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Contingent partitioning and adaptation in hydrological systems

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Abstract

The question of whether the concept of adaptation can be applied to Earth surface systems (independently of biological adaptation) is addressed by examining hydrological flow systems. Hydrological systems are represented in terms of a partitioning of water inputs among various flux and storage components and outflows or outputs of the system. Partitioning is contingent on the flow system in question and the synoptic situation (i.e., drier, low-input vs. wetter, high-input conditions). The general allocation among inputs, flows through or within the system, storage and outputs is examined via analysis of 20 scenarios for soil hydrology, a fluvial channel-wetland complex and a fluviokarst landscape representing different combinations of positive, negative and zero (neutral) relationships among these elements, and positive self-reinforcing and negative self-limiting effects. Conditions for stability were determined using the Routh–Hurwitz criteria and linked to the two fundamental roles or 'jobs' of hydrological flow systems. The ecological job is to support biota and biogeochemical fluxes and transformations necessary for ecosystem functions. The geophysical job is to remove excess water. Results show that low-input scenarios for the soil, fluvial wetland and fluviokarst scenarios are marked by dynamical instability. During drier periods the geophysical job is irrelevant and the ecological functions are suboptimal. Instability allows for rapid state changes when moisture inputs increase, to system states that support ecosystem functions. High-input, excess moisture and flood scenarios, by contrast, are generally dynamically stable. In wetter conditions, the ecological functions are not moisture-stressed, and the geophysical job becomes paramount. The high-input stability is associated with activation of 'spillway' mechanisms that allow the systems to maintain themselves by efficient export and augmented storage of excess water. Contingent partitioning indeed appears to be an adaptation mechanism in hydrological systems and suggests the possibility of adaptation in other Earth surface systems with important abiotic components.

KEYWORDS

adaptation, contingent partitioning, dynamical stability, ecological job, flow system, geophysical job

1 | INTRODUCTION

1.1 | Adaptation and partitioning

Do environmental systems adapt to changes in their inputs, boundary conditions or internal structures and processes? Certainly, they respond to such changes, and as those responses are finite and often decelerate, they can often be said to have adjusted. Biological adaptation is often defined as the adaptation of living things to environmental factors for the ultimate purpose of survival, reproduction, and an optimal level of functioning. To avoid defining something in its own terms, substitute 'adjustment' for adaptation, and to broaden the definition, substitute 'environmental systems' for living things; adaptation is adjustment of environmental systems so as to enable survival and an optimal level of functioning. Abiotic phenomena cannot have purpose, and as far as we are aware, the adaptation of most living things is also without conscious planning or goals. Thus, if hydrological (or other Earth surface) systems adjust to enhance their persistence or functioning, they can be said to adapt. Ecohydrological responses to drought, for example, can be explained by changes in process connectivity (Goodwell et al., 2018). To the extent this facilitates survival and optimal functioning, it is a form of adaptation as defined above. The purpose of this paper is to assess whether hydrological systems more broadly and generally are adaptive.

Hydrological and other environmental systems (and even more economic, social, political, cultural, biomedical and computing systems) have been characterized as *complex adaptive systems* (CAS). *Web of Science* (as of October 2022) turns up 80 titles of the form '_____________ as a complex adaptive system' from almost as many different disciplines and subdisciplines. However, as applied to hydrology, water resources and geosciences, these studies have focused on design or human management (e.g., stormwater or resource management systems), on CAS as a descriptive or metaphorical device or on the global scale (e.g., Earth or the biosphere as a CAS). This study differs from the CAS literature by focusing on whether and how local to landscape scale systems may adapt as defined above, in a manner broadly analogous to biological adaptation.

Hydrological analysis is fundamentally based on partitioning or budgeting of water. Examples include the hydroclimatic water balance, which apportions precipitation inputs among evapotranspiration (ET), soil moisture storage and runoff (including percolation to groundwater). The approach is flexible in that any component—for example, soil moisture or runoff—can be the focus and its inputs and outputs budgeted. Rainfall-runoff modelling is another familiar example, whereby effective precipitation inputs are partitioned among surface runoff, infiltration, soil moisture storage, saturated throughflow and groundwater responses. Either of these methodologies, and other budget-based frameworks, can readily be expanded to include additional fluxes and storages.

Rainfall-runoff analysis and water balances or budgets are inherently linked to dynamic situations at event to seasonal scales and recognize that partitioning of water varies from one event or episode to the next. This applies not just to quantitative amounts and relative proportions but also to qualitative dynamics—that is, whether pathways or partitions operate or not. For instance, the two major conceptual models of overland flow generation are based on shutoff/inhibition or activation of processes. With respect to saturation-excess runoff, infiltration and soil moisture recharge are shut off when soil is saturated, and no surface runoff by this mechanism occurs if soil moisture is not fully recharged. Infiltration-excess (Hortonian) runoff occurs when precipitation intensity exceeds infiltration rates, inhibiting infiltration and soil moisture recharge. In addition to quantitative variations in allocations, and (in)activity of flux and storage mechanisms, some flow pathways and connectivity patterns can be reversed in different situations (e.g., Hiatt et al., 2022; Phillips, 2022c; Tull et al., 2022).

Specifically, this study examines four propositions:

- Dynamic, contingent partitioning of water in hydrological systems constitutes adaptation.
- Contingent partitioning may involve the *reversal* of fluxes as well as the operation or non-operation of flux or partition pathways.
- Changes in partitioning are associated with changes in the dynamical stability of hydrological systems.
- Successful hydrological systems are dynamically unstable during low-input periods, allowing for rapid response to increased inputs, and stability during high inputs maintains the system state. This is linked to the jobs of hydrological systems discussed below.

A 'successful' hydrological system persists (and sometimes expands) through subcatastrophic environmental change; operates efficiently to process moisture via storage, utilization and transport; and supports a vegetation community. The subcatastrophic caveat recognizes that any environmental system may be unable to survive extremely large disturbances or environmental changes.

This study was motivated by the question of adaptation in environmental systems in general and hydrological systems in particular. However, the analysis is relevant to urgent contemporary questions about the effects of climate (and other environmental) changes on hydrological and ecological systems and water resources. For instance, Fowler et al. (2022) noted recent major hydrological shifts in relationships between precipitation and stream flows associated with persistent droughts such as the Australian 'megadrought' of 1997–2010. There, and on other continents, stream discharges were reduced during the dry periods even beyond what would have been expected based on existing trends and historical records, and discharge recovery post-drought was also lower than expected. Causes are unknown but must involve shifts in the partitioning of rainfall inputs within the watershed systems. These could plausibly be related to dynamical instabilities that amplified some effects of the drought, or to the loss or diminishment of amplification or damping effects. In southwestern Australia, for example, Kinal and Stoneman (2012) found that drought caused disconnection of ground and surface water as water tables fell. Connected groundwater amplified other streamflow generating processes, and these feedbacks were lost as surface and groundwater became disconnected.

1.2 | The job(s) of hydrological flow systems

What is the role of a hydrological system? From a geophysical perspective, it is simply to move excess water. When more

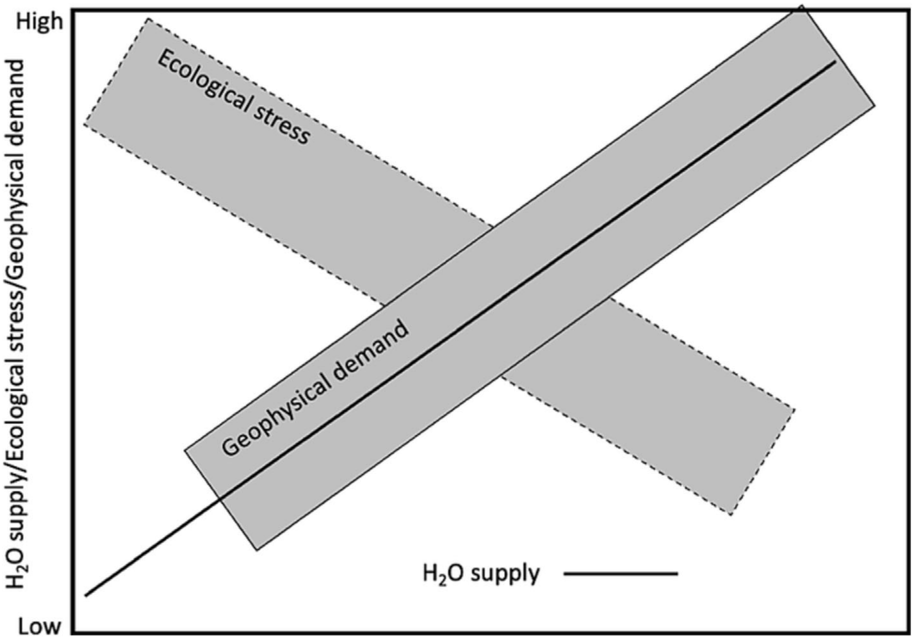

FIGURE 1 Highly simplified conceptual model of the relationship between water inputs to a flow system, stress on the ecological functions and the need to move excess water (geophysical demand). Ecological stress and geophysical demand are shown as bands to represent the fact that they will vary according to factors other than moisture supply. All are shown as straight lines or bands for simplicity; actual functions are more complex (for instance, in some systems ecological functions may be limited by excess moisture).

precipitation falls than can be evaporated, than the ground can hold or that organisms can use, it must go somewhere. In liquid form, going somewhere is driven by gravity. Fluvial systems, for instance, develop so as to do this, with selection processes favouring concentrated or channelized over diffuse flows and branching channel networks (Phillips, 2010). Associated processes, such as erosion, sediment and solute transport, and biogeochemical fluxes are byproducts of the fundamental hydrological job of accommodating excess water.

From an ecological perspective, the job of a hydrological system is to support biota, particularly plants, in various ways—supplying water, removing or transferring byproducts and facilitating biogeochemical cycles. Of course, biota must adapt to hydrological conditions, particularly those largely dictated by climate. However, via their own critical impacts on the hydrological cycle and various ecosystem engineering processes, plants and other organisms affect, as well as being affected by, hydrology.

A successful hydrological system performs both its geophysical and ecological roles. For many flow systems, when inputs are low, the ecological functions are stressed and may not be fully or optimally supported. The geophysical job is mostly, if not wholly, irrelevant as there is little or no excess water to move. Thus, the ability to respond quickly to increased inputs is advantageous to fully perform the ecological job (Figure 1).

During high, excess inputs water supply for ecological functions is not limited, so the geophysical function becomes paramount. Of course, anaerobic conditions and other impacts of excess moisture can cause ecological stress, but these will be minimized if the geophysical role is performed. If the system is to survive, for example, floods, downpours and inundations (and they do not always do so, as erosion, sedimentation, waterlogging, etc. may transform them), mechanisms to handle the excess water must exist. I previously argued that this happens via 'store and pour' morphologies and mechanisms, whereby augmented storage and, especially, high-input-activated 'spillways' exist (Phillips, 2022c).

This implies that adaptation in hydrological systems is characterized by dynamically unstable configurations during dry and stable configurations during wet periods.

Note that the concern here differs from water balance-based distinctions between energy limitations and water limitations at the catchment or ecosystem scale, such as the Budyko (1974) curve. The Budyko curve is based on the ratio of potential ET and precipitation, with a ratio of 1.0 separating energy limitations versus water limitations in determining the rate of ET. It is based on a long timescale perspective where all precipitation is partitioned to ET and runoff, with net storage implicitly considered zero (see review by Sposito, 2017). The Budyko curve is typically applied at broad spatial scales, such as the recent application to global scale hydrological shifts in response to climate change (Denissen et al., 2022). This paper is concerned with shorter time scales where storage is important (and generally more limited spatial scales as well) and with the partitioning of effective precipitation (precipitation minus ET).

1.3 | Dynamical stability and adaptability

If (or when) a system is dynamically stable, it is relatively insensitive to small perturbations or changes and can return to its predisturbance state (even a dynamically stable system is not necessarily stable to larger disturbances). When a system is dynamically unstable, it is sensitive to small changes and perturbations, with impacts that are large and long-lived compared to the magnitude and duration of the disturbance. Instability is often associated with system state changes. State changes are qualitative changes in the nature or character of the system. For instance, fluctuations in absolute humidity of air do not constitute a state change unless they cross the dew point threshold, triggering a state change between condensation or not. For another example, changes in the quantitative values of width, depth, velocity, hydraulic slope or friction factor do not, in and of themselves, constitute state changes in stream flow. However, different modes of adjustment to variations in imposed flow—combinations of increases, decreases or constancy of the hydraulic values to accommodate the flows—are state changes (Phillips, 1990, 1991). Dynamical stability is consistent with some concepts and definitions of resilience. However, sometimes system state transitions are necessary to adapt to changes. Simple examples are when a stream shifts from single-channel to multichannel flow in response to floods, normally dry conduits in karst are activated during wet episodes, or plant stomatal resistance changes during dry periods. Adaptation of environmental systems may thus be related to both dynamically stable and unstable behaviour in different situations.

Though dynamical stability is not constant in time, space or at different scales, we nonetheless tend to think of it as an either/or phenomenon. That is, a system is either stable, unstable or on a cusp between the two. Mathematically, dynamical stability is determined by the positive and negative linkages among system components. In hydrological and other environmental systems, however, these links can change frequently. Various water flow and storage relationships are activated or deactivated, for example, during wetter or drier periods, modifying stability (e.g., Guo et al., 2019; Rusjan & Mikoš, 2015; Teuling et al., 2010). This has some parallels in other Earth surface systems. Over landscape evolution time scales, geomorphological systems may undergo shifts between dynamically stable and unstable modes as interrelationships increase or decrease in relative strength or intensity (Davidson et al., 2021; Thompson et al., 2016). Several authors have argued, for example, that global or whole-system stability of environmental systems may require local or subsystem dynamical instability (e.g., Dambacher et al., 2009; Dambacher, Li, & Rossignol, 2003; Dambacher, Luh, et al., 2003; Marzloff et al., 2011; Trofimov & Phillips, 1992). For river systems, sensitivity to disturbances at multiple scales effect those of larger and smaller scales in complex ways (Fryirs, 2017).

In this study, a generalized hydrological system is analysed with respect to its dynamical stability properties and the ability of the system to adapt to changes in its external environment and flow and storage dynamics within the system. The analysis will not shed new light on the mechanics of hydrological system functions; rather, the goal is to analyse and interpret these functions in the context of hydrological system adaptations. Neither will the analysis identify any previously unknown adjustments or adaptations of hydrological systems, except perhaps with respect to particularities of the case studies. Rather, I seek to reinterpret hydrological phenomena through the lens of adaptation. The results should also be relevant to the study of adaptation and resilience in environmental systems more generally.

2 | METHODS

2.1 | Hydrological flow systems

A generalized hydrologic system is presented, applicable at least in broad strokes to most, if not all, such systems. The simplest and most general representation of an environmental flow system has four components—inputs and outputs of water, and flow through and storage within the system. For example, a soil hydrology system has precipitation and run-on inputs, runoff (including percolation and subsurface lateral flow) and ET outputs, matrix and macropore flow within the soil, and soil moisture storage. Here we are concerned with apportioning of *effective* precipitation, accounting for ET. Such a system can be represented as shown in Figure 2, which is described in more detail below.

The system is translated into an interaction matrix, with the entries a_{ij} indicating fluxes or exchanges between components (Table 1). A positive link indicates water flow from the row to the column component. Negative links indicate that the row component is 'competing' for water with the row component in a zero-sum manner. For example, in the version shown in Figure 2, moisture stored within the system reduces both throughflow and outputs. Inputs, throughflow, storage, and outputs may also have self-limiting effects (e.g., finite storage or conveyance capacities). Though Figure 1 shows all self-effects as negative, they may sometimes be positive, as when wetting, or drowning of roughness elements, enhances conveyance or storage capacity.

In this analysis, inputs are taken as effective precipitation (precipitation–evapotranspiration) and run-on or inflow. Input–output relationships are mediated by flow and storage within the system, so there are no direct links from input to output. Note that the interaction matrix shows some entries associated with links not shown in Figure 2—these are links that may be, but often are not, nonzero.

Each a_{ij} in Table 1 was assessed with respect to its positive, negative, or zero (non-active) status in various scenarios. Then the dynamical stability of various scenarios (combinations of positive, negative and zero links) was assessed.

2.2 | Stability analysis

Figure 2 is a signed, directed, unweighted graph or a signed digraph. A graph interaction matrix $\boldsymbol{A}$ consists of an $N \times N$ ($N = 4$ in this case) matrix with entries that are positive, negative or zero depending on the links between the row and column elements. $\boldsymbol{A}$ has N complex eigenvalues λ_i, the real parts of which are the Lyapunov exponents of the underlying dynamical system; $\lambda_1 > \lambda_2 >. \ldots \lambda_N$. If all $\lambda < 0$ (which must be the case if $\lambda_1 < 0$), the system is stable. If any $\lambda > 0$ (i.e., $\lambda_1 > 0$), the network is unstable.

F_k ($k = 1, 2, \ldots, N$) is the feedback at level k of the system, with $F_o = -1$ by definition:

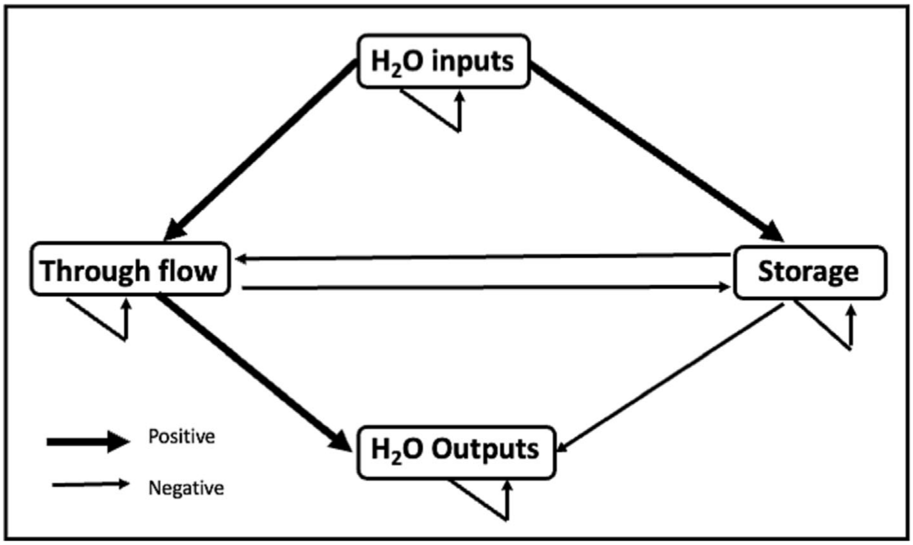

FIGURE 2 Generalized hydrological system. Through flow refers to all water flux through the system, as opposed to throughflow within soil.

TABLE 1 Interaction matrix for generalized hydrological system.

	Inputs	Throughflow	Storage	Outputs
Inputs	a_{11}	a_{12}	a_{13}	0
Throughflow	0	a_{22}	a_{23}	a_{24}
Storage	0	a_{32}	a_{33}	a_{34}
Outputs	0	a_{42}	0	a_{44}

Note: Nonzero entries may be positive, negative, or negligible (≈0) under various circumstances.

$$F_k = \Sigma(-1)^{m+1} Z(m,k) \quad (1)$$

Z(m,k) is the product of *m* disjunct loops with *k* components. The F_k are equal to the coefficients in the characteristic equation of the system, which can be written

$$F_o\lambda^n + F\lambda^{n-1} + F_2\lambda^{n-2} + ... + F_{n-1}\lambda + F_n = 0. \quad (2)$$

The system is dynamically stable according to the Routh–Hurwitz criteria if and only if $F_k < 0$ for all *k* and successive Hurwitz determinants are positive. The second condition implies $F_1\ F_2 + F_3 > 0$, for $n = 3$ or 4. If the first criterion is satisfied, the second indicates that stability is contingent on the feedbacks represented in F_1, F_2 being stronger than those in F_3.

Stability analyses of numerical models are fairly common in hydrology, but qualitative stability analyses are relatively rare. The latter, however, can provide rapid insights into system behaviour that cannot be achieved through observational studies or direct analyses of mathematical structures of numerical models, according to Maneta et al. (2018), who illustrated the point using a qualitative phase space model of catchment storage dynamics. Jenerette et al. (2012) argued that a view of water-limited ecohydrological systems as complex adaptive systems focused on system self-organization, feedbacks and thresholds, for example, is needed to understand system dynamics.

Qualitative modelling of complex systems was pioneered in ecology (e.g., Levins, 1974), where analyses have mainly been limited to determining whether specific ecological interaction networks are stable, or to addressing the relationship between stability and complexity in ecosystems (Dambacher, Li, & Rossignol, 2003). The methods were introduced to geomorphology and hydrology by Slingerland (1981), who used an example from river hydraulic geometry. Phillips (1990, 1991) updated that analysis, defining interactions based on flow resistance equations. Other examples of Routh–Hurwitz stability analyses in hydrology, aquatic ecology and fluid mechanics include Phillips and Steila (1984), Phillips (2017), Wengert et al. (1999), Dambacher et al. (2009), Redondo et al. (2020), Ahuja and Girotra (2021), Xiong et al. (2021) and Hai and Daripa (2022).

2.3 | Entropy

In recent years, an approach to modelling hydrological and other Earth surface systems (ESS) based on information theory has gained prominence (Kumar & Gupta, 2020). This approach views information as both a physical quantity and a statistical measure, as reflected, for example, in the use of similar mathematical tools to examine both thermodynamic entropy and Shannon (statistical or information) entropy. Like the analysis in this paper, the information theory approaches are often applied to networks of interactions or flows and are concerned with emergent patterns and complexity. Hydrological examples reflecting these themes include Goodwell et al. (2018), Konapala et al. (2020), Budakoti et al. (2021) and Goodwell and Bassiouni (2022). Entropy was computed in this study to determine whether it has a systematic relationship with contingent partitioning and dynamical stability.

Information theory approaches to hydrology commonly use transfer entropy (e.g., Goodwell et al., 2018; Goodwell & Bassiouni, 2022; Kumar & Gupta, 2020). This requires a probability density function (PDF) for transfers among components. Estimates of PDFs are

TABLE 2 Interactions for the soil hydrology scenarios, with −, + or 0 indicating negative, positive and neutral links, respectively.

Scenario	a_{11}	a_{22}	a_{33}	a_{44}	a_{12}	a_{13}	a_{23}	a_{24}	a_{32}	a_{34}	a_{42}
Stable benchmark	−	−	−	−	+	+	+	+	−	−	0
1. Base case	−	−	−	−	+	+	−	+	−	−	0
2. Dry	0	0	−	0	+	+	−	+	−	−	0
3. Recharge	−	0	+	0	+	+	−	−	−	−	0
4. Wetting	−	+	−	0	+	+	−	+	−	−	0
5. Saturation	−	−	−	−	+	+	+	+	+	−	−
6. Hortonian	−	−	−	−	+	+	−	+	−	−	−

Note: Links that are always zero are not shown.

certainly possible for the kind of systems analysed here, but they are situation specific and are not used in this study so as to maintain generality. Instead a form of entropy suited to directed digraphs was used.

Von Neumann entropy *S*, originally developed in quantum mechanics, is an extension of Shannon entropy. It quantifies the amount of quantum information in a state when multiple identical and independent states are available. Its application in information theory is the extension of the Shannon entropy defined over the re-scaled eigenvalues of the normalized Laplacian matrix. A quadratic approximation of the von Neumann entropy gives a simple expression for the entropy associated with the degree combinations of nodes forming edges.

Ye et al. (2014) developed a method for approximating the Von Neumann entropy of directed graphs, and Wang et al. (2018) gave several example applications. *S* is based on the in- and out-degrees of system components or vertices (d^{in}, d^{out}) and varies with the degree distribution and the number of vertices *N*. The subscripts *u* and *v* refer to a component *u* and *v* to the components or nodes it is connected to. In Equation (3), there is a separation of one-way and two-way edges or arrows (*E*, *E2*).

$$S = 1 - \frac{1}{N} - \frac{1}{2N^2}\left\{\sum_{u,v \in E} \frac{d_u^{in}}{d_v^{in}\; d_u^{out^2}} + \sum_{u,v \in E2} \frac{1}{d_u^{out} d_v^{out}}\right\} \tag{3}$$

The systems and scenarios analysed here are based on potential positive, negative and zero (no edge exists) links, so only one-way edges are used. In this situation, the approximation in Equation (4) can be used (Ye et al., 2014).

$$S = 1 - \frac{1}{N} - \frac{1}{2N^2}\left\{\sum_{u,v \in E} \frac{d_U^{in}}{d_v^{in}\; d_u^{out^2}}\right\} \tag{4}$$

2.4 | Case studies

The implications of the stability analysis were tested using three case studies, each examining multiple scenarios to determine conditions for dynamical stability.

2.4.1 | Soil hydrology

Soil hydrology scenarios are generic, based on general principles of rainfall response and soil moisture storage. The signs of the interaction links are shown in Table 2. A stable scenario is also included as a benchmark case where all signs were selected to achieve dynamical stability by the Routh–Hurwitz criteria. The scenarios are intended to represent common synoptic situations but do not include all possible configurations.

The base case has the same positive and negative links as Figure 2. The dry scenario applies to limited precipitation inputs to soil with available soil moisture storage capacity, and no pre-event flow. Accordingly, self-limits other than storage are irrelevant, and storage and through flow compete for inputs, with storage dominant. The recharge scenario includes unfilled storage, with self-enhancement of storage due to wetting front propagation and activation of pores. The wetting scenario is similar but is based on storage capacity being approached so that self-limits become relevant, and flow competes more effective for inputs. In the saturation scenario, all self-limitations are operating, outputs may limit flow, and flow and storage are mutually reinforcing as gravity water and surface ponding and runoff can both feed, and be fed by, flow within the system. The Hortonian case applies to infiltration-excess runoff, where precipitation intensity exceeds infiltration capacity.

2.4.2 | Neuse river fluvial–estuarine transition zone

These scenarios are based on field observations of the fluvial–estuarine transition zone (FETZ) of the lower Neuse River, North Carolina (Figure 3), made in the context of evaluating impacts of Hurricane Florence (Phillips, 2022a) and examining the geomorphology and hydrology of the FETZ (Phillips, 2022b).

The Neuse River flows across the Piedmont province of North Carolina and joins the Neuse estuary at New Bern, with a drainage area upstream of the FETZ of about 10,000 km^2. The Neuse estuary is a drowned river valley connected to the lagoonal Pamlico Sound, which buffers the Neuse from the ocean and astronomical tidal effects. The estuary is wind-dominated with respect to water level changes. Northeasterly (NE) winds result in higher stages and push water upstream, and strong NE winds can result in minor flooding and

FIGURE 3 Fluvial–estuarine transition zone, Neuse River, North Carolina. Base map: US Geological Survey, National Aerial Image Program.

TABLE 3 Interactions for the Neuse River fluvial–estuarine transition zone scenarios.

Scenario	a_{11}	a_{22}	a_{33}	a_{44}	a_{12}	a_{13}	a_{23}	a_{24}	a_{32}	a_{34}	a_{42}
1. Low flow	0	0	−	0	+	+	−	+	−	−	0
2. Low flow/low tide	0	0	−	0	+	+	−	+	−	−	+
3. Low flow/high tide	−	0	−	0	+	+	−	+	−	−	−
4. Rising flow	−	+	−	−	+	+	−	+	−	−	0
5. Rising flow/low tide	−	+	−	−	+	+	−	+	−	−	+
6. Rising flow/high tide	−	+	−	−	+	+	−	+	−	−	−
7. Flood	−	+	+	−	+	+	−	+	+	−	0
8. Flood + surge	−	+	+	−	+	+	−	+	+	−	−

Note: Links that are always zero are not shown.

storm surges in the estuary and lowermost river. Southwest (SW) winds lower water levels and push water out into Pamlico Sound towards the Outer Banks. Strong SW wind events can lead to reduced water levels in the Neuse FETZ and estuary with or without low river flows. Tropical cyclones can also cause significant storm surge in the lower river. During Hurricane Florence (2018), surges of nearly 4 m above mean low water levels occurred in New Bern.

The riparian zone and floodplain along the study reach is comprised primarily of bottomland hardwood swamp forests, with fringes or islands of marsh increasingly common near New Bern. Within the generally wet valley bottom, characterized by fine-grained and organic hydric alluvial soils, there occur 'islands' of sandier fluvial terrace soils where non-hydrophytic vegetation also occurs. Further details on the study area and on observation methods and data sources are provided by Phillips (2022a, 2022b).

The scenarios (Table 3) are based on various combinations of low, rising and flood flows, and low and high tides. Falling flow scenarios were not examined in detail, but their interaction matrices are similar to those of rising discharges. Low and high tides refer to strong or prolonged SW or NE winds that significantly lower or raise water levels. At low flows, flow occurs primarily in the main channel and tributaries. The other perennially inundated channels in the area—anabranches and backwater channels—serve primarily as storage, along with floodplain depressions and the floodplain itself. High or low wind tides may either inhibit or facilitate flow via gradient effects. At higher flows, self-limits on outflow and inputs come into play, and flow becomes self-reinforcing as roughness elements are drowned and anabranches and some backwater channels begin transporting water downstream. Whereas flow tends to dominate the competition with storage at low flows, during rising flows storage exerts a greater claim. Tides may have positive or negative effects on low flows.

Though banks are often indistinct in the FETZ (Phillips, 2022b; Figure 4), floods are defined as stages where banks are overtopped, and water moves from channels to and across floodplain surfaces. In flood, all perennial channels are exporting water downstream, and high-flow flood channels become activated. These are mainly Neuse

FIGURE 4 Pinetree Creek, an anabranch of the lower Neuse River. At low flows, this channel is ponded or backwater flooded and functions as storage. At high flows, it serves as spillway for downstream transport.

TABLE 4 Interactions for the fluviokarst scenarios.

Scenario	a_{11}	a_{22}	a_{33}	a_{44}	a_{12}	a_{13}	a_{23}	a_{24}	a_{32}	a_{34}	a_{42}
1. Dry	0	0	–	0	+	+	–	+	–	–	0
2. Recharge	–	0	–	0	+	+	–	+	–	–	0
3. Saturation	–	–	–	–	+	+	–	+	+	–	0
4. Overflow	–	–	+	–	+	+	–	+	+	–	0
5. Flood	–	–	+	–	+	+	–	+	+	–	–

Note: Links that are always zero are not shown.

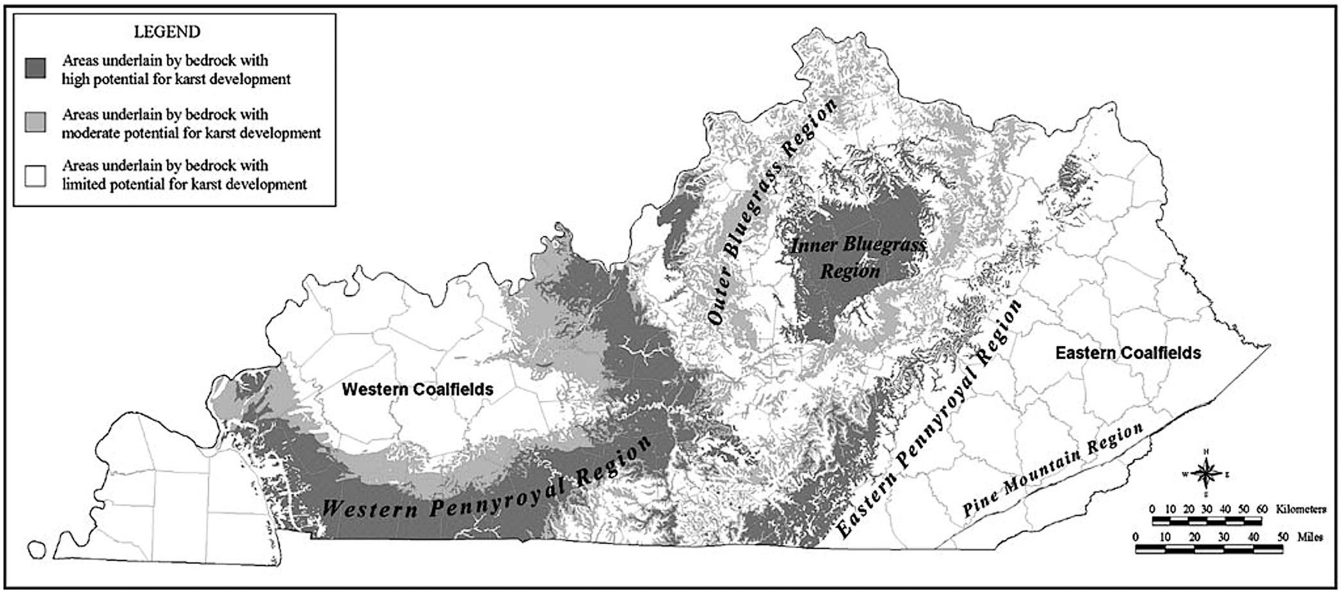

FIGURE 5 Kentucky geological survey map of karst regions of Kentucky, showing the inner bluegrass region.

FIGURE 6 Surface channel overlying subsurface karst features in Garrard County, Kentucky. The channel is normally dry, but when underground storage and transport capacity is filled, the channel is activated. Arrow indicates a surface connection to subsurface.

paleochannels that do not convey flow except during floods. In addition, floodplain depressions such as sloughs become connected to channels and each other by high-flow distributary channels and cross-floodplain flow. The flood + surge scenario involves flooding by both fluvial discharge and storm surge. This is typically associated with tropical cyclones such as Hurricane Florence in 2018 (Phillips, 2022a), but can also occur during strong extratropical cyclones (northeasters).

2.4.3 | Fluviokarst

These scenarios (Table 4) are based on studies of the coevolution of landforms and hydrological systems in the Inner Bluegrass region of central Kentucky. Methods, data sources and a detailed description of the study area are available in Phillips (2017, 2018). Unlike the soil hydrology scenarios, which represent the plot to hillslope scale, these characterize the landscape scale.

The humid subtropical Inner Bluegrass karst region (Figure 5) is characterized by thick, often nearly pure, beds of Ordovician limestone. The Kentucky River bisects the region and is the base level for both karst and fluvial processes. The river has been downcutting for ~1.5 Ma, driving active landscape evolution that features transitions among fluvial and karst landforms, and between drainage dominated by surface channels and groundwater conduits (Phillips, 2017). Subsurface conduits (including cave passages) and surface streams are the main flow mechanisms. The most important storage elements are subsurface karst cavities, fissures and porosity within the limestone, depressions in rock beneath soil cover, and soil and epikarst matrix storage. The scenarios are based on the study area but are likely common in many fluviokarst landscapes.

TABLE 5 Description of hydrological flow system model links.

Link	Description	Sign(s)
a_{11}	Water input self-effects	Negative in most cases due to depletion of H_2O supply Zero for small events or during early stages of inputs
a_{22}	Flow self-effects	Negative at high flow, limited by conveyance capacity Potentially positive when wetting, flushing, inundation decrease resistance Negligible or zero at moderate flows
a_{33}	Storage self-limitations	Negative as storage capacities approached or exceeded Potentially positive during wetting front propagation or as storage elements become connected Negligible or zero at moderate storage
a_{44}	Outflow self-effects	Negative as flux capacities approached or exceeded Zero otherwise
a_{12}	Inflow effects on flow	Usually positive, except. .... Zero during soil or groundwater wetting
a_{13}	Inflow effects on storage	Usually positive, except. .... Zero at saturation
a_{21}	Flow effects on input	Negligible or zero in most cases[a]
a_{23}	Flow effects on storage	Negative in many cases due to competitive apportioning of inputs Potentially positive at high flows due to flow diversions to storage, activation of distributaries
a_{24}	Throughflow effects on outflow	Positive
a_{31}	Storage effects on input	Negligible or zero in most cases[a]
a_{32}	Storage effects on through flow	Negative when zero-sum partitioning of inputs occurs Positive if storage is draining via throughflow.
a_{34}	Storage effects on outflow	Negative
a_{42}	Outflow effects on through flow	Negative if slow outflow reduces gradients or blocks through flow Positive if accelerated outflow increases gradients Zero in most cases

[a]Here I assume inputs are externally controlled. In some cases at broad scales, where local moisture recycling is important, these feedbacks could be nonzero.

Like the other dry scenarios, in fluviokarst the storage self-limits are the only ones relevant, and even then are usually relatively weak. In the dry and recharge scenarios, there is strong competition between flow and storage. During recharge, belowground storage begins to fill, and in the saturation scenario, all self-limits are activated, and storage components such as karst cavities begin exporting water to flow elements. This continues in the overflow scenario, with storage also becoming self-reinforcing. In these conditions, normally dry or non-flowing conduits and stream channels begin conveying the overflow water (Figure 6). In the flood scenario, river and stream backwater effects retard throughflow.

3 | RESULTS

3.1 | General hydrological system

Feedbacks for the generalized hydrological system are below. Signs for the individual a_{ij} are not shown; possible signs are shown in Table 5:

$$F_1 = a_{11} + a_{22} + a_{33} + a_{44} \tag{5}$$

$$F_2 = a_{23}a_{32} + a_{24}a_{42} - a_{11}a_{22} - a_{11}a_{33} - a_{11}a_{44} - a_{22}a_{33} - a_{22}a_{44} - a_{33}a_{44} \tag{6}$$

$$F_3 = a_{23}a_{34}a_{42} - a_{24}a_{42}a_{33} - a_{23}a_{32}a_{44} + a_{22}a_{33}a_{44} \tag{7}$$

$$F_4 = -(a_{23}a_{34}a_{42}a_{11}) + a_{23}a_{32}a_{11}a_{44} + a_{24}a_{42}a_{11}a_{33} - a_{11}a_{22}a_{33}a_{44} \tag{8}$$

As an example of how stability conditions were determined for each scenario, for the system structure depicted in Figure 2 and shown as the base case in Table 2,

$$F_1 = (-a_{11}) + (-a_{22}) + (-a_{33}) + (-a_{44}) \tag{9}$$

$$F_2 = (-a_{23})(-a_{32}) - (-a_{11})(-a_{22}) - (a_{11})(-a_{33}) - (a_{11})(-a_{44}) - (-a_{22})(-a_{33}) - (-a_{22})(-a_{44}) - (-a_{33})(-a_{44}) \tag{10}$$

$$F_3 = -(-a_{23})(-a_{32})(-a_{44}) - (-a_{23})(-a_{32})(-a_{11}) + (-a_{11})(-a_{22})(-a_{44}) + (-a_{11})(-a_{33})(-a_{44}) + (-a_{22})(-a_{33})(-a_{44}) \tag{11}$$

$$F_4 = (-a_{23})(-a_{32})(-a_{11})(-a_{44}) - (a_{11})(-a_{22})(-a_{33})(-a_{44}) \tag{12}$$

F_1 is negative. F_2 will be negative if the negative self-effects limiting inputs, flow, outputs and storage capacity are stronger than the mutual negative feedbacks associated with partitioning among flow and storage. $F_3 < 0$ if the three terms involving exclusively self-effects are greater than the two terms that include the flow and storage partitioning. Similar reasoning applies to F_4. The system is contingently (un)stable, depending on the relative strengths of the feedbacks. Stability is unlikely during low-input situations when the self-effects are likely to be negligible, as all except a_{11} represent conveyance or storage capacities.

Figure 2 represents a system where storage and flow compete for inputs and the flow and storage capacities are at or approaching their limits. This situation is highly plausible as a long-term average condition, but during an actual event, the self-limits are likely to be relevant (that is, $a_{ii} \neq 0$) only during higher-input periods. When the self-limits become strong, then flow and or storage may begin exporting water to the other (switch to positive feedback).

TABLE 6 Stability conditions for soil hydrology scenarios.

Scenario	Stability conditions	Instability conditions
Stable benchmark	Unconditionally stable	None
Base case	Self-limits stronger than through flow-storage feedbacks. Unlikely except during low inputs.	Through flow-storage feedbacks dominant.
Soil 2 dry	Flow and storage self-effects dominant. Not plausible under dry conditions.	Flow-storage partitioning dominant. Generally unstable.
Soil 3 recharge	Storage self-reinforcement relatively weak. Self-limits stronger than through flow-storage feedbacks.	Storage self-reinforcement relatively strong. Self-limits weaker than flow-storage feedbacks.
Soil 4 wetting	Storage, input self-limits stronger than flow self-reinforcement. Self-limits stronger than flow-storage feedbacks; likely under wet conditions.	Storage, input self-limits weaker than flow self-reinforcement.
Soil 5 saturation	Flow-outflow feedbacks stronger than flow-storage. Likely at saturation.	Flow-storage feedbacks stronger than flow-outflow. Unlikely at saturation.
Soil 6 Hortonian	Flow-outflow feedbacks stronger than flow-storage.	Flow-storage feedbacks stronger than flow-outflow.

Note: Shaded entries indicate stable or unstable conditions that are clearly more likely for the scenario.

TABLE 7 Stability conditions for Neuse River FETZ scenarios.

Scenario	Stability conditions	Instability conditions
FETZ 1 low flow	None	Unstable
FETZ 2 low flow, low tide	None	Unstable
FETZ 3 low flow, high tide	Flow-outflow feedbacks + self-limits stronger than flow-storage feedbacks.	Flow-outflow feedbacks + self-limits weaker than flow-storage feedbacks.
FETZ 4 rising flow	Flow self-reinforcement does not overwhelm other self-effects. Likely during rising flow.	Flow self-effects stronger than other self-effects. Unlikely.
FETZ 5 rising flow, low tide	Flow self-reinforcement does not overwhelm other self-effects. Inflow self-effects strong compared to other self-effects. Flow-storage, outflow feedbacks weak compared to self-effects. Unlikely during rising flow.	Reverse of stability conditions. Likely during rising flow.
FETZ 6 rising flow, high tide	Flow self-reinforcement does not overwhelm other self-effects. Flow-outflow interactions stronger than flow-storage competition.	Flow-storage competition and flow reinforcement relatively strong compared to flow-outflow interactions and other self-effects.
FETZ 7 flood	Storage enhancement of throughflow active. Likely in study area.	Unlikely in study area.
FETZ 8 flood + surge	Unconditionally stable	None

Note: Shaded entries indicate stable or unstable conditions that are clearly more likely for the scenario.

TABLE 8 Stability conditions for fluviokarst scenarios.

Scenario	Conditions for stability	Conditions for instability
1. Dry	None	Unstable
2. Recharge	None	Unstable
3. Saturation	Storage self-limits not dominant Flow-storage interactions relatively strong	Storage self-limits dominant over other self-effects Flow-storage interactions relatively weak
4. Overflow	Storage self-reinforcement does not dominate	Storage self-reinforcement dominates other self-effects
5. Flood	Storage self-reinforcement does not dominate	Storage self-reinforcement dominates other self-effects

Note: Shaded entries indicate stable or unstable conditions that are clearly more likely for the scenario.

If all $F_i < 0$ the first Routh–Hurwitz criterion is met. For the second to be satisfied, the self-effects and storage-throughflow feedbacks represented in F_1, F_2 must together be stronger than F_3, which will typically be the case unless negative effects of outflow on flow ($-a_{42}$) are particularly strong.

The same approach was used for all scenarios, plugging the associated values of the a_{ij} into Equations (5)–(8) and determining conditions under which the Routh–Hurwitz criteria could or could not be met.

3.2 | Scenario results

Results for the soil hydrology, Neuse River FETZ, and fluviokarst cases are shown in Tables 6–8.

The scenario analyses reveal two important general points. First, in many cases, dynamical stability is dependent on contingent partitioning—whether specific self-effects or interactions are positive, negative or zero, and the relative strengths thereof. Second, instability exists for the dry and recharge or rising flow situations in all three case studies, with dynamical stability more likely at high flows. This is discussed in the next section.

3.3 | Entropy

Because all scenarios have the same N values, the range of S *values* is relatively small. Comparing the last term of Equation (4), termed the node degree index here, gives a relative assessment of the contribution of the specific degree distributions to the entropy, independently of the number of components common to all scenarios.

Figure 7 shows that the lowest entropy is associated with high or increasing inputs—the Neuse River flood and rising stage (with high or low tides), and fluviokarst overflow, but also the base scenario. Higher entropies were associated with the soil wetting, dry soil and low flow scenarios in fluviokarst and the Neuse River. However, there is not a monotonic relationship between S or the degree index and wetter or drier scenarios. The soil saturation and Neuse River flood plus storm surge models, for instance, are nearer the high-S end, and higher still are the Hortonian runoff and fluviokarst flooding scenarios. Entropy is apparently not clearly related to the stability and adaptation of the systems.

4 | DISCUSSION

Adaptation can be associated with dynamical instability, where state changes are necessary or advantageous to responses, or to stability, where resilience is necessary. Adaptive systems may have both stable and unstable modes in various circumstances or situations. In the case of hydrological flow systems, results here suggest that instability in dry or low-input scenarios enables hydrological systems to rapidly reconfigure to accommodate or take advantage of new or increased water inputs. Stability in high-input wet scenarios allows the systems to adapt to excess inputs and maintain their states.

Results are graphically summarized in Figure 8. This shows that, as a broad first-order generalization, geophysical demand (the need to move or store excess water) is directly related to water inputs, while ecological limitations are inversely related. At low inputs, dynamical instability enables rapid state changes when new inputs occur to begin fulfilling the ecohydrological job. At high inputs, stability maintains the system so that the geophysical job can be performed. Transitions between the two regimes are associated with changes in the relative importance of flow and storage feedbacks, and activation of flow paths and auxiliary storage (or deactivation in the case of declining inputs). Not all hydrological systems exhibit these dynamics, but those that do are adaptive.

In all three case studies above, instability exists for the dry and recharge or rising flow situations. With respect to soils, it was long ago established in water balance studies that soil moisture storage is generally recharged before surface runoff or percolation begins. This is clearly advantageous for vegetation and other biota. It also helps set the stage for preferential flow paths and saturated matrix flow as moisture increases. In soils, stability often emerges in the soil wetting scenario where self-reinforcement of flow occurs, and analogous dynamics occur in karst systems. This often happens as preferential flow paths are activated and become connected (e.g., Liu & Lin, 2015; Mohammadi & Illman, 2019; Nieber et al., 2006; Nieber & Sidle, 2010; Sidle et al., 2001; Wilson et al., 2017; Worthington, 2015, 2019). Dynamical stability at saturation is also associated with temporary phenomena such as surface ponding and gravity water which can transition to either flow or storage. During the low-input drier scenarios, instability is associated with strong feedbacks between throughflow and soil moisture storage as inputs are partitioned between them. In the stable wetting and saturation scenarios, self-limits

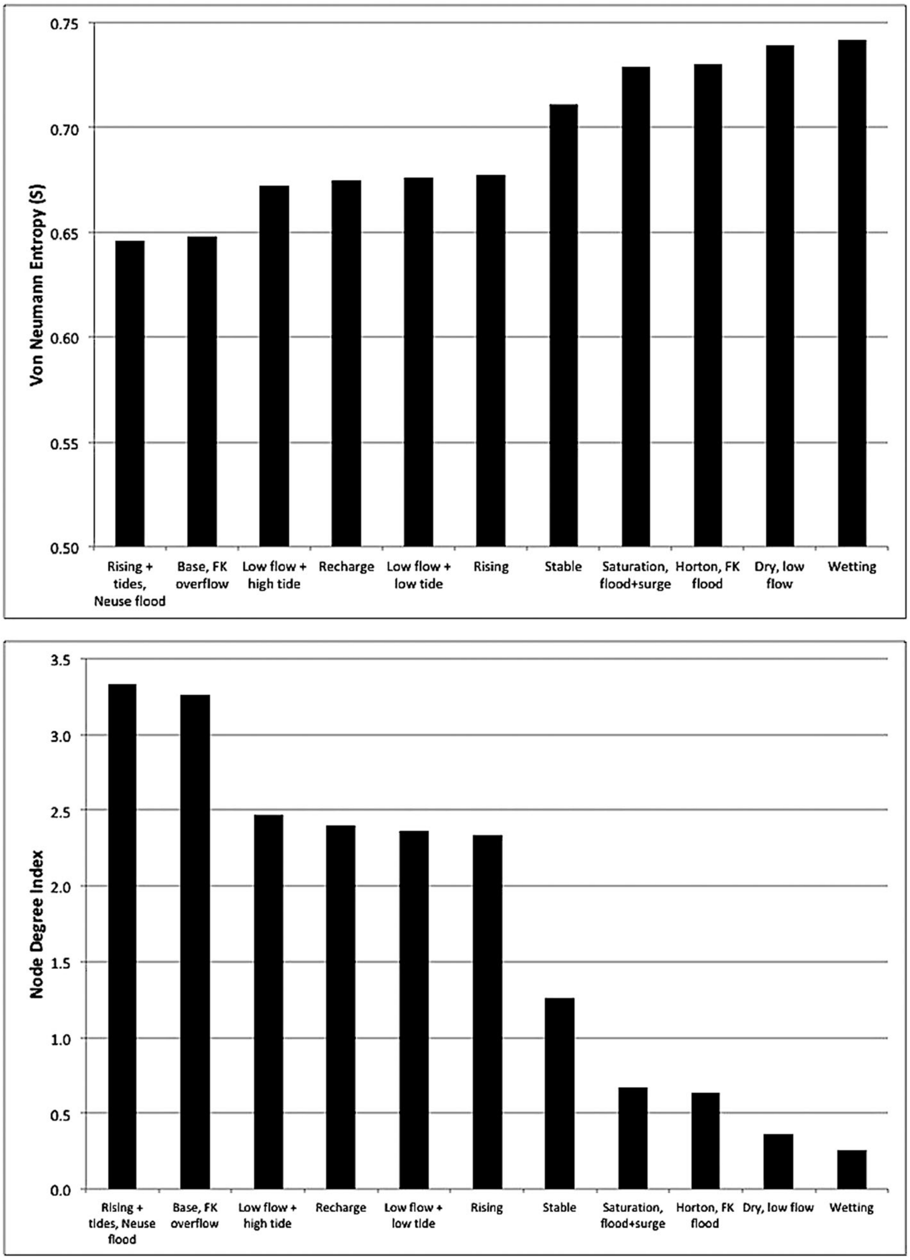

FIGURE 7 Von Neumann entropy and node degree index for the hydrological scenarios.

become more important, and flow-storage feedbacks are less so. In the Hortonian case, stability is determined by the relative importance of throughflow/outflow interactions versus the throughflow versus storage allocation.

In the channel-wetland complex of the Neuse River, low flow instabilities enable rapid state changes in flow system elements, such as switches from storage to downstream transport, and from disconnected to connected. This facilitates ecosystem functions in the wetland and aquatic environments and primes the river corridor for activation of 'spillway' flow paths and additional storage if excess inputs occur. In the FETZ, the general sequence of unstable to stable modes from lower input to higher input scenarios is complicated by the effects of wind tides. However, note that the system is well-adapted to the river flood plus storm surge effects of tropical cyclones, as illustrated by the Hurricane Florence event in 2018 (Phillips, 2022a). In general, activation of spillway mechanisms marks the transition between unstable and stable modes.

Similar phenomena are evident for the fluviokarst scenarios. Instability in dry and recharge situations is associated with the prevalence of storage replenishment over conduit flow. The overflow and flood stages are dynamically stable due to the activation of spillway features such as flow in ephemeral stream channels and overflow springs. The saturation scenario may be stable or unstable and reveals an important threshold with regard to the relative importance of storage capacity and storage–flow interactions.

Examples of contingent partitioning and switches in flux–storage relationships can be found in the literature, though not necessarily framed in terms of dynamical stability. In 23 runoff events in an

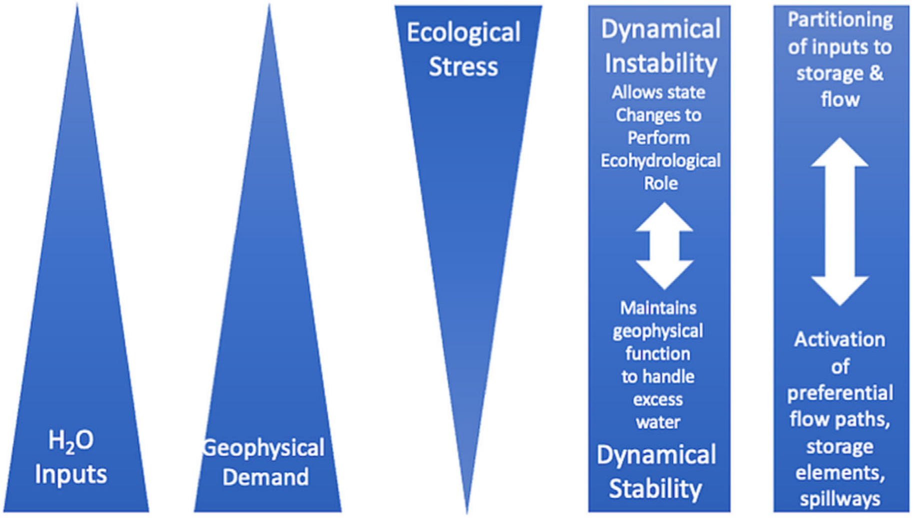

FIGURE 8 Simplified summary of relationships among water inputs, ecological stress, geophysical demand to move excess moisture, dynamical stability and adaptations.

agricultural watershed in North Carolina, Slattery et al. (2006) identified different modes of runoff generation at the same locations in different events. The Swiss watershed examined by Teuling et al. (2010) is insensitive to precipitation at low storage levels, but under high storage responds more strongly to inputs. The watershed behaves as a simple dynamical system, but more so under wet than dry conditions. Under higher inputs, rapid pathways such as surface runoff and saturated throughflow are activated, creating a more direct link between precipitation inputs and runoff outputs. Rusjan and Mikoš (2015) studied a flysch watershed in Slovenia, finding that it underwent state changes with respect to flow dynamics according to hydrometeorological conditions. The watershed acted primarily as a deeper subsurface storage-dependent system during most conditions. However, when rainfall reached a threshold of ≥ 10 mm h^{-1}, secondary streamflow mechanisms were activated characterized by rapid bypass flow. These are but a few examples of studies showing hydrological system dynamics that switch in different synoptic situations (see reviews by Blöschl, 2022; Bonell, 1993 and Spence, 2010).

The scenarios examined here do not encompass all plausible combinations of interactions and self-effects among inputs, throughflow, storage and output for the three cases explored here. Those examples, in turn, are only a few samples among innumerable possibilities. Yet, the scenarios are both diverse and common enough to illustrate the fact that partitioning of water inputs within hydrologic system is strongly conditional even in a qualitative sense, and contingent on synoptic situations. Of the 16 possible links (a_{ij}), 12 are always or sometimes nonzero. Of these, nine may have at least two different signs (negative, zero and positive).

Adaptation reflects a flow system's ability to perform both its ecological and geophysical jobs, and the dynamical stability scenarios suggest that hydrological systems are often well-adapted in this respect. Exceptions—non-adapted hydrological flow systems—certainly exist. This is inevitable due to disturbances and changes that disrupt, delay or even prevent development towards adaptation. The development of key features such as storage elements, preferential flow paths and spillways is also nondeterministic. Rather, it is emergent and subject to selection, and therefore probabilistic and imperfect. Like selection, adaptation is not restricted to biota and occurs in abiotic Earth surface systems.

5 | CONCLUSIONS

Four propositions were addressed here. First was that dynamic, contingent partitioning of water in hydrological systems constitutes adaptation. Contingent partitioning has long been recognized. The argument advanced here links this to preservation or enhancement of the ecological role of hydrological systems during low-input (dry) situations and the geophysical job of flow systems during periods of excess input. This meets the definition of adaptation: adjustment of environmental systems to enable survival and an optimal level of functioning.

Second, contingent partitioning has generally been conceived as the activation or deactivation (switching on and off), or the connection or disconnection of, for example, preferential flow paths and storage sites. In this study, the *reversal* of fluxes and influences as well as the operation or non-operation of flux or partition pathways was considered—for example, cases where throughflow and storage may either compete for water inputs in a zero-sum manner or may enhance the other via activation of exchange pathways and processes. Third, this study confirmed that changes in partitioning are associated with changes in the dynamical stability of hydrological systems.

Finally, results suggest that successful (persistent and performing both geophysical and ecological functions) hydrological systems tend to evolve such that instability during low-input periods allows for rapid response to increased inputs, and stability during high inputs maintains the system state.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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