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

EDITOR

We would like to thank the Editor for handling our contribution. The first reviewer provided very positive and extremely constructive comments, which helped us substantially improve the quality of our manuscript. We have modified some parts of the manuscript in accordance with his suggestions. The second reviewer raised concerns, especially regarding the initial section of the manuscript. Therefore, we have removed the first two figures (which actually were not well received by both reviewers) from the second section and expanded the last part of the manuscript pertaining to the comparison of two hypothetical scenarios for managing hydrological observatories (HOs). In response to the first reviewer's suggestion, we have added two new figures (Figures R1 and R2 in this reply letter) to Section #4 to provide further emphasis on the comparison of the two management scenarios.
We have revised the original manuscript submitted to Hydrology and Earth System Sciences, and we do hope that the new version addressed the majority of the reviewers' concerns. For reference, we have included line numbers relevant to the manuscript without tracked changes.

Reviewer 1

Review by Andrew J. Guswa, Smith College, aguswa@smith.edu

This editorial, which grew out of discussions at the 8th Galileo Conference held in Napoli, Italy in June 2023, raises the question of how funding and resources for hydrological observatories could best be deployed, considering two scenarios: 1) a large number of moderately instrumented sites or 2) a small number of highly instrumented "super sites" (the dynamic-response approach notwithstanding). The question is a provocative and important one. With the current version of the manuscript, I also found myself wishing for more details of the two models, more discussion of the scientific tradeoffs between them, and perhaps considering ideas beyond the two. Additionally, I think it would be interesting and valuable to discuss potential differences in governance structures, data access, and equity issues. To make room for such detail and discussion, I think some of the preamble/motivation could be shortened and one or two of the figures removed/replaced.
REPLY: We would like to thank Ref. #1 (A. Guswa) for reviewing our work. In the following sections, we addressed his concerns and integrated his suggestions where appropriate. In this response, line numbers refer to the manuscript without using tracked changes. We have removed any elements that might have caused confusion and clarified several points.

Specifically, perhaps Figure 1 could be expanded into two – one that presents the instruments and their distribution associated with a site for Scenario 1, and a second figure that presents the vision for a super-site associated with Scenario 2. Would they have the same types of instruments, but with different levels of intensity and resolution? Or would there be additional variables and characteristics measured in the super-sites? Providing more concrete detail – even if purely hypothetical – will help the reader better understand the two models and the differences between them.
REPLY: Before illustrating the main differences between the two management scenarios, a hydrological observatory is defined as the cyber-physical infrastructure established within a catchment to monitor the hydrological variables and fluxes and to characterize the hydrological behavior of the 3D 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 concentrates on a cluster of representative sub-catchments (spatial resolution of hectares) which are representative of land use,

geomorphology, topography, and pedology similarities (Bogena et al., 2006). Therefore, the selected sub-catchments are equipped with wireless sensor networks for continuous data collection and subjected to different field campaigns depending on budget constraints.
As described in the original manuscript (Section 4), we have assumed that a fixed community budget has been allocated for the establishment and operation of a hypothetical network of HOs in the European Union (EU). Figure R1 shows an example of a moderately-instrumented site belonging to a hydrological observatory network in Scenario 1. This plan reflects the current situation at most HO networks around the world. S1 offers the clear advantage of widely distributed HOs across each continent, enabling cross-site synthesis of the lumped hydrological response (e.g., rainfall-runoff relationship, Budyko analysis) across diverse continental landscapes.

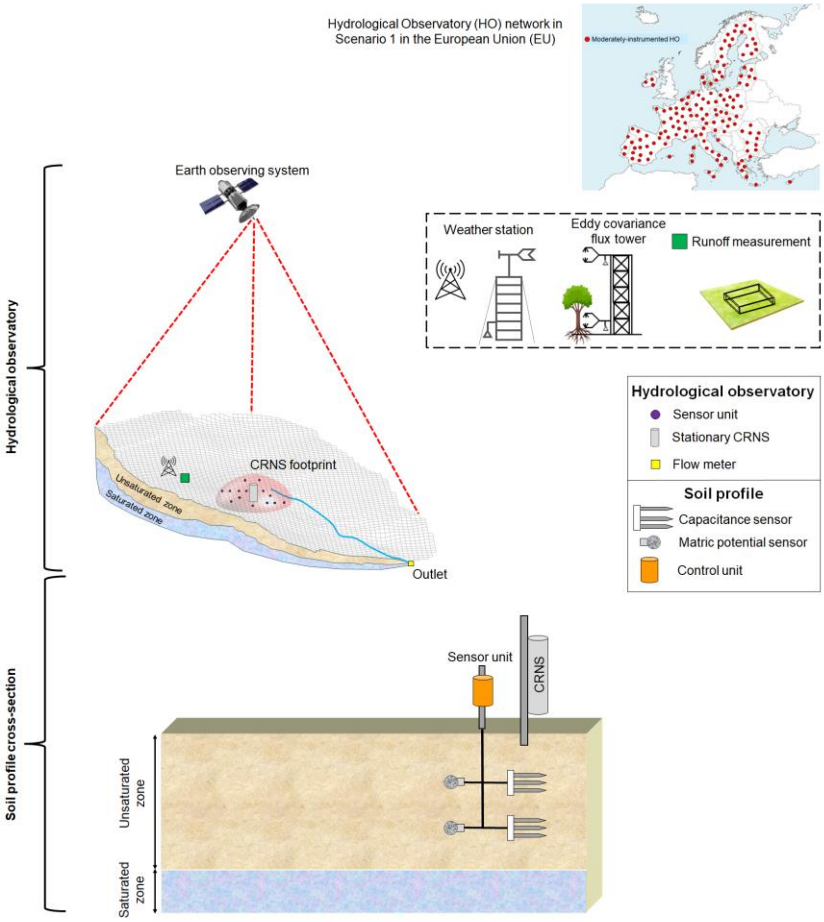

Figure R1. Graphical illustration of a hydrological observatory (HO) network in the European Union (EU) in Scenario 1. Each sub-catchment is equipped with basic instrumentation: a weather station, a runoff gauging station, a Cosmic-Ray Neutron Sensor (CRNS) with a wireless sensor network controlling 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.

Figure R2 delineates a hypothetical super-site established along an ideal transect in the European Union (Scenario 2). Each super-site should have a high-density network of sampling and monitoring units for soil hydrology research. 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 in 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 modulated by scale-dependent feedback and multiscale spatio-temporal heterogeneity.

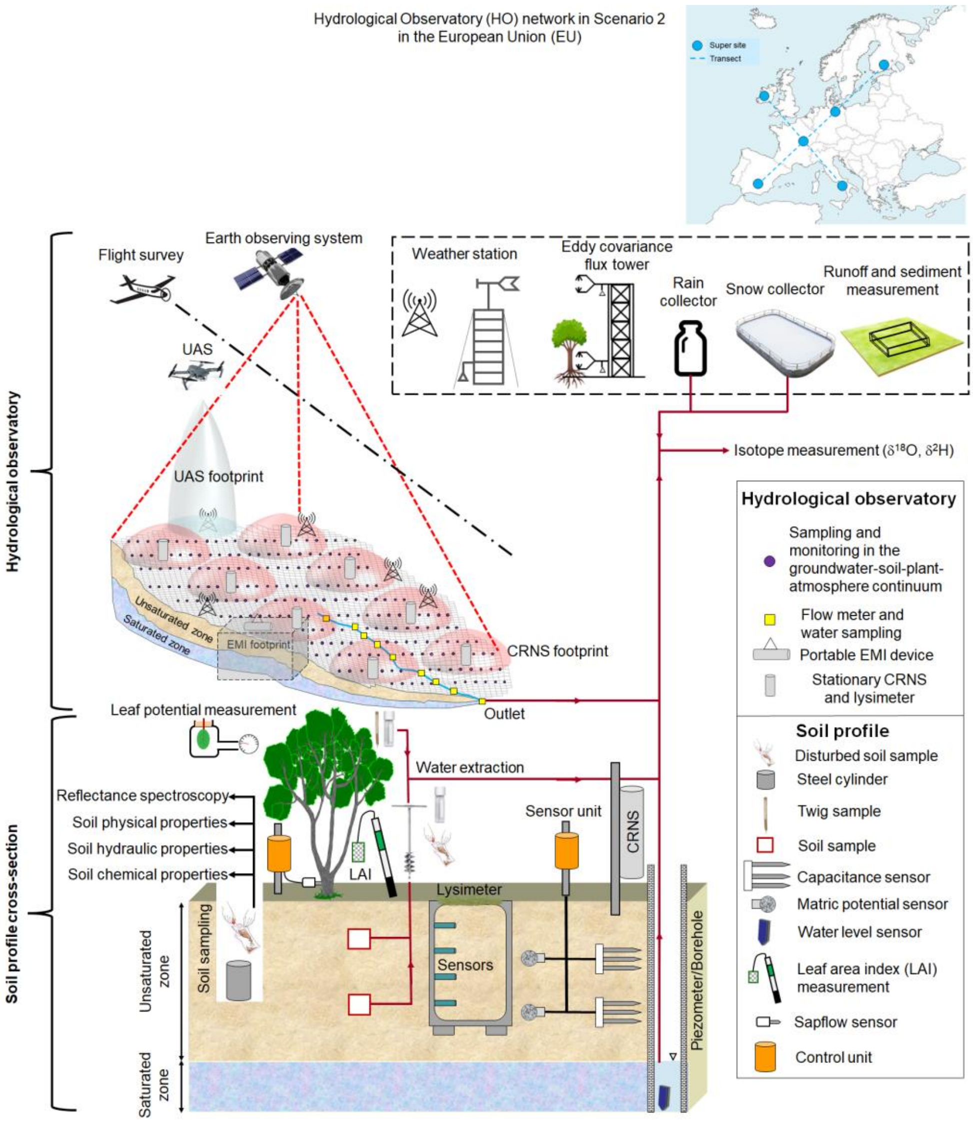

Figure R2. Graphical illustration of a hydrological observatory (HO) network in the European Union (EU) in Scenario 2. Each sub-catchment established along an ideal transect is equipped with high-density network of sampling and monitoring units for soil hydrology research. Frequent unmanned aerial system (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).

We thoroughly revised Section 4 by following this suggestion.

Then, given those differences, which of the UPH would be more amenable to Scenario 1 versus Scenario 2? The Appendix provides a list of important and intriguing questions – which would be better addressed by which Scenario? The manuscript already calls out differences in representativeness: e.g., Scenario 1 can cover more of "existing gradients of geology, climate, and land-use," whereas Scenario 2 would achieve "high spatial and temporal resolutions." More directly connecting these differences to the important questions would be a valuable enhancement to the paper.

REPLY: In our view, all of the UPH mentioned below (and many others) are susceptible to both scenarios, which are not mutually exclusive but rather mutually reinforcing concepts. For example, detailed investigations necessitating unparalleled instrumentation in S2, would facilitate the transfer of acquired knowledge to other biogeographical regions in S1. We aim to clarify this point in the revised article.
To reply to this reviewer, we grouped the UPH according to the associated Scenario:

	Questions in Scenario 1
1	How can we improve the quantity and quality of measurements in data-poor regions?
2	Where and how can the sensors be allocated to get full information without wasting excessive effort?
3	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?
4	What role(s) do continuous and ephemeral water bodies, including ponds, lakes, rivers, streams, marshes, swamps, etc. influencing watershed water quantity and quality?
	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 various multi-scale observations be assimilated into a hydrologic model to enhance model predictability?
4	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?
5	How is the water cycle influenced by the other cycles (carbon, nitrogen, etc.)?
6	How can the dynamics and feedback at groundwater-soil, groundwater-surface water, soil-plant, soil-atmosphere, and plant-atmosphere interfaces be assessed?
7	How do we include plant physiological aspects in hydrological models?
	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 suitable 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, reaction 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 structural/parameter/input uncertainty in hydrological prediction?
6	Is it better to give more importance to uncertainty or causality?
7	What is the role of vegetation in the catchment?
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 considering anthropogenic disturbances in the ecosystem?

We highlight the predominant number of UPH valid for both scenarios.

Additionally, I found myself wondering about the associated tradeoffs in governance, equity, site access, and data availability between the two scenarios. Perhaps this is not the place for such discussions; nevertheless, if possible, I think a modest discussion of those issues would be interesting and useful. What processes could/would be put in place to encourage participation from a broad range of stakeholders from the hydrologic community, particularly for Scenario 2?

REPLY: Thank you for this valuable comment. In the revised version, Section 4 has been expanded to include a more detailed discussion of the trade-offs between the two scenarios in terms of governance, site access, and equity.

Scenario 1 (S1): S1 relies on a combination of centralized and distributed components. Distributed components provide observed data managed by different entities (e.g., universities, research institutions, government agencies, etc.) across geographically spread sites. To ensure data comparability, it is essential to implement standardized protocols for data collection, storage, quality assurance and analysis. This will mitigate the burden of the cross-site synthesis. Centralized data management facilitates the accessibility of data across multiple sites. In addition, additional central thematic elements can be provided, such as those pertaining to communication and knowledge transfer, or those relevant to modeling applications. The organizational structure can be based on other successfully established or planned distributed continental infrastructures. Notable examples include ICOS (Integrated Carbon Observation System) or 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. Collaboration and partnership among different stakeholders are crucial in S1 that might provide broader opportunities for citizen and stakeholder participation, particularly given the distributed nature of the scenario and the encouragement of local initiatives.

Scenario 2 (S2): A few super-sites would require a central governing body that would likely be 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 with substantial resources.
The establishment of a single entity, operating as a central authority, would facilitate a more streamlined decision-making process regarding instrument upgrades, research focus, and site and data access.
Super-sites equipped with advanced instrumentation might attract highly specialized researchers, leading to a concentration of knowledge and experience in specific hydrological domains. The implementation of standardized sensors would result in cost savings and improved efficiency in data collection and processing. In contrast, different hydrological environments may require specialized instrumentation or measurement techniques. A lack of flexibility in standardization may impede the ability to adapt to new research questions or emerging challenges. Examples of standardization efforts include the Global Network of River Observatories (GLORIA; https://www.gloria.ac.at) and the World Meteorological Organization (WMO; https://community.wmo.int/en) guidelines for hydrological stations. By carefully considering these factors and adopting a balanced approach, hydrological observatories can harness the benefits of standardization while maintaining flexibility and adaptability. To ensure equity and encourage greater participation in S2, it is essential to establish a collaborative governance structure that incorporates a diverse range of stakeholders in decision-making processes related 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 georesources, and environmental change (https://www.icdp-online.org/about-icdp/entities/). Another relevant 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 employed for studies related to oceanography, meteorology, and geophysics (https://www.awi.de/en/expedition/observatories.html).

Relatedly, while the authors position their two scenarios as end-members, I could imagine a scenario further in the direction of Scenario 1 (perhaps Scenario 0), in which instrumentation is deployed in a purely opportunistic way, taking advantage of construction projects associated with infrastructure upgrades. For example, one could imagine a policy that stipulates that any time a culvert is rebuilt or rehabilitated (e.g., in response to increasing storm intensity), a suite of monitoring instruments must also be installed. This would significantly reduce the upfront costs associated with hydrologic observation. The locations of such added monitoring would be far from planful, but there might be advantages in the sheer number of sites,

and ongoing advances in data handling/storage and machine-learning and data-science tools could facilitate new insights.
REPLY: We agree that by leveraging infrastructure upgrades for hydrological monitoring offers great opportunities to significantly reduce initial costs compared to the construction of new observation sites from scratch. Nevertheless, the opportunistic approach is applicable to all scenarios.

To make space for those expanded discussions, I think either Figure 2 or Figure 3 could be removed. Those schematics are nice, but perhaps are not necessary for communicating the central ideas of the paper (vs. the Graphical Abstract, which really presents the Scenarios in a compelling way).
REPLY: We concur with this comment and decided to remove the first two figures while expanding the discussion in the last part. Here, we added the new figures presented in the reply letter (R1 and R2 in this reply letter). The new figures illustrate a hypothetical super-site in comparison to a moderate site.

In summary, I appreciate the editorial as a provocation for the hydrologic community to consider and discuss the vision for hydrologic observations. I recommend expanding the comparison of the two scenarios to help the reader better understand the tradeoffs between them.
REPLY: We concur with this assessment and will therefore shorten the initial section as much as possible while expanding the discussion on the trade-offs, including the issues of governance, site access, and equity.