HESS Opinion paper:
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.~~gain a deep understanding of the complex hydrologic processes occurring within diverse environmental conditions. The already existing monitoring infrastructures have provided an enormous amount of hydrometeorological data, ~~which has helped gain~~facilitating detailed insights into the ~~causality~~causal mechanisms of hydrological processes, ~~test~~the testing of scientific theories and hypotheses, and ~~reveal~~the revelation of the physical laws governing catchment behavior. ~~Nevertheless, we are still a long way from being able to fully unravel all the mysteries of~~Yet, hydrological ~~processes to solve practical water-related problems. Hydrological~~ monitoring programs have often produced limited outcomes ~~because of~~due to 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 potential end members of ~~possible~~a future hydrological observatory (HO) ~~networks for~~network, based on 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 a broad spatial coverage across the major pedoclimatic regions~~, help address UPH about the impact~~ by supporting cross-site synthesis of ~~climate and social systems~~the lumped hydrological response (e.g., ~~land use change and global warming) on water resources, and enhance the potential for knowledge transfer~~rainfall-runoff relationship, Budyko analysis) across diverse continental landscapes. However, the moderate instrumentation at each site may hamper an in-depth understanding of complex hydrological processes. In contrast, a ~~few~~small number of extensively instrumented research sites would ~~allow for~~enable community-based experiments in an unprecedented manner, thereby ~~providing more fundamental insights into~~facilitating a deeper understanding of complex, non-linear processes modulated by scale-dependent feedback and multiscale ~~spatio-temporal~~spatiotemporal 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 potential limitation of this approach is that 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~~to build 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~~integrating 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.

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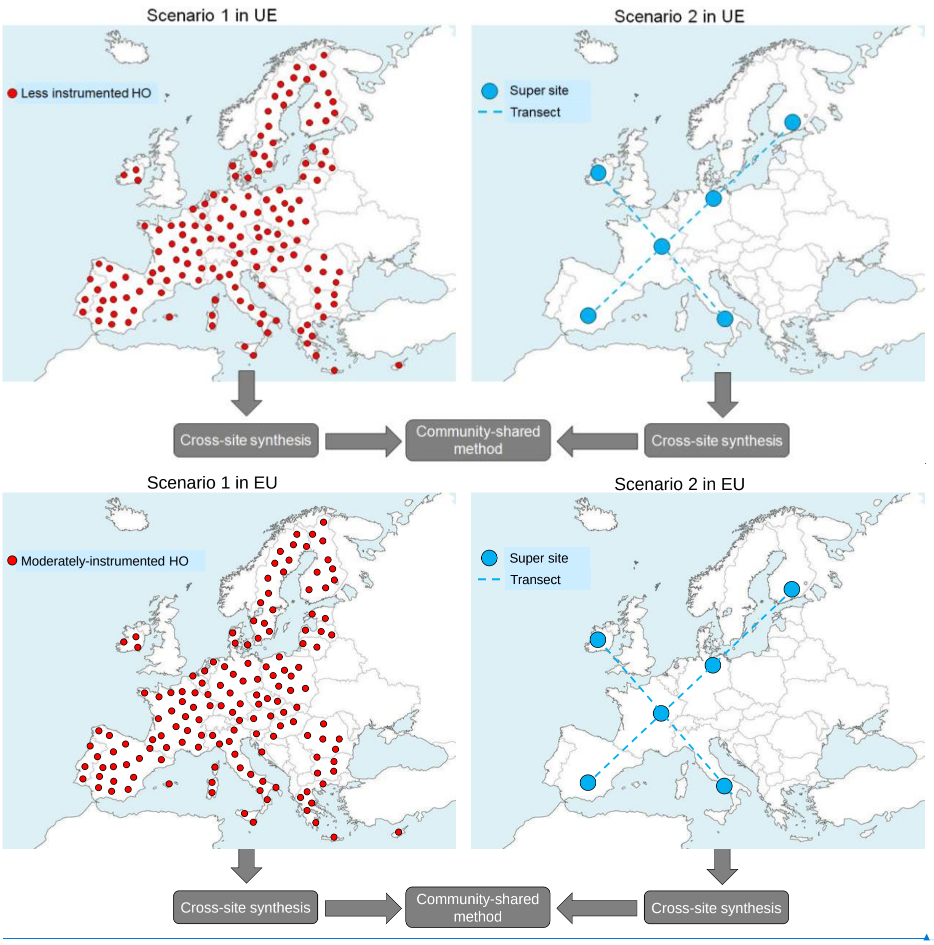

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1. How do we ~~address the Unsolved Problems in Hydrology~~advance scientific understanding of hydrological processes?

Water is ~~essential for life, yet certain~~under increasing threat due to human activities~~ put this precious resource at risk.~~. Rapid changes in land use, such as the adoption of more intensive farming practices, ~~expanding~~the expansion of urbanization, and ~~land~~the abandonment of land 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~~.~~ and the effectiveness of adaptation actions to guide the management of water resources has yet to be fully evaluated. 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 in relation to the impact of human activities on the critical zone and catchment functionality, and to address the Unsolved Problems in Hydrology (UPH), several ~~long-term~~ hydrological observatories (HOs) have been established around the world ~~to monitor~~with the specific purpose of monitoring 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~~hydrological observatories (HOs) can be traced 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~~initially collected in the Sperbelgraben and Rappengraben experimental catchments in the Emmental ~~(~~region of Switzerland~~), which are still in operation~~. These catchments remain operational 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~~Since the 1950s~~ and~~, there has ~~grown exponentially since~~been a notable increase in the ~~1980s.~~number of HOs established across the globe. The HO sites have provided ~~valuable~~invaluable information for ~~managing~~ the effective management of water resources~~ and are currently funded and supported by~~ . Currently, a diverse range of entities, including government agencies (e.g., the Hydrologic Benchmark Network of the US Geological Survey), universities and research institutions~~ including universities~~, international organizations, and non-governmental organizations, provide funding and support for these sites.

2. Building integrated observation platforms ~~to address the UPH~~

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A ~~significant~~considerable number of rivers ~~around the globe~~worldwide have been equipped with gauges to monitor precipitation and streamflow by governmental agencies for the purpose of water management. The data collected have been primarily ~~used~~utilized at the national level, although there are several transnational initiatives~~ as e.g.,~~, including the Global Runoff Data Centre in Koblenz, Germany~~;~~, and 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~~HOs extend beyond these ~~standard~~conventional networks, striving to gain a more comprehensive understanding of hydrological processes, typically in smaller catchments.

~~While some instruments are based on well-~~A hydrological observatory is defined as a cyber-physical infrastructure established ~~monitoring technologies, others~~within a catchment area to monitor the hydrological variables and fluxes, as well as to characterize the hydrological behavior of the three-dimensional spatial domain. The catchment is assumed to be the fundamental hydrological unit with well-defined system boundaries. It is from this unit that the impact of anthropogenic disturbances (global warming, land use change, aquifer contamination, etc.) on water resources can be evaluated through a long-term data analysis. Given the impracticality of full catchment coverage, the hydrological observatory focuses on a selected cluster of sub-catchments (spatial resolution of hectares) which are representative of land use, geomorphology, topography, and pedology similarities (Bogena et al., 2006). Consequently, the selected sub-catchments are ~~more experimental.~~equipped with wireless sensor networks for continuous data collection and subjected to disparate field campaigns, contingent upon budgetary constraints.

The selection of sensors is crucial for the effective collection of hydrometeorological data within a hydrological observatory. Weather station networks (also called synoptic stations) ensure the collection of meteorological ~~measurements~~data and have been ~~combined~~integrated in many countries with weather radar networks for the purpose of 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~~United States) 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~~measurements of soil water content~~,~~ and matric potential, soil temperature, and soil bulk electrical conductivity ~~in soil is~~are conducted across soil profiles at the point scale (Hoffmann et al., 2015; Peng et al., 2019; Bogena et al., 2022~~), while cosmic~~). Cosmic-ray neutron sensors, meanwhile, are capable of extending the footprint of soil moisture to approximately 150-200 meters in 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, the 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~~, thus enabling the extension of 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~~The measurement of soil physical, chemical, and hydraulic properties ~~are~~is typically ~~measured~~conducted in field campaigns and laboratory experiments, with remote sensing serving as a ~~complement.~~complementary technique. Geophysical tools, such as electromagnetic (EM) surveys, ~~offer great~~have the potential ~~for~~to provide valuable insights into the imaging of aquifer systems and the characterization of subsurface heterogeneity (Nasta et al., 2019; Dewar and Knight, 2020). To ~~unravel~~elucidate the interactions of the water cycle with the biochemical,

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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~~which are connected through networks, such as Fluxnet, ~~measure~~are used to obtain evapotranspiration and carbon fluxes at the local level. Sapflow sensors, some of which are organized in the Sapflux network (Poyatos et al., 2021), can be used to ~~measure~~quantify transpiration rates. ~~Tracer~~The use of tracer measurements, such as isotope and dye studies, ~~are employed to track~~enables the tracking and ~~differentiate~~differentiation of water fluxes (Klaus and McDonnell, 2013; Penna et al., 2018~~), while lysimeters~~). Lysimeters are used to determine groundwater recharge and the associated concentrations of, e.g~~.~~., nitrate, at the point scale.

~~Remote sensing from~~The use of 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~~for remote sensing has emerged as a valuable supplementary ~~information~~method to ground-based observation in HOs~~, which can be used~~ for gathering information over large heterogeneous areas as well as 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,~~ various hydrological variables have become available, including 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~~). These observations can be used together with coarser~~-~~-scale products, ~~such as~~including total water storage data from the Gravity Recovery and Climate Experiment (GRACE) mission, ~~or~~and discharge data from the Surface Water and Ocean Topography (SWOT) mission. ~~Multi-sensor combinations, such as those employed by~~The deployment of multiple sensors, as seen in 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~~integrate technologies such as remote sensing, high-performance computing resources, artificial intelligence, and the Internet of Things, ~~yet keeping in mind that~~while acknowledging the ~~water and energy fluxes are influenced by~~influence of 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.~~, on water and energy fluxes.

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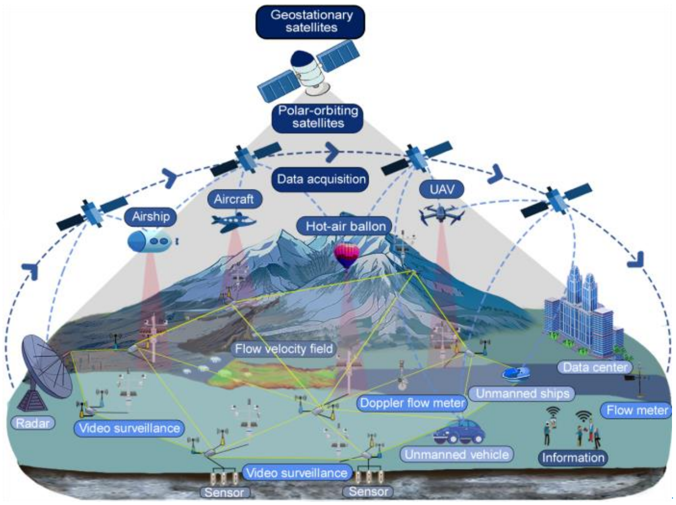

~~**Figure 1. Air-space-ground observation of hydrological processes at catchment scale.**~~

While observations are the ~~backbone~~cornerstone of progress in hydrological understanding (Sivapalan and Blöschl, 2017), models are equally essential for hypothesis testing and making predictions ~~of practical relevance~~that are practically relevant (Brooks et al., 2015; Baatz et al., 2018; Bogena et al., 2018; Bechtold et al., 2019; ~~Nearning~~Nearing et al., 2024). However, hydrological models, particularly those of a complex nature, frequently rely on lumped parameter calibration. This means that model parameters are adjusted based on aggregated (or lumped) fluxes, such as those observed in streamflow measurements at the outlet of the catchment. Although this approach can be effective, it can also result in limitations. A significant challenge is the assumption that the model's behavior is uniform across the entire catchment. This assumption might not hold true, especially in heterogeneous catchments with diverse topography, land use, and soil types. In such cases, relying exclusively on lumped fluxes may result in suboptimal model performance. An integrated observation approach enables the ~~development of new methods that rely less on~~ calibration ~~and more~~based on insightful analysis of ~~landscape heterogeneity and~~ process complexity through systematic learning from distributed 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~~heterogeneities, which give rise to non-linear interactions and feedback between the component processes (Vereecken et al., 2015; 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~~represent another example of integration and are instrumental in developing a ~~better~~more comprehensive understanding of how dynamic, abiotic, and biotic ~~watershed~~catchment characteristics have co-evolved well before the advent of instrumental records~~ started~~ (Troch et al., 2013). Climate shifts leave a multitude of signatures in the natural world, influencing processes such as tree growth and the distribution of plant species. ~~With the~~The advent of increasingly sophisticated analytical techniques~~,~~ has facilitated a rapid growth in knowledge ~~of~~regarding past climate and river ecosystem variability~~ is rapidly growing, benefiting from~~. Of particular

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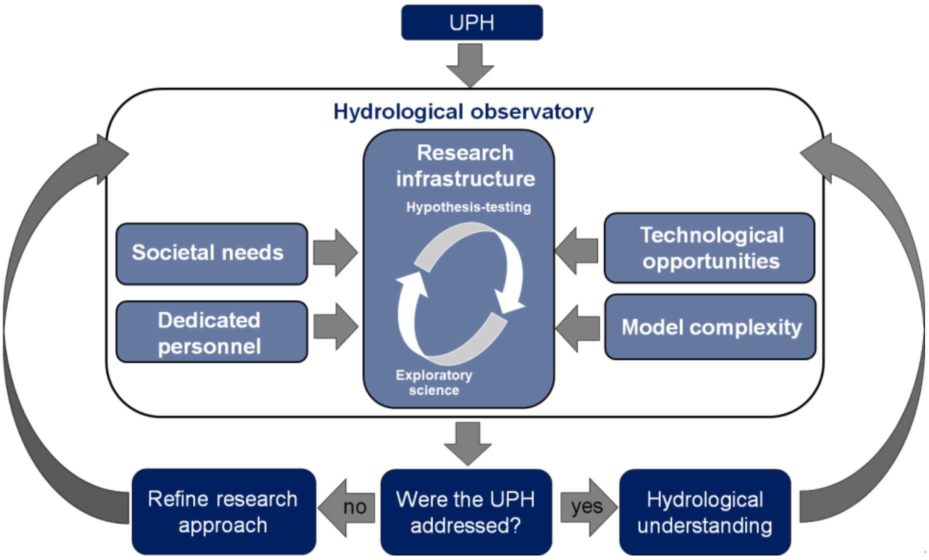
benefit are reconstructions of river flow and erosion derived from natural archives (Chaussé et al., 2008; Torbenson et al., 2021; Büntgen et al., 2021; Schöne et al., 2020; Strelnikova et al., 2023).



~~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~~which represents a significant societal ~~needs~~need for hydrology ~~at~~in the present and ~~in~~ the future (Montanari et al., 2013). ~~Given the often limited budget per~~In light of the frequently constrained budgetary resources available for each site, many studies have ~~concentrated~~focused on measuring lumped hydrological fluxes (e.g., the streamflow at the catchment outlet), while observatories that ~~focus on~~ prioritize the analysis of spatial details ~~are~~remain relatively ~~rare~~scarce (e.g., Blöschl et al., 2016). Site-specific methods, tailored to site-specific UPH, have ~~often led to research progress on~~frequently resulted in advancements in the understanding of a ~~single~~specific

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hydrological process, ~~without~~but have not fully ~~leveraging~~exploited the potential for synergies with other HOs. Consequently, the outcome has ~~often~~frequently been an increase in fragmented knowledge, rather than progress in understanding the ~~interaction~~interactions of hydrological processes~~ that,~~ which is so urgently needed.

To address these issues, scientists have proposed initiatives to sustain long-term operation, harmonize, and standardize both ~~data and models (Zoback 2001; Reid et al., 2010; Kulmala, 2018).~~hydrometeorological data and eco-hydrological models in HO networks (Zoback 2001; Reid et al., 2010; Kulmala, 2018). In numerous instances, hydrological observations are now integrated into interdisciplinary research programs in terrestrial observatories which are scientific facilities designed to observe and study various aspects of the Earth's surface, atmosphere, and interior. Terrestrial observatories collect data on a range of phenomena, including earthquakes, volcanic activity, weather patterns, climate change, and the movement of tectonic plates. Hydrological observations play a crucial role in the context of terrestrial observatories. 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~~at understanding critical zone processes~~ and includes~~, with a particular focus on hydrologic monitoring (Brantley et al., 2017; Anderson et al., 2018; Gaillardet et al., 2018). The integrated European Long-Term Ecosystem, Critical Zone, and socio-ecological Research Infrastructure (https://elter-ri.eu) ~~will establish~~is establishing a network of ~~around~~approximately 200 integrated terrestrial observatories across Europe, ~~and~~with hydrological monitoring ~~will be part~~forming a component of ~~it.~~this initiative. In the field of agriculture, the United States Department of Agriculture (USDA) is ~~supporting~~providing support for the Long-Term Agroecosystem Research (LTAR) initiative (https://ltar.ars.usda.gov/), which combines strategic research projects with common measurements ~~on~~across 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~~This is contingent upon the standardization and harmonization of existing protocols and methods for hydrological observation. ~~Existing~~The extant 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~~The cross-site synthesis of hydrological processes ~~fills~~serves to fill the gap between site-specific studies and broader, more 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 the development of a more robust and transferable body of knowledge for model development and~~ eventually~~, ultimately, more effective decision-making. The implementation of cross-site synthesis typically ~~involves~~entails the following steps~~ (Fig. 3):~~, as illustrated in Figure 1;

- Formulating the UPH;
- Data collection by using standardized protocols;
- Use of community-shared hydrological models;
- Comparative hydrology;

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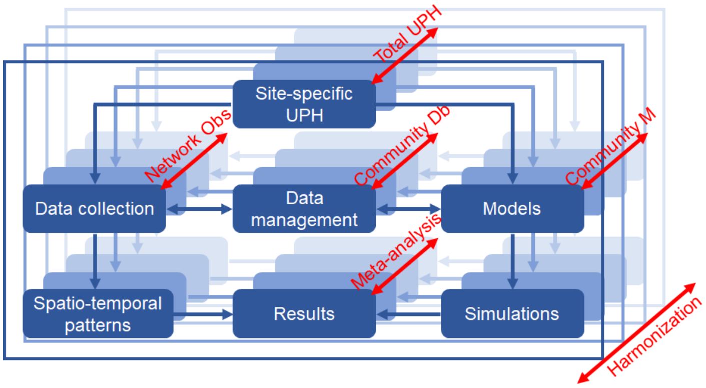
~~-~~– Meta-analyses to consolidate results.

The initial step is to formulate scientifically interesting questions that ~~not only~~ address existing knowledge gaps ~~but also~~and contribute to a broader understanding and societal benefits in the field of hydrology (see Appendix). To ensure consistency in data quality, it is essential to harmonize the measurement ~~methods,~~techniques and quality control protocols ~~need to be harmonized~~employed. 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~~The models are calibrated and tested using the harmonized data from multiple sites~~ to improve~~, thereby enhancing their predictive capabilities and generalizability. ~~Interesting~~Notable initiatives are already ~~operative, such as~~operational, including 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~~have been instrumental in identifying the key drivers of hydrological variability and ~~identify~~in establishing generalizable principles~~ by systematically comparing~~. This is accomplished through a comprehensive and systematic comparison of hydrological processes and responses across ~~different~~a range of sites, while accounting for several factors, ~~such as~~including climate, topography, land-use, and management practices. ~~Finally~~In addition, meta-analyses can ~~combine~~synthesize and compare ~~results~~findings from multiple studies, identify ~~common~~recurrent patterns and trends ~~on~~in integrated measurements and model simulations, and present consolidated results in a coherent ~~way~~manner.

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



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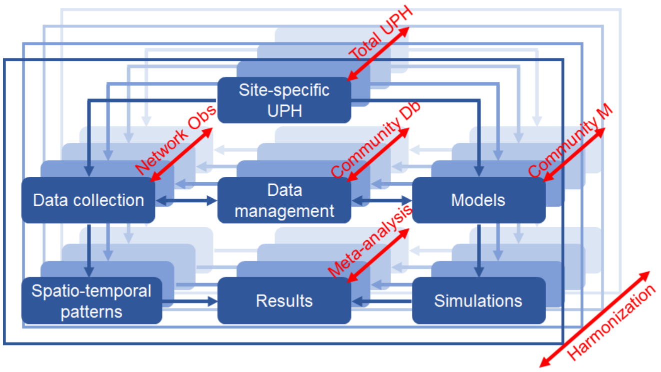

Figure ~~3~~1. Schematic of the proposed cross-site synthesis. Obs, Db, M, and UPH indicate Observatories, Database, ~~Model~~Models, and Unsolved Problems in Hydrology, respectively.

Cross-site synthesis helps unveil hidden assumptions that may be embedded in site-specific studies~~ and enables~~, thereby enabling researchers to critically assess the validity of these assumptions and explore alternative perspectives. ~~Identifying~~The identification of common principles and practices ~~enables~~allows researchers to develop transferable knowledge that can be applied to other settings, thereby accelerating progress in research and practice. ~~Some examples~~Examples of cross-site synthesis already exist in the literature. 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. Similarly, Addor et al. (2018) ~~similarly looked at~~examined the predictability of hydrologic signatures for the catchments ~~that are part of~~included in the Camels dataset but found that the ~~relation~~relationship between these signatures and catchment attributes other than climate characteristics was ~~poor~~weak.

Comparative analyses have ~~also~~ yielded a range of interesting ~~conflicting~~ results, although there is not yet complete concordance. 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~~aforementioned conflicting results (Ellison et al., 2012). The *demand-side* perspective ~~emphasizes~~places emphasis on 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, the impact of reforestation ~~may increase or decrease~~on dry season flows ~~depending on~~is contingent upon the relative importance of increased infiltration and evapotranspiration rates (Bruijnzeel, 1989).

~~The aforementioned~~As demonstrated by the preceding case studies~~ demonstrate the advantages of~~, cross-site synthesis ~~in~~provides a valuable approach for 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.

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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~~ in the European Union (EU). Two potential scenarios can be envisaged. In the first scenario (*Scenario* 1), the available financial resources are ~~allocated to numerous less intensively~~distributed among a multitude of moderately instrumented HOs ~~distributed around~~situated throughout the ~~world~~EU, with the objective of addressing challenges in hydrology with ~~broad~~extensive 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.~~Figure 2 illustrates an example of a moderately instrumented site belonging to a hydrological observatory network in *Scenario* 1. This plan reflects the current status of the majority of HO networks around the world. The ~~cross-site synthesis involves the gathering of information from each HO to identify~~principal benefit of this approach is that the HOs are widely and effectively distributed, enabling the identification of cause-and-effect relationships ~~(i.~~and supporting the cross-site synthesis of the lumped hydrological responses (e~~., ~~.g., rainfall-runoff ~~ratio, nutrient input-output~~relationship, Budyko~~-type approaches) among different~~ analysis) across diverse continental landscapes (Wagener et al., 2007; Ehret et al., 2014; Jones et al., 2012; Kuentz et al., 2017; 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 *Scenario* 1, a combination of centralized and distributed components is utilized. Distributed components provide observed data that is managed by different entities (e.g., universities, research institutions, government agencies, etc.) across geographically spread sites. To guarantee the comparability of data, it is essential to implement standardized protocols for data collection, storage, quality assurance, and analysis. This will alleviate the burden associated with the cross-site synthesis. Centralized data management facilitates the accessibility of data across multiple sites. Furthermore, additional central thematic elements may be provided, such as those pertaining to communication and knowledge transfer, or those relevant to modeling applications. The organizational structure may be based on other successfully established or planned distributed continental infrastructures. Notable examples include ICOS (Integrated Carbon Observation System) and eLTER (Integrated European Long-Term Ecosystem, Critical Zone and Socio-ecological Research Infrastructure). Free data availability and accessibility of the sites should be a fundamental aspect of the scenario designs.

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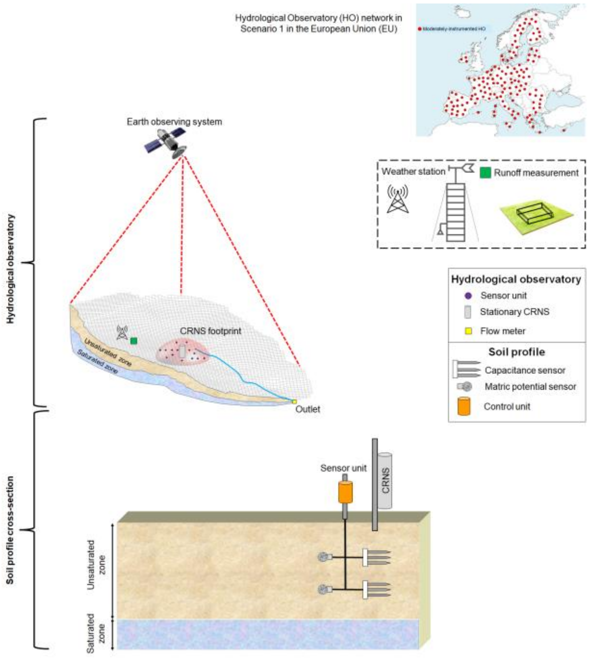

Figure 2. Graphical illustration of a hydrological observatory (HO) network in the European Union (EU) in *Scenario* 1. Each sub-catchment is equipped with basic instrumentation: a weather station, a runoff gauging station, a Cosmic-Ray Neutron Sensor (CRNS) with a wireless sensor network controlling soil profile sensors, a streamflow sensor at the catchment's outlet. Satellite products are available anywhere in the world. The soil profile cross-section illustrates the soil profile sensor unit and the stationary CRNS.

In *Scenario 1*, collaboration and partnership among different stakeholders are crucial. Such collaboration may facilitate broader opportunities for citizen and stakeholder participation, particularly given the distributed nature of the scenario and the encouragement of local initiatives.

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~~related fields of ~~hydrology~~study. In oceanography, a limited number of costly research vessels are made available, primarily through the financial support of national governments. This approach ~~allows~~enables numerous researchers to ~~collaborate on~~engage in collaborative community experiments, thereby facilitating a deeper understanding of specific ~~ocean~~oceanic regions. One ~~such~~illustrative example is the Multidisciplinary Drifting Observatory for the Study of the Arctic Climate (MOSAiC~~)~~)), which ~~organized the~~undertook a drift with the Arctic Sea ice from October 2019 to September 2020 ~~of~~aboard the Polarstern research vessel (Rabe et al~~.~~., 2022). In the field of geology, the cost of drilling into the Earth is almost equally expensive. ~~Lumping~~The consolidation of resources ~~enables~~permits geologists from ~~around the world~~diverse geographical locations to ~~combine efforts into a single~~engage in collaborative drilling ~~program~~programs, 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~~have been designated as World Geological Sites. Of course, in both cases, the research questions or aims are ~~clearly~~

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~~identified.~~explicitly delineated. In the case of MOSAiC, the aim was to gain a ~~better~~deeper understanding of the influence of the Arctic on the global climate, given that the Arctic has ~~warmed up~~experienced a more pronounced warming trend than any other region of the world. ~~In the case of~~Concerning ICDP, the ~~aim~~objective was to ~~better understand~~gain a deeper understanding of the Earth's processes and structure at the most interesting locations. In both instances, participation is ~~managed through~~contingent upon the successful completion of an application and review process overseen by an international committee.

~~In a similar way~~Similarly, 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. Figure 3 shows a hypothetical super-site established along an ideal transect within the European Union (*Scenario* 2). A high-density network of sampling and monitoring units for soil hydrology research is designed and planned for each super-site. This infrastructure, as yet unrealized, would facilitate a comprehensive understanding of water dynamics in the groundwater-soil-plant-atmosphere continuum and water circulation in the surface and subsurface domains within a few sites on each continent. In this case, cross-site synthesis would support the application and refinement of complex hydrological models based on fundamental insights into complex, non-linear processes that are modulated by scale-dependent feedback and multiscale spatiotemporal heterogeneity.

A wealth of data would ~~unravel~~enable an unprecedented unraveling of hydrological processes at the 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 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~~In *Scenario* 2, the research questions should be presented boldly (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 have already ~~exist~~been documented in controlled ~~settings~~environments. 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~~) comprises three artificial hillslopes equipped with a dense network of soil sensors (Pangle et al., 2015~~), which~~). The observatory is ~~geared towards~~focused on 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~~The Austrian Hydrological Open Air Laboratory (HOAL) (Blöschl et al., 2016~~), aims at better~~) was designed with the specific objective of facilitating a more comprehensive understanding of rainfall-runoff processes ~~and it~~. It is ideally suited for this purpose ~~because it features~~, featuring a range of different runoff generation processes ~~(~~, including surface runoff, springs, tile drains, and wetlands~~).~~. Another example is provided by the Alento hydrological 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

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(Nasta et al., 2017; Romano et al., 2018). ~~If~~To explore land-atmosphere ~~feedbacks are to be explored (Späth et al., 2023),~~feedback, it is recommended that a catchment of considerable size ~~should~~ be selected~~. Another factor to be taken into account~~ (Späth et al., 2023). In addition, when selecting ~~the~~a location for a new ~~(~~, high-budget~~) HOs~~ HO, it may ~~relate~~be beneficial to consider 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.~~

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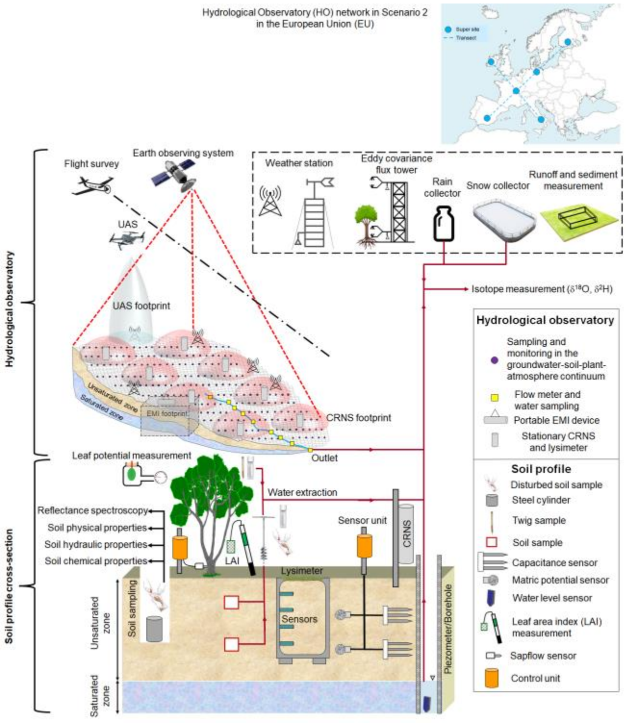

Figure 3. Graphical illustration of a hydrological observatory (HO) network in the ~~two scenarios should, or will,~~European Union (EU) in *Scenario* 2. Each sub-catchment established along an ideal transect is equipped with a high-density network of sampling and monitoring units for soil hydrology research. Frequent unmanned aerial system (UAS) and aircraft surveys are organized over the experimental area. Satellite products are available anywhere in the world. Frequent campaigns of geophysical (electromagnetic induction, EMI technique) and tracing (stable isotopes in water such as δ^2H and δ^{18}O) measurements are carried out across the HO. Flow monitoring and water sampling are carried out along the stream. The soil profile cross-section shows the monitoring and sampling activities in the groundwater-soil-plant-atmosphere continuum in a position of the dense point grid (purple circles).

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Few super-sites would require a central governing body that would likely be ~~preferred depends~~responsible for overseeing all aspects of the super-sites, including instrument deployment and maintenance, as well as data collection and analysis. Such an entity could be a dedicated government agency with a specific mandate or a research consortium

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with significant resources. The establishment of a single entity in charge, operating as a central authority, would facilitate the decision-making process with regard to instrument upgrades, research focus, and site and data access. Super-sites with advanced instrumentation might attract highly specialized researchers, leading to a concentration of expertise in specific areas. The implementation of standardized sensors would result in cost savings and enhanced efficiency in the collection and processing of data. Conversely, the specific hydrological environment may require the use of specialized instrumentation or measurement techniques. A lack of flexibility in standardization can limit the ability to adapt to new research questions or emerging challenges. Notable examples of standardization efforts include the Global Network of River Observatories (GLORIA) and the World Meteorological Organization (WMO) guidelines for hydrological stations. By taking these factors into careful consideration and adopting a balanced approach, hydrological observatories can harness the power of standardization while maintaining flexibility and adaptability. To ensure equity and stimulate greater involvement in *Scenario* 2, it is essential to establish a collaborative governance structure that incorporates a diverse range of stakeholders in decision-making processes pertaining to super site operations and data utilization. The governance and site access aspects are well presented in initiatives such as the International Continental Scientific Drilling Program (ICDP), which addresses geodynamic processes, solid Earth geohazards, sustainable geo-resources, and environmental change (https://www.icdp-online.org/about-icdp/entities/). Another noteworthy example is the Alfred Wegener Institute (AWI), which aims to understand the complex processes in the Earth system and the impact of global warming on the oceans and polar regions (https://www.awi.de/en/). The AWI maintains a network of well-instrumented long-term observatories, comprising both stationary devices and mobile components that are used for studies pertaining to oceanography, meteorology, and geophysics (https://www.awi.de/en/expedition/observatories.html).

The selection of the optimal scenario is contingent upon the research questions deemed most ~~important~~pertinent, the ~~ability~~capacity to ~~leverage~~secure funding, and the ~~degree~~extent to which the hydrological community is willing and able to collaborate. ~~No single better option exists under~~In the context of financial constraints~~: a~~, no single alternative can be considered inherently superior. A distributed network of numerous HOs is well-suited to broad-scale ~~questions~~inquiries, whereas a network of a few super-sites ~~excels~~is particularly adept at facilitating in-depth process understanding.

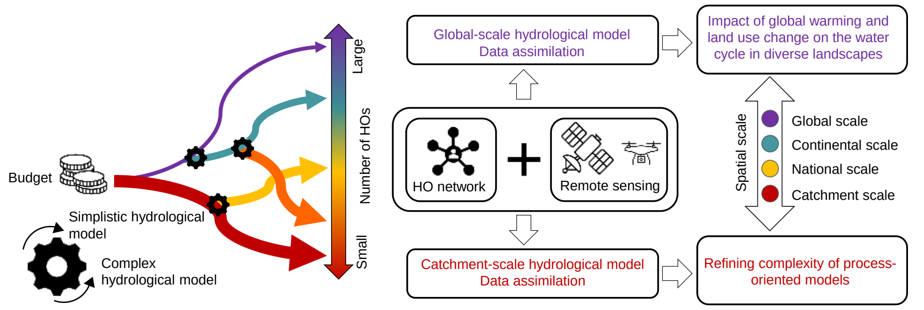

Figure 4. **Possible configurations of Hydrological Observatory (HO) networks are illustrated, spanning a range from a few (color-coded in red) to numerous (color-coded in blue) HOs. The thickness of the arrows indicates the quantity of instrumentation present in each HO. The data obtained from the HO network and remote sensing platforms are used to inform hydrological models of different complexities, enabling the addressing of specific scientific questions across disparate spatial scales.**

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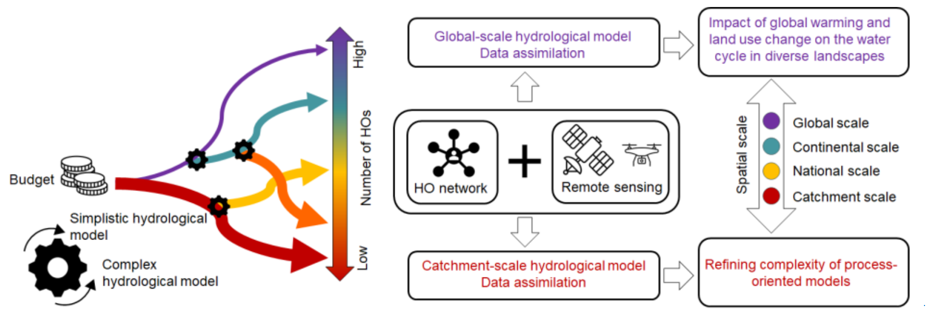
A potential way forward to the aforementioned issues could be to merge the two scenarios into a dynamic or adaptive hybrid approach (~~Fig.~~see Figure 4). The establishment of a network of geographically distributed observatories would facilitate the achievement of a high level of representativeness 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,~~ The development of some of these observatories ~~can be developed~~ into hydrological super-sites~~ that are particularly suitable~~, contingent on the availability of resources, would allow for the investigation of specific questions, such as karst hydrology, water scarcity, floodplains, forest hydrology, precision agriculture, ~~or~~and different runoff generation mechanisms. This approach ~~allows for~~enables targeted investigations at ~~selected~~specific locations with high-resolution data, which can then be ~~used~~exploited to support the development of 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~~models.



It is similarly feasible to reverse this scenario. Should a super-site situated in a particular bioclimatic zone yield scientific breakthroughs, it may be possible to establish a network of HOs in regions exhibiting analogous hydrological behavior. The key factor is to leverage the strengths of each approach while operating within the confines of the allocated budgetary resources. By integrating the strengths of the two approaches, one can attain a balance between representativeness (a distributed network) and a detailed understanding (super-sites). This approaches 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~~ To address water-related ~~problems~~ issues at the catchment scale across ~~the continents require~~diverse global contexts, it is imperative to develop adaptation and mitigation ~~solutions, based on~~ strategies that are grounded in evidence gathered in HOs. The ~~past~~previous situation, which was characterized by a myriad of relatively unconnected, moderately and differently instrumented HOs that were supported by grant-to-grant funding, has resulted in ~~important~~significant but fragmented knowledge. This has ~~hindered~~impeded comparative studies and has

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~~hampered~~hindered scientific progress. New initiatives are being proposed with the ~~aim~~objective of ~~improving~~enhancing the coordination of HO networks, thereby enabling efficient cross-site synthesis. ~~Under~~In light of financial constraints, we need to ~~find~~identify a common vision for the optimal allocation of resources.

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

In ~~times~~the context of ~~rapid~~accelerated global ~~changes~~transformation, there is ~~an urgent~~a pressing need ~~for the establishment of~~to establish 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.~~remains a topic of discussion. Both distributed networks and super-sites offer valuable contributions to the advancement of hydrological understanding. We envision a dynamic hybrid approach that combines the two aforementioned visions~~, without mutually excluding~~ in a manner that does not exclude either of them~~.~~ from consideration. It is important to raise public awareness about the ~~importance~~significance of hydrological research and its linkages with ~~many~~a multitude of other disciplines, including atmospheric science, soil science, biochemistry, pedology, ecology, microbiology, geology, plant physiology, and remote sensing. ~~This~~Such an approach can garner support and increase funding opportunities. It is our hope that all hydrologists will engage in a discussion process with the aim of refining and building upon the ideas presented in this paper.

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~~**Acknowledgements**~~

Acknowledgments

This paper is ~~an outcome~~a result of the presentations and discussions held at the 8th Galileo Conference, entitled “A European ~~vision~~Vision for ~~hydrological observations~~Hydrological Observations and ~~experimentation” held~~ Experimentation”, which took place in ~~Napoli~~Naples, Italy, ~~during 12-15~~from June 12th to 15th, 2023. ~~The idea of the paper of concentrating on a few research catchments worldwide was proposed by Günter Blöschl in~~ In his keynote lecture ~~on~~, entitled “The Future of Hydrology: Nature or Nurture~~?””~~”, on ~~14~~ June 14th, 2023~~.~~, Günter Blöschl discussed the concept of focusing research efforts on a limited number of catchments worldwide. This prompted a lively exchange of opinions among the attendees. The USDA is an equal opportunity provider and employer. Salvatore Manfreda acknowledges the RETURN Extended Partnership which received funding from the Next-Generation EU (National Recovery and Resilience Plan - NRRP, Mission 4, Component 2, Investment 1.3 - D.D. 1243 2/8/2022, PE0000005). Paolo Nasta and Nunzio Romano acknowledge the partial support provided by the the Ministry of University and Research (MiUR) through the MiUR-PRIN-PNRR-2022 project entitled “ASAP: Assessing and mapping novel agroecosystem vulnerability and resilience indicators in southern Italy” (grant P20228L3KX). The authors would also like to express their gratitude to the executive editor in charge, Thom Bogaard, and the two reviewers (A. Guswa and an anonymous) for their constructive comments, which have contributed to enhance the quality of this paper.

Appendix

The 8th Galileo Conference “A European ~~vision~~Vision for ~~hydrological observations~~Hydrological Observations and ~~experimentation~~Experimentation” was held in ~~Napoli~~Naples (Italy) on 12-15 June 2023. Upon presentations and discussions, we report the most intriguing questions in hydrology that emerged from the conference~~, but~~. Additionally, we ~~also took some UPH from~~conducted a literature review and identified several key points that warrant further investigation:

- ~~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?~~

Research questions in *Scenario* 1	
1	How can we improve the quantity and quality of measurements in data-poor regions?

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2	Where and how can we deploy the sensors to get the most information without wasting too much effort?
3	Are measurements taken in the past still valid in the future? How will accuracy/precision change with as technological advances? 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?
4	What role(s) do continuous and ephemeral water bodies, including ponds, lakes, rivers, streams, marshes, swamps, etc., play in influencing water quantity and quality in the catchment?
	Research questions in *Scenario* 2
1	What are the hydrologic laws at the catchment scale, and how do they change with scale?
2	How can we use innovative technologies to measure surface and subsurface properties, states, and fluxes at a range of spatial and temporal scales?
3	How can different multi-scale observations be assimilated into a hydrological model to improve model predictability?
4	How do we obtain large-scale flux measurements and feedbacks to analyze the water dynamics within and between the compartments of the groundwater-soil-plant-atmosphere continuum?
5	How is the water cycle influenced by the other cycles (carbon, nitrogen, etc.)?
6	How can the dynamics and feedbacks at groundwater-soil, groundwater-surface water, soil-plant, soil-atmosphere, and plant-atmosphere interfaces be assessed?
7	How do we incorporate plant physiological aspects into hydrological models?
	Research questions in both scenarios
1	What is the impact of preferential flow on catchment-scale water flow dynamics?
2	How can remote sensing provide more reliable information on soil moisture, changes in water storage, surface energy balance, and evapotranspiration at appropriate spatial and temporal scales (Lettenmaier et al., 2015)?
3	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, response coefficients)?
4	How can hydrological models be adapted to be able to extrapolate changing conditions, including changing vegetation dynamics?
5	How can we disentangle and reduce model structure/parameter/input uncertainty in hydrological prediction?
6	Is it better to emphasize uncertainty or causality?
7	How do vegetation types, distribution, and dynamics shape hydrological processes, particularly in terms of water quality, quantity, and energy fluxes at the catchment scale?
8	How can we integrate the different spatial and temporal scales of observations, processes, and models?
9	How can we develop socio-hydrological models by allowing for anthropogenic disturbances in the ecosystem?

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