Discussion

Hydropedology: Towards new insights into interactive pedologic and hydrologic processes across scales

Henry Lin

Dept. of Crop and Soil Sciences, Pennsylvania State Univ., University Park, PA, USA

1. Introduction

Healthy academic debate provides beneficial clarifications of possible misunderstandings or misperceptions, so I welcome the invitation to address the concerns and challenges raised by Prof. Philippe Baveye (this issue). I will first make a brief remark on the difference between “compartmentalization of hydrology into sub-disciplines” that Prof. Baveye focused on in his comments vs. “synergies across scientific interfaces” that I would emphasize here. I will then highlight the problems in the classical study of soil hydrology, and explain why hydropedology is needed for a shift in our basic thinking and approach towards pore, pedon, landscape, and watershed scale analysis of interactive pedologic and hydrologic processes. I believe the discussion here is about the art itself, rather than the label of visitors at an art museum as Prof. Baveye suggested.

Prof. Baveye is right in cautioning the naming game in modern academia and in reminding us of the need for a holistic approach to the hydrologic science. His remarks, however, should be balanced by recognizing the tremendous synergies across the interfaces of scientific disciplines and by appreciating the unique contribution that pedology can make to the study of hydrologic processes. One might discern two questionable assumptions underlying Prof. Baveye’s remarks: (1) new names are merely combinations of words to create compartmentized sub-disciplines of hydrology; and (2) the way soil hydrology research has been done in the past is satisfactory. While I will leave it to more qualified colleagues to comment on other subjects raised in Prof. Baveye’s remarks, here I will focus on rebutting his incorrect statements about hydropedology. More extensive discussions on why hydropedology is needed and what hydropedology can contribute have been published by Lin et al. (2005, 2006, 2008), which were not cited in his remarks.

2. The true meaning of pedology

To begin, I would ask the readers to ponder on a simple and yet revealing question: “What is the difference between a cow and the ground beef?” To illustrate the fundamental difference between naturally-formed soils in the landscape vs. ground-sieved soil materials in the laboratory, Kubiena (1938) insightfully pointed out that a crushed sample of soil is as akin to a natural soil profile as a pile of debris is to a building. The ground beef is no longer a living entity and has no structure, while a cow is alive and has intricate internal architecture for its appropriate functioning. Hence, the traditional way of studying soils using ground-sieved soil materials (or even beach sands or glass beads) and isolated soil cores or columns (especially repacked ones) create significant deviations from field soils where distinct pedogenic features (such as structure, macropores, horizons, and coatings) and open boundary conditions (with dynamic changes induced by climate, biota, and human activities) prevail.

It is unfortunate that the term pedology continues to be misunderstood or undervalued by many, including some fellow soil scientists and hydrologists. “Ped” (naturally-formed soil aggregates with various strengths, sizes, and shapes) is a unique term in soil science, and “pedology” captures that uniqueness well. Historically, the term pedology has evolved into two meanings in the earth science community: one is the original – specifically referring to the integrated study of soils as natural or anthropogenically-modified landscape entities, including soil genesis, morphology, classification, survey,
mapping, interpretation, and modeling (Wilding, 2000; Buol et al., 2003; Minasny et al., 2008); while the other is synonymous with the discipline of soil science. Hydropedology emphasizes the original meaning of pedology. It was Dokuchaev (1893) who formulated the theory of soil formation through extensive field investigations across wide geographic regions that gave birth to modern soil science. Up to this date, pedology remains a unique sub-discipline of soil science and earth science, while the other sub-disciplines of soil science have been (for the most part) applied mathematics, physics, chemistry, biology, and others in the study of soils or, more often than not, soil materials.

3. Problems in the classical study of soil hydrology

Some alarming statements from well-established scholars with whom I have interacted serve here to illustrate fundamental problems associated with classical soil hydrology.

During an interdisciplinary meeting of vadose zone hydrology held in 1995 at UC-Davis in honoring Donald Nielsen's career, soil physicist Bill Jury told the audience that “the foundation of our models is shaky.” I wondered: without a solid foundation, how can we build a reliable skyscraper? No matter how fancy a skyscraper (or a computer model) may look like, it will crash sooner or later if it is built on a shaky foundation. As an example, 10 conceptually different hydrologic models all failed to predict catchment discharge in a 6-ha artificial catchment (called Chicken Creek) in Germany, given soil texture and topography data as inputs (Holländer et al., 2009). None of the model simulations came even close to predicting the observed water balance for the 3-year period monitored. A key missing piece in all these models was significant biological soil crusts emerged at the surface in the initial development of the ecosystem. Discharge was mainly predicted by these classical models as subsurface discharge with little direct runoff; in reality, surface runoff was a major flow component despite the fairly coarse soil texture throughout the entire catchment (Gerwin et al., 2011).

At a hydrology meeting held at Iowa State University in 2004 (the purpose of which was to develop a vision paper for the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc.), hydrologist Ken Potter commented that “the advent of computer has actually slowed down the advancement of hydrologic sciences.” In the past decades of computer modeling frenzy, the collection and analysis of field data has been undervalued. Previously, however, many publications were devoted to field data collection, analysis, and interpretation, and such publications have provided some of the most fundamental insights into soils and hydrologic processes. For instance, Darcy’s Law (1856), Buckingham’s Law (1907), Jenny’s theory (1941), and Horton’s Law (1945) were all developed prior to the advent of the computer. Yet decades thereafter, no new theory has been solidly established in soil hydrology.

In a thought-provoking paper, hydrologist Keith Beven (2006) noted that “Nearly all hydrologic, water quality, and sediment transport models use the same small scale laboratory homogeneous domain theory to represent integrated fluxes at the much larger scales of hillslope and catchment… This is the root of many discrepancies between model predictions and the reality.” This view is now widely shared across the hydrology community (e.g., Uhlenbrook, 2006; Kirchner, 2006; McDonnell et al., 2007). Among the challenged assumptions in standard models of flow and transport in the real-world is unknown boundary condition (Beven, 2006).

In an interesting paper of flow configuration generation and evolution in nature, mechanical engineer Bejan (2007) challenged the hydrology community by stating that “Hydrology research is proving every day that science has hit a wall.” The open, interactive discussions associated with this article revealed many controversies and problems in the field (see http://www.hydrol-earth-syst-sci-discuss.net/3/1773/2006/hessd-3-1773-2006-discussion.html).

Finally, during the 11th National Congress of Chinese Soil Science in Beijing in 2008, pedologist Zitong Gong pointed out an interesting paradox in the scientific community: “We now have more and more people studying soils, but we have fewer and fewer people knowing what soil really is.” Many young and energetic researchers who have been trained in various disciplines are tackling complex issues related to soils, but fewer and fewer of them have ever touched a real soil profile in the field. This situation hinders their in-depth understanding and appreciation of the complexity and dynamics involved in soil processes, leading to their simplified and often unrealistic assumptions about real-world soils.

4. Scope and characteristics of hydropedology

Broadly speaking, hydropedology is the study of the interface between the pedosphere and the hydrosphere, with an emphasis on interactive pedologic and hydrologic processes across scales in situ. Considerable synergies can be generated by bridging pedology with soil physics and hydrology, along with other related bio- and geo-sciences, to holistically address the following two basic questions of hydropedology (Lin et al., 2005, 2006, 2008):

(1) How do soil architecture and the distribution of soils over the landscape exert a first-order control on hydrologic processes (and associated biogeochemical and ecological dynamics) across spatio-temporal scales?

(2) How do landscape hydrologic processes (and the associated transport of energy, sediment, chemicals, and biomaterials by flowing water) influence soil genesis, evolution, variability, and functions?

The first question calls for quantitative relationships between soil architecture and functions across scales. Soil architecture here refers to the entirety of how the soil is structured from the microscopic to macroscopic levels, which encompasses (1) solid components (including soil texture, microfabric, aggregation, and horizons), (2) pore space (size distribution, density, connectivity, and morphology of pores and their networks, as well as liquids, gases, and biota within the pore space) and (3) interfaces between the solid component and the pore space (such as coatings on ped surfaces or pore edges, and the interfaces of macropore–matrix, soil–root, microbe–aggregate, horizon–horizon, soil–rock, and others). These interfaces are often active zones of biogeochemical reactions or triggers of preferential flow of water, chemicals, gases, and microorganisms. Numerous water-restricting subsoil horizons and features have been identified in Soil Taxonomy (Soil Survey Staff, 2006), which act as an aquitard or aquiclude to downward moving water, ultimately resulting in seasonal perched water table or water moving laterally within the soil as subsurface throughflow (e.g., Freer et al., 2002; Gbur et al., 2006; McDaniel et al., 2008).

Whereas considerable knowledge on soil structure has been amassed over decades, a comprehensive theory and an effective means of quantifying soil architecture across scales remain elusive. To propel the field out of the stagnation, and to represent soil architecture in a manner that can be coupled into models of flow, scaling, and rate processes, considerable efforts remain needed, not least non-invasive, continuous, and precision quantification of sub-surface structure, especially in situ. Encouragingly, non-invasive investigations (e.g., through computing tomography and geophysical tools) and continuous mapping (e.g., using spectroscopy and remote sensing) are being employed increasingly to reveal soil architectural complexity across scales. However, how to enhance
the resolution of field investigations and how to quantitatively link soil structural parameters to hydrologic (and biogeochemical and ecological) functions remains the challenge.

The second question has been ignored in traditional soil hydrology, but is a new arena for pedological research. It takes pedology out of its traditional sphere by emphasizing the nature, origin, function, and significance of pore space at multiple scales. How water moves through soils – along with associated shrink-swell, freeze-thaw, dissolution-precipitation, oxidation-reduction, and other processes – dictates the dynamic evolution of soil heterogeneity, the formation of soil structural features including pore space, and the feedback mechanisms of soil functions. Hydrology is a key integrating factor of soil formation and evolution, and is a main driving force of soil change; hence hydrology may offer a unifying theme for monitoring, mapping, and modeling soil evolution and functions across scales.

It becomes increasingly apparent that solid Earth is not a continuous fluid; rather, it poses hierarchical heterogeneities with discrete flow networks embedded in the mosaics of the surface and subsurface. For instance, there are a variety of networks in soils, such as crack and fissure networks, root branching networks, animal burrow networks, mycorrhizal mycelial networks, and man-made drainage networks (Lin, 2010b). These belowground networks can lead to threshold-like hydrologic responses as well as hot spots or not moments in biogeochemical dynamics (e.g., Tromp-van Meerveld and McDonnell, 2006; McClain et al., 2003). Enhanced partition of flow currents between more transitional porous portion of the soil and the preferential flow domain could lead to the next generation of hydrologic and biogeochemical models.

5. Bridges that hydropedology builds

Lin (2003) and Lin et al. (2005) discussed the role that hydropedology plays in bridging disciplines, scales, data, and education. Lin (2010a) further described the opportunities in coupling hydropedology with related bio- and geo-sciences towards the holistic study of the Earth’s Critical Zone (e.g., coupling hydropedology with ecohydrology to improve the linkage of belowground and aboveground processes, and coupling hydropedology with biogeochemistry to enhance the identification of hot spots and hot moments in the landscape). In the following, three important bridges that hydropedology is in a unique position to build are highlighted, providing hopefully some compelling justifications for us to come together (rather than to be separated).

5.1. Bridging fast and slow processes

There are three types of soil change – irregular (or random) variability, cyclic fluctuations, and trend changes. Soil formation and evolution refer mostly to trend changes over long time periods, while random and periodical changes are more of concern for soil functions within shorter time periods. However, the short- and long-time scale changes are intertwined, with interactions, feedbacks, thresholds, and accumulative effects (Lin, submitted for publication). With growing interests in sustainability and global changes, both short- and long-term changes of soil systems should be considered simultaneously.

Hydropedology encapsulates the co-evolution of fast (water) and slow (soil) changes in multiphase soil systems, where fast and cyclic soil functioning processes (SFPs) involve mostly liquids, gases, and biota (in which circulating water is a key), while slow and irreversible specific pedogenic processes (SPPs) involve predominantly solids (Targulian and Goryachkin, 2004). Each SPP is characterized by a set of solid-phase pedogenic features formed over hundreds to thousands or more years, while SFPs are dominated by diurnal, seasonal, and annual changes (Targulian, 2005). Many SFPs and related cycles are not completely closed, and many input–output fluxes are not necessarily balanced in the open, dissipative soil system (Rode, 1947; Targulian and Goryachkin, 2004). Such non-closed cycles and off-balanced fluxes of SFPs generate residual solid-phase products in the soil profile over time. Each single cycle may generate a micro amount of transformed or newly-formed solid products, which may hardly be detected; but being produced repeatedly over long time these micro amounts gradually accumulate into macro amounts that are detectable morphologically or analytically (Targulian and Goryachkin, 2004). Such residual products generated in SFPs will feedback to alter SFPs, mostly in a gradual manner, but some could lead to threshold changes in the soil system (Lin, submitted for publication).

5.2. Bridging stochastic variability and deterministic pattern

Pedologists are foremost among basic soil scientists who help develop integrated systems approach to scale up knowledge from small samples to global pedosphere (Sposito and Reginato, 1992). Pedologists have studied both the mechanisms and the magnitudes of spatial variability of soils and landforms as a basis for broad generalizations about soils (especially pedogenesis, classification, and mapping). Whereas soil physicists and hydrologists have studied scaling theories and spatial variability using similarities, fractals, geostatistics, and other means. As noted by Nielsen and Wendroth (2003), while a versatile and powerful set of statistical tools exist for diagnosing spatially and temporally variable field observations, we have to explore the cause of variation and to improve and expand soil classification concepts. However, the efforts made by pedologists, soil physicists, and hydrologists on soil variability and scaling have not converged well in the past.

Hydropedology can help make that convergence happen, and can help de-mystify the seemingly mind-boggling variability in field soils via identifying myriad of soil patterns. This is because all processes in the soil are bound to an underlying structural control that exhibits a hierarchical organization (Vogel and Roth, 2003; Lin et al., 2006). This organization can be used to discern deterministic and stochastic components at each scale. For instance, at micro-scales water flow is controlled by capillarity and laminar flow through individual soil pores and around pedds. As scale increases, flow often becomes controlled by impeding layers in a soil profile, then accumulation of water downslope as dictated by soil catena and associated bedrock geology, and finally routing of flow through a stream network that in itself is controlled by soil-landscape characteristics.

5.3. Bridging mapping with monitoring and modeling

Jenny (1941) noted, “The goal of soil geographer is the assemblage of soil knowledge in the form of a map. In contrast, the goal of the ‘functionalist’ is the assemblage of soil knowledge in the form of a curve or an equation... Clearly, it is the union of the geographic and the functional method that provides the most effective means of pedological research.” Hydropedology is intended to promote such a union of soil maps and soil functions. This means that soil mapping must go beyond the classical taxonomy-dominated exercises and should consider soil functional characterizations as well as soil variability quantifications. A soil map can no longer be a static product; rather, soil changes (especially anthropogenic alternations) and functional units (such as soil hydrologic functions) should be defined and mapped.

Bridging mapping with monitoring and modeling helps soil map quantification and the inter- or extra-polation and upscaling of...
point-based data. Mapping can diagnose and stratify the soil–landscape for optimal location and number of sites needed for monitoring or sampling, as well as facilitate spatially-distributed modeling. On the other hand, monitoring and/or modeling can permit dynamic and functional mapping and ground truthing for maps. The link between mapping and monitoring/modeling is an important one for integrating space and time and for developing a systems-based understanding, especially in an iterative fashion (Lin, 2010a).

6. Examples of funding opportunities related to hydropedology

The following multimillion-dollar funding cases illustrate the opportunities of integrated approach to landscape studies, of which hydropedology is an integral part.

After spending billions of dollars, the US Army is still struggling with effective counter-landmine sensing technologies that are applicable to real-world soils. Geophysical tools and many other sensing techniques have been developed in sophisticated ways but often based on sand boxes. In 2003, the US Army Research Office released a call for University Countermine Research Center to “focus primarily on developing an in-depth understanding of the top half meter of the heterogeneous, complex, and dynamic terrestrial environment, the soil and soil–mine interaction phenomenology and on the geo-environmental factors that can affect mine detection and neutralization in different environmental settings within the context of a variety of sensing modalities and neutralization approaches” (http://www.arl.mil/aro/research/ucrc/). As described in the RFP, this effort includes descriptions of different soil types and their degree of heterogeneity under various environmental conditions; soil physical properties that affect landmine sensors and their intrinsic interrelationships, geospatial scaling behavior, and natural variation in different soil types, environments, and climates; soil moisture spatial and temporal variability, and its impacts on sensing signals. Another important aspect of this call for help is that all sensor work must be tied back to real soils and be integrated into the overall functional system that can be used in the battle field. Such a call has a strong flavour of hydropedology – that is, the holistic understanding of the landscape–soil–water relationship and its influence on soil–mine interaction under a wide range of real-world soil and environmental conditions.

In recognizing that processes occurring at and near the Earth’s surface do not operate independently, a holistic framework for integrated studies of water with soil, rock, and biotic resources in the terrestrial environment was called for by the US National Research Council (NRC, 2001). In 2006, the US National Science Foundation solicited proposals and funded three Critical Zone Observatories (CZOs) “that will operate at the watershed scale and that will significantly advance our understanding of the integration and coupling of Earth surface processes as mediated by the presence and flux of fresh water” (http://www.nsf.gov/pubs/2006/nsf06588/nsf06588.pdf). In 2009, three additional CZOs were funded in the US. In the meantime, German Helmholtz Association has established four Terrestrial Environmental Observatories (TERENO) in 2008–2009 to investigate the consequences of global change for terrestrial ecosystems and the associated socioeconomic implications (http://www.tereno.net/). In 2009, the EU 7th Framework Programme funded four CZOs to study soil processes at the field scale and to describe from 1st principles how soil structure impacts processes and functions at the soil profile scale (http://www.soiltrec.eu/). As the landscape–soil–water interaction across scales is a key to understanding the Earth’s Critical Zone, hydropedology will be an important contributor to these observatories. Long-term health of the soil, through monitoring its “blood pressure” (soil water potential), temperature, respiration, carbon content, structural dynamics, and other potentially key signs of global land change, is essential to the sustainability of ecosystem services, secure food production, lasting air and water quality, and a balanced growth of human society with natural systems.

7. Concluding remarks

The value of differentiating a cow and the ground beef is obvious. Apparently, it is much more challenging to raise a cow than to keep the ground beef. But to address the seminal question of “what is soil,” one needs to have an in-depth understanding and appreciation of this unique gift from nature and its essential characteristics in the landscape. Kung (1990) summarized well: until pedologists and sedimentologists can offer a more detailed description of the texture and structure of the vadose zone, simulated results of field-scale solute transport by models based on the classical concept could be completely misleading. He also noted that although flow pattern in soils could be extremely complex, it is not random. Thus, all transport parameters that are treated as random variables in stochastic models probably will never be accurately assessed unless the real flow paths can be estimated (Kung, 1990).

However, there are two bottlenecks in advancing hydropedology and hydrology in general. On the conceptual and theoretical front, going beyond small-scale physics and embracing a hierarchical structural framework can provide a more meaningful connection between point-based observations and landscape patterns as well as guide the appropriate development and use of models. The disconnect between the Dokuchaev–Jenny’s theory of soil formation and the Darcy–Buckingham’s law of soil water movement needs to be resolved, which offers a great opportunity for hydropedology to contribute to an improved theory of flow and transport in heterogeneous and structured field soils. On the technological front, the emergence of real-time sensor networks, coupled with improved non-invasive geophysical and remote sensing tools, can provide increasingly spatially and temporally extensive datasets about the subsurface and flow dynamics. However, while landforms and vegetation can now be mapped with high resolution (e.g., using LiDAR and the Worldview), non-invasive mapping of the subsurface with precision over space and time remains a significant challenge. As Beven (2006) noted, the most important need to advance hydrology of the 21st century is to provide techniques that can measure integrated fluxes and storages at useful scales, and the second one is the search for appropriate closure schemes at various scales.

Science advances through both integration and interfaces. Thus the development of justified sub-disciplines of hydrology is not necessarily in contradiction with the need for unity. A possible way that Journal of Hydrology may move forward with its debate over sub-sections vs. unity is to perhaps provide a broad categorical grouping (e.g., physical vs. socio-economical dimensions of hydrology), which may benefit those who like to scan over various issues; however, online search engines nowadays can easily resolve this issue by pulling out relevant papers regardless how they are grouped in a journal.

References

Baveye, P., this issue. Hydropedology biohydrology and the compartmentalization of hydrology into sub-disciplines: necessary evolution or dispersal of efforts? J. Hydrol.


Soils and Their Vegetation. Catena Verlag, Cremlingen, Destedt.


Soils and Their Vegetation. Catena Verlag, Cremlingen, Destedt.


