COMMENTARY

Comment on Beven (2025) "the Seven Ages of Hydrology": Recognizing the Remote Sensing Era of Hydrology (1990s -)

Yang Hong[1] | Venkataraman Lakshmi[2] | Efi Foufoula-Georgiou[3] | Soroosh Sorooshian[3] | James S. Famiglietti[4] | Viviana Maggioni[5] | Emmanouil N. Anagnostou[6] | Siyu Zhu[1] | Mengye Chen[1] | Songkun Yan[1]

[1]HyDROS Lab at the National Weather Center, School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma, USA | [2]Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, Virginia, USA | [3]Departments of Civil and Environmental Engineering & Earth System Science, University of California, Irvine, California, USA | [4]School of Sustainability, Arizona State University, Tempe, Arizona, USA | [5]Department of Civil, Environmental & Infrastructure Engineering, George Mason University, Arlington, Virginia, USA | [6]School of Civil and Environmental Engineering, University of Connecticut, Storrs, Connecticut, USA

Correspondence: Yang Hong (yanghong@ou.edu)

Received: 30 March 2026 | **Revised:** 17 April 2026 | **Accepted:** 27 April 2026

ABSTRACT

This commentary offers a constructive extension to Beven (2025), arguing that the Remote Sensing Era has already transformed hydrology's observational and inferential foundation, enabling globally consistent, process-relevant analysis of the water cycle.

1 | Defining the Remote Sensing Era

Beven's "Seven Ages of Hydrology" is an unusually useful provocation because it foregrounds hydrological process and the historical role of observation, rather than treating modelling fashions as inevitable progress (Beven 2025). The proposed ages are deliberately debatable, and Beven explicitly invites that debate. In that spirit, we offer one focused refinement intended to strengthen, rather than dispute, the framework: remote sensing has already initiated a distinct era in hydrology since the early 1990s, coinciding with the emergence of sustained global hydrologic observing systems and data records, even if this transformation remains ongoing.

Here, we use the term *era* to denote a sustained shift in hydrology's epistemic workflow—what can be observed, how hypotheses are tested, and how uncertainty is communicated from measurement to prediction and decision. This framing aligns with broader historiographies of hydrology that identify 1990–2010 as a "Geosciences Era," in which remote sensing (RS)—including spaceborne and airborne observations and their derived products—emerged as a defining technological shift (Sivapalan and Blöschl 2017). The defining question of this period is how RS, together with models, can be used to address hydrological science questions and quantify where water is stored, where and how it moves, and how these patterns evolve beyond what in situ networks alone can provide (Sorooshian et al. 2000; Lakshmi 2004; Lettenmaier et al. 2015; Sheffield et al. 2018).

Historically, major shifts in hydrology have often followed expansions in observational capability—from tracer techniques to distributed measurements and large-sample analysis. This trajectory was already recognized in foundational assessments of the field, which emphasized the central role of observation in advancing hydrologic science prior to the widespread availability of global Earth observations (National Research Council 1991). By the same logic, the emergence of sustained, global, multi-sensor Earth observation systems since the 1990s represents a comparable shift in what hydrology can observe, test, and evaluate. This transition has been widely recognized as transformative, with satellite observations providing the "big-picture" spatial coverage and regional-to-global perspective essential for understanding water availability and change (Famiglietti et al. 2015; NAS 2018). In this sense, recognizing a Remote Sensing Era is less a proposal than a reflection of how the discipline has already evolved over the past three decades. This emphasis on epistemic workflow matters because, as Beven (2020) argue, apparent advances in modelling sophistication can create an "illusion of real progress" when observational uncertainty and conceptual gaps remain limiting; the Remote Sensing Era is precisely the period in which hydrology reorganized to confront those limits through observation-driven inference.

2 | Revisiting Indirectness and Uncertainty

Beven (2025) notes that remote sensing (RS) has "had the potential to transform our appreciation of the spatial heterogeneity of hydrological processes," but suggests that its full impact remains in the future. His argument centers on two concerns: that RS often provides hydrological variables indirectly, and that RS data may lack explicit uncertainty statements. These concerns are valid, but they are not unique to RS. On the contrary, the RS system now operates as a full-spectrum observing architecture (visible → thermal → microwave → gravimetric) that enables hydrology to observe not only states and extents, but also spatial patterns and process signatures that were previously inaccessible at scale.

Importantly, while many hydrologic quantities derived from remote sensing are retrieved, they are rooted in a broad spectrum of physically grounded observations, some of which are observed relatively directly. In the visible and near-infrared, optical sensors observe surface water extent, flood inundation, river and lake planform, shoreline position, snow cover, glacier extent, vegetation condition, and water colour. Thermal infrared sensors measure land and water surface temperature, revealing spatial structure in groundwater-surface water exchange and thermal signatures of flow pathways. LiDAR measures topography, floodplain geometry, channel form, and, in some settings, water-surface elevation. Synthetic aperture radar (SAR) observes inundation dynamics, wetland connectivity, and flood extent under all-weather conditions. Radar altimetry and interferometry measure water-surface elevation and slope, extending these capabilities to large river and lake systems. Collectively, these observations constitute a physically grounded, multi-sensor measurement system that captures hydrologically relevant extents, geometries, temperatures, elevations, and physical signals across the water cycle.

At the same time, some hydrologic variables derived from these observations—such as precipitation rate, evapotranspiration, root-zone soil moisture, river discharge, recharge, and certain storage components—are retrieved or inferred through radiative transfer models, inverse methods, empirical relationships, data assimilation, or hybrid process–learning frameworks. However, this indirectness is not fundamentally different from other forms of hydrologic inference. Hydrology has long relied on indirect measurements to infer system behaviour: river discharge is commonly derived from stage–discharge relationships, groundwater contributions are inferred from tracers and geochemical signatures, and many state variables are estimated through model-based integration of sparse observations. If in situ streamflow is accepted as an indirect, model-dependent estimate, then the indirectness of many remote-sensing products is not, by itself, a reason to discount their hydrologic significance. Rather, remote sensing extends this long-standing measurement–inference framework to the global domain, providing spatially continuous, physically interpretable observations that can be translated into hydrologic states and fluxes with explicit uncertainty characterization. In this sense, RS does not introduce a fundamentally different epistemology; it scales established hydrologic observation–inference relationships across space, time, and process domains.

The issue of uncertainty in RS retrievals further reinforces, rather than weakens, this argument. The nontrivial error structures of RS data have driven advances in uncertainty quantification, data assimilation, and model–data fusion. The community has increasingly treated uncertainty as a first-class quantity, developing methods to propagate information from sensor-level observations through hydrologic states to predictions and decisions (Hong et al. 2006; Dorigo et al. 2021). By building translation layers—such as data assimilation and hybrid modelling—the discipline now converts RS information into hydrologic states while demanding end-to-end uncertainty traceability.

Partial indirectness and uncertainty are therefore not disqualifiers; they are the defining catalysts that have shaped the Remote Sensing Era around inference discipline and uncertainty accountability. In this sense, RS does not introduce a fundamentally different epistemology, but extends existing hydrologic inference frameworks to the global domain.

3 | What Has Changed: From Observation to Global Hydrology

A useful criterion for identifying an era is not simply that a technology exists, but that it forces the discipline to change how it observes, evaluates, and operationalizes hydrological understanding. By that criterion, remote sensing has already been field-structuring. Five developments illustrate how remote sensing has already restructured hydrologic science in ways comparable, if not larger, in scope to earlier hydrologic ages.

First, the globalization of hydrology. Traditional hydrology has been shaped by data-rich regions with dense gauge networks. In many parts of the world, particularly the Global South, such networks never existed. In these regions, RS provides the first scalable sources of hydrologic forcing and state information, enabling quantitative hydrology where conventional approaches are not feasible (Clark et al. 2016). It provides the regional-to-global perspective that would not be possible with sparse in situ measurements alone (Famiglietti et al. 2015). For much of the developing world, this represents the first period of globally continuous, quantitative hydrologic observation.

Second, RS has enabled water-cycle–spanning observing systems that changed what hydrology can ask. Since the early 1990s, Earth observation has evolved into a multi-sensor system capturing precipitation, snow, soil moisture, surface water, and terrestrial storage (Lettenmaier et al. 2015). Satellite precipitation has progressed from early neural-network estimates (Hsu et al. 1997) to multi-sensor global products (Hong et al. 2004; Huffman et al. 2007; Hou et al. 2014) with multi-decadal records and kilometre-scale resolution (Ashouri et al. 2015; Zadeh et al. 2026). Missions such as GRACE and SWOT, together with emerging high-resolution soil moisture products

(Fang et al. 2025), have expanded the observable dimensions of the water cycle. These advances have enabled integrated assessments of global freshwater availability and its variability, revealing patterns that were previously unobservable (Rodell et al. 2018). The result is a shift toward spatially continuous, multi-variable, and dynamically consistent observation of hydrologic processes.

Third, hydrologic science is the discipline that seeks to observe, understand, explain, and predict the storage, movement, and transformation of water across the coupled Earth system. By that standard, remote sensing has advanced hydrologic science not merely by extending spatial coverage, but by improving process-level understanding and sharpening the science questions that can be posed across key components of the water cycle. Without remote sensing, hydrology would have remained far more confined to point-based, catchment-scale studies, with limited ability to observe and test the larger-scale atmospheric, terrestrial, and cross-basin connections that organize the water cycle. Precipitation is a central example. Satellite observations have transformed precipitation from a sparsely sampled forcing input into an observable and testable hydrologic process. They now allow hydrologists to track and predict where storms initiate, how cloud systems grow, mature, and decay through their life cycles, and how those dynamics shape downstream rainfall-runoff response and flood generation (Zhu et al. 2025; Guilloteau and Foufoula-Georgiou 2024). Similar advances apply across other major domains of hydrologic science: remote sensing of surface water using Synthetic Aperture Radar has improved understanding and modelling of runoff routing, floodplain exchange, and inundation dynamics (Getirana et al. 2017; Shen et al. 2019); satellite observations have also clarified land–atmosphere coupling by revealing soil moisture–cloud–precipitation feedbacks that lead to improved prediction of localized convection storms (Gao et al. 2024); remote-sensing-based evapotranspiration has revealed the spatiotemporal dynamics of water and energy flux exchange between land and atmosphere (Yang et al. 2023); and GRACE observations have made terrestrial water storage an observable integrative state, advancing understanding and modelling of large-scale groundwater depletion and groundwater-surface water exchange (Rodell et al. 2018). Owing to page limits, we mention only a few examples rather than attempting a comprehensive review. Together, these results show that remote sensing has changed not only what hydrologists can monitor, but also which hydrologic process hypothesis and broader hydrologic science questions can be posed, modelled, and explained across scales.

Fourth, RS established large-sample hydrology across global basins. The availability of consistent observations across thousands of basins enables cross-basin hypothesis testing, regime-based analysis, and evaluation of transferability across climates and physiographic settings (Sheffield et al. 2018). Hydrology is no longer constrained primarily by where gauges exist, but by how hypotheses are formulated and tested. This transition enables continental-scale diagnostics and systematic evaluation that were previously infeasible (Lettenmaier et al. 2015).

Fifth, RS has enabled operational sensor-to-decision hydrologic systems. Over the past three decades, hydrology has evolved toward end-to-end workflows linking observations to states, forecasts, and decisions. These systems integrate multi-sensor data through data assimilation and model–data fusion, supporting near-real-time situational awareness and early warning at continental scales. A key requirement is end-to-end traceability, ensuring that observational uncertainty is propagated through models to decision-relevant outputs. RS has therefore been central to the emergence of scalable, observation-driven hydrology as an operational service (Dorigo et al. 2021).

4 | Implications for the Next Phase

Recognizing a Remote Sensing Era does not require claiming that RS directly observes all hydrologic variables with complete certainty. Rather, it reflects the fact that hydrology has reorganized around translating observational information into states and fluxes through model–data integration. Community modelling systems such as GLDAS explicitly integrate RS observations into hydrologic inference (Rodell et al. 2004). The discipline has matured through the development of translation layers—data assimilation, model–data fusion, and emerging hybrid approaches—that progressively improve uncertainty characterization (Guilloteau et al. 2025; Sun et al. 2026). In this sense, RS has redefined the observational foundation of hydrology.

Recognizing a Remote Sensing Era does not compete with Beven's framework but complements it. Hydrologic advances are not strictly sequential; they are overlapping shifts in observation, modelling, and inference. Remote sensing provides the spatially continuous constraints that allow modelling, tracer studies, and uncertainty frameworks to be tested at larger scales. It therefore completes the observational–computational structure of modern hydrology.

In summary, hydrology advances when new observations enable new analysis, a principle articulated decades ago (National Research Council 1991). Since the early 1990s, remote sensing has fundamentally altered hydrology's observational capabilities, evaluation strategies, and operational reach. Recognizing this Remote Sensing Era clarifies both what has matured and what remains to be developed. If earlier ages were defined by new ways of seeing hydrologic processes, then the Remote Sensing Era represents the first time hydrology can observe those processes continuously across the globe—an identifiable historical phase that helps explain how hydrology has evolved over the past three decades and how it is likely to evolve next.

Funding

The authors have nothing to report.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

References

Ashouri, H., K. L. Hsu, S. Sorooshian, et al. 2015. "PERSIANN-CDR: Daily Precipitation Climate Data Record From Multisatellite Observations for Hydrological and Climate Studies." *Bulletin of the*

American Meteorological Society 96, no. 1: 69–83. https://doi.org/10.1175/BAMS-D-13-00068.1.

Beven, K. 2020. "Developing Observational Methods to Drive Future Hydrological Science." *Hydrological Processes* 34: 868–873.

Beven, K. 2025. "The Seven Ages of Hydrology." *Hydrological Processes* 39: e70233.

Clark, R., Z. Flamig, H. Vergara, et al. 2016. "Hydrological Modeling and Capacity Building in the Republic of Namibia." *Bulletin of the American Meteorological Society* 98, no. 8: 1697–1715. https://doi.org/10.1175/BAMS-D-15-00130.1.

Dorigo, W. A., S. Dietrich, F. Aires, et al. 2021. "Closing the Water Cycle From Observations Across Scales: Where Do We Stand?" *Bulletin of the American Meteorological Society* 102, no. 10: E1897–E1935. https://doi.org/10.1175/BAMS-D-19-0316.1.

Famiglietti, J. S., A. Cazenave, A. Eicker, J. T. Reager, M. Rodell, and I. Velicogna. 2015. "Satellites Provide the Big Picture." *Science* 349, no. 6249: 684–685. https://doi.org/10.1126/science.aac9238.

Fang, B., V. Lakshmi, C. Hain, and V. Mishra. 2025. "A Global High Spatial Resolution 400 m Soil Moisture Dataset Using SMAP and VIIRS Observations." *Scientific Data* 13: 65. https://doi.org/10.1038/s41597-025-06356-z.

Gao, Y., C. Guilloteau, E. Foufoula-Georgiou, C. Xu, X. Sun, and J. A. Vrugt. 2024. "Soil Moisture–Cloud–Precipitation Feedback in the Lower Atmosphere From Functional Decomposition of Satellite Observations." *Geophysical Research Letters* 51: e2024GL110347.

Getirana, A., S. Kumar, M. Girotto, and M. Rodell. 2017. "Rivers and Floodplains as Key Components of Global Terrestrial Water Storage Variability." *Geophysical Research Letters* 44: 10,359–10,368. https://doi.org/10.1002/2017GL074684.

Guilloteau, C., and E. Foufoula-Georgiou. 2024. "Life Cycle of Precipitating Cloud Systems From Synergistic Satellite Observations: Evolution of Macrophysical Properties and Precipitation Statistics From Geostationary Cloud Tracking and GPM Active and Passive Microwave Measurements." *Journal of Hydrometeorology* 25: 789–805. https://doi.org/10.1175/JHM-D-23-0185.1.

Guilloteau, C., G. Kerrigan, K. Nelson, et al. 2025. "A Generative Diffusion Model for Probabilistic Ensembles of Precipitation Maps Conditioned on Multisensor Satellite Observations." *IEEE Transactions on Geoscience and Remote Sensing* 63: 1–15. https://doi.org/10.1109/TGRS.2025.3548518.

Hong, Y., K. L. Hsu, S. Sorooshian, and X. Gao. 2004. "Precipitation Estimation From Remotely Sensed Imagery Using an Artificial Neural Network Cloud Classification System." *Journal of Applied Meteorology* 43, no. 12: 1834–1853.

Hong, Y., K. L. Hsu, S. Sorooshian, and X. Gao. 2006. "Uncertainty Quantification of Satellite Precipitation Estimation and Monte Carlo Assessment of Error Propagation Into Hydrologic Response." *Water Resources Research* 42: W08421. https://doi.org/10.1029/2005WR004398.

Hou, A. Y., R. K. Kakar, S. Neeck, et al. 2014. "The Global Precipitation Measurement Mission." *Bulletin of the American Meteorological Society* 95: 701–722. https://doi.org/10.1175/BAMS-D-13-00164.1.

Hsu, K. L., X. Gao, S. Sorooshian, and H. V. Gupta. 1997. "Precipitation Estimation From Remotely Sensed Information Using Artificial Neural Networks." *Journal of Applied Meteorology* 36, no. 9: 1176–1190.

Huffman, G. J., D. T. Bolvin, E. J. Nelkin, 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. https://doi.org/10.1175/JHM560.1.

Lakshmi, V. 2004. "The Role of Remote Sensing in Prediction of Ungaged Basins." *Hydrological Processes* 18, no. 5: 1029–1034.

Lettenmaier, D. P., D. Alsdorf, J. Dozier, G. J. Huffman, M. Pan, and E. F. Wood. 2015. "Inroads of Remote Sensing Into Hydrologic Science During the WRR Era." *Water Resources Research* 51, no. 9: 7309–7342. https://doi.org/10.1002/2015WR017616.

National Academies of Sciences, Engineering, and Medicine. 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation From Space*. National Academies Press. https://doi.org/10.17226/24938.

National Research Council. 1991. *Opportunities in the Hydrologic Sciences*. National Academy Press.

Rodell, M., J. S. Famiglietti, D. N. Wiese, J. T. Reager, F. W. Landerer, and M.-H. Lo. 2018. "Emerging Trends in Global Freshwater Availability." *Nature* 557: 651–659.

Rodell, M., P. R. Houser, U. Jambor, et al. 2004. "The Global Land Data Assimilation System." *Bulletin of the American Meteorological Society* 85, no. 3: 381–394.

Sheffield, J., E. F. Wood, M. Pan, et al. 2018. "Satellite Remote Sensing for Water Resources Management: Potential for Supporting Sustainable Development." *Water Resources Research* 54, no. 11: 8334–8360.

Shen, X., D. Wang, K. Mao, E. Anagnostou, and Y. Hong. 2019. "Inundation Extent Mapping by Synthetic Aperture Radar: A Review." *Remote Sensing* 11, no. 7: 879.

Sivapalan, M., and G. Blöschl. 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.

Sorooshian, S., K. L. Hsu, X. Gao, H. V. Gupta, B. Imam, and D. Braithwaite. 2000. "Evaluation of PERSIANN System Satellite-Based Estimates of Tropical Rainfall." *Bulletin of the American Meteorological Society* 81, no. 9: 2035–2046.

Sun, S., C. Nai, B. Pan, et al. 2026. "Fusion of Multi-Source Precipitation Records via Coordinate-Based Generative Models." *Nature Communications* 17: 1227. https://doi.org/10.1038/s41467-025-67987-9.

Yang, Y., M. L. Roderick, H. Guo, et al. 2023. "Evapotranspiration on a Greening Earth." *Nature Reviews Earth & Environment* 4: 626–641. https://doi.org/10.1038/s43017-023-00464-3.

Zadeh, M. B., P. Nguyen, K. L. Hsu, A. AghaKouchak, T. Ung, and S. Sorooshian. 2026. "A Global High-Resolution Precipitation Climate Record: PERSIANN-CCS-CDR Version 2.0." *Scientific Data* 13: 314. https://doi.org/10.1038/s41597-026-06625-5.

Zhu, S., G. Tang, S. Yan, et al. 2025. "A New Approach to Identifying and Analyzing Precipitation Events and Their Typical Lifecycles Over Conterminous United States." *Geophysical Research Letters* 52: e2025GL115640. https://doi.org/10.1029/2025GL115640.