A Hydrologist's Guide to Open Science

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Abstract

Hydrologic research that is open, accessible, reusable, and reproducible will have the largest impact on the scientific community and broader society. While more and more members of the hydrology community and key hydrology organizations are embracing open science practices, technical (e.g., limited coding experience), resource (e.g., open access fees), and social (e.g., fear of being scooped) challenges remain. Furthermore, there are a growing number of constantly evolving open science tools, resources, and initiatives that can seem overwhelming. These challenges and the ever-evolving nature of the open science landscape may seem insurmountable for hydrologists interested in pursuing open science. Therefore, we propose general Open Hydrology Principles to guide individual and community progress toward open science. To increase accessibility and make the Open Hydrology Principles more tangible and actionable, we also include the Open Hydrology Practical Guide. We aim to inform and empower hydrologists as they transition to open, accessible, reusable, and reproducible research. We discuss the benefits as well as common challenges of open science and how hydrologists can overcome them. The Open Hydrology Principles, Practical Guide, and additional resources reflect our knowledge of the current state of open hydrology; we recognize that recommendations and suggestions will evolve and expand with emerging open science infrastructures, workflows, and research experiences. Therefore, we encourage hydrologists all over the globe to join in and help advance open science by contributing to the living version of this document and by sharing open hydrology resources in the community-supported repository (https://open-hydrology.github.io).

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1. Motivation for Open Hydrology

The geosciences, including the field of hydrology, have experienced a considerable increase in the number and size of research outputs, such as datasets and publications (Addor et al., 2020, Arsenault et al., 2020; Chagas et al., 2020, HiHydroSoil, n.d., Linke et al., 2019, Olarinoye et al., 2020). Hydrologic research intersects various Earth science (e.g., climatology, meteorology, biogeochemistry, geology, soil science, ecology) and social science (e.g., policy and public health) disciplines to tackle environmental and other societal challenges. Additionally, hydrologic research often incorporates qualitative and quantitative data from numerical models, laboratory techniques, field observations, and stakeholder surveys, which rely on separate sets of assumptions and methods. When combined, the interdisciplinary nature and wide range of methods used in hydrology can result in research that is not accessible and usable by members of the science community and relevant stakeholders. A recent study found that only 1% of hydrology papers were fully reproducible (Stagge et al., 2019). Therefore, hydrologists must evolve to ensure their research is transparent and reproducible because doing so will strengthen their contribution to hydrologic research practices, resources, knowledge base, applications, and societal engagement and trust (Cudennec et al., 2020).

Open science offers an established framework for hydrologists who are interested in improving the transparency and reproducibility of their research. Open science is a movement where all aspects of scientific work are purposefully documented and shared widely on (web) platforms that are accessible to scientists and the general public (Section 2). Open science is transforming the very nature of research design and conduct. Researchers across disciplines, regions, institutes, and governmental agencies have called for open science and open data policies and see open as a path to prosperity (e.g., Baker et al., 2020; Jeppesen, 2020; *UNESCO*, 2021;

WMO Data Conference, 2021; COPDESS; European Commission). In many scientific disciplines, community-driven research papers have cemented the demand and necessity for open science (Armeni et al., 2020; Beck et al., 2020; Blumenthal et al., 2014; de Vos et al., 2020; Ferrari et al., 2018; Hampton et al., 2015; Mwelwa et al., 2020; Onie, 2020; Powers & Hampton, 2019; Tai & Robinson, 2018; Zuiderwijk & Hinnant, 2019), research projects (e.g. Beck et al., 2020; Lowndes et al., 2017), and conferences (e.g., (*About* FOSTER, 2021; *About* ORION, 2017; OPEN SCIENCE FAIR, 2021; Mavrantoni, 2021). Likewise, many organizations have begun to provide support to overcome challenges to research sharing, access, reproducibility (Baker et al., 2020).

In hydrology, open science is becoming an important aspect of day-to-day research. There is growing momentum around public accessibility of hydrologic datasets (Pecora & Lins, 2020; *WMO Data Conference*, 2021; *World Hydrological Cycle Observing System*, n.d.) and calls for open research data (Addor et al., 2020; Cudennec et al., 2020; Lindersson et al., 2020; Zipper et al., 2019), research processes and approaches (Choi et al., 2021; Stagge et al., 2019; Wagener et al., 2020), and publication sharing (Blöschl et al., 2014; Rosenberg et al., 2019; Quinn et al., 2020). Conference sessions and online repositories dedicated to open science initiatives in hydrology have been introduced to support the transition to open science. Several hydrology journals now require data and analyses to be made publicly available upon article publication (e.g., Rosenberg and Watkins, 2018; AGU, 2019). Table 1 provides a summary of hydrology-focused efforts (e.g., academic articles, GitHub pages, web platforms, etc.) that discuss and support open science. At a first glance, it is clear that open science has achieved high interest among hydrologists during the last decade. On the other hand, there is little mention of open science in recent influential hydrology papers. For example, a recent publication outlining important future goals for sociohydrology does not discuss openness (Di Baldassarre et al., 2019), despite the direct relevance of this sub-discipline's findings for pressing water resources issues that are impacting communities. The same concerns apply to the recent work on empowering citizen science (Nardi et al., 2020; Pelacho et al., 2021). Also, open science is mentioned only briefly, in recent high-profile articles on the history and evolution of hydrology (Peters-Lidard et al., 2018; Sivapalan, 2018) and articles on addressing unsolved problems in hydrology (Blöschl et al., 2019). In short, despite these general calls and efforts for open science, practical guidance for the steps hydrologists can take to incorporate open principles in their research is lacking.

Table 1. A selection of efforts that discuss and support openness in hydrology and related sub-disciplines (*peer-reviewed article, **community contribution).

Theme	**Reference**	Title
General	Hampton et al. (2015)	The Tao of open science for ecology*
	Tai & Robinson, 2018	Enhancing Climate Change Research With Open Science*
	de Vos et al., 2020	Open weather and climate science in the digital era*
	Turner et al., 2020	Cracking “Open” Technology in Ecohydrology*
	Beck et al., 2020	The importance of open science for biological assessment of aquatic environments*
	https://open-hydrology.github.io/	Open Hydrology Website (established with this manuscript)
	https://www.hydroshare.org/	HydroShare is CUAHSI's online collaboration environment for sharing data, models, and code.
Open Publishing	Blöschl et al., 2014	Joint Editorial—On the future of journal publications in hydrology*
	Hughes et al., 2014	Improving the visibility of hydrological sciences from developing countries*
	Stagge et al., 2019	Assessing data availability and research reproducibility in hydrology and water resources*
	Quinn et al., 2020	Invigorating Hydrological Research Through Journal Publications*
	Hutton et al., 2016	Most computational hydrology is not reproducible, so is it really science?*

Open Source and Reproducibility	Borregaard & Hart, 2016	Towards a more reproducible ecology*
	Mislan et al., 2016	Elevating The Status of Code in Ecology*
	Melsen et al., 2017	Comment on “Most computational hydrology is not reproducible, so is it really science?”
	Slater et al., 2019	Using R in hydrology: a review of recent developments and future directions*
	Enemark et al., 2019	Hydrogeological conceptual model building and testing: A review*
	Powers and Hampton, 2019	Open science, reproducibility, and transparency in ecology*
	Wagener et al., 2020	On doing large-scale hydrology with Lions: Realising the value of perceptual models and knowledge accumulation**
	Añel et al., 2021	Current status on the need for improved accessibility to climate models code*
	https://github.com/hydrosoc	Created for EGU GA short course “Using R in Hydrology”**
	https://github.com/Open-Environmental-Science/awesome-open-hydrology	“a specific list of open hydrology-relevant projects. This list is curated from repositories that make our lives as (eco-)hydrologists easier.”**
	https://github.com/ropensci/hydrology	Hydrological Data and Modeling in R. This initiative was built on the EGU GA short course “Using R in Hydrology”**
Open Data	Reichman et al., 2011	Challenges and Opportunities of Open Data in Ecology*
	Michener, 2015	Ecological data sharing*
	Cudennec et al., 2020	Editorial – Towards FAIR and SQUARE hydrological data*
	Addor et al., 2020	Large-sample hydrology: recent progress, guidelines for new datasets and grand challenges
	Crochemore et al., 2020	Lessons learnt from checking the quality of openly accessible river flow data worldwide*
Open Education	CUAHSI	Educational Resources for Hydrology & Water Resources**
	Tom Gleeson (2020)	A buffet of new resources for teaching hydrology and water resources!**

	Anne van Loon (2020)	Online teaching in courses related to climate risk, drought, water resources and sustainability**
	Matthias Sprenger (2020)	When the students are gone: Transition to online teaching**
	Bettina Schaefli (2021)	Open teaching to navigate hydrology: how ready are we?**
Data Exchange	Viglione et al., 2010	Barriers to the exchange of hydrometeorological data in Europe: Results from a survey and implications for data policy*
	Zipper et al., 2019	Balancing Open Science and Data Privacy in the Water Sciences*
	Dixon et al., 2020	Intergovernmental cooperation for hydrometry – what, why and how?*
	Pecora & Lins, 2020	E-monitoring the nature of water*
	Mukuyu et al., 2020	The devil's in the details: data exchange in transboundary waters*
	WMO Workshop	"Hydrological data and WMO Data Policy", in November 2020, as part of the WMO Data Conference**

Given the limited adoption of open science in hydrology, the objective of this paper is to introduce the Open Hydrology Principles and Open Hydrology Practical Guide to help hydrologists take actionable steps towards open science. We focus on four major research stages: (1) research process and approach, (2) data collection and analysis, (3) software development and use, and (4) open science publishing. For each of these research stages, we discuss guiding principles for meaningful engagement in open science, practical steps to answer "How to engage in and further research openness?", and potential challenges to talk through the "What if…?" questions hydrologists might ask when pursuing open science. This manuscript focuses on the field of hydrology and draws on existing open science research, efforts, and experiences in other disciplines that have made significant progress toward open science. We approach open science as hydrologists from diverse career stages, sub-disciplines, and geographic backgrounds, who conduct hydrologic research in the field, laboratory, and on the computer. Our experience in doing open science is also broad, from beginners with a general interest in practicing open science to experts using open science principles in our day-to-day research. We are brought together by our shared motivation to improve science accessibility for all—from students and scientists to the general public, including policymakers.

The Open Hydrology Principles and Open Hydrology Practical Guide introduced here are available online at open-hydrology.github.io. This website provides a platform to facilitate continued discussion and evolution of open hydrology presented in this manuscript (i.e., serve as a living document), highlight emerging open hydrology resources, and connect open hydrologists. We invite everyone to contribute to the discussion, share resources and experiences, and formally endorse their commitment to the Open Hydrology Principles on the website; thereby indicating they will work towards incorporating open science principles in all stages of their hydrology research.

2. Open Hydrology Principles & Practical Guide

Open hydrologists can use the Open Hydrology Principles and Open Hydrology Practical Guide to expand their open hydrology practice, including those who are beginning their journey to those who are more experienced. Adoption of these open hydrology principles is not restricted to the design stage or the final stage of research; open hydrology practices can and should be implemented throughout a research project's timeline. Transitioning to fully open hydrology research will likely remain a work in progress. We recognize that a shift to open hydrology will not happen overnight. Hydrologists will need to work within current logistical, legal, financial, cultural, and other constraints of the field and connected social, economic, and political entities (e.g., governmental funding sources). In this section, we outline four guiding principles corresponding to four major research stages and explain why each is particularly important in hydrology, illustrated in Figure 1. Each guiding principle is followed by a practical guide to help hydrologists apply these principles.

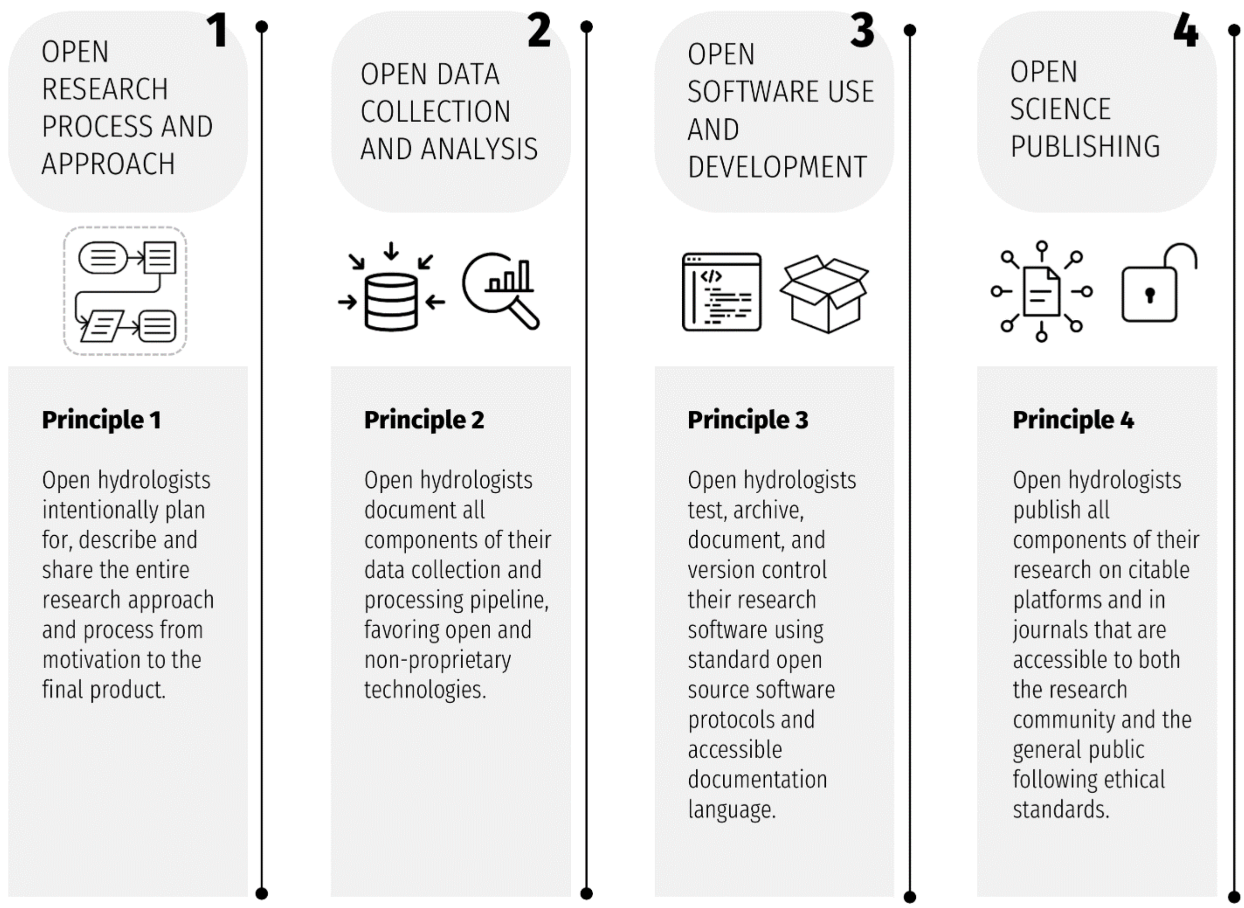

Figure 1. The Open Hydrology Principles

Principle 1 - Open Research Process and Approach: ***Open hydrologists intentionally plan for, describe, and share the entire research process and approach from motivation to the final product.***

Research process and approach includes everything from the original study motivation and research proposal to the final results. All parts of the research process should be shared openly on platforms that foster open science. This includes openly discussing stakeholder engagement practices, stakeholder-researcher agreements, failed methods, negative results, use of public datasets, and feedback from third parties. Sharing the entire research approach and process is important in hydrology because not including all aspects of research may result in the loss of critical information and lessons learned, which may not be fully captured in journal articles. Openly sharing a well-documented research process and approach will improve the efficacy of internal research and give critical insight to future researchers. Furthermore, sharing the entire research process and approach is critical for the field of hydrology because research applications directly impact society (e.g., water management, climate model simulations). Thus, open hydrologists must ensure their research is accessible to the science community and the general public while adhering to ethical standards and respecting the goals and wishes of their collaborators. Open hydrologists must make plans for practicing open science as early in the research process as they can. Whenever possible, non-proprietary methods, tools, and resources must be prioritized.

Practical Guide to Open Research Process and Approach

In hydrology, published studies that allow the reader to follow every step of the work, from motivation to publication, remain scarce. Although results are the main focus of a paper, sharing the entire research process and approach (e.g., failed attempts and lessons learned that impacted research outcomes) alongside the paper can improve the impact and openness of research (Lowndes et al., 2017; Colavizza et al., 2020). To ensure the entire research process and approach is openly shared, we suggest including a reasonable explanation of why certain data and methods were chosen and how they were used in the main text of journal articles or an appendix. When in doubt, strive to explain the research process and approach using accessible language to maximize openness. Open hydrologists can do this by minimizing the use of jargon in all materials to enable experts and non-experts alike to reproduce and understand the research and underlying assumptions. Several tools and examples for accessible language have been developed and are free to use. For example, words common in hydrology like ‘dam’ and ‘flood’ can have different meanings between experts and non-experts (Venhuizen et al., 2019).

Recent hydrologic studies highlighting the importance of describing perceptual models underlying research approaches (Enemark et al., 2019; Wagener et al., 2020) provide a framework for how hydrologists can incorporate open science into their research approach and process. Perceptual models represent process understanding and project stages visually and will vary by researcher and information and resource availability. Perceptual models help researchers describe and decide which methods (e.g., sampling protocols or model structure and parameters) are most appropriate to address the study objective. Similar methods can be applied to different hydrologic applications (e.g., describing how qualitative and quantitative data were used to drive methods and inform results). This description should be accessible to non-experts and include an in-depth description and/or visualization of the current system knowledge, known as a *perceptual model* (Wagener et al., 2020) also known as a workflow model, a description of any underlying assumptions, and an explanation for the choice of field-, lab-, or computer-based methods. By including properly described perceptual models, researchers can communicate differences in the interpretation and understanding of hydrologic processes while identifying dominant hydrologic processes across scales and experiment types (e.g., integrated data, numerical modeling, and physical experiments), explicit handling of uncertainties and failures during the research process, and provide a coherent picture of the entire research (van Emmerik et al., 2018; Wagener et al., 2020). From an open science perspective, perceptual models help communicate research approaches to others by outlining how information is used.

Given the important societal and policy implications of hydrologic research, it is important for open hydrologists to have honest conversations with collaborators about openness as early as possible and then take action to respect the needs and wishes of these collaborators. A global survey found that 87% of climate research that engaged Indigenous communities was extractive; communities had minimal participation or decision-making authority in the researcher-stakeholder relationship (David-Chavez and Gavin, 2018). Consequently, it is important for open hydrologists to co-develop data sharing plans, research focus, and research dissemination plans alongside stakeholders as early as possible in the research process. Collaborators may include various stakeholders, be they fellow researchers, industry professionals, non-profit organizations, government officials, communities, members of the public, and other parties that have an interest in hydrologic research. We suggest incorporating FAIR (Wilkinson et al., 2016; Garcia et al., 2020) and CARE (Carroll et al., 2020; Walter et al., 2020) data standards into open hydrology research. FAIR data standards were developed to improve machine readability of data and ultimately increase research reproducibility. CARE data standards were developed by Indigenous scholars to advance data governance and data sovereignty. Setting up guidelines on how open hydrologists will ethically and respectfully engage with relevant stakeholders in their research approach and process is especially important when conducting community or citizen science.

Principle 2 – Open Data: ***Open hydrologists document all components of their data collection and analysis pipeline, favoring open and non-proprietary technologies.***

Hydrologists often combine data from a wide variety of field, laboratory, and computer sources, such as streamflow gauges, remote sensing datasets, digital elevation models, land use maps, and meteorological data, the last of which may be a combination of site-specific measurements and gridded spatial datasets. Data collected in the field is collected manually (e.g., water grab samples) and using sensors either manually (e.g., hand-held soil moisture probe) or stored on loggers whose design and specification can impact the (quality of) collected data. This data quality can only be assessed, and potential results replicated when the hardware design and specifications are available to the public.

Data from the laboratory is often exported in formats that are specific to the laboratory device and typically requires some data wrangling to reformat into outputs that are useful for downstream analyses. The format of computer-generated data (e.g., hydrology model outputs) also varies with the software that generated it. An open data collection and analysis pipeline includes everything from descriptions and versions of the hardware and software used, descriptions of data and database versions used, descriptions of data sharing restrictions (if applicable), metadata (i.e., data about data) for all datasets, copies of original and processed data, descriptions of data wrangling (i.e., filter, selecting, tidying) and analysis techniques and tools, and documentation of the overall analysis process, including assumptions and perceptual models (see Principle 1). Re-usability and transferability of software and data processing pipelines greatly accelerates scientific progress in hydrology, as it reduces time wasted on re-inventing the wheel, and helps discover problems and improve the accuracy of fundamental steps of hydrologic research. Whenever possible, open hydrologists must document and openly share all components of their data collection and analysis pipeline.

Guide to Open Data Collection and Analysis

Open hydrologists always strive to share the source and collection method of all data involved in hydrologic research and cite these data and methods appropriately. This includes data collected in the field, generated in the laboratory and computer, or data from other (online) sources being used as an analysis input. Quantitative and qualitative data are equally important to document and attribute. Numerous venues exist to store and share data while adhering to open science standards. The best place to store data for an open hydrology project depends on the type and size of the data, the specific scientific domain, and other specific requirements stipulated by the funders and stakeholders. A current list of repositories often used by hydrologists is kept on open-hydrology.github.io. If an open hydrology study relies on third-party data that is not (yet) open, either ask the original creators of the data to make it openly available or ask them if a subset of their data can be made openly available. Archived versions (e.g., original, intermediate, and final datasets) of all data used to obtain the results of a particular study are crucial for reproducing open hydrology research. See Principle 4 for more details on publishing data.

To make this less daunting, open hydrologists can start each project by writing a data management plan to emphasize open data principles, while maintaining cyberinfrastructure and community standards. Data management plans may be required by funders and should be developed in the early stages of a research project. These plans describe where data will come from, what formats it will be stored in, who will manage and maintain it, how privacy will be maintained (if applicable), and how data and results will be shared and stored in the short- and long-term. Most funders limit data management plan length to about two pages, but open hydrologists can have an extended data management plan that they share publicly to increase research project transparency. Hydrologists can create their own or use openly available data management plan development tools (e.g., ckan, DMPTool, resources.data.gov) and prioritize openness while adhering to funder requirements and grant formatting. Additionally, some tools (e.g., ckan) can help hydrologists make previously unpublished data openly available, even after publication.

Ideally, open hydrologists explicitly provide public access (e.g., through a link accessible on the journal publication site) to: (1) raw data and associated metadata (including specifications of the devices used to collect data), (2) descriptions and citations to the analysis methods and software versions used, (3) workflow, code/software developed to collect and analyze data, and quality controls used when processing raw data, (4) the final processed data, and (5) descriptive methods to facilitate the integration of data into other processing tools (Das et al., 2017). Always state the reasons and, if possible, explain how readers can access the raw data themselves when raw data cannot be included. The level of detail necessary to ensure openness can differ wildly between studies. When data sources and accessibility are complex (e.g., requiring detailed datasets and processing steps), additional descriptions in an appendix or supplementary information may be appropriate upon publication of the research.

An amazing amount of data goes into each project and it is not always clear what can and cannot be open. This is especially true when considering different types of data (e.g., discrete, metadata, designs, qualitative, quantitative). Ideally, all data used to draw conclusions are published to ensure that open hydrology results are reproducible. If an open hydrologist is using proprietary or data deemed sensitive, discuss, agree, and document what can and cannot be shared with all collaborators as early as possible. If certain datasets cannot be shared openly, add a statement to the final publication explaining what conditions need to be fulfilled for obtaining access to the data and why some data remain private. For example, high-resolution qualitative and quantitative data describing water quality at specific geographic locations may need to be anonymized and blurred spatially before it is shared publicly to reduce unintentional harm. Many countries, locales, organizations, and projects have guidelines on how to anonymize data. Open hydrologists should check for this before developing a data management plan and conducting research. General information is available (Zipper et al., 2019) and all data sharing must adhere to applicable data regulations (e.g., General Data Protection Regulation in the European Union), as well as confidentiality or non-disclosure agreements.

When making data publicly available, open hydrologists strive to store data in universal, non-proprietary, and software agnostic formats that are compatible with most operating systems and include metadata--data about the data that provides background context (e.g., who, what, when, where, why, and how) for each dataset. For example, text and tabulated data are best stored as text (i.e., .txt) and comma-separated variable (i.e., .csv) files instead of proprietary or software-specific types (e.g., Microsoft Word or Excel files). Many proprietary file types require a paid license to use these products while text and comma-separated variable files do not require a license and are more software agnostic. Even if it might be computationally efficient, try to avoid creating new file types that are specific to a certain model or another piece of software. For most hydrologic data, NetCDF is currently the gold standard because the NetCDF file format stores metadata along with other types of data. If the metadata cannot be part of the data (file) itself, always store the metadata as close to the actual data as possible, include links in the metadata to where the data is stored and vice versa, use standard conventions (i.e., SI units) and metadata formats (e.g., Water Metadata Language; WaterML), and be informative and sufficiently complete to allow for better understanding of the data and reproduction of study results.

Principle 3 – Open Software Use and Development: ***Open hydrologists test, archive, document, and version control their research code and software using standard open source software protocols and accessible documentation language.***

Hydrologic research often relies on the use of computational models and research software of varying complexity. We consider research software to be any code used to compile, filter, and process data, create model simulations, and generate data tables or plots, including compilable programs, stand-alone and embedded scripts (e.g., in spreadsheets), and computational notebooks (e.g., Jupyter notebooks). Programs used in the simulations and computations, the source code, and appropriate documentation must be archived and publicly accessible for verifiability and reproducibility of results. Open hydrologists strive to clearly describe code, software versions, and descriptions of each variable name, meaning, and units when developing software. Whenever possible, open hydrology software must build on open source software and programming languages to ensure that the open hydrology software can be used by anyone. This is particularly relevant for hydrology, as the diversity of models and associated software components would otherwise lead to excessive licensing and setup costs for anyone trying to use these models.

It is crucial to capture and document the complete version history of software development in a clear and comprehensible way using standardized version tracking and version management tools (i.e., version control tools) to help prevent duplication of failed attempts, improve understanding of the rationale behind modeling decisions, and ensure reproducibility. This is particularly important in hydrology, which relies heavily on testing continuous improvements and adaptations of existing models as new data becomes available. Systematic and transparent version control, software documentation (i.e., help manual), and software unit tests--standard tests created by the software developer to check that the software runs under a variety of conditions--are prerequisites for meeting expectations of producing reliable predictions regarding the future of water resources and hydrologic risks. For licensing and publishing of software, see Principle 4.

Practical Guide to Open Code and Software Use and Development

We recommend that open hydrologists use a modern version control system, such as Git, which can capture and manage changes made to code (Perez-Riverol et al., 2016; Lowndes et al., 2017;

Bryan, 2018). This prevents file duplication and mistakenly overwriting previous work while allowing others to trace the progression of code, track code issues, and collaboratively write code. However, the command-line application form of version control systems such as Git can pose a steep learning curve. Fortunately, graphical user interfaces exist and public repositories, such as Git Desktop, Git Cola, and GitKraken offer easy-to-use interfaces, helpful documentation, and tutorials. Also, various courses are available through the Carpentries (e.g., Version Control with Git) to help you get started using Git and online Git collaboration platforms like GitHub and GitLab. Furthermore, these public repositories facilitate collaborative software development, issue tracking, and detailed documentation of modeling decisions.

Open science offers a quick and effective way to use and develop research software by building upon or re-using software created by others. Generic repositories such as GitHub, GitLab, Bitbucket, and language-specific repositories such as CRAN and PyPI are treasure troves of software, often solving a large part of your problem. Using these public and open repositories saves you time and allows others to make use of your software more easily, help you improve it, and in turn build on it for your research.

The simplest way of creating code documentation is often to include it with the software in some form. Variables need to be clearly defined and include the units in the code or in an associated appendix, to avoid code becoming unwieldy and complex. Various languages offer ways to generate technical documentation from the code itself, e.g., pydoc for Python and roxygen for R. Readthedocs is currently the most used platform for hosting technical documentation as a website.

Even if all the source code of the different packages used in a research project is freely available, it may be difficult to reproduce an analysis if the versions of the packages are not known, or if the version of the operating system is not compatible. For this reason, several methods for sharing a computational environment have been created in recent years. The use of software containers (e.g., Docker; Nüst et al., 2020) can help to share a complete computational environment including the operating system and necessary packages with your code. The binder service can reproduce a computational notebook in a single click from a software repository. Renkulab allows for version control of data, software, and computational environments from within a single platform. Renkulab further enables transparent tracking of the lineage of research results, from external data sources to final figures in manuscripts.

When using a git repository, automatic testing of code and workflows can be implemented using continuous integration software, which essentially runs a pre-designed workflow and tests if it runs without errors. Such a workflow can include a comparison of model results with a reference dataset and hence alert the user to changes in the model results.

Principle 4 – Open Publishing: ***Open hydrologists publish all components of their research on citable platforms and in journals that are accessible to both the research community and the general public following ethical standards.***

Research sharing is pivotal to enable the transferability of hydrological insights and to build on existing work. Thus, open hydrologists must publish all research components using a permissive license that allows editing and sharing derivative works with all scientists and the general public, including policymakers. There are, however, special cases where information (e.g., from water utility providers or governmental agencies) cannot be shared publicly due to privacy and safety (i.e., national security) reasons. The potential reproducibility limitations associated with these data need to be considered and openly discussed.

Scientific findings are traditionally published in academic journal articles. Publishers and libraries have the appropriate infrastructure in place for bibliographic tracking, transparent cross-referencing between research objects, and appropriate crediting of researchers for their contributions. How and where open hydrologists publish their work is crucial for the global accessibility and preservation of open hydrology research. Recently, many research funding organizations have mandated that all research funded by them must be published openly and without delay after publication in a chosen journal, e.g. cOAlition S. Regardless of the rules stipulated by their research grants, open hydrologists must strive to publish all their results (including articles, data, and software) as openly as possible.

Practical Guide to Open Science Publishing

There are primarily three main open access (OA) journal publication models: (1) "gold or diamond OA", which provides free access to everyone, (2) "hybrid OA", which involves subscription-based journals that charge an additional fee for making a particular article freely accessible, and (3) "green OA", in which the authors can self-archive the accepted authors' version of an article (i.e., a postprint) in a suitable repository. Publishing in a gold or diamond OA or hybrid journal has the advantage that the final article in its typeset form is freely shared, whereas the green OA route only allows sharing the manuscript version before final typesetting. Gold OA journals charge no subscription fees, but typically require an article processing charge (APC) fee. Diamond OA journals do not charge an APC and are generally funded by non-profit organizations, governments, societies, or other revenue streams. The copyright for articles published in gold or diamond OA journals stays with the authors. Hybrid open access refers to the concept where publishers follow a subscription-based model but provide the option that authors pay for obtaining the copyright on an individual article (in its final, typeset version) and for making it OA on the publisher's website.

Hybrid publishing has been criticized because the scientific community typically pays twice - once for subscription to the journal and once for OA fees for individual articles (Mittermaier, 2015; Pinfield et al., 2016). As of April 2021, many journals impose an embargo period (typically between 6 and 24 months) before the postprint can be published.

Manuscripts that have not yet undergone peer-review (i.e., preprints), on the other hand, can typically be published at any stage during an open hydrology project. Preprints are a good opportunity to accelerate the publishing progress and to avoid blockage of follow-up papers during a potentially lengthy review process. It is advisable, however, to check with your target journal if it accepts submission of manuscripts that have already been published as preprints. Read Saia (2019) to learn more about preprints in hydrology and visit Sherpa Romeo or the Journal Checker Tool (provided by cOAlition S) to find out about copyrights and open access archiving policies from various publishers and journals.

Another important aspect related to OA publishing is the license attached to an article. Creative Commons licenses (e.g., CC-BY) are widespread, but some publishers choose more restrictive versions, indicated by additions such as NC for non-commercial use, or ND, indicating that "No derivatives or adaptations of the work are permitted". The latter hampers re-use of the published work because it disallows extracting figures or tables from the paper.

When publishing data or code, it is important to ensure that these have a permissive license (e.g., Creative Commons) so that the product cannot legally be reused. For software, an existing open source license reduces licensing conflicts (see Choose a License for suitable licenses). Text, images, videos, photos, or other media created during or associated with a hydrologic project can be licensed using a CC-BY license to ensure creator attribution.

Overall, there are numerous aspects to consider when choosing a journal. This includes not only OA options, licenses, and archiving services, but also review and publication finance policies as well as release requirements for data, code, and software. Responsibility for moving towards more open science publishing lies with the author and with editors and reviewers. As a reviewer, open hydrologists can help promote proper citing and acknowledgment of data and code sources by requesting that these be made publicly available when they are missing from the paper that is being reviewed. They can first check if the article adheres to the open science standards of the journal. If it does not, the open hydrologist can indicate clearly in their review that the work does not comply with the standards of the journal. If the journal does not have adequate open science standards, open hydrologists can point the authors and editors to examples of open science standards at other journals. Even in the absence of open science standards, journal editors are usually very sensitive to a reviewer's verdict that the results of a study are not reproducible. For example, not having access to data or software may prevent others from assessing the quality of the work. Consider writing the editor that clear open science standards would provide guidance to authors and generally improve the quality of submitted articles.

Data and code associated with an article must be cited in the article and published in a suitable long-term repository, with a separate Digital Object Identifier (DOI) and a permissive open source license (e.g., re3data for suitable repositories). This facilitates citations and allows for re-use and modification of the work. To ensure that researchers providing software and data get properly credited for their efforts, third-party data or software used by others must be cited accordingly.

Unlike data, source code for research software rarely requires much storage. Therefore, it can be shared quite easily (see Principle 3). The problematic part is to ensure it is available for a long period (i.e., decades). Journals often allow for software to be published as a supplement, which is most suitable for scripts and notebooks created specifically for a publication. Software of more general use should be published and archived in a suitable public repository with a separate DOI. One prime example is Zenodo, a free service for hosting data and software, offering long-term storage, integration with GitHub, and issues a DOI for each version of software deposited there. These DOIs can be used as references in publications and leave no doubt about the version of the software.

3. Anticipating and Overcoming Challenges to Practicing Open Hydrology

There are no “one-size-fits-all” open hydrology best practices since each hydrology project exists within a unique context of research inputs and outputs, institutional structures, and collaborators, each motivated by different incentives and policies in place. Challenges to practicing open hydrology may arise throughout the research process—from first identifying a research goal to publishing research findings. Additionally, challenges to practicing open hydrology may depend on the career stage of researchers—from student to early career to senior. In general, challenges to practicing open hydrology revolve around socio-cultural, organizational, economic, technological, political, and legal themes (*About FOSTER*, 2021; Allen and Mehler, 2019; Table 2). Socio-cultural challenges refer to a hydrologist’s limited knowledge of, confidence in, and access to open hydrology practices and tools. Technological, organizational, and economic themes refer to challenges beyond the control of individual researchers trying to do open hydrology. For example, hydrologists may strive to do open research but be limited by unstable internet connections (i.e., technical challenge), power to advocate for publishing their work openly (i.e., organizational), or lack of funds to pay for open access publication fees (i.e., economic).

Resolving obstacles to open hydrology takes know-how and persistence since challenges can be complex. To facilitate direct practice in addressing challenges to open hydrology, we present five scenarios and outline key discussion points and recommendations for each. Each scenario highlights a particular career stage and specific challenges listed in Table 3. These five scenarios are inspired by active learning educational materials (i.e., The Carpentries' learner profiles). Researchers interested in open hydrology can use these scenarios to roleplay common challenges and brainstorm strategies with colleagues (e.g., in your lab's or department's journal club) to overcome these challenges. For each scenario, we encourage up-and-coming open hydrologists to ask: (1) *What are the important challenges and themes highlighted in this scenario?* and (2) *How might I/we overcome these challenges as a lab group/department/institution/organization?* We encourage open hydrologists to suggest additional challenges and scenarios that we may have missed by contributing to the living document (open-hydrology.github.io).

Table 2. List of common challenges that open hydrologists may experience.

Number	Challenge	Categories
1	Challenges surrounding navigating open hydrology resources, which may result in a lack of confidence, fear of criticism, and decreased motivation to pursue open hydrology.	Socio-cultural
2	Time spent practicing open hydrology is not supported, valued, nor rewarded and benefits may not be felt.	Socio-cultural
3	Lack of community to provide technical and motivational support addressing different experience and institutional levels (i.e., research group, departmental, institutional, regional, global scale).	Socio-cultural
4	Lack of power to advocate for open hydrology practices, e.g., resistance from senior colleagues and institutional policies.	Socio-cultural, Political
5	Unrecognized privileges within the research community (e.g., technologies, publications, limited access to funds, etc.) limit equitable participation in open hydrology, which further exacerbates inequities and "gatekeeping".	Socio-cultural
6	Lack of proper acknowledgement or citations of open hydrology resources	Socio-cultural

	(e.g., open data and code), which may result in limited sharing due to the fear of being scooped or not getting credit for work.	
7	Lack of incentive to publish iterations (i.e., lessons learned) in research approaches and null and negative results.	Socio-cultural
8	Limited documentation and sustained maintenance of publicly available data, code, etc.	Technological
9	Limited access to technical resources and/or physical facilities that are required for practicing open hydrology (e.g., cloud computing, stable internet connection, work computer).	Technological
10	Prohibition and/or restriction of open source software installation on work computers.	Technological, Organisational, Political
11	Lack of and/or limited funds to afford the high cost of open access publishing, which may depend on complex institutional, regional, national, and global open science factors.	Organizational, Economic, Political
12	Restrictions on practicing open hydrology imposed by public and private institutional rules and national policies.	Political, Legal
13	Need to respect and honor privacy, data sovereignty, and data governance of stakeholders and collaborators.	Legal, Political, Socio-cultural

Table 3. Scenario summary table.

Letter	Scenario Title	Actor	Career level	Challenges
A	Knowledge of and Support for Practicing Open Hydrology	Jaime	Early career student	#1, #3
B	Collaborator Influence on Practicing Open Hydrology	Deniz	Established researcher	#2, #6, #12
C	Respecting and Upholding Stakeholder Interests	Alex	Research project principal investigator	#12, #13
D	Cost of Open Publishing	Robin	Postdoc	#4, #11
E	Promoting a Culture of Open Hydrology	Dr. Hydro	Department head	#4, #5, #6, #9

Scenario A—Knowledge of and Support for Practicing Open Hydrology

Jaime is a Ph.D. student studying the impacts of irrigation strategies on groundwater levels. Jaime recently saw the terms "open science", "open access", "preprints", and "open source software" used by hydrologists they follow on Twitter. No one in Jaime's *lab/department has ever mentioned these terms and Jaime does not know where to go to learn more specifics or how to participate.*

Knowing where to look, how to find, and how to use open science resources is an essential skill of any successful open hydrologist. Furthermore, these fundamental skills take time to learn and are often developed during school, early career workplace experiences, or as a result of personal motivation. When knowledge of open hydrology resources and skills is accompanied by freely accessible tools (e.g, code repositories, software, tutorials, platforms) and supportive online communities, it becomes easier and less overwhelming to pursue open science strategies. However, it can be especially challenging when researchers do not know where to start (Challenge #1, Table 2) and/or when they work in isolated environments (Challenge #3, Table 2), as are the cases for Jaime in Scenario A. The challenges that define Jaime's circumstances in Scenario A are primarily socio-cultural. As an early career scientist, Jaime's ability to practice open hydrology is hampered by their limited knowledge of open hydrology resources and limited (local) support. As a result, Jaime may feel overwhelmed, uncertain, and anxious about practicing open hydrology.

It is important to recognize that anyone, regardless of career stage, can become an open hydrologist. On a personal level, self-study can be an effective first step to learning about open science principles and tools. Set aside time to read papers on reproducible research, version control, etc. as well as time to practice putting what you learn into use. You can also attend free online seminars or listen to podcasts (e.g. EOSC, ORION) to learn at your own pace. There are plenty of freely accessible resources on the web that explain basic Open Science practices (e.g., EGU 2020) (Allen & Mehler, 2019; Hampton et al., 2015). However, if this all becomes too overwhelming, another important option is to reach out to friends (including those on social media), mentors, and colleagues that are more familiar with practicing open science. These folks will likely have some great tips on what resources they found helpful and why. They may even be interested in giving an introductory seminar or facilitating a lab group discussion. It may also help to engage with other like-minded early career scientists during institutional or professional society meetings. This way you can learn from one another and support each other's open hydrology initiatives. If you are reading this paper, you are already on the right path!

Scenario B—Collaborator Influence on Practicing Open Hydrology

Deniz is an established hydrologist working at a government agency and is co-advising a Master's student in ecohydrology at a nearby university. In a recent committee meeting, the Master's student asked Deniz to post a preprint of their paper after it is submitted to the journal for review. The Master's student also asked if Deniz knew of places where they could post the dataset from their study upon acceptance to the journal. Deniz has an agency colleague with experience publishing datasets but was worried that preparing the datasets for publication might take the Master's student too much time. Also, Deniz needed to check if it was against agency policy to publish the paper before it was peer-reviewed. Not to mention, what if the non-peer-reviewed results were scooped by other scientists or used prematurely by decision-makers?

Open hydrologists will likely encounter collaborators who are less supportive about practicing open hydrology and this limited enthusiasm may present itself throughout the research process, from sharing data and code to posting preprints, to paying for open access fees, and more. In the case of Scenario B, River's hesitation might stem from the concern that time spent documenting and publishing data will outweigh long-term benefits, like the increased research exposure and citations associated with open science (e.g., Challenge #2, Table 2). Fear of being scooped—when one researcher group publishes work before another research group doing very similar work

(Challenge #6, Table 2)—is a common reason for limited participation in open science (Laine, 2017). As Deniz supposes, research staff may also be subject to government agency policies that limit their ability to practice open hydrology (e.g., Twitter; Challenge #12, Table 2). In Scenario B, a combination of socio-cultural, political, and legal challenges come into play when researchers at various career stages consider practicing open hydrology.

Research supervisors and supervisees both play a critical role in the promotion and practice of open hydrology. If you are a supervisor, explicitly discuss and incorporate aspects of open hydrology into new, ongoing, and completed research collaborations. Additionally, keep an open mind when supervisees approach you about practicing open hydrology. This may include having candid conversations with supervisees to find a solution that addresses your concerns while ensuring transparency in research outputs and the supervisee's aspirations. If you are a supervisee, provide your valid arguments for open hydrology, while still being considerate of your supervisor's concerns and honoring potential policies limiting open practices. One point to address can be highlighting the potential long-term impact of open hydrology on your career (Allen and Mehler, 2019). Another approach might be to ask established open hydrologists to discuss with you and your supervisor their points of hesitation (e.g., Twitter). For both supervisors and supervisees, reflect on each aspect of your research pipeline and how each adheres (or does not adhere) to open hydrology principles. Remember to start with small changes and try to build on your open hydrology practices with each new project (Allen and Mehler, 2019). Furthermore, advocate for policy changes and long-term perspectives that value open hydrology practices. Time and effort dedicated to making research more open is not a loss because it will benefit open hydrology practices for current and future collaborators, stakeholders, and society.

Scenario C—Respecting Stakeholder Interests

Alex is a principal investigator conducting a sociohydrology research project in collaboration with local stakeholders who hold diverse beliefs on a particular issue impacting the region. Alex has had in-depth conversations with these stakeholders and all members of the project have agreed to participate in an anonymous survey that will assess their perspectives on the regional issue. In this project, Alex must protect personally identifying information when sharing results. Furthermore, Alex and the stakeholders have come to an agreement on specific data outputs and use cases that can be shared publicly; all other data and use cases are property of the stakeholders.

It may be difficult or even against research agreements to share some aspects of hydrology research openly. For example, sharing of proprietary datasets can be restricted (Challenge #12, Table 2). Since an increasing amount of hydrology research is conducted in collaboration with stakeholders, it is important to respect the rights and requests of these stakeholders (Challenge #13, Table 2) and maintain their privacy. In Scenario C, Alex must navigate a combination of political, legal, and socio-cultural challenges when conducting transdisciplinary hydrology research alongside communities.

There are several strategies that open hydrologists can take to uphold their commitment to transparency and reproducibility while respecting the rights and policies of their collaborators. Principal investigators like Alex in Scenario C have a fundamental responsibility to spend time openly discussing and formulating an open research plan with collaborators and stakeholders that describes public versus private research outputs, use cases, and what will be shared to whom and when. Importantly, all impacted community members must co-produce this open research plan with the research team and also consent to data collection, analysis, and dissemination. You can look to standard privacy guidelines (e.g., the General Data Protection Regulation and research on data governance and data sovereignty principles (Carroll et al., 2020). It is also important that you document decisions made around public research sharing for a particular project so outsiders can refer to this context. For example, the United Nation's GEMStat program describes how their research policies adhere to General Data Protection Regulation (see Principle 2). When possible, you may be able to share anonymized data such as metadata that does not indicate water quality issues for a specific geographic region.

Scenario D—Cost of Open Publishing

Robin recently defended their Ph.D. thesis and started a postdoctoral researcher position. In their free time, Robin is finishing up an irrigation water management project that they worked on alongside agricultural producers during their Ph.D. research. Robin will present these findings to agricultural producers during a virtual webinar and wants to publish these findings in an open access journal article so it is easier for people outside academia to find and read. However, Robin does not have enough grant funds to cover the expensive open access fees and feels uncomfortable asking their postdoctoral advisor, who is in a different sub-hydrology field, for these funds.

A common challenge to sharing research publicly is lacking the extra funds needed to pay open access publication fees (Challenge #11, Table 2). Scenario D represents an example of how distressing and disruptive this challenge can be. Furthermore, this frustrating situation can be exacerbated when early career open hydrologists, like Robin, are transitioning between positions and projects and/or have limited power and resources to advocate for covering the cost of these fees (Challenge #4, Table 2). Ultimately this inability to cover the cost influences the impact of the research; open access publications tend to be cited more (Wang et al., 2015) and are accessible to research partners and the general public who do not have a journal subscription. It is important to note that open access publishing is a common and effective starting point for practicing open hydrology. Moreover, be aware that the economic, political, and organizational challenges may hamper open access publishing for researchers from developing countries.

To overcome the challenges outlined in Scenario D established open hydrologists can start as early as possible in the research process to plan for open access publishing. The easiest solution is to look for an OA journal that does not charge an Article Processing Cost (APC) to the authors or any of the authors' institutions. You can budget funds to cover the cost of these fees in a grant, use discretionary funds, or cost-share with co-authors. In some cases, researchers who work for government agencies can retain the copyrights to their publications. More specifically, journals have special provisions to allow them to share the journal formatted paper without infringing on the journal's copyright laws. However, you should check the policies for each journal as the corresponding author may have to be from the government agency and/or several co-authors may also have to be from a government agency to qualify. In other cases, journals waive fees and/or discounts to researchers from certain countries or per individual requests. You can also check the journal website and publisher's policy to learn about your institution's or country's eligibility conditions. If you are an early career open hydrologist who was not present at the start of the research project, you can discuss the possibility of open access publishing with your supervisor. Some libraries and institutions have dedicated supplemental funds to support researchers who choose to publish their papers as open access. If all else fails, researchers typically can post a plain copy of the journal article on a non-for-profit preprint server (e.g., EarthArXiv). This can be done at any stage of paper preparation but all corresponding authors need to agree to post the preprint.

Scenario E—Promoting a Culture of Open Hydrology

Dr. Hydro is the faculty chair of an environmental sciences department and is providing mentorship and departmental support (e.g., funding for open access and technology fees, honors to researchers doing open science) to several graduate students and faculty members in the department who have started organizing discussion groups and developing training materials to promote short- and long-term open science practices within their research groups. Some members of the department feel like this is a waste of time, but Dr. Hydro thinks these are important initiatives that will benefit the members of their department and beyond, especially in the long term.

Unlike Scenarios A-D, Scenario E represents an example of a senior researcher supporting open hydrology efforts at their institute. Open science is a cultural movement, which ought to find deep roots in the hydrology community given the potential impact of our work on society. However, promoting a culture of open science requires individual- and community-based responsibility. We are each a part of a cultural shift towards open hydrology. At the individual level, researchers' roles in open hydrology are crucial and diverse. In Scenario E, Dr. Hydro strives to overcome socio-cultural, technological, and political challenges to promote open hydrology in their department, institution, and beyond. Specifically, Dr. Hydro uses their position (i.e., power) as a department chair to advocate for open hydrology practices (Challenge #4, Table 2), ensures that all members of the department have equitable opportunities for practicing open hydrology (Challenges #5 and #9, Table 2), and promotes and honors community-driven open hydrology initiatives in the department (Challenge #6, Table 2). Although this might seem like a huge challenge at the beginning, Dr. Hydro is convinced that these efforts will not only benefit the hydrologists at their institute but ultimately the entire field of hydrology, and society.

Researchers interested in practicing open hydrology can organize or attend regular seminars or journal clubs, during early to established researchers can learn about open science principles and ways to apply them to their work. Such a space can serve as a platform to discuss open hydrology, brainstorm solutions for common issues that are encountered. If you are a principal investigator of a research group, you can play an important role in promoting open hydrology by establishing guidelines for your trainees. Last but not least, students, staff, and faculty can all promote the use of open source software like R, Python, or QGIS for hydrology research and participate in local, regional, national, and global efforts to sport open science.

4. Summary and Outlook

Hydrologic research that is open, accessible, reusable, and reproducible will have the largest equitable impact on the scientific community and broader society. Funding agencies, publishers, and hydrologic organizations are increasingly requiring hydrologists to adopt open science practices. We wrote ‘A Hydrologist’s Guide to Open Science’, to facilitate the transition to fully open science within hydrology—both for hydrologists who have been at the forefront of this movement, as well as for those taking their first steps. Recognizing the practice of open science is in constant development, we wrote this guide around four guiding Open Hydrology Principles on 1) Open Research Process and Approach, 2) Open Data Collection and Analyses, 3) Open Software Use and Development, and 4) Open Science Publishing. For each principle, we provided actionable steps (i.e., “Open Hydrology Practical Guide”) on how to become a more open hydrologist.

Hydrologists intending to implement the advice in the Open Hydrology Practical Guide will, undoubtedly, run into challenges on their path. We identified and addressed twelve challenges in five scenarios that cover various hydrology career stages. These scenarios are meant to facilitate discussion while giving practical suggestions on how to be an as-open-as-possible hydrologist in the face of common challenges.

While approaches and methods related to open science will evolve, the Open Hydrology Principles will guide us in the future. The Open Hydrology Practical Guide is written based on currently available paradigms, tools, policies, and experiences. These will be updated or replaced by others as the state of hydrology and policies surrounding open science change. Therefore, we created open-hydrology.github.io—a living version of this manuscript. This also will act as a shared community resource for practical, up-to-date open hydrology resources. We invite the hydrologic community to join us, the authors of this manuscript and a growing number of colleagues, to endorse the Open Hydrology Principles and contribute to this living document at open-hydrology.github.io.

It is a long road towards fully open hydrology. Getting to the point where a majority (or more) of hydrologists are participating in open hydrology will take time and effort, driven by individual hydrologists implementing openness along with organizational and governmental policies that incentivize open science. This step-by-step, slow process needs to be regarded as a valuable contribution to hydrology and systemically supported by scientific institutions and beyond. Only then can the entire hydrology community come together, build on each other's results, and strengthen hydrologic knowledge and maximize the benefits to society as a whole.

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