https://doi.org/10.5194/egusphere-2024-1678
Preprint. Discussion started: 12 June 2024

HESS Opinions: Towards a common vision for the future of hydrological observatories

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Abstract. The Unsolved Problems in Hydrology (UPH) initiative has emphasized the need to establish networks of multi-decadal hydrological observatories to tackle catchment-scale challenges on a global scale. The already existing monitoring infrastructures have provided an enormous amount of hydrometeorological data, which has helped gain detailed insights into the causality of hydrological processes, test scientific theories and hypotheses, and reveal the physical laws governing catchment behavior. Nevertheless, we are still a long way from being able to fully unravel all the mysteries of hydrological processes to solve practical water-related problems. Hydrological monitoring programs have often produced limited outcomes because of the intermittent availability of financial resources and the substantial efforts required to operate observatories and conduct comparative studies to advance previous findings. Recently, some initiatives have emerged aiming at coordinating data acquisition and hypothesis testing to facilitate an efficient cross-site synthesis of findings. To this end, a common vision and practical data management solutions need to be developed. This opinion paper provocatively discusses two end members of possible future hydrological observatory (HO) networks for a given hypothesized community budget: a comprehensive set of moderately instrumented observatories or, alternatively, a small number of highly instrumented super-sites.

A network of moderately instrumented, hydrological monitoring sites distributed across the globe would provide broad spatial coverage across the major pedoclimatic regions, help address UPH about the impact of climate and social systems (e.g., land use change and global warming) on water resources, and enhance the potential for knowledge transfer. However, the moderate instrumentation at each site may hamper an in-depth understanding of complex hydrological processes. In contrast, a few extensively instrumented research sites would allow for community-based experiments in an unprecedented manner, thereby providing more fundamental insights into complex, non-linear processes modulated by scale-dependent feedback and multiscale spatio-temporal heterogeneity. Lumping resources has proven to be an effective strategy in other geosciences, e.g. for research vessels in oceanography and drilling programs in geology. On the downside, a few catchments will not be representative of all pedoclimatic regions, necessitating the consideration of generalization issues.

A discussion on the relative merits and limitations of these two visions on HOs is presented with the objective of building consensus on the optimal path for the hydrological community to address the UPH in the coming decades. A final synthesis proposes the potential for combining the two end members into a flexible management strategy.

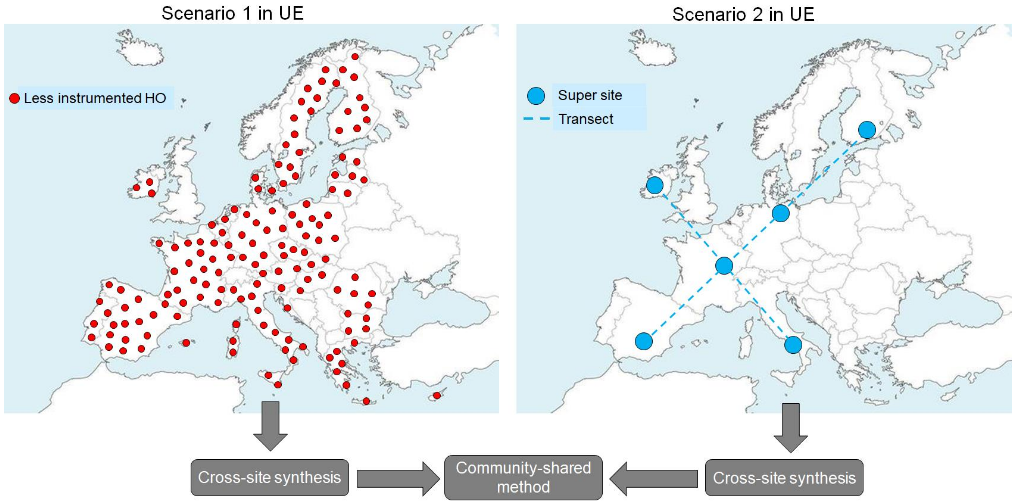
Keywords: hydrological observatory network, experimental catchments, cross-site synthesis, hypothesis testing vs. exploratory science, unsolved problems in hydrology, societal needs, technology advancements.

Highlights

- The historical situation of HOs has led to fragmented knowledge and sub-optimal research progress
- Some initiatives emerged to coordinate and standardize data and models resulting in efficient cross-site synthesis
- It is important to stimulate discussion within the hydrological community to arrive at a consensus view on HOs

https://doi.org/10.5194/egusphere-2024-1678
Preprint. Discussion started: 12 June 2024

Graphical Abstract



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1. How do we address the Unsolved Problems in Hydrology?

Water is essential for life, yet certain human activities put this precious resource at risk. Rapid changes in land use, such as the adoption of more intensive farming practices, expanding urbanization, and land abandonment in rural areas, have a significant impact on the hydrological cycle and water quality, whereas unsustainable water withdrawals lead to the depletion of resources. Global warming is expected to exacerbate hydrological extremes, resulting in more disastrous floods and severe droughts that will further threaten water security. In light of these challenges, the mission of hydrologists and water managers is to sustainably meet human needs while preserving biodiversity and ecosystem services, based on the most accurate and up-to-date information. However, the extent to which anthropogenic stressors influence the hydrologic cycle is not yet fully understood. Hydrology is a data-hungry discipline but the limited observations on all components of the terrestrial hydrosphere, from bedrock to the lower atmosphere, represent a significant obstacle to progress in the understanding of hydrologic process dynamics (Siebert et al., 2024).

To grasp the daunting complexity of the hydrological cycle, particularly the impact of human activities on the critical zone and catchment functionality, several long-term hydrological observatories (HOs) have been established around the world to monitor hydrological states and flows. HOs are long-term research sites dedicated to collecting data on the movement of water on land, from precipitation to groundwater. Observatories are important research infrastructures for understanding and forecasting how water resources are and will be affected by natural events and anthropogenic factors. HOs have been established to address the Unsolved Problems in Hydrology (UPH) that have been identified in the literature (Blöschl et al., 2019; Arora et al., 2023).

The concept of HOs dates back to the early 1900s when scientists began to recognize the significance of long-term data collection for understanding hydrological processes (McDonnell et al., 2007). In 1903, runoff and other hydrological variables were first collected in the Sperbelgraben and Rappengraben experimental catchments in the Emmental (Switzerland), which are still in operation and hold one of the longest continuous discharge records in the world (Stähli et al., 2011). In the United States, the first HOs were the Wagon Wheel Gap Experiment in Colorado (Bates and Henry, 1928), the Coweeta Hydrological Laboratory in North Carolina (Neary et al., 2012), and a catchment network across the continental U.S. established by the USDA-Agricultural Research Service (Goodrich et al., 2021). These sites were designed to study the influence of human activities on hydrological systems, with a particular focus on deforestation and afforestation, land-use changes, and agricultural practices (Whitehead and Robinson, 1993). The number of HOs has steadily increased since the 1950s and has grown exponentially since the 1980s. The HO sites have provided valuable information for managing water resources and are currently funded and supported by government agencies (e.g., the Hydrologic Benchmark Network of the US Geological Survey), research institutions including universities, international organizations, and non-governmental organizations.

2. Building integrated observation platforms to address the UPH

A significant number of rivers around the globe have been equipped with gauges to monitor precipitation and streamflow by governmental agencies for water management. The data collected have been primarily used at the national level, although there are several transnational initiatives as e.g., the Global Runoff Data Centre in Koblenz, Germany; the Camels datasets, such as those for the US, Chile, and Brazil, (Addor et al.; Alvarez-Garreton et al. 2018; Chagas et al. 2020). Hydrological Observatories go beyond these standard networks, striving to gain a more comprehensive understanding of hydrological processes, typically in smaller catchments.

While some instruments are based on well-established monitoring technologies, others are more experimental. Weather station networks (also called synoptic stations) ensure meteorological measurements and have been combined in many countries with weather radar networks for detailed precipitation estimation (Sokol et al., 2021). Snow water equivalent is already measured on a routine basis with snow pillows (e.g. by the SNOTEL network in the US) or more experimentally by airborne LiDAR snow depth surveys (Painter et al., 2016). Groundwater levels are monitored on a routine basis, whereas distributed temperature sensing technology is a more novel approach for estimating infiltration rates and potentially catchment-scale groundwater recharge (Medina et al., 2020). The measurement of water content, matric potential, temperature, and electrical conductivity in soil is conducted across soil profiles at the point scale (Hoffmann et al., 2015; Peng et al., 2019; Bogena et al., 2022), while cosmic-ray neutron sensors are capable of extending the footprint of soil moisture to approximately 150-200 meters radius (Romano, 2014; Köhli et al., 2015; Baatz et al., 2017). At experimental sites, surface and subsurface runoff from hillslopes are measured using flowmeters in runoff plots (Fu et al., 2024). In addition, mapping of saturation areas on hillslopes (Silasari et al. 2017) and channel-network dynamics (Jenssen et al., 2019; Strelnikova et al., 2023; Noto et al., 2024) provide insight into the spatial patterns of catchment-scale processes that extend beyond point measurements. Topographic surveys assist in determining surface flow paths within a catchment and can be used to extend point measurements to the catchment scale (e.g., Rinderer et al., 2019; Fan et al., 2019; Refsgaard et al., 2021). The rates of soil erosion and deposition are quantified through the use of sediment fences, soil profile surveys, and cosmogenic nuclide analysis, in addition to repeated high-precision topographic surveys. Soil physical, chemical, and hydraulic properties are typically measured in field campaigns and laboratory experiments, with remote sensing serving as a complement. Geophysical tools, such as electromagnetic (EM) surveys, offer great potential for imaging aquifer systems and subsurface heterogeneity (Nasta et al., 2019; Dewar and Knight, 2020). To unravel the interactions of the water cycle with biochemical, energy, and carbon cycles, numerous other variables are monitored (Valdes-Abellan et al., 2017). The key vegetation characteristics that are monitored include canopy height, leaf area index (LAI), leaf water potential, sap flow, rooting depth and distribution, plant water stress, canopy/vegetation water content, and temperature (Poyatos et al., 2021; Loritz et al., 2022; Zeng and Su, 2024). Eddy covariance measurements, some of them connected through networks, such as Fluxnet, measure evapotranspiration and carbon fluxes at the local level. Sapflow sensors, some organized in the Sapflux network (Poyatos et al., 2021), can be used to measure transpiration rates. Tracer measurements, such as isotope and dye studies, are employed to track and differentiate water fluxes (Klaus and McDonnell, 2013; Penna et al., 2018), while lysimeters are used to determine groundwater recharge and the associated concentrations of, e.g. nitrate, at the point scale.

Remote sensing from unmanned aerial systems (UAS; e.g. Dugdale et al., 2022; Romano et al. 2023) and satellite platforms (e.g. Durand et al., 2021, De Lannoy et al., 2022) offer valuable supplementary information to ground-based observation in HOs, which can be used for upscaling or downscaling hydrological variables (e.g., McCabe et al., 2017; Manfreda et al., 2018, 2024; Su et al., 2020). Recently, higher resolution observations of, for example, soil moisture (Burdun et al., 2023; Han et al., 2023), snow depth (Lievens et al., 2021), and irrigation rate (Dari et al., 2023) have become available and can be used together with coarser scale products, such as total water storage from the Gravity Recovery and Climate Experiment (GRACE) mission, or discharge from the Surface Water and Ocean Topography (SWOT) mission. Multi-sensor combinations, such as those employed by the various Sentinel and Landsat missions, can enhance the accuracy and resolution of the data. The European Space Agency (ESA) and the United States National Aeronautics and Space Administration (NASA) are engaged in collaborative efforts with public and private organizations to develop relevant new missions and to disseminate a range of products, including evapotranspiration estimates through the SEN-ET (Guzinski et al., 2019; 2020) and OpenET (Melton et al., 2021) initiatives.

It is evident that the key to progress in hydrological understanding will be contingent upon the integration of these observation platforms. These platforms should combine technologies such as remote sensing, high-performance computing resources, artificial intelligence, and the Internet of Things, yet keeping in mind that the water and energy fluxes are influenced by geochemical and biotic heterogeneity, as well as socio-economic processes. A hypothetical illustration of a ground-aerial-space monitoring network to transmit sensor data from observation devices to data centers through relay communication equipment such as UAS, satellites, airships, and hot air balloons is presented in Fig. 1.

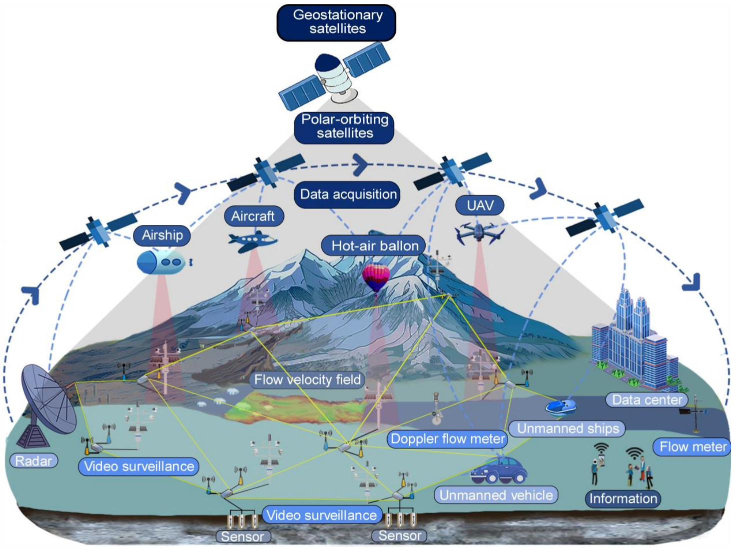

Figure 1. Air-space-ground observation of hydrological processes at catchment scale.

While observations are the backbone of progress in hydrological understanding (Sivapalan and Blöschl, 2017), models are equally essential for hypothesis testing and making predictions of practical relevance (Brooks et al., 2015; Baatz et al., 2018; Bogena et al., 2018; Bechtold et al., 2019; Nearning et al., 2024). An integrated observation approach enables the development of new methods that rely less on calibration and more on insightful analysis of landscape heterogeneity and process complexity through systematic learning from hydrometeorological data (Vereecken et al., 2015). The integration of these approaches is of paramount importance, given that catchments are complex systems with structured heterogeneity that give rise to non-linear interactions and feedback between the component processes (Li et al., 2022). One aspect of integration is the assimilation of observations into hydrological models (Mwangi et al., 2020; Kumar et al., 2022; De Lannoy et al., 2022) to estimate unobserved variables, improve predictions, and calibrate and validate satellite retrieval (Colliander et al., 2021). Paleo-reconstructions hold the key to a better understanding of how dynamic, abiotic, and biotic watershed characteristics have co-evolved well before instrumental records started (Troch et al., 2013). Climate shifts leave a multitude of signatures in the natural world, influencing tree growth and the distribution of plant species. With the advent of increasingly sophisticated analytical techniques, knowledge of past climate and river ecosystem variability is rapidly growing, benefiting from reconstructions of river flow and erosion from natural archives (Chaussé et al., 2008; Torbenson et al., 2021; Büntgen et al., 2021; Schöne et al., 2020; Strelnikova et al., 2023).

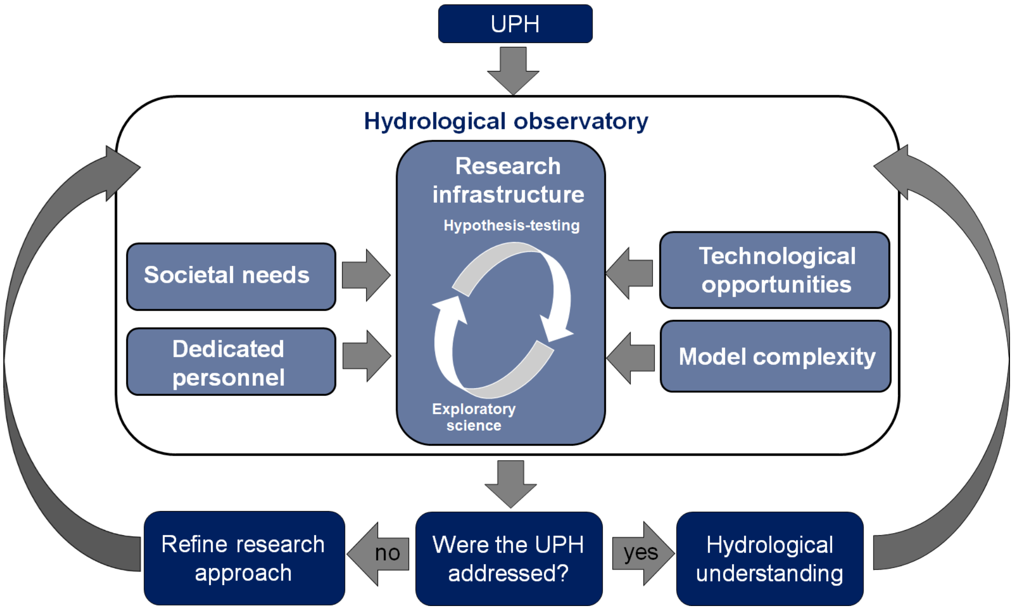

Figure 2. Organization of a hypothetical research infrastructure to address the unsolved problems in hydrology (UPH), inspired by Sivapalan and Blöschl (2017). Drivers are societal needs, including policy demands and industry needs. Progress is facilitated by the expertise and ideas of dedicated personnel, process fidelity of complex models, and new technological opportunities. Missing or gaining knowledge can help improve the further development of HO.

The organization of a hypothetical research infrastructure is illustrated in Fig. 2, which is inspired by the evaluation of research progress in hydrology of Sivapalan and Blöschl (2017). Understanding hydrological processes in terrestrial systems and the connections between their sub-systems is contingent upon the extent to which hypothesis-testing and exploratory science are facilitated by technological opportunities, the fidelity of complex models, and the expertise and ideas of dedicated personnel (Beven, 2018). The driving factors are societal needs that set an overall research agenda with the objective of growing hydrological knowledge to assist in more efficient resource management.

3. HO networks and hydrological synthesis

The sustainability of HO is a matter of concern. Financial and logistical constraints have posed challenges to the long-term operation of HOs, jeopardizing essential maintenance, equipment upgrades, and personnel training. This ultimately compromises the quality and continuity of hydrological data collection and analysis. Data gaps and the lack of continuity in the data collection process hamper the identification and understanding of hydrological change, one of the main societal needs for hydrology at present and in the future (Montanari et al., 2013). Given the often limited budget per site, many studies have concentrated on measuring lumped hydrological fluxes (e.g., the streamflow at the catchment outlet), while observatories that focus on spatial details are relatively rare (e.g., Blöschl et al., 2016). Site-specific methods, tailored to site-specific UPH, have often led to research progress on a single hydrological process, without fully leveraging the potential for synergies with other HOs. Consequently, the outcome has often been an

https://doi.org/10.5194/egusphere-2024-1678
Preprint. Discussion started: 12 June 2024

increase in fragmented knowledge rather than progress in understanding the interaction of hydrological processes that is so urgently needed.

To address these issues, scientists have proposed initiatives to sustain long-term operations, harmonize, and standardize both data and models (Zoback 2001; Reid et al., 2010; Kulmala, 2018). Notable initiatives that have integrated existing environmental research infrastructures include the pan-European ENVRI initiative (https://envri.eu) and the global GERI initiative (https://global-ecosystem-ri.org/, Loescher et al., 2022). Networks such as Fluxnet (https://fluxnet.org) and the Integrated Carbon Observation System (https://www.icos-cp.eu) collect standardized data on the soil surface energy balance and evapotranspiration. The network of Critical Zone Observatories aims to understand critical zone processes and includes hydrologic monitoring (Brantley et al., 2017; Anderson et al., 2018). The integrated European Long-Term Ecosystem, Critical Zone, and socio-ecological Research Infrastructure (https://elter-ri.eu) will establish a network of around 200 integrated terrestrial observatories across Europe, and hydrological monitoring will be part of it. In the field of agriculture, the USDA is supporting the Long Term Agroecosystem Research (LTAR) initiative (https://ltar.ars.usda.gov/), which combines strategic research projects with common measurements on multiple agroecosystems, including croplands, rangelands, and pasturelands. The advent of digital technology and data exchange platforms has enabled scientists to aggregate and jointly analyze data streams from disparate locations in a manner that was previously unfeasible. A prerequisite for this is the standardization and harmonization of existing protocols and methods for hydrological observation. Existing research infrastructures have already established standards for the environmental variables they collect. The harmonization of such standards across disciplinary infrastructures represents a crucial building block toward enhanced integration and should be reflected in future strategies for designing international environmental research.

Cross-site synthesis of hydrological processes fills the gap between site-specific studies and broader, generalizable knowledge (Zacharias et al., 2024). The objective is to integrate information from multiple sites and sources to identify patterns, trends, and relationships that can lead to more robust and transferable knowledge for model development and eventually more effective decision-making. The implementation of cross-site synthesis typically involves the following steps (Fig. 3):

- Formulating the UPH;
- Data collection by using standardized protocols;
- Use of community-shared hydrological models;
- Comparative hydrology;
- Meta-analyses to consolidate results.

The initial step is to formulate scientifically interesting questions that not only address knowledge gaps but also contribute to a broader understanding and societal benefits in the field of hydrology (see Appendix). To ensure consistency in data quality, measurement methods, and quality control protocols need to be harmonized. Community networks and centralized data repositories can facilitate this process and provide access to standardized and curated datasets. Community-shared hydrological models can be employed to represent the complex interactions between hydrological processes, ecosystems, and human activities. These models are calibrated and tested using the harmonized data from multiple sites to improve their predictive capabilities and generalizability. Interesting initiatives are already operative, such as the Unified Forecast System (UFS) which is a community-based, coupled, comprehensive Earth modeling system used for weather forecast applications (https://www.ufscommunity.org/articles/hierarchical-system-development-for-the-ufs/). Comparative studies reveal key drivers of hydrological variability and identify generalizable principles by systematically comparing hydrological processes and responses across different sites, accounting for factors, such as climate, topography, land-use, and management practices. Finally, meta-analyses can combine and compare results from multiple studies, identify common patterns and trends on integrated measurements and model simulations, and present consolidated results in a coherent way.

By following these steps, hydrologists can effectively implement cross-site synthesis, thereby advancing the field of hydrology towards a more generalizable and transferable body of knowledge. This can inform more effective decision-making for water resource management and climate change adaptation in a variety of contexts.

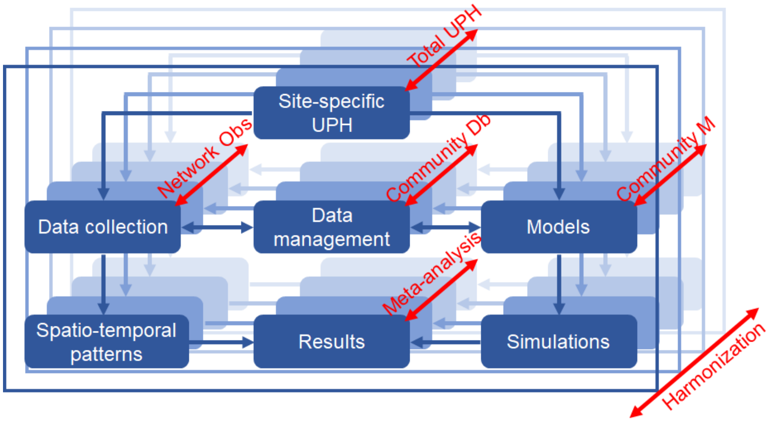

Figure 3. Schematic of the proposed cross-site synthesis. Obs, Db, M, and UPH indicate Observatories, Database, Models, and Unsolved Problems in Hydrology, respectively.

Cross-site synthesis helps unveil hidden assumptions that may be embedded in site-specific studies and enables researchers to critically assess the validity of these assumptions and explore alternative perspectives. Identifying common principles and practices enables researchers to develop transferable knowledge that can be applied to other settings, thereby accelerating progress in research and practice. Some examples of cross-site synthesis already exist. For example, Wlostowski et al. (2021) conducted a meta-analysis of hydrologic signatures from 15 catchments in the U.S. Critical Zone Observatory (CZO) network, which revealed consistent relationships between critical zone structure and hydrologic response across sites. Addor et al. (2018) similarly looked at the predictability of hydrologic signatures for the catchments that are part of the Camels dataset but found that the relation between these signatures and catchment attributes other than climate characteristics was poor.

Comparative analyses have also yielded interesting conflicting results. For instance, some studies have indicated that afforestation may result in a decrease in water yield, whereas others have identified an increase. Two distinct theoretical frameworks have been put forth to explain the observed phenomena (Ellison et al., 2012). The *demand-side* perspective emphasizes the increase in transpiration and the subsequent reduction in streamflow, particularly in catchments smaller than a few square kilometers (Schilling et al., 2008; Kim et al., 2013; Nasta et al., 2017). In contrast, the *supply-side* perspective posits that afforestation will intensify precipitation, thereby increasing streamflow, in downwind catchments (Ellison et al., 2012). Similarly, reforestation may increase or decrease dry season flows depending on the relative importance of increased infiltration and evapotranspiration rates (Bruijnzeel, 1989).

The aforementioned case studies demonstrate the advantages of cross-site synthesis in quantifying the spatial variability of hydrological processes and identifying consistent patterns of phenomena, such as droughts and floods. These examples will ultimately inform water management practices around the world, while maintaining track and awareness of local hydrological particularities.

4. How to manage a network of hydrological observatories?

For the sake of the argument, we will assume that a fixed community budget has been allocated for the establishment and operation of a hypothetical network of HOs. Two extreme scenarios can be envisaged. In the first scenario (*Scenario* 1), the available financial resources are allocated to numerous less intensively instrumented HOs distributed around the world, with the objective of addressing challenges in hydrology with broad geographical coverage. Each HO will focus on those atmospheric, river/stream, groundwater, soil, and vegetation processes that are most pertinent in the region in which it is situated. The cross-site synthesis involves the gathering of information from each HO to identify cause-effect relationships (i.e., runoff ratio, nutrient input-output, Budyko-type approaches) among different landscapes (Jones et al., 2012; Templer et al., 2022), and the combination of this information in a meaningful way (Ehret et al., 2014). The combination can be achieved through the use of dynamic modeling and/or classification schemes (Wagener et al., 2007), which may employ proxies such as the aridity index (Kuentz et al., 2017).

In the second scenario (*Scenario* 2), research efforts and financial resources are pooled into a limited number of pilot HOs, each equipped with massive instrumentation. Similar initiatives can be found in sister disciplines of hydrology. In oceanography, a limited number of costly research vessels are made available, primarily through the financial support of national governments. This approach allows numerous researchers to collaborate on community experiments, thereby facilitating a deeper understanding of specific ocean regions. One such example is the Multidisciplinary Drifting Observatory for the Study of the Arctic Climate (MOSAiC) which organized the drift with the Arctic Sea ice from October 2019 to September 2020 of the Polarstern research vessel (Rabe et al. 2022). In geology, the cost of drilling into the Earth is almost equally expensive. Lumping resources enables geologists from around the world to combine efforts into a single drilling program, such as the International Continental Scientific Drilling Program (ICDP) (Harms et al., 2007). The scientific drilling programs were conducted at locations of global geological significance, which are designated as World Geological Sites. Of course, in both cases, the research questions or aims are clearly identified. In the case of MOSAiC, the aim was to gain a better understanding of the influence of the Arctic on the global climate, given that the Arctic has warmed up more than any other region of the world. In the case of ICDP, the aim was to better understand the Earth's processes and structure at the most interesting locations. In both instances, participation is managed through an application and review process overseen by an international committee.

In a similar way, a small number of HOs equipped with comprehensive instrumentation and managed by an international team of experts from various disciplines could represent the pinnacle of hydrological field research. A wealth of data would unravel hydrological processes at hillslope/catchment scale in an unprecedented manner, based on observations of water and energy fluxes in the groundwater-soil-vegetation-atmosphere continuum at high spatial and temporal resolutions. Some of these networks already exist at the national scale, such as the networks of Critical

https://doi.org/10.5194/egusphere-2024-1678
Preprint. Discussion started: 12 June 2024

Zone Observatories (Brantley et al., 2017; Gaillardet et al., 2018), but a global network of observatories is currently missing.

As with the sister disciplines, it is necessary to define research questions in a clear and precise manner, both for the purpose of obtaining funding and for structuring research in a way that maximizes the chances of progress. The UPH may indeed serve as the basis for these questions. The research questions should be bold, and potentially outrageous (see discussion in Davis, 1926; Beven and Germann, 2013; McDonnell, 2014; Burt and McDonnell, 2015; Kirchner, 2016; Blöschl et al., 2019; Gao et al., 2023). Some interesting examples of *Scenario* 2 already exist in controlled settings. Biosphere-2 (B2) in Tucson, Arizona, (Evaristo et al., 2019) is a research facility comprising a tropical rainforest biome, a mesocosm enclosed in a pyramidal glass structure. Additionally, the site comprises the Landscape Evolution Observatory, LEO, consisting of three artificial hillslopes equipped with a dense network of soil sensors (Pangle et al., 2015), which is geared towards understanding the interaction between water and weathering processes (Van Den Heuvel, 2018; Bauser et al., 2022). Another example is the artificial Chicken Creek catchment in Germany, which has served as the fulcrum of comparative community research on runoff generation (Holländer et al., 2009).

Once more, as with the sister disciplines, the choice of location is of the utmost importance. The selected locations should represent hydrological situations that are particularly conducive to addressing the primary research question. For example, the Austrian Hydrological Open Air Laboratory (HOAL) (Blöschl et al., 2016), aims at better understanding rainfall-runoff processes and it is ideally suited for this purpose because it features a range of different runoff generation processes (surface runoff, springs, tile drains, wetlands). Another example is provided by the Alento observatory, which aims at elucidating the effects of the typical Mediterranean seasonality of climate, as well as land-use/land-cover changes on water flow in the critical zone of a representative southern European catchment (Nasta et al., 2017; Romano et al., 2018). If land-atmosphere feedbacks are to be explored (Späth et al., 2023), a catchment of considerable size should be selected. Another factor to be taken into account when selecting the location for new (high-budget) HOs may relate to the existence of so-called environmental archives in the area of interest. The ease of accessibility and the availability of infrastructure may be another factor to consider, but this could result in a geographic and climatic bias of the research sites. In any case, extrapolation to other climate zones and hydrogeological settings in *Scenario* 2 will be much more problematic than in *Scenario* 1 and requires careful planning.

Which of the two scenarios should, or will, be preferred depends on the research questions deemed most important, the ability to leverage funding, and the degree to which the hydrological community is willing and able to collaborate. No single better option exists under financial constraints: a distributed network of numerous HOs is well-suited to broad-scale questions, whereas a network of a few super-sites excels at in-depth process understanding.

A way forward to the aforementioned issues could be to merge the two scenarios into a dynamic or adaptive hybrid approach (Fig. 4). The establishment of a network of geographically distributed observatories would facilitate the achievement of a high level of representativeness regarding existing gradients of geology, climate, and land-use. This would assist in the identification of priority areas requiring further investigation, and alleviate some of the bias in current hydrological studies (Burt and McDonnell, 2015; Tarasova et al., 2024). Depending on the availability of resources, some of these observatories can be developed into hydrological super-sites that are particularly suitable for specific questions, such as karst hydrology, water scarcity, floodplains, forest hydrology, precision agriculture, or different runoff generation mechanisms. This approach allows for targeted investigations at selected locations with high-resolution data, which can then be used to support high-fidelity modeling. It is also possible to reverse this scenario. If a super-site located in a specific bioclimatic region yields scientific breakthroughs, it may be feasible to establish a network of HOs in regions with similar hydrological behavior. The key factor is to leverage the strengths of each approach, while working within the constraints of the available budget. By combining the strengths of both approaches, one can achieve a balance between representativeness (distributed network) and detailed understanding (super-sites). This ensures the optimal exploitation of resources while maximizing the scientific output.

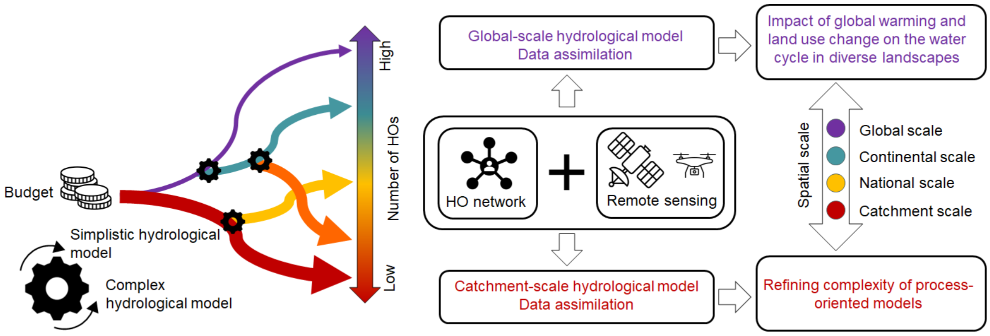

Figure 4. Possible arrangements of Hydrological Observatory (HO) networks, from a few (color-coded in red) to many (color-coded in blue) HOs. The thickness of the arrows indicates the quantity of instrumentation in each HO. The data retrieved from the HO network and remote sensing platforms inform hydrological models of different complexities to address specific science questions across different spatial scales.

5. Concluding remarks

Catchment-scale water-related problems across the continents require adaptation and mitigation solutions, based on evidence gathered in HOs. The past situation, characterized by a myriad of relatively unconnected, moderately and differently instrumented HOs supported by grant-to-grant funding has resulted in important but fragmented knowledge. This has hindered comparative studies and has hampered scientific progress. New initiatives are being proposed with the aim of improving the coordination of HO networks, thereby enabling efficient cross-site synthesis. Under financial constraints, we need to find a common vision for the optimal allocation of resources.

A network of numerous HOs provides broad spatial coverage, enabling the variations in environmental conditions across regions, ecosystems, and land uses to be captured. Environmental change can manifest itself differently in various regions due to local climate, geography, and human activities. A network of many observatories enables the monitoring of these interactions, the capturing of feedbacks, teleconnections, and cross-scale dynamics that may not be observable at individual observatories. In contrast, a small number of intensively instrumented observatories permit the collection of high-resolution data, the testing of new hypotheses, and informing complex process-oriented hydrological models. This choice can capture variations at smaller spatial and finer temporal scales, providing a more nuanced understanding of environmental and hydrological processes. However, the scenario of pooling all financial efforts into a small number of intensely instrumented hydrological observatories will exacerbate the issue of knowledge transferability and geographic bias in hydrological data and understanding. Therefore, strategies for generalization, perhaps inspired by the Prediction in Ungauged Basins initiative, are needed.

In times of rapid global changes, there is an urgent need for the establishment of a network of HOs. The question of how to organize and manage such a global network, including the number of observatories, is still under debate. Both distributed networks and super-sites offer valuable contributions to hydrological understanding. We envision a dynamic hybrid approach that combines the two visions, without mutually excluding either of them. It is important to raise public awareness about the importance of hydrological research and its linkages with many other disciplines including atmospheric science, soil science, biochemistry, pedology, ecology, microbiology, geology, plant physiology, and remote sensing. This can garner support and increase funding opportunities. It is our hope that all hydrologists engage in a discussion process with the aim of refining and building upon the ideas presented in this paper.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Hydrology and Earth System Sciences.

Acknowledgements

This paper is an outcome of the presentations and discussions at the 8th Galileo Conference "A European vision for hydrological observations and experimentation" held in Napoli, Italy, during 12-15 June 2023. The idea of the paper of concentrating on a few research catchments worldwide was proposed by Günter Blöschl in his keynote lecture on "The Future of Hydrology: Nature or Nurture?" on 14 June 2023. USDA is an equal opportunity provider and employer.

Appendix

The 8th Galileo Conference "A European vision for hydrological observations and experimentation" was held in Napoli on 12-15 June 2023. Upon presentations and discussions, we report the most intriguing questions in hydrology that emerged from the conference, but we also took some UPH from literature review:

- How do landscapes release and store water?
- What is the impact of preferential flow on catchment-scale water flow dynamics?
- How can remote sensing provide more reliable information on soil moisture, changes in water storage, surface energy balance, and evapotranspiration at suitable spatial and temporal scales (Lettenmaier et al., 2015)?
- What are the hydrologic laws at the catchment scale, and how do they change with scale?
- What causes spatial heterogeneity and homogeneity in runoff, evapotranspiration, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g., snowfall regime, aridity, reaction coefficients)?
- How can we use innovative technologies to measure surface and subsurface properties, states and fluxes at a range of spatial and temporal scales?
- How can hydrological models be adapted to be able to extrapolate changing conditions, including changing vegetation dynamics?
- How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?
- How can various multi-scale observations be assimilated into a hydrologic model to enhance model predictability?
- Is it better to give more importance to uncertainty or causality?
- What is the role of vegetation in the catchment?
- How can we integrate the different spatial and temporal scales of observations, processes, and models?
- How can we improve the quantity and quality of measurements in data-poor regions?
- How do we get large-scale flux measurements and feedback to analyze the water dynamics within and between the compartments of the groundwater-soil-plant-atmosphere-continuum?
- How is the water cycle influenced by the other cycles (carbon, nitrogen, etc.)?
- Where and how can the sensors be allocated to get full information without wasting excessive effort?
- How can the dynamics and feedback at groundwater-soil, groundwater-surface water, soil-plant, soil-atmosphere, and plant-atmosphere interfaces be assessed?
- How do we include plant physiological aspects in hydrological models?
- Are measurements taken in the past still valid in the future? How about accuracy/precision change with technological advancements? Do we need to remove all "inaccurate" historical data and keep only "currently accurate" data? Is the assumption of a steady hydrological system valid? Can we simplify the system by linearizing a nonlinear system behavior?
- How can we develop socio-hydrological models by considering anthropogenic disturbances in the ecosystem?
- What role(s) do continuous and ephemeral water bodies, including ponds, lakes, rivers, streams, marshes, swamps, etc. influencing watershed water quantity and quality?

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