Emergent Properties of Water Resources and Associated Watershed Systems

D.L. Marrin *

Water Sciences & Insights, California, USA.
* Correspondence: marrin@watersciences.org; Tel.: +01-760-274-7713

Abstract: A challenge to managing water resources is characterizing the heterogeneity created by the interactions among hydrological, ecological and anthropological processes. An option applied to other scientific disciplines includes identifying and analyzing emergent phenomena in 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. Predictions based on the functionally emergent properties of watershed systems (top-down) differ from predictions based on reductionist models (bottom-up). This presentation reviews the ways in which emergent properties may be applied to water resources and associated systems.

Keywords: emergence; water; watersheds; connectivity; networks; information

1. Introduction

The topic of emergence has received considerable attention during the last several decades as scientists have applied systems oriented approaches to describing and predicting the properties and behaviors of complex phenomena. Systems theory describes the interactions among water resource or watershed components as spatiotemporal patterns or relationships. Whereas matter and energy are cycled through a system, the focus is on describing a system's organization and component connectivity, thus permitting the identification of controls, hierarchies, and feedback dynamics that govern its trajectory and properties. Emergence is the unexpected observation of higher-order complexity arising out of interactions among diverse lower-order components of system, thus permitting the system to coalesce into something novel [1]. A distinction is often made between weak and strong emergence whereby the former results from presumably known interactions among components according to discernable rules or principles, while the latter involves disruption or radical change in which rules and principles are unreliable [1]. The water resource systems and watersheds discussed in this presentation generally exhibit weak emergence with regard to their novel and unpredictable properties.

From a theoretical perspective, the recognition of emergence offers a number of unique perspectives from which to interpret, if not predict, the behavior of complex and self-organizing natural systems (see Table 1). One reason is that entropy, which maximizes the options for system components to alter their arrangements or interactions with one another, plays a role in emerging system complexity and its underlying processes [2]. These options can actually increase the order of systems, even though increased entropy is usually associated with randomness or decreased order. Rules governing the interactions among components of self-organizing systems may be relatively simple and yet produce complicated and highly variable structures or processes [2]. Groundwater confined within the pore spaces of an aquifer can self-organize, permitting the maximum flexibility in rearranging connections among molecules and allowing water to flow as fluid while retaining much of the crystalline structure of solid ice. Water is a classic example of emergence because its fluid properties cannot be predicted from its molecular properties, either as solitary H_2O molecules or as the interactions among them.

Table 1. Selected characteristics of emergence as generally applied to complex self-organizing systems and presented in the form of questions and answers [1,2].

Question	Answer
What is it?	Higher order complexity arises from apparent disorder.
What is the process?	System components interact to produce disruption.
What happens?	System differentiates and coalesces into something novel.
How is it modeled?	Nonlinear mathematics rather than linear heuristics.
When is it weak?	Unpredictable patterns emerge from specific rules.
When is it strong?	Unpredictable patterns emerge that defy specific rules.
Are the rules known?	Sometimes in simple systems—rarely in complex ones.
Are rules complicated?	Simple rules can yield complicated behaviors/structures.
How is it coherent?	Coherence arises solely out of component interactions.
Are properties novel?	Novel properties can arise from identical components.
Are properties unique?	Different components can generate similar properties.
Why is it not reductionist?	Emergent system exceeds the sum of its components.
Is it static or dynamic?	System continually changes, evolves, and is in process.
Is there system feedback?	Emergent system affects the behavior of its components.
How is it orchestrated?	No orchestrating agent involved—system self organizes.
Is it related to entropy?	Entropy offers component possibilities for interacting.
Is entropy just disorder?	Entropy can yield more or less ordered arrangements.

At the scale of watersheds, increased entropy is of interest largely because of its relationship to information content that, in turn, is indicative of the probabilities for a system's attaining different states, which are attributed to the configurations of or interactions among its components. This probability reflects the uncertainty associated with the state of any selected variable describing a system as well as the system's apparent disorder [3]. Hence, analyzing the behaviors of a system according to emergence brings with it the possibility of evaluating the information content related to its interconnected and continuously interacting components. An explanation of "information" in this context is reserved for the following section; however, it is worth noting here that physicists are questioning whether information is the ultimate reality from which our observable world of matter, fields and forces is derived. Even assuming a less fundamental role for information, other sciences (e.g., quantum mechanics, astrophysics, biochemistry, ecology) have explored information as one of the probable underlying principles for natural phenomena.

The ubiquitous presence of spatial and temporal fractal structures in nature (e.g., river deltas, hurricanes, earthquakes, storms) may relate to their providing an efficient means for systems to dissipate energy gradients and produce entropy, thus enhancing variability and adaptability over a range of scales [3]. Increased entropy may be a reason that nature has been described as fractal-like, which relates to a mathematical power law that emerges as a property of patterns observed in physical, chemical and biological systems [4]. Fractal patterns exemplify emergence in a physical system such as a watershed, and the produced or increased entropy is often considered to be a measure of the information content they possess. Fractals describe spatial and temporal patterns that repeat across a range of scales, thus generating a pattern self-similarity that can be quantified mathematically. It is the variability of spatial and temporal fractals that permits complex systems to maximize entropy and, consequently, exhibit emergent properties [3]. The intricate patterns created influence hydrologic regimes, water quality/quantity dynamics, and the ability of watersheds to buffer extreme natural events

2. Emergent Properties

2.1. Networks and Connectivity

River networks have been shown to function as hierarchically nested processes from which stability emerges as a property that can buffer variation and extreme events [5]. The connectivity and interactions (over a wide range of spatiotemporal scales) among geomorphic and hydrologic components of watersheds or river networks are theorized to give rise to the emergent properties. River networks integrate and propagate water, materials, and organisms downstream through their hierarchical and fractal branching structure, such that watershed stability becomes a function of the connections established through its rivers [5]. Human activities that decrease connectivity and the associated diversity compromise the stability of river processes. As such, downstream dynamics are a function of upstream dynamics for flowing water ecosystems described by fractal geometries and scaling relationships, which are ultimately shaped by their landscapes. The resulting stability is theorized to be an emergent property of river networks.

Connectivity describes the efficiency of transfer between hydrologic system components, such as geomorphology and river dynamics, that essentially form a network in which these components are connected over a range of scales [6]. Indications of connectivity among network components can be found in system inputs such as changes in storm-related hydrographs or increases in sediment loads. Structures such as dams, diversions and weirs can affect the system's connectivity, which serves as a conceptual framework for identifying factors that enhance or detract from the transfer of materials. Moreover, the connectivity among various watershed components can change spatially or temporally depending on the evolution of hydrological and ecological systems.

Measuring connectivity requires data collection over a range of spatial scales using techniques such as frequency distributions or statistical analyses, yet no single metric is likely to characterize all forms of connectivity [6]. The other consideration in measuring connectivity is that it may not necessarily be an all-or-nothing parameter, but instead may occur along a continuum. A recent study documented a gradient for lake connectivity within a floodplain (as isolated, transitional or connected) that was reflected by the diversity and density of zooplankton [7]. Different flood-pulse dynamics within the connecting river determined the degree of connectivity between the lakes via the river, thus influencing zooplankton populations in the lakes. Because zooplankton structure is a function of numerous physical and chemical parameters, it can reflect the connectivity-related hydrologic or water quality differences among lakes.

Correlations between the spatial patterns of a watershed's elevation contours, land cover, and hydrologic responses exhibit fractal, or fractal-like, relationships over a wide range of scales [8]. Observations that some spatial scales produce more significant correlations than do others and that some watershed sections contribute disproportionately to hydrologic responses have encouraged the use of fractal analyses and models to quantify watershed discharge dynamics and to select practical management boundaries. The optimum spatial resolution over which watersheds are described, modeled, and managed depends on the range of scales over which fractal relationships exist [9]. For example, fractal characteristics and hydrologic responses in a tropical watershed were observed to correlate over two orders-of-magnitude (i.e., 90 meters to about one kilometer), beyond which differences in land cover and drainage patterns skewed the response.

The frequency and duration of storm events and the residence time of water inputs within a watershed are a function of interactions among a multitude of variables or components that, even if considered jointly, cannot accurately predict the watershed's emergent properties. The assumption that extreme precipitation events play the major role in affecting water resource management and maintaining aquatic ecosystems has recently been challenged by analyzing very large datasets that indicate slight changes in seemingly normal precipitation events actually exert the greater effect [10]. Subtle shifts in precipitation patterns (e.g., rainfall duration or periods between rainfall events) produce a cumulative effect that is subsequently transmitted through watersheds, influencing their emergent behaviors and properties over a range of time scales. This cumulative effect is sometimes characterized as information that is transmitted through the connected components of a watershed (e.g., precipitation, runoff, stream flow, vegetation, soil moisture), resulting in the emergence of integrated upstream information as downstream dynamics and properties.

2.2. Information and Entropy

In the context of complex systems, "information" simply refers to probabilities that may be expressed either as symbols (e.g., integers) or patterns (e.g., geometries). Unlike information in the colloquial sense of facts or knowledge, this information transmits possible states of or processes within a system. The aggregate activity of system components is nonlinear and hierarchical, such that the resulting system properties cannot be predicted (at least by simple linear approximations) and information processed on the system level can affect its components via so-called downward causation. Events are posited to transmit information (as probability functions) through connected components of watersheds in a manner such that the accrued information underlies a system's emergent properties. As previously noted, information is also related to system entropy inasmuch as greater entropy accommodates more possible states and greater information. System entropy is most often considered to be synonymous with randomness or disorder; however, the latter terms are inherently comparative and decidedly subjective so that greater entropy can sometimes be perceived as greater order [2].

From the perspective of temporal connectivity, fluxes within the atmosphere, vegetation and soil exhibit a concurrent variability arising from system dynamics (e.g., forcing, feedback, nonlinear response, chaotic behavior) that cause fluctuations to propagate between components or variables over a range of timescales [11]. This connectivity is observed as the hydrologic system's responses to changes in climate, land use, and other natural or anthropogenic disturbances. Therefore, information theory can be used to assess the flow of information related to the fluctuations among components, and this methodology has been employed to analyze data from diverse watersheds and aquatic ecosystems [11]. These information-based analyses have identified different drought responses to shifting rainfall patterns, thus permitting a description of drought responses (to the aforementioned fluxes) under variable conditions of the system as is required to generate a range of probable outcomes.

The propagation of information through the network of components, including its temporal attenuation or amplification, establishes the system's overall response to environmental change. Advantages of characterizing forcing and feedback relationships among components of aquatic and water resource systems include providing clues to system resilience, sensitivity and vulnerability without performing field experiments that are seldom feasible at this scale [11]. Different system components and processes are the focus of the following examples, but in every case the transfer of information through aquatic ecosystems or watersheds (via connected components) is the key to understanding how these systems respond to changing conditions.

Besides aquatic organisms (e.g., zooplankton), information in the form of matter can emerge within water-related systems as nutrient dynamics, which result from hydrological, biogeochemical and ecological interactions [12]. The structure and function of aquatic ecosystems, including their water quality and nutrient dynamics, in combination with human activities give rise to changing spatiotemporal patterns within natural waters. For example, nutrient additions in agricultural areas can accumulate in shallow soils during dry periods and then rapidly infiltrate into groundwater aquifers or flow via runoff into surface waters during rainfall events [12]. This is considered an emergent property of the watershed because the magnitude of water quality degradation cannot be predicted as a result of the myriad ways in which a system's hydrological, biogeochemical and ecological components interact and of the disparity in spatiotemporal scales within which it is most affected. Hence, measurements of heterogeneity are best performed over a number of pertinent scales as both upward and downward causation pathways have been postulated. Because the effects of nutrient addition to waters are normally observed at the level of an aquifer or surface water body, interactions occurring on much larger (e.g., entire watersheds) or smaller (e.g., aquifer grains) scales are frequently overlooked.

On a global basis, research indicated that nitrogen and phosphorus removal from lakes and reservoirs was a function of residence times, such that a shorter residence resulted in greater removal [13]. This result is apparently due to smaller lakes and reservoirs, which exhibit shorter resident times, actually facilitating greater contact between the sediments and water column due to the maximized surface-to-volume ratios. Paradoxically, shorter residence times in a shallower water body yield (on average) greater nutrient removal rates than much longer residence times in a deeper water body [13]. This paradox exemplifies why interactions and feedback loops among the components of a system often produce results that are unpredictable or even counterintuitive.

3. Discussion

The development of physically based models for hydrologic predictions has been hampered by an inability to sufficiently measure and map the heterogeneity of critical parameters for deriving accurate mass balance equations on different scales [14]. An alternative to attempting to measure heterogeneity everywhere is an approach that encompasses co-evolved hydrological, ecological, geological and, more recently, anthropological processes over a range of spatiotemporal scales in creating the watersheds themselves. The objective is to replace the details of heterogeneity with the functions that emergent complex systems perform [14]. Processes such as stream flow rate/duration and flood frequency are then perceived as emergent temporal patterns of the particular system in question. In essence, the reductionist or bottom-up approach to predicting the behavior aquatic systems is supplanted by a functional or top-down approach, whereby the latter is not dependent upon a precise understanding of the physical, chemical or biological mechanisms responsible for all system processes. Instead, the objective is improving water resource predictions by more accurately describing and reproducing watershed or aquatic ecosystem functions [14].

Emergence of global scale hydrological processes has long been recognized as one of the keys to forecasting watershed-scale effects related to changes in atmospheric and landscape processes that modify the earth's water cycle and its observed patterns [15]. By the end of the century, it has been predicted that more that 40% of the USA's land area will experience substantial changes in the aforementioned probability distribution functions, which are related to summer and winter runoff and, therefore, affect surface water supply [16]. On smaller scales, the changes are predicted to be somewhat different due to emergent hydrologic regimes that are dominated by regional variability rather than by mean global trends. Such predictions again highlight the importance of scale (both temporal and spatial) in predicting changes in water supply and of information (as variability or entropy) flow through regional system components in altering a watershed's emergent properties and behaviors. It is worth noting that the timing of changes in runoff, rather than in precipitation, has been identified as the better indicator of global warming in regions where water supply is an issue or has been predicted to be one [16].

The observed patterns of processes within complex hydrologic systems emerge from collective interactions of all the components involved and, according to emergence theory, are not caused by controlling or orchestrating agents of any kind. Consequently, emergent (non-sequential) processes such as aqueous diffusion are not considered causally based [17]. In fact, the presumed causation of even recognized sequential phenomena (e.g., the water cycle) is being challenged on the basis of whether the perceived causality is imposed by the human brain's pattern-seeking prowess, which separates and labels apparently distinct stages of a single event as cause-and-effect relationships. In other words, any perceived upward or downward causation of a system's emergent properties may be a function of how the human brain is hardwired to perceive and/or infer relationships among sequential events.

Whereas this extreme view of emergent phenomena challenges the physical realism that dominates science today, the notion that our perception of the physical world and its presumed relationships may not be fundamental has propelled the concept of information realism [18]. Information realism differs markedly from conventional physical realism in that the former view posits information (as possible states of an entity or system) as fundamental and ultimately giving rise to the abstractions of matter, energy and forces that the latter view considers fundamental.

Emergence theory is certainly not universally accepted within the scientific community as a metric or as a conceptual framework from which to describe or predict the behavior of complex systems, such as those of water resources or aquatic ecosystems. Critics contend that emergence is a vaguely defined process that currently lacks a satisfactory mechanistic explanation. Accordingly, almost all phenomena could be considered emergent. The type of weak emergence described in this paper does not necessarily invoke strict adherence to emergence theory, but instead presents a top-down method of describing and predicting changes in these systems by focusing on their functions instead of their causal mechanisms. The practical value of this approach is circumventing the practically impossible task of generating sufficient heterogeneity data over the range of scales required to construct reductionist models that will facilitate bottom-up descriptions or predictions of complex natural systems.

Acknowledgments: Water Sciences & Insights funded the preparation of this manuscript.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Holman, P. *Engaging Emergence: Turning Upheaval into Opportunity*; Berrett-Koehler: San Francisco, CA, USA, 2010.
2. Wolchover, N. Digital alchemist Sharon Glotzer seeks rules of emergence. *Quanta Magazine*, 8 March **2017**, www.quantamagazine.org/digital-alchemist-sharon-glotzer-seeks-rules-of-emergence-20170308/.
3. Seely, A.J.; Macklem, P. Fractal variability: An emergent property of complex dissipative systems. *Chaos* **2012**, *22*, doi:10.1063/1.3675622.
4. Avnir, D.; Biham, O.; Lidar, D.; Malcai, O. Is the geometry of nature fractal? *Science* **1998**, *279*, 39–40.
5. Moore, J.W.; et al. Emergent stability in a large, free-flowing watershed. *Ecology* **2015**, *96*, 340–347.
6. Wohl, E.; et al. Connectivity as an emergent property of geomorphic systems. *Earth Surface Processes and Landforms* **2018**, doi:10.1002/esp.4434.
7. Napiorkowski, P.; et al. The effect of hydrological connectivity on the zooplankton structure in floodplain lakes of a regulated large river. *Water* **2019**, *11*, doi:10.3390/w11091924
8. Marrin, D.L. Water, fractals and watershed processes. In *Water Issues Relating to Environmental Landscape Sustainability*, Hammami, M.A., Ed., Sousse University Press: Sousse, Tunisia, 2012; 161–169.
9. Colby, J.D. Simulation of a Costa Rica watershed: Resolution effects and fractals. *Journal of Water Resources Planning and Management* **2001**, July/August, 261–270.
10. National Science Foundation. Changes in non-extreme precipitation may have not-so-subtle consequences. *NSF Critical Zone Observatory News Release 17-091*, 2017.
11. Goodwell, A.E.; Kumar, P.; Fellows, A.W.; Flerchinger, G.N. Dynamic process connectivity explains ecohydrologic responses to rainfall pulses and drought. *Proceedings of the National Academy of Sciences* **2018**, *115*, E8604-E8613.
12. Covino, T.; Golden, H.E.; Li, H-Y.; Tang, J. Aquatic carbon-nutrient dynamics as emergent properties of hydrological, biogeochemical, and ecological interactions. *Water Resources Research* **2018**, *54*, 7138–7142.
13. Cheng, F.Y.; Basu, N.B. Biogeochemical hotspots: Role of small water bodies in landscape nutrient processing. *Water Resources Research* **2017**, *53*, 5038–5056.
14. Sivapalan, M. From engineering hydrology to earth system science: Milestonres in the transformation of hydrologic science. *Hydrology and Earth System Sciences* **2018**, *22*, 1665–1693.
15. Eagleson, P.S. The emergence of global-scale hydrology. *Water Resources Research* **1986**, *22*, doi:10.1029/WR022i09Sp0006S.
16. Leng, G.; et al. Emergence of new hydrologic regimes of surface water resources in the conterminous United States under future warming. *Environmental Research Letters* **2016**, *11*, doi:10.1088/1748-9326/11/11/114003.
17. Chi, M.T.H.; et al. Misconceived causal explanations for emergent processes. *Cognitive Science* **2012**, *36*, 1–61.
18. Kastrup, B. Physics is pointing inexorably to mind. *Scientific American Magazine*, 25 March **2019**, https://scientificamerican.com/observations/physics-is-pointing-inexorably-to-mind/.