co-author John Norman are in the photo (Figure 6) working on the ground. In the 1990s, I also became involved in smaller scale but longer-term field studies at the USDA-ARS Jornada Experimental Range near Las Cruces, New Mexico-the JORnada EXperiments (JORNEX), led by the late Al Rango, where there has been a long-term transition from grassland to shrubland. We measured the energy balance of grassland and shrubland ecosystems, where the mesquite shrublands (dunes) have a unique canopy structure significantly affecting the microtopography and energy balance of the landscape. I also became involved in evaluating water use of riparian vegetation (the invasive salt cedar) near the Bosque del Apache wildlife refuge in New Mexico. Then in the early 2000s, NASA was supporting remote sensing field experiments with a primary focus on microwave remote sensing of soil moisture -the Soil Moisture EXperiments (SMEX). In 2002 (SMEX02), the study area (the USDA-ARS Walnut Creek watershed) was over rainfed corn and soybean production region in central Iowa near Ames, and NASA additionally supported the Soil Moisture Atmosphere Coupling EXperiment (SMACEX), which I organized in concert with SMEX02. These data led to a special issue in Journal of Hydrometeorology (Kustas et al., 2005) containing refinements of TSEB using both thermal-IR and microwave remote sensing. Around this same time and reaching a significant level of maturity by the mid-2000s, Martha Anderson who was newly hired at the lab (now named Hydrology and Remote Sensing Lab; HRSL) from University of Wisconsin and who had worked with John Norman on developing ALEXI/DisALEXI, further enhanced this multiscale modeling system and evaluated output with data from these field experiments. Martha also began generating a thermal-based drought product that did not require precipitation. These were highlighted in two EOS articles in 2008 (Anderson and Kustas, 2008; Kustas et al., 2008).

I took a break from large scale field experiments, but used this treasure of ground biophysical, micrometeorological along with airborne and satellite remote sensing data to evaluate and refine the TSEB model over these different landscapes. I had the opportunity to work with John Albertson on a sabbatical during the 2000 fall semester when he was at University of Virginia and incorporated the TSEB land surface scheme into his large eddy simulation model. This resulted in several papers exploring the coupling of land surface states (i.e., surface temperature soil moisture) and fluxes with the lower atmosphere (Kustas and Albertson, 2003). I continued testing and improving TSEB model formulations going to challenging regions such as the Southern High Plains in the Texas Panhandle with strong advection and major groundwater issues due to the drawdown of the Ogallala Aquifer from irrigated agriculture. Indeed, irrigated agriculture is under extreme pressure to conserve water in this region since the Ogallala Aquifer has been declining at unacceptable rates with agricultural irrigation accounting for up to 90% of the groundwater withdrawals. Consequently, significant advances in technologies are urgently needed for improving irrigation management and water use efficiency if agriculture is to remain sustainable in this region. The Bushland Evapotranspiration and Agricultural Remote sensing Experiment 2008 (BEAREX08) was designed to test the utility of the TSEB/ALEXI/DisALEXI modeling system for accurately determining plant water use/ET over a strongly advective agricultural setting in the Texas Panhandle. The field campaigns took place in the experimental facilities at the USDA-ARS, Conservation and Production Research Lab in Bushland, Texas. The field site contains four large weighing lysimeters (3x3 m x 2.3 m deep) with each lysimeter in the center of a 4.4-ha field, which were planted in cotton during BEAREX08. Two of the fields were rainfed and two were irrigated and contained soil moisture profile sensors and eddy covariance towers to measure ET rates as well as a host of additional ground-based micrometeorological and biophysical measurements. Advancements in TSEB modeling and flux measurements for this strongly advective environment were published in a BEAREX08 special issue in Advances in Water Resources (Evett et al. 2012). For operational applications of remotely sensed ET in agricultural water management, the spatial resolution was being addressed with the DisALEXI framework, but we were still limited by the frequency of ET estimates from satellite observations for monitoring stress and irrigation management, which needed nearly daily estimates to be useful. This limitation was addressed through a data fusion technique, developed by Feng Gao at HRSL, originally for reconstructing time series of spectral reflectances and vegetation indices, and adapted to work within the DisALEXI modeling framework for daily ET estimation by Cammalleri et al (2013).

While my efforts have focused on quantifying ET over agroecosystems, the importance of quantifying ET and its impacts on ecosystem functioning, carbon cycling and climate gained significant traction with the 2017 US National Research Council Decadal Survey (http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm) providing policy recommendations for next decade of satellite missions. The Surface Biology and Geology mission recommended by the recent Decadal Survey will include hyperspectral imagery in the visible and shortwave infrared, and multi- or hyperspectral imagery in the thermal-IR, thus supporting efforts using land surface temperature in monitoring ET and drought.

I have been very fortunate to have a plethora of national and international researchers, graduate students and postdocs who have worked with me to

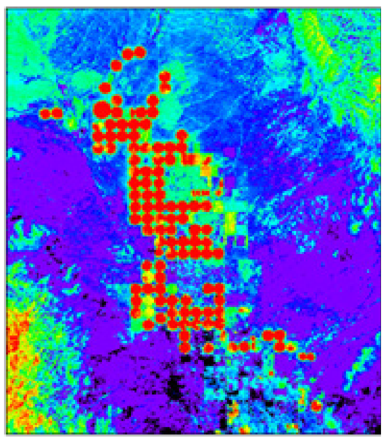


Figure 7. Global ET map generated using satellite imagery collected by a constellation of international geostationary satellites (top left); Martha Anderson and I viewing a global scale map of ET generated with the ALEXI model (bottom left); me checking sensor alignment of an eddy covariance flux tower we have operating near our Beltsville MD research facility that we use for model validation (center); and an ET map for an irrigated area in Arizona, using center pivots illustrating the need for high spatial resolution imagery (30 m Landsat) in order to assess water use on a field-by-field basis (right). Photos courtesy of USDA-ARS AgResearch Magazine https://agresearchmag.ars.usda.gov/archive.

evaluate and improve TSEB algorithms over a variety of complex ecosystems such as the dehesa (a mixed grassland and open forest agroecosystem) in Spain, arid and semiarid shrublands and grasslands in China, rice fields in South Korea and the US, forests on the east and west coast of the US and in the Arctic tundra, to name a few. There was also the development of a version of TSEB for snow covered surfaces in the hopes that eventually it could be implemented in the ALEXI/DisALEXI model for regional applications over the winter months.

All these collaborations and efforts are moving this modeling approach to continental and ultimately global scales with Martha Anderson and Chris Hain at NASA-MSFC leading this effort (Anderson et al., 2011). However, as with any modeling approach that attempts to encompass larger spatial domains and/or use coarser resolution information, the inputs have greater uncertainty/error and so will the model output along with greater difficulty in the validation. That is why my efforts and those of my colleagues and collaborators have worked on ways to sharpen thermal imagery (Gao et al., 2012) in order to have resolutions commensurate with land cover changes (Landsat optical resolution of ~30-m). Additionally, for agricultural applications, field sizes require such resolutions if we are to manage crop water use and stress for different cropping systems and determine within field variability in plant available water. These efforts in model application and validation are summarized in the collage above (**Figure 7**)

So, after more than 30 years of research into remote sensing-based modeling and measurement of ET, I have started to work with the HRSL research team and outside collaborators in transitioning the modeling system into an application/toolkit for irrigation management. However, at the same time I continue to refine the TSEB model with more robust formulations, such as incorporating a more universal soil aerodynamic resistance algorithm which is shown in a recent publication in Water Resources Research (Li et al., 2019) to have a significant impact on model output for sparse canopies. Moreover, others in the international community are applying and evaluating TSEB using European Space Agency Sentinel satellites with a goal to provide earth observations for agriculture and food security applications (Guzinski and Nieto, 2019). I need to especially thank Hector Nieto who has converted the TSEB source code into Python and is freely available on line (https://github.com/hectornieto/pyTSEB/releases/tag/v1.4).

The work on application of the modeling system for agricultural water management led to a multiyear project with the wine and grape industry in California, which was precipitated by the extreme and extended drought in California from the fall of 2011 through the fall of 2015. This period was the driest since record keeping began in 1895 and was exacerbated by high temperatures with 2014 and 2015 also being the hottest on record. The impact on agriculture was significant and for high valued perennial crops such as vines and nut and fruit orchards, groundwater pumping was the only alternative in some areas to save such significant investments.

The groundwater pumping from agriculture contributed to a significant decrease in groundwater resources observed regionally with the GRACE satellite, particularly for the Central Valley (Xia et al., 2017). This prompted the California Department of Water Resources to enact the Sustainable Groundwater Management Act (SGMA) in 2014, in order to curtail the severe overdraft of water in regions dependent on groundwater resources. At the same time, many in the agricultural community were taking proactive steps on implementing robust water management plans that would reduce consumptive water use and at the same time enhance resilience against future droughts.

The Grape Remote sensing Atmospheric Profile and Evapotranspiration eXperiment (GRAPEX) project which began in 2013 at a single vineyard site in collaboration with E&J Gallo Winery has such a goal; namely, to develop and evaluate an ET model using remote sensing in order to provide reliable water use information over multiple vineyards for improved irrigation scheduling and water management. This has required research and field data collected by a multidisciplinary team to understand the impact of vine canopy architecture and row structure on water, energy and carbon exchange and effects on remote sensing retrievals of biophysical and plant parameter information for modeling the fluxes (Kustas et al., 2018; **Figure 8**). After a few years NASA Applied Sciences Water Resource program funded GRAPEX. The proj-

Figure 8. Cover for Bulletin of the American Meteorological Society (BAMS) containing the feature article by Kustas et al (2018). Image from © American Meteorological Society. Used with permission.

ect mission under NASA's grant is two-fold:

•Develop an ET toolkit using remote sensing platforms capable of deciphering water use and crop stress at the field scale.

•Work with California vineyard managers to incorporate the ET toolkit into their irrigation/ water management decision support system for improved and sustainable water management.

Very recently we have made significant progress in showing the capability of the ET toolkit in detecting vine water use and stress on a daily to weekly basis which has potential for irrigation management. This work was recently published by Knipper et al. (2019) who applied the ET toolkit to a variable rate drip irrigation system under development by E&J Gallo for improving water use efficiency and generating uniform grape yield and quality. Next steps are being made to implement the ET toolkit output into an irrigation scheduling dashboard, which was initiated at the start of the 2019 growing season. At the same time, NASA has recognized the potential of unmanned aerial vehicle (UAV)/drone technologies to enhance satellite observations and we've been making significant advances with Utah State University AggieAir program supported by this project (https://uwrl.usu.edu/aggieair/uav-service-center/projects).

Although this work focuses on vineyards, the ET toolkit will directly apply to other highly-structured canopy crops, such as fruit and nut orchards. This is the next phase of my work and I am excited to have collaborators who want to extend the model into other complex canopies that use substantial water resources in California and in other countries, including, Spain, Italy and Israel.

I am very thankful to the many ARS and university colleagues involved in many of the past field experiments and need to mention several who significantly contributed to their success – the late Ray Jackson, Tom Jackson, John Prueger, Jerry Hatfield, the late Al Rango, Dave Goodrich, Susan Moran, Steve Evett and Paul Colaizzi from USDA-ARS, Dave Stannard from USGS, Larry Hipps from Utah State University and John Norman from University of Wisconsin.

With ongoing GRAPEX project there are many students, technicians and researchers/scientists to thank; here I mention those significantly involved in the project: John Prueger and Larry Hipps who were involved in many prior field experiments, Maria mar Alsina, Luis Sanchez, Brent Sams and Nick Dokoozlian from E&J Gallo Winery, Joe Alfieri, Lynn McKee, Alex White, Kyle Knipper, Feng Gao and Martha Anderson from USDA-ARS in Beltsville, Mac McKee, Alfonso Torres-Rua and the AggieAir team from Utah State University, Hector Nieto from COMPLUTIG, Spain, Nurit Agam from Ben Gurion University of the Negev, Israel, Andrew McElrone from USDA-ARS at Davis and Nicolas Bambach and Yufang Jin from UC Davis. I also need to mention the USDA-ARS National Program Staff, specifically National Program Leader Teferi Tsegaye, who has been very supportive of GRAPEX.

I have been very fortunate having the opportunity to work with many bright and talented students, post docs and scientists. During John Norman's closing remarks at the 28th Conference on Agricultural and Forest Meteorology Special session honoring his academic and scientific contributions, John indicated how his productivity and impact was greatly enhanced when he began to actively share his scientific ideas with others. I have truly benefitted from this approach to research and this award also belongs to the many students, postdocs and research colleagues, as well as ARS science support staff with whom I have had the privilege working with throughout my career. I am very grateful for their contributions recognized by this award.

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Paul Witherspoon Lecture:

Hydrology as a Fulcrum for Change

Patrick M. Reed, Cornell University

The Paul Witherspoon Lecture award is given in recognition of outstanding achievements by a mid-career scientist (within 10 to 20 years since PhD) in advancing the field of hydrologic sciences. The award also acknowledges that the awardee shows exceptional promise for continued leadership in the hydrologic sciences.

I am incredibly honored to serve as the 2019 Witherspoon Lecturer. Paul A. Witherspoon has been an influential figure in my training. His work shaped the content of my early Geological Engineering coursework (B.S., Missouri University of Science and Technology) as a key founder of the discipline itself. His legacy at the Illinois State Geological Survey shaped facets of my PhD research related to designing groundwater observation systems (Ph.D., University of Illinois). The trajectory of his career is itself an inspiration. His vision in transitioning to a broader focus on Energy and the Environment as the initiating Director of the Earth Science Division of the Lawrence Berkeley National Laboratory is a clear demonstration of the importance of promoting translational science to address societal challenges. Leaving the infinite horizons of Champaign-Urbana in 2002, my first eleven years as a faculty were spent at The Pennsylvania State University in the Department of Civil and Environmental Engineering. My early work focused on creating stochastic groundwater flow-and-transport modeling and analysis frameworks seeking to "predict where to observe". The ambition in this work was to evaluate and advance our ability to use physical modeling, data assimilation, and multiobjective optimization to design groundwater observation networks. As a short-hand, I viewed this as a physics informed statistical design-of-experiments where we seek to balance tradeoffs across societal objectives and network information objectives. As is likely obvious to many, it turned out this was not the easiest class of problems to solve. In fact, my technical ambitions outmatched the state-of-technology in terms of solving the high-dimensional, stochastic, combinatorial, and computationally demanding problems my research group was formulating. As a consequence, my research group has spent a fair amount of my professional career inventing new computational tools and scaling them to emerging high-performance computing platforms so that we can better discover the tradeoffs inherent to bridging observation, prediction, and management objectives within water resources systems. Since joining Cornell University in 2013, my research group has focused on the planning and management of water resources systems given conflicting demands from renewable energy systems, ecosystem services, expanding populations, and climate change. Our work is focused on developing and evaluating new frameworks for effectively combining a wide range of knowledge sources with simulation, optimization, and machine learning technologies to capture impacted systems' governing processes, elucidate human and ecologic risks, limit management costs, and satisfy stakeholders' conflicting objectives. A fundamental question underlying our work is how to map "state-action-consequence" feedbacks in highly contentious and uncertain decision contexts to improve real-world decisions (e.g., mega dam development in the Mekong or regional competition in urban water supply systems). Given that hydrologic modeling has a central role in mapping "state-action-consequence" feedbacks, there is the need and opportunity to dramatically improve the fidelity of how we represent state-aware, limited foresight human actions at operational (hourly to weekly) and planning (seasonal to decadal) time scales. Climate change and human pressures are making adaptation actions a central focus in water resources systems globally. Consequently, there is a tremendous opportunity for hydrologic science to better explore how the co-evolution of human institutions, financial pressures, and increasingly severe extremes should shape our formulation of adaptation pathways to be more resilient and robust to the many challenging futures water resources systems may confront.

James B. Macelwane Medal:

Amir AghaKouchak, University of California, Irvine

The James B. Macelwane Medal is given annually to three to five early career scientists in recognition of their significant contributions to Earth and space science. Nominees are selected for the medal based on their depth and breadth of research, impact, creativity as well as service, outreach, and diversity.

Receiving the James B. Macelwane Medal is a humbling pleasure, and I am deeply grateful to my nominators, mentors, collaborators and also the AGU's Honors Committee. Of course, I owe this recognition to my graduate students, postdocs and collaborators that I have had the pleasure of working with over the past ten years. In the following, I offer some thoughts and ideas on compound and cascading hazards that my group has been working on for a while.

Most climate extremes (e.g., floods, droughts, heatwaves) are caused by a combination of often dependent and interacting physical drivers/processes across space and time [Zscheischler et al., 2018]. The combination of hazards and/or climate drivers leading to significant societal impacts is referred to as a compound event [Moftakhari et al., 2017; Wahl et al., 2018]. There are a wide range of compound events including (a) multiple extreme events occurring simultaneously (e.g., drought and heatwaves); (b) cascading hazards occurring successively (e.g., extreme rain over burned areas causing debris flow); (c) extreme events (e.g., flood) combined with non-climatic drivers (e.g., urbanization, deforestation) amplifying the overall impact; and (d) combination of non-extreme events leading to an extreme impact (e.g., a moderate drought and a warm spell causing crop failure) — [Seneviratne et al., 2012; Wahl et al., 2018].

While relationships between different extremes have been investigated for years, most existing frameworks for risk assessment consider one hazard or driver at a time, potentially leading to significant underestimation of the underlying risk [Moftakhari et al., 2017a, 2019; Zscheischler et al., 2018]. In coastal areas and estuary systems, for example, flooding is primarily driven by the riverine discharge (fluvial flow) and

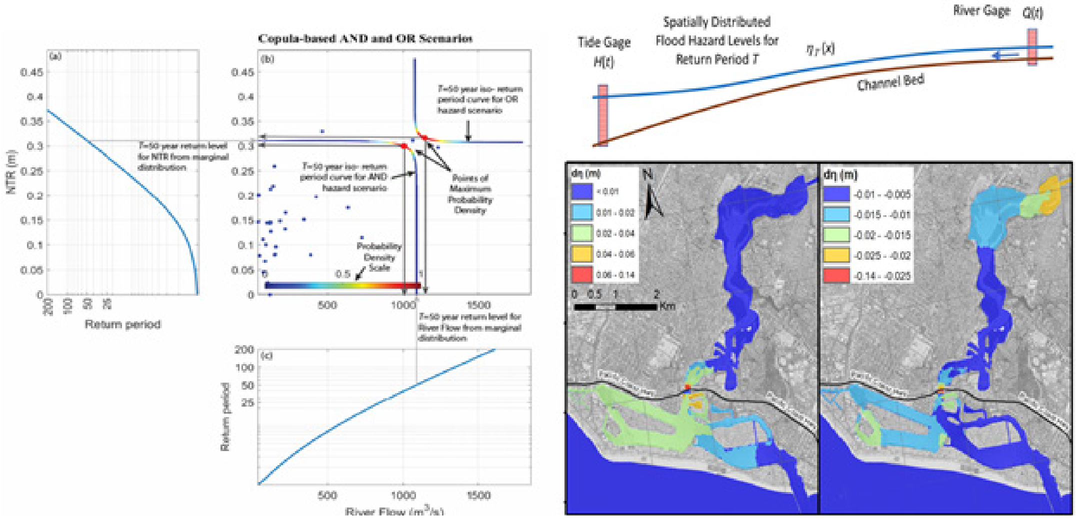

Figure 1 – Framework for hybrid statistical-dynamical compound coastal flood analysis (after Moftakhari et al., 2019). Multi-hazard Scenario Analysis Toolbox (MhAST; Sadegh et al., 2018) generates hazard scenarios (left) that can be used to generate the water profile (right - top), and the corresponding flood inundation map (right - bottom).

the ocean water level. The latter may be influenced by other drivers such as winds and waves. The amount of fluvial flow that can be drained into the ocean is a function of the gradient between the fluvial water head and the ocean water level. The dynamics of the fluvial flow and ocean water level are well understood [Chow 1959], and there are advanced models [e.g., Sanders et al. 2001 and references therein] for simulating the corresponding interactions specially when the drivers are known (e.g., the 100-yr fluvial flood interacting with the long-term average ocean water level). However, the current guidelines for coastal flood frequency analysis ignore the dynamics of ocean water level [Moftakhari et al., 2017]. A recent study shows that when the two flood drivers are dependent, even the relatively conservative approach of Federal Emergency Management Agency (FEMA) for coastal flood risk assessment [FEMA 2015] can potentially underestimate the compound coastal flood risk [Moftakhari et al., 2019]. For this reason, we have focused on developing frameworks for multi-hazard analysis specifically for compound hazards [e.g., Sadegh et al., 2017, 2018]. Multi-hazard Scenario Analysis Toolbox (MhAST; Sadegh et al., 2018), for example, is designed for deriving multi-hazard design and risk assessment scenarios and their corresponding likelihoods for different types of inter-dependent hazards (see Figure 1).

While progress has been made in multivariate analysis of dependent extremes, we lack methods for evaluating the risk of cascading hazards with (at least statistically) independent drivers. In the past few decades, warming temperatures and prolonged dry spells have contributed to observed increases in fire frequency and burned areas. Intense precipitation events succeeding wildfire events can trigger floods, debris flows and landslides [Bladon, 2018] — a type of cascading hazard projected to increase due to the increasing trend in fires in most places around the world. A recent example is the devastating 2018 debris flow even in Montecito, California that led to the death of 20 people following a major wildfire that scorched the upstream area one month prior. In this type of cascading hazards, the main drivers (i.e., rainfall, and wildfire) are often statistically independent and may occur in different seasons or even years. However, they are linked through their potential impacts (e.g., debris flow, landslide). In such cases, our existing multivariate concepts for compound events cannot be used for reliable risk assessment as they rely on the dependence among drivers. For this reason, our group is working on developing theoretical models specifically designed for cascading hazards with statistically independent drivers. Given the projected increase in wildfires, heatwaves and even extreme precipitation, this topic deserves a great deal of attention. Recent observations in California indicate that the fire elevations have begun to encroach on snow-covered mountains, which can have implications for increased and earlier snowmelt and consequently result in higher debris flow risk [AghaKouchak et al., 2018] — see Figure 2. This combined with the observed increase in wildfires and atmospheric warming will most likely intensify the related cascading disasters. We hypothesize that fire-snow interactions can increase the risk of cascading hazards. The interactions between wildfires and snow and their associated changes in snowmelt (amount and sea-

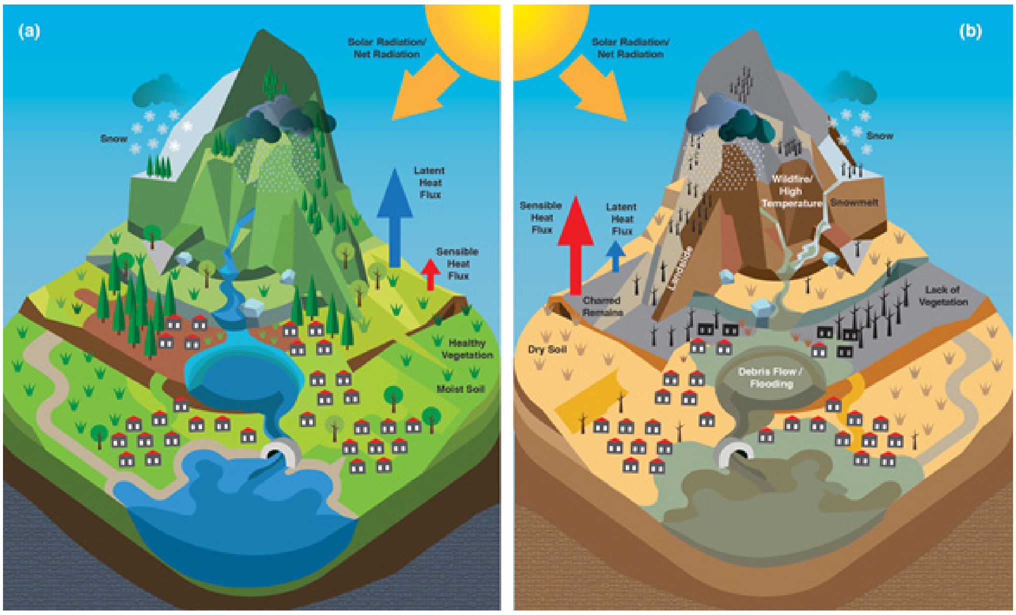

Figure 2 – Conceptual figure depicting two scenarios: (a) pre-wildfire conditions, and (b) cascading disasters caused or intensified by wildfires. In scenario (a), solar radiation reaches the land surface and the available soil moisture moderates the partitioning of sensible and latent heat flux. In scenario (b), solar radiation reaches a drier land surface, which creates a relatively higher partitioning of sensible heat, increasing the local temperature. The combination of dry and warm conditions increases the risk of wildfire events, which subsequently increases the risk of soil erosion, landslide, debris flow and flooding downstream. In addition, particulate matter from wildfire events can also decrease surface albedo over snow-covered areas, changing the rate and timing of runoff from melt.

sonality) and the potential cascading hazards are not fully understood and deserve more attention.

While a myriad of studies have investigated the possible impacts of climate change on individual extreme events, and more recently bivariate extremes, we need to turn our attention to the influence of climate change on cascading hazards with dependent and independent drivers. This is fundamental to development of mitigation and adaptation measures to cope with the cascading hazards. Future research in this direction should go beyond quantifying trends and changes in the statistics of extremes and delve into their interactions with natural and built environments.

Finally, natural hazards and climate extremes will continue to happen, perhaps more in a warming climate. While we cannot prevent them from happening, we must work hard to prevent the extreme events from becoming human disasters. Let's consider a piece of rock with a certain failure load (a load that if applied leads to failure/fracture). The science of fracture mechanics tells us that applying the failure load for a fraction of a second may even strengthen the rock (i.e., increase its resilience against future external loads). In other words, if the external load doesn't break the rock, it will make it stronger [see also Madani, 2019]. This can serve as a good analogy when considering societal response to extremes events (external loads). A society that faces frequent floods often (but not necessarily) reacts and adapts by updating building codes and regulations to enhance its resilient against future floods. Over time, even a major flood may not lead to a human disaster. However, a moderate flood, if occurred in an unprepared society or unexpected region can easily turn in a human disaster. Understanding our societal critical thresholds (failure loads) are fundamental to prevent climate extremes from becoming human disasters. This leads to another important question: How can the hydrologic science community help communities understand their critical thresholds and enhance their resilience against climate extremes? In hydrologic science community, most studies on climate extremes focus on causes, drivers and understanding (historical and projected) changes to their frequency and intensity. However, critical thresholds of a society largely rely on the existing infrastructure, level of preparedness and coping capacity. The engineering community has a long tradition of designing the critical infrastructure based on observed historical extremes (considering some safety factors to address variability and uncertainties in historical data). However, in many regions, the statistics of extremes (e.g., mean, frequency, variability) have changed and/or are expected to change in the future. Further, changing the way we prepare our societies and design our infrastructure would not be possible without support from policy makers. This calls for the three hydrologic science, infrastructure engineering and policy research communities to focus more on the interactions between climate extremes, the built environment and human societies to reduce the likelihood of a human disaster.

Note: This piece does not provide a comprehensive literature review on this topic. It primary focuses on ideas and directions my group is working on.

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Robert E. Horton Medal

S. Majid Hassanizadeh, Utrecht University

The Robert E. Horton Medal is given annually to one honoree in recognition of outstanding contributions to hydrology. Established in 1974, the Horton Medal is named in honor of Robert E. Horton, who made significant contributions to the study of the hydrologic cycle. Medal recipients typically work in one of the following disciplines: biogeosciences, cryosphere, Earth and planetary surface processes, hydrology, nonlinear geophysics and near surface geophysics.

I am extremely honored to receive the Horton Medal. After a long journey in research and education, it is the most rewarding feeling to know that many have found value in my work. The Horton Medal is given for lifetime achievements, and I am very aware that lifetime achievements are not the result of work of a single person. I know that many individuals, starting with my parents and immediate family and, later on, my colleagues and collaborators, have played a crucial role in my accomplishments. A simple but clear indicator is the fact that almost all my publications have at least one co-author. I am enormously grateful to my family, students, collaborators, and colleagues for their countless contributions over the years, helping me to get here. I proudly share this recognition with them.

One of my students once asked me to show him the path to or the recipe for success. I pointed out that success means different things to different people; it is as individual as we are. However, let's not get philosophical. I guess one can say we have success when the main goals in our lives are achieved and we are happy and proud of the life we are living. Also, I said, there is no single path or recipe. Nevertheless, there are some general factors that can make success possible. Number one is to have a clear goal, preferably early in your life. With the goal of becoming an applied scientist, you must have a strong basis not only in physics, mathematics, chemistry, and such, but also in language, literature, social sciences, and even psychology. So, you should start as early as in high school. Of course, it must be an achievable goal; but, if many of us have achieved the goal of becoming an applied scientist, you can too. In any case, as the saying goes, aim for the far galaxies and if you miss, you'll be among the star

"One of my students once asked me to show him the path to or the recipe for success. I pointed out that success means different things to different people; it is as individual as we are."

Then, you should never ever lose your goal out of sight. The life will be full of ups and downs and you cannot always focus on your goal. Whatever happens, you have to go back to it. I'll give a personal example shortly. Then, you need to give that goal the best there is in you. It should be your passion and your hobby; you can't do it half-heartedly. Just like athletes who work hard to be able to perform at high levels, you need to do work diligently, effectively, consistently, and conscientiously. Another factor is that you must team up with those who share your ideals and goals. As I said above, it is not possible to achieve much single-handedly. This is one of those cases that arithmetic laws fail; one plus one is more than two. Finally, you always need a bit of luck. Coincidences play an important role in our lives. Look for favorable coincidences. When opportunities come along, grab them. Of course, you need to be ready; all factors I mentioned above contribute to that readiness. Remember that some problems you face may actually be opportunities begging for solutions. Thomas Jefferson has said: "I'm a great believer in luck, and I find the harder I work the more I have of it."

I have been fortunate to have benefitted from many favorable factors that helped me enormously in my life. I was born in Tuiserkan, a small town at the foothills of Alvand Mountains in Western Iran. In the orchards and countryside surrounding the town, there were many natural springs. I was always fascinated by them as the water seemed to appear from nowhere. At times, they would disappear, only to appear later again. There were also qanats; manmade underground waterways that bring groundwater to the land surface by gravity (cf. Ardakanian, 2005). They were such a mystery to me. Reading through Persian literature, one notices the precious role that water has played in the Iranian history and civilization. In Iranian mythology, water was considered holy and it was prohibited to pollute it. One of the twelve months of the year was called Aban (which is plural of Ab, meaning water) and the tenth day of each month was also named Aban, when water was celebrated. The Persian words for a settlement and (urban) development are Abadi and Abadani, respectively, referring to the fact that a flourishing civilization without water is not possible.

So, early on, I decided that I want to know more about hidden water, its engineering, and its science. When I was admitted to Pahlavi University (Shiraz, Iran), I chose civil engineering as my subject and water for my specialized courses. Later, at Princeton University, I chose subsurface flow as my focus.

My Ph.D. research was on developing generalized laws of fluid flow in porous media under the guidance of William Gray. At that time, the common approach was: apply volume averaging method to mass balance and Navier-Stokes equations, and then make "appropriate" assumptions to approximate certain terms, in order to arrive at Darcy's law. I didn't find it satisfactory, as we knew what the result should look like; it wasn't really the derivation of unknown. I thought a fundamental derivation of governing equations shou1d follow a systematic approach and yield results that we don't necessarily have yet. I came to know Çemal Eringen, professor of continuum mechanics at Princeton, who was a pioneer in rational thermodynamics. In particular, I learned continuum theories of mixtures from him. I realized that those concepts can be employed for the description of a porous medium, which can be considered as a sort of mixture too. I was able to develop a unified approach based on combining volume averaging and rational thermodynamics for deriving equations governing fluids flow and solute transport in porous media[1,2,3,4,6]

To explain the difference with traditional averaging approaches, let's consider the flow equation. As mentioned above, the common approach was to average Navier-Stokes equation, which is a combination of the law of momentum conservation and Newton's law of viscosity. The latter is actually not a law but a constitutive equation. Conservation laws are valid for any material type under all conditions, whereas constitutive equations are only approximate formulas for the description of behaviour of certain materials for a limited range of conditions. For example, Newton's law of viscosity prescribes (or assumes) a linear relationship between viscous stress tensor and the velocity gradient; it can be violated for some materials and/or when there are large velocity gradients. In the Averaging-Thermodynamic approach, we average only conservation laws, which are known at the microscale (cf. Hassanizadeh and Gray, 1979a, b). Then, following the methods of rational thermodynamic, we develop constitutive equations at the macroscale, which is the scale we perform observations of porous materials, and is the scale of interest for applications (cf. Hassanizadeh and Gray, 1980). This has several advantages, that I will highlight below.

The Averaging-Thermodynamic approach produced a number of equations that we didn't know them beforehand. In particular, we obtained a truly generalized Darcy's law for two-phase flow and a related non-equilibrium capillarity theory (cf. Hassanizadeh and Gray, 1990). Although similar to Darcy's law, our derived flow equation was fundamentally different. For multiphase flow, it can be written as (Hassanizadeh and Gray, 1993b):

$$\mathbf{q}^{\alpha} = -\rho^{\alpha} K^{\alpha} \cdot \left(\nabla G^{\alpha} - \mathbf{g}\right) \tag{1}$$

where α refers to the fluid phase of interest, q^{α} is specific flowrate of fluid phase, ρ^{α} is mass density, G^{α} is α-phase Gibbs free energy density, g is gravity vector, and K^{α} denotes a material property related to the ease of flow of phase through the porous medium. The central question in using this equation was what does G^{α} depend on. In other words, what are the state variables that if we know them, we know everything about the system. The clue came from the volume averaging. When one averages microscopic conservation laws, macroscale state variables present themselves. In the case of flow of a single fluid phase through a (fully saturated) porous medium, the only state variables for energy density function G^{α} are found to be temperature and fluid mass density, which are related to the pressure p^{α} via equation of state. Then, one can show that $\rho^{\alpha}\nabla G^{\alpha} = \nabla p^{\alpha}$, which upon substitution in Equation (1) gives us Darcy's law for single-phase flow through a saturated porous medium. However, when there are two fluids simultaneously present in the porous medium, in addition to temperature and mass density, two new state variables emerge: saturation and specific interfacial areas (area of interfaces between phases per unit volume of the porous medium). Due to the dependence of on these state variables, an expansion of equation (1) yields the following generalized Darcy's law (Hassanizadeh and Gray, 1990):

$$\mathbf{q}^{\alpha} = -K^{\alpha} \cdot \left(\nabla P_{\alpha} - \rho_{\alpha}\mathbf{g} - \lambda_{s}^{\alpha}\nabla S^{\alpha} - \lambda_{a}^{\alpha}\nabla a^{wn}\right) \tag{2}$$

where S^{α} is saturation, a^{wn} is specific interfacial area of fluid-fluid interfaces, λ_{s}^{α} and λ_{a}^{α} are new material coefficients. The introduction of specific interfacial area has been a major feature of the new theory of two-phase flow in porous media. It is a drastic departure from the traditional approach where phase saturation and pressures are the only state variables. Given the fact that phenomena such as capillarity and kinetic mass transfer or heat transfer occur across interfaces, we need a macroscale (lumped) variable for a macroscale characterization of interface configurations. Specific interfacial area is exactly such a variable. Also, there is now overwhelming evidence that at any given saturation, fluids within pores can be distributed in many different ways. This means that a given saturation may occur at many different capillary pressure values depending on how that saturation was reached. No wonder that we have always observed hysteresis in capillary pressure-saturation relationship. There are many reasons given in the literature for the occurrence of hysteresis in capillary pressure-saturation relationships (see e.g., Bear, 2013; Morrow and Harris, 1965; Morrow, 1970). Almost all those reasons tell us that, at a given saturation, different fluid distributions may exist during drainage and imbibition, and interfaces have different curvatures under different conditions. All of this suggest that there must be another state variable in the capillary pressure-saturation relationship, which quantifies the differences in phase distributions and curvature of interfaces under various conditions. Indeed, the Averaging-Thermodynamic approach predicts a relationship between capillary pressure, saturation, and the specific interfacial area:

$$f(P^{c}, S^{w}, a^{wn}) = 0 \tag{3}$$

This equation suggests that instead of a large number of capillary pressure-saturation *curves* of the hysteresis loop, one should have a single capillary

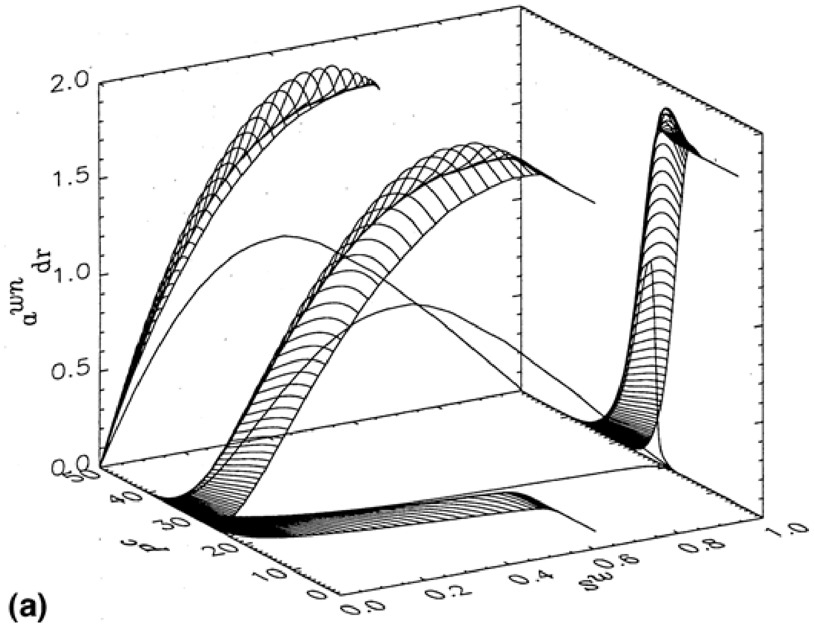

Figure 1. A capillary pressure-saturation-interfacial area surface obtained from pore-network modelling results (Held and Celia, 2001).

pressure-saturation-interfacial area *surface*. The fact that such a surface exists was shown for the first time by Held and Celia (2001), who produced **Figure 1**, based on quasi-static pore-network modelling results. As this graph shows, the projection of this surface on the $P^c - S^w$ plane produces the familiar capillary pressure-saturation hysteresis loop. The scanning curves are actually trajectories of paths on the $P^c - S^w - a^{wn}$ surface. Similar graphs were produced by Joekar-Niasar et al. (2008) and Porter et al. (2009), using pore-scale computational models. The first experimental evidence for the existence of a $P^c - S^w - a^{wn}$ surface was provided by Cheng et al. (2004) and later by Chen et al. (2007) and Pyrak-Nolte et al. (2008), based on results from two-phase flow experiments in a micro-model. A combination of pore-network modeling and micro-model experimental studies was performed by Joekar-Niasar et al. (2009) and Karadimitriou et al. (2013), again showing the existence of $P^c - S^w - a^{wn}$ surface.

The specific interfacial area is also of great significance in the modelling of kinetic heat and mass transfer processes among phases. Currently, the rate of mass transfer among two immiscible fluids is written as a function of the fluid saturation. However, as the mass or heat transfer among two phases occurs at their interfaces, the rate of transfer must be related to the amount of interfacial area. This was clearly shown by Cho et. (2005), who studied mass transfer between water and NAPL in sandy columns. They estimated bulk mass transfer coefficients, and measured the specific interfacial area using interfacial tracer. They found that bulk mass transfer coefficients were correlated with NAPL–water specific interfacial area rather than NAPL saturation, particularly at large values of NAPL–water interfacial area. The significance of including specific interfacial area in models of heat and mass transfer in two-phase flow were illustrated numerically by Niessner and Hassanizadeh (2009a,b) and through experiments in micromodels by Karadimitriou et al. (2013) and Nuske et al. (2014). Recently, Nikooee et al. (2013a,b) have shown that, in the description of deformation of unsaturated porous media, specific interfacial area should be also included as an independent variable in order to be able to model the observed hysteresis in the effective stress parameter.

The capillary pressure mentioned in the foregoing discussion is a macroscale variable, but it has its roots in the pore-scale processes driven by the relative affinity of two fluids in wetting the surface of a porous solid. In traditional two-phase flow models, macroscale capillary pressure is defined to be equal to the difference in macroscale pressures of two fluid phases, without any link to its roots. In the Averaging-Thermodynamic approach, the capillary pressure appears as a macroscale property that is related to the decrease in free energy of the porous medium as a result of increase in saturation of the phase with a higher affinity to wet the porous solid surfaces (see Hassanizadeh and Gray, 1993a). We also found that capillary pressure is indeed equal to the difference in macroscale pressures of two fluids phases, but only under no-flow (equilibrium) conditions. Under flow conditions, the difference in fluid pressures is not just equal to capillary pressure but includes a non-equilibrium term, given by the following equation (which is a linear approximation):

$$P_n - P_w = P_c\left(S^w, a^{wn}\right) - \tau \frac{\partial S^w}{\partial t} \qquad (4)$$

where τ [ML-1T-1] is a damping coefficient; it is a material property that may still be a function of S^w and a^{wn}. This equation is known as the dynamic capillarity formula. Obviously, the second term on the right-hand side of (4) will vanish under equilibrium conditions but it may be very significant under non-equilibrium conditions. In fact, this must be expected because capillary pressure-saturation curves are almost always measured under equilibrium (i.e., no flow) conditions. Often, the time scale of measurement of capillary pressure curves does not match the time scale of flow processes. The measurement of drainage capillary pressure-saturation curve for a typical soil may take up to a week. The curve is subsequently used to simulate (very) dynamic processes! For example, when there is a rainfall-induced landslide, there are fast changes in saturation and pore pressure, and the use of equilibrium capillary pressure curves is not justified.

I must admit that, when deriving equations of two-phase flow using Averaging-Thermodynamic approach back in 1990, we expected to find the difference in fluid pressures to be equal to the capillary pressure, as prescribed by traditional models. So, when we arrived in Equation (4), we thought we had made a mistake and tried to find “appropriate” assumptions in order to lose the extra term. This, however, was not admitted by the procedure we were following. It was only later that we found that researchers who had measured the difference between fluid pressures under flow conditions, had obtained very different curves. In fact, this phenomenon was already known in soil physics literature for many years (see Hassanizadeh et al., 2002 for an overview). In our recent studies, we have regularly obtained dynamic curves that were distinctly different from static curves; see Figure 2 for an example. The behavior shown in this figure for curve relative to the equilibrium curve is very well described by Equation (4). This equation makes it possible to model phenomena that cannot be explained by standard capillarity theory. For example, it is known that the gravity infiltration of water in homogeneous dry soil does not occur as a uniformly distributed front but fingers will develop. Moreover, the saturation distribution within the fingers is nonmonotonic. This phenomenon cannot be modeled by Richards equation, which will always give a stable and monotonic saturation distribution. Using Equation (4) together with standard Darcy’s law, however, will result in unstable capillary fingers and non-monotonic saturation distributions (cf. Nieber et al., 2003; van Duijn et al., 2007; Zhuang et al., 2019). This was another good example of how the Averaging-Thermodynamic approach resulted in deriving an equation we didn’t know a priori that we should have.

During the last year of my PhD studies at Princeton, a revolution that had started in Iran against the rule of Shah intensified and led to the establishment of

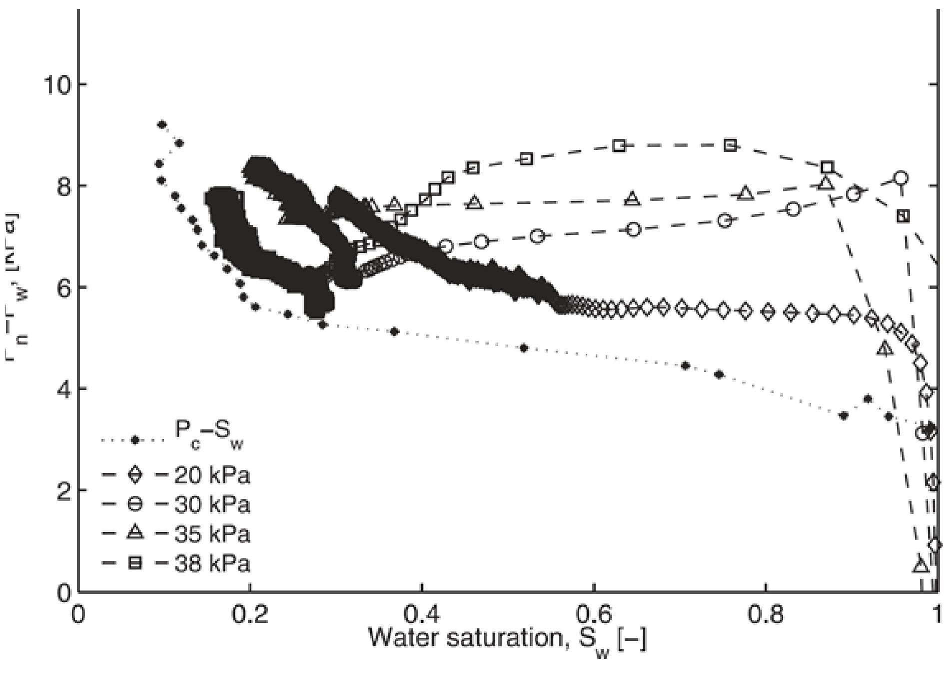

Figure 2. Measurement of the difference in two fluid pressures versus saturation under dynamic conditions at injection pressures of 20 kPa, 30 kPa, 35 kPa, and 38 kPa. The lowest curve is the equilibrium P c– Sw curve (Bottero et al., 2011).

Islamic Republic of Iran. I was not religious at all but, like the majority of Iranians, I believed that the new government will bring democracy, independence, and social justice to the country. So, the day after I defended my PhD thesis on 5 October 1979, my wife and I flew back to Iran as we were keen to participate in reconstructing a fair and free society; we didn't want to be a day late!! I started as an assistant professor in Abadan Institute of Technology close to the border with Iraq. Unfortunately, soon it became evident that it was all an ugly mirage. A few months after my return, the government closed all universities in the name of a cultural revolution; the universities remained closed for almost three years! All my dreams seemed to be turning into a nightmare. The start of war with Iraq in September 1980 made things much worse. Performing any real scientific research was out of question. University libraries stopped functioning and subscriptions to journals were discontinued. Three papers, based on my PhD work, had been published, but I didn't see them until a few years later, when I went to the Netherlands in October 1984.

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For a period of five years that I was in Iran, I tried to make myself useful in various ways. At some point, I joined a consulting company and worked on projects related to the design of irrigation and drainage systems, small dams, and other hydraulic structures. During that whole period, I never gave up my goal of becoming a groundwater scientist. I kept looking for opportunities. I managed to arrange for attending a post-graduate course at the Institute of Hydraulic and Environmental Engineering, IHE, Delft, The Netherlands. Once there, I contacted a research group at the National Institute of Public Health and Environment of the Netherlands and told them I was willing to work on hydrogeological research projects for free. This led to a position as a project researcher and finally a permanent position with the Institute. I renewed my research activities and published two papers on the derivation of Fick's law of dispersion for transport in porous media (Hassanizadeh, 1986a,b), six years after the publication of my previous papers. So, my real research career started in 1985.

Since then, the field of porous media research has changed enormously, in terms of improved theories, robust and powerful computational tools (for both pore-scale and macroscale computations), and imaging of porous media processes. There was a time that a porous medium was a black box. One could not observe dynamic processes occurring inside the pores. Nowadays, advanced imaging instruments are making it possible for us to look into the porous media, see the distribution of phases and movement of interfaces, and even measure microscale pressures within the pores (the latter for now only in micromodels; see recent work of Zarikos et al., 2018). This has opened up wonderful opportunities for increasing our understanding, and thus improving our models, of various flow and transport phenomena. Also, porous media models and research methodologies, which were developed and employed in the study of geological media, are now being used increasingly in investigating industrial and biological porous media. Often, researchers that were solely active in the areas of groundwater studies or reservoir engineering, are now studying porous media such as paper, hygienic tissues, fuel cells, wood, food, and textiles. Thus, it is important to train our students to be multi-facetted. I suggest that we should re-name various study programs from hydrogeology or reservoir engineering to porous media science and engineering. This will prepare future scientists much better to address complex porous media processes we are trying to understand and model. Such developments will lead to a faster improvement of our porous media models and their predictive ability.

I am very happy that I have succeeded in reaching one of the earliest goals in my life: finding out about how the springs in hillsides come to existence and how qanats work. Along the way, I have also enjoyed learning about groundwater pollution and remediation, flow of oil and gas in the subsurface, movement of viruses and colloids in soil and groundwater, penetration of liquids into paper, distribution of fluids in a fuel cell, and spread of a well-known liquid in layers of a diaper. I have been truly fortunate to have had so much pleasure in my life, specially that I could share it with talented students and knowledgeable collaborators. As the last word, I would like to dedicate my Robert E. Horton Medal to all hydroscientists inside Iran who work hard under very trying conditions at home, and encounter many difficulties in interacting with the outside scientific community.

"I would like to dedicate my Robert E. Horton Medal to all Iranian hydroscientists who work hard under very trying conditions at home, and encounter many difficulties in interacting with the outside scientific community."

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2019 Horton Research Grant Awardees

In 1982, the Hydrology Section of AGU was granted access to a portion of the income of the Robert E. Horton Fund for Hydrologic Research. This permitted the initiation of the Horton Research Grant for Ph.D. students, with a purpose to promote excellence through encouragement of the next generation of professionals in the hydrological sciences.

David Litwin, Johns Hopkins University

I'm excited and honored to have been selected for a Horton Research Grant this year in support of my doctoral research at Johns Hopkins University. I became fascinated with hydrology while I was an undergraduate student at the University of Illinois at Urbana-Champaign. Incidentally, it was not through coursework that I first discovered hydrology, but through attending colloquia. Here, I learned about research being conducted on the world's large river deltas, nutrient and sediment transport in the upper Mississippi river basin, and many more topics. I was captivated by the application of math and physics to understand and solve environmental problems, and I continued to pursue this kind of thinking as I worked toward my degree in civil engineering. I have many mentors to thank at Illinois, University of Arizona, Johns Hopkins, and University of Colorado for inspiring me to continue to study hydrology and the many other environmental processes intimately linked to hydrology.

Motivation and Research:

One of the key challenges in hydrology that is of interest to me is the prediction of runoff pathways through watersheds. These pathways are important controls on the quantity, quality, and timing of water exiting catchments and the sensitivities of these characteristics to changing climate and land use[1–3]. Runoff pathways vary in space and time but appear to be systematically related to climate and landscape properties such as topography, regolith thickness, permeability, and vegetation structure[4]. Still, generalization of these relationships remains elusive[5].

In the face of the extraordinary complexity and heterogeneity of landscape characteristics, one of the greatest sources of information we have available for improving hydrological prediction and process understanding is the history of the landscape itself. Runoff generation and catchment water storage play essential roles in determining landscape properties through time, as they translate the effects of climate, lithology, and tectonics into processes such as surface erosion, subsurface weathering, and vegetation growth[6]. The coevolution of surface runoff and landforms appears to have been of great interest to Robert Horton himself, as seen in his extensive article, "Erosional development of streams and their drainage basins," which was published shortly before his death in 1945[7].

The goal of my research is to leverage the coevolution of catchment properties and runoff generation to develop quantitative relationships between dominant runoff pathways and readily observable catchment properties including climate, topography, vegetation. These relationships may be especially valuable in improving representation of hillslope hydrological processes in large-scale models that are used to understand diverse and societally relevant environmental problems[8].

The primary tool that will be used to achieve this goal is a landscape evolution model that couples surface erosion, soil production, and vegetation growth with a sophisticated but parsimonious hydrological model. The funding from the Horton Research Grant is essential to support the development of this model in collaboration with geomorphologists Dr. Greg Tucker and Dr. Katy Barnhart at the University of Colorado Boulder. I would like to thank AGU and the hydrology section for this great opportunity to advance my research and broaden my connections in the geoscience community.

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Lorenzo Rosa, University of California, Berkeley

A global hydrological model to assess water limits to food and energy systems.

Water is increasingly recognized as an important factor constraining humankind's ability to meet its burgeoning food and energy needs[1-3]. Water plays an important role in the production of energy[4-6] and is a major factor limiting crop production in many regions around the world[7]. Irrigation can greatly enhance crop yields, but the local availability and timing of freshwater resources hinders the ability of humanity to intensify food production. At the same time, the twin costs of mitigating climate change and competing for water resources are vexing factors in managing climate mitigation technologies. For example, carbon capture and storage (CCS) is broadly recognized as a technology that could play a key role in limiting the net anthropogenic CO_2 emissions[8]. However, CCS technologies are energy-intensive processes that would require additional power generation and therefore additional water consumption for the cooling process[9]. The nexus between food, energy, and water is made even more complex by the globalization of agriculture and rapid growth in food trade, which results in a massive virtual transfer of water among regions and plays an important role in the food and water security of some areas[10,11].

Recent studies have shown that some of the world's major agricultural baskets consistently exhibit unsustainable water consumption that is depleting groundwater stocks and environmental flows (Figure). Unsustainable water consumption raises significant threats to local and global water, energy, and food security. Given current societal trends in water use, in many regions of the world we will not achieve the Sustainable Development Goal Target 6.4, which consists in ensuring by 2030 a sustainable use of water resources in order to reduce the number of people suffering water scarcity.

Global hydrological models are powerful tools that can be used to simulate and quantify hydrological limits to food and energy systems. I developed a global hydrological model that through data-intensive calculations estimates at an unprecedented spatial and temporal resolution water availability and water consumption from energy and food systems. With the AGU Horton Hydrology Research Grant, I intend to further develop this model to assess water requirements and hydrological limits to CCS technol-

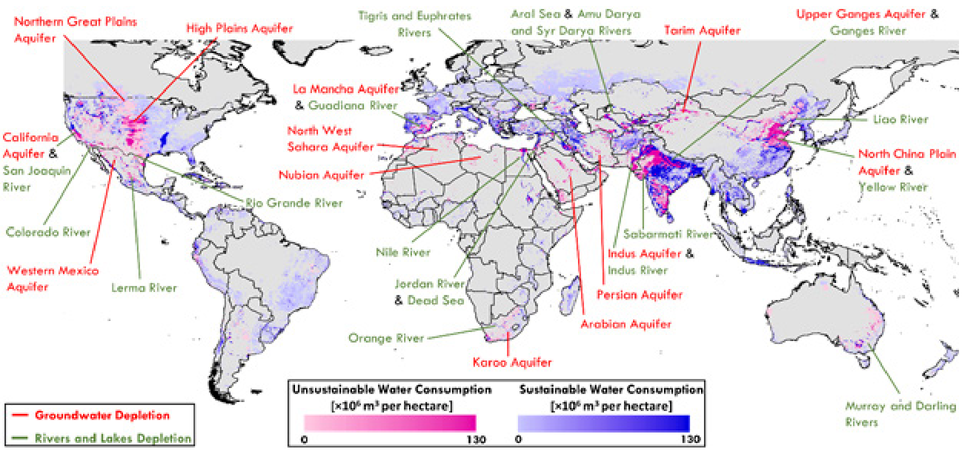

Figure. Global hotspots of unsustainable water consumption for irrigation. The map shows sustainable and unsustainable irrigation water consumption volumes and lists some of the freshwater stocks (aquifers, rivers, lakes) that are being depleted to grow crops. Source: Rosa et al., 2019 (ref. 12).

ogies. Despite the mounting concerns about global water scarcity and its impact on energy production, the potential hydrological consequences of large-scale CCS have not yet been explored. Using my hydrological model I will simulate the potential impacts on water resources that would result from retrofitting global coal-fired power plants with four different CCS technologies. I will present preliminary results of these research project at the AGU Fall Meeting. My research concentrates on the assessment of the impacts of energy and agricultural systems on the local water balance using a hydrologic approach. This framework also helps to identify areas in which water demand from food systems could not be sustainably met because of water scarcity. Indeed, neglecting water availability as one of the possible factors constraining the development of economic activities may lead to unaccounted business, social, and environmental risks. By adopting a hydrologic perspective that considers water availability and demand together, decision makers, investors, and local communities can better understand the water, energy, and food security implications of energy and agricultural production while avoiding unintended environmental consequences. My dissertation will provide a quantitative framework to make informed decisions involving food and energy systems that are susceptible to the risk of water scarcity.

Being a recipient of the AGU Horton Hydrology research Grant is giving me the time, resources, and intellectual freedom I need to research and publish in a field – sustainable food and energy systems – I am deeply passionate about. It is my hope that all this work can contribute to improving the water sustainability of the global food and energy systems, while preserving our Planet's freshwater resources.

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Magali Furlan Nehemy, University of Saskatchewan

I am truly honored and delighted to have been selected as a recipient of the 2019 Horton Research Grant. I would like to sincerely thank my mentors, collaborators and lab mates who have supported this research (during field seasons in both warm summers and cold winters). They have fostered great discussions that have helped me develop new research ideas.

Where does water go when it rains? This beguilingly simple question has been the focus of many studies in hydrology for the past 50 years. We know that precipitation recharges soil water storages and is ultimately drained by streamflow or plant transpiration. We know too that plant transpiration dominates the terrestrial water flux[1]. However, the mechanisms that drives source apportionment and age distributions of transpiration are poorly understood. This hampers our ability to estimate groundwater recharge[2] and the connectivity between surface and subsurface waters[1,3,4]. At the catchment scale, these mechanisms are vital for a more holistic understanding of the water balance and how the ages of water taken up by roots affect the residence times of subsurface waters. Stable isotopes of hydrogen and oxygen (δ^2H and $\delta^{18}O$) have been used to quantify where in the subsurface plants withdraw water[5,6]. Field-based isotopic investigations have shown that plants often use resident water bound to the soil matrix and isotopically distinct from recent precipitation that recharges groundwater and forms streamflow[5]. Thus, transpiration flux appears to be functionally segregated from the more mobile water. This ecohydrological separation[5] challenges the widely held well-mixed soil water assumptions embed in many hydrological models. Despite large evidence of ecohydrological separation from field investigations[6] and satellite-based global vapor measurements[4], there are still many open research questions[7], especially related to how tree water status and phenology affect plant water uptake and source apportionment.

The overarching question for my PhD is: How do trees and streams drain water from the subsurface? My null hypothesis is that plants and streams drain water from the same mixed pool in the subsurface. Three strategic and inter-related sub-questions guide my work: i) How does antecedent soil water condition, plant water status, and precipitation amount interact to determine the uptake depth distribution of available water sources? ii) What is the influence of plant phenological processes on observed source water? iii) Is ecohydrological separation a by-product of hitherto, unknown fractionation processes in the soil and plant? To address these pressing and important hydrological community questions[7]. I am using experimental designs that leverage different research facilities in Switzerland (Figure 1), Canada, and the USA. I am integrating high resolution stable isotope tracers, plant water status monitoring under controlled conditions as well as natural sites, phenological observations, and plant hydraulic models to systematically investigate mechanisms that drive tree water source apportionment. I also seek to improve methodological assessment of tree water source[8]. The Horton Research Grant will allow me to conduct research that demonstrates the value of interdisciplinary approaches in hydrology by incorporating plant physiology into ecohydrological observations to produce novel and rigorous insights regarding the source of transpiration at multiple spatial and temporal scales. We expect that using more integrative research approaches will enable us to better understand what drives source water apportionment and governs patterns of tree water use, a critical step towards improving forest management and predicting impact on water resources at the catchment scale.

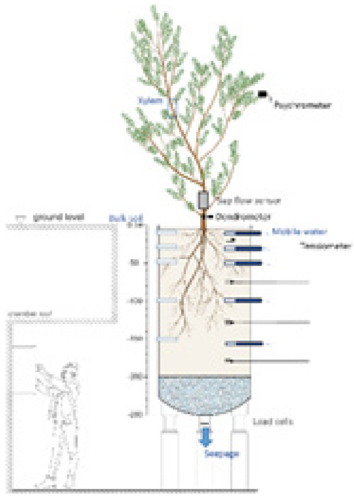

Figure 1: Experimental setup at EPFL, Switzerland. Source: Nehemy et al,[9].

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Obituary: Henry Lin (1965-2019)

Dr. Hangsheng "Henry" Lin, a highly respected soil scientist at Penn State who was widely regarded as the founding father of hydropedology and an active participant in AGU Hydrology Section activities, died Sept. 26, at the age of 54 in his State College home after a battle with lung cancer. Henry was internationally recognized for his visionary leadership and significant efforts in spearheading the development of hydropedology as an intertwined branch of soil science and hydrology that has now gained global recognition. He had also been at the forefront of multidisciplinary and international efforts in the holistic understanding of the Earth's Critical Zone. Furthermore, Henry had been very creative in promoting a new way of thinking about soils through the lens of complexity science and systems theory. He had also been an effective ambassador of our profession through his publications in Science, Nature, and other outlets (such as environmental poems). Henry had worked diligently and productively in the past more than two decades in "Addressing Fundamentals" and "Building Bridges" - the former focused on the critical importance of fundamental processes of water flow and solute transport in structured soils and heterogeneous landscapes, while the latter recognized the need for interdisciplinary and integrated approaches to understand the workings of complex landscape-soil-water-ecosystem relationships. Henry had made significant contributions in innovative quantification of soil structure and preferential flow across scales, an area that is critical to sustainable soil and water management.

Henry was clearly one of the most dynamic and elite leaders who had made noticeable contributions to Chinese soil science, hydrology, agriculture, and the environment. During his career, Henry received the Outstanding Research Award by the Soil Science Society of America. He was also elected as the fellow of the Agronomy Society of America and of the Soil Science Society of America. He had mentored over 40 graduate students and postdocs and published over 260 scientific articles. The exciting ideas of hydropedology will be carried on.

Gary Petersen, Penn State Distinguished Professor Emeritus

Obituary: Nicholas Constantinos Matalas (1930–2019)

Nicholas C. Matalas - a pioneer in the fields of stochastic hydrology, flood frequency methods, and the use of multivariate statistical methods in hydrology - passed away on 16 August 2019, at age 88, from complications of Parkinsons disease. Nick, as he was known to his colleagues, had a distinguished career at the U.S. Geological Survey (USGS) for over 42 years. In 1961–1962, on assignment for the USGS, Nick served as a founding faculty member of the University of Arizona's hydrology program (and gave the inaugural Chester Kisiel Memorial Lecture at the University of Arizona in 1982.).Following his retirement in 1995, he continued scholarship as a both a hydrological consultant and pursuing 'hydrology as a hobby' at his home in Vienna, Virginia.

Nick received his Ph.D in 1958 from Harvard University. Nick and his Harvard contemporary and close friend Myron B. Fiering, along with their academic advisor, the legendary hydrologist Harold Thomas, as well as V. M. Yevjevich of Colorado State University, are credited with creating the field of stochastic hydrology. While at the USGS, Nick developed a framework for multivariate stochastic hydrologic models used today, as well as the mathematical foundation for extending short hydrologic records using nearby longer records. He identified how spatial cross-correlations and autocorrelation affected the information content of hydrologic and other natural resource records. He is known for many seminal publications which are now required reading for hydrologic studies, including "Just a Moment" and "The

Information Content of the Mean". His 1967 paper "Mathematical assessment of synthetic hydrology" was honored with a retrospective AGU Robert E. Horton Award (now known as the Hydrologic Sciences Award) in 1968. With colleagues J. M. Landwehr and J. R. Wallis, Nick developed the probability weighted moments parameter estimation method, which is widely used in hydrology and other fields, and underlies the method of L-moments.

Nick also served as president of the Hydrology section of AGU. He was elected Fellow of AGU and presented the third Walter Langbein Lecture in 1995. The U.S. Department of the Interior (DOI) awarded Nick both the Meritorious Service Award and the Distinguished Service Award.

With his warm, open demeanor and twinkly sense of humor, he was an insightful resource to professional colleagues and an approachable mentor to students and anyone else who arrived at his office door to discuss a serious scientific inquiry. He was a wonderful role model, a pioneer, and a generous colleague.

R. M. Vogel (richard.vogel@tufts.edu), Department of Civil and Environmental Engineering, Tufts University,
J. R. Stedinger, School of Civil and Environmental Engineering, Cornell University, Ithaca, N.Y.;
and J. M. Landwehr, Washington, D.C.

Photo: Nicholas Constantinos Matalas (1930–2019) Credit: Stella Matalas

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* contact Antonio Meira to request your account to be added: antoniomeira@gmail.com