References

Anderssen, R.S. and Stuart. W.D. (2007) The challenge for the piano maker. *Math. Scientist*, 32: 71-82.

Asher, M., Croke, B.F.W., Jakeman, A.J. and Peeters, L. (2015) A review of surrogate models and their application to groundwater modeling. *Water Resources Research*, 51(8): 5957-5973.

Beven, K. (2006) A manifesto for the equifinality thesis. J Hydrology, 320: 18-36.

Constantine, P.G. (2015) *Active Subspaces: emerging ideas for dimension reduction* in parameter studies. SIAM.

Hamilton, S., El Sawah, S., Guillaume, J.H.A. and Jakeman, A.J. (2015) Integrated assessment and modelling: a review and synthesis of salient dimensions. *Environmental Modelling and Software*, 64: 215-229.

Jakeman, A.J. and Hornberger, G.M. (1993) How much complexity is warranted in a rainfall-runoff model? *Water Resources Research, 29*(8): 2637-2649.

Jakeman, A.J. and Letcher, R.A. (2003) Integrated Assessment and Modelling: Features, Principles and Examples for Catchment Management. *Environmental Modelling and Software*, 18: 491-501.

Shin, M-J., Guillaume, J.H.A., Croke, B.F.W. and Jakeman, A.J. (2015) A review of foundational methods for checking the structural identifiability of models: results for rainfall-runoff. *J Hydrology*, 510: 1-16.

Rasmussen, C.E. and Williams, C.K.I (2006) *Gaussian Processes and Machine Learning*. MIT Press.

Spear, R.C. and Hornberger, G.M., 1980. Eutrophication in Peel Inlet: II, Identification of critical uncertainties via generalized sensitivity analysis, *Water Resources Research*, **14**, 43-49.

Sudret, P. (2008) Global sensitivity analysis using polynomial chaos expansions. *Reliab. Eng. Syst. Safety*, 93: 964-979.

Young, P.C., Jakeman, A.J. and McMurtrie, R.E. (1980) An instrumental variable method for model order identification. *Automatica*, 16: 281-294

A Fellow Speaks: Go deep, young hydrologist, go deep

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"Not since Moses was discovered among the bulrushes of the Nile has there been such a propitious moment for hydrology as the present: a rare conjunction of interest in both the science of water and the management of water." So began M. Gordon (Reds) Wolman's acceptance speech for the Robert Horton medal in the year 2000. Since then Reds' point has only been sharpened by ever more frequent and intense floods and droughts, mounting evidence of global human impacts on the climatic and hydrologic cycles, and an ever-heightened awareness that water, and its abundance, scarcity, quality, and cost, will be defining issues for centuries.

But addressing these issues will not be easy. Both studying and writing about water are difficult, reflecting the nebulous properties of the substance itself. Water is ubiquitous and therefore not easily circumscribed; it runs across geographical, political, and disciplinary boundaries with impunity; it assumes many forms and is therefore simultaneously everywhere and nowhere. It is a shape- and phase-shifter of the first rank, conforms to whatever seeks to contain it and is therefore not easily characterized. It is a precursor and precondition of life, and intimately intertwined in all things biological, yet we often measure and talk about it as if it were an inert, independent substance. But these very properties are the ones that make it so fascinating. As a hydrologist it is all too easy to be distracted by its sparkling reflection or lost in its mesmerizing depths.

This leads me to offer some modest heuristic reflections on navigating the currents of this discipline. There is no lack of exciting research directions that this and future generations of young hydrologists have to look forward to. We are poised to make real progress towards transformative scientific ideas, questions, and perspectives that are not yet within our grasp.

For example, the emergence of "critical zone science" is a potential game-changer. I say this as someone who was originally quite skeptical of the concept; to me it seemed like a rebranding of soil science. Years of close engagement with the program proved me wrong, and now I serve as the chair of the Science Steering Committee for the U.S. NSF-funded Critical Zone Observatory program. The critical zone is the thin, dynamic, and life-sustaining skin of the terrestrial earth, extending from the top of the vegetation canopy to the top of the unweathered bedrock that never sees groundwater. Studying the states, fluxes, feedbacks and evolution of the critical zone in different lithologic, climatic, and land use environments is now an international effort, bringing together hydrologists, geomorphologists, biogeochemists, ecologists, and climatologists to focus on critical and scientifically rich questions. How deep is the critical zone and how did it get that way? Does the vegetation know what kind of bedrock lies beneath the root zone, and does the bedrock know what's growing on top of it? How will a climatically changed atmosphere and a land surface modified by human activities affect the deeper critical zone and vice versa? Can the critical zone be managed to better sustain human health and well-being? In a real sense, the term "critical zone" occupies the same place as an organizing principle for both the earth and biological sciences as "ecosystem" did for ecology half a century ago.

One of the lessons we're learning from critical zone science is that we don't understand trees very well: why they grow where they do, why they experience water stress and die, what strategies they have for obtaining and using water, and how these strategies vary by species, setting, and climate. For example, we're learning that different tree species growing right next to each other use isotopically dissimilar water (Moreno-Gutierrez et al, 2012). Why? We don't know yet, but suspect it relates to species-specific survival strategies. These observations underscore an urgent need to better understand the interactions among roots, vegetation, soil moisture, and groundwater in different climatic settings (e.g., *Fan, 2015*). Understanding these dynamics are critical if we want to predict water stress on vegetation and its consequences at the landscape level, a societally critical question in the face of massive droughts and widespread forest mortality.

The same isotopes used to reveal differences in water use by vegetation point to a deeper set of questions. What controls the chemical evolution of water – in the atmosphere, vegetation, ground, and rivers? What does the chemical "flavor" of water in the river tell us about what's happening on the hillslopes. Even more broadly, how does the chemistry together with measurements of storage and fluxes inform our understanding of hydrologic partitioning? Despite the lovely pictures of the hydrologic cycle that grace every entry-level textbook, our understanding of the specifics and dynamics of these fundamental processes is rudimentary at best. New measurement and sensing techniques and instrumentation, including remote sensing and distributed sensor networks, are going to provide dramatically new perspectives on these key processes in the near future.

What intriguing possibilities might lie just beyond our current abilities? Going way out on an unsupported limb, perhaps we will tag and follow individual "packets" of water as they move through the hydrological cycle over continental scales. Emerging observations and modeling studies show how air passage over dense tropical forests results in greater precipitation downwind and, conversely, how air masses are depleted of moisture when deforestation occurs (e.g., Spracklen et. al., 2012). Imagine if we could calculate water budgets, not just for watersheds, but for large-scale atmospheric rivers and fluxes. Consider the societal and legal implications of an expanded conception of everyone living both down- and upwind from somebody else.

These thoughts are primarily intended for students and early-career scientists who have chosen to make hydrology their disciplinary home. I find myself enviously thinking that never before has there been such a good time to be a student of water in its myriad, captivating forms. Hydrology sits at a fortuitous confluence of insight, interest, and tools, and, above all else, critical questions that must be answered if the global community is to survive and prosper in the years ahead.

References

Moreno-Gutiérrez C, Dawson TE, Nicolás E, Querejeta JI (2012) Isotopes reveal contrasting water use strategies among coexisting plant species in a Mediterranean ecosystem. New Phytol 196:489–496.

Fan, Ying. "Groundwater in the Earth's critical zone: Relevance to large-scale patterns and processes." *Water Resources Research* 51.5 (2015): 3052-3069.

Spracklen, Dominick V., Steve R. Arnold, and C. M. Taylor. "Observations of increased tropical rainfall preceded by air passage over forests." *Nature* 489.7415 (2012): 282-285