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The evolution of hydrology (1900-) under changing scientific paradigms: From catchments to Earth-system synthesis

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Abstract

Since 1900, hydrology has evolved from a predominantly empirical and applied discipline into an increasingly integrated Earth-system science. This Commentary interprets that evolution through eight cumulative hydrologic eras shaped by five broader scientific paradigms: empirical, theoretical, computational, data-intensive, and artificial intelligence. Twentieth-century developments established the foundation of catchment-based hydrology in quantitative observation, analytical and process explanation, numerical simulation, and uncertainty diagnostics. Tracer, remote sensing and geospatial approaches subsequently expanded hydrologic inquiry across time, space, and connected systems; artificial intelligence now adds new capacity for data-model integration and possible scientific discovery. Together, these capabilities point toward an emerging phase of Earth-system synthesis that connects local process realism with global hydrology and coupled natural-human dynamics. The challenge is not to integrate everything at every scale, but to combine complementary capabilities where scientific questions demand it. Future progress depends on whether such synthesis is observationally supported, physically constrained,

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uncertainty-aware, diagnostically transparent and transferable across changing environments, and actionable for advancing Earth science and benefiting society.

Keywords

Scientific Paradigm, Earth system synthesis, Hydrology, Catchments, Evolution of Hydrology

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The evolution of hydrology (1900–) under changing scientific paradigms: From catchments to Earth-system synthesis

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Key Points

The Evolution of hydrology shows how scientific paradigms advanced and expanded capabilities without replacing earlier modes of inquiry.

Tracer and remote sensing hydrology expanded inference across time and space, while AI boosts data-model integration and automation.

Question-driven Earth-system synthesis should connect local process realism with global understanding across changing environments.

Abstract

Since 1900, hydrology has evolved from a predominantly empirical and applied discipline into an increasingly integrated Earth-system science. This Commentary interprets that evolution through eight cumulative hydrologic eras shaped by five broader scientific paradigms: empirical, theoretical, computational, data-intensive, and artificial intelligence.

Twentieth-century developments established the foundation of catchment-based hydrology in quantitative observation, analytical and process explanation, numerical simulation, and uncertainty diagnostics. Tracer, remote sensing and geospatial approaches subsequently expanded hydrologic inquiry across time, space, and connected systems; artificial intelligence now adds new capacity for data-model integration and possible scientific discovery. Together, these capabilities point toward an emerging phase of Earth-system synthesis that connects local process realism with global hydrology and coupled natural-human dynamics. The challenge is not to integrate everything at every scale, but to combine complementary capabilities where scientific questions demand it. Future progress depends on whether such synthesis is observationally supported, physically constrained, uncertainty-aware, diagnostically transparent and transferable across changing environments, and actionable for advancing Earth science and benefiting society.

Plain Language Summary

Hydrology has changed markedly over the past century as scientists gained new ways to observe, explain, and simulate Earth's water cycle. This Commentary traces that evolution through eight overlapping eras shaped by five broad modes of scientific inquiry: observation, theory, computation, data-intensive analysis, and artificial intelligence. Early catchment-based studies established the foundation of modern hydrology; numerical simulations made water systems testable; tracer revealed water age and pathways; and remote sensing and geospatial tools extended observations across scales and regions. Artificial intelligence now offers new ways to connect data, models, and understanding. We argue that the next phase should be a science-driven Earth-system synthesis that links local process knowledge with global observations and interactions among water, climate, ecosystems, and society. The goal is not to integrate everything at every scale, but to combine capabilities where broader connections are needed to answer specific hydrologic questions.

Keywords: hydrology, scientific paradigm, remote sensing, artificial intelligence, Earth system synthesis

1. Introduction: The evolution of hydrology

Historically, hydrology did not emerge fully formed as a modern theoretical science; rather, it built its conceptual and quantitative foundations gradually from the muddy reality of local catchments. Early conceptual ideas about rainfall, runoff, groundwater and hydraulic measurement extend back centuries, from early philosophical accounts of the hydrologic cycle to the experimental and hydraulic advances of the seventeenth through nineteenth centuries. By the early twentieth century, however, these threads were increasingly reorganized into a more explicitly quantitative discipline centered on rainfall-runoff relations and catchment-based water study.

This Commentary uses 1900 as a practical starting point not because earlier hydrologic thoughts were unimportant, but because the twentieth century marks the transition to a more quantitative, catchment-based, and system-oriented modern hydrology. For much of the first half of the twentieth century, hydrology nevertheless remained strongly shaped by practical applications. By the late twentieth century, landmark U.S. National Research Council reports —Opportunities in the Hydrologic Sciences and Hydrologic Sciences: Taking Stock and Looking Ahead—recognized and consolidated a transition already underway toward hydrology as a distinct geoscience, with a scientific agenda encompassing continental hydrologic processes, the global water balance, and stronger observational, educational, and institutional infrastructure (National Research Council, 1991, 1998).

Major advances in hydrology have often followed the emergence of capabilities that expanded what could be observed, represented, or explained. Drawing on Kuhn's concept of scientific paradigms and later formulations of data-intensive and AI-enabled scientific discovery (Hey et al., 2009; Ioannidis, 2024; Kuhn, 1962), we use five broad paradigms as the background lens: empirical observation, theoretical explanation, computational simulation, data-intensive inference, and AI-enabled integration and discovery. We use "paradigm" here to describe changing modes of scientific inquiry, not to imply that one mode displaced another. Their cumulative interaction has expanded both the observational reach of hydrology, and the kinds of explanations hydrologists can test (Sivapalan & Blöschl, 2017).

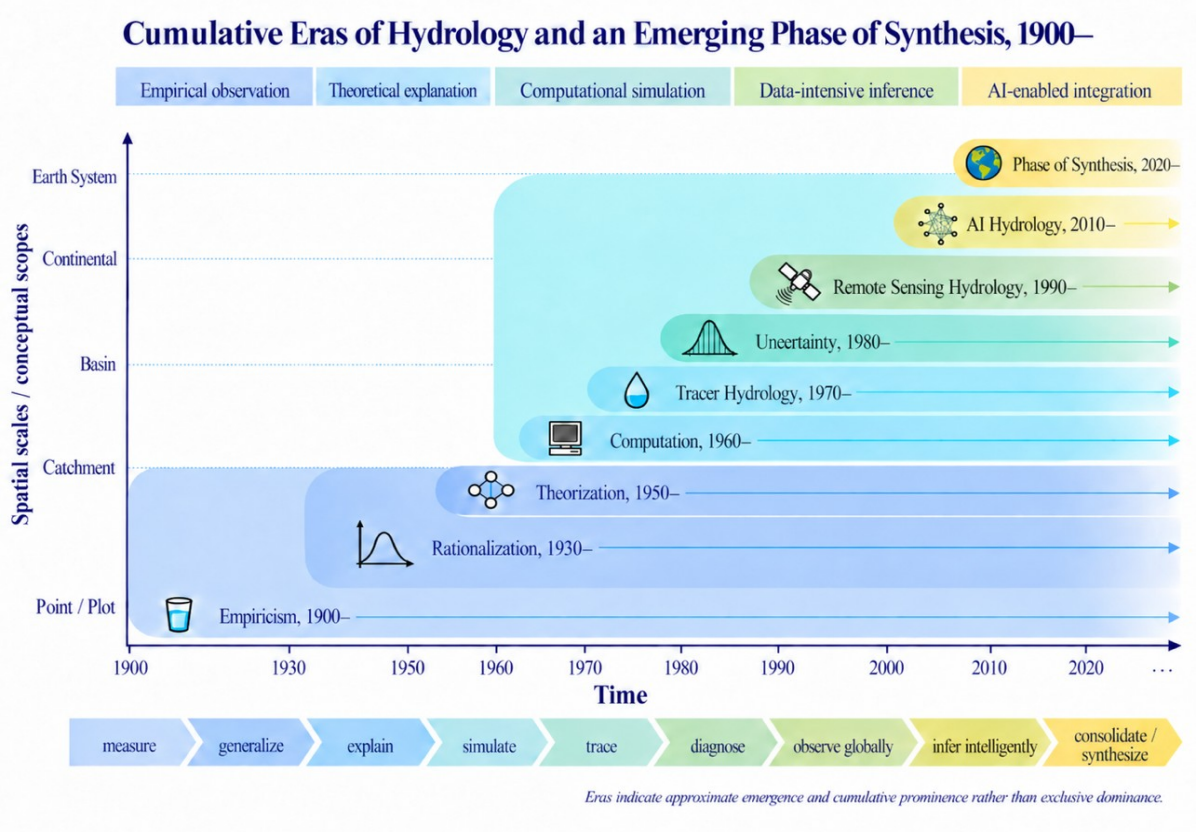
Table 1. Hydrologic eras (1900–) and their approximate emergence under changing scientific paradigms. Note that "eras" indicate approximate emergence or rising prominence rather than periods of exclusive dominance. Supported by the accumulated capabilities of the eight eras, the final row denotes an emerging phase of cross-paradigm synthesis, not a well-defined ninth chronological era.

Scientific paradigm	Hydrologic era	Approx. emergence	Core question	Distinctive capability or constraints	Enduring epistemic shift in hydrology
Empirical	Empiricism: Empirical hydrology	1900–	How much water is stored and how fast it moves, and with what impacts?	Direct observation and field experimentation	From qualitative observation to quantitative description
Theoretical	Rationalization: Analytical hydrology	1930–	Can hydrologic response be generalized through analytical rules?	Parsimonious equations, statistical relations, and regression of processes	From measurement to statistical predictive generalization
Theoretical	Theorization: Process and catchment hydrology	1950–	Why does water behave as it does within catchments?	Conceptual and physical explanation of hydrologic processes and response	From empirical to causal explanation of catchment-scale processes
Computational	Computation: Computational hydrology	1960–	Can processes be represented explicitly in space and time?	Executable numerical simulation constrained by conservation principles	From analytical reasoning to numerical simulation of hydrologic systems
Computational	Uncertainty and diagnostic hydrology	1980–	How should models be judged under partial observability and equifinality?	Probability, ensembles, sensitivity analysis, and uncertainty-aware diagnostics	From deterministic to probabilistic prediction and conditional inference
Data-intensive	Tracer hydrology	1970–	Where does water come from, how old is it, and which pathways does it follow?	Water age, mixing, transit time, storage history, and Lagrangian pathway constraints	Inference of hidden states, storage/transit times, and temporal connectivity
Data-intensive	Remote sensing hydrology	1990–	Can hydrology be observed consistently across regions and scales?	Global observation, geospatial connectivity, and Eulerian continuity across large domains	From local analysis to globally consistent, observation-constrained and geospatially connected hydrologic analysis
Artificial intelligence	Artificial intelligence hydrology	2010–	How can artificial intelligence integrate data, models, and theory into trustworthy hydrologic intelligence?	Pattern discovery, high-capacity data-model integration, and physics-informed reasoning and explanation	From prediction to artificial intelligence-enabled reasoning and discovery
Cross-paradigm integration	Phase of consolidation and synthesis	Emerging since 2020	How does water interact across scales and coupled Earth-system components?	Integration across scales and Earth-system components to investigate the generality and limits of hydrology	From local knowledge to global and Earth-system synthesis

Within this framing, eight hydrologic eras mark approximate periods when distinctive capabilities became prominent (Table 1). Early eras established observation, analytical

generalization, process explanation, numerical simulation, and uncertainty diagnosis; tracer, remote sensing/geospatial technologies, and later AI developments expanded hydrologic inquiry across time, space, data-model relationships and Earth-system questions. The eras are cumulative rather than exclusive: all remain active and coexist in contemporary hydrology as shown in Figure 1. Earlier classifications and retrospectives—from Chow's Handbook of Applied Hydrology and Dooge's search for hydrologic laws to Beven's Seven Ages of Hydrology and a recent extension recognizing a remote sensing era—are acknowledged for providing important precedents for this Commentary (Chow, 1964; Dooge, 1986; Beven, 2025; Hong, Lakshmi, et al., 2026).

Figure 1. Cumulative eras of hydrology and an emerging phase of synthesis since 1900. Eight hydrologic eras are shown under five changing scientific paradigms, illustrating the cumulative expansion of hydrologic capabilities, dominant spatial scales and conceptual scope from point/plot studies to Earth-system synthesis.



2. Empirical and theoretical paradigms: Foundations of modern hydrology

The early development of hydrology was shaped by the empirical paradigm, in which observations and in situ measurement formed the primary basis of understanding. Empirical hydrology was marked by the rise of experimental watersheds and field-based catchment studies—such as the Sperbelgraben and Rappengraben catchments in Switzerland around 1900 and the Wagon Wheel Gap in the United States in 1928—which provided some of the earliest quantitative experimental tests of the catchment water balance. This era transformed hydrology from a largely descriptive practice into measurement-based scientific inquiry. Critically, during this era, ground observations defined not only the scope of inquiry but also its epistemic limits, and they remain indispensable today for process discovery and hypothesis testing (Beven, 2020).

Building on this empirical foundation, hydrology progressed toward predictive generalization through simplified empirical–analytical relationships. The rationalization era, emerging prominently in the 1930s, introduced analytical and rational methods for estimating runoff and catchment response, allowing behavior to be generalized beyond isolated observations. Representative milestones of this era included Sherman's Unit Hydrograph (1932), Horton's infiltration-capacity curves (1933), the Theis equation for transient groundwater flow (1935) founded on Darcy's Law (1856), and a broader movement toward analytical prediction in rainfall-runoff and groundwater problems (Beven, 2021). Although these approaches often favored applicability over complete process representation, they marked a decisive transition from direct measurement to formalized prediction.

Subsequent developments in the theoretical hydrology era (1950–) introduced process-based explanations of rainfall-runoff generation, infiltration, and catchment-scale response. Driven by advances such as Penman's physically based evaporation equations (1948), the introduction of Budyko's hydroclimatic framework (1956), Philip's mathematical solutions for infiltration (1957), and the widespread application of the Richards equation (1931) for unsaturated flow, the catchment was established as the central unit of analysis. Water fluxes and storages could increasingly be interpreted through physically meaningful mechanisms. This theoretical paradigm shifted hydrology from empirical generalization toward conceptual

and mathematical explanations of process behavior. Across these three earlier foundational eras, the progression from measurement to predictive generalization to process explanation established the conceptual scaffolding of modern hydrology, although field understanding remained limited by spatial heterogeneity and mostly deterministic calculation.

3. Computational paradigm: Probabilistic and uncertainty-aware inference

The emergence of the computational hydrology era (1960–) marked a transition from analytical calculations toward executable numerical simulation of hydrologic systems. Catalyzed by theoretical blueprints such as the Stanford Watershed Model (1966), the Freeze and Harlan's hydrologic response model (1969), and TOPMODEL (1979), digital computing enabled the development of semi-distributed and distributed hydrologic models capable of representing spatially heterogeneous processes while respecting conservation principles and process conceptualizations (Beven & Kirkby, 1979). The computational paradigm enabled hydrologists to use digital models as virtual laboratories for comparing process hypotheses and exploring system behavior within an extensible and reproducible modeling framework. Early macroscale and georeferenced simulations further demonstrated that large connected river systems could be represented beyond individual catchments (Clark et al., 2015; Maidment, 1993; Vörösmarty et al., 1989).

During the 1970s, immense computational cost limited the routine use of large ensembles and optimal parameter exploration. As computing power increased after the 1980s, thousands of iterative model evaluations became feasible. The same expansion also exposed non-uniqueness and equifinality: multiple parameter sets, process formulations, and model structures could reproduce similarly acceptable results. Computational progress therefore made uncertainty-aware inference unavoidable and brought equifinality to the center of hydrologic diagnosis (Beven & Freer, 2001).

This computational paradigm also helped establish an uncertainty and diagnostic era in hydrology (1980–), supported by increasingly systematic model evaluation and parameter-space exploration. Frameworks such as the Generalized Likelihood Uncertainty Estimation (GLUE), the Shuffled Complex Evolution (SCE-UA) algorithm, multi-objective calibration,

ensemble modeling, and Monte Carlo exploration formalized diagnosis of forcing, parameter, and structural uncertainty (Beven & Freer, 2001; Duan et al., 1992; Gupta et al., 1998; Vrugt et al., 2003). Hydrology consequently shifted toward conditional or probabilistic inference. Models became not only predictive tools but also diagnostic instruments for evaluating competing hypotheses. The computational paradigm made hydrology numerically executable and testable in digital labs, yet its inferences remained limited by the scarcity and often fragmented spatial coverage of observations.

4. Data-intensive paradigm: Complementary spatiotemporal constraints

The data-intensive paradigm has transformed hydrology not simply by increasing data volume, but by expanding what could be observationally discovered and diagnosed across space and time. This paradigm underpins two consequential and complementary hydrologic eras: tracer hydrology and remote sensing hydrology. Although often associated with separate research communities, their deeper significance lies in the convergence of the complementary temporal and spatial constraints they jointly provide on hydrologic systems.

The tracer hydrology era (1970–) introduced a new capacity to interrogate the temporal organization of hydrologic systems by revealing water age, transit pathway, mixing, and residence time. Foundational studies using environmental isotopes showed that storm hydrographs could be dominated by displaced pre-event water, revealing pathways and system memory that flux observations alone could not identify (Dinçer et al., 1970; Kirchner, 2003; McDonnell et al., 2010; Pinder & Jones, 1969; Sprenger et al., 2019). This moved hydrology beyond observable flux response toward the diagnosis of hidden internal states, making it possible to ask not only where water came from and how fast it moved, but also how long it had been stored and which pathways it followed. Tracer hydrology thus introduced Lagrangian internal time—the history of a water parcel—as an explicit component in hydrologic inference.

The remote sensing hydrology era (1990–), by contrast, expanded the spatial observability of water from point to global scales. Remote sensing did not merely add new data streams; it moved hydrology beyond reliance on point interpolation toward spatially continuous observation and provided a practical basis for quantitative inference in many data-poor

regions. The 1990s and 2000s brought hydrologically useful satellite observations of precipitation, terrestrial water storage, soil moisture, and surface water, including TRMM, PERSIANN and PERSIANN-CCS, TMPA, GRACE, SMAP, and later SWOT (Hsu et al., 1997; Biancamaria et al., 2016; Entekhabi et al., 2010; Hong et al., 2004; Huffman et al., 2007; Tapley et al., 2004). In epistemic terms, remote sensing hydrology introduced Eulerian spatial continuity as a first-order hydrologic constraint. Together with other Earth-observing systems and reanalysis, these observations now support spatially consistent, regionally comparable, and temporally repeatable analysis of hydrologic systems (Dorigo et al., 2021; Durand et al., 2021; Hong, Lakshmi, et al., 2026; Sheffield et al., 2018).

A parallel development was the emergence of geospatial technology from the late 1980s onward. Geographic information systems, digital elevation models, georeferenced hydrography, and large river-network topology enabled drainage basins to be represented as connected, hierarchical systems rather than isolated study units. These advances helped hydrology move toward continental and global representations of water balance, flow routing and transport (Bierkens, 2015; Fekete et al., 2002; Oki & Sud, 1998; Vörösmarty et al., 2000, 2010).

Together, tracer and geospatial remote sensing approaches moved hydrology toward complementary temporal and spatial constraints. The former reveals hidden states and histories in time; the latter provides hydrologic organization and connectivity across space. Their combination can provide a stronger basis for questions involving processes with very different timescales, such as surface water–groundwater exchange (Ma et al., 2024). A central challenge is to connect these forms of information without losing their distinct spatiotemporal signatures and physical meanings.

5. Artificial intelligence paradigm: From prediction toward reasoning and discovery?

Corresponding to the fifth scientific paradigm, the AI hydrology era (2010–present) reflects the growing use of machine learning for hydrologic prediction, model–data integration, physics-informed inference, knowledge discovery, and the still-debated prospect of autonomous scientific discovery (Karpatne et al., 2017; Kratzert et al., 2019; Nearing et al.,

2021, 2024; Reichstein et al., 2019; Shen, 2018; Shen et al., 2023). AI may be considered neither the terminus of hydrologic science nor a replacement for hydrologists. Its scientific value ultimately depends on whether its capacity to learn high-dimensional representations can be translated into physically explainable inference constrained by conservation principles.

Much of AI's current success in hydrology has been demonstrated through improved predictive skill, particularly in large-sample settings. These advances are consequential, but predictive success does not by itself constitute scientific understanding. Because hydrologic inference is often underdetermined and shaped by hidden states, non-uniqueness, and changing boundary conditions, a model can predict well without revealing why the system behaves as it does (Maier et al., 2024).

The deeper challenge is therefore not simply how accurately AI predicts, but whether it advances understanding of why hydrologic systems behave as they do, which processes and constraints govern their behavior, and why those relationships vary among hydrologic regimes. Hydrologic models have long been affected by structural ambiguity, and high-capacity AI can amplify this underdetermination by learning multiple internal representations that produce similarly strong predictions but likely imply competing—and potentially inconsistent—process interpretations. This form of Neural Equifinality weakens the correlation between predictive performance and scientific explanation (D'Amour et al., 2022; Hong, Gupta, et al., 2026). The critical questions are thus under what conditions AI predictions should be trusted, whether learned representations correspond to meaningful hydrologic processes, and whether competing hypothesis can be distinguished using independent observations and physical laws.

A credible pathway forward requires moving from epistemic opacity toward diagnostic reasoning transparency. The aim is not to simply replace hydrologic knowledge with machine learning, but to embed learning within scientifically defensible architectures that respect conservation principles, represent uncertainty explicitly, evaluate competing hypotheses, and remain robust beyond their training domains. AI becomes scientifically transformative when it synthesizes the observational, theoretical, and computational capabilities accumulated during earlier hydrologic eras. One of its deeper potentials lies in integrating tracer-derived results for internal states and water histories, remote-sensing observations of spatial organization and

change, geospatial representations of connectivity, and process-model knowledge within a coherent inference architecture.

AI should therefore be judged not only by predictive skill, but by whether it improves process understanding, reveals hidden states and relationships, discriminates among plausible explanations, and supports transparent reasoning and reproducible conclusions. In that role, AI adds to rather than replaces the capabilities accumulated across earlier hydrologic eras.

6. The phase of Earth-system synthesis

The next phase of hydrology is less likely to be another discrete era than an emerging Earth-system synthesis. Such synthesis is critical where scientific questions cross scales, compartments, or natural–human system boundaries; it does not imply that every hydrologic problem requires integration across all scales. Two directions are especially consequential: global hydrology, seeking terrestrial coherence without sacrificing local realism, and Earth-system hydrology, asking how water mediates interactions among natural and human systems.

Global hydrology has moved from aspiration to an active field supported by Earth observation, global reanalysis, geospatial infrastructure and connected river-network representations (Bierkens, 2015; Eagleson, 1986; Fekete et al., 2002; Oki & Kanae, 2006; Oki & Sud, 1998; Vörösmarty et al., 2000). Its scope now includes global water storage and fluxes, transboundary water resources, land–atmosphere exchange, and comparisons across climatic and physiographic regimes (Fowler et al., 2025; Gleason & Brown, 2025; Lall, 2014; Sivapalan, 2018). The central challenge is to achieve broad coherence while retaining local realism. Field measurements and process knowledge remain essential constraints, while global analyses reveal spatial organization, teleconnections, regional patterns, and human alterations that individual catchments cannot. High-resolution hydrography increasingly helps preserve fine-scale river-network structure within continental and global analyses (Vörösmarty et al., 2015; Yamazaki et al., 2019). The goal is therefore not global coverage at any cost, but representations that retain hydrologically consequential features as spatial extent expands.

Earth-system hydrology asks how water connects, mediates, amplifies, or buffers interactions among the atmosphere, hydrosphere, cryosphere, biosphere, lithosphere, and human systems

across scales. Water transports mass, energy, sediment, carbon, and nutrients among these components, so the scientific objective is not simply to build more coupled models but to explain how storage, pathways, connectivity, memory, thresholds, and extremes shape Earth system behavior and coevolution (Steffen et al., 2020; Vereecken et al., 2022). Today human interventions materially alter natural hydrologic cycle; dams, irrigation, urbanization, infrastructure, markets, policy, and risk perception may need to be considered. This synthesis requires models and explanations to be evaluated against more than discharge or aggregate predictive skill and to remain credible under non-stationarity.

This synthesis is epistemic as well as technological. Observations can serve not only as constraints on predictive models and statistical inference, but also as evidence for abductive discovery—the formulation and testing of plausible causal explanations from incomplete traces (Baker, 2017). Hydrology may therefore benefit from combining Newtonian modes of analytical explanation with Darwinian modes of historical and synthetic reasoning, especially for causes that exist over long timescales, under changing boundary conditions, and in only partially observable systems (Harman & Troch, 2014; Harte, 2002).

7. Conclusion and Outlook

Since 1900, hydrology has expanded from local catchment inquiry toward a more integrated Earth-system science. Its defining challenge is how to connect point-, hillslope-, and catchment-scale process knowledge with global observation, coupled Earth-system modeling, human–water interactions, and AI-enabled integrative inference. The accumulated capabilities of hydrologic eras now converge toward an emerging phase of synthesis. This new phase may further extend hydrologic inquiry across terrestrial scales through global hydrology, across coupled natural and human systems through Earth system hydrology.

Hydrology’s evolution is therefore not a sequence in which one paradigm replaces another. Empirical observation, theoretical explanation, simulation, uncertainty diagnosis, tracer inference, remote sensing and geospatial analysis, and artificial intelligence all remain active and complementary in contemporary hydrology. Each has advanced what the field can observe, test, explain, and predict, but each remains incomplete when used alone. To date, hydrologic inquiry has broadened in both spatiotemporal scale and conceptual scope—from plots and hillslopes to catchments, continents, and the coupled Earth system.

The future of hydrology is unlikely to be defined by any single paradigm. It will depend on the field's ability to connect local process realism with global observation and analysis, represent consequential human influences where needed, and investigate explanations that remain coherent across scales and systems. As water-related extremes, nonstationary regime shifts, and human interventions reshape the hydrologic cycle, this integrative capacity will matter increasingly for water security and resilience in the 21st century. Its success should ultimately be judged by whether hydrology can better understand and predict the movement, storage, age, quality, and hazard potential of water across scales and regimes—in ways that are observationally supported, physically constrained, uncertainty-aware, transferable under change, and useful for advancing science and benefiting society.

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Conflict of Interest

The authors declare there are no conflicts of interest for this manuscript.

AI Use

ChatGPT was used to assist with language proofreading and reference-format checking. All scientific arguments, interpretations, and final wording were critically reviewed and approved by the authors, who take full responsibility for the manuscript.

Open Research Statement

No new data or software were generated or analyzed for this Commentary.

References

Baker, V. R. (2017). Debates—Hypothesis testing in hydrology: Pursuing certainty versus pursuing uberty. Water Resources Research, 53, 1770–1778. https://doi.org/10.1002/2016WR020078

Beven, K. (2020). Developing observational methods to drive future hydrological science. Hydrological Processes, 34, 868–873.

Beven, K. (2021). The era of infiltration. Hydrology and Earth System Sciences, 25, 851–866.

Beven, K. (2025). The seven ages of hydrology. Hydrological Processes, 39, e70233. https://doi.org/10.1002/hyp.70233

Beven, K. J., & Freer, J. (2001). Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. Journal of Hydrology, 249, 11–29.

Beven, K. J., & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin, 24, 43–69.

Biancamaria, S., Lettenmaier, D. P., & Pavelsky, T. M. (2016). The SWOT mission and its capabilities for land hydrology. Surveys in Geophysics, 37, 307–337.

Bierkens, M. F. P. (2015). Global hydrology 2015: State, trends, and directions. Water Resources Research, 51, 4923–4947. https://doi.org/10.1002/2015WR017173

Chow, V. T. (Ed.). (1964). Handbook of applied hydrology. McGraw-Hill.

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., et al. (2015). A unified approach for process-based hydrologic modeling: 1. Modeling concept. Water Resources Research, 51, 2498–2514. https://doi.org/10.1002/2015WR017198

D'Amour, A., et al. (2022). Underspecification presents challenges for credibility in modern machine learning. Journal of Machine Learning Research, 23, 10237–10297.

Dinçer, T., Payne, B. R., Florkowski, T., Martinec, J., & Tongiorgi, E. (1970). Snowmelt runoff from measurements of tritium and oxygen-18. Water Resources Research, 6, 110–124.

Dorigo, W. A., et al. (2021). Closing the water cycle from observations across scales: Where do we stand? Bulletin of the American Meteorological Society, 102, E1897–E1935.

Duan, Q., Sorooshian, S., & Gupta, V. K. (1992). Effective and efficient global optimization for conceptual rainfall–runoff models. Water Resources Research, 28, 1015–1031. https://doi.org/10.1029/91WR02985

Durand, M., et al. (2021). Achieving breakthroughs in global hydrologic science by unlocking the power of multisensor, multidisciplinary Earth observations. AGU Advances, 2, e2021AV000455. https://doi.org/10.1029/2021AV000455

Eagleson, P. S. (1986). The emergence of global-scale hydrology. Water Resources Research, 22, 6S–14S. https://doi.org/10.1029/WR022i09Sp0006S

Entekhabi, D., et al. (2010). The Soil Moisture Active Passive (SMAP) mission. Proceedings of the IEEE, 98, 704–716.

Fekete, B. M., Vörösmarty, C. J., & Grabs, W. (2002). High-resolution fields of global runoff combining observed river discharge and simulated water balances. Journal of Hydrology, 261, 70–88.

Fowler, H. J., Coxon, G., & White, C. J. (2025). Hydrology in the 21st century: Challenges in science, to policy and practice. Philosophical Transactions of the Royal Society A, 383, 20240299.

Gleason, C. J., & Brown, C. M. (2025). The once and future hydrology is Whole Earth Hydrology. Perspectives of Earth and Space Scientists, 6, e2024CN000267.

Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1998). Toward improved calibration of hydrologic models: Multiple and noncommensurable measures of information. Water Resources Research, 34, 751–763. https://doi.org/10.1029/97WR03495

Harman, C., & Troch, P. A. (2014). What makes Darwinian hydrology "Darwinian"? Asking a different kind of question about landscapes. Hydrology and Earth System Sciences, 18, 417–433. https://doi.org/10.5194/hess-18-417-2014

Harte, J. (2002). Toward a synthesis of the Newtonian and Darwinian worldviews. Physics Today, 55, 29–34.

Hey, T., Tansley, S., & Tolle, K. (Eds.). (2009). The fourth paradigm: Data-intensive scientific discovery. Microsoft Research.

Hong, Y., Gupta, H. V., Yong, B., Chen, M., Yan, S., Wang, Y., et al. (2026). HP Commentary: Neural equifinality and predictive mirages in AI-enabled hydrology and Earth system modelling. Hydrological Processes, 40(7), e70647. https://doi.org/10.1002/hyp.70647

Hong, Y., Hsu, K.-L., Sorooshian, S., & Gao, X. (2004). Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. Journal of Applied Meteorology, 43, 1834–1853. https://doi.org/10.1175/JAM2173.1

Hong, Y., Lakshmi, V., Foufoula-Georgiou, E., Sorooshian, S., Famiglietti, J. S., Maggioni, V., et al. (2026). Comment on Beven (2025) "The Seven Ages of Hydrology": Recognizing the remote sensing era of hydrology (1990s–). Hydrological Processes, 40(5), e70560. https://doi.org/10.1002/hyp.70560

Hsu, K., Gao, X., Sorooshian, S., & Gupta, H. V. (1997). Precipitation estimation from remotely sensed information using artificial neural networks. *Journal of Applied Meteorology*, 36(9), 1176–1190

Huffman, G. J., et al. (2007). The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. Journal of Hydrometeorology, 8, 38–55.

Ioannidis, Y. (2024). The 5th paradigm: AI-driven scientific discovery. Communications of the ACM, 67, 5.

Karpatne, A., et al. (2017). Theory-guided data science: A new paradigm for scientific discovery from data. IEEE Transactions on Knowledge and Data Engineering, 29, 2318–2331.

Kirchner, J. W. (2003). A double paradox in catchment hydrology and geochemistry. Hydrological Processes, 17, 871–874.

Kratzert, F., et al. (2019). Towards improved predictions in ungauged basins: Exploiting the power of machine learning. Hydrology and Earth System Sciences, 23, 5089–5110. https://doi.org/10.5194/hess-23-5089-2019

Kuhn, T. S. (1962). The structure of scientific revolutions. University of Chicago Press.

Lall, U. (2014). Debates—The future of hydrological sciences: A (common) path forward? One water. One world. Many climes. Many souls. Water Resources Research, 50, 5335–5341. https://doi.org/10.1002/2014WR015402

Ma, R., et al. (2024). Methods for quantifying interactions between groundwater and surface water. Annual Review of Environment and Resources, 49, 623–653.

Maidment, D. R. (Ed.). (1993). Handbook of hydrology. McGraw-Hill.

Maier, H. R., et al. (2024). How much X is in XAI: Responsible use of 'explainable' artificial intelligence in hydrology and water resources. Journal of Hydrology X, 25, 100185.

McDonnell, J. J., et al. (2010). How old is streamwater? Open questions in catchment transit time conceptualization, modelling and analysis. Hydrological Processes, 24, 1745–1754.

National Research Council. (1991). Opportunities in the hydrologic sciences. National Academy Press.

National Research Council. (1998). Hydrologic sciences: Taking stock and looking ahead. National Academy Press.

Nearing, G. S., Kratzert, F., Sampson, A. K., Pelissier, C. S., Klotz, D., Frame, J. M., et al. (2021). What role does hydrological science play in the age of machine learning? Water Resources Research, 57, e2020WR028091. https://doi.org/10.1029/2020WR028091

Nearing, G. S., et al. (2024). Global prediction of extreme floods in ungauged watersheds. Nature, 627, 615–622.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. Science, 313, 1068–1072.

Oki, T., & Sud, Y. C. (1998). Design of total runoff integrating pathways (TRIP): A global river channel network. Earth Interactions, 2, 1–37.

Pinder, G. F., & Jones, J. F. (1969). Determination of the ground-water component of peak discharge from the chemistry of total runoff. Water Resources Research, 5, 438–445. https://doi.org/10.1029/WR005i002p00438

Reichstein, M., et al. (2019). Deep learning and process understanding for data-driven Earth system science. Nature, 566, 195–204.

Sheffield, J., Wood, E. F., Pan, M., Beck, H., Coccia, G., Serrat-Capdevila, A., & Verbist, K. (2018). Satellite remote sensing for water resources management: Potential for supporting sustainable development in data-poor regions. *Water Resources Research*, 54(12), 9724–9758. https://doi.org/10.1029/2018WR022714

Shen, C. (2018). A transdisciplinary review of deep learning research and its relevance for water resources scientists. Water Resources Research, 54, 8558–8593. https://doi.org/10.1029/2018WR022643

Shen, C., et al. (2023). Differentiable modelling to unify machine learning and physical models for geosciences. Nature Reviews Earth & Environment, 4, 552–567.

Sivapalan, M. (2018). From engineering hydrology to Earth system science: Milestones in the transformation of hydrologic science. Hydrology and Earth System Sciences, 22, 1665–1693. https://doi.org/10.5194/hess-22-1665-2018

Sivapalan, M., & Blöschl, G. (2017). The growth of hydrological understanding: Technologies, ideas, and societal needs shape the field. Water Resources Research, 53, 8137–8146. https://doi.org/10.1002/2017WR021396

Sprenger, M., Seeger, S., Blume, T., & Weiler, M. (2019). The demographics of water: A review of water ages in the critical zone. Reviews of Geophysics, 57, 800–834. https://doi.org/10.1029/2018RG000633

Steffen, W., et al. (2020). The emergence and evolution of Earth system science. Nature Reviews Earth & Environment, 1, 54–63.

Tapley, B. D., Bettadpur, S., Watkins, M. M., & Reigber, C. (2004). The Gravity Recovery and Climate Experiment: Mission overview and early results. Geophysical Research Letters, 31, L09607. https://doi.org/10.1029/2004GL019920

Vereecken, H., et al. (2022). Soil hydrology in the Earth system. Nature Reviews Earth & Environment, 3, 573–587.

Vörösmarty, C. J., et al. (2010). Global threats to human water security and river biodiversity. Nature, 467, 555–561.

Vörösmarty, C. J., Fekete, B. M., Meybeck, M., & Lammers, R. B. (2000). Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. Global Biogeochemical Cycles, 14, 599–621. https://doi.org/10.1029/1999GB900092

Vörösmarty, C. J., Hoekstra, A. Y., Bunn, S. E., Conway, D., & Gupta, J. (2015). Fresh water goes global. Science, 349, 478–479.

Vörösmarty, C. J., Moore, B., III, Grace, A. L., Gildea, M. P., Melillo, J. M., Peterson, B. J., et al. (1989). Continental scale models of water balance and fluvial transport: An application to South America. Global Biogeochemical Cycles, 3, 241–265. https://doi.org/10.1029/GB003i003p00241

Vrugt, J. A., Gupta, H. V., Bouten, W., & Sorooshian, S. (2003). A shuffled complex evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. *Water Resources Research*, 39(8), 1201. https://doi.org/10.1029/2002WR001642

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P. D., Allen, G. H., & Pavelsky, T. M. (2019). MERIT Hydro: A high-resolution global hydrography map based on latest topography dataset. Water Resources Research, 55, 5053–5073. https://doi.org/10.1029/2019WR024873