Observation to Openness: Governing Hydrological Data in a Non-Stationary World

Bhanu R. Neupane[1], Dhiraj Pradhananga[2, 3]

[1] UNESCO World Water Assessment Programme (WWAP), 7 Place de Fontenoy, 75352 Paris 07 SP, France
[2] UNESCO Chair in Mountain Cryosphere and Water, Department of Meteorology, Tri-Chandra Multiple Campus, Tribhuvan University, Ghantaghar, 44600 Kathmandu, Nepal
[3] The Small Earth Nepal (SEN), 626 Bhakti Thapa Sadak, Thapagaon, New Baneshwor, 44600 Kathmandu, Nepal
b.neupane@unesco.org, dhiraj.pradhananga@trc.tu.edu.np

Abstract. The movement from observation to openness has become a defining challenge in environmental sciences. This challenge is particularly acute for hydrological governance in a non-stationary world. The assumptions underpinning water management, planning, and infrastructure design have been increasingly challenged by climatic variability, land-use change, and urbanization. These pressures have increased both the volume of environmental data produced and the strategic importance of governing that data effectively. However, hydrological data systems remain dispersed across institutions, scales, and jurisdictions. This paper argues that the transition from observation to openness is no longer a secondary technical reform but a core condition for water security, scientific reproducibility, risk governance, and equitable adaptation. Using a systems lens, it examines the full hydrological observation and data lifecycle and shows how bottlenecks at any stage can undermine decision-making. The paper then interrogates the quality-versus-quantity debate under conditions of non-stationarity, uncertainty, and the abundance of multi-source data, emphasizing that openness without metadata, standards, and accountability can reproduce rather than address epistemic weaknesses. A new governance paradigm is proposed, anchored in FAIR data principles, interoperability, public-value logic, and the doctrine of openness, as open as possible, and as closed as necessary. Particular attention is given to transboundary hydrology, data sovereignty, institutional asymmetries, and the growing need for trusted cross-border data flows. The paper concludes with a layered policy agenda for Member States, distinguishing what should, might, or can be done. Its central claim is that, in a non-stationary world, hydrological observation achieves full public value only when it is embedded in a culture of governed openness.

Keywords: Anthropocene, Environmental Data, Open Data, Hydrological Data Governance, FAIR, Interoperability, Non-stationarity, Water Security, Metadata, Digital Public Infrastructure.

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1 Introduction

The Anthropocene denotes a historical condition in which human activity has become a major force shaping Earth-system processes (Crutzen, 2006). In hydrology, this is no longer a background observation but a defining condition of the field. River regulation, large dams, abstractions, irrigation, land conversion, urban expansion, and climate change are altering flow regimes, evapotranspiration, groundwater storage, runoff generation, and the timing and magnitude of extremes (Vörösmarty et al., 2010; Sivapalan et al., 2012; Montanari et al., 2013; IPCC, 2021). Glacial retreat is also shifting seasonal runoff patterns in mountain-fed systems, while rapid urbanization is changing infiltration pathways and hydrographs (Milly et al., 2008; Guzha et al., 2018; Marhaento et al., 2018; IPCC, 2021). Hydrology can therefore no longer be treated simply as the study of water in a natural system. It is increasingly concerned with coupled human-water systems whose behaviour is shaped by feedback, institutional choices, infrastructure, and uneven exposure to risk (Sivapalan et al., 2012; Montanari et al., 2013).

This shift has major implications for data. Much of classical hydrology relied on the assumption that historical records could serve as a reasonable guide to future variability. That assumption is now far less secure (Milly et al., 2008; Hannah et al., 2011). Water managers increasingly work in settings defined by non-stationarity, compound uncertainty, and rapidly changing environmental baselines. At the same time, the evidentiary base has widened: in-situ monitoring now sits alongside remote sensing, Earth observation products, citizen-generated data, and machine-learning outputs (Reichstein et al., 2019; Lindersson et al., 2020). This is not simply a matter of more information. It is a change in the architecture of hydrological knowledge itself. A recent example is the HiM-DATA initiative in the high Himalayas, which explores whether monasteries can provide a durable local basis for hosting and protecting automated weather stations in regions that remain critically under-monitored (Pradhananga et al., 2025) (see Box 1 below).

Box 1. Reimagining High-Altitude Data Systems: The HiM-DATA Model for Resilient Climate Monitoring.

The High-altitude Monasteries for Data Acquisition, Tracking and Awareness (HiM-DATA) effort illustrates an emerging approach to locally anchored climate-data stewardship by embedding certified automated weather stations (AWS) in monasteries—starting with a pilot at Namkha Khyung Dzong (Yalbang) Monastery (3,155 m) in Humla (The Small Earth Nepal, 2026)—in settings where vandalism, maintenance constraints, and extreme remoteness have repeatedly undermined high-altitude monitoring systems (The Rising Nepal, 2026).

HiM-DATA innovations include the following:

- Monasteries offer constant protection and trustworthy local supervision where traditional infrastructure frequently fails.
- In addition to conventional AWS, the initiative also explores low-cost solutions, such as night vision cameras and staff gauges, to monitor snow depth and precipitation phase. This also provides opportunities for integration of local innovations, e.g., Hydro Antarikchya (Antarikchya, n.d.).
- HiM-DATA also promotes community engagement by involving monks, nuns, and students as local climate stewards.

Environmental data has therefore moved from the periphery to the centre of hydrological governance and has also expanded the potential for participation across the hydrological data ecosystem (see figure 2). The issue is not simply the volume of data now available. It is the architecture through which observations are processed within data ecosystems until they are converted into actionable knowledge (Janssen et al., 2012; Wilkinson et al., 2016; Kidd et al., 2025). When those architectures are weak, even in data-rich environments, they produce poor decisions. Conversely, when they are open, interoperable, and accountable, comparatively modest datasets can yield high public value (Tenopir et al., 2011; Wilkinson et al., 2016; UNESCO, 2021).

This paper argues that the transition from observation to openness, especially in hydrological data, has become a strategic necessity in a non-stationary world. It does so by taking a systems perspective on the hydrological data ecosystem, examining not only access and sharing, but also upstream questions of generation and governance. It treats openness not as an ideological slogan but as an institutional design problem (Janssen et al., 2012; Pahl-Wostl, 2015). The objective is to articulate why hydrological observations must increasingly be governed for openness, what kind of openness is actually useful, and what governance changes are required to make openness scientifically robust and politically durable.

2 Openness has Become an Imperative

The case for open environmental data arises from structural changes in both hydrology and digital infrastructure. On the hydrological side, change is accelerating. Stationarity is no longer a defensible general assumption for water management, because climatic and socio-economic drivers are shifting the distributions on which design standards and operating rules were historically based (Milly et al., 2008; Montanari et al., 2013; IPCC, 2021). Flood regimes are changing in timing and geography, drought dynamics are intensifying under rising temperatures, and groundwater systems are under severe pressure in many heavily managed basins (Blöschl et al., 2019; Rodell et al., 2018). Under these conditions, calibration against historical averages is not enough. Hydrological infrastructures need to be more iterative, more transparent, and more adaptive (Beven, 2012; Clark et al., 2015a).

On the digital side, the observation landscape has expanded dramatically. Satellite constellations, radar products, telemetry, cloud computing, low-cost sensors, machine-learning workflows, and emerging digital-twin approaches have multiplied the ways in which hydrological processes can be observed and analysed (Reichstein et al., 2019; Kratzert et al., 2023; Kidd et al., 2025). Large-sample hydrology has shown the value of harmonized datasets for comparative analysis, benchmarking, and model transfer (Addor et al., 2017; Kratzert et al., 2023). However, this expansion has produced a familiar paradox: more data does not automatically translate into more usable knowledge. Fragmentation persists because datasets remain scattered across incompatible systems, poorly documented portals, restrictive licensing arrangements, and organizational silos (Janssen et al., 2012; Wilkinson et al., 2016; Crystal-Ornelas et al., 2022) (see Box 2 below).

Box 2. From Data Silos to Life-Saving Systems.

The Department of Hydrology and Meteorology (DHM) in Nepal has transitioned from manual observation and reporting to more structured archival policies to support national disaster risk reduction (DRR). This transition ensures that precipitation and river-stage data are not just collected but also utilised for early warning systems (EWSs). These are particularly important during the summer monsoon season from June to September.

In the past, data silos hampered regional responsiveness; however, DHM's modern archival policies now prioritize the FAIR principles to ensure hydrological data (precipitation and river-stage) are treated as strategic assets for national and regional DRR. Operational flood forecasting in the HKH relies on integrated hydrometeorological modelling systems and cross-border data sharing frameworks developed through a coupled socio-technical system combining satellite-informed forecasting, regional modelling frameworks, and community-based EWS, enabling partial operationalization of transboundary flood risk communication between Nepal and downstream regions in India (Tsering et al., 2021; Pradhan et al., 2017; Wester et al., 2019). The sharing of real-time precipitation and river stage data from Nepal's upstream stations has been instrumental in saving lives through downstream early warning systems in India (Pradhan et al., 2017).

Openness matters for several reasons. It strengthens reproducibility and cumulative science by allowing datasets, assumptions, and workflows to be inspected and reused (Tenopir et al., 2011; Wilkinson et al., 2016). It improves modelling and prediction by broadening the evidentiary base available for calibration, validation, and comparison (Clark et al., 2015a; Reichstein et al., 2019). It supports policy legitimacy where decisions about risk, allocation, or compliance affect multiple constituencies (Pahl-Wostl, 2015; Wing et al., 2022). It reduces duplication of effort in monitoring, cleaning, and preprocessing, thereby freeing scarce institutional resources for maintenance and analysis (Janssen et al., 2012; Hannah et al., 2011). It also supports cooperation across administrative and international boundaries, where trust depends in part on shared evidentiary baselines (WMO, 2021; GEO, 2022). Finally, it creates conditions for innovation by enabling the development of new analytical tools, decision-support systems, and machine-learning applications on common foundations (Reichstein et al., 2019; UNESCO, 2021).

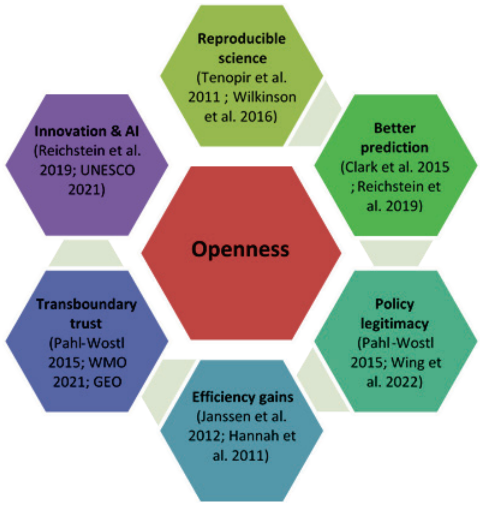

Fig. 1. Openness Matters.

A necessary caveat follows. The argument for openness should not be confused with an argument for indiscriminate release. Some hydrological data touches on privacy, Indigenous rights, security concerns, ecological sensitivity, or commercially sensitive infrastructure information (UNESCO, 2021; GEO, 2022). The relevant principle is therefore not maximal exposure, but governed openness: data should be as open as possible and as closed as necessary (UNESCO, 2021; WMO, 2021). That distinction is crucial because it allows openness to be defended as a public-interest orientation without collapsing legitimate restrictions into a simplistic binary of open versus closed.

3 Hydrological Data Ecosystem: from Observation to Openness

A narrow focus on data access obscures the reality that hydrological knowledge depends on an entire chain of interdependent processes (Figure 2). The hydrological data ecosystem can be understood as six linked functions: observation and data generation; quality assurance and metadata creation; access, interoperability, and licensing; treatment, assimilation, and analysis; archiving and provenance preservation; and sharing, reuse, and accountability (Wilkinson et al., 2016; Clark et al., 2015a; Crystal-Ornelas et al., 2022). Failure in any one of these functions weakens the overall evidentiary system.

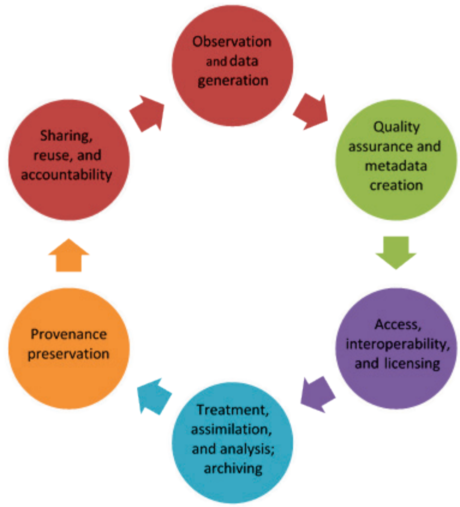

Fig. 2. Hydrological Data Ecosystem.

Observation and data generation form the foundation of the system. Hydrological data originates from river gauges, rainfall stations, snow and glacier monitoring systems, groundwater wells, water-quality sensors, utilities, treatment facilities, remote-sensing products, and, increasingly, community and citizen observatories (Hannah et al., 2011; Lindersson et al., 2020; Bäthge et al., 2026). The problem is not only sparse monitoring in many parts of the world, but also unevenness in what is measured, how often it is measured, and in the format in which it is stored. Streamflow may be measured daily in one basin, estimated intermittently in another, and not measured at all elsewhere. Groundwater records are particularly uneven and often remain fragmented or difficult to access (Rodell et al., 2018; Bäthge et al., 2026). The result is uneven visibility: some basins become legible to governance because they are well observed, while others remain poorly understood because observation itself is weak.

The second function is quality assurance and metadata. Open data without provenance, calibration information, uncertainty estimates, quality flags, or processing histories has limited scientific value (Wilkinson et al., 2016; Crystal-Ornelas et al., 2022). Metadata is not administrative surplus. It is what allows hydrological observations to be interpreted across time, institutions, and software environments. The FAIR agenda has made this point forcefully by insisting that data should be findable, accessible, interoperable, and reusable (Wilkinson et al., 2016; Mons et al., 2017). In hydrology, reuse depends especially on metadata about instrumentation, catchment properties, temporal coverage, processing steps, and quality control (Addor et al., 2017). Without that context, openness may invite misuse rather than robust reuse, especially where environmental data is ingested at scale by automated analytical systems.

The third function is access, interoperability, and licensing. Many open-data initiatives stall here. Hydrological data may be nominally public but practically unusable because it is scattered across poorly indexed portals, embedded in PDFs, released without machine-readable standards, or published under unclear terms of use (Janssen et al., 2012; Wilkinson et al., 2016). Interoperability requires more than downloadability. It requires common vocabularies, service standards, stable identifiers, and adequate documentation for cross-agency and cross-border integration (Crystal-Ornelas et al., 2022; WMO, 2023).

The fourth function is treatment, assimilation, and analysis. Raw observations rarely become decision-relevant knowledge without extensive preprocessing. Gap-filling, bias correction, homogenization, downscaling, uncertainty estimation, data assimilation, and model coupling are increasingly normal parts of hydrological analysis (Beven, 2012; Clark et al., 2015a; Clark et al., 2015b). Openness at this stage should extend not only to data inputs but also to workflows, transformation rules, and version histories. Otherwise, black-box processing can erode confidence even when source data is available (Reichstein et al., 2019; UNESCO, 2021).

Archiving and provenance preservation make up the fifth function. In a non-stationary world, long historical records remain essential, not because the future will mirror the past, but because change can only be detected against credible baselines (Milly et al., 2008; Montanari et al., 2013). Yet many hydrological archives remain fragile. Pre-digital records, field notes, rating-curve histories, and legacy measurements are still vulnerable to loss, degradation, or poor digital migration (Hannah et al., 2011). Digitization and curation are therefore not peripheral tasks. They are strategic investments in longitudinal evidence.

The sixth function is sharing, reuse, and accountability. Hydrological observations create public value only when they can be discovered, assessed, and applied by others (Tenopir et al., 2011; Wilkinson et al., 2016). This is also where the politics of data becomes most visible. Data infrastructures do not merely reflect reality; they help determine which problems are seen, whose claims are legible, and which decisions appear justified (Pahl-Wostl, 2015; Wing et al., 2022). Openness therefore redistributes not only information, but also epistemic authority.

4 Data Quality, Data Quantity, and Uncertainty under Non-stationarity

One of the most persistent misunderstandings in digital governance is the belief that more data automatically resolves uncertainty. In hydrology, the relationship is more complex. Increasing the number of observations can improve models, but only if data quality and comparability are sufficient (Beven, 2012; Wilkinson et al., 2016). Otherwise, data abundance may magnify noise, propagate bias, or create false confidence (Beven, 2012).

The quality-versus-quantity debate has intensified with the adoption of remote sensing products and machine-learning tools (Addor et al., 2017; Kratzert et al., 2023; Reichstein et al., 2019). These developments are valuable because they reveal broad patterns and enable model generalization. However, they also expose epistemic asymmetries. Data-rich regions often dominate model benchmarking, potentially leading to the optimization of supposedly general models for conditions unlike those in data-scarce basins (Addor et al., 2017; Kratzert et al., 2023). This creates risks of transfer error, especially in settings characterized by informal water use, unstable institutions, or rapidly changing land-water dynamics (Sivapalan et al., 2012; Pahl-Wostl, 2015).

A related issue concerns probabilistic frameworks. Hydrological decision-making increasingly depends on forecasts expressed as distributions rather than single-point predictions. Ensemble climate projections, probabilistic flood forecasting, groundwater depletion estimates, and drought outlooks are all sensitive to the quality of observational inputs (Beven, 2012; Blöschl et al., 2019; Rodell et al., 2018). When observation systems are sparse, uncertainty is not merely statistical; it becomes structural. Some processes remain weakly constrained because the observations needed to characterize them do not exist or are not interoperable across scales (Hannah et al., 2011; Lindersson et al., 2020).

The challenge is sharper in settings where hydrological processes display thresholds, long memory, and path dependence. Groundwater systems, soil moisture regimes, snow accumulation, reservoir operations, and ecosystem feedback often respond over long time horizons and in non-linear ways (Beven, 2012; Montanari et al., 2013; Rodell et al., 2018). Short, discontinuous, or weakly documented records are poorly suited to capturing such behaviour. This is one reason why open historical archives remain so important. Long records do not merely provide chronology; they help reveal regime shifts and the interaction between slow variables and extremes (Milly et al., 2008; Hannah et al., 2011).

Non-stationarity further complicates conventional notions of model performance. If climate, land use, and operating rules are changing simultaneously, a model cannot be judged only by how well it reproduces the recent past (Milly et al., 2008; IPCC, 2021). Hydrological data systems must instead support repeated updating, recalibration, and scrutiny. Closed or delayed data systems raise the cost of this adaptation. Open and well-described systems lower the transaction costs of learning under uncertainty and make it easier to revise risk estimates as conditions change (Clark et al., 2015a; UNESCO, 2021).

For policy, the more useful framing is not quality versus quantity, but quality at scale. Dense and sustained observation matters, but so do metadata, communication of uncertainty, traceable processing, and open standards. Quality makes quantity usable; openness makes quality visible.

5 A New Paradigm of Hydrological Data Governance

Hydrological data governance has historically been shaped by state-centric monitoring traditions, sectoral mandates, and assumptions of scarcity in both data and computational capacity (Hannah et al., 2011; Pahl-Wostl, 2015). Those arrangements are increasingly mismatched to contemporary needs. Though national hydrological services remain indispensable, many governance arrangements were designed for a world in which observation was slower and cross-sector integration was less essential (Montanari et al., 2013; WMO, 2021).

A different paradigm is now needed for three reasons. Environmental data has become strategic infrastructure for forecasting, planning, insurance, regulation, disaster management, and public accountability. The range of actors producing relevant data has expanded far beyond public agencies to include utilities, research consortia, private platforms, humanitarian organizations, and community networks (Crystal-Ornelas et al., 2022; Kidd et al., 2025). Moreover, the value of data increasingly emerges through interoperability rather than isolated collection (Wilkinson et al., 2016; WMO, 2023). Governance models centred on a single custodial institution are poorly suited to this reality.

The FAIR principles offer an important foundation, but they are not sufficient on their own (Wilkinson et al., 2016; Mons et al., 2017). While FAIR principles improve the discoverability and reuse of environmental datasets, effective hydrological data governance also depends on institutional factors such as incentives for data sharing, legal mandates, accountability mechanisms, sustained public funding, long-term stewardship responsibilities, and disparities in technical capacity (Tenopir et al., 2011; UNESCO, 2021). In many cases, agencies are not withholding data because they oppose openness in principle; they are doing so because they lack resources to curate, standardize, and publish data safely and reliably. Open data policy without institutional investment can therefore become performative. Portals appear, but datasets are incomplete, outdated, or unusable (Janssen et al., 2012; UNESCO, 2021).

A stronger governance approach should combine at least seven elements: legal clarity on default public-interest status; technical standardization; stewardship funding; accountability for timeliness and correction; capacity development; safeguards for legitimate restrictions; and a clear public-interest orientation. In practice, which means treating hydrological data not as an administrative by-product, but as enabling infrastructure for resilience, adaptation, and public decision-making (UNESCO, 2021; WMO, 2021; Crystal-Ornelas et al., 2022).

This governance shift can be understood as a move from custodial secrecy to trusted stewardship. Custodial secrecy treats data possession as a form of control. Trusted stewardship treats institutions as guarantors of quality, continuity, and fair access. The latter does not erase authority; it redefines authority around reliability and service rather than exclusivity

6 FAIRness, Interoperability, Metadata, and Standards

If openness is the normative objective, interoperability is the operational condition that makes openness meaningful. Hydrological datasets become useful across institutions only when they can be discovered, interpreted, and joined with other datasets without excessive bespoke effort. This is the practical significance of FAIR-aligned design (Wilkinson et al., 2016; Mons et al., 2017).

Findability requires searchable metadata, persistent identifiers, and inclusion in catalogues or federated discovery systems (Wilkinson et al., 2016). Accessibility requires clear retrieval protocols, whether via open downloads, APIs, or web services, along with transparent licensing (Crystal-Ornelas et al., 2022). Interoperability requires common semantics, standardized units, coordinate reference systems, temporal conventions, and shared schemas (Markovinović et al., 2022; WMO, 2023). Reusability requires documentation of provenance, quality control, and conditions of use, including hydrology-specific details such as catchment delineation, measurement methods, processing assumptions, and uncertainty descriptors (Addor et al., 2017; Kratzert et al., 2023).

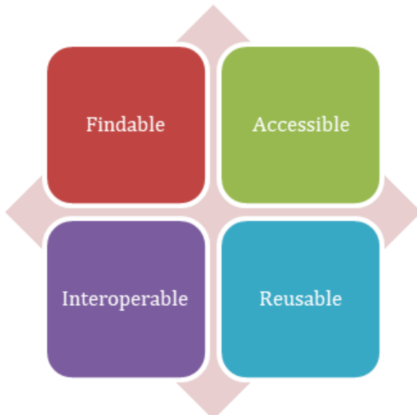

Fig. 3. FAIR Principle.

Metadata deserves particular emphasis because it remains chronically undervalued. Many failures of reuse stem not from a lack of data, but from a lack of context. A streamflow series without a gauge-relocation history, rating-curve notes, gap flags, or time-standard consistency can mislead even experienced users. The same is true of remote-sensing products that circulate without clear validation pathways or uncertainty ranges. Metadata is therefore not ancillary to openness. It is one of the main ways in which openness becomes scientifically safe (Wilkinson et al., 2016; Crystal-Ornelas et al., 2022).

Standards matter for another reason: they lower the transaction costs of cooperation. Initiatives such as GEOSS and WHOS demonstrate that brokered architectures and standards-based exchange can expand discoverability while preserving distributed data custody (GEO, 2022; WMO, 2023). This is especially useful in hydrology, where a system-of-systems approach avoids the false choice between full centralization and complete fragmentation.

The standards agenda should not be reduced to file formats alone. It should also include minimum metadata profiles for hydrological time series, crosswalks between vocabularies, licensing templates, stable identifiers for stations and catchments, and machine-readable quality reporting (Crystal-Ornelas et al., 2022; Markovinović et al., 2022). More advanced semantic approaches may become increasingly relevant, especially where hydrological data needs to be linked to ecological, infrastructure, or health datasets (Lippolis et al., 2025). But the immediate challenge is more basic: standardizing enough of the ecosystem to make routine exchange possible on scale A

7 Openness, Sovereignty, Privacy, and Transboundary Waters

The governance challenge becomes more acute in transboundary settings, where hydrological data is entangled with sovereignty and power asymmetries (Pahl-Wostl, 2015). Shared rivers and aquifers require shared situational awareness, yet countries often regard hydrological information as sensitive. Data about upstream storage, releases, abstraction, groundwater levels, or flood conditions can be interpreted as strategically consequential (Pahl-Wostl, 2015; WMO, 2021). In some contexts, data withholding is justified in security terms; in others, it reflects bargaining leverage or institutional mistrust.

For this reason, a simplistic open-data discourse can be counterproductive. Member States are unlikely to embrace openness if it is presented as an external demand that ignores legitimate restrictions. What is needed instead is a layered architecture for trusted cross-border data flows. Such architecture should distinguish among openly releasable public-interest data, institutionally shared data under basin agreements, data that can be exchanged after aggregation or masking, and data that remains restricted but discoverable through metadata. This graduated approach is better aligned with political reality and with the principle of being as open as possible and as closed as necessary (UNESCO, 2021; WMO, 2021).

Transboundary hydrology also raises questions of data ownership and stewardship. Hydrological facts do not respect borders, but data infrastructures do. An upstream observation may have downstream public value; a groundwater record collected by one state may be essential to understanding a shared aquifer; and satellite observations may create independent evidence that changes negotiating dynamics (Rodell et al., 2018; Pahl-Wostl, 2015). In practice, the most productive approach is often not to resolve ownership in absolute terms but to institutionalize reciprocity and verification. Data-sharing agreements, joint technical committees, third-party repositories, and common metadata frameworks can all help reduce the trust deficit (WMO, 2021; WMO, 2023).

There is also an equity dimension. Data-rich states and institutions have greater capacity to model risks, justify infrastructure, and influence basin narratives. Data-poor actors may therefore be disadvantaged not only materially but epistemically (Pahl-Wostl, 2015). Open regional systems can partly offset this asymmetry by reducing dependence on bilateral discretion and by creating common evidentiary baselines. This does not eliminate politics, but it can reduce contestation over basic facts.

Privacy concerns should likewise be treated seriously, especially where environmental data is linked to utilities, household behaviours, farm-level irrigation, or critical infrastructure (UNESCO, 2021). Yet privacy should not be used as a blanket rationale for opacity. Techniques such as aggregation, masking, secure enclaves, and tiered access can protect legitimate interests while preserving the public value of hydrological information (GEO, 2022; WMO, 2021). A mature governance regime can differentiate wisely among these cases rather than defaulting to secrecy.

8 Open Data in the Age of AI, Digital Twins, and Automated Decision Support

The case for moving from observation to openness becomes even stronger as hydrology enters an era of artificial intelligence, machine learning, and digital twins (Reichstein et al., 2019; Kidd et al., 2025). These tools depend on broad, well-documented, and continually updated data ecosystems. They do not eliminate the need for hydrological judgment; rather, they make the quality of underlying observation systems and governance arrangements even more consequential.

AI-based applications can improve flood forecasting, anomaly detection, drought classification, groundwater mapping, and reservoir operation. Community datasets such as CAMELS and Caravan have already enlarged the scope for comparative learning across basins (Addor et al., 2017; Kratzert et al., 2023). But AI systems are only as robust as the data on which they are trained. Unevenly documented or closed datasets produce brittle models, hidden bias, weak transferability, and limited explainability (Reichstein et al., 2019). If such systems are to inform public decisions, their training data, validation pathways, and core assumptions must be open to scrutiny.

Digital-twin ambitions intensify these requirements. Any attempt to maintain near-real-time representations of hydrological systems depends on sustained interoperability across observations, infrastructure operations, demand data, ecosystem indicators, and hazard information. The challenge here is not merely computational. It is institutional. Without clear rules on stewardship, version control, error correction, and access to model assumptions, digital systems risk becoming opaque instruments of authority rather than aids to public reasoning.

This is why open data should be understood as a precondition for trustworthy hydrological AI. Open environmental data makes it easier to audit model behaviours, compare methods, detect drift, improve transferability, and contest decisions where automated systems are wrong or inequitable (Reichstein et al., 2019; Wing et al., 2022). At the same time, AI can help improve the utility of open data by supporting quality screening, metadata enrichment, harmonization, and anomaly detection (Reichstein et al., 2019). The relationship is therefore reciprocal: open data enables better AI, and carefully governed AI can enhance the value of open data.

However, a warning is necessary. The more environmental governance depends on digital infrastructures, the more essential it becomes to invest in human capacity, institutional memory, and maintenance. Open data regimes cannot be reduced to portals and dashboards. They require steward institutions capable of explaining, curating, and defending the quality of what is shared (Hannah et al., 2011; Kidd et al., 2025).

9 Policy Implications: from Principle to Institutional Design

The policy significance of governing hydrological observation for openness lies in its capacity to improve anticipatory governance. Water policy in the Anthropocene must increasingly make decisions before certainty is available (Milly et al., 2008; IPCC, 2021). Openness supports such anticipatory action by making evidence more visible and reusable (UNESCO, 2021; WMO, 2021).

At the global level, the priority is norm consolidation. International organizations and scientific bodies should converge around a coherent doctrine for hydrological data stewardship that links open science, digital public infrastructure, and climate adaptation (UNESCO, 2021; WMO, 2021; GEO, 2022). The UNESCO Recommendation on Open Science, WMO's Unified Data Policy, and GEO data-sharing principles already provide a partial foundation.

At the regional and basin levels, the priority is institutionalized exchange. Regional hydrological platforms, standards-based portals, and shared metadata registries can reduce duplication and create common evidence (WMO, 2023; Lindersson et al., 2020). Basin organizations should move beyond ad hoc document exchange toward formalized data-sharing protocols with defined timeliness, quality requirements, and procedures for dispute resolution (Pahl-Wostl, 2015). Where political trust is weak, third-party brokering and distributed system-of-systems architectures may be more feasible than centralized repositories (GEO, 2022; WMO, 2023).

At the national level, the key challenge is legal and fiscal. Many countries need updated regulations clarifying which environmental datasets are public by default, how exceptions are justified, and who is responsible for stewardship (UNESCO, 2021; WMO, 2021). Open-data mandates should be backed by line-item funding for metadata, digitization, quality control, and platform maintenance. Hydrological services should not be expected to deliver interoperable public data under unfunded mandates (Hannah et al., 2011; Janssen et al., 2012). In many cases, modest but sustained investment in curation will yield more value than flashy short-lived digital projects.

At the institutional level, agencies and research organizations should embed openness in routine practice. This means assigning persistent identifiers, documenting workflows, preserving version histories, using open or widely interoperable formats, and publishing metadata even when the underlying data cannot be fully opened (Wilkinson et al., 2016; Crystal-Ornelas et al., 2022). Institutions should also adopt internal data-governance frameworks that clarify custodianship, quality assurance responsibilities, review cycles, and retention rules. Importantly, performance systems should recognize data stewardship as scholarly and public service work rather than as invisible administrative labour (Tenopir et al., 2011; UNESCO, 2021; UNESCO, n.d.). A useful illustration of how multilateral hydrological openness can be operationalized in practice is provided by UNESCO's IHP-WINS platform (see Box 3 below).

Box 3. UNESCO IHP-WINS: from Hydrological Observation to Governed Openness.

UNESCO's Intergovernmental Hydrological Programme Water Information Network System (IHP-WINS) (https://ihp-wins.unesco.org/) is a practical example of how hydrological observation can be translated into governed openness. Developed under UNESCO-IHP, IHP-WINS is designed to promote the sharing and dissemination of water-related data and knowledge among stakeholders involved in water resources management. Its stated purpose is to strengthen international cooperation, improve data availability, and support understanding and management of water resources.

From a governance perspective, IHP-WINS is significant because it does not treat openness simply as data release. Rather, it functions as a "system-of-systems platform" that aims to connect distributed datasets, services, resources, and institutional actors while preserving the role of multiple data custodians. In that sense, it reflects the paper's central argument: in a non-stationary world, the challenge is not only to observe hydrological change, but to ensure that observations are organized through interoperable and policy-relevant infrastructures.
IHP-WINS also illustrates the move from isolated monitoring to a broader digital public infrastructure logic for water. The platform supports datasets, visualization, resource discovery, and thematic integration, including areas such as groundwater, river systems, citizen science, and open hydrology. This broad architecture is important because the public value of hydrological information increasingly depends on the ability to link observations across domains and scales. Not least and importantly, it includes user communities in breaking institutional silos of data.
A further strength of IHP-WINS is that it operationalizes UNESCO's wider commitment to open science and water security. UNESCO presents the platform as a means of making water knowledge more accessible and collaborative. In contrast, the platform's more recent positioning aligns it with interoperability to support IHP-IX priorities (UNESCO, 2022). In this sense, IHP-WINS is not merely a repository but an institutional mechanism that aligns openness with capacity-building, knowledge exchange, and evidence-based decision-making.
At the same time, IHP-WINS also reveals the practical demands of governed openness. For such a platform to deliver durable value, datasets must be accompanied by institutional commitments to updating and user-centric quality control. The lesson is therefore broader: platforms matter, but their credibility depends on the governance scaffolding around them. IHP-WINS is a perfect example of the transition from observation to openness in hydrology, demonstrating both the promise and the institutional requirements of open water data in a changing world.

At the research-policy interface, a further implication arises. Open hydrological data can support more plural forms of accountability by enabling stakeholders to engage with environmental evidence (Janssen, et al., 2012; Wing et al., 2022). This matters especially where water risks are unequally distributed or where official narratives are contested. Well-governed openness can strengthen democratic oversight without undermining scientific rigour.

These governance reforms are not occurring in isolation. They align with broader efforts to modernize international cooperation in science, digital infrastructure, and global public goods, most recently articulated in the United Nations Pact for the Future (see Box 4 below).

Box 4. From Observation to Openness under the Pact for the Future.

The transition from hydrological observation to governed openness aligns closely with the direction set out in the Pact for the Future (United Nations, 2024a). The

Pact emphasizes stronger science-policy interfaces, improved digital cooperation, and better use of data in addressing shared global risks.

For hydrology, this matters in several ways. First, the Pact reinforces the importance of evidence-based decision-making in areas directly relevant to water security, including climate change, disaster risk, and sustainable development. Second, it recognizes the growing importance of trusted digital infrastructures, within which hydrological data forms part of a wider ecosystem linking Earth observation, early warning, and development monitoring. Third, it underscores the need for collective approaches to transboundary challenges. In river basins and shared aquifers, better data sharing is not a technical luxury; it is part of the institutional basis for cooperation. Finally, the Pact's concern with more inclusive access to knowledge and technology speaks directly to current asymmetries in hydrological monitoring and analytical capacity.

In that sense, strengthening hydrological data governance is one practical route by which the ambitions of the Pact can be translated into operational action.

10 Call to Action

A useful policy agenda distinguishes between normative urgency, political feasibility, and immediate practicality.

What should be done is clear. Countries and institutions should recognize hydrological data as essential public-interest infrastructure (UNESCO, 2021; WMO, 2021). Publicly funded environmental observations should default toward openness, supported by standards, metadata, interoperability rules, and sustained stewardship finance (Wilkinson et al., 2016; GEO, 2022). Cross-border basins should develop trusted exchange mechanisms, and global organizations should harmonize guidance on FAIRness, licensing, quality control, and public-value use (WMO, 2023; GEO, 2022). Historical hydrological archives should be digitized and preserved as strategic assets (Hannah et al., 2011). Finally, the transition from observation to openness should be embedded in climate adaptation, disaster risk reduction, groundwater governance, and digital transition strategies (IPCC, 2021; United Nations, 2024b).

What might be done depends on the political context. Some countries can establish full national hydrological open-data programmes with APIs, machine-readable metadata, and integrated portals. Others may move first through sectoral pilots, basin agreements, or regional observatories (Janssen et al., 2012; WMO, 2023). In politically sensitive transboundary settings, a phased model may be more realistic: start with metadata transparency, shared standards, and selected real-time variables; then expand toward richer exchange as trust grows (Pahl-Wostl, 2015; WMO, 2021). In data-scarce environments, international partnerships can help build stewardship capacity before full openness is mandated (United Nations, 2024a).

What can be done immediately is often overlooked. Institutions can publish metadata catalogues even before they can publish complete datasets (Wilkinson et al., 2016; Crystal-Ornelas et al., 2022). They can assign station identifiers, standardize file structures, document uncertainty, digitize vulnerable archives, and make code lists and schemas public (Markovinović et al., 2022; Nicholson et al., 2025). Research projects can deposit cleaned hydrological datasets and workflow documentation in repositories (Tenopir et al., 2011; UNESCO, 2021). Funding agencies require data management and sharing plans that include maintenance after project closure. Basin organizations can begin with common glossaries and station registries (WMO, 2023). These steps may appear incremental, but they are precisely what turn openness from aspiration into operating practice.

The core message is that progress does not require waiting for perfect global consensus. It requires institutional sequencing. Open hydrological data ecosystems are built through cumulative decisions about standards, incentives, and stewardship. With stationarity no longer a defensible default for water-risk assessment and planning, postponing decisions can lock in maladaptive pathways and escalate cost by narrowing feasible adaptation options and increasing losses and damages (Milly et al., 2008; IPCC, 2023).

11 Conclusion

The Anthropocene has made hydrological governance more dependent on data while exposing the limits of fragmented data systems. Climate variability, groundwater depletion, river regulation, urbanization, and digitalization are reshaping both water systems and the infrastructures through which they are known. The central question is therefore no longer whether hydrological data should be open in principle, but how hydrological observation can be governed for openness in ways that are scientifically credible, institutionally durable, and politically legitimate.

This paper has argued that open hydrometeorological data should be understood as enabling infrastructure for anticipatory governance. Its significance extends beyond transparency. It strengthens scientific collaboration, improves modelling and risk assessment, reduces duplication, broadens accountability, and supports cooperation in transboundary settings. But openness produces these benefits only when embedded in a full data ecosystem that includes observation, metadata, quality assurance, interoperability, archiving, and long-term stewardship. Without standards, openness becomes disorderly; without openness, standards remain exclusionary; and without sustained investment, neither is likely to endure.

The policy challenge is therefore institutional at its core. Hydrological data must be treated as a shared societal asset and managed through governed openness. In a nonstationary world marked by rising uncertainty, effective water governance will depend not only on observing change but on ensuring that observations are accessible, interoperable, quality-assured, and trusted across institutions and borders. Governed openness is not an optional add-on to hydrological practice. It is one of the conditions for resilient, evidence-based water management in the twenty-first century.

12 Disclaimer

The views and opinions expressed in this paper are those of the authors and do not necessarily reflect the official policy or position of any affiliated institution or organisation. Any errors or omissions remain the responsibility of the authors.

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