

Ecohydrology Bearings — Invited Commentary

Ecohydrological flow networks in the subsurface

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ABSTRACT

Preferential flow in hillslope systems through subsurface networks developed from a range of botanical, faunal and geophysical processes have been observed and inferred for decades and may provide a large component of the bulk transport of water and solutes. However, our dominant paradigm for understanding and modelling hillslope hydrologic processes is still based on the Darcy–Richards matrix flow framework, now with a set of additional methods to attempt to reproduce some of the aggregate function of the two-phase system of network and matrix flow. We call for a community effort to design and implement a set of well planned experiments in different natural and constructed hillslopes, coupled with the development of new theory and methods to explicitly incorporate and couple the co-evolution of subsurface flow networks as intrinsic components of hydrological, ecological and geomorphic systems. This is a major community challenge that can now benefit from new experimental infrastructure, renewal of older infrastructure and recent advances in sensor systems and computational capacity but will also require a sustained and organized interdisciplinary approach. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS hillslope hydrology; flow networks; co-evolution; community challenge

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INTRODUCTION

Coupled ecological and hydrologic flow networks play a major role in mediating hillslope drainage, biological access to water and solutes, and ecosystem development in many biomes. Network theories are now developing in many disciplines (e.g. Albert and Barabasi, 2002; Bejan and Zane, 2012). Studies of the quantitative structure and macroscopic behaviour of surface channel networks (e.g. Horton, 1945; Shreve, 1966; Rodriguez-Iturbe and Rinaldo, 1997; Perron *et al.*, 2012) and interactions with aquatic ecosystems (e.g. Vannote *et al.*, 1980; Power and Dietrich, 2002; Paola *et al.*, 2006) date back decades. However, the coupling of geophysical and biological

processes and outcomes in subsurface networks of significance to ecohydrology is at an early stage.

This commentary derives from a workshop held in Chapel Hill, NC, in 2013, and outlines a vision for tackling the important question of co-evolution of subsurface water drainage and ecological flow networks. In particular, we address the following questions: How can a predictive understanding of subsurface flow networks be developed? At what rates and by what geophysical and biological mechanisms do they develop? How can their structure, morphology and effects on flow and ecosystems be observed or fingerprinted?

We focus our remarks on the applicability of theories to ecohydrological questions aimed at measuring, understanding and predicting subsurface flow networks in hillslope systems. A number of approaches for the ecohydrology community are outlined including observations, experiments and modelling aimed at development of new theories and analytical methods.

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WHAT IS A FLOW NETWORK?

We define networks as a connected set of links and nodes that can transmit a signal (or flow) from regions of high to low energy potential. The concept of a hillslope subsurface network flow system typically assumes the presence of connected higher conductivity flow paths that can converge or diverge to move water and solutes at higher rates compared to a diffuse porous media flow system. The degree of connectivity may vary in space and time and may dynamically expand and contract with flow conditions, environmental disturbance and the level of biotic activity. Interaction between advective flow in network elements (e.g. root cavities, animal burrows, fractures and other conduits) and diffusive flow within the surrounding porous matrix is a key feedback controlling rates, residence times and biogeochemical activity at the hillslope level. Exchange of water and solutes between the (fast) network flow system and the (slow) diffusive soil matrix is a multi-phase flow system whose properties are qualitatively explored here.

Two closely coupled water flow networks in terrestrial ecohydrology are the subsurface drainage networks at the pedon to hillslope scale and ecological flow networks that control transpiration. Ecologists and soil scientists have described the role of network architecture in plant root function (e.g. Fitter, 1986; Hopmans and Bristow, 2002), and hydrologists have recognized the significance of subsurface pipes and fracture flow for drainage, landslides and solute breakthrough (e.g. Dunne, 1978, 1990; Beven and Germann 1982; Kirkby, 1988; Germann 1990; Burt and Pinay 2005; Dietrich and Dunne 1993; Salve *et al.*, 2012). However, hydrologists have only recently begun coupling ecological and geophysical aspects of subsurface flow networks as part of their concepts or models (e.g. Sidle *et al.*, 2001; Weiler and McDonnell, 2007; Ghestem *et al.*, 2011; Graham and Lin, 2012).

Beyond the pedon scale, hillslope-scale tracer measurements (Tsuboyama *et al.*, 1994; Weiler and McDonnell, 2007) and whole-hillslope excavations (Anderson *et al.*, 2009; Graham *et al.*, 2010) have revealed considerable network-like flow (drainage) patterns at the hillslope scale. Whereas soil physicists have long described vertical network and preferential flow systems in soil profiles and column experiments (see chapters in Lin, 2012; Jarvis, 2007; Beven and Germann, 2013), recent work points to organized flow laterally at the hillslope scale. The effects of lateral preferential flow systems activating at high moisture conditions have to date been mainly 'represented' in Darcy-based flow models by adjustment of bulk soil characteristic (e.g. $K_s-\Psi$) curves (e.g. Duffy, 1996) or the addition of dual-porosity methods coupled to Richards–Darcy mechanisms. The consensus in the workshop was the need to address network flow explicitly to advance beyond the limitations of current practice, which include effects indirectly or in an *ad hoc* manner by parameter adjustments.

Subsurface (soil, saprolite and bedrock) network topology may range from more convergent (tree-like), concentrating flow from the matrix through a hierarchy of increasing diameter 'pipes', to more divergent that would have the effect of distributing flow through decreasing diameter pipes, and then into matrix volume. Examples of the latter may include preferential flow paths in root channels that can distribute storm infiltration to the root volume. Fracture systems, developed initially in response to geologic stress fields, and further modified by chemical, physical and biological weathering processes, can rapidly channel large amounts of recharge water through the critical zone (Brantley *et al.*, 2011; Salve *et al.*, 2012), even if they do not form completely connected networks. A major question is whether distinct network patterns (e.g. topology and geometry) develop as a function of substrate and drainage boundary conditions, and network function (water flux to matrix storage, plant uptake or drainage).

Botanical branching patterns extend as near inverse systems above ground through below ground, facilitating the bidirectional exchange of water between atmosphere and critical zone. The connection from leaves to branches to trunk provides an efficient collection and delivery of intercepted canopy water to the branching root system, and reverse flow of soil water by transpiration. Subsurface root networks are in contact with additional flowpaths within the critical zone, which can activate as organized systems or disconnect under different hydraulic conditions. The network connectivity between systems developed by distinct processes (root growth and decay, faunal activity, shrink–swell and rock fracture) is a key theme for understanding the dynamics and function of network flow at the hillslope scale. Development of biofilms in network flow segments increases biogeochemical transformation rates. Consequently, nutrient transport and retention within preferential flow networks can be distinct from the soil matrix and are dependent on exchange between the two phases, and transport and reaction rates, as influenced by pore diameter, composition (mineral or organic content) and cumulative flow length (Luxmoore *et al.* 1990; Newman *et al.*, 1998).

Hydraulic lift is 'the nocturnal vertical transfer of soil water from moister to drier regions in the soil profile by roots' (Lee *et al.*, 2005). The maintenance of shallow soil mesic water content by lift is widely recognized and can be significant for plant uptake and for nutrient mineralization (e.g. Dawson, 1993). Water redistribution along root channels can also cause rapid downward transfer of moisture when rains moisten the shallow soils relative to deeper drier conditions.

Work on above-ground canopy branching patterns has a long history and can be extended to subsurface root networks. In a very early application of the mean continuity equation to flow networks (but ignoring lateral inflow), Leonardo da Vinci stated that 'All the branches of a water [course] at every stage of its course, if they are of equal

rapidity, are equal to the body of the main stream'. Applying this insight to vegetation, he noted that 'branches of a tree at every stage of its height, when put together, are equal in thickness to the trunk below them' (Richter, 1970). The da Vinci relation (labelled as Pythagoras's theorem of trees) is one of the first attempts to link aspects of plant network structure to biological function and underpins the so-called pipe-flow model of tree hydraulics that has received significant attention (Huber, 1928; McCulloh *et al.*, 2003; Bohrer *et al.*, 2005; Bejan *et al.*, 2008; Thompson and Katul, 2012). The geometric arrangement of xylem throughout the branching template of a tree crown offers a set of physical constraints on sap transport, presumably underlying da Vinci's original observation about network branching, albeit in an above-ground system. An optimality hypothesis for this system, on the basis of minimization of both energy inputs per unit stem length required to sustain xylem flow rate, and construction and maintenance respiration, could be used to develop efficient network designs, a selective advantage over evolutionary scales (Thompson and Katul, 2012). The work-minimization hypothesis emphasizing physiologic transport has a long history (e.g. Murray, 1926). Bejan *et al.* (2008) and Eloy (2011) have recently developed a new theory that resistance to wind load can also influence above-ground branching pattern systems.

The significance of this work to subsurface flow networks is in the specification of root (and root channel)

branching architecture that may be expected under different biophysical, physiological and physical stress (wind and gravitational) conditions. The generalization or extension of theory from above-ground to below-ground physiological branching systems (e.g. Bejan *et al.*, 2008) requires additional constraints of soil 'volume filling', access to limiting moisture and nutrients (Schenk and Jackson, 2002) and root response to physical stress (Hales *et al.*, 2009). Dynamic allocation of carbon to alter root extent and architecture, as well as rhizosphere dynamics, in response to resource limitations is well known (e.g. Franklin *et al.*, 2012) and may contribute to dynamic root branching and root channel networks as a function of hydrologic state and physical constraints. However, it may be conjectured from a constructal law argument (refer to subsequent discussions) that the diffusive time scale of water and nutrient movement from the soil pores into the roots would be matched by an advective time scale (of transpiration and phloem) in the trunk delivering water (or nutrients) to the transpiring and photosynthesizing leaves.

A VISION FOR RESEARCH IN ECOHYDROLOGICAL FLOW NETWORKS

The perception of the linked network and diffusive flow in ecohydrological systems is illustrated in Figure 1. Our central

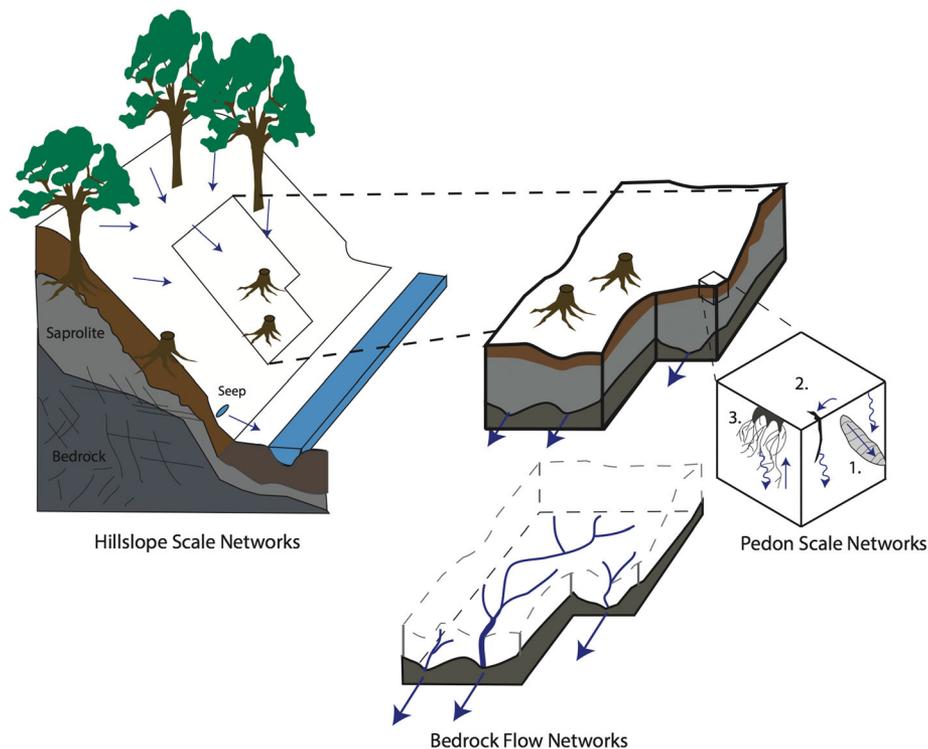


Figure 1. Elements of biologically and geophysically developed network flow systems in the hillslope critical zone at different scales. From right to left, at the soil pedon level, these include temporally varying (1.) faunal burrows, (2.) shrinkage cracks and (3.) root and root channel networks, interacting with bedrock depressions (fill and spill), and saprolite/bedrock fracture flow systems. Figure modified from Graham and Lin, 2012.

themes here are based on recent field evidence suggesting the following:

1. Network, hierarchical and organized surface and subsurface flow occurs above the upper limit of the stream channel and integrates abiotic and biotic elements.
2. Drainage flow via organized networks occupies the same limited critical zone (soil, saprolite and bedrock) volume mantling the hillslope as the diffusive matrix and spans the root system in the soil, through fracture networks in bedrock.
3. Therefore, there are three interacting phases: diffusive matrix flow, drainage networks and biologically developed faunal, root and associated rhizosphere networks, all of which may predominate at different soil moisture, groundwater levels, lithology, hillslope topography and climate conditions.

Ultimately, our questions on the controls of the co-development of the two discrete (non-matrix) subsurface networks seek to turn this qualitative understanding into a predictive tool for the evolution of subsurface ecohydrological networks. A key question then is what level of process and form specification is necessary. In fine-grained materials, evolution of subsurface drainage networks through shrinkage cracks, fractures or along bedding planes (and other physical preferential flow paths) and through weathering and erosion increases conductivities (e.g. Nieber and Sidle, 2010). Such flow networks may dissipate high pore pressures, suppressing the development of saturation overland flow (Montgomery and Dietrich, 1995) or reducing the likelihood of hillslope failure (Graham *et al.*, 2010). In coarser-grained soils, recent work has shown that evidence for flow networks within the soil profile is minimal—pore pressures can typically be dissipated by diffusive flow. However, we do not fully understand the complete mechanisms or conditions at which flow transforms from diffusive to network systems. Significant advances in rock fracture/matrix interactions and solute transport in aquifers (e.g. Neuman 2005; Houseworth *et al.*, 2013) can contribute to new methods and need to be further interfaced with root growth and weathering mechanisms (Anderson *et al.* 2012) to interface biotic and abiotic systems.

Structural heterogeneity, disturbance and physiological networks are ubiquitous. Vegetation root networks will tend to reduce pore pressures by active long-term soil moisture uptake and also provide advective flow conditions around root channels in high moisture/pore pressure conditions (e.g. Ghestem *et al.*, 2011). Faunal networks from burrowing animals include a large diameter range from invertebrates to mammals may form and decay in response to hydrological and other environmental factors. Growth, maintenance and decay of physiological networks are better understood, but their coupling and dynamic feedback

to water and nutrient levels are typically not incorporated into hydrologic models, a logical next step.

The desire to understand subsurface interwoven networks has encountered significant challenges with a paucity of well-designed measurements and complete mathematical treatments. We remain challenged to describe the aggregate behaviour of hydrologic systems for which physical distance is clearly relevant and for which the constitutive physical, chemical and biological components interact and evolve via laws that are scale dependent (Levin, 1992; Turcotte and Rundle, 2002). Early efforts in subsurface characterization and representation to accommodate distance relationships made use of percolation theory, which is intended to describe the behaviour of connected clusters in a random graph (thereby explicitly accounting for the effect of physical distance). These theories proved successful in explaining aspects of the transport in porous media and highlighted universal links between the parameters describing unsaturated hydraulic conductivity, gas diffusivity, solute diffusion and electrical resistivity (e.g. Hunt, 2005). However, the simultaneous evolution of the various interwoven networks forming the system here restricts the use of percolation theories.

A rather different theoretical approach to the co-evolution of networks at a general level is constructal theory (Bejan, 1997; Bejan and Zane, 2012). The most basic statement of the constructal law is 'for a finite-size system to persist in time (to live) it must evolve such that it provides greater and greater access to the currents that flow through it' (Bejan, 1997, p. 815). It is important to note that the constructal theory does not offer mechanistic explanations for how the networks form and grow by transport and erosional processes. However, the theory promotes the formation of hypotheses addressing how properties of the sequence of transient networks should progress through time with respect to flow and transport efficiency, and as flow boundary conditions change. A pertinent aspect of constructal theory for ecohydrology is the consequence of network system properties. Within an evolving flow system, a specific proportionality exists between network advective time scales and aggregate diffusive time scale, where the advective time scales are associated with flow in the large elements (the few) and its diffusive time scales associated with the small-sized elements (matrix porous media) abundant in space.

Controlled experiments might enable the community to test these ideas. As process dynamics in network formation may range from storm event to geological time scales, a mix of experimental and observational inference would be useful. This may include new experimental facilities specifically built to control and scale processes over different length and time scales, material strength and process intensity, and natural analogues. The new Landscape Evolution Observatory (LEO) at Biosphere 2, The University of Arizona, offers unique opportunities to test hypotheses related to subsurface flow networks (Huxman

et al., 2009) on experimental hillslopes. LEO offers the potential to assess network development under the combined constraints and interactions among hydrologic partitioning, geochemical weathering, ecological, geomorphic and atmospheric processes. The infrastructure is designed to facilitate investigation of emergent structural heterogeneity that results from the coupling among Earth surface processes by rapidly iterating dense experimental measurement with development and validation of coupled computational models. As initial and boundary conditions are known, evolution of flow networks may be studied on the basis of emergent landscape drainage properties, transient development of potential fields, geophysical imaging and the use of the controlled tracer delivery systems. The impacts of transient development of networks over different time scales and in response to controlled boundary flux and manipulation experiments (e.g. installation of structured soil features and drainage lines) could be used as sub-experiments within a landscape.

Additional experimental facilities such as Hydrohill in China (Kendall *et al.*, 2001) and the Hewlett and Hibbert trough(s) at Coweeta (Hewlett and Hibbert, 1963, Scholl and Hibbert, 1973) may provide additional opportunities for observation and experimental manipulation. At Hydrohill, there is now almost 30 years of soil development that has occurred at the site with known boundary and initial conditions. As such, network development can be chronicled from a known starting point. In Coweeta, drainage properties of constructed soil profiles along long, constructed troughs were carried out >50 years ago. The troughs appear to be intact, but with five decades of soil development from their initial conditions. The opportunity to excavate and map soil structure, or repeat rainfall and drainage experiments represent an additional potential to study long-term transient evolution of these systems. Beyond these time scales, landscapes with known time of disturbance (e.g. agriculture and fire) that may have reset the network clock, and methods of inferring rates of development of existing preferential flow systems need to be investigated.

CONCLUSIONS

The presence, structure, dynamics and interactions of the diffusive matrix flow, advective drainage networks and physiological networks (derived from both floral and faunal processes) are central to understanding coupled small scale physical and biological processes occurring at the hillslope scale, as well as bulk water storage and release at the pedon, hillslope and watershed level. Although observations and analysis of each system date back decades, we have rarely incorporated these systems within an integrated framework that explicitly couples their function and evolution in our theory and models. The interacting networks are difficult to measure, are likely highly nonlinear in response to drainage

and climate conditions and may show considerable transience in structure. Bulk effects have been parameterized by various nonlinear calibrated processes in models, which may effectively capture aggregate storage-release mechanisms, but do not provide a sufficient process understanding to predict impacts on many ecological and biogeochemical processes, as well as geomorphic threshold events. Considering both academic interest in the interaction and co-evolution of critical zone ecosystems, hydrologic and geomorphic systems, potentially under strongly varying climate and land use, and our practical needs to restore and manage ecosystems to regulate freshwater flows and protect water quality, an increased focus by the scientific community is timely. Many questions remain: What key metrics describe these network systems and their coupling? How do we infer and quantify dynamics of the invisible heterogeneous, subsurface flow networks that develop in soils and underlying weathered bedrock? Can we turn this understanding into a predictive tool for the evolution of coupled subsurface hydrological networks? What level of process specification is necessary? We hope that this short commentary spurs the ecohydrological community to embrace the study of multi-phase subsurface flow networks. We are convinced that specific efforts in observing, measuring and understanding network dynamics are needed to develop new community understanding of ecohydrological systems. In addition, new analytical and numerical methods to represent their dynamics and functions within watersheds could be a major new direction in our young science.

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