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Store and pour: Evolution of flow systems in landscapes

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ABSTRACT

Concentrated or preferential flow patterns occur at all scales in hydrologic systems. They shape, and are shaped by, geomorphic and pedologic patterns and structures. Preferential flow patterns in surface channel networks and dual-porosity subsurface flow systems are a way of achieiving maximum efficiency, as predicted by dissipative systems, constructal, network evolution, percolation, and ecohydrological theories. These all converge on the same predictions and interpretations of preferential flow, which satisfactorily answer "why" these patterns form and persist. However, as geomorphic and hydrologic systems have no intentionality or agency, and thus no ability to actively seek improved efficiency, *how* these systems evolve is an open question. I propose an emergent explanation based on five phenomena. First, concentrated flows form due to principles of gradient and resistance selection. Second, positive feedback reinforces the concentrated preferential flow paths and their relationship to potential moisture storage zones. Third, intersecting flow paths form networks. Fourth, the expansion of concentrated flow paths and networks is limited by thresholds of flow needed for channel, macropore, or conduit growth and maintenance. This results in a "store and pour" flow system that can retain water during dry periods and transport it efficiently during wet periods. These systems survive provided they develop "spillway" and/or secondary storage mechanisms to accommodate excess water inputs. Finally, store-and-pour systems are maintained (selected for) because they are often stable. Store-and-pour structures are advantageous for flow systems, and for vegetation and ecosystems. These entities cannot actively pursue goals, and no laws dictate evolution toward such patterns. Their development is an emergent phenomenon and their persistence a matter of selection, i.e., survival of the most stable.

1. Introduction

In a variety of climates, geologic settings, and biogeographic contexts, stream channel networks typically take a branching, dendritic form (except where structural or human constraints prevent it or promote other forms). Beyond the general architectural similarities, these networks often display commonalities of more specific topological, geometric, and statistical properties that are remarkable given the broad range of environmental contexts (Fig. 1).

Such similarities suggest the possibility—even the likelihood—of some unifying underlying principles or laws that are independent of local and regional environmental controls. Geomorphologists, hydrologists, geographers, and geologists have investigated this phenomenon for more than a century, joined by a number of mathematicians, physicists, systems theorists, and even philosophers intrigued by the question of why and how these patterns form. One important outcome is the discovery that a branching, dendritic network is a maximum-efficiency configuration for any system of gathering fluids from an area (in landscapes, a watershed or catchment), and delivering it to (or in some cases redistributing it from) a central location. Thus, the pattern shows up in, e.g., networks of blood vessels in fauna; branching of plant roots, stems, and leaf veins; and engineered flow systems. This gets at the "why" of network formation, though it is not clear why abiotic systems would seek maximum efficiency, as they cannot care about or desire any such thing.

While work on fluvial channel networks continues apace, in recent years attention to subsurface flow networks has grown. This is often framed in terms of *preferential flow*, contrasting concentrated flows along or through, e.g., macropores, soil pipes, root channels, organic layers or biomats and "fingers" of irregular wetting fronts (Fig. 2) with diffuse flow through a porous matrix (Darcian flow). Reviews of preferential flow in soils are provided by Lin (2015), Jarvis et al. (2016), Guo and Lin (2018) and Stewart (2019). Meanwhile, groundwater hydrology in many bedrock aquifers was known to be dominated by flow through

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Fig. 1. Continental scale surface drainage of South America. The map shows stream segments, with width proportional to Strahler order. Map produced by Jared Prince, Muir-Way (https://muir-way.com) and used by permission.

Fig. 2. Macropores (≥0.6 mm) revealed by CT scanning of soil core 20 cm in diameter by 20 cm tall from a loamy soil in Denmark. Imaging by Dorthe Wildenschild, modified from a figure shown at https://www.producer.com/crops/ct-scan-tech-used-to-check-soil-health/.

fractures or conduits, or along joints and bedding planes, though a Darcian "averaging out" approximation was often applied. In this case the preferential flow paths were considered, logically enough, to be structurally predetermined.

Darcian frameworks and associated models have dominated groundwater and soil hydrology. Even though hydrologists recognized that Darcian flow conditions are often a major oversimplification, it was frequently assumed, in some cases with justification, that a flow-through-porous-media representation averages out variations associated with non-uniform flow sufficiently well for many applications. As the importance of preferential flow was increasingly recognized and demonstrated in field and laboratory studies, the discipline underwent what some hydrologists have called a period of denial, on the one hand being aware of the prevalence of preferential flow, while on the other hand largely ignoring it (Uhlenbrook, 2006).

A fundamental question emerging from studies of, or including, subsurface preferential flow is why soil hydrological systems—again, in a wide variety of environmental settings—develop a common structure characterized by a higher-resistance matrix with slower diffuse flow, and preferential flow paths with faster flow. Hunt (1998), using percolation theory in the context of upscaling solute transport processes, identified several possibilities. These include preferential selection of initial conditions based on mobility, and nonlinear flow. The latter case involves changes in the medium (which may be subtle) by transport leading to preferential flow paths.

In addition to studies of channel networks, many geomorphologists in recent decades have turned their attention to multi-channel planforms, from anastomosing and braided patterns to deltaic and other distributary flow networks. Some of this work also interpreted these patterns as maximum efficiency configurations (e.g., Huang and Nanson, 2007). In studying one such pattern, in the fluvial-estuarine transition zone of the Neuse River, North Carolina, I discovered that rather than a clear distinction between channels and floodplains or islands, the entire river corridor is a complex of open channels, vegetated channels, ponded storage, and flowing wetlands (Fig. 3; Phillips, 2022b). This raised the question of whether this was in some way analogous to soils—i.e., wetlands/matrix vs. channels/preferential flow paths. This example is revisited below.

Preferential flow is most often and traditionally used in reference to soil hydrology, but in fact applies to hydrologic systems in general. Surface channels and groundwater conduits are also preferential flow paths, and preferential flow occurs at all scales, from soil physics to continental drainage systems (Uhlenbrook, 2006; Kleidon et al., 2013).

The goal of this paper is to examine the evolution of hydrological flow systems within landscapes, focusing on these questions:

- Do hydrological systems evolve toward a "store-and-pour" (S&P) configuration consisting of slow-flow, high-resistance components capable of storing or delaying flow and rapid-flow, low-resistance components capable of transmitting high water inputs and draining excess water?
- If so—and the first question is partly rhetorical, as we already know that many have such a configuration—why? Existing theories, reviewed below, suggest that store-and-pour configurations are maximum-efficiency patterns. This leads to the main open research questions addressed here:
- How do these configurations develop? The questions here do not concern the process mechanics of, e.g., macropore formation or channel incision, but rather, what are the system-level processes or mechanisms by which S&P patterns develop?
- What (if any) underlying principles link the formation of S&P systems in surface watersheds, soils, and groundwater?

There exists an extensive and ever-growing literature on fluvial channels and networks, and preferential flow in soils and groundwater. Here the focus is on research that explicitly relates to the evolution of

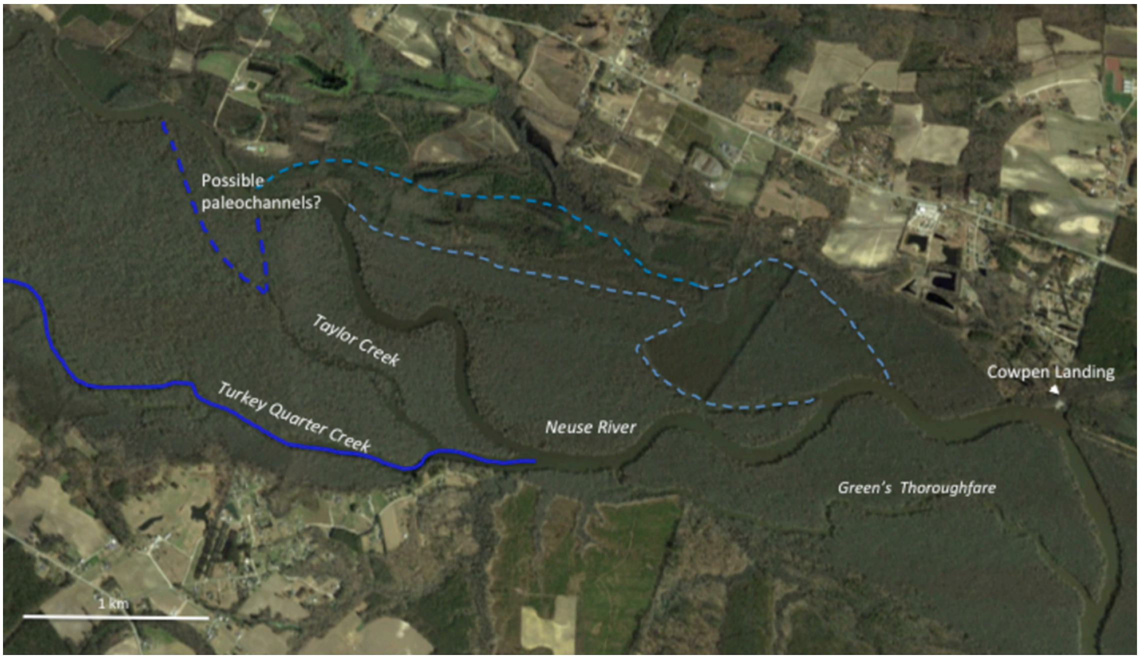

Fig. 3. Complex of channels and wetlands in the lower Neuse River, North Carolina. Channels not readily visible on the Google Earth™ image at this scale are drawn in.

S&P patterns, and on selected examples to illustrate the specific principles, contentions, and questions expressed here.

The filling of storage components in hydrological systems so that they begin exporting or transferring water is a common and critical phenomenon with respect to crossing thresholds for runoff generation, multi-channel flow or between different flow regimes, and for establishing and expanding hydrological connectivity. These dynamics are sometimes referred to as fill-and-spill (Bonacci and Bojanić, 1991; Troch et al., 1994; Tromp-van Meerveld and McDonnell, 2006; Graham et al., 2010; Phillips, 2013; Stewart, 2019). Favis-Mortlock et al. (2021) give an example of how such dynamics can influence connectivity between upland runoff and erosion sources and fluvial channels, and approaches to modeling effects of landscape elements on flow and storage patterns, particularly blind or closed depressions. S&P refers to the ability to retain moisture during dry, low-input periods, and to store and/or release (pour) excess water during wet, high-input periods. Fill-and-spill dynamics are often an important part of S&P, but S&P is a broader concept that also applies during dry periods when filling does not occur, and floods when all normal storage components are full. Fill-and-spill is primarily concerned with temporal dynamics, while S&P is primarily concerned with the structure of hydrological systems with respect to their capacities to store moisture and transport or export it via both slower and more rapid pathways. The relationships between form and function in the context of preferential flow and fill-and-spill dynamics are treated in detail by Angermann et al. (2017) and Jackisch et al. (2017).

2. Why are store-and-pour patterns ubiquitous?

Below several theories and concepts are summarized relating to the development of surface and subsurface flow systems. These directly or indirectly address the issue of why such patterns are so common.

2.1. Optimality and efficiency

Michael Woldenberg (1969) found that fluvial channel networks are organized to minimize overland flow work for streams in small watersheds and maximize work savings in large channels. Under this tradeoff, entropy approaches the maximum possible. Michael Kirkby (1971) reached analogous conclusions. The best way to trade off local efficiency within a flow network and efficiency of the whole network is a branching, dendritic channel pattern. This has been demonstrated via field, laboratory, and theoretical mathematical studies, many in recent decades from the perspectives of optimality, self-organization, and fractals (for reviews see Abrahams, 1984; Hergarten, 2002; Molnar and Ramirez, 1998; Kleidon et al., 2010). Hydrologists and geomorphologists were quick to realize that the principles applied to flow systems in general, such as circulatory systems in organisms (e.g., Woldenberg and Horsfield, 1986; Rodriguez-Iturbe and Rinaldo, 1997; Dodds, 2010).

If flow network development were entirely determined by optimality or efficiency principles with respect to transmitting flow, networks would expand indefinitely, until constraints such as the minimum size for a channel (be it fluvial, a blood vessel, a root hair, or otherwise) and the maximum amount of space that can be occupied by channels come into play. This rarely, if ever, happens (badlands topography is a possible exception). Beyond geological or other physical constraints, which may prevent or inhibit formation of dendritic networks, a minimum amount of contributing area is required to form and maintain a length of channel (or other preferential flow paths; PFP).

Drainage density is total channel length per unit area, and empirical and modeling studies of fluvial systems indicate a rapid increase in drainage density during initial stages of network development. Slower growth follows, and eventual achievement of a relaxation time equilibrium where density remains more or less constant (see, e.g., Zhou et al., 2014). This is implied in the well-known relationship between channel length and drainage area and suggests that no advantages are associated with indefinite network expansion.

An early study of this in hydrology is Carlston (1963), who studied relationships among drainage density, discharge, and groundwater levels, based on:

$$T = (RD^{-2})/(8h_o) \tag{1}$$

where T is transmissivity, R is groundwater recharge, D is drainage density, and h_o the height of the water table at the groundwater drainage divide. In 15 drainage basins of varying lithology and topography, Carlston found that for a constant recharge and h_o, baseflow varies inversely and flood discharge directly with D^2. He concluded that D is adjusted to the most efficient removal of flood runoff. Similar conclusions with respect to drainage density and efficiency of transmitting flood flows were reached by Pallard et al. (2009) by examining the relationship between flood statistics and drainage density.

Drainage density varies with climate, geology, and other factors, but other things being equal, if there exists an optimal density, then drainage density should increase with the amount of water to be distributed. Zhou et al. (2014) found this to be the case in their study of tidal networks, where the substrate is relatively uniform and discharge per unit area is entirely determined by the tidal range. Measuring drainage density based on which channels are inundated or conveying flow, Godsey and Kirchner (2014) examined the changes in drainage density over time in four California headwater watersheds. They showed that the stream networks expand, contract, disconnect, and reconnect dynamically, with higher drainage densities during wetter periods and lower during dry spells.

In summary, barring physical constraints, branching dendritic networks are the most efficient way to collect and transmit flow. Such networks increase in total channel length and drainage density in response to greater amounts of water, but cannot increase indefinitely, in part because some non-channel area is required to support channels.

Optimality principles explain *why* branching, dendritic networks are common, but not *how* this happens. The mechanisms of channel incision, extension, and branching do not dictate the formation of any particular topology. The answer may lie in principles of *selection*, to be discussed further.

2.2. *Dissipative systems and thermodynamics*

This argument explains the general phenomenon of heterogeneity and non-uniform (preferential) flow in hydrological systems. Hydrological systems are open, *dissipative systems* with continuous energy inputs and mass exchanges with the surrounding environment. Dissipative systems are characterized by *symmetry-breaking* (leading to anisotropy) and *formation of complex structures*, leading to heterogeneity. Hydrological systems therefore evolve toward heterogeneity and non-uniform flow. A simplified summary (or perhaps caricature) is: Hydrological systems are dissipative systems, and this is what dissipative systems do.

A dissipative structure requires that a portion of the energy flowing through it be used to maintain the far from equilibrium, stable, steady state, while the entropy of the universe increases at a more rapid rate than would occur if the dissipative structure did not exist.

Explicit links between dissipative systems and preferential flows in soil and groundwater hydrology are explained by Zehe et al. (2013). Macropores act as dissipative structures by enhancing dissipation plus export of free energy in the rainfall-runoff process. Preferential flow accelerates mass fluxes relative to driving gradients in soil water potentials or in surface water levels, implying a faster depletion of these gradients. Reduction of free energy moves the hydrologic system state closer (but not necessarily back) to local thermodynamic equilibrium. This enhances mechanical stability of the system as mass flows in the conduit, pipe or macropore networks exert less stress on the system, and mechanical/hydraulic loads are quickly reduced (Zehe et al., 2013). This mechanical stability favors the persistence of the PFP structures. Analogous reasoning applies to preferential flow at broader scales, including continental surface drainages (Kleidon et al., 2013).

Loritz et al. (2019) also examined hydrological flow systems as dissipative structures, noting that most potential energy of rainfall is dissipated rather than transformed to kinetic energy of flow, and that further dissipation occurs in hillslope runoff and stream networks. They developed a unitless index of energy dissipation per unit length:

$$D_l = -\ln(h_i/l_i) \tag{2}$$

The index is zero if the flow length l_i is equal to the elevation relative to the nearest drainage (e.g., channel or conduit) h_i, positive if $l_i > h_i$, and negative if $l_i < h_i$. Higher D_l (this parameter is called *r*DUNE in Loritz et al., 2019) indicates less dissipation of potential energy relative to landscapes with lower D_i. Their analysis explicitly links the architecture of a flow system with its energy dissipation functions.

2.3. *Constructal theory*

Constructal theory holds that for a finite-size flow system to survive, it must evolve in such a way that it provides easier and easier access to the currents that flow through it (Bejan, 2007). This results in a tendency toward at least two flow regimes, of higher and lower resistivity. The combination of faster and slower paths results in a dynamic configuration that offers the least global flow resistance over time. This applies to the dual-porosity (matrix and preferential flow paths) in soils, as well as to the interfluve-and-channel configuration of surface channel networks. Constructal theory provides no mechanistic explanations for how flow networks form and grow, but it does facilitate hypotheses addressing how properties of an evolving network should progress through time with respect to flow and transport efficiency (Lin, 2010; Hunt, 2017).

The global (i.e., system-level) measure of performance is flow resistance (R) or its reciprocal, conductivity (K). The external size is L, and the internal size is V. A measure of the configuration of resistance/conductivity is svelteness:

$$S_v = L/V^{1/3} \tag{3}$$

Constructal theory holds that flow systems survive by increasing flow performance, svelteness, and/or flow territory (Bejan, 2007). If flow configurations are able to change, they will evolve toward smaller R (larger K). Increased svelteness occurs in flow architectures with fixed R, L, which evolve toward compactness, reducing V by reducing the volumes dedicated to internal channels and increasing that of interstitial matrix. Survival by increasing flow territory (greater L) occurs by flow systems with fixed R, V growing to cover larger territories. Systems that do not exhibit one of these trends are less likely to survive (Bejan, 2007). The elaborative growth of channel networks within a watershed, for example, represents increases in K, while extension of the network corresponds to larger L. Development of macropores and preferential flow paths within a fixed soil volume increases K and reduces R.

2.4. *Network evolution and percolation*

Graph theory and the study of networks provides some insight into the structures and patterns that achieve efficiencies in the transfer of energy, matter, and information. Tradeoffs exist between maximization of connectivity, minimization of complexity, and synchronization, which relates to the extent to which the network responds contemporaneously throughout, or at least in a regular sequence. In general, bifurcating tree-type graphs are the most efficient structure for transmission (of mass and energy fluxes, information, etc.) in a network, accounting for their widespread use in computer science and information technology.

Percolation theory is a branch of mathematics and statistical physics focused on the behavior of a network relative to the number of nodes and links. The name arises from a classic, seminal problem that illustrates its applicability to environmental flows. If a liquid is poured or placed at the top of some porous material, will the liquid be able to make its way from hole to hole and reach the bottom? This is modelled as a three-dimensional network of $n \times n \times n$ nodes or vertices, ("sites"), where the links or "bonds" between each two neighbors can be open (allowing the liquid through) with probability p, or closed with probability $1 - p$, and they are assumed to be independent. Therefore, for a given p, what is the probability that an open path (meaning a path where each link is an "open" bond) exists from the top to the bottom?

Various forms of percolation theory have been applied to development of stream networks, fluvial erosion, solute transport, soil hydrology, and coevolution of soil, vegetation, and drainage patterns (e.g., Stark, 1991; 1994; Hunt, 2016; 1998; Hunt and Ghanbarian, 2016; Hunt and Manzoni, 2016). These analyses point to surface and subsurface flow network structures as often found in nature as arising from dynamics predicted by percolation theory.

2.5. Gradient, resistance, and network selection

Matter and energy fluxes will, if not impeded, follow the steepest gradients available, though in many cases this gradient selection is highly localized—that is, runoff on a hillside, for instance, can only “see” the steepest path in the immediate vicinity (for empirical illustrations, see Favis-Mortlock et al., 2021). The overall steepest path down the slope is not detectable to the water, and may differ from the local steepest gradient (Phillips, 2021: 246–249). Positive feedbacks often enhance these steeper-gradient paths, even where they are a collection of locally selected gradients. Channel incision, pipe or macropore erosion, and solutional enlargement of conduits are all examples.

Resistance selection refers to weathering and erosion differentially removing weaker, lower-resistance materials and features, such that more resistant ones are preferentially preserved. Again, positive feedbacks often reinforce these trends. This is especially evident in chemical weathering at the weathering front, where initial variations in resistance are often magnified as the least resistant portions tend to collect more water. Gradient and resistance selection predict the formation of PFPs, and by implication, of non-flow storage/contributing areas.

Preferential formation, enhancement, and preservation of specific networks of flow also occurs. This is one form of efficiency selection, where more efficient patterns and structures tend to emerge and be preserved (Phillips, 2021: 240–245). PFPs often, and when their density is high enough, inevitably, intersect. When they converge, they combine into a single, larger PFP (notwithstanding some rare exceptions of intersecting groundwater passages where fissures cannot be enlarged enough to accommodate the combined flow). In channels, a single larger channel is more efficient than two smaller ones conveying the same total flow, due to reduced boundary friction. Efficiency selection thus favors convergence of PFPs, and in some cases (such as the dendritic patterns discussed above) specific topologies. The selection for particular patterns of flow, and densities of flow paths is termed *network selection*. Network formation in surface hydrology and karst conduit systems is well known, but formation of preferential flow networks in other subsurface flow situations also occurs (e.g., Guo et al., 2014; Hunt and Manzoni, 2016; Angermann et al., 2017; Jackisch et al., 2017).

2.6. Ecohydrology

Store-and-pour, particularly in soils, is highly advantageous for vegetation, allowing for storage of moisture between flow events, and rapid movement when excess water is present (Lin, 2010). Thus the dual-conductivity patterns that appear in a wide range of natural systems are likely linked to ecological processes (Savenjie and Hrachowitz, 2017). Zehe et al. (2013: 4318) speculated that “co-evolution selects species whose ecological optimum (pattern and density) coincides with the thermodynamic optimum partitioning of rainfall water” into overland flow and infiltration in such a landscape. These optimum configurations may be most probable states in landscape evolution.

Plants and other biota play a crucial direct role in creating macroporosity due to root growth, burrowing, and tunneling, and indirectly via their role in the formation of soil aggregates and organic layers, pockets, or biomats. Organisms are also critical in exploiting and widening rock joints, fractures, etc. in chemical weathering. The role of vegetation in stabilizing channels and channel banks is well-known, and the spatial distribution of vegetation—for example, establishment and stabilization of non-channeled areas—can be critical in reinforcing store-and-pour patterns.

3. Emergence of store-and-pour

It seems reasonably clear *why* store-and-pour configurations are favored by selection processes. They are generally efficient, and they also offer ecological advantages. It can also generally be worked out how the preferential flow paths are formed, in a process mechanical sense, for individual landscapes or cases. But the question of how Earth surface systems with no intentionality or goal functions achieve these configurations is not clear. Here a five-step emergent explanation is proposed, and summarized in Fig. 4. The steps do not necessarily represent a temporal sequence, strictly speaking, but are listed in order of logical necessity (though one could debate the relative importance of items 2, 3 in some contexts; e.g. Hunt and Mazoni, 2016). Individually, all five elements represent established principles widely accepted in hydrological sciences.

Step 1: Concentrated flow

Concentrated flow happens. The principles of gradient and resistance selection favor concentrated flow paths, which are more efficient for moving water than dispersed or diffusive paths. These pathways are often initiated opportunistically where water exploits pre-existing routes such as microtopographic depressions, rock joints and fractures, roots and root channels, soil macropores, etc.

Step 2: Reinforcement by positive feedback

Concentrated flow paths are enhanced by positive feedback. Erosional enlargement of fluvial channels, soil pipes, and conduits allows them to both attract and convey more water, and the flow and transport processes often reduce roughness and frictional resistance, which also makes these preferential flow routes more efficient. Sometimes these feedbacks can also steepen driving gradients. The formation and enlargement of these paths also creates local gradients that enhance the ability of the flow paths to capture water—for instance, water table drawdown adjacent to fluvial channels or lateral inflow to soil pipes. Resistance can also be reduced—and flux enhanced—via wetting and saturation, as observed in fingered flow and other wetting front instability phenomena in soils.

Store-and-pour structure is therefore dictated at the local scale by segregation into preferential flow paths (pour) and interstitial or interfluvial areas (store).

Step 3: Flow paths intersect

When converging flow paths intersect, they invariably combine. Thus flow networks are formed in the down-flux direction. These

1. Flow convergence happens.
2. Positive feedback reinforces, enhances, & locks in convergent flows and preferential flow paths.
3. Flow paths intersect & converge, forming networks.
4. Growth of flow paths & networks is limited by thresholds, preserving separation of flow paths & contributing/storage areas: Store & Pour
5. Store & Pour configurations are dynamically stable (thus tend to persist) & may be reinforced by ecohydrological feedbacks.

Fig. 4. The emergence of store and pour patterns.

networks are sometimes maximum efficiency forms, such as dendritic fluvial networks. Even where dictated by geological structures, however, the preferred flow paths typically allow for overall flow velocities much faster than if the entire volume behaved as a single-porosity medium (Worthington, 2019). The development of these networks—again, preserved by positive feedbacks—creates store-and-pour structures at the network (or watershed or aquifer) scale.

The formation of channels or channel-like features such as macropores and soil pipes, enhancement by positive feedback, and their organization into networks is much more difficult to observe in soil and groundwater, but has been demonstrated in both soils and carbonate aquifers (e.g., Sidle et al., 2001; Nieber et al., 2006; Nieber and Sidle, 2010; Liu and Lin, 2015; Worthington et al., 2015; 2016; 2019; Worthington and Ford, 2009; Wilson et al., 2017; Mohammadi and Illman, 2019) and, though with less empirical evidence, in non-carbonate aquifers (Tsang and Neretnieks, 1998; Worthington, 2016; Klepikova et al., 2020).

Step 4: Threshold limitation

Why don't concentrated flow paths and flow networks expand indefinitely to occupy the entire medium? It is intuitively obvious why pathways can only become finitely large, due to mechanical constraints on their maximum size, and availability and frequency of flows capable of maintaining them. At the other end, however—think of channels or macropores extending up-gradient—they cannot become infinitely small, either. There exist minimum sizes for macropores, conduits, channels, and plant roots. There must also exist some minimum contributing area to supply the necessary flow to maintain channels. With respect to fluvial channel networks, Schumm (1956) called this the constant of channel maintenance, which in a fully developed network at its maximum drainage density is equal to the mean drainage area per unit of channel length (inverse of drainage density). Because PFPs and networks cannot become indefinitely dense, dual conductivity persists.

Step 5: Stability and ecohydrological feedback

S&P patterns are dynamically stable in most cases, leading to their preservation (survival of the most stable). This is explored further below. Ecohydrological feedbacks may also contribute to maintenance of S&P.

3.1. *Flow system survival*

Flow system survival depends on limited degradation during dry, low flow periods, efficient transport during wet periods, and mechanisms for handling excess flow. In the discussions that follow, normal conveyance capacity refers to flux capacities of all perennial channels, conduits and macropores and other flow paths that are connected in unsaturated as well as saturated conditions. Normal storage refers to capillary storage in the soil matrix, matrix storage of groundwater, and surface water storage during non-flood and unsaturated conditions.

Limited degradation during dry periods requires that preferential flow paths are maintained; that at least some of these channels, macropores, and conduits persist when flows are low, or in some cases, when they are dry. It also depends on some retention of water for use by biota, and to maintain fluvial, palustrine, or wetland features. Belowground moisture storage occurs within the soil or aquifer matrix, and before drawdown becomes advanced, in subsurface cavities, conduits, and macropores. Aboveground storage occurs in wetlands and ponded features such as ponds, lakes, sloughs, and non-flowing or slowly flowing subchannels. Significant long-term storage in dryland systems may also occur within plants such as succulents.

Preferential flow paths and networks provide efficient transport, and there exist several possible ways to handle moisture in excess of normal transport capacities. One is via *spillways*, which serve the same function as a literal spillway at a dam, to activate a flow path for excess water. In natural hydrological systems spillways include high-flow subchannels or flood channels (including subsurface conduits in some cases), and high-flow distributary channels (including tie channels) connecting main channels to flood basins of various kinds. In some low-gradient streams there exist subchannels that are essentially ponded—no or very low flow—during normal inputs, but can be activated to convey downstream excess flow. Some floodplain wetlands may also convey flow during floods. In some groundwater systems, especially in karst areas, there exist high-flow conduits that are activated only during wet periods, and associated overflow springs. Some fluviokarst areas also feature intermittent surface channels that are activated when underground conduits and cavities are filled. In many soil hydrological systems, surface runoff, saturated throughflow, and percolation to groundwater serve as the main spillway mechanisms.

Note that spilling may occur at two distinct stages of wetness. The first is when wet zones within the soil enlarge and become connected, when subsurface bedrock depressions fill up and overflow their boundaries, and when surface depression storage overflows. These occur at the upper end of normal flow or input conditions as described above. Spillway-type spilling occurs at above-normal flow conditions when additional pathways or processes of flow conveyance are activated. In a karst system, for instance, the first stage of spilling occurs when bedrock cavities become full enough to overflow and become connected, and the second when conduits are entirely filled, displacing flow to normally dry conduits or to surface channels.

Store-and-pour patterns can therefore store, delay, or pour via spillway flow when transport or conveyance capacity is exceeded without undergoing a permanent or persistent transition. They can also retain some water during dry, low-input periods. Fig. 5 shows a high-input scenario. If the excess water is accommodated (stored or delayed without triggering a large transformation), then the system is sustainable and stable. If excess water cannot be accommodated, transformative changes such as erosional stripping, sedimentary burial, or waterlogging occur, and the original system state is thus unsustainable. Geomorphic, hydrologic, and ecological adjustments can sometimes increase excess flow accommodation and move the system toward a more stable condition.

In the dry scenario (Fig. 6), hydrogeomorphic systems with inadequate storage capacity develop moisture stress on vegetation, and plant mortality when such stress is prolonged or frequent. This unstable, non-sustainable situation leads to desiccation, unless some moisture storage capability is developed. Low inputs in a system with significant storage allows vegetation to persist, and a stable, sustainable state can exist. A system with high moisture storage capability but little or no ability to export flow ("all store, no pour") is likely to be, or become, a wetland environment with hydrophytic vegetation (except in arid climates).

These scenarios illustrate how both store and pour capabilities are required for system survival.

3.2. *Dynamical stability*

The dynamical stability of store-and-pour systems can be generally and formally explored using a simple qualitative model of the interrelationships between the "pour" component involving flow and rapid movement of moisture through and out of the system and the "store" component whereby water is stored in non-flowing states or via slow, delayed flow (Fig. 7). Pour and store components may have positive or negative effects on each other in various scenarios. The two components may have negative relationships on each other when there is a fixed quantity of excess moisture partitioned to one or the other. That is, any stored moisture or delayed flow reduces the amount of water in preferential flow paths, and vice-versa. However, flow and storage may also be mutually reinforcing during wet conditions. Channel-wetland-floodplain connectivity and interflows are one example. Large storage amounts in aquifers and soil matrices may enhance preferential

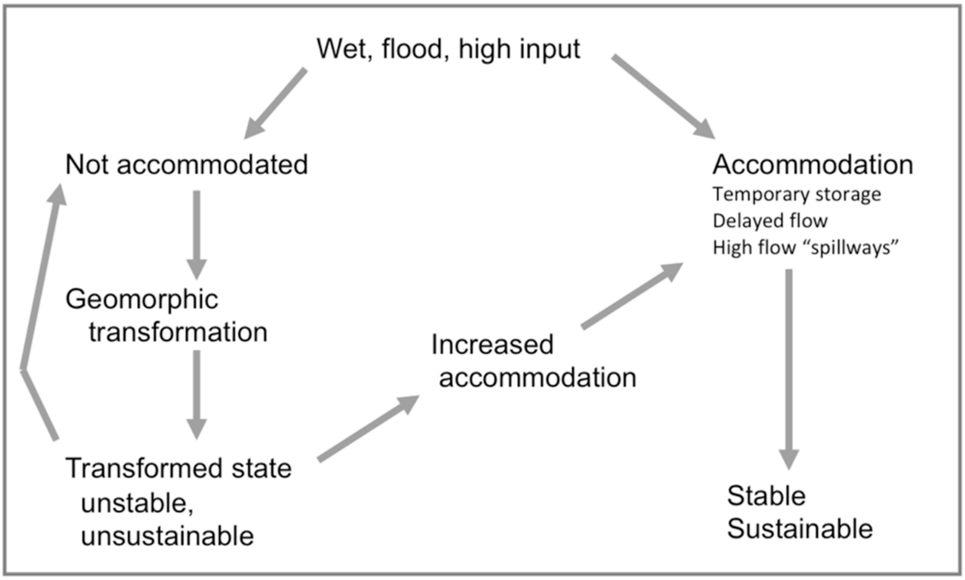

Fig. 5. Wet scenario.

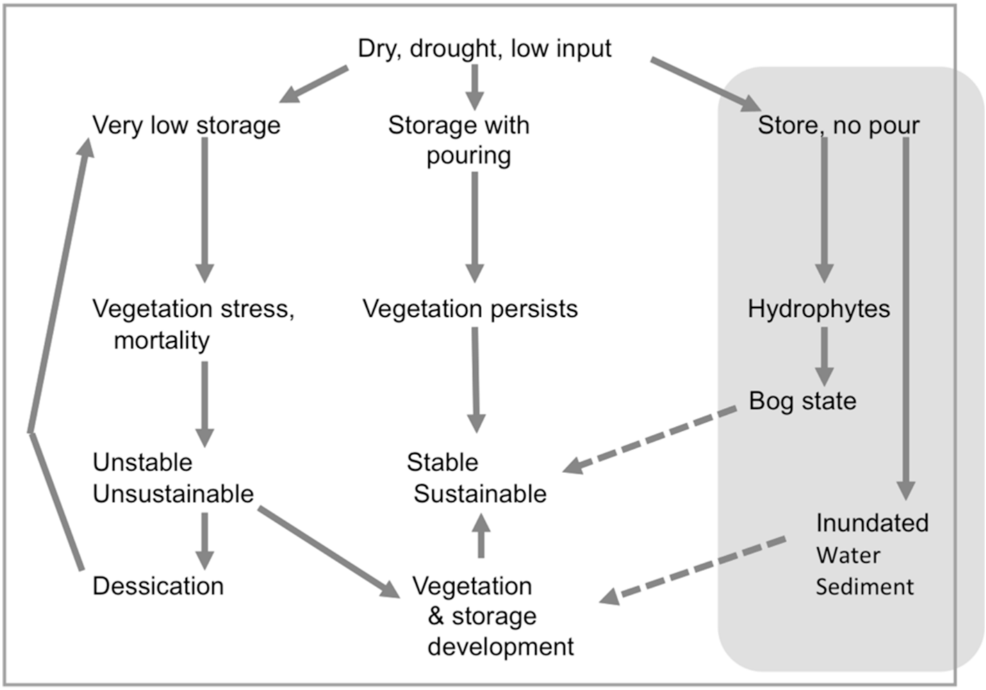

Fig. 6. Dry scenario.

flow via exfiltration and return flow, and large channel or conduit flows may feed subsurface storage.

There also exist scenarios where pour components have negative links to storage, and storage has positive effects on flow/pour components. This occurs when excess storage promotes flow, and when pour processes are draining storage. The opposite may occur when pour or flow promotes storage (positive effect), while storage also limits flow. Overbank flooding, for instance, delivers "pour" water to storage, and this reduces, limits, or delays channel flow. Preferential flow paths may be key for recharging aquifers and raising water tables, for another example, which in turn reduces rapid flows.

Pour and store components also have self-effects. These may be self-limiting, where some factor (e.g., storage or conveyance capacity) limits flow or storage (negative feedback), or self-reinforcing and positive, as for example when soil wetting increases hydraulic conductivity, enabling faster recharge, or as greater flow depths in channels inundates roughness elements, increasing conveyance capacity.

The stability criterion for the system according to the Routh-Hurwitz criteria requires that.

$$a_{ps}a_{sp} - a_{pp}a_{ss} < 0 \tag{4}$$

where a_{ps}, a_{sp}, a_{pp}, a_{ss} respectively indicate feedback links from pour to store, from store to pour, self-effects on pour/flow components, and storage self-effects (see Puccia and Levins, 1985 for mathematical background).

If pour and store components are mutually reinforcing or mutually limiting, the system is dynamically unstable unless negative self-limiting

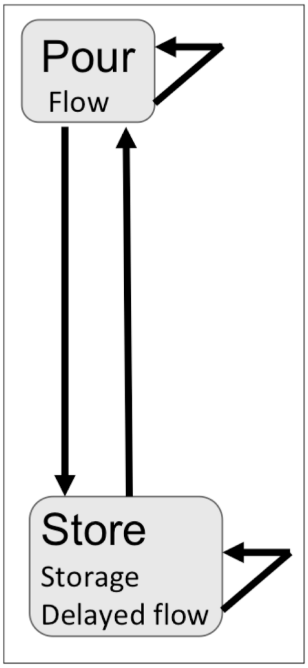

Fig. 7. System model.

effects are dominant. If $a_{ps} > 0$ and $a_{sp} < 0$, $a_{ps} < 0$ and $a_{sp} > 0$ and self-effects are negative (or negative self-effects are stronger than positive ones) the system is dynamically stable.

Table 1 indicates stability analyses of several different scenarios. Stability under dry scenarios depends on moisture storage (scenarios 1, 2). Flow systems with limited storage capacity are prone to vegetation stress and mortality and dessication during dry periods.

Dynamical instability under excessive moisture inputs (defined as greater than normal PFP conveyance capacities and storage) occurs under scenarios when high flows cause enlargement of channels, conduits, etc., unless expanding flow paths capture stored water in sufficient quantities (scenarios 5A, 5B). Limited spillway or secondary storage capacity also creates instability (scenario 6). The presence of spillways to convey excess flows creates dynamical stability (scenario 3), as does secondary storage capability if not overwhelmed (scenario 4).

4. Examples

The conceptual model of emergent S&P systems and the conditions for stability and survival are contrived to explain phenomena that are ubiquitous in nature; thus, examples abound. The examples discussed below are based on hydrologic or geomorphic problems that I am familiar with and are intended to illustrate how S&P reasoning can be applied, and include both specific cases and more generic examples. They are by no means a geographically balanced sampling of flow systems in landscapes.

4.1. *Forest soils*

In work on forest soils and regoliths, we found the presence of PFPs operating in multiple directions through the subsurface to be an importance source of complexity in the evolution of weathering profiles, regolith, and soil (Phillips et al., 2019; Šamonil et al., 2020). In terms of how event-scale moisture flux becomes imprinted in forest soils, Sidle et al. (2001) presented evidence of self-organization of preferential flow systems and developed a general conceptual model for this phenomenon based on studies of forested hillslopes in Japan. PFPs are important conduits for subsurface flow in forest hillslopes. Early studies focused on vertical fluxes, but lateral transport is also important. The “backbone” for lateral flowpaths, Sidle et al. (2001) found, is comprised of macropores formed by decayed and live roots, piping erosion, bedrock joints and fractures, and faunal burrows. Their field studies showed that while individual macropore segments are typically <0·5 m long, they often coalesce into larger preferential flow systems as sites become wetter (Fig. 8). Mechanisms include flow through decayed root channels and subsurface erosion cavities; overflow of small depressions in the bedrock substrate; fracture flow in weathered bedrock; exchange between macropores and mesopores; and flow at the organic horizon–mineral soil interface and in buried pockets of organic material and loose soil. Sidle et al.’s (2001) conceptual model is based on potential connecting nodes such as zones of loose material or subsurface organic matter becoming activated by local soil water conditions to connect macropores. In this way normal conveyance capacity becomes better connected (self-organizing in Sidle et al.’s terms) to provide spillway-type capacity.

Subsequent work has confirmed the fundamentals of the conceptual model above in a variety of soils and extended it to show how macropore connectivity during wet periods also stimulates surface runoff—another spillway effect (e.g., Nieber et al., 2006; Nieber and Sidle, 2010; Liu and Lin, 2015; Wilson et al., 2017).

Table 1
Dynamical stability of pour/flow vs. storage relationships in several scenarios. S = stable; U = unstable; CS = conditionally stable.

Scenario	a_{ps}	a_{sp}	a_{pp}	a_{ss}	*Stability*
1. Dry, with moisture storage	Flow enhances or has no effect on storage	Retention of stored water reduces flow	Negligible or negative	Negative due to increasing tension	S
2. Dry with limited moisture storage	Flow enhances or has no effect on storage	Storage enhances flow due to limited retention, or no effect	May be positive, negative, or negligible	Negligible, or negative due to increasing tension	U
3. Excessive moisture (>storage & conveyance capacities) with spillway overflow	Flow reduces storage	Storage enhances flow by feeding spillways	Negative due to finite conveyance capacity	Negative due to finite storage capacity	S
4. Excessive moisture (>storage & conveyance capacities) with secondary storage	Flow enhances storage by filling depressions, cavities, gravity water	Storage limits flow by activation of secondary storage	Negative due to finite conveyance capacity	Positive, as saturation or filling activates secondary storage	CS[1]
5A. Excessive moisture with erosional enlargement of flow pathways	Flow reduces storage	Storage reduces flow	Positive due to increasing conveyance capacity	Negative due to finite storage capacity	U
5B. Excessive moisture with erosional enlargement of flow pathways	Flow reduces storage	Storage enhances flow due to moisture capture by expanding channels, macropores, or conduits	Positive due to increasing conveyance capacity	Negative due to finite storage capacity	CS[2]
6. Excessive moisture with limited spillway or secondary storage capacity	Positive or negligible	May be positive, negative, or negligible	Negative due to finite conveyance capacity	Positive	U

[1] Stable if conveyance capacity self-effects stronger than storage ($a_{pp} > a_{ss}$); unstable otherwise.
[2] Stable if flow-storage feedbacks (a_{ps}, a_{sp}) greater than self-effects, or if $a_{ss} > a_{pp}$; unstable otherwise.

Fig. 8. Soil in southeast Queensland, Australia originally formed under subtropical forest. Segregated dark areas and visible partings show macropores, looser subsurface material, and buried organic matter pockets that become connected during wet periods.

As some of the other examples illustrate, this shows how storage features (in this case the wettable nodes) begin storing some of the excess moisture inputs, eventually triggering or augmenting spillway processes.

4.2. *Fluviokarst in central Kentucky*

Like many fluviokarst areas, the inner Bluegrass region of central Kentucky features a complex, interconnected mixture of ground and surface water flow, underground conduits and cavities, and surface channels (Fig. 9). The hydrology and Quaternary geomorphic evolution of this landscape has been outlined by White et al. (1970), Thrailkill et al. (1991), Currens and Graham (1993), Ray and Blair (2005), Reed et al. (2010), and Phillips, (2015; 2016; 2017; 2018).

The region has gone through multiple climate changes—mainly glacial and interglacial cooling and warming periods throughout the Quaternary, and prolonged lowering of the base level due to the incision of the Kentucky River over the past 1.5 Ma. Yet, despite these changes in boundary conditions (and human impacts, accelerating since the 18th century), continuing evolution of the geomorphic landscape and hydrogeology, and local transformations (all described in the references above), the general nature of the fluviokarst flow system has remained intact. This suggests general, broad-scale stability at the regional scale, and (according to the conceptual model above) that the necessary conveyance and storage capacities and mechanisms are present.

Normal flow conveyance occurs via underground karst conduits, perennial surface stream channels, and ground-surface water interconnections. These are primarily perennial (underflow) springs, and swallets delivering surface flow to groundwater. Normal storage occurs in underground karst cavities, in more-or-less vertical or unconnected rock joints and fractures, as soil moisture, and in the weathered upper limestone layer (epikarst).

Secondary storage during excessive moisture inputs is accomplished by filling of larger subsurface cavities (e.g., cave rooms), depressions in

Fig. 9. Limestone bank of the Dix River, Kentucky showing a variety of fissures and conduits.

the upper epikarst (typically bowl or saucer-like weathering cavities on surface rock outcrops or beneath a thin soil cover), and karst surface depressions such as dolines. Spillway flow occurs as filled karst conduits or cavities spill or exfiltrate into overlying, normally dry stream channels, activating surface flow. Activation of overflow springs also serves as a spillway.

4.3. *Shrub invasions of drylands*

Establishment of woody vegetation in semi-arid and arid environments often results in landscape divergence into vegetated patches or thickets with thicker soil and more soil moisture storage than sparsely vegetated or bare inter-patch areas. These become patches or islands of vegetation, organic matter, soil fertility, and soil moisture within a matrix of unvegetated, low-fertility, dryer areas (Fig. 10). While I have worked on landscape-scale biophysical feedbacks in this context (Phillips, 1993), with respect to the hydrological processes involved I have relied mainly on experimental studies in the Chihuahuan Desert of North America (Neave et al., 2002; Wainwright et al., 2002; Abrahams et al., 2003; Parsons et al., 2003). However, the general hydrologic phenomena revealed by these studies are apparently common in other dryland systems (Schymanski et al., 2010). The ecosystem engineering aspects are well illustrated by studies in Eucaplypt drylands in Australia (Verboom and Pate, 2006; Verboom et al., 2013).

As the woody plants become established, they create or enhance PFPs that direct water into and through the soil. Within the vegetated patches, normal conveyance thus feeds storage, and the enhanced storage in turn promotes vegetation survival through the inevitable, frequent, and lengthy dry periods in such environments. Additional storage is minimal for excessive inputs, and the spillway mechanisms export water to interpatch areas. The interpatch areas provide the landscape-scale spillway capacity, but the lack of moisture storage capability within the interpatch areas inhibits vegetation establishment and survival (see Fig. 11).

4.4. *Tidal marshes*

In many tidal wetlands, freshwater inflows are negligible compared to tidal and storm flooding. The volume of water associated with tidal inundation between low and high tides is known as the *tidal prism.* Under contemporary sea-level rise, tidal prisms increase unless marsh surface accretion keeps pace with sea-level rise and any compaction or subsidence of the wetlands. In most cases on tectonically stable coastlines, net coastal submergence and thus increasing tidal prisms are occurring (Passeri et al., 2015; Sweet et al., 2017; Burns et al., 2021).

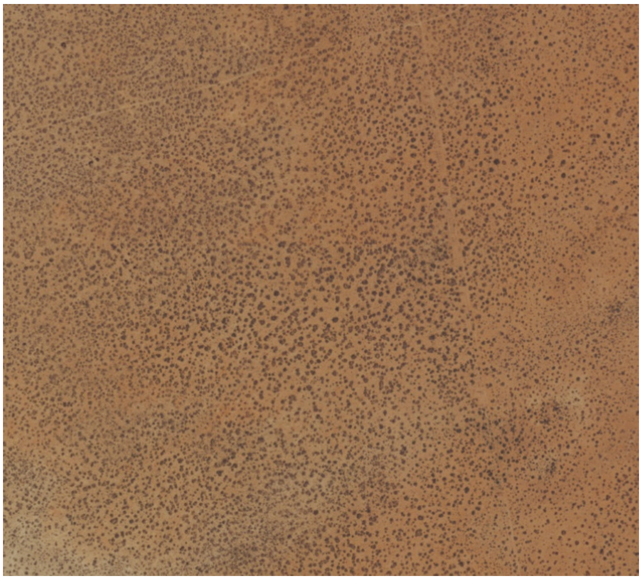

Fig. 10. Matrix of vegetated shrub patches and bare ground near Jornada, New Mexico, USA. Image is about 1500 m east–west by 1350 m north–south. Center of image is at 33.113°N, 106.994°W (U.S. Geological Survey National Aerial Image Program).

The S&P model indicates that marsh survival depends on development of auxiliary storage and/or spillway capacity. Moisture storage capacity may increase due to accretionary increases in normal, matrix storage. Secondary storage is associated with development of depressional storage such as marsh ponds and pans. Conveyance capacity may be increased by expansion of tidal networks as tidal prisms increase, as illustrated by Zhou et al. (2014). Extra spillway capacity could be increased by the formation of high-flow channels, not inundated during normal tides, but activated during spring tide or storm inundation.

Interpreted in this way, the geomorphic transformations such as net marsh loss that sometimes occur as marshes respond to coastal submergence (e.g., Phillips, 2018c; 2018d) are evidence of a failure to develop spillway and secondary storage capacity rapidly enough.

4.5. *Ravine swamps, eastern North Carolina*

Along some drowned river valley estuaries in North Carolina there exist fluvially dissected areas along the valley sides. These relatively short, high relief freshwater tributaries were incised during lower Pleistocene sea-levels. Their former lower reaches are now obscured and buried within the estuary, and they typically terminate near the estuarine shoreline as ravine swamps. The ravine swamps are mainly fed by freshwater runoff, but occasionally get inputs from storm surges from the adjacent estuary. The ravine swamps have almost literal spillways in terms of high flow channels and overflow outlets, and secondary storage available by inundating the lower slopes of adjacent uplands. They are thus stable under most circumstances.

However, ravine swamps along the Neuse River estuary were overwhelmed by storm surge inputs during Hurricane Florence in September 2018. Storm surges of about 3 m inundated the swamps, and persisted for several days. This overwhelmed the secondary storage and spillway capacities, resulting in a transformation of portions of the ravine swamps from wetlands with perennial standing water and muck or mucky clay substrate to rarely flooded sandy lowlands. These changes are described in Phillips (2022a).

4.6. *Neuse River fluvial-estuarine transition zone*

Upstream of the Neuse estuary, the fluvial-to-estuary transition zone of the Neuse River is characterized by a multi-channel planform that does not conform to any of the classic or archetypical anastomosing or anabranching planform types. Rather, the entire valley bottom, with the exception of some slightly higher islands composed of Pleistocene alluvial terrace remnants, is a complex of active channels (including both a dominant channel and perennially flowing subchannels), backwater channels, high-flow channels, floodplain depressions, and floodplains that often convey flow downstream (Phillips, 2022a;b). The distinctions among these are often gradual and transitional rather than sharp—channel margins, for instance, often consist of a transition over several meters to > 10 m from open water to emergent in-channel vegetation to perennially or frequently-flooded swamp rather than distinct banks.

Normal conveyance capacity is provided by the active channels, though at all but the lowest flow levels some delayed flow occurs through the floodplain wetlands. Normal storage capacity is in floodplain soils and abandoned, isolated channel segments (sloughs; oxbows are not present in the area). The downstream flow that occurs within the floodplains at all but the lowest discharges can be considered part of both normal conveyance capacity and storage, as the flow is delayed (due to lower depth and much greater roughness compared to channel flow).

Fig. 11. Tidal marsh at Huntington Beach, South Carolina showing tidal channel networks, marsh depressions, and high flow channels. Area shown is about 0.6 × 0.5 km; coordinates at center are 33.5149 N, 79.0665 W. GoogleEarth^{TM} image.

The backwater channels are Neuse River anabranches and are a part of storage at low and typical flows. As total discharge increases, they provide some additional storage, but are eventually converted to downstream-flowing channels—spillways. Floodplain depressions likewise provide secondary storage, but are converted to downstream flow at high inputs to provide another spillway.

Astronomical tides are minimal, though detectable, in the area, but wind-driven water level changes, especially storm surges, frequently push water upstream. However, the store-and-pour capabilities of this area are able to handle even the most extreme events. This is illustrated by minimal changes that occurred due to Hurricane Florence, where the highest storm surges ever recorded in the lower Neuse River and estuary occurred, and where upstream discharges were at least the third highest on record (the lowermost stream gage on the river failed before the peak flow was reached) (Phillips, 2022b).

4.7. *Artificially drained landscapes*

Another example from eastern North Carolina concerns artificially drained agricultural land. The outer coastal plain is flat and low (<6 m above sea level). Large scale commercial agriculture and intensive silviculture require artificial drainage to lower water tables, typically achieved with rectangular networks of drainage ditches and canals. Studies of the hydrological impacts of these systems and of the hydrology and geomorphology of the artificial channels themselves allow a before-and-after comparison between undrained, drained, and post-drained conditions in the S&P context, using “drained” here to refer to the constructed ditches and canals (Phillips, 1988; 1997; Belk and Phillips, 1993; Lecce et al., 2006a, 2006b; Dollinger et al., 2017; Kamrath et al., 2020; Skaggs et al., 2020).

In the undrained condition, normal storage is entirely within the soil and underlying unconsolidated coastal plain sediments, including water tables regularly at or within 0.5 m of the surface. Secondary storage occurred in shallow surface depressions, and by local ponding and elevation of water tables above the ground surface. Flow and conveyance capacities were low, due to minimal gravitational driving gradients and limited to low-gradient streams subject to backwater effects, and groundwater flow directly to estuaries. As a result, the unmodified landscape was a mosaic of wetland and other poorly drained lowland environments supporting vegetation tolerant of soil saturation.

The artificial drainage system increased conveyance capacity, and water table rise to or near the ground surface became a means of temporary secondary storage rather than normal storage capacity. Spillway mechanisms were still limited, but sometimes augmented with pumping systems. In some cases, water tables are mechanically manipulated via water control structures, essentially creating an engineered S&P system.

Flow in the ditches and canals is inadequate to maintain the channels, however, as drainage density has been increased such that the contributing area per unit of channel length is insufficient, given the low velocities due to the minimal slope gradients. Without maintenance such as vegetation and debris removal and re-excavation, the channels rapidly lose conveyance capacity. Typically, maintenance is required every two to five years to maintain flow in the ditches and canals. In a post-drainage state, when maintenance is discontinued and/or water control structures such as flashboard risers are permanently left in place to dam canals, the channels become, essentially, linear ponds. The post-drainage hydrologic system is therefore similar to the pre-drainage, with storage augmented by the ditches and canals. Non-maintenance or simple plugging of canal outlets is often a viable method of restoring wetlands in the area. The main difference between pre- and post-drainage is that the channels may fill-and-spill during exceptionally wet periods to provide some limited spillway capacity.

This example reiterates that hydrological systems without sufficient spillway and/or secondary storage capacity are, or will become, wetlands.

5. Discussion

Like many other environmental phenomena, hydrologic flow patterns in landscapes often take optimal forms or approachoptimality in terms of flux efficiency, thermodynamics, or biological suitability. Yet, hydrological systems have no goals or intentionality. And while inheritance exists in the form of historical contingency and relic features, those optimal configurations are not heritable; subsequent flow systems on ever-changing landscapes must develop them independently.

At the broadest level of generalization, optimal flow configurations consist of a combination of a network of faster preferential flow paths coupled with interstitial areas of moisture storage and slow flow. These structures can store water during dry periods and "pour" excess water when necessary, thus the store-and-pour shorthand. S&P patterns are predicted, or their advantages explained, from several different theoretical perspectives, including dissipative systems and thermodynamics, least-work principles, constructal theory, network and percolation theory, and plant ecohydrology.

S&P patterns can be explained without implying teleology, teleomatics, or goal functions, as emergent phenomena. Concentrated flow happens, and positive feedbacks reinforce these as preferential flow paths. Intersecting PFPs form networks. Establishment of PFP networks also segregates the surface or medium into pour or flow pathways, and interstitial storage and flow-generating areas. Thresholds limit the growth of PFPs and networks, ensuring the preservation of the S&P segregation. Once formed, S&P patterns survive because, or when, they are dynamically stable.

The dynamical stability hinges mainly on the ability to handle inputs greater than the normal storage capacity of the matrix and the conveyance capacity of the PFPs. This occurs due to secondary storage (e.g., in surface depressions, subsurface cavities, gravity water in pore spaces) and spillways able to pour off excess water. Spillways are intermittent flow paths activated by overflow of normal conveyance and storage capacities. Some secondary storage features are of the fill-and-spill variety, connecting or activating spillways when their storage capacity is exceeded. In addition to examples mentioned above, fill-and-spill dynamics have been shown to apply to floodplain lakes and depressions (Phillips, 2013), and to flow through fractured bedrock (Guo et al., 2019). These fill-and-spill dynamics may occur at multiple scales or stages of wetting at a single site (Stewart, 2019).

As an emergent process including selection, evolution of S&P configurations is probabilistic, not deterministic. Maximum-efficiency patterns do not always develop, even where there are no constraints that prevent it. One key reason for this is that gradient and resistance selection is highly localized. Flowing water is only affected by factors in its immediate vicinity, and maximum efficiency locally may or may not be consistent with efficiency at a broader scale. Another is that multiple criteria are often in play. Ecosystem engineer organisms, for instance, may modify store and pour conditions for their own benefit that are not optimal in other respects. Changes in soil porosity created by tunnelling and mounding ants, construction of ponds by beavers, and accumulation of peat from sphagnum mosses are examples.

Survival of S&P systems is enabled by their stability, but some caveats are in order. First, no hydrological or geomorphological system is dynamically stable with respect to all disturbances—any system can be overwhelmed. Transformation of the ravine swamps described above by a hurricane is an example, as are some transformations created by, e.g., megafloods, damming or dam breaks, or anthropic modifications. Stability can also vary spatially, or at different scales, within a single system. Thus, overall dynamical stability of a S&P system does not guarantee or imply stability at all places or times within it. Local instabilities within globally stable S&P systems are in fact quite common.

Finally, the emergent concept presented here is intended only to explain the ubiquitous and repetitive formation of S&P phenomena in diverse hydrologic settings. There is still much to learn about the process mechanics involved, the dynamics of hydrologic systems at a range of scales from pore to planet, and many other factors. For example, preferential flow in soils is not always due to channel or conduit-like features such as macropores or pipes—Guo and Lin (2018), for instance, enumerate 14 forms in all. Not all of these—for example, flow along textural boundaries or soil-rock interfaces—are as readily amenable to S&P reasoning, particularly as it relates to networks. And as Radolinski et al. (2021) point out, there still exist many unanswered questions regarding the mechanisms of interactions between matrix flow/storage and PFP in soils.

6. Conclusions

Preferential flow patterns occur at all scales in hydrologic systems. At the broadest level of generalization, optimal flow configurations consist of a combination of a network of faster preferential flow paths coupled with interstitial areas of moisture storage and slow flow. These structures can store water during dry periods and "pour" excess water when necessary. S&P patterns are predicted, or their advantages explained, by dissipative systems and thermodynamics, least-work principles, constructal theory, network and percolation theory, and plant ecohydrology. These all converge on the same predictions and interpretations of preferential flow, which satisfactorily answers the "why" of how these patterns form and persist. But as hydrologic systems have no ability to actively seek improved efficiency, *how* these systems evolve is an open question.

A five-part emergent explanation is presented here. First, concentrated flows form due to principles of gradient and resistance selection. Second, positive feedback reinforces the concentrated preferential flow paths and their relationship to potential moisture storage zones. Third, intersecting flow paths form networks. Fourth, the expansion of concentrated flow paths and networks is limited by thresholds of flow needed for channel, macropore, or conduit growth and maintenance. This results in a store-and-pour flow system that can retain water during dry periods and transport it efficiently during wet periods. These systems survive provided they develop "spillway" and/or secondary storage mechanisms to accommodate excess water inputs. Finally, store-and-pour systems are maintained (selected for) because they are often dynamically stable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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