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 2

The paper is overall a useful contribution and well written. I hope that my comments below will improve its impact to the larger hydrologic community. I have blended below both higher level comments (approach for have more impact for the international community) and more specific for improving logic. I have no problem with its publication but I am also not impressed with the message it tries to send to the community and what it can accomplish to improve a vision for HOs. Also, its focus on the "UPH" limits its reach and the community that would buy into it, while a more high-level approach of basically understanding complex hydrologic processes to improve modeling and prediction that will allow us to address pressing water related problems… will reach a larger audience and sponsors.
REPLY: We would like to thank this reviewer for reviewing our work. We concur that improving hydrological modeling within a hydrological observatory is crucial for a more comprehensive understanding, prediction, and management of water resources. Data collection is the key component to perform reliable modeling simulations of water balance, solute and heat, transport, and soil erosion. The use of sensors with greater density and data interpolation helps capture a diverse range of hydrological processes. It is also crucial to include human impacts on model simulations, such as land-use change, water resources management practices, and the impacts of global warming on the hydrological systems. Nevertheless, the initial step is to formulate a new UPH, as previously discussed at the beginning of Section 3. The new UPH will dictate the HO functioning and model implementation/refinement.
The following sections address Ref.#2 concerns and integrate the relevant suggestions where appropriate. In this response, line numbers are referenced to the manuscript without the use of tracked changes. Any elements that might have caused confusion have been removed, and several points have been clarified.

1. Line 36 -- "Nevertheless we are still a long way from being able to solve the mysteries of hydrologic processes…" – the mysteries of many scientific problems are never completely solved. I would present this differently such as " Yet, solving important water resources problems requires a deep understanding of the complex hydrologic processes which require long records of observations over diverse environments etc.…"
REPLY: To avoid repetitions, the first part of the abstract was reformulated in a manner that partially accommodated this suggestion. In lines 33-40 we wrote: "*The Unsolved Problems in Hydrology (UPH) initiative has emphasized the need of establishing networks of multi-decadal hydrological observatories to gain a comprehensive understanding of the complex hydrologic processes occurring in diverse environments. The already existing monitoring infrastructures have provided an enormous amount of*

hydrometeorological data, facilitating detailed insights into the causality of hydrological processes, the testing of scientific theories and hypotheses, and the development of physical laws governing catchment behavior. Yet, 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."

2.Line 46 – "help address UPH about the impact of climate and social systems…" –First, is this the only UPH to address from the whole list of UPH? Second, I would present this need here in a more general setting. Recall that one does not even know the long list of UPH and if this is an international effort it has to be presented from an even larger perspective …
REPLY: We agree and, as a result, this part has been reformulated by accommodating this suggestion. In lines 45-48 we report: "*A network of moderately instrumented monitoring sites would provide a broad spatial coverage across the major pedoclimatic regions by supporting cross-site synthesis of the lumped hydrological response (e.g., 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*."

3.Fig 1 is ok but again, cross site synthesis is not the key to many problems but depends on the problem to be addressed… as also articulated later in the paper for ocean missions etc.
REPLY: We decided to remove this figure and the corresponding text as suggested by the first reviewer. We prefer to give more emphasis to the last part in which we compare two different scenarios.

4.Line 82 – I would strongly suggest that the title of this section is changed to something like "The need for HOs to advance scientific understanding of hydrologic processes " instead of "How to address the UPH" for which probably not everyone agree or might have a different problem not included in that list!
REPLY: We agree with this comment and modified the title:
"*How do we advance scientific understanding of hydrological processes?*"

5.Line 89 – "the extent that anthropogenic stressors influence the hydrologic cycle is not yet fully understood…" – I would argue that if we know the stressor then we can address the forward problem of translating it to an outcome or impact, but the challenge is when we do not know what actions will affect what and how, and we need basic understanding to guide decisions and management for guiding the future of water…
REPLY: We reformulated this sentence by including the suggested comment. The new sentence in lines 88-89 is:
"*However, the extent to which anthropogenic stressors influence the hydrologic cycle remains unclear, and the effectiveness of adaption actions to guide water resources managers has not been fully evaluated.*"

6.Line 95 – HOS are not always long-term sites
REPLY: We removed "long-term" to avoid confusion

7.Lines 98-99 – stretching it by much here. If this is to have an international and broad audience, this has to be seen from a higher level. CZOs, NEON etc had nothing to do with the UPH, as an example… -- check their vision when established
REPLY: We understand that the majority of currently operational observatories worldwide are guided by interdisciplinary research goals that extend beyond the scope of UPH. Such observatories are, in fact, defined as terrestrial observatories. In this opinion paper, however, we will limit our discussion only to the hydrological aspects. The proposed hydrological observatories can be part of comprehensive terrestrial observatories, such as eLTER. We integrated the text in lines 209-215 to accommodate this suggestion: "*To address these issues, scientists have proposed initiatives to sustain long-term operation, harmonize, and standardize both hydrometeorological data and eco-hydrological models in HO networks (Zoback 2001; Reid et al., 2010; Kulmala, 2018). In many cases, hydrological observations are now integrated into interdisciplinary research programs within terrestrial observatories, which are scientific facilities designed to observe and study a range of aspects related to the Earth's surface, atmosphere, and interior. Terrestrial observatories collect data on various 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." Indeed, in lines 215-226 we mention some examples of hydrological and terrestrial observatory networks. Hydrological observations play a crucial role in terrestrial observatories.

8.Lines 104 – check history papers for some early observatories of Horton (Beven special IAHS volume)
REPLY: We found the following reference:

Beven, K. J. (2006), Streamflow Generation Processes, 431 pp., IAHS Press, Wallingford, U. K.

However, adding historical papers is not necessary as some important very early papers have already been cited.

9.Line 109 – evidence for this exponential growth?
REPLY: To avoid confusion, we reformulated this sentence: "*The number of HOs has increased since the 1950s by setting many HOs across the globe*" (line 106)

10.Lines 121-122 – will benefit from some editing
REPLY: We reformulated this part: "*The selection of sensors is crucial for the effective collection of hydrometeorological data within a hydrological observatory*." (line 126-127)

11.Line 124 – we are beyond this and LiDAR can help with determining surface flow paths etc with a lot of developments over the past decade
REPLY: We agree with this comment, indeed we mentioned the use of LIDAR snow depth surveys in line 125 of the original manuscript.

12.Lines 151 on – RS observations are not only to upscale or downscale ground observations but to provide data for larger areas extents and different environments, and the limited ground observations play a fundamental role in that
REPLY: We agree with this comment and we expanded the original sentence: "*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) provide valuable supplementary information to ground-based observation in HOs. This information can be used for obtaining data over large, heterogenous areas, and for upscaling or downscaling hydrological variables (e.g., McCabe et al., 2017; Manfreda et al., 2018, 2024; Su et al., 2020).*" (lines 157-161)

13.Line 166 – some discontinuity in arguments and logic here
REPLY: The text referred to Fig. 1 (lines 166-169 in the original manuscript) and Fig. 1 were removed by following both reviewers' suggestions

14.Fig 1 is ok but not too telling
REPLY: Fig. 1 was removed by following both reviewers' suggestions

15.Line 185 – only SMAP? Precipitation is the most important input to the hydrologic cycle and some reference to GPM, IMERG etc should be given, probably also highlighting the successful international cooperation of NASA, JAXA and ESA…
REPLY: This section is not about the use of remote sensing products, but about data assimilation in general. The focus of this paper should be on the HO instrumentation with in-situ sensor technology and an exhaustive listing of the numerous remote sensing products is not within the scope of this paper. In any case we reformulated the entire part (lines 175-189): "*While observations are the backbone of progress in hydrological understanding (Sivapalan and Blöschl, 2017), models are equally vital 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). However, hydrological models, particularly complex ones, often rely on lumped parameter calibration. This means that model parameters are adjusted based on aggregated (or lumped) fluxes, such as streamflow measurements at the catchment's outlet. While this approach can be effective, it can also lead to limitations. One 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 varying topography, land use, and soil types. In such cases, relying solely on lumped fluxes can result in suboptimal model performance. An integrated observation approach enables the calibration based on insightful analysis of process complexity through systematic learning from distributed hydrometeorological data given that catchments are complex systems with structured heterogeneity that give rise to non-linear interactions and feedback between the component processes (Vereecken et al., 2015; Li et al., 2022). One way of model-observation 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)."

16.Fig 2 – UPH is everywhere and distractive. This is not the mission here but process understanding in general. The figure says …"Where the UPH addressed?" No or yes, and depending on the answer we follow a path of "refine approach" or "Hydrological understanding" … First, fundamental questions change and a long-term vision from HOs should not be tied to a limited concept of questions not everyone probably has seen or agrees with…
REPLY: In accordance to Reviewer#1's suggestion we removed also Fig. 2. We agree that the design of the HO should not be tied solely to the UPH, but to fundamental hydrological processes. Nevertheless, we believe that the appropriate selection of UPH can support the design of HO. The key factors underlying the planning of HOs are:

1. Research objectives: What specific hydrological processes are you interested in?
2. Spatial and temporal scales: What is the desired resolution of your data?
3. Budget constraints: What is the available funding for sensor acquisition and maintenance?
4. Data management capabilities: How will you handle the volume of data generated?
5. Sensor reliability and accuracy: What level of precision is required?
6. Model selection: What kind of eco-hydrological model are you going to use?

We will make this clearer in the revised version.

17.Line 245 – yes! "Formulate scientifically interesting questions …" not follow "prescribed questions…"
REPLY: We modified the second section, and we kept in mind all previous suggestions provided by this Reviewer.

18.Fig 3 is ok but not impressive
REPLY: We prefer to keep it to help understand the steps of cross-site synthesis

19.Line 276 – It depends on so many other variables so it is hard to throw this statement as a contradiction …
REPLY: We wanted to report some examples of cross-site synthesis. Sometimes the site comparisons lead to conflicting hypotheses and theories that certainly depend on many factors (some of them though remain still unknown or unexplored)

20.Line 278 – "observed phenomena" – which phenomena?
REPLY: We reformulated this sentence as: "*Two distinct theoretical frameworks have been put forth to explain the above mentioned conflicting results (Ellison et al., 2012).*" (lines 277-278)

21.Line 312- 316 –Yes, these observatories were designed for specific scientific questions not for "UPH" -- resonates much more with the community at large.
REPLY: OK

22.Line 317 – In analogy with the above questions, what would be examples of questions to be addressed by these sites?
REPLY: Please refer to the reply given to Reviewr#1. We added a new Table by grouping the UPH according to each management scenario in the Appendix.

23.Line 324 – Yes I agree with this. This contradicts the whole framing of the paper focused on "the UPH"! Also, the arguments in Lines 335-on defeat the arguments on the starting point of this paper.
REPLY: We tried to follow this suggestion throughout the manuscript. Thank you for pointing it out.

24.Line 374 – Yes but as argued above deep observations in one site can significantly knowledge our knowledge in important problems. Some examples as from the CZOs. So there are some contradicting staments here referring to a "global network" etc. Please check.
REPLY: We considered this suggestion to modify some parts of the manuscript

25.Line 393 – 399 -- "We envision a hybrid approach …" Yes, ok but how? This is the question and the end of the paper kind of fails to have a "call to action" and inspire a movement. It is a difficult problem of course but the paper left me at the end with no recommended approach …
REPLY: The main target of this opinion paper is to raise critical discussion on the management of HOs. It is beyond the scope of this opinion paper to provide a manifesto on how to plan and run a hypothesized "hybrid" management approach. This process would require a focused report by inviting stakeholders, research institution, governmental actors, etc.

REFERENCES

Bogena, H., Schulz, K., and Vereecken, H.: Towards a network of observatories in terrestrial environmental research, Adv. Geosci., 9, 109–114, https://doi.org/10.5194/adgeo-9-109-2006, 2006.