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The “long and winding road” from soil physics to catchment hydrology and hydrogeomorphology

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When the Editor-in-Chief of the Journal of the Japanese Society of Soil Physics, Professor Hirotaka Saito, invited me to submit a paper to inspire graduate students and early career soil physicists to explore diverse avenues in their respective careers, I was more than happy to oblige. My ongoing affiliation with Tokyo University of Agriculture and Technology during the past five years has given me many opportunities to further expand my interests and contribute to research in hydrological and sediment connectivity in catchments (e.g., Kharismalatri et al., 2019; Miyata et al., 2019), hydrogeomorphic processes in earthquake affected volcanic soils (e.g., Sidle et al., 2018; Koyanagi et al., 2020; Arata et al., 2023), and, most recently, assessing the benefits of living mulch on soil hydrology (Nishiwaki et al., 2022) and examining hydrogeomorphic factors affecting rice paddy fields. These latter studies with Professor Saito, Dr. Nishiwaki, and Denis Bwire, have forced me to apply my background to completely new areas of inquiry, challenging the old adage “you can’t teach an old dog new tricks”.

Unlike the many graduates that entered the field of hydrology by in past years via their backgrounds in civil engineering, geography, and geology, as noted by the well-respected hydrologist Vit Klemeš (1986), I decided to study hydrology to ‘escape’ from an engineering major during my undergraduate program at University of Arizona. In the late 1960’s, hydrology was a newly developing interdisciplinary major at University of Arizona fostering a unique approach to the science (the Hydrology Department was still being organized). Professor Art Warrick was an important inspiration for me at that time as a struggling engineering student who was looking to make a better connection to the environment. I look back on this as a very positive decision for my career, and I continue to tell students that the world needs both engineers that focus on the optimal answers to problems and scientists who strive to unravel the underlying processes. I was much better at the latter than the former. Soil physics seems to fit somewhere between these two disciplinary arenas with typically more emphasis on quantitative scientific inquiry.

While I would not characterize any stage of my career as being entrenched in soil physics, I experienced a good introduction to this discipline during my undergraduate and Master’s studies at University of Arizona under the influence of Art Warrick and in classes with Dan Evans. Then during my PhD studies at Pennsylvania State University, I took another soil physics class from Dan Fritton and proceeded to apply miscible displacement theory to the transport of nitrate and heavy metals in soils and soil water. This latter research involved a very helpful connection with Rien van Genuchten who was a post-doctoral researcher at Princeton University at that time. Rien collaborated with me on the final paper from my PhD research, which is some of the first work to demonstrate the importance of preferential flow in soils (Sidle et al., 1977). I vividly remember walking back and forth from my office to Penn State’s computer center late at night (when run time was less expensive) with two boxes of punch cards that contained my solute transport model hoping I didn’t trip and drop the boxes.

While I moved away from relatively small-scale soil water and solute transport research over the years, one common denominator that has stayed with me is the importance of preferential flow in soils and weathered substrate. This initiated from the ‘unintended discovery’ of this important phenomenon during my PhD research. As such, although my research has become generally broader with time, I have not forgotten the importance of understanding some of the small-scale pro-

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cesses imbedded in soil physics (e.g., Sidle, 2006). But unfortunately, the fields of soil physics and catchment hydrology still seem to be evolving separately.

It is interesting to me that some of the ‘new discoveries’ in catchment processes are based on decades old ideas that have been repackaged in attractive ways. A prime example of this was a flurry of recent articles published in high level journals elucidating the concept of “two water worlds”. These studies used detailed and expensive tracer investigations to show how plants use soil water held at different matric potentials compared to water that discharges to streams and groundwater (e.g., Brooks et al., 2010; Evaristo et al., 2015; Berry et al., 2018). While these studies have likely produced greater precision in estimates of, for example, transpiration versus evapotranspiration ratios, this in my opinion does not seem like a quantum leap beyond what soil physicists knew for nearly a Century. That is, gravitational water flows rapidly through soils to recharge groundwater and support streamflow, and unsaturated water held in micropores at high tensions does not appreciably contribute to groundwater or streamflow, but instead is available for uptake by plants as long is tensions do not exceed the so-called ‘wilting point’. While I am obviously over-simplifying this comparison and probably doing these studies some level of injustice, it appears to me that that more emphasis on soil physics and less focus on expensive isotope analyses would have better addressed the problem and put this issue to bed.

As my career evolved, I became interested in landslide processes and related sediment transport in catchments. In early field investigations in coastal Alaska where it was almost impossible to do any detailed laboratory or instrumental analyses, I was able to observe the importance of preferential flow in relation to rapid piezometric response in hillslope hollows. We published a few papers on this phenomenon, including likely the first paper showing pore water pressure conditions during the occurrence of a small landslide (Sidle and Swanston, 1982). At that time, I was not aware of some of the studies in Japan, particularly those by Professor Tsukamoto. Just after leaving Alaska, I had the pleasure of meeting Professor Tsukamoto at an IAHS meeting in Corvallis, Oregon, which provided my initial insights into the excellent research being conducted in Japan.

An unexpected opportunity arose in 1991 that literally changed my career and life. I received a nine-month Science & Technology Agency Fellowship from Japan based on an invitation from Professor Makoto Tani (at that time he was at Forestry and Forest Products Research Institute, FFPRI). This initial visit opened my horizons to some of the excellent hydrology research that was being conducted in Japan, much of which was published in Japanese with little recognition in the western world. This and numerous follow-up visits provided the basis for developing the relatively new science of hydrogeomorphology, including numerous publications with Japanese scientists. Working with FFPRI researchers we developed the hydrogeomorphic concept of stormflow generation (Sidle et al., 2000) supported by extensive field studies and long-term monitoring at various spatial scales. Through this research I recognized the benefits of nested catchment studies in elucidating spatial and temporal stormflow runoff response in headwater catchments. Within this context, we also employed soil physics theory to assess experimental tracer test data collected from soil pits (e.g., Tsuboyama et al., 1994). Combining these data and inferences at different spatial and temporal scales shed important light on the dominant processes that contribute to storm runoff during changing antecedent moisture conditions. Importantly, wetness thresholds were identified that dictate conditions that control the release of subsurface runoff to streams from geomorphic hollows (zero-order basins) and those that facilitate the self-organization of preferential flow across larger hillslope domains (Tsuboyama et al., 2000; Sidle et al., 2001). Later work with John Nieber using soil physics theory modelled how discrete macropore segments can connect under conditions of increasing soil wetness (Nieber and Sidle, 2010).

Ultimately, a parsimonious conceptual model was developed based on the hydrogeomorphic paradigm that simulated discharge from hillslopes and zero-order basins using multi-tank models and a kinematic wave model to route runoff from riparian areas and zero-order basins through channels (Sidle et al., 2011). The objective of this model was this demonstrate that better prediction of runoff from various flow paths and catchment elements (zero-order basins with variable soil depth, riparian zones, linear hillslope segments, soil matrix, and preferential flow) can be achieved by a semi-distributed model that effectively captures runoff processes rather than a highly parameterized physics-based model that incorporates only small-scale hydrologic information (e.g., saturated hydraulic conductivity, K_s, values). While this hydrogeomorphic model for headwater catchments did not directly utilize soil physics theory, the subsurface flow analogues were derived from miscible displacement field experiments that elucidated dynamic flow contributions and threshold behavior in macropores and the soil matrix.

This scale conundrum related to parameterization of hydrologic models exposes an important issue concerning how hydrologists misuse soil physics data as well as the need for soil physicists to quantify important parameters (e.g., K_s) at scales useful in catchment hydrology. This ‘wicked’ problem is typically glossed over by simply calibrating catchment discharge by K_s as part of an inverse modelling exercise. While such modelling may be useful to generate simulated discharge that matches measured catchment runoff, such practices embrace equifinality – i.e., getting the right answer for the wrong reasons (Klemeš 1986). As such, my knowledge of distributed catchment processes together with my rather meager soil physics expertise has pushed me to better understand flow pathways and dynamics in catchments and how these can be parsimoniously incorporated into models (e.g., Sidle, 2021). During a presentation of some the earlier work related to how preferential flow self-organizes across hillslopes based on antecedent moisture thresholds and then contributes to runoff generation, a rather well-known hydrologist (unnamed here) accused me of being a 'reductionist'. While that may be somewhat true, I would argue that by ignoring flow paths at multiple scales (including detailed scales), one may conclude erroneous mechanisms and pathways that contribute to runoff. And if the objective of the research is to assess impacts of land use practices on runoff and material transport, then we are setting ourselves up for erroneous inferences. Unfortunately, I do not see much attention focused on this important issue, either in catchment hydrology or soil physics. Thus, this appears to be an important intersection where these disciplines could collaborate better to 'move the needle forward'.

After holding professor positions at University of British Columbia and National University of Singapore where I conducted research on catchment hydrology, erosion processes, and landslides, I joined Kyoto University's Disaster Prevention Research Institute in 2002 as the first foreign professor succeeding Professor Okunishi who advanced early ideas in hydrogeomorphology. This opportunity came with many challenges and rewards and was the most productive period of my career due to an excellent group of post-doctoral researchers and graduate students that worked in my laboratory. This research produced important findings related to modelling preferential flow with implications for slope stability (e.g., Tsutsumi et al., 2005), hydrogeomorphic linkages between landslides/debris flows and sediment transport in catchments (e.g., Imaizumi and Sidle, 2007), and insights into scale effects on runoff connectivity (e.g., Gomi et al., 2008). The three lead authors on these papers now hold full professor positions at Mie University, Shizuoka University, and Nagoya University, respectively, and are some of the leading voices in their fields in Japan. During the six years I spent at Kyoto University, I also benefited from numerous interactions with Japanese scholars in fields of engineering, soil science, water resources management, geography, and geomorphology, as well as numerous international colleagues, particularly related to continuing catchment hydrology studies in Southeast Asia. Another accomplishment during my time at Kyoto University was writing the American Geophysical Union monograph "Landslides: Processes, Prediction and Land Use" with my colleague and good friend Hirotaka Ochiai (Sidle and Ochiai, 2006). This book examined landslide processes from multiple perspectives, including the important role of soil physical properties and subsurface hydrology. Overall, I found that the freedom I had to explore hydrological processes across various scales and within the context of land use scenarios fostered scientific discovery and was appreciated by most of my Japanese colleagues.

During the past decade or so, my research horizons have expanded to deal with issues such as fate and transport of contaminates in managed catchments while I was Director of the Ecosystems Research Division of US Environmental Protection Agency, sustainability science issues during my time in Australia at University of the Sunshine Coast, and effects of climate trends, water supplies in the cryosphere, and natural hazards on mountain communities in my current role as Director of the Mountain Societies Research Institute at University of Central Asia. The latter has been by far the most challenging experience in my career dealing with not only the rugged and remote terrain in the Pamir, but also working with impoverished mountain communities in Tajikistan along the precarious Afghanistan border. In approaching many of these recently encountered scientific venues, I keep refocusing on hydrological processes and how these shape landforms, deliver water and pollutants to streams and rivers, affect mountain food security, and manifest with changing climates. So, while focus may change, it should be supported by robust process understanding.

Thus, as I reach the twilight of my 'winding road' that has allowed me to work in six continents, I feel grateful that I have been intimately exposed to all three parts of this water-based journey — soil physics, catchment hydrology, and hydrogeomorphology. Early in my career, I learned the value of careful field investigations, an aspect that has stuck with me through today. I sometimes see this important attribute being lost on some younger colleagues and students who focus mostly on modelling without properly understanding how hydrological processes manifest in the field, particularly at different scales. The opportunity I had to work in coastal Alaska as a young hydrologist/soil scientist with US Forest Service Research instilled a deep interest in landslide initiation and other hydrogeomorphic processes, as well as a respect for the importance of field investigations. I am indebted to the many colleagues in Japan who have supported my work over the years and contributed to what I feel are the most important research products of my career. I learned so much from these scientists in places like Kyoto Univrsity, FFPRI, Tokyo University of Agriculture and Technology, Niigata University, and University of Tsukuba. The varied environments I have worked in have shaped my understanding of hydrological and hydrogeomorphic processes. These range from the mountains and landscapes of Appalachia, Pacific

Northwest USA, coastal Alaska, Japan, the Andes, China, India, Denmark, Holland, Australia, New Zealand, Southeast Asia, Italy, France, Saudi Arabia, Central Asia, and Afghanistan. Few people have been afforded such opportunities and I feel very grateful for these experiences, including working on publications with scientists in most of these regions.

In closing, I would urge soil physicists, catchment hydrologists, and hydrogeomorphologists to collaborate more on issues of common interest to improve quantification and insights related to complex hydrological processes that span various scales and media (e.g., overland flow, flow in the vadose zone, contributions to stream and river runoff, interactions at the soil-atmosphere interface), especially related to addressing environmental management issues. Working together, these combined disciplines can help solve some of the 'wicked problems' facing our ever-changing environment. As I noted in an earlier paper, one of my favorite ballads ("The Long and Windy Road" by Paul McCartney) contains a line that embraces these challenges and some frustrations that I have tried to address during my career — "The wild and windy night, that the rain washed away, has left a pool of tears crying for the day".

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