Perceiving Complex Water Resource Systems from the Perspective of Emergence and Information

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Abstract

A challenge to managing water resources is characterizing the scale-dependent heterogeneity created by the interactions among hydrological, ecological and anthropological processes. It is often difficult to collect sufficient empirical data over the range of scales required to construct mathematical models that facilitate robust bottom-up descriptions or predictions. An alternative is identifying emergent properties of complex systems, whose components self-organize into novel structures or processes via their collective interactions with each other and the environment. A new level of organization and complexity emerges that cannot be predicted from or attributed to the components alone. Emergence offers a number of perspectives from which to interpret, if not predict, the behavior of complex water resource systems. One of these is entropy, which maximizes the options for system components to alter their interactions and, thus, permits variability and adaptability. At the scale of watersheds, increased entropy is pertinent because of its relationship to information (as probability functions), which is transmitted through connected components of a watershed in a manner such that the accrued information gives rise to emergent properties. Hence, analyzing the behaviors of a system according to emergence introduces the possibility of evaluating the information content via its interconnected components. Connectivity then assumes an integral role in a hydrologic system's response to natural or anthropogenic disturbances (e.g., climate change, land use). Replacing the details of multi-scale heterogeneity and causal mechanisms with the functions that watersheds perform allows processes such as stream flow rate/duration and flood frequency to be construed as emergent spatiotemporal patterns. A reductionist or bottom-up approach to assessing the behavior of aquatic systems shifts to a functional or top-down approach that does not depend upon an understanding of all the physical, chemical or biological mechanisms involved. This latter approach could supplement conventional water resource descriptions and predictions via more comprehensively characterizing watershed or aquatic ecosystem functions.

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THE CHALLENGE

A challenge to managing water resources is detecting the scale-dependent heterogeneity created by interactions among hydrological, ecological and anthropological processes. It is frequently difficult to collect sufficient empirical data to construct mathematical models that will facilitate robust bottom-up descriptions or predictions. An alternative is identifying the emergent properties of complex systems, whose components self-organize into novel structures or processes as a function of their collective interactions with each other and the environment.

EMERGENCE & INFORMATION

Emergence offers a number of perspectives from which to interpret, if not predict, the behavior of water resource systems. One of these is entropy, which maximizes the options for system components to modify their interactions and enables variability and adaptability. This increased entropy is pertinent because of its relationship to information, which is transmitted through connected components of water systems in a manner such that the accrued information gives rise to emergent properties. Hence, analyzing the behaviors and functions of a system according to emergence allows the possibility of evaluating its information content via the interconnected components. Connectivity then assumes an integral role in a water system's response to natural or anthropogenic disturbances (e.g., climate change, land use shifts). In this context, information refers to the probabilities, expressed as temporal or spatial patterns, that transmit possible states of a system.

CONSTRAINTS & RESILIENCE

The type of emergence considered here is referred to as weak, which describes an outcome that is unexpected but deducible scientifically. Strong emergence refers to a novel structure/process that's not deducible from current scientific laws. Constraints on emergence are exerted by the environment, serving to increase the probability of some outcomes and to decrease the options for all components that influence each other as parts of a cohesive system. Resilience and adaptability, which refer to maintaining a system's cohesion in the midst of change, are dependent upon the diversity of its components. Such water systems exhibit a distributed, rather than centralized, control. Examples of river system stability and of watershed responses are provided below.

River System Stability

- Stability of river systems is an emergent property that buffers change and extreme events
- Connectivity and interactions among geomorphic and hydrologic components spanning spatial and temporal scales facilitate stability and resilience
- Human activities that decrease connectivity (e.g., dams) compromise the system's stability
- Downstream dynamics are related to upstream events that transmit information as probabilities

Watershed Responses

- Events (e.g., rainfall, infiltration) are transmitted through its components as accrued information that underlies watershed's emergent properties
- Fluxes in the atmosphere, vegetation and soil exhibit concurrent variability arising from forcing, feedback, nonlinear response and other system dynamics
- Information-based analyses identify the range of drought responses to shifting rainfall patterns
- Emergent properties constrain watershed functions

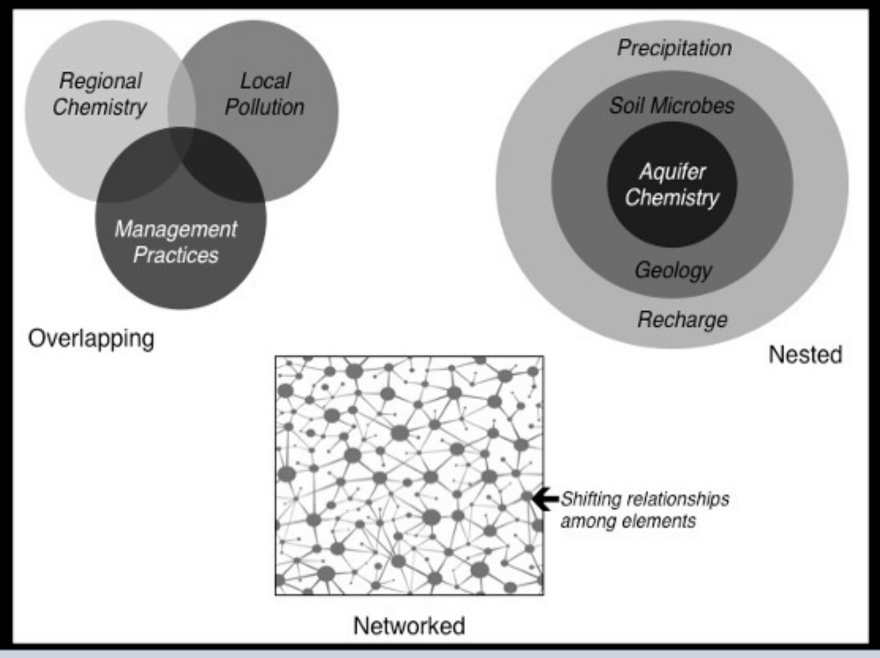
Water Quality Patterns

- Predicting water quality changes is difficult due to the ways watershed components interact
- Pollutants influence each other, microbes, soils, and regional chemistry—directly and indirectly
- Spatiotemporal water quality patterns emerge from component interactions (bottom-up), hydrologic constraints (cyclic), and evolving changes in overall chemistry (top-down).
- Patterns can reveal functions and connectivity

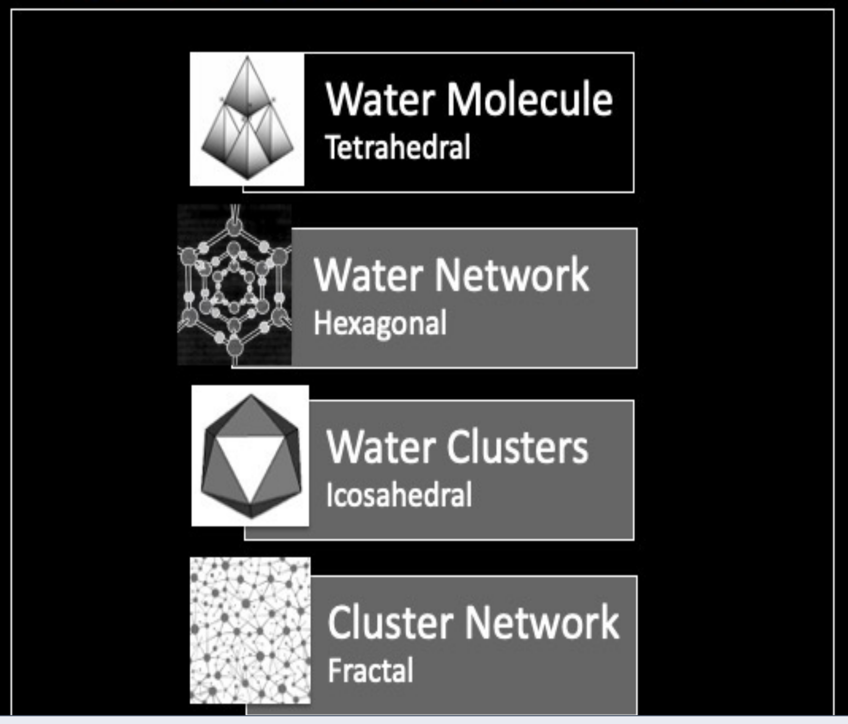
EMERGENT PATTERNS

Explaining spatial and/or temporal patterns solely through analyses of their components and processes (i.e., reductively) is difficult because patterns emerge as a property of systems. Evaluating the connectivity among water chemistry parameters in terms of a coherent network, rather than isolated data points, can expose data limitations and shifts in relationships among system components that influence water quality. Simple pattern-based approaches are used to compare actual water quality patterns with ideal patterns (modeled) and abstract patterns (theorized) in order to assess their practicality and relevance to observed data. The approach is also utilized to present water quality data.

Patterns of Connectivity & Emergence



Molecular Patterns of Water



SUMMARY

Replacing the myriad details of multi-scale heterogeneity and causal mechanisms with the functions that water resource systems perform allows processes such as stream flow rate or duration, flood frequency, and even water quality to be interpreted as emergent spatial and temporal patterns. A reductionist or bottom-up approach for assessing behaviors of aquatic ecosystems or watersheds then shifts to a functional or top-down approach that does not depend upon a thorough understanding of all the physical, chemical, biological mechanisms involved, but rather on the organization and flow of information among its components. This approach could supplement the more conventional descriptions and predictions for a range of water-related resources via a characterization of the functions performed by watersheds, aquatic ecosystems or other water resource systems.

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