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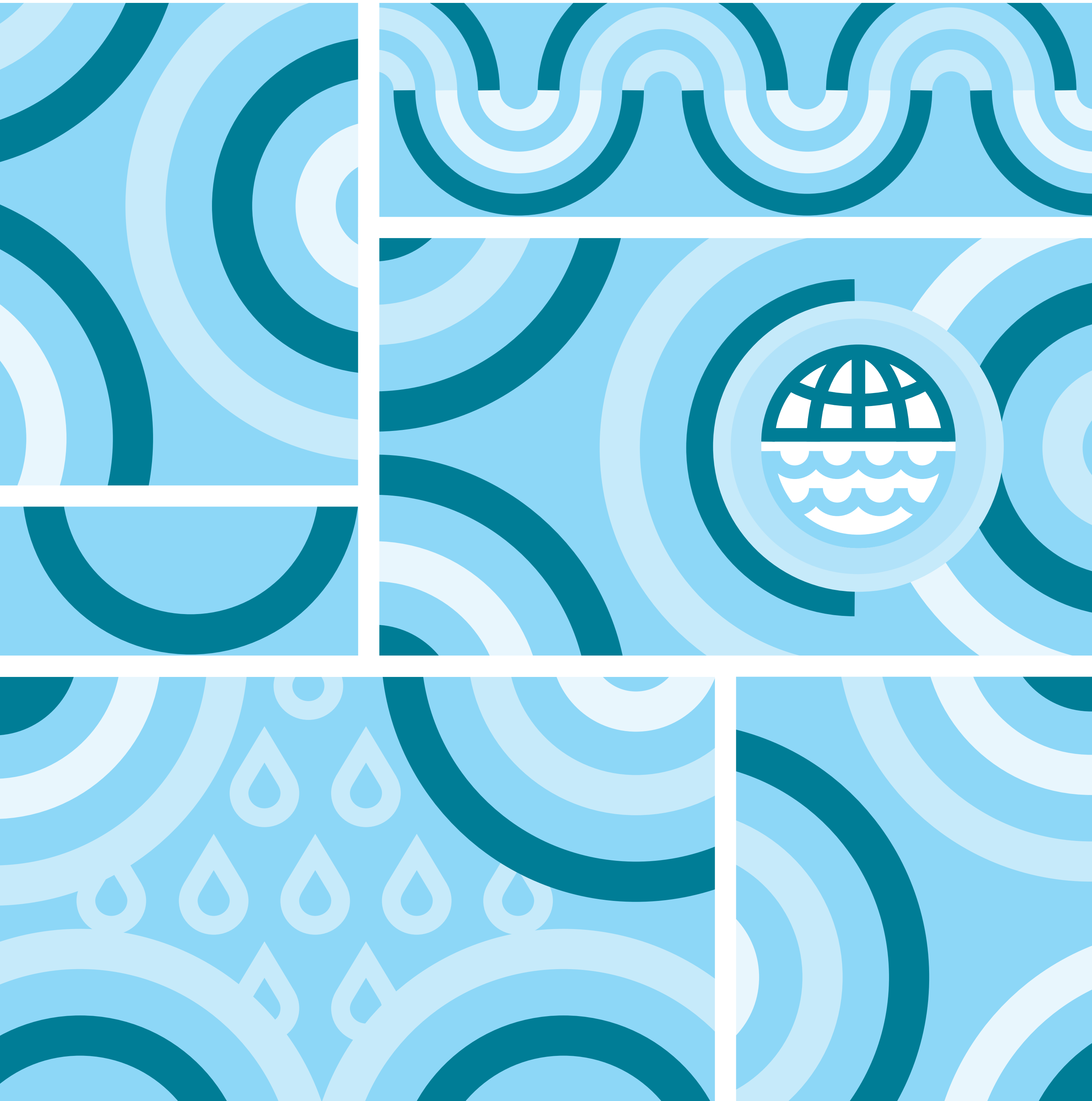
Open Hydrology



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SHORT SUMMARY

The Open Hydrology framework: mainstreaming Open Science principles into hydrology

The UNESCO Recommendation on Open Science has set an international standard of guiding principles for Open Science. It encompasses a set of principles and practices aimed at making scientific research from all fields accessible to everyone for the benefit of scientists and society as a whole. Open Science emphasizes not only accessibility but also inclusivity, equity, and sustainability in the production of scientific knowledge.

This publication has laid out a strategic framework to integrate Open Science into hydrology, illustrating its true potential to enhance research transparency, collaboration, and accessibility within water management practices. The six pillars — open data, open source, open publishing, open infrastructure, open education, and open participation — constitute the structure of the Open Hydrology framework designed to promote transparency and reproducibility.

According to the ***Open Hydrology* survey, 80%** of respondents share data while a greater majority (93%) uses open access data

The Open Hydrology framework advocates for the accessibility of hydrological research to a broad spectrum of researchers, practitioners, and policymakers. Free and equal access to hydrological knowledge, technology, and tools is indispensable for FAIR advancement and innovation in addressing the current intricate water challenges.

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"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"

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This publication has been developed under the framework of the Hydro-Resilience Project ('Addressing Hydro-climatic Vulnerability through Citizen and Open Science'), made possible with the support of UNESCO/Flanders Fund-in-Trust for the support of activities in the field of science (FUST).

Hydro Resilience
CITIZEN AND OPEN SCIENCE FOR CLIMATE ADAPTATION

Flanders
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Open Hydrology

CONTENTS

FOREWORD

Climate change poses unprecedented challenges to our world, affecting every aspect of our lives, including the availability and management of water resources. In response to these challenges, the call for openness in scientific research has never been more urgent. The UNESCO recommendation on Open Science, adopted at the 41st General Conference of UNESCO in November 2021, underscores the importance of transparency, accessibility, and collaboration in scientific endeavors, providing a set of principles and practices that aim to make scientific research from all fields accessible to everyone for the benefits of scientists and society as a whole.

This publication reflects on the transformative potential of Open Science, particularly within the field of hydrology, where the need for interdisciplinary research and innovation is paramount. It examines how Open Science principles, guided by the FAIR data principles, can enhance collaboration, innovation, and trust within the hydrological community, ultimately leading to more effective water management strategies.

The ninth phase of UNESCO-IHP, "Science for a Water Secure World in a Changing Environment" (2022-2029), identifies Open Science as one of the central tools to achieve its five priority areas. The idea behind Open Science in IHP-IX is to allow scientific information, data and results to be more widely accessible (Open Access) and more reliably harnessed (Open Data) with the active engagement of all the stakeholders (Open to Society). To assess the status of Open Science and to identify the key factors that hinder and promote Open Science practices within the hydrological community, a survey was released to the UNESCO

This publication aims to contribute to the ongoing dialogue on Open Science in hydrology

Water Family. This survey collected 61 responses from UNESCO Water Family members, highlighting the importance of open data collection, analysis, and publishing in hydrology research.

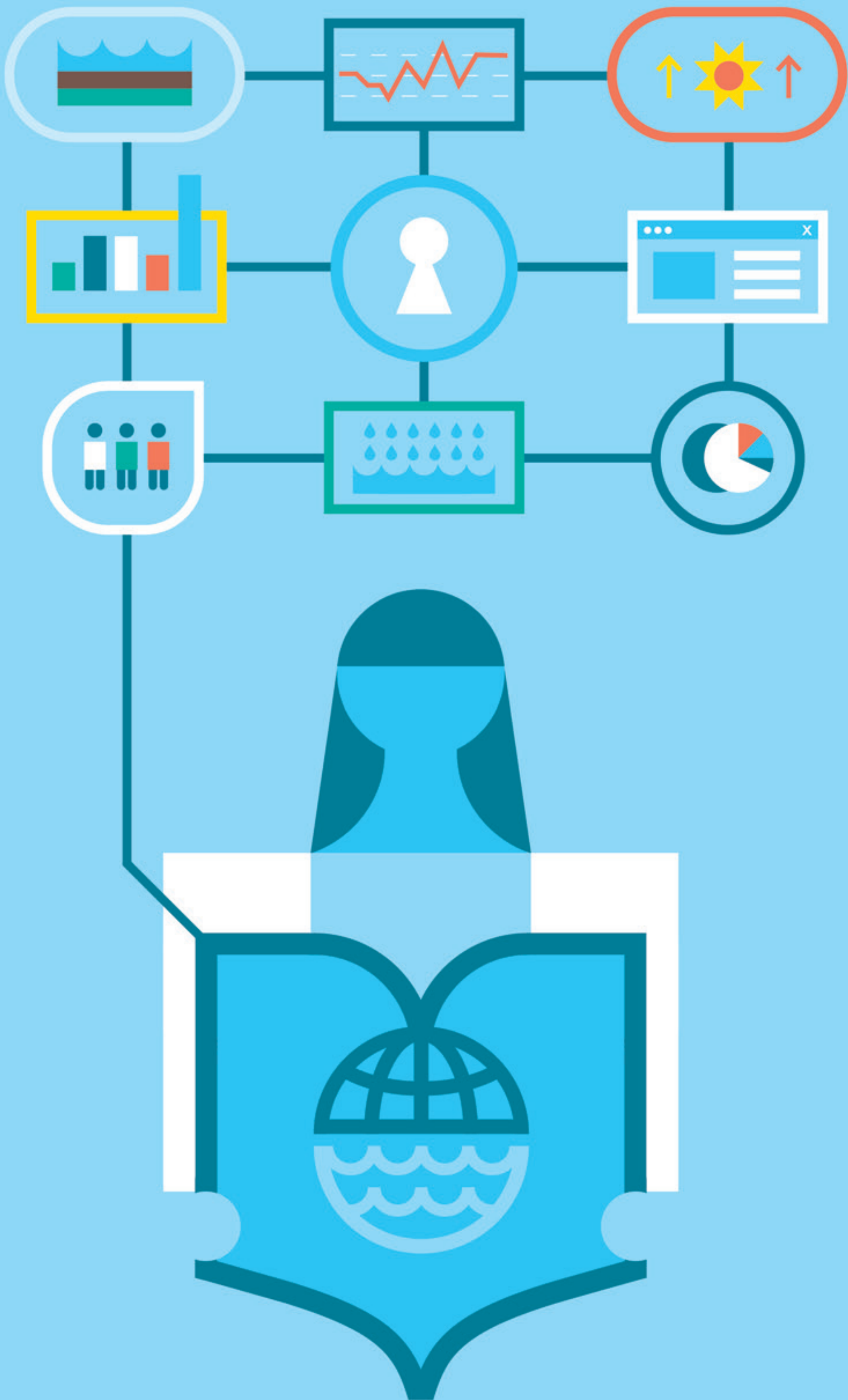
Based on the insights from the survey, this publication aims to contribute to the ongoing dialogue on Open Science in Hydrology. It acknowledges the diverse needs and interests of stakeholders within the hydrological community and seeks to promote a culture of openness, transparency, and collaboration.

This publication was developed within the context of UNESCO's project on 'Addressing Hydro-climatic Vulnerability through Citizen and Open Science', in which promoting open science for hydrology is a clear objective. This project on hydro-resilience and citizen and open science for climate adaptation is supported by the Flanders-UNESCO Science Trust Fund (FUST) and aims to enhance the resilience of communities to water-related challenges and support hydroclimatic risk management strategies through innovative research, capacity building, and knowledge sharing.

Abou Amani
Director of the Division of Water Sciences
UNESCO

ABBREVIATIONS

AGU: American Geoscience Union
AI: Artificial Intelligence
APC: Article Publishing Charge
CARE: Collective Benefit, Authority to Control, Responsibility and Ethics
CRAN: Comprehensive R Archive Network
CUAHSI: Consortium of Universities for the Advancement of Hydrologic Science, Inc.
DOI: Digital Object Identifier
DWG: Digital Water Globe
EGU: European Geoscience Union
FAIR: Findability, Accessibility, Interoperability, and Reusability
IAHS: International Association of Hydrological Sciences
ICON: Integrated, Coordinated, Open science, and Networked
ICT: International Centre for Theoretical Physics
IHP: Intergovernmental Hydrological Programme by UNESCO
iMHEA: Iniciativa Regional de Monitoreo Hidrológico
ILK: Indigenous and Local Knowledge
LSH: Large Sample Hydrology
ML: Machine Learning
MOOC: Massive Open Online Course
OA: Open Access
OS: Open Science
OSPP: Open Science Policy Platform
RHN: Reference Hydrometric Networks
ROBIN: Reference Observatory of Basins for International hydrological climate change detection
SDG: Sustainable Development Goals
SMP: Software Management Plans
UNESCO: United Nations Educational, Scientific and Cultural Organization
WINS: Water Information Network System
WMO: World Meteorological Organization



TOWARDS A FRAMEWORK FOR OPEN HYDROLOGY

The universal nature of science calls for openness in research in its entirety. Openness has substantial transformative potential for addressing 21st century's societal challenges, including the water-related ones, based on science-informed services (practice) and decision making (policy).

The need for Open and FAIR Science

The concept of openness (open science, open innovation, open knowledge) has transformed the culture of science and research across the world. In essence, Open Science (OS) promotes research accessibility, transparency and reliability coupled with the FAIR – *Findability, Accessibility, Interoperability, and Reusability* data principles. Benefits of OS include strengthened scientific community, expanded visibility and impact, improved innovation and commercialization as well as increased public engagement and public trust. Open science is about ensuring not only that scientific knowledge is accessible but also that the production of that knowledge itself is inclusive, equitable and sustainable.

Achieving OS requires strong leadership, advocacy, policy, and implementation, along with digital infrastructure, training and capacity building, networking and collaboration, citizen science and engagement. The universe of OS is expanding with many scientific disciplines, organizations and countries committing to openness, transparency, accessibility, and reproducibility. In this regard, the *UNESCO Recommendation* on *Open Science* (UNESCO, 2021) has set an international standard for picking up the pace to evolve together and for each other.

The need for Open Hydrology

Hydrological sciences and water resources management underpins the global water agenda (Smith et al., 2023). The intrinsic complexity and variety of challenges within disaster risk reduction (Sendai Framework), climate change adaptation (Paris Agreement) and sustainable development (2030 Agenda) highlight the critical need for interdisciplinary water research and innovation across all scales, which also became the main focus of the UN 2023 Water Conference (Ovink et al., 2023). Admittedly, free and equal access to hydrological knowledge, technology and tools is a prerequisite for equitable advancement and innovation to solve our current complex and intertwined water challenges (Cudennec, Sud & Boulton, 2022). Hence, it is crucial that water-related research be open, accessible, reusable, and reproducible (Hall et al., 2022; Schymanski & Schymanski, 2023).

OS is progressively becoming more prevalent in the hydrological sciences community, and has gained progressive attention through journal articles (e.g., Hall et al., 2022; Cudennec et al., 2022; Dogulu et al., 2023; Zipper et al., 2019; Stagge et al., 2019; Hutton et al., 2016), in dedicated symposia (e.g., UNESCO Open Water Symposia) and sessions in scientific conferences (e.g., European Geosciences Union General Assembly, International Association of Hydrological Sciences Scientific Assembly). Despite the many scientific endeavors which are available (mostly) to researchers, an integrative and inclusive vision on hydrology and OS is currently missing.

"A Hydrologist's Guide to Open Science" by Hall et al. (2022) provides a clear pathway towards a culture of OS in hydrology. The 9th Phase of the *UNESCO Intergovernmental Hydrological Programme (2022-2029) "Science for a Water Secure World in a Changing Environment" (UNESCO, 2022a)* also has strong emphasis on OS. Consequently, OS principles are paving the future for hydrological sciences, with seeds leaping over services enhanced by the uptake of hydrology research (technology, IT, governance). In fact, OS can be a powerful enabler of an improved Science-Policy-Practice interface since transparency is fundamental to vigorous and functional processes of research uptake (Reichmann & Wieser, 2022).

The hydrological community therefore has an opportunity to become an 'Open Science Ambassador', by facilitating the publishing on open platforms, creating a community of practice on Open Hydrology, and by investing in OS and adopting OS principles.

Introduction of existing Frameworks

This publication aims to introduce a set of complementary elements that should underpin a broader framework for streamlining *Open Hydrology*. For the purpose of this publication, *Open Hydrology* is defined as the practice of conducting hydrological research and providing hydrological services in accordance with the principles of OS. This entails the open sharing of hydrological data, methodologies, software, hardware and learning, making it accessible and reusable for everyone, to increase scientific collaborations and sharing of information for the benefits of science and society, and to open the process of hydrological knowledge creation, evaluation and communication to societal actors beyond the traditional scientific community.

The Open Hydrology approach will therefore build on the value and guiding principles defined by the UNESCO Recommendation on Open Science (UNESCO, 2021), but will specify and elaborate those elements that are of particular relevance for hydrological sciences.

The UNESCO Open Science framework embraces a set of key elements. It identified *Open Scientific Knowledge* as the first pillar, which includes scientific publications, open research data, open educational resources, open source software and source code, as well as open hardware. The second pillar concerns both physical and virtual *Open Science Infrastructures*. The third pillar aims at ensuring Open Engagement of societal actors, such as crowdfunding, crowdsourcing, scientific volunteering, citizen and participatory science. The fourth pillar focusses on establishing an Open Dialogue with other knowledge systems, such as Indigenous Peoples, marginalized scholars, and local communities.

With its roots in the hydrological sciences and research, a set of principles on Open Hydrology have been introduced by Hall et al. in 2022. These principles are:

Principle 1 – *Open research process and approach*:
Open hydrologists intentionally plan for, describe, and share the entire research process and approach from motivation to final output.

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

Principle 3 – *Open code, software development, and use*:
Open hydrologists test, archive, document, and version control their research

code and software using standard open source software protocols and accessible documentation language.

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

A new Framework for Open Hydrology

Open Hydrology aims to strengthen the role of hydrological sciences in the Science-Policy-Practice interface. Providing an open, transparent, and participatory approach to hydrology ultimately leads to better science and more trust in science. This facilitates the role of hydrological sciences in decision and policy making, and ensures a more relevant and positive impact of hydrological sciences on society. This publication therefore envisions the concept of Open Hydrology as a way to promote OS within and beyond the hydrology community and acknowledge its potential as an enabler of an improved Science-Policy-Practice interface.

In early 2024, the current state of OS in the UNESCO Water Family was analysed through an online survey (in English, French and Spanish). The aim of this survey was to identify the factors that hinder OS in hydrology research and education, and the opportunities to further unlock the potential of Open Hydrology. A demographic overview of this comprehensive survey, with 61 respondents within the UNESCO Water Family members, is provided in Appendix I. According to the Open Hydrology survey, "open data collection and analysis" (Principle 2) and "open publishing" (Principle 4) are by far the two most important principles for personal work. At the institutional level, "open & FAIR" data and "open access" stand out in terms of importance among all other aspects of OS. Moreover, the survey participants rated research reproducibility and transparency of high importance similar to open license, open education and open source.

Building on both the UNESCO Open Science Recommendation and the four key principles by Hall et al. (2022) as well as the UNESCO Water Family survey findings, this publication proposes a new framework for Open Hydrology which merges these different elements and integrates the diverse needs and interests of all research stakeholders in hydrology across the Science-Policy-Practice interface.

This Open Hydrology framework introduces six pillars of Open Hydrology: (1) open data, (2) open source, (3) open publishing, (4) open infrastructure, (5) open education and teaching, and (6) open participation. To drive the implementation of Open Hydrology, three cross-cutting elements are key to their success: policy, leadership and capacity building (Figure 1).

The Open Hydrology framework is a practical step towards mainstreaming Open Science principles into hydrological sciences. With this publication, we are hoping to embark upon a new era in which creative and innovative forms of *Open Hydrology* in research find their way to water-related policy and practice in alignment with the *UNESCO IHP-IX (2022-2029)*.

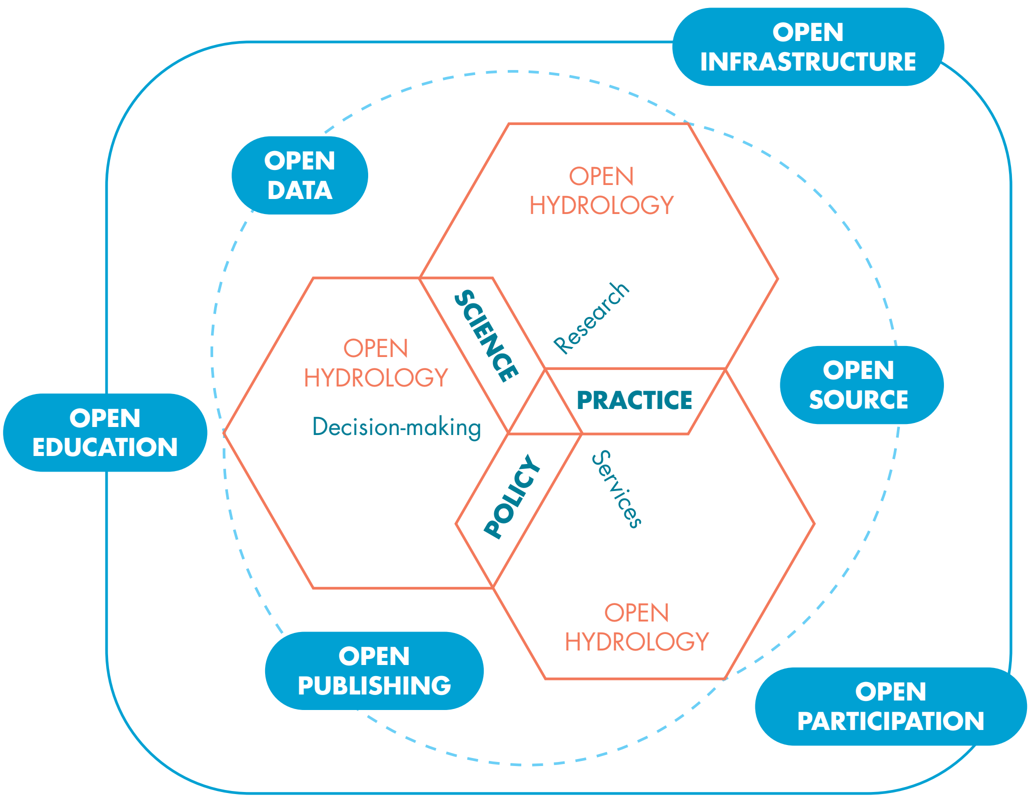


FIGURE 1. The pillars of Open Hydrology and Science-Policy-Practice interface

A living document

This *Open Hydrology* publication is developed for members of (water) research communities and infrastructures, hydrological service providers (including private sector), research administrators and facilitators of research, publishers, policy makers and funders, citizen science groups and initiatives who have a stake in hydrology and water resources research.

The key objectives of this publication are:

- to introduce key components of *Open Hydrology* and discuss required policies, leadership and capacity building,
- to highlight *Open Hydrology* stakeholders and existing initiatives, tools, resources, etc. for knowledge generation and science governance,
- to establish steps forward on how to address the needs and gaps in implementation of an *Open Hydrology* framework,
- to identify opportunities and share recommendations for sustaining *Open Hydrology* and,
- to enable the hydrological community to become an *'Open Science Ambassador'.*

Figure 2 shows the *Open Hydrology* framework along with its subcomponents. There is a separate dedicated chapter for each pillar where the key concepts and definitions are introduced. The remainder of this publication is organized as follows: *Chapters 1, 2, 3, 4, 5* and *6* are dedicated to the six pillars of *Open Hydrology*. *Chapter 7* discusses the importance of policy, leadership and capacity building for advancing *Open Hydrology. Chapter 8* outlines a community vision for a sustainable future of *Open Hydrology*.

Approaches and best practices of today might look different tomorrow. While one can find inspiration in the overview of existing initiatives, tools, platforms, etc. provided in each chapter for each pillar of Open Hydrology, additional elements may emerge over time. Recent updates of this publication may therefore be accessed from the dedicated Open Hydrology page on the UNESCO website[1].

[1] https://www.unesco.org/en/ihp/open-hydrology

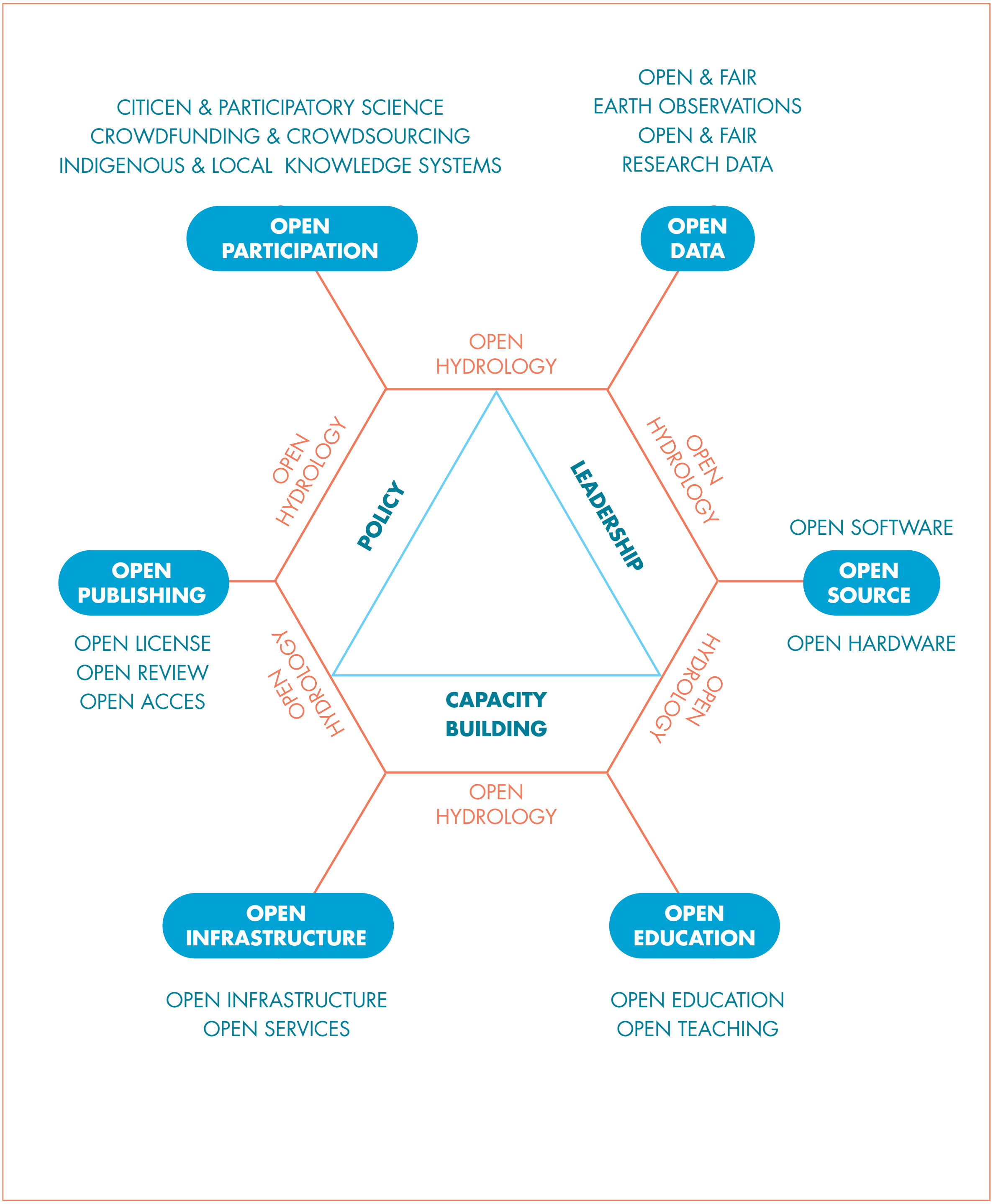


FIGURE 2. The Open Hydrology Framework

Open Hydrology Pillar 1: Open Data

1

Hydrology is a data-intensive discipline which requires motivation and strategy to overcome the many challenges that arise when working with diverse earth observations and sharing vast amount of data generated during a research project (i.e., research data). These challenges often emerge due to multiplicity of water-dependent disciplines, sectors, stakeholders, methods and policies; and impact practices of data collection, analysis, management and sharing (Cudennec et al., 2020, 2022b; Zolghadr-Asli et al., 2024).

According to the *Open Hydrology* survey, 80% of respondents share data (i.e. earth observations and/or research data) while a greater majority (93%) uses open data. This shows the importance of availability of open data and highlight the need for more open data sources. It must be noted that sharing of data is not necessarily a strict standard among those who reported to be using open data as implied by a higher percentage of respondents indicating they sometimes share data, but not always.

Open Science (OS) and FAIRness – *Findability, Accessibility, Interoperability, and Reusability* is revolutionizing hydrology through standards and protocols on hydrological data collection, analysis, management and sharing. As such, the first pillar of *Open Hydrology*, **Open Data**, is aimed at ensuring reliable, sustainable knowledge generation and synthesis processes which is key to the delivery of hydrological data products and services.

1.1 Open & FAIR earth observations

Consistent monitoring of the earth system and long-term observation strategies have great socioeconomic benefits for societies. Earth observation refers to “direct or indirect measurements made by any surface-based or space-based instrument of any physical or chemical quantity of the earth system” (WMO, 2022). The basis of hydrological research and services is earth observations, as is for all earth system domains like weather and climate. It is through comparative analysis of diverse water-related earth observations (e.g., streamflow, soil moisture, groundwater, water quality, temperature) that we gain an understanding of processes in hydrological systems and their responses to climate change disturbances and human-induced interferences at different spatial and temporal scales (Viglione et al., 2010; Dorigo et al., 2021). In particular, large sample hydrology research (LSH) with Artificial Intelligence/Machine Learning (AI/ML) methods rely greatly on community datasets created using earth observations (Addor et al., 2019; Kratzert et al., 2023). Availability of open and FAIR earth observations is thus critical to water resources management and climate change adaptation.

As an example, the ROBIN initiative recognizes this need and is advancing a worldwide effort to bring together a global network of Reference Hydrometric Networks (RHNs). The aim of the initiative is to establish a long-term collaboration of international experts which develop global capacity for sustaining freely available RHN datasets (Case Study Box 1).

The demand for open and FAIR earth observations provided by public and private organizations has been increasingly persistent over the years. In this respect, the World Meteorological Organization (WMO) Unified Data Policy for the International Exchange of Earth System Data[2] (WMO, 2022) is a milestone for countries to reaffirm their commitment to free and unrestricted data exchange. It is crucial that earth observations (along with their analyses, predictions and derived products) are shared under appropriately specified license or terms and conditions. Regardless of their scope, data attribution is strictly encouraged on every occasion.

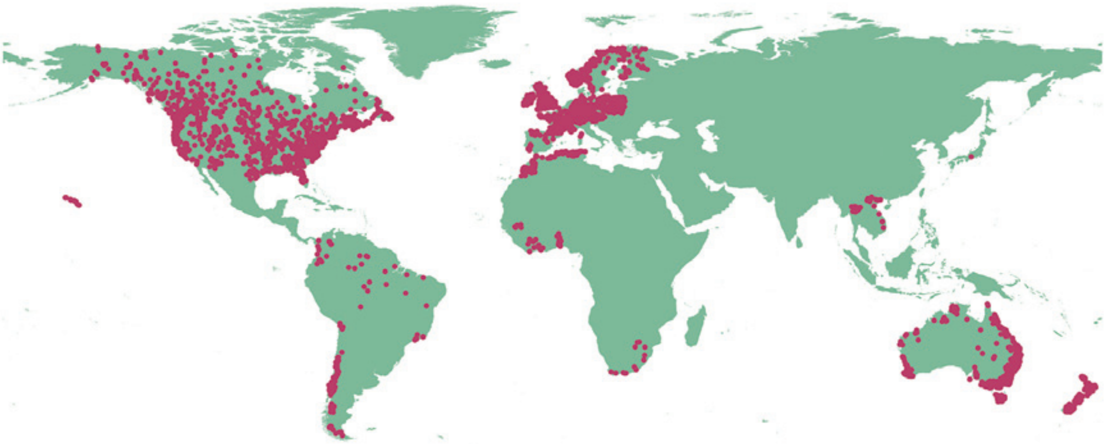
The measurement and collection of earth observations relevant to hydrological systems can greatly benefit from citizen and participatory sciences through data crowdfunding and crowdsourcing initiatives. These initiatives can facilitate the generation of new or alternative observations as well as data rescue efforts (Seibert & van Meerveld, 2022). In this respect, greater attention should be given to maintaining an open dialogue with other knowledge systems (e.g., Indigenous Peoples' and local communities' knowledge). Furthermore, open and FAIR earth observations play a key role in hydrology teaching and education using open source software at undergraduate and graduate levels. Hence, earth observations can be considered as a staple open educational resource.

[2]https://library.wmo.int/records/item/58009-wmo-unified-data-policy

CASE STUDY BOX 1

ROBIN (Reference Observatory of Basins for INternational hydrological climate change detection) by the UK Centre for Ecology & Hydrology

The Reference Observatory of Basins for INternational hydrological climate change detection (ROBIN) initiative brings together experts and hydrological data from countries across the world to create a truly global Reference Hydrometric Network (RHN) dataset for the hydrological community to use in detecting long-term hydrological change. RHNs consist of catchments with good quality data and relatively natural streamflow regimes, to allow climate-driven changes to be discerned from other confounding human interventions (e.g. dam construction, water withdrawals for irrigation). The first ROBIN dataset consists of over 3000 catchments from some 30 countries, and is freely and openly available, along with code libraries for use in analysis. New versions of the dataset will be published as further data contributions are added and more countries join the ROBIN network. The ROBIN network looks to ensure a consistent and integrated approach across its contributors to ensure a dataset suitable for robust international comparisons and analysis, and enable increased confidence in appraisals of global streamflow change, such as future IPCC assessments. ROBIN also provides a channel for international collaboration amongst hydrological experts with unique specialist knowledge, in turn developing global capacity for the establishment and sustaining of RHNs.



The boundaries and names shown, and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

ROBIN
Reference observatory of basins for international hydrological climate change detection

1.2 Open & FAIR research data

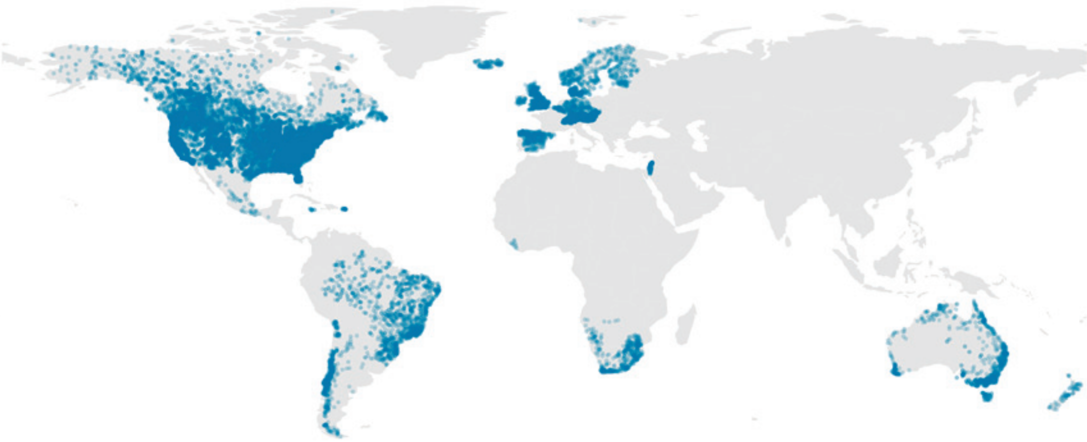
Scientific research processes include data collection and analysis. Every research project generates new data through either collection of data or data analysis (and modelling). **Open and FAIR research data** should be a common principle in the water sector. It is imperative that open hydrologists document – favoring open and non-proprietary technologies – all components of their data collection and analysis pipeline which includes information on (1) the hardware and software used, (2) original and processed (meta-) data and databases, (3) data processing and analysis techniques and tools used, and (4) documentation of the overall analysis process, including assumptions and perceptual models (Hall et al., 2022). Reporting all this information when publishing is a major step forward to make hydrologic research more transparent.

Open and FAIR research data management is about applying standardized file names and directory organizational schemes, best practices related to documentation, standards, and (meta-)data, choosing appropriate methods for backing up and archiving data, data management–related mandates and requirements (e.g., data management plans (DMP)), and data security, privacy, licensing, and citation (Borghi & Van Gulick, 2022). Data management plans can help hydrologists to achieve **Open Data** principles and maintaining cyberinfrastructure and community standards. They describe where data will come from, which formats it will be stored in, who will manage and maintain them, how privacy will be maintained (if applicable), and how data and results will be shared and stored in the short and long term (Hall et al., 2022).

As an example of a FAIR data approach, Caravan presents an open, global, community-driven dataset for large-sample hydrology. The open source code also allows anyone to contribute new data and extend the dataset to new regions (Case Study Box 2).

CASE STUDY BOX 2

Caravan a global community dataset for large-sample hydrology by Kratzert et al.



The boundaries and names shown, and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Caravan is an open, community-driven, large-sample hydrology dataset designed for global-scale studies. It is actively maintained by a group of researchers from Google, Fathom and various universities.

The idea of Caravan is to create a large-sample hydrology dataset that is derived from globally consistent meteorological data (ERA5-Land) and catchment attribute sources (HydroATLAS). On release, the dataset included 6830 gauges from 14 different countries with daily streamflow records (median record length ~30 years), 9 meteorological variables (from 1981 – 2020) in different daily aggregations, 4 ERA5-Land states (such as soil moisture), and a total of 221 catchment attributes. Caravan was derived entirely in the cloud, using Google Earth Engine and the corresponding code is open sourced together with the dataset.

Caravan is designed to be easily extensible. The provided code allows anyone to contribute new streamflow data records and extend the dataset to new geographical regions. At the time of writing this article (April, 2024), six community contributions have been published, extending Caravan to a total of 35 countries. Combined with an update from the original developers, Caravan with all community extensions currently totals to 22,495 basins with more than 660,000 years of streamflow observations.

SOURCE https://github.com/kratzert/Caravan

1.3 Stakeholders

There is a multitude of **Open Data** stakeholders ranging from data producers (data collectors) to data providers (responsible for data analysis, management and quality assurance) and to data users (who benefit from data in their work). All these diverse stakeholders, from individuals to organizations across science and industry, are vital to sustainable data practices in hydrology research and operational hydrology. Their collaboration and influence on standards and protocols for **Open Data** should be continuous and ever-changing. The *Info Box* 1 presents a diverse selection of key Open Data stakeholders involved in existing initiatives, platforms, resources, etc.

1.4 Existing initiatives, platforms and resources

The **Open Data** pillar of Open Hydrology relies greatly on availability of various initiatives, platforms and resources. Community progress can accelerate if there is higher awareness on these. Outstanding examples of major initiatives, platforms and resources are listed in the Info Box 1.

The Open Hydrology survey reveals that, within the UNESCO Water Family, the highest awareness exists for **Open Data**, followed by **Open Source**, **Open Education** and **Open Infrastructure** (Figure 3). This is possibly because data underpins everything related to hydrological research, education and services.

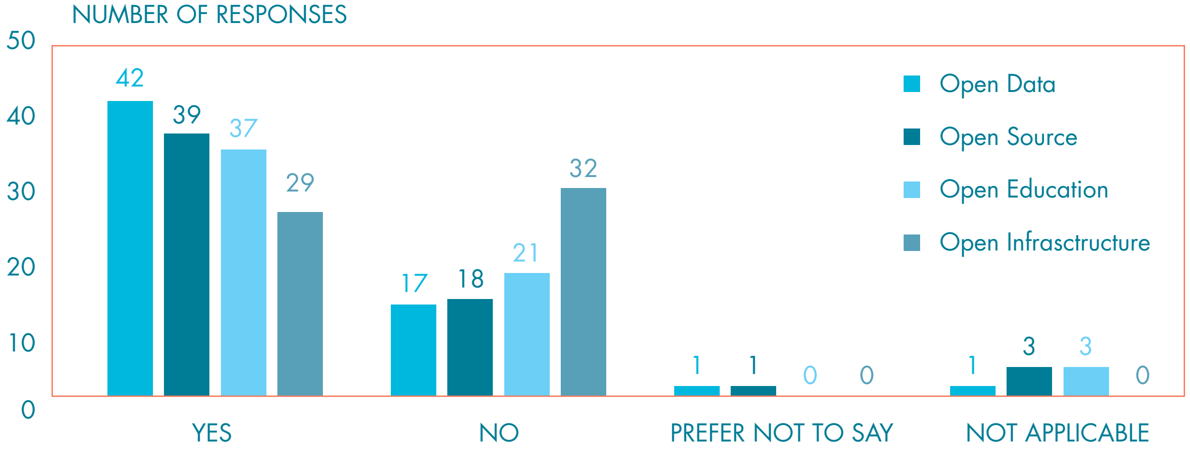


Figure 3. Open Hydrology survey: comparative overview of awareness levels on existing initiatives, tools, platforms, resources, etc.

INFO BOX 1

OPEN DATA: examples of initiatives, platforms, resources, etc.

Relevant Policy documents

- Unified Data Policy (2022) – by the World Meteorological Organization (WMO) https://library.wmo.int/records/item/58009-wmo-unified-data-policy
- UNESCO Water IHP-IX (2022-2029) Priority Area #3 "Bridging the data-knowledge gap" https://unesdoc.unesco.org/ark:/48223/pf0000381318
- DPGA, ITU, WMO (2022) Call for weather, climate & hydrological information datasets to be made open and freely available as digital public goods https://digitalpublicgoods.net/DPGA-Climate_Change_Adaptation_Report.pdf
- Canada Tri-Agency Research Data Management Policy https://science.gc.ca/site/science/en/interagency-research-funding/policies-and-guidelines/research-data-management/tri-agency-research-data-management-policy

Online platforms, data viewers, web apps, repositories:

- Global Terrestrial Network – Hydrology (GTN-H) – by ICWRGC https://www.gtn-h.info/
- The Water Information Network System (IHP-WINS) – by UNESCO https://ihp-wins.unesco.org
- Open EO Platform – by European Space Agency (ESA) https://openeo.cloud/
- Hand-in-Hand (HIH) Initiative – Geospatial platform – by FAO https://www.fao.org/hih-geospatial-platform/en/; https://data.apps.fao.org/
- EU-Hydro – by EU Copernicus https://land.copernicus.eu/en/products/eu-hydro
- HydroMT Data Catalogs – by Deltares https://deltares.github.io/hydromt/latest/user_guide/data_existing_cat.html
- CARAVAN – community effort led by Kratzert et al. https://github.com/kratzert/Caravan
- Canadian Surface Prediction Archive (CaSPAr) – by NSERC Canadian FloodNet https://caspar-data.ca/
- HydroShare – by CUAHSI https://www.hydroshare.org/
- Digital Water Globe – by IAHS https://dwg.smhi.se/dwg/

Projects

- Reference Observatory of Basins for International hydrological climate change detection (ROBIN) https://www.ceh.ac.uk/our-science/projects/robin
- Open data initiative for the UK water utilities – by the UK Water Services Regulation Authority (OFWAT) https://www.ofwat.gov.uk/regulated-companies/open-data-in-the-water-industry/

Journal Special Issue

- Hydrological Sciences Journal: Hydrological Data- Opportunities and Barriers
- https://www.tandfonline.com/toc/thsj20/65/5; https://www.tandfonline.com/toc/thsj20/67/16

1.5 Needs and gaps

For the benefits of **Open Data** to be fully harnessed by the water sector, it is essential to explore the underlying factors that hinder implementation of open and FAIR data practices. These factors are often indicative of needs and gaps that require prime attention. Based on the responses to the *Open Hydrology* survey, the current needs and gaps for open and FAIR data in hydrology can be grouped into two themes: 1) lack of willingness, policy or guidance, and 2) limited technical infrastructure. Specific examples of needs and gaps are:

- Continuation and expansion of existing observation systems as well as new observations systems in accordance with **Open Data** requirements.

- Awareness on available open and free datasets should be increased through improved publicity.

- The many different variety of data sources, types and formats complicate data management and analysis practices. Comprehensive guidelines with step-by-step actions are needed to establish community standards for individual researchers and organizations separately.

- Ensuring higher data quality. More awareness on quality issues of existing open and free datasets (e.g., data gaps, data correction and calibration).

- Lack of knowledge and/or experience in adopting a data management plan.

- Easy access tools and platforms with regularly maintained databases (accessible also to public, i.e., citizen scientists). Site guide maps should be available to make the process of accessing and downloading easier.

- Cyberinfrastructure with poor maintenance and limited functionality negatively impacts the provision (delivery) and use of open data. There is substantial gap in the definition and evaluation of technical requirements on cyberinfrastructures.

- Lack of universal code of conduct (e.g., standardization of exchange formats) or multilateral agreements.

- Inefficient planning and coordination in terms of both policy and digital interoperability within (and across) organizations responsible for open and FAIR data causes delays and coherency issues.

- More communication between data providers and data users to resolve conflicts of interests and legal issues concerning data sharing.

- A study or survey on research data management practices in the hydrology community is needed to explore challenges and find ways to tackle them.

1.6 Opportunities and recommendations

At the individual researcher level, the underlying factors that hinder data sharing are threefold (Gomes et al., 2022): career incentives (scooping, lack of time, lack of incentives), knowledge barriers (data too large, unclear process, unclear value) and reuse concerns (sharing rights, transient storage, sensitive content, inappropriate use). The uncertainty and hesitation further exacerbate the failure to adopt Open Data practices. Thus, overcoming these barriers require targeted training and capacity building by funding agencies and research institutes to incentivize individual behavior. In addition, sharing best practices of research data management can be quite effective too. A summary of best practices in managing water science data is provided by Persaud et al. (2021) and can be used as a guideline to develop a data management plan.

For the benefits of **Open Data** to be fully harnessed in the water sector there has to be strong motivation, effective policy tools and technological infrastructure development. The *Open Hydrology* survey sets out a number of opportunities and recommendations to pursue. These are:

- Creation of an intergovernmental platform as a one stop shop for open and free global operational hydrological observations..

- Comparison and validation of open and free data (i.e., on water quantity, quality and use).

- Provision of guidance, encouragement and training on **Open Data** in hydrology.

- Making more use of the data that communities can collect and involve them in research, creatively communicate the results to communities.

The *UNESCO IHP-IX (2022-2029)* Priority Area #3 “Bridging the data-knowledge gap” is envisaged to achieve improved data exchange and open data policies, and make scientific results useable with operational services. Hence, it presents a great opportunity for the UNESCO Water Family to design concerted efforts on utilizing the value of open and FAIR earth observations and research data.

Open Hydrology Pillar 2: Open Source

2

The *Open Hydrology* framework promotes transparency, reproducibility and free access for all computational hydrological models, software and hardware. Therefore, the second pillar of Open Hydrology, **Open Source**, helps increasing the pace of access to open modelling tools which form the basis of hydrological services. Technological advances combined with digital innovation fosters more practical and efficient procedures in support of **Open Source** software and hardware. Examples include collaborative modelling tools, code sharing platforms and cloud computing.

Public availability of source code, i.e., open sharing of software and hardware in hydrology, can boost the development and implementation of solutions to address environmental and societal challenges where water plays a key role. However, the results of the *Open Hydrology* survey show that sharing of code, software or hardware publicly is not always preferred: those who always share (15%) is five times less than those who sometimes share (75%). Yet willingness to share in the future exists. This might be due to the fact that nearly 90% of those surveyed use open (i.e., publicly shared) code, software or hardware in their work. The many already existing **Open Source** tools (Astagneau et al., 2021), exemplified in community repositories and resources on hydrology (*Info Box 2*), suggests affinity within the hydrology community, especially in academia, to collaborate and benefit from each other's research products.

2.1 Open Software

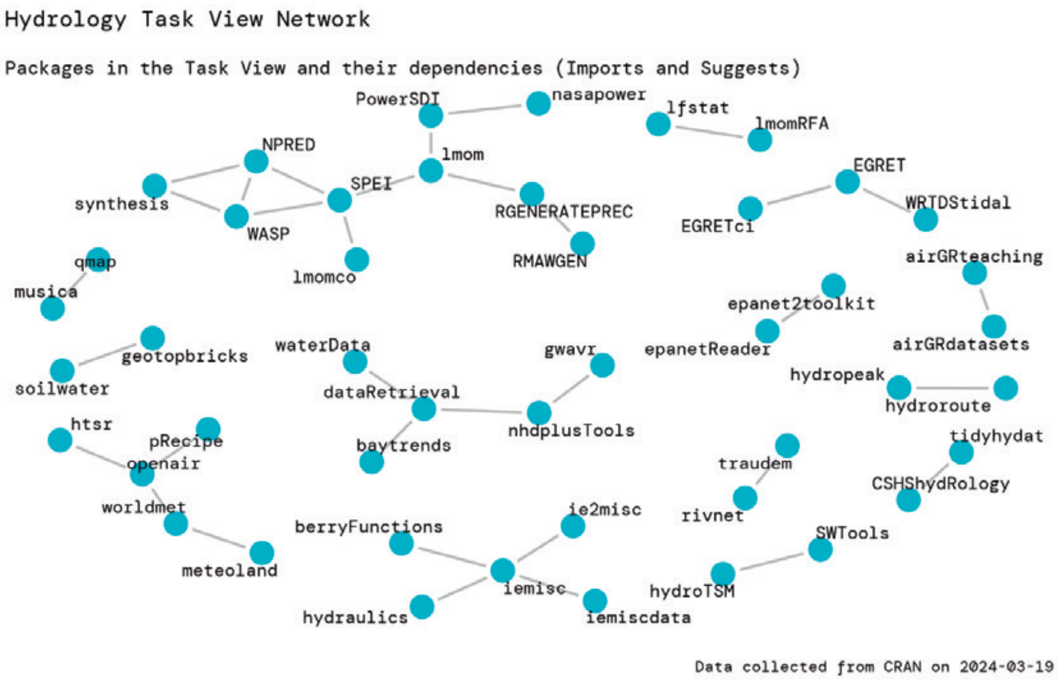
Research software is imperative to academic research; and open source code, software development, and use has lately sparked more attention due to reproducibility concerns. Open software invokes the public availability of source code files, algorithms, scripts, computational workflows, desktop applications, or even operating systems (Schymanski & Schymanski, 2023). Uptake of these software in the water industry and other stakeholders in the public sector improves the quality, efficiency and integrity of hydrological services.

According to Hall et al. (2022), 'open hydrologists test, archive, document, and version control their research code and software using standard open source software protocols and accessible documentation language'. There are different license options for copyright owners to make their code and software openly available (Ramachandran et al., 2021). Open software management helps ensure accessibility, reusability and sustainability of research software. Recently proposed software management plans (SMP; Gomez-Diaz & Recio, 2023) can greatly support implementation standards of open software. Hydrologists can use open source programming languages (e.g., R and Python), version control systems (e.g., Git) and collaboration platforms (e.g., GitHub, GitLan, BitBucket, CRAN, PyPI). The CRAN Task View: Hydrological Data and Modeling, for example, lists information on available R packages specifically relevant to hydrology (Case Study Box 3). The respondents of Open Hydrology survey prefer mostly R and Python in their work which is a promising sign in favor of the **Open Source** pillar of the *Open Hydrology* framework. It should be noted that publications like Astagneau et al. (2021) and Slater et al. (2019) create substantial impact resulting in more widespread adoption of open software developed in R. Other programming languages used include C++, Fortran and Java among others.

It is clear that open software for hydrology exists in a huge variety of programming languages and standards, which limits their re-usability and reproducibility. For example, the eWaterCycle project developed a collaborative platform where hydrologists can work work together to make hydrological modeling fully reproducible, open and FAIR (Case Study Box 4).

CASE STUDY BOX 3

CRAN Task View: Hydrological Data and Modeling by Sam Albers and Ilaria Prosodocimi



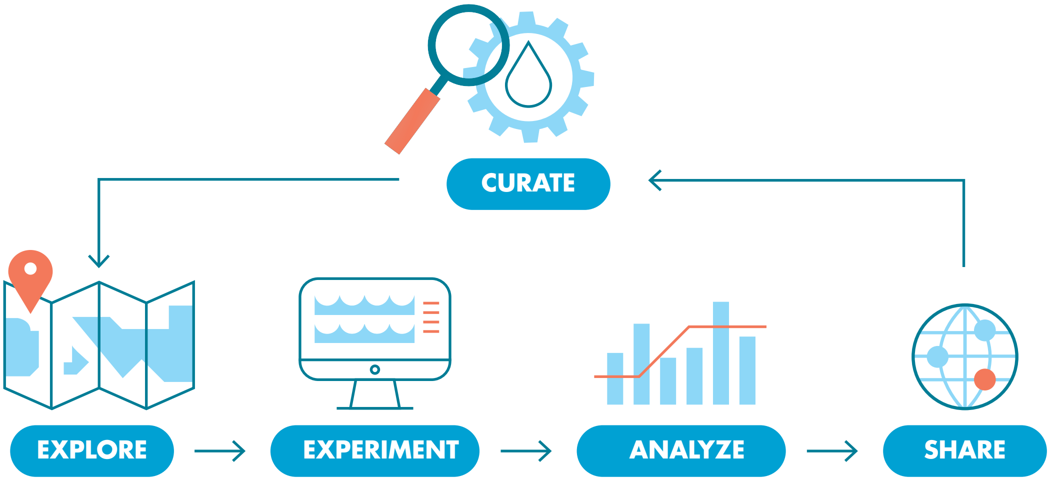
R is a popular open-source statistical computing language which has gained popularity in many fields of applied sciences as a data analysis and general purpose scripting tool. One of the great assets of the R language is the ease of installation of R packages, which extend the capabilities of the programming language through community written add-ons to the base installation.

The Comprehensive R Archive Network (CRAN) acts as a central repository for R and its packages, and maintains the so-called Task Views, which are curated lists of packages useful for a particular field or application. The Hydrology Task View is one of the many task views available on the CRAN website: it references more than 100 packages under the broad categories of Data Retrieval, Data Analysis and Modeling. The Task View is an excellent place to start exploring the many additional tools made available to the hydrological community by open-source developers who make their software available on CRAN or on external repositories such as Github or R-Forge. The packages listed in the Task View allow R users to perform a number of tasks related to hydrology, such as download hydrological data from (inter-)national repositories or generate synthetic data, manipulate data, calibrate and run hydrological models, and estimate statistical quantities of interest. We have examined the inter-connectedness of the Hydrology Task View by visualizing which packages depend on each other using a network graph. The graph illustrates groupings of packages that work with the same data, use the same methods or are otherwise similar for hydrological analysis. R users who are interested in hydrology are invited to contribute to the Task View by suggesting packages which they consider to be useful.

SOURCES https://CRAN.R-project.org/view=Hydrology
https://github.com/cran-task-views/Hydrology/

CASE STUDY BOX 4

eWaterCycle by TU Delft and the Netherlands eScience Center



The release of the eWaterCycle platform and software package available on Zenodo provides the hydrological community with a "FAIR by design" (Findable, Accessible, Interoperable, and Reproducible) platform to do science.

The eWaterCycle platform separates the experiments done on the model from the model code. In eWaterCycle, hydrological models are accessed through a common interface (BMI) in Python and run inside of software containers. In this way all models are accessed in a similar manner facilitating easy switching of models, model comparison and model coupling. Models are added to eWaterCycle as plug-ins and can be added by users themselves. Commonly used models that are available include: PCR-GLOBWB 2.0, wflow, Hype, LISFLOOD, MARRMoT, and WALRUS. While these models are written in different programming languages, they can all be run and interacted with from the Jupyter notebook environment within eWaterCycle. Furthermore, the pre-processing of input data for these models has been streamlined by making use of ESMValTool. Forcing for the models available in eWaterCycle from well-known datasets such as ERA5 can be generated with a single line of code. To illustrate the type of research that eWaterCycle facilitates we provide a repository of examples from a simple "hello world" where only a hydrograph is generated to a complex coupling of models in different languages.

For computational hydrologists that want to work with eWaterCycle a video is provided
https://youtu.be/eE75dtIJ1lk

SOURCE https://www.ewatercycle.org/

2.2 Open Hardware

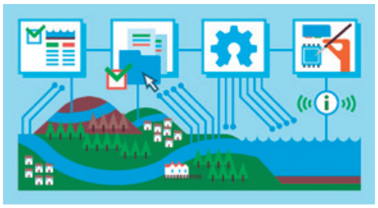
Open source hardware is a complementary movement to open source software, which is gradually gaining momentum in hydrology due to its tangible benefits. It facilitates the sharing of knowledge required for the design and construction of hardware such as electronics and industrial machinery (Turner et al., 2020). Open and low-cost hardware are the two success factors in environmental monitoring and water resources management (Segovia-Cardozo et al., 2021), especially in remote and/or ungauged catchments.

Open hardware might sometimes have non-free and proprietary components and designs. In such cases, transfer and adaptability of measurement technologies is limited due to financial and legal constraints. Hence, a key objective of open hardware should be creation and recreation of universally accessible products, platforms, tools and devices using entirely open and non-proprietary technologies (Turner et al., 2020).

In 2023, UNESCO has launched the training course 'Cookbook for Open Hardware Sensors for Water Resources management', in collaboration with the Imperial College of London and the International Centre for Theoretical Physics (ICTP) (Case Study Box 5). This provides further opportunities for upscaling of Open Hardware for hydrology worldwide.

CASE STUDY BOX 5

Cookbook for Open Hardware Sensors for Water Resources management by UNESCO



The online course 'Cookbook for Open Hardware Sensors for Water Resources Management' is designed to equip participants with the skills to harness open hardware sensors for hydrological monitoring to improve water resources management. The course offers a hands-on approach aimed at building, maintaining, and deploying open hardware sensors to gather crucial data for information decision-making in local environments. Open hardware sensors offer the possibility for accessible and affordable data collection and monitoring, and can fill knowledge gaps for locations and variables that are not well covered by statutory monitoring networks.

The specific learning objectives include understanding hydrological monitoring, building environmental data loggers, setting up remote data reading and storage systems, and deploying sensors effectively. By opening access to knowledge and tools, the course fosters an inclusive and informed approach to water resource management. The course is integrated in the UNESCO Open Learning platform which serves as an open-access hub for capacity building on Open Hydrology.

SOURCE https://openlearning.unesco.org/courses/course-v1:UNESCO+OpenWater+2024/about

2.3 Stakeholders

The stakeholders of **Open Source** software and hardware are primarily researchers working in academia and industry, as well as governmental organizations in charge of water resources monitoring and early warning. From the Science-Policy-Practice interface perspective, National Hydrological Services are particularly relevant stakeholders, as they actively rely on scientific software and hardware developed. With increasing popularity of open source, more and more organizations are expected to dedicate (both individual and collaborative) efforts on relevant policy and guidance on sharing practices of code, software and hardware.

2.4 Existing initiatives, tools, software/hardware and resources

There are numerous hydrology specific **Open Source** initiatives, tools, software (and hardware) as well as resources available. Info Box 2 presents a comprehensive list of leading examples. It is promising to note that the level of awareness within the UNESCO Water Family on **Open Source** is high.

INFO BOX 2

OPEN SOFTWARE AND HARDWARE: examples of initiatives, tools, software/hardware, and resource

Initiatives

- Open Water Network – by UNESCO Chair
  https://www.openwater.network/ https://github.com/OpenWaterNetwork
- Open-Source Science Initiative (OSSI) – by NASA
  https://science.nasa.gov/researchers/open-science/

Online platform

- HydroShare –by CUAHSI
  https://www.hydroshare.org/
- eWaterCycle – by TU Delft & Netherlands eScience Center
  https://www.ewatercycle.org/ https://github.com/eWaterCycle

Repositories, resources

- awesome-open-hydrology – by Schymanski et al.
  https://github.com/Open-Environmental-Science/awesome-open-hydrology
- GitHub public repositories on hydrological-modelling (74 results)
  https://github.com/topics/hydrological-modelling
- CRAN Task View: Hydrological Data and Modeling – by Sam Albers & Ilaria Prosdocimi
  https://github.com/cran-task-views/Hydrology/ https://cran.r-project.org/view=Hydrology
- R resources for Hydrologists – by Riccardo Rigon
  https://abouthydrology.blogspot.com/2012/08/r-resources-for-hydrologists.html
- Python resources for Hydrologists – Riccardo Rigon
  http://abouthydrology.blogspot.com/2016/11/python-resources-for-hydrologists.html
- Open Source Python Packages in Hydrology – Raoul Collenteur
  https://github.com/raoulcollenteur/Python-Hydrology-Tools
- Codes from the EGU GA short course "Using R in Hydrology" – by Young Hydrologic Society (YHS)
  https://github.com/hydrosoc
- Training course on open hardware:
  https://openlearning.unesco.org/courses/course-v1:UNESCO+OpenWater+2023_01/about
- Inventory of models and platform – by WMO
  https://www.floodmanagement.info/e2e-ews-ff-community-of-practice-area/resources/inventory/

Modelling Toolbox

- Geomorphology-based Prediction of Hydrographs in Ungauged Basins (SIMFEN) as an R code or an ergonomic API – by Dallery et al., 2022 and de Lavenne et al., 2023
- HydroMT: Automated and reproducible model building and analysis – by Deltares
  https://deltares.github.io/hydromt/latest/index.html
- Modular Assessment of Rainfall–Runoff Models Toolbox (MARRMoT) – by Knoben et al.
  https://github.com/wknoben/MARRMoT 6

2.5 Needs and gaps

There has been substantial progress on **Open Source** in hydrology. Yet, a number of issues still need to be overcome for not only popularizing but also advancing free sharing and public availability of open software and hardware. The *Open Hydrology* survey reveals important insights as to what the current needs and gaps for open source software/hardware are. These include:

- Lack of willingness at the individual researcher level due to unclear value or benefits.
- Lack of training and capacity building.
- Lack of open source software/hardware policies.
- Limited or no use of software management plans (SMP).
- Lack of awareness on available technical infrastructure.
- Lack of documentation and version control.
- Absence of journals to publish open hardware.
- Lack of imperatives to encourage software/hardware citation in journals.
- Lack of a central repository of open source software/hardware.
- Lack of universal code of conduct (e.g., standardization of sharing formats).
- Equal recognition and adoption of open source software/hardware from the Global South in the Europe, North America and beyond.

2.6 Opportunities and recommendations

It might not be straightforward to promote **Open Source** in hydrology since sharing software/hardware publicly is often perceived as a burdensome task and the fear of scooping prevails. There are various entry points to foster change in attitudes and practices. The Open Hydrology survey demonstrates key opportunities and recommendations to pursue. First and foremost, the hydrology community should endorse **Open Source** as equally important as **Open Data**, and merge efforts to develop relevant policy tools and cyberinfrastructure. Stakeholders responsible for OS at institutional, national and international levels are invited to lead efforts on (or contribute to):

- Creation of software management plans (SMP).

- Development of guidelines on proper acknowledgement and citation of open source software and hardware (e.g., in journal articles) and making it mandatory in hydrology journals.

- Reporting and sharing best practices of open source software/hardware development.

- Creation of an online catalog of existing software/hardware for hydrological applications (not only academic but also operational methods and tools). It should have a mechanism for trusted maintenance. This web-based platform should allow hydrologists register their open source tools regardless of where they are originally shared (e.g., GitHub, HydroShare). Such an online searchable inventory where all research stakeholders can look up the available models, code and software/hardware options can enhance the Science-Policy-Practice interface.

- Establishing a system of approval at the national level by research or government institutions.

- Promoting the use of open source software/hardware in classrooms while supporting faculty members to learn and practice their use.

- Strengthen participation of under-represented groups in open source applications and development.

The *UNESCO IHP-IX (2022-2029)* Priority Area #3 “Bridging the data-knowledge gap” supports capacity building to develop, share and apply scientific tools for data processing – e.g., data assimilation and visualization methods, quality assurance protocols to connect existing databases and outreach protocols (output 3.4). In this respect, **Open Source** software/hardware plays a critical role in sustaining functional and efficient systems for the use of National Hydrological Services and the UNESCO Water Family.

Open Hydrology Pillar 3: Open Education

3

Teaching, education and training in hydrology forms the cornerstone of success in tackling the world's water-related problems by raising highly qualified water experts (Seibert et al., 2013). Teaching and education should go hand in hand with scientific research. Hydrology is a discipline that favors innovative teaching methods and learning activities. Besides, there cannot be real progress in practice and policy if the progress in hydrology research is not incorporated into education curriculums and teaching materials (Ruddell & Wagener, 2015).

Open Science (OS) offers a great opportunity to transform both education and teaching in times of rapid advancements in technology, knowledge generation and science governance. The third pillar of *Open Hydrology*, **Open Education**, promotes openness, FAIRness and inclusivity in two areas: education and teaching.

Hydrology and water-related sciences at universities has picked up on the inevitable changes brought by the disruptions due to the COVID-19 pandemic (Fischer & Tatomir, 2022). Consequently, one of the current highlights of the hydrology agenda is public and free availability of courses, tools, materials and practices.

According to the *Open Hydrology* survey, OS is as important for teaching (~87%) as for research (~97%) (Figure 4). The survey also shows that there is no discrepancy between those who share and those who use open educational and teaching resources. This result supports the argument that when the decision to share or not lies in the individual researchers it is more straightforward to harness a culture of openness.

3.1 Open Education

The true engine of the *Open Hydrology* framework is open education, which calls for publicly available and free educational systems, programs and resources inclusive of all hydrologists (or those aspiring to become hydrologists) regardless of their professional levels and backgrounds.

Educational priorities in hydrology relating to openness have long been recognized at institutional and intergovernmental levels, fostering also personal engagement by academic hydrologists. Remote and online education (Mulvey et al., 20222) has been a feasible and effective alternative to traditional education systems, especially for hydrologists in the global south. Making educational and learning resources openly and freely available is utterly important at both undergraduate and postgraduate levels. Also, open access educational resources are valuable to support continuing education of practicing hydrologists (Ruddell & Wagener, 2015).

A key aspect of open education concerns is making reproducible research and OS training the norm in hydrology (Kohrs et al., 2023). The importance of open access educational infrastructure is another essential element supportive of equity due to its role in **Open Source** and **Open Data** (Castronova et al., 2023).

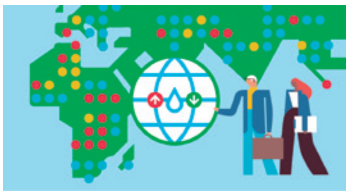
UNESCO launched the Open Learning platform in 2020, to address the challenges to access physical training during the COVID19 Pandemic, which has become a large resource of hydrology-related courses that are open access to all. In 2023, the platform had already attracted over 33 000 learners, demonstrating the importance of open access infrastructure to education (Case Study Box 6).

CASE STUDY BOX 6

Open Learning platform by UNESCO

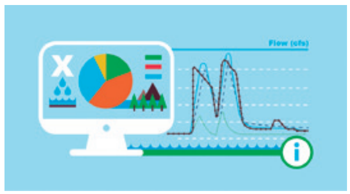
The UNESCO Open Learning platform, endorsed by UNESCO's Intergovernmental Hydrological Programme (IHP), serves as an open-access hub for capacity-building materials, training modules, and educational resources related to water resources management. Functioning as a platform for the dissemination of knowledge and best practices, it fosters the enhancement of technical competencies and expertise within water-related disciplines. This platform brings together scientists, researchers, and policy-makers globally to collaboratively curate Massive Open Online Courses (MOOCs) addressing diverse water-related subjects, with particular emphasis on engaging youth, women, and indigenous communities. The Open Learning platform facilitates capacity-building on Open Hydrology, by offering online courses on Open Data, Open Source, Open Education, Open Infrastructure, Open Publishing, and Open Participation. It serves as a hub for advancing scientific knowledge and exploration in hydrology and associated fields, while advocating for the widespread acceptance, promotion, and evolution of Open Hydrology on a global scale.

Ongoing



Drought and Flood Risk Management for Policy Making

Introduction to Climate Risk Informed Decisión Analysis



Hydrologic Modeling with HEC-HMS

SOURCE https://openlearning.unesco.org/program/intergovernmental-hydrological-programme-ihp/

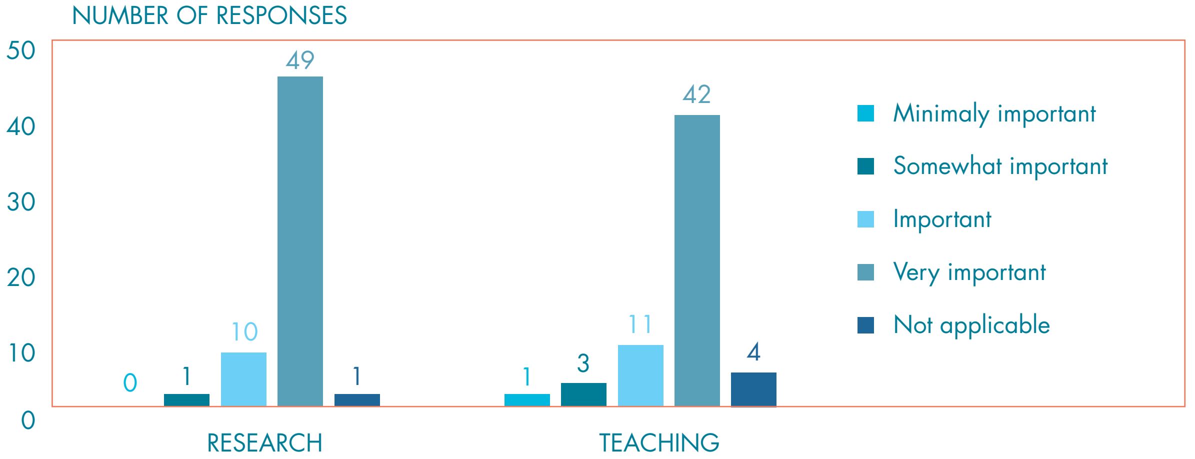


Figure 4. Open Hydrology survey: importance of Open Science for research vs. teaching

3.2 Open Teaching

In the *Open Hydrology* framework, open teaching refers to availability, accessibility and inclusivity of teaching methods and materials. Openness in teaching focuses on new principles and approaches to curriculum development, hybrid teaching formats (e.g., online field trips – Geange et al., 2020), coding and laboratory experiments in classes.

Open access teaching resources (textbook, video, audio, games, etc.) designed to facilitate effective learning and knowledge acquisition in hydrology are regrettably scarce. Similarly, novel teaching formats and methods for remote and online education are not common either (Lane et al., 2021; Mulvey et al., 2022; Van Loon, 2019).

As a computational science, teaching of hydrologic content strongly requires coding skills. Hence, teaching coding in physical, hybrid and virtual classrooms is highly essential in support of the *Open Hydrology* pillars, **Open Source** and **Open Data** – particularly for hydroinformatics and water data science instruction (Jones et al., 2022). Sharing of best practices towards this goal can be helpful to those tasked with designing or revising hydrologic coursework (see, e.g., Kelleher et al., 2022; Marti et al., 2023; Delaigue et al., 2023).

3.3 Stakeholders

In essence, **Open Education** is of interest to all stakeholders in hydrology regardless of the Science-Policy-Practice sector they are engaged in. Both researchers and practitioners should be exposed to continuous education and training at every level of their career. Major ongoing initiatives on hydrology education and teaching that promote OS are led by UNESCO and the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). Open Education has a long history within the UNESCO-IHP and the UNESCO Water Family. Also the International Association of Hydrological Sciences (IAHS) Working Group has contributed greatly. Close inspection of the *Info Box 3* highlights the need for not only more but also more diverse actors who can commit to the **Open Education** pillar of the *Open Hydrology* framework.

3.4 Existing initiatives, platforms, resources, etc.

The number of existing initiatives on **Open Education** is not too many, however those in place are well established. In recent years, more and more small-scale volunteer efforts by individual researchers have emerged. Interestingly, these create a ripple effect higher than expected within hydrology and water-related disciplines. Some of the well-known examples can be seen in the *Info Box 3*.

According to the *Open Hydrology* survey, **Open Education** comes at the third rank in terms of awareness level right after **Open Data** and **Open Source** (Figure 3). However, the issue of awareness on publicly and freely available opportunities remains. In the UNESCO Water Family, only 60% considers themselves aware of ongoing initiatives, platforms, resources, etc. that support the **Open Education** pillar of *Open Hydrology*.

INFO BOX 3

OPEN EDUCATION: examples of policy document, initiatives, platforms and resources

Policy documents

- IHP-IX (2022-2029) Priority Area #2 "Water Education in the Fourth Industrial Revolution including Sustainability" https://unesdoc.unesco.org/ark:/48223/pf0000381318

Online learning platforms, repositories

- UNESCO Open Learning https://openlearning.unesco.org/
- HE Delft OpenCourseWare https://ocw.un-ihe.org/
- HydroLearn by University of Louisiana et al. https://www.hydrolearn.org/
- CUAHSI Virtual University https://www.cuahsi.org/virtual-university
- CUAHSI Educational Resources for Hydrology & Water Resources https://www.hydroshare.org/resource/148b1ce4e308427ebf58379d48a17b91/
- The Hydrology Micro-video project (YouTube Channel) – by John Selker

Resources (web-apps, books, etc.)

- Bookdown with examples of using R in hydro (links to notebooks to download in GitHub) – by JP Gannon https://vt-hydroinformatics.github.io/
- Rshiny Water Balance web-app, slides, and activities – by JP Gannon https://cuahsi.shinyapps.io/WaterBalance/ https://www.hydroshare.org/resource/0ecadff374aa4a2b84e41f146d39f48c/
- airGRteaching: an open-source tool for teaching hydrological modeling with R – INRAE & CNRS https://cran.r-project.org/web/packages/airGRteaching/index.html https://hydrogr.github.io/airGRteaching/

Courses on education and teaching

- Open and Distance Education" – UNESCO Open Learning https://openlearning.unesco.org/courses/course-v1:UNESCO+UNESCO-06+2022_01/about

Journal Special Issue

- Innovations in Remote and Online Education by Hydrologic Scientists (2022, in "Frontiers in Environmental Science" - edited by Bridget Mulvey, Adam Scott Ward, Anne Jefferson, Jerad Bales) – by CUAHSI https://www.frontiersin.org/research-topics/22677/innovations-in-remote-and-online-education-by-hydrologic-scientists

3.5 Needs and gaps

Despite the importance and increasing popularity of **Open Education** in hydrology, progress on coordination of existing efforts has been inadequate. These efforts are in general mostly small-scale short-lived initiatives. The *Open Hydrology* survey sheds light into some of the reasons behind this issue. Lack of time, motivation and funding are the three main issues that researchers must overcome. Current needs and gaps on **Open Education** are:

- An open access, integrative, interdisciplinary hydrology textbook designed in consideration of the *Open Hydrology* framework. Two separate versions, one for undergraduate and one for postgraduate level, are needed.
- Lack of coordinated, collaborative resource development and central sharing platforms which are sustained continuously (Mulvey et al., 2022).
- Low participation in activities and strategies due to little interest by the broader hydrology community.
- The multi-linguality aspect is not addressed adequately.
- Lack of guidelines on developing course curriculums that integrate all components of the *Open Hydrology* framework.
- Lack of systematic pedagogical evaluation of education and teaching, with focus on the pillars of the *Open Hydrology* framework.
- Lack of OS training or courses in hydrology curriculums.
- Lack of support and training on hybrid education and teaching.
- The general lack of institutional and multilateral funding to finance activities towards improving **Open Education** in hydrology.

3.6 Opportunities and recommendations

Lately, the call for *Integrated, Coordinated, Open science, and Networked* (ICON) principles and practices in geosciences education opened new possibilities, including for hydrological sciences (Fortner et al., 2022). The hydrology community should take urgent steps to create a better future for open hydrology education and teaching. Some of these steps are also recommended by the respondents of the *Open Hydrology* survey. Most importantly, it is advised to develop accessible online resource collections and databases on hydrology education and teaching. Other recommendations are:

- A web platform that brings together globally available open access educational resources, in the form of an online catalog. Ensuring wide publicity through tailored dissemination strategies is key to its success.

- An online repository of teaching methods and tools that utilize the *Open Hydrology* framework components (including Citizen Science).

- A 'call for projects' to incentivize well-designed and coordinated efforts aimed at advancing current practices of **Open Education** and go beyond the one institute implementation.

- Inclusion of OS training and practices (such as seminars, workshops, etc.) in hydrology education and teaching – if possible, with issuance of certificates for those who enrolled in and successfully completed.

- Design of an intergovernmental system to strengthen the pedagogical and didactic capacities of teachers and instructors.

- An international policy instrument to support open education and teaching practices in hydrology.

Above all, the **Open Education** pillar of the *Open Hydrology* framework requires OS training and reproducible research to be embedded in hydrology teaching and education. Kohrs et al. (2023) shares eleven strategies for making OS training and reproducible research the norm at research institutions (Figure 5). There are three types of strategies: 1) adapting research assessment criteria and program requirements (cyan), 2) offering training (purple), and 3) building communities (yellow). Responsibilities and capabilities of instructors, researchers, supervisors, mentors, institutional leadership and administrative staff are many and diverse. It is crucial that these strategies are taken up by hydrologists in academia too.

A. STRATEGIES

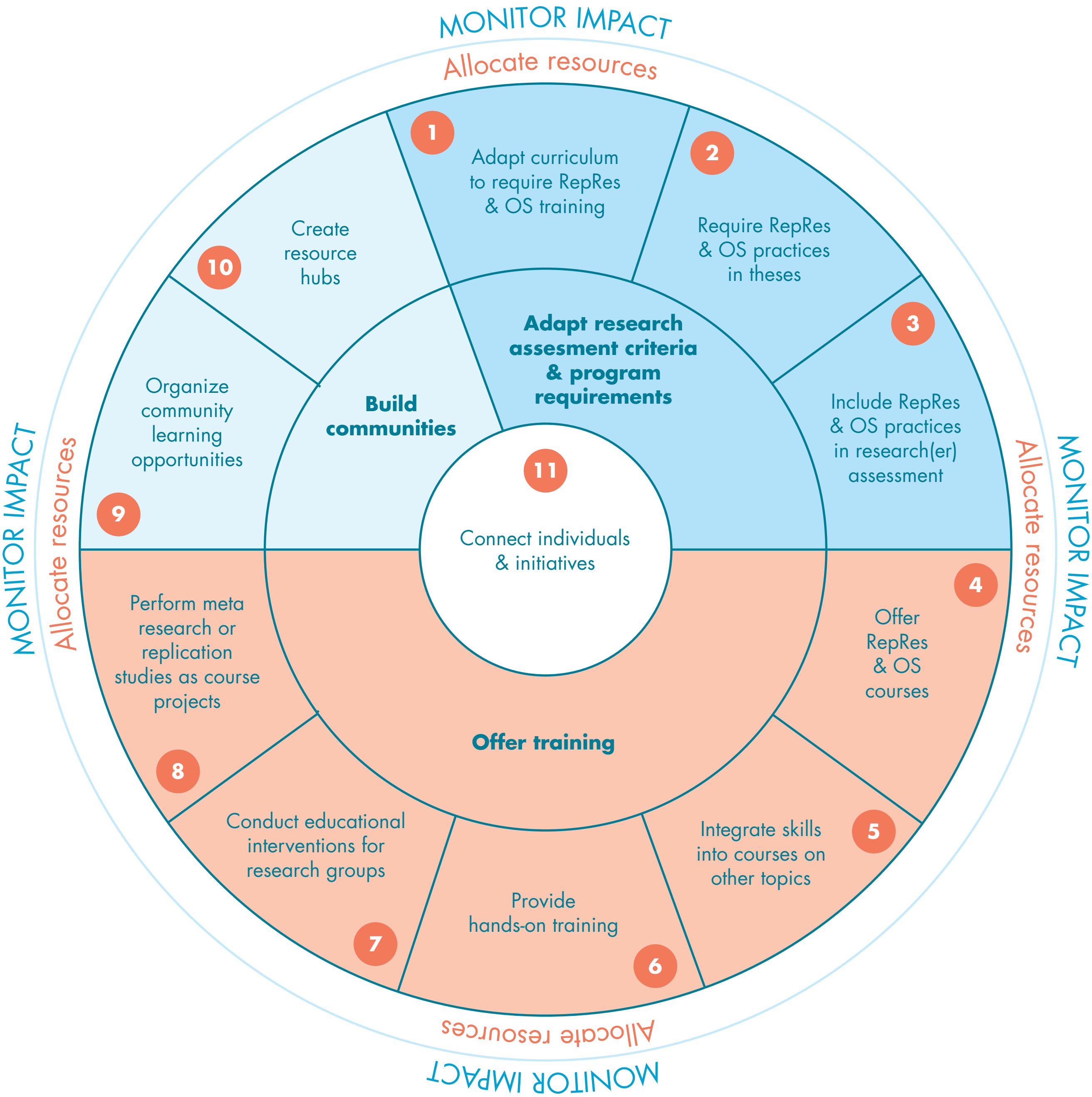
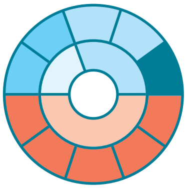


Figure 5. Eleven strategies for making OS training and reproducible research the norm at research institutions (Source: Kohrs et al., 2023)

B. WHAT CAN I DO?

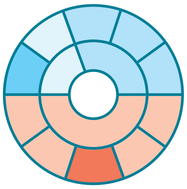


INSTRUCTORS

This includes researchers, research support, and admin staff with teaching responsibilities

AMPLIFY OTHER STRATEGIES:

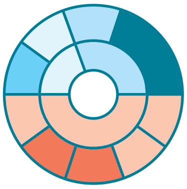
Provide expert guidance in how to implement strategies 7 & 8



RESEARCHERS

AMPLIFY OTHER STRATEGIES:

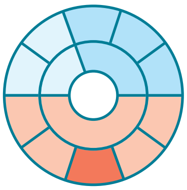
Request, organize, or facilitate training, join communities, and advocate for changes in assessment and evaluation criteria



SUPERVISORS

AMPLIFY OTHER STRATEGIES:

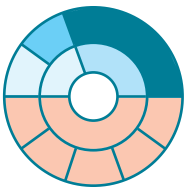
Request training, encourage students to take advantage of training and community learning opportunities, and support the uptake of RepRes & OS practices into theses



MENTORS

AMPLIFY OTHER STRATEGIES:

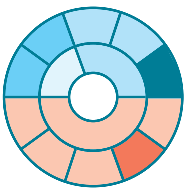
Encourage mentees to participate in training, join communities, and integrate RepRes & OS practices into their research



INSTITUTIONAL LEADERSHIP

AMPLIFY OTHER STRATEGIES:

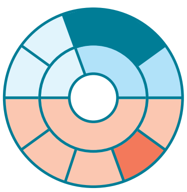
Encourage people to take training and join communities



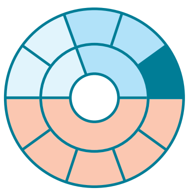
RESEARCH SUPPORT OR ADMIN. STAFF

AMPLIFY OTHER STRATEGIES:

Organize, facilitate, or request training



CURRICULUM COMMITTEE MEMBERS



HIRING & EVALUATION COMMITTEE MEMBERS

Open Hydrology Pillar 4: Open Infrastructure

4

In scientific research, cyberinfrastructure that is publicly available and free is key to implement Open Science (OS) principles and approaches, specifically with regards to Open Data, **Open Source and Open Education.**

In the *Open Hydrology* framework, openness in both the digital infrastructure and the hydrological services provided are considered. The fourth pillar, **Open Infrastructure**, embodies two subcomponents: open infrastructure and open services. While the former refers to relevant infrastructure that support hydrologists in their work to access and share research data, workflows, analyses or code/software, the latter is about provision of hydrological services for practitioners, decision makers, etc.

The benefits of infrastructures and services that enable hydrologists achieve openness and FAIRness are quite substantial: at individual level, for the community, in the short-term, and in the long-term. However, the *Open Hydrology* survey findings indicate that not a limited number of hydrologists within the UNESCO Water Family use open and free infrastructures and services (only 40%). Those that host or contribute to hosting these services is even less (30%). It should be noted that **Open Infrastructure** has the lowest rate of usage compared to **Open Data, Open Source** and **Open Education** (Figure 6). This clearly shows the need for more awareness, support, guidance and training on the **Open Infrastructure** pillar of the Open Hydrology framework.

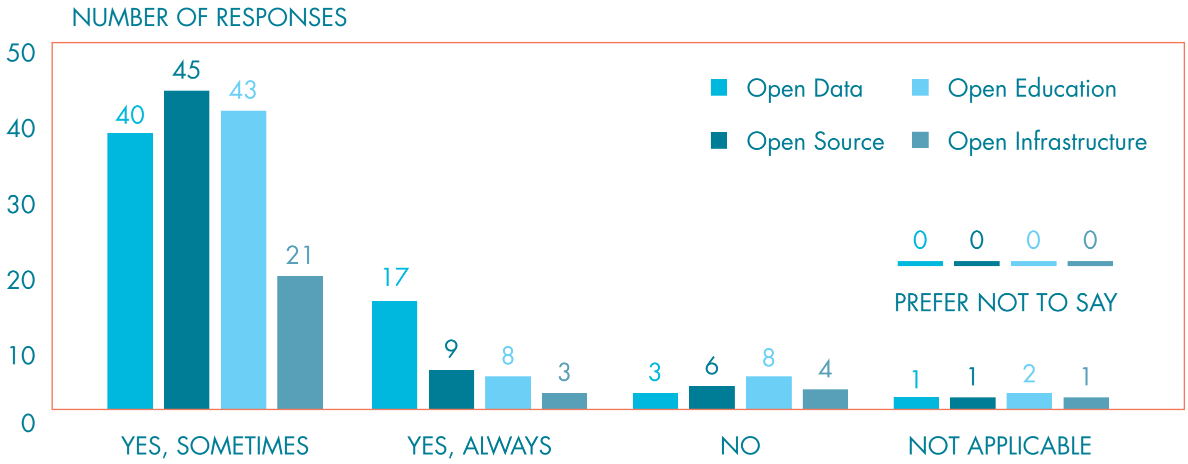


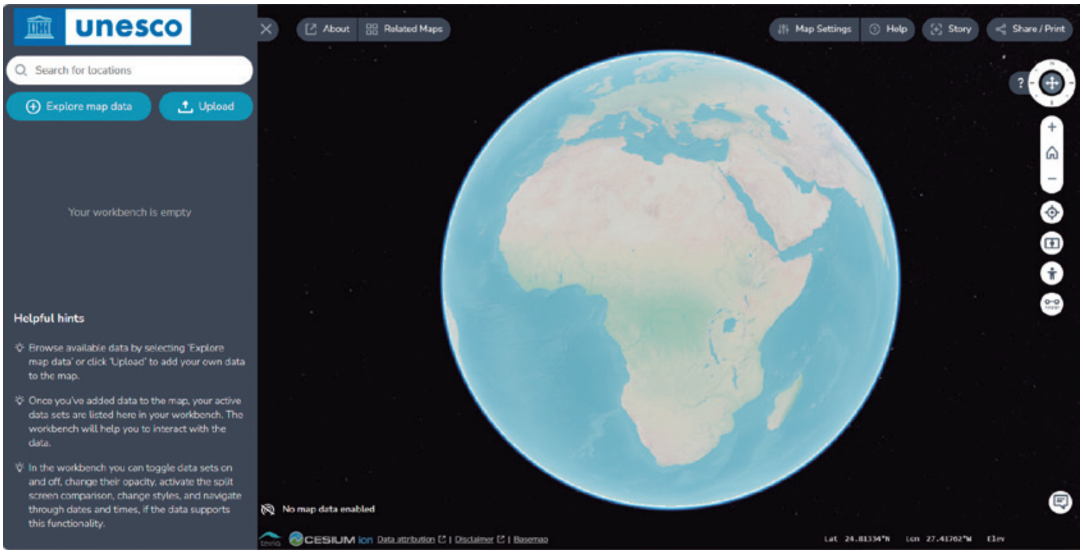
Figure 6. Open Hydrology survey: comparative overview of usage rates for the pillars Open Data, Open Source, Open Education and Open Infrastructure

4.1 Open Infrastructure

OS (cyber)infrastructure involves open and free web-based platforms for sharing research data and software, as well as public code repositories (e.g., CRAN for R, GitHub, Zenodo) and computational notebooks (e.g., R Markdown, Jupyter Notebooks) for sharing workflows, and analyses. There are also infrastructures created and maintained by hydrology specific actors. The IHP-WINS by UNESCO, HydroShare by CUAHSI, and the Digital Globe by IAHS are three leading examples (Case Study Box 7, 8 and 9, respectively). All these help hydrologists collaborate with each other flexibly and independently. Within the UNESCO Water Family, there are a diverse range of tools and platforms used by hydrologists – with R Markdown and Jupyter; and GitHub and CRAN for R (code/software sharing platform) being the most preferred, as evidenced by the *Open Hydrology* survey.

Open (cyber)infrastructure is a major necessity for teaching education as well. For example, community cloud computing infrastructures can help promote equitable education in hydrology and water-related disciplines (Castronova et al., 2023). It should be noted that a certain level of training is required for hydrologists to develop open (cyber)infrastructures skills.

CASE STUDY BOX 7
Water Information Network System (IHP-WINS) by UNESCO



The Intergovernmental Hydrological Programme's Water Information Network System (IHP-WINS) is developed as a contribution to Open Science. The platform supports seamless data sharing, integration and capacity-building, and provides thematical viewers for evidence-based decision-making. Built upon the foundation of advancing sustainable water practices, IHP-WINS endorses the FAIR principles: Findability, Accessibility, Interoperability, and Reusability. Beyond being a robust, open repository for data, IHP-WINS provides tools to transform this data into actionable insights, enhancing accessibility to information. Thematic Geospatial Viewers enable the tailored interpretation of data, allowing users to analyze information through tempo-spatial visuals such as maps and time-series plots. IHP-WINS additionally serves as a central hub that guides users to other relevant platforms, organizations, and partners, while highlighting the latest accomplishments, capacity-building initiatives, and publications. IHP-WINS provides a direct contribution to the open hydrology principles through its information network system, emphasizing collaboration, data accessibility, and ongoing learning opportunities to address global water challenges effectively.

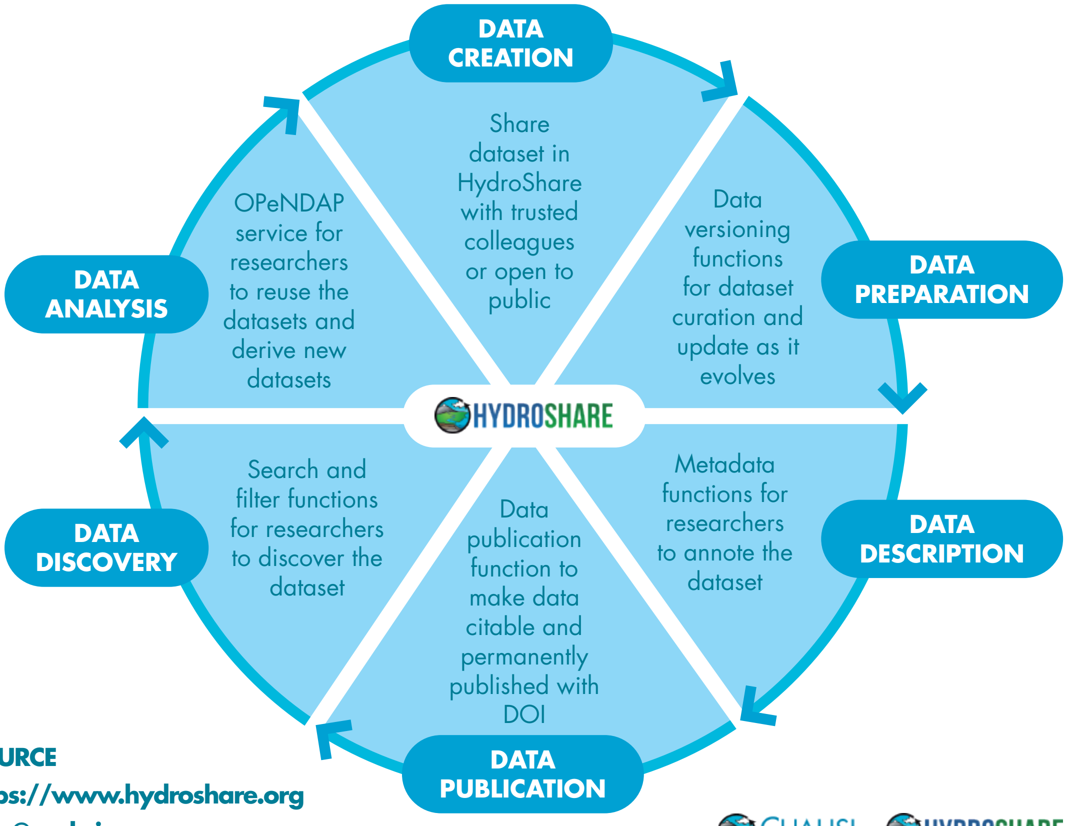
SOURCE http://ihp-wins.unesco.org/

CASE STUDY BOX 8

Online collaboration environment for sharing data, models and code by CUAHSI

HydroShare is a U.S. National Science Foundation funded web-based water data repository operated by the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). It is open source and was developed to enable users to share and publish data, models, scripts, and applications. As a file agnostic repository with publication and collaboration tools built in, HydroShare supports user data across the data lifecycle (Fig. 1). It helps users meet Findable, Accessible, Interoperable, and Reusable (FAIR) data mandates. HydroShare serves the data sharing, collaboration and publication needs of a broad range of users.

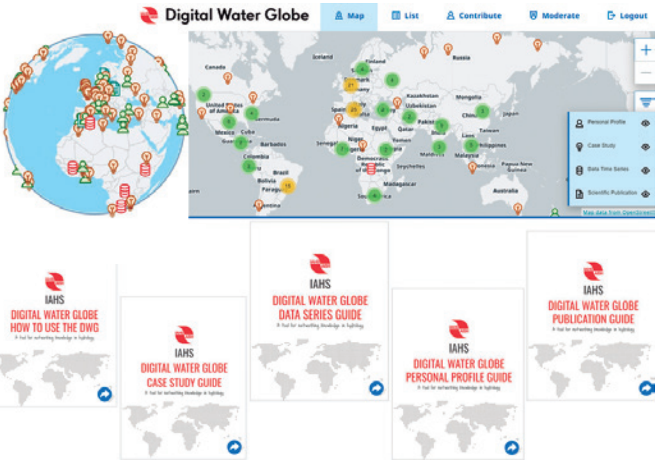
Beyond content storage, HydroShare is integrated with CUAHSI's free cloud computing resources, enabling users to reproducibly run code, models, and analyses and share documented workflows, reducing challenges of software installation and configuration. Anyone can upload, share, and publish water related data in HydroShare free of charge. Researchers using HydroShare advance understanding and generate knowledge through collaboration and integration of information from multiple sources. For several specific data formats common in hydrology the resource data model holds additional content specific metadata and supports web services, enabling interoperability and analysis with other systems. A well documented API and helpful Python client (HSclient) enable programatic, object oriented interaction with HydroShare resources, such as updates to ongoing datasets.



SOURCE
https://www.hydroshare.org
help@cuahsi.org

CUAHSI HYDROSHARE

CASE STUDY BOX 9
Digital Water Globe (DWG) by IAHS



The Digital Water Globe (DWG) gathers case studies using a web platform to facilitate scientific communication and knowledge exchange across the globe. The development of the tool is community driven but anyone can access and contribute content, which is tagged by key-words for easy filtering and attached with coordinates to display position on the Earth. It runs under a Creative Commons license (CC BY-SA 4.0).

As such, the DWG displays global hydrological knowledge and scientific findings at specific sites and it facilitates new networking and knowledge management through personal profiles, case studies, links to publications and to datasets. When populated, the DWG will stimulate and facilitate engagement, interactions, and dialogues between IAHS members and other scientists, stakeholders, experts, practitioners, media, and citizens.

The DWG promotes internal community building within and between IAHS Commissions, Committees and Working Groups, as well as IAHS Scientific Decades, i.e. Prediction in Ungauged Basins (PUB) and Changes in hydrology and society (Panta Rhei), and the current Science for Solutions decade: Hydrology Engaging Local People IN one Global world (HELPING).

As the items in the DWG are also tagged to Unsolved Problems in Hydrology (UPH) and Sustainable Development Goals (SDG), the tool is well aligned with UNESCO IHP-IX (2022-2029). It promotes principles from UNESCO Open Science, as well as FAIR principles (Findable, Accessible, Interoperable and Reusable) of data management and CARE principles (Collective benefit, Authority to control their data, Responsibility to engage respectfully with communities, Ethics to promote justice).

The boundaries and names shown, and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

SOURCE https://iahs.info/Initiatives/digital-water-globe/

4.2 Open Services

Provision of hydrological services to different stakeholders spanning water, energy, agriculture, etc. across science, practice and policy has direct implications for management of water resources and adaptation to climate change. In this context, open and free online platforms such as data viewers, web-apps, and databases are used extensively all over the globe. Of particular interest is the delivery of hydrological observations along with their analyses, predictions and derived products for flood and drought forecasting at various scales.

4.3 Stakeholders

The stakeholders of **Open Infrastructure** are many and varied due to the nature of its/their benefits. From developers to users, all the infrastructure and services require strategic partnerships, learning and innovation. As can be seen in the Info Box 4, current stakeholders of (hydrological) services are in essence mostly intergovernmental and/or multi-institutional. This is generally due to the fact that provision of open and free (cyber)infrastructures and services demands for strong political will as well as large financial resources to keep them running smoothly and efficiently.

4.4 Existing infrastructures, services, platforms, repositories

The **Open Infrastructure** pillar of the *Open Hydrology* framework has many examples of initiatives *(Info Box 4)*. Some of these are open and free hydrological services which are equally popular among researchers and practitioners. The *Open Hydrology* survey confirms that there is a need to achieve higher awareness within the UNESCO Water Family members on existing initiatives, platforms, resources, etc. that support open infrastructures, services, platforms, repositories, etc. in hydrology (Figure 6).

INFO BOX 4

OPEN INFRASTRUCTURE: examples of infrastructures, services, platforms, repositories, etc.

Infrastructure

- The Water Information Network System (IHP-WINS) – by UNESCO https://ihp-wins.unesco.org
- Digital Water Globe – by IAHS https://dwg.smhi.se/dwg/
- HydroShare –by CUAHSI https://www.hydroshare.org/
- Global Delta App – by Utrecht Uni https://experience.arcgis.com/experience/c3fbc08de72d4977a150ca73f31d1098
- HydroATLAS – by World Wildlife Fund US & McGill University et al. https://www.hydrosheds.org/hydroatlas
- GroMoPo — Groundwater Model Portal – by Zamrsky et al. https://gromopo.streamlit.app/
- Flood and Drought Monitors - by Southampton University https://hydrology.soton.ac.uk/apps/

Services (online platforms: data viewers, web-apps, databases, etc.)

- NASAaccess – A tool for access, reformatting, and visualization of remotely sensed earth observation and climate data https://github.com/nasa/NASAaccess
- HydroSOS - Global Hydrological Status and Outlook System https://eip.ceh.ac.uk/hydrology/HydroSOS/
- WHOS - Hydrological Observing System https://hydrohub.wmo.int/en/whos
- WHYCOS - World Hydrological Cycle Observing System https://hydrohub.wmo.int/en/world-hydrological-cycle-observing-system-whycos
- GEOGloWS Global Streamflow Forecasting https://www.geoglows.org/pages/geoglows-streamflow-forecasting
- World Water Map – by Utrecht Uni & National Geographic https://worldwatermap.nationalgeographic.org/#exploration-map
- Perceptual Models Around the World – by McMillan Hydrology Lab
- https://sdsugeo.maps.arcgis.com/apps/dashboards/71e3e8cf745847928ecb7db8467b023b
- HydroHub - Platform to share and visualize data – by Juliane Mai
  https://hydrohub.org/
  https://juliane-mai.com/projects.html#hydrohub
- Aqueduct – by WRI, WB, Deltares, IVM, VU, Utrecht Uni https://www.wri.org/aqueduct
- Aqueduct Water Risk Atlas https://www.wri.org/applications/aqueduct/water-risk-atlas/
- Aqueduct Country Rankings https://www.wri.org/applications/aqueduct/country-rankings/
- Aqueduct Food https://www.wri.org/applications/aqueduct/food/#/
- Aqueduct Floods https://www.wri.org/applications/aqueduct/floods/#/
- Database Global Dam Watch – by WWF, EC JRC, WRI, Nature Conservancy, UN WCMC https://www.globaldamwatch.org/
- Climate Information – by Green Climate Fund, WMO, WCRP, SMHI https://climateinformation.org/
- Interactive Database of the World's River Basins (Beta) – by UN Global Compact - the CEO Water Mandate, WWF, WRI http://riverbasins.wateractionhub.org/

4.5 Needs and gaps

Open Hydrology cannot exist without the availability of open and free web-based platforms, public code repositories or online tools such as data viewers, web-apps, and databases. Current needs and gaps for the **Open Infrastructure** pillar should be carefully identified and appropriately addressed in an integrated and continuous manner. To this end, the *Open Hydrology* survey provides valuable insights. Specific examples of needs and gaps are:

- Awareness on available open and free infrastructure and services should be increased.

- Lack of promotion (and support) to encourage hydrologists to use existing open and free infrastructure and services, particularly those working in the industry.

- Lack of technical skills and training in using various (cyber)infrastructure and services available to researchers.

- Continuation and expansion of existing (cyber)infrastructure and services.

- More intergovernmental and/or multi-institutional collaboration and investment.

4.6 Opportunities and recommendations

The future of **Open Infrastructure** is exciting, and the hydrology community holds a great advantage as to determine how and in what way the technology and innovation can be brought up to support OS principles and approaches. First and foremost, intergovernmental and/or multi-institutional funding on collaborative projects will certainly play a critical role in enhancing availability and efficiency of open (and free) infrastructures and services. The *Open Hydrology* survey outlines further opportunities and recommendations to pursue:

- Diversification of available infrastructures and services with principles of centralization and integration in mind.

- Strategic focus on improving the buy-in by relevant stakeholders in support of optimized funding and hosting opportunities.

- Enhanced role of local infrastructure for inter-institutional, governmental and non-governmental collaborative actions with equal representation and participation across nations and continents.

- Adoption of frameworks and regulations to ensure diversity and centrality in coordination efforts.

Open Hydrology Pillar 5: Open Publishing

5

Publishing work outputs is a common tradition in many sectors and disciplines. Academic communication through journal publications and at conferences are by far the most prominent form of research assessment and knowledge sharing. Thus, openness, transparency and inclusivity in publishing articles, data and software underpins scientific legitimacy and quality.

Open Science (OS) has influenced the culture of publishing in all disciplines, and hydrology is no exception (Clark et al., 2021). The principle of open publishing by Hall et al. (2022) states that 'open hydrologists publish all components of their research on citable platforms and in journals that follow ethical standards and are accessible to both the research community and general public'. Within the UNESCO Water Family, this principle is rated of highest importance making it the most popular after open data collection and analysis.

The fifth pillar of the *Open Hydrology* framework, **Open Publishing**, deals with three aspects: open access, open license and open peer review. According to the *Open Hydrology* survey, open access is considered of higher importance followed by open license with open peer review the least. On the whole, it is the combination of all these three aspects that will shape the success in the publishing landscape of hydrology research and practice. Whether it is a journal article, conference proceeding or a client report, the **Open Publishing** pillar presents a clear and valid context for the hydrology community.

5.1 Open Access

Open access (OA) refers to unrestricted (online) access to publications at no cost – though with limited restrictions on reusability that are defined by licenses. As such, open access publishing contributes to transparency, reproducibility and accessibility of scientific results. There is an increasing demand for open access as more research funding agencies, and users of research outputs, oblige authors to publish their articles openly (Quinn et al., 2018). This motivates journals to shift their business strategy from the "reader pays" to the "author pays" (Clark et al., 2021; Blöschl et al., 2014).

Publication finance policies of journals are diverse for publishers which can be non-profit or for-profit (i.e., commercial), and associated with non-profit associations or not. There are diverse open access models (Hall et al., 2022; Clark et al., 2021;): gold (diamond, fully open), hybrid (OA is optional), green (self-archiving) and bronze (OA after the embargo period). The cost of open access publishing is called the article publishing charge (APC), however some journals offer fee waiver or discount for authors from developing countries. When determining where to publish, it is important that authors consider journals' policies on preprint, archiving and copyright/license as well as embargo times (Hall et al., 2022), in conjunction with journals' intrinsic quality management processes and values (Koutsoyiannis and Kundzewicz, 2007; Cudennec and Hubert, 2008; Koutsoyiannis et al., 2016).

The O*pen Hydrology* survey reports that only 76% of those who share their work in journal articles prefer publishing in OA journals, with lack of funds expressed as a reason for not being able to do so. To the contrary, almost all (93%) respondents read OA research papers. This clearly emphasizes the benefits of open access for higher accessibility, thus wider visibility of hydrological research. OA publishing is equally valid for client reports. In the UNESCO Water Family, nearly 62% of respondents sharing their work through client reports make them open to public. This percentage might be indicative of conservative attitude prevalent in the non-academic sectors.

5.2 Open License

Open access publishing requires open source license agreements. Choosing an appropriate license is important not only for the article ('free to read') but also for the associated data, code and software ('free to use'). To facilitate citation and reproducibility, these can be stored and published in public repositories (GitHub, CRAN, Zenodo etc.) with a separate digital object identifier (DOI) and a permissive open source license.

The *Open Hydrology* survey, conducted within the UNESCO Water Family, found that more than a third of participants (44%) were not considerate of different open license options. Hydrologists should have a basic understanding of universal copyright laws. The most popular licenses for sharing and reuse are the Creative Commons licenses (e.g., CC-BY), however, there also exist more restrictive versions. These are usually indicated by additions such as NC ("for noncommercial use") or ND ("no derivatives or adaptations of the work are permitted") (Creative Commons About CC Licenses, 2019). It is important that one identifies the most appropriate open license option under the circumstances that define their case.

5.3 Open Peer Review

The process of peer review in scholarly publishing is traditionally conducted based on the principle of blindness to reduce bias during the assessment of manuscripts submitted to (scientific) journals. Among the three types of blinded review, triple blind is the most conservative approach as all parties involved remain anonymous. A less conservative approach in pursuit of removing bias is the double peer review where only the identity of the handling editor is revealed. The most popular strategy adopted, also in many hydrology journals, is the single blind review where both the editors and the reviewers are aware of authors' identity but not the vice versa.

With discussions on advantages and disadvantages of blind review still in the air, the concept of open peer review has emerged as a way to promote full transparency and accountability (Wolfram et al., 2020). Open peer review can be defined as making the reviewers' reports public, by including the peer review history, such as the authors' replies and editors' recommendations. Open peer review is currently not a common standard among hydrology journals. This also confirmed by the *Open Hydrology* survey: almost half of respondents (48%) reported that they had not engaged in open peer review process.

In the hydrological sciences community, there is an ongoing debate on the addition of code and data to the peer review process (Clark et al., 2021). It is not yet clear whether this responsibility should be given to reviewers who already serve voluntarily.

5.4 Stakeholders

The beneficiaries of open access are many– all the diverse research stakeholders, from individuals to institutions, have a role to play. It is important that they have round-table discussions to formulate **Open Publishing** strategies inclusive of everyone's interests and mindful of multi-linguality.

5.5 Needs and gaps

In the publishing landscape of hydrology, openness exists in diverse forms. The current OS policies of major journals in hydrology and water-related disciplines do not sufficiently support the **Open Publishing** pillar of the *Open Hydrology* framework, particularly in regards to **Open Data** and **Open Source**. The highlights from a comparative overview of thirty journals by Dogulu et al. (2022) and Dogulu (2022) are:

- Many journals offer some kind of OA option extending from fully OA to hybrid OA, with the latter being the predominant model.
- The article publishing charge (APC) is high regardless of embargo period and publication license options.
- Preprints are accepted in most journals, yet eligible preprint servers (or repositories) differ among journals.
- Data sharing is expected by journals more and more, with exceptions granted due to data privacy and national security concerns. However, "encouragement" of data sharing does not always imply shared data. Most journals require data availability statement.
- In the journal guidelines on release requirements, there is often no mention of code and software sharing.
- Release requirements for data, code and software/hardware are different for each and across journals.

It is clear that there are needs and gaps which require critical attention. According to the Open Hydrology survey these include:

- Lack of training on **Open Publishing**.
- Lack of affordability of the OA system, particularly for authors from financially disadvantaged countries (also reported in the literature by Blöschl et al., 2014; Clark et al., 2021).
- Ineffective journal policies that will require authors to fully disclose all of the data and models they used before acceptance of manuscripts (Koutsoyiannis et al., 2016).

- No consistent policy across hydrology journals, even for data sharing (Dogulu et al., 2022; Dogulu, 2022).

5.6 Opportunities and recommendations

The hydrologic publishing landscape should continuously evolve within, with each other and collectively to foster **Open Publishing**. Open access models, publication finance policies, preprint policies, release requirements for data, code, software and peer review procedures can be vastly upgraded to foster reproducibility, accessibility and inclusivity. Key opportunities and recommendations as described in the *Open Hydrology* survey, along with those reported in the literature, are:

- Removal of paywalls or reduction of OA fees (for both authors and readers).

- Greater dissemination of opportunities on **Open Publishing**.

- Collaboration with scientific publishing companies.

- Journals should develop open access policies in compliance with authors' needs and preferences relevant to proprietary data and models (Quinn et al., 2018; Blöschl et al., 2014).

- Journals can provide detailed guidance for authors on how to share data, code and software/hardware (Dogulu et al., 2022; Dogulu, 2022).

- Editors and reviewers can advocate OS practices when reviewing papers – e.g., requiring proper data or code citation (Hall et al., 2022).

- Creation of a cross-journal task force whose members are representatives from publishers and editors of journals on hydrology and water-related disciplines can help promote **Open Publishing**.

Open Hydrology Pillar 6: Open Participation

6

Accessibility of formal scientific knowledge and evidence to non-formal scientific audiences (i.e., the general public) is a critical factor for not only establishing trust and accountability but also encouraging public engagement with science. In this context, *Open Science* (OS) promotes transparency through open research environments and practices.

The sixth pillar of the *Open Hydrology* framework, **Open Participation**, has three components: i) crowdfunding and crowdsourcing, ii) citizen and participatory science and iii) Indigenous and local knowledge systems. For the *Open Hydrology* framework to be fully open and inclusive, this pillar is of utmost value as it emphasizes open, transparent and participatory processes of knowledge generation and engagement – especially in publicly funded science projects.

6.1 Crowdfunding and crowdsourcing

Crowdfunding, crowdsourcing and scientific volunteering approaches are aimed at engaging societal actors beyond the formal scientific community such as the members of the public. These approaches are increasingly implemented in research projects which require adoption of open source software and hardware for collaboration.

In hydrology, data crowdsourcing is widely practiced for environmental monitoring – for example, through the use of low-cost sensors and mobile apps. However, the *Open Hydrology* survey shows that science crowdfunding and crowdsourcing experience is lacking: only 21% of respondents reported having experience. It is crucial that practices of crowdfunding and crowdsourcing be equally and commonly employed in all countries.

As an example, iMHEA presents an inclusive network to advance hydrological data collection and knowledge co-production to support water management in the high-Andes regions. It is an open community of practices and experiences to support evidence-based water management and governance (Case Study Box 10).

CASE STUDY BOX 10

Building communities of practice for hydrological knowledge co-production: the iMHEA example (Initiative for the Hydrological Monitoring of Andean Ecosystems)

The Initiative for the Hydrological Monitoring of Andean Ecosystems (iMHEA) is a network of institutes from the academic, government, civil society, and industry sectors to advance hydrological data collection and knowledge co-production to support sustainable water management in the high-Andes regions.

IMHEA's aim is to fill hydrological knowledge gaps by supporting data collection for locations, variables, and management questions that are not well covered by statutory monitoring networks. It focused originally on assessing the impact of land-use and land-cover change on the hydrological response of headwater catchments. However, over time it has expanded its remit toward a wider range of management questions, including wetland conservation, sediment dynamics, and local water sowing and harvesting activities, among others.

IMHEA was founded in 2010 as a small network of 5 institutes supporting the monitoring of 6 catchments in Ecuador and Peru, but it has since then grown into a network of 22 partners, monitoring 51 catchments in 24 sites along 5 Andean countries. It is conceived as an open community of practice, sharing data, technical knowledge and capacity, and experiences to support evidence-based water management and governance.

The grassroots and inclusive nature of iMHEA, with no centralised funding and a lightweight and diverse coordinating team, has enabled it to evolve and adapt to changing policy needs and varying funding availability. A major step-change in its evolution was the recent inclusion of water companies to support head-water management and benefit sharing mechanisms in Peru.

SOURCE https://www.imhea.org

PHOTO: ©Wouter Buytaert

6.2 Citizen and participatory science

Citizen science refers to public participation in scientific research beyond the walls of academia, thus making citizen science products a common good (Riesch et al., 2013; Pelacho et al., 2021; Nardi et al., 2022). The citizen and participatory science perspective on OS was first consolidated in the UNESCO Recommendation on Open Science (UNESCO, 2021). In many citizen science initiatives, open data and publications as well as open source software and hardware are used (Hecker et al., 2018).

Both OS and citizen science have a large community of practice, yet their collaboration is currently limited, hampering impactful and harmonious change (Wehn et al., 2020). The supportive link between OS and citizen science is not well established in the hydrology community neither. Within the UNESCO Water Family, citizen science experience was found to be relatively low (~38%) as well. This points out the need for greater uptake of citizen and participatory science practices. To this end, UNESCO is developing a Citizen Science Toolbox for open data collection in water resources management through citizen engagement (Case Study Box 11).

CASE STUDY BOX 11

Citizen Science Toolbox by UNESCO

As part of the Recommendation for Open Science, UNESCO is developing a Citizen Science toolbox, aimed at increasing citizen engagement in water resources management through open data collection.

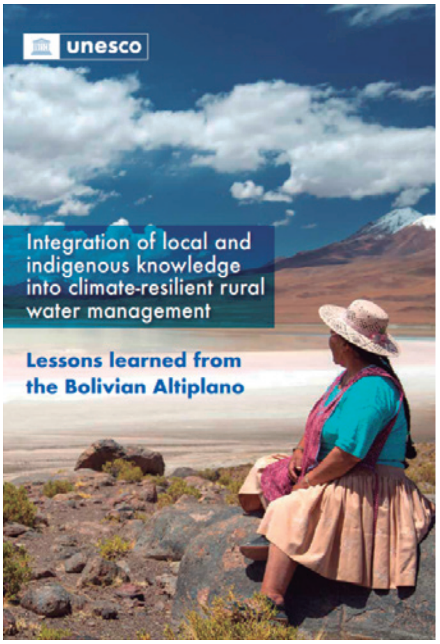
This toolbox presents a versatile smartphone application capable of offline data entry and empowers citizen scientists to contribute valuable water-related insights. Citizen scientists can report observations on water clarity, pH levels, temperature fluctuations, and the presence of pollutants, providing invaluable insights into the health of local water bodies. Beyond water quality, the toolbox empowers users to document flora and fauna sightings, aiding in the monitoring of ecosystem health and biodiversity. By providing a portal that allows a standardized process of offering Citizen Science data to a central repository, stakeholders benefit from streamlined data management and accessibility. This standardized approach enhances data quality and reliability, enabling researchers, policymakers, and community members to make informed decisions based on a robust evidence base. The application harnesses the power of mobile technology and cloud-based systems to facilitate real-time data collection and storage. The integration of the toolbox within the IHP Water Information Network System (IHP-WINS) further ensures the seamless incorporation of citizen-generated data into broader networks.

Through meticulous development, piloting, and training, the Citizen Science toolbox empowers stakeholders to actively participate in water resources management. The requirements of the toolbox are developed and piloted in cooperation with four UNESCO Biosphere Reserves in South Africa, as community involvement is a key part of the UNESCO Man and the Biosphere Programme (MAB).

PHOTO: ©UNESCO

CASE STUDY BOX 12

Engaging Indigenous and local knowledge systems



The acceleration of climate and global change in recent decades has resulted in unprecedented changes in the landscape and livelihoods of rural populations. These changes demand the rapid response of communities to adapt to new conditions.

The publication 'Integration of local and Indigenous knowledge into climate-resilient rural water management: lessons learned from the Bolivian Altiplano' reflects on the importance of Indigenous and local knowledge (ILK) to complement and cocreate sciencebased climate adaptation in areas where communities may have limited access to weather observations.

Much ILK has its roots in centuries of systematic observation by local experts, passed down through generations, to correlate environmental conditions with signs from nature. Indigenous Peoples' and local communities' knowledge systems offer nuanced insights that complement scientific data, providing invaluable precision and details crucial for developing hydro-climate models and assessing climate change scenarios, especially at broader scales.

Farmers' Indigenous knowledge holds weight as a credible, legitimate, and quantifiable resource, and plays a crucial role in guiding adaptive behaviours, especially in environments where data is scarce. The advent of rapid technological advancements, coupled with the increasing accessibility of cheaper and easier-to-use tools, empowers local communities to both generate and access information about their resources. This paves the way for easier documentation and systematization of Indigenous knowledge, particularly within more inclusive, participatory frameworks.

However, as technology integrates into participatory processes, it should not overshadow the importance of the participatory approach itself. Instead, it should seamlessly complement it, thereby amplifying the potential of Indigenous knowledge for resilient communities in the face of climate change.

SOURCE https://unesdoc.unesco.org/ark:/48223/pf0000384719

6.3 Indigenous and Local knowledge systems

Openness in scientific research and practice refers also to the principles of diversity and inclusivity from a human rights perspective. Accordingly, Indigenous and local knowledge (ILK) systems take a fundamental role in OS approaches. In this respect, the 2001 UNESCO Universal Declaration on Cultural Diversity, the 2007 United Nations Declaration on the Rights of Indigenous Peoples, and the CARE (Collective Benefit, Authority to Control, Responsibility and Ethics) data principles for Indigenous Data Governance are relevant to the **Open Participation** pillar of the *Open Hydrology* framework.

In hydrology, the values of Indigenous and local knowledge holders should be recognized and utilized to the greatest extent possible in consideration of custodianship, ownership, governance, and administration of data on traditional knowledge and on their lands, water resources and settlements.

6.4 Stakeholders

The pillar of **Open Participation** aims at engaging the larger public community, beyond the hydrological community. These include interested citizen scientists, as well as Indigenous and local knowledge holders that aim to contribute to the design and execution of hydrological research and water resources management. Thus, communication and outreach beyond researchers are instrumental to successful citizen science projects and enable the public to leverage the benefits of OS (Golumbic et al., 2019; Schmidt et al., 2018). Adoption of OS practices can alleviate public (and academic) concerns about replication and reproducibility which trigger trust issues (Dienlin et al., 2021; Song et al., 2022). Likewise, free accessibility of research outputs equips those public members interested in learning with the necessary background and training.

6.5 Needs and gaps

Open Participation is not fully acknowledged in the hydrology community as equally as the other pillars of the *Open Hydrology* framework. Hence, the most salient need is the lack of incentives and pathways for promoting public science engagement as an effective and valuable OS practice. Further gaps reported in the *Open Hydrology* survey are the followings:

- Lack of understanding and awareness.
- Lack of (government or private) funding.
- Lack of policy support.

6.6 Opportunities and recommendations

The rising popularity of participatory and citizen science activities in hydrology is yet to manifest itself within the context of OS culture. The enthusiasts of *Open Hydrology* can (and should) take tangible steps to strategize on how they can further utilize the benefits of crowdfunding and crowdsourcing in support of openness and transparency. Some of the recommendations highlighted in the *Open Hydrology* survey are:

- Creation of platforms for presenting a collection of best of practices.
- Incentives to fund projects.
- Application of cross-national data collection in transboundary rivers around the principles of the **Open participation** pillar.
- Streamline Indigenous and local knowledge systems, and develop tools and guides for inclusiveness, equity and empowerment, while raising the profile of the methodologies at national, regional and international levels.
- Develop the capacity of water experts and institutions on methodologies to engage with Indigenous Peoples and local communities in a manner that ensures respect to their rights, protocols, values and practices.

Policy, Leadership and Capacity Building for Open Hydrology

7

There are several elements that relate to *Open Science* (OS) which are all critical to its success: policy and implementation, leadership and advocacy (incentives, governance and funding), training and capacity building, collaboration and networking. These will be critical elements for OS in support of a stronger water science in a changing world.

The *Open Hydrology* framework necessitates **Policy, Leadership and Capacity Building** for formulation and development of relevant policies, proactive and strong leadership as well as deliberate and comprehensive capacity building in the hydrology community.

7.1 Policy

The development of effective OS policies at national level is a key element of the UNESCO Recommendation on Open Science. Member States, according to their specific conditions, governing structures and constitutional provisions, should develop or encourage policy environments, including those at the institutional, national, regional and international levels that support operationalization of OS and effective implementation of OS practices, including policies to incentivize OS practices among researchers. The guide by UNESCO (2022b) "Developing policies for open science", which is part of the UNESCO Open Science Toolkit[3], provides a comprehensive overview of key factors that should be considered in policy development. The Open Science Policy Platform[4] (OSPP, also EUOSPP - https://openscience.eu/policies) presents a list of national OS policies in Europe.

[3] https://www.unesco.org/en/open-science/toolkit

[4] https://openscience.eu/policies

In hydrology, there are no dedicated policies in place at any level on OS. However, the OS movement pushed by the international science organizations that involve hydrological sciences, e.g. the International Science Council [5,6], the European Geosciences Union[7]], the American Geophysical Union[8], the United States National Aeronautics and Space Agency[9] has greatly influenced hydrologists, especially early career hydrologists in academia. In particular, the UNESCO IHP-IX (2022-2029)[10] (UNESCO, 2022a) and the WMO Unified Data Policy for the International Exchange of Earth System Data[11] (WMO, 2022) puts a special emphasis on aspects relevant to various pillars of the Open Hydrology framework. On the other hand, the publishing landscape in hydrology currently lacks a consistent and reliable policy across hydrology journals (Dogulu et al., 2022; Dogulu, 2022; Quinn et al., 2018).

Hydrologists that aim to practice OS principles can only thrive when their efforts are supported by institutional policy and guidance at their workplaces. According to the Open Hydrology survey, only 50% of respondents from the UNESCO Water Family reported that their institution or workplace had an OS policy. Despite the prevalence of intergovernmental policies that promote OS practices *(Info Box 6)*, local and/or institutional level commitments and values remain mostly unaffected to a great extent. In these cases, the role of bottom-up approaches for systemic change should be explored.

7.2 Leadership

The *Open Hydrology* framework sets a path forward for the communities of hydrology and water-related disciplines. There is a need for leadership in the hydrology community to support and nurture the culture of OS. Not only international science organizations and intergovernmental bodies but also the water industry/consultancy sectors should contribute to the best of their capabilities to align with the objectives of the *Open Hydrology* framework.

[5] https://council.science/actionplan/open-science/

[6] https://council.science/publications/open-science-for-the-21st-century/

[7] https://www.egu.eu/publications/open-access-journals/

[8] https://www.agu.org/learn-about-agu/about-agu/open-science

[9] https://science.nasa.gov/researchers/open-science/

[10] https://unesdoc.unesco.org/ark:/48223/pf0000381318

[11] https://library.wmo.int/records/item/58009-wmo-unified-data-policy

At the micro-scale, institutions and companies should first identify their capabilities and allocate enough human and financial resources to pursue its six pillars.

Each and every small step counts towards cumulative and synergetic action. This can happen by institutions leading national, regional or global efforts; or through individual hydrologists taking on leadership roles at their workplace. Within the UNESCO Water Family, the former option is not fully realized as the *Open Hydrology* survey finds out: only 36% of respondents reported that their institution was involved in any leadership role concerning OS activities. Personal level involvement in taking leadership is similarly not widespread (31%), but is a major driving force as affirmed by the Info Box 6. Majority of OS- and hydrology-related sessions at the scientific conferences are led by enthusiastic individuals, including early career scientists, that are especially supportive of OS.

7.3 Capacity building

Policy and leadership alone cannot help sustaining the *Open Hydrology* framework. For the pillars of *Open Hydrology* to be actively and continually implemented, various capacity building efforts must be designed. Examples include organization of workshops, courses and seminars for training purposes. Unfortunately, availability of such activities is a major concern as the results of the Open Hydrology survey shows: only 52% of respondents reported that their institution was involved in any capacity building initiative on OS, with only 33% of respondents personally involved.

It is crucial that the conduct of these efforts be based on openness, FAIRness and inclusivity. Also important is making such training highly recommended or mandatory for researchers, as well as for practitioners.

7.4 Existing initiatives

Hydrology is one of the pioneering disciplines to embrace principles and approaches of OS. There exist many initiatives that set good examples, particularly on policy and leadership. Info Box 6 presents key activities that are aligned with the *Open Hydrology* framework.

INFO BOX 6

POLICY, LEAFERSHIP & CAPACITY BUILDING: examples of initiatives

Policy documents

- International Science Council (ISC) Action Plan 2022-2024: Science and society in transition (Theme 4.1) https://council.science/actionplan/
  https://council.science/actionplan/open-science/
  https://council.science/publications/open-science-for-the-21st-century/
- UNESCO Recommendation on Open Science
  https://unesdoc.unesco.org/ark:/48223/pf0000379949
- UNESCO Water IHP-IX (2022-2029) https://unesdoc.unesco.org/ark:/48223/pf0000381318
- UNESCO Water IHP-IX (2022-2029) Priority Area #1 "Scientific research and innovation"
  https://unesdoc.unesco.org/ark:/48223/pf0000381318
- WMO Unified Data Policy (2022)
  https://library.wmo.int/records/item/58009-wmo-unified-data-policy
- Open-Source Science Initiative (OSSI) – by NASA
  https://science.nasa.gov/researchers/open-science/

Early career initiatives

- A hydrologist's guide to open science https://open-hydrology.github.io/
- Open and FAIR Hydrology Zotero Library of the (literature cited in Hall et al., 2022)
  https://www.zotero.org/groups/2552826/open_and_fair_hydrology
- Introduction to Open Science for Hydrologists (YouTube Video)
  https://www.youtube.com/watch?v=dpD0dGpFdSc

Projects

- Addressing Hydro-Climatic Vulnerability through Citizen and Open Science – by UNESCO Water
  https://fust.iode.org/en/hydroclimvar
- Hydro-Resilience: Citizen and Open Science for Climate Adaptation – by UNESCO
  https://www.unesco.org/ihp/hydro-resilience
- Open Methods in Operational Flood Hydrology – Considerations for researchers and practitioners (Christopher Skinner & Duncan Faulkner) - UK Environment Agency
  https://doi.org/10.5194/egusphere-egu23-11975

7.5 Needs and gaps

Policy, leadership and capacity building should contribute to timely solutions to evolving needs and challenges of the *Open Hydrology* framework. The current needs and gaps pinpointed by the *Open Hydrology* survey participants are as follows:

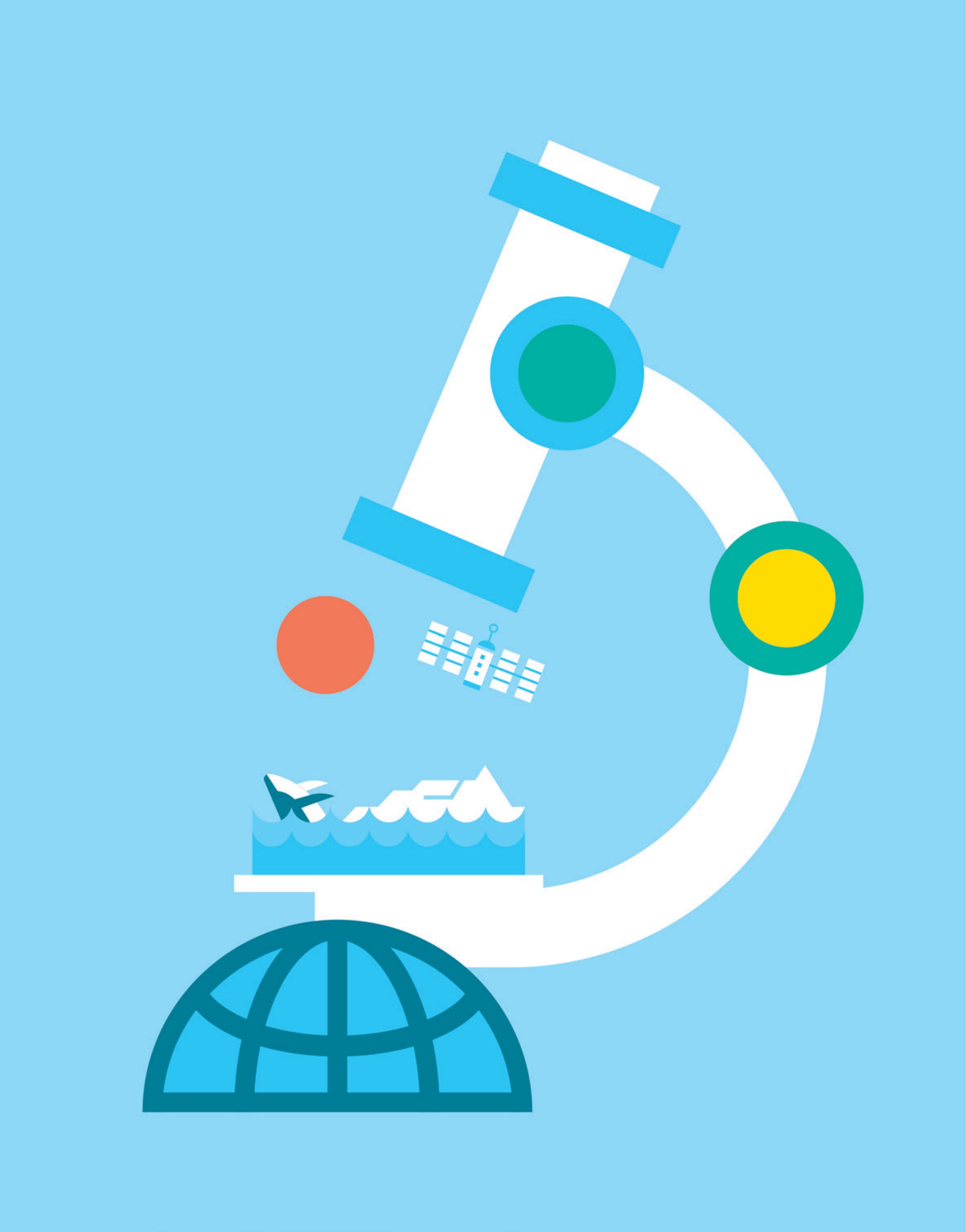
- Low uptake of OS e.g., due to lack of initiatives at national scale.
- Clearer government policy, accountability in operational context and organizational direction around OS.
- Poor coverage of policy, leadership and capacity building in common curricula and syllabi related to OS in higher education institutions.
- Lack of economic resources on the part of institutions.
- The predominant top-down approach to policymaking and leadership which is not aligned well with the core values of inclusivity, transparency and collaboration embedded in the culture of OS.

7.6 Opportunities and recommendations

Open Hydrology has an exciting future that will be representative of translational links between science, policy and practice interfaces. The success of the *Open Hydrology* framework can be long-lasting if the right actions are made for the right purposes. The *Open Hydrology* survey identifies a set of opportunities and recommendations for policy, leadership and capacity building:

- Design of more initiatives at national scale.
- Design of initiatives aimed at joint sharing of experiences on good and bad practices.
- Design of symposiums (e.g., led by one or several national IHP committees).
- "Harnessing OS's futuristic perspective on climate change and its implications for hydrology can be a compelling approach to engaging young people in scientific

endeavors. Highlighting the pivotal role of *Open Hydrology* in understanding and solving the challenges posed by climate change can inspire young people to consider careers and interests in this field. By highlighting the relevance of *Open Hydrology* in shaping a sustainable future, the OS community can create educational programs, awareness initiatives and interactive platforms aimed at not only increasing awareness, but also engaging actively young people in meaningful OS ventures. Integrating OS principles into hydrology connects to real-world issues such as climate change, providing a tangible context for young people to see the impact and importance of their contributions to the OS."



Future, Sustainability and Community Vision 8

The spirit of *Open Science* (OS) is equitable access to scientific knowledge and innovation globally. Research products such as data, software and publications should be made openly and freely accessible through **Open Data** policies, **Open Source** principles and **Open Access** options. The *Open Hydrology* framework presented in this publication holds a great potential to create a community vision and ensure the future of hydrology is sustainable.

8.1 Opportunities and recommendations

There are vast opportunities to align the *Open Hydrology* framework with major ongoing efforts, including the UNESCO IHP-IX (2022-2029): "Science for a Water Secure World in a Changing Environment" and the WMO Hydrology Action Plan. For instance, all the five priority areas of IHP-IX implicate the practical value of one or several components of the *Open Hydrology* framework.

To begin with, the hydrology community should establish a cross-organizational collaborative coalition jointly led by UNESCO, WMO, IAHS, European Geosciences Union (EGU), American Geophysical Union (AGU), CUAHSI, etc. to develop and implement actionable strategies for advancing the *Open Hydrology* framework. This *Open Hydrology* coalition can (and should) certainly assure complementarity and synergy, thereby avoiding duplication of efforts.

8.2 Action plan

Recommended activities for this coalition could be:

- "*Open Hydrology* Declaration" – Coordination of drafting a joint declaration to be endorsed by every coalition member through their individual mechanisms.

- "*Open Hydrology* Catalog" – An online platform that consists of several webpages with each corresponding to one of the components of the Open Hydrology framework. This catalog needs to be continuously maintained for hydrologists to be able to register their products on **Open Data**, **Open Source**, **Open Education**, etc. along with its meta-data (regardless of where they are originally shared, e.g., IHP-WINS, HydroShare, GitHub, etc.).

- "*Open Hydrology* Medal/Prize" – A joint medal/prize by IAHS-UNESCO-WMO can be a convincing motivation to foster individuals adopt the Open Hydrology pillars in their research, education and teaching practices.

- Regional centres of excellence.

- Annual event showcasing national capability and emerging best practices.

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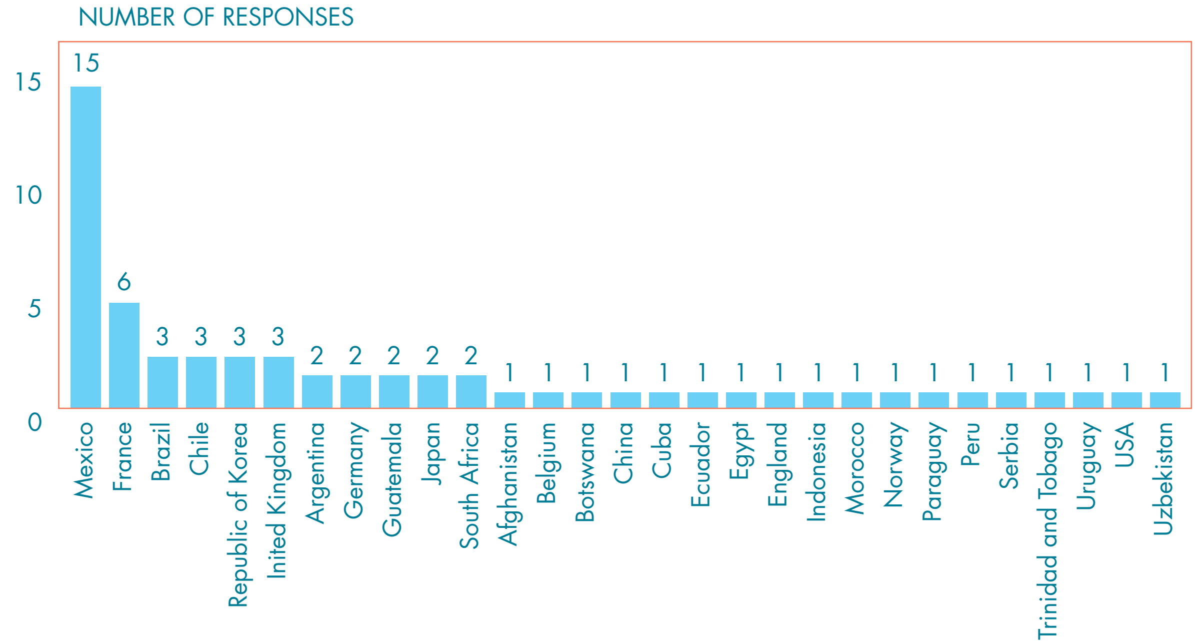
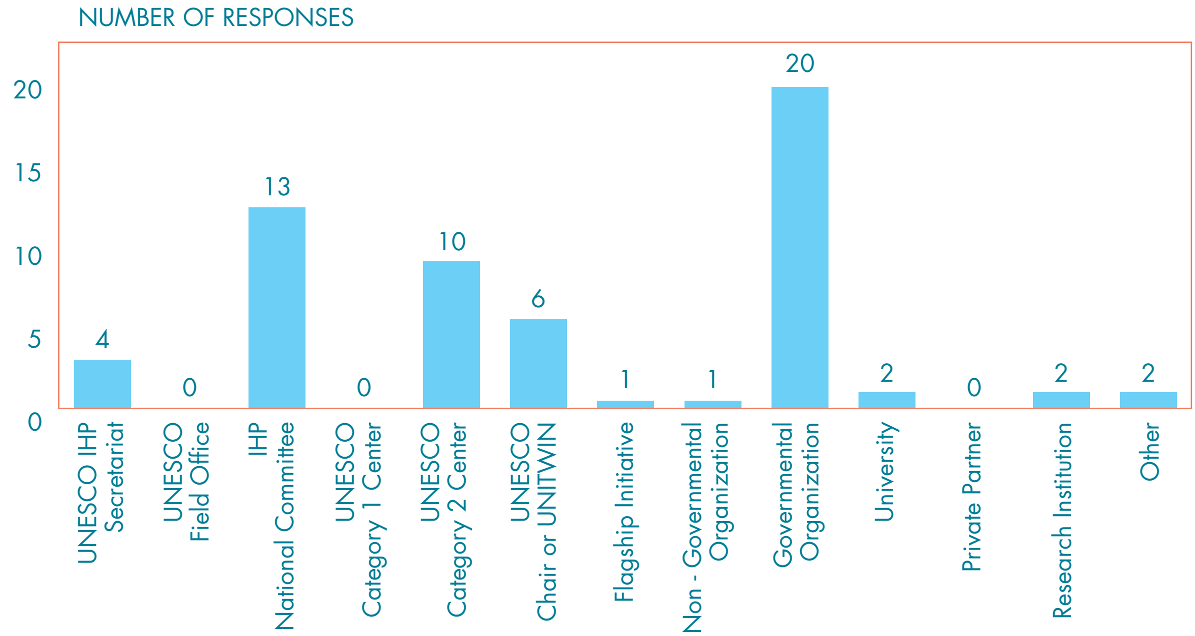
APPENDIX

Open Hydrology survey demographics and results

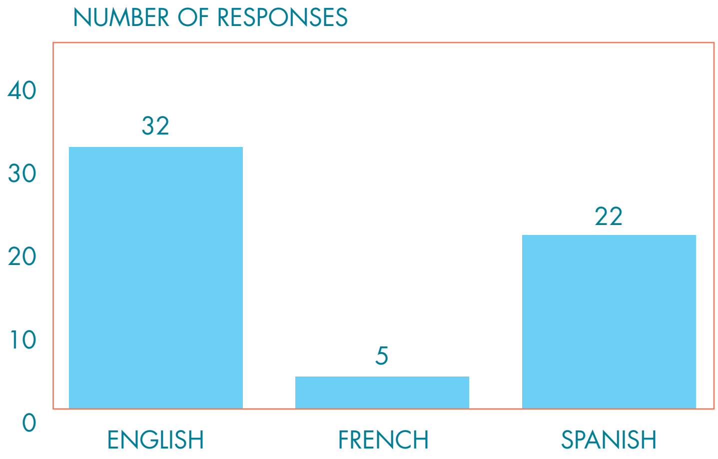
IN WICH COUNTRY ARE YOU CURRENTLY BASED? (n=61)



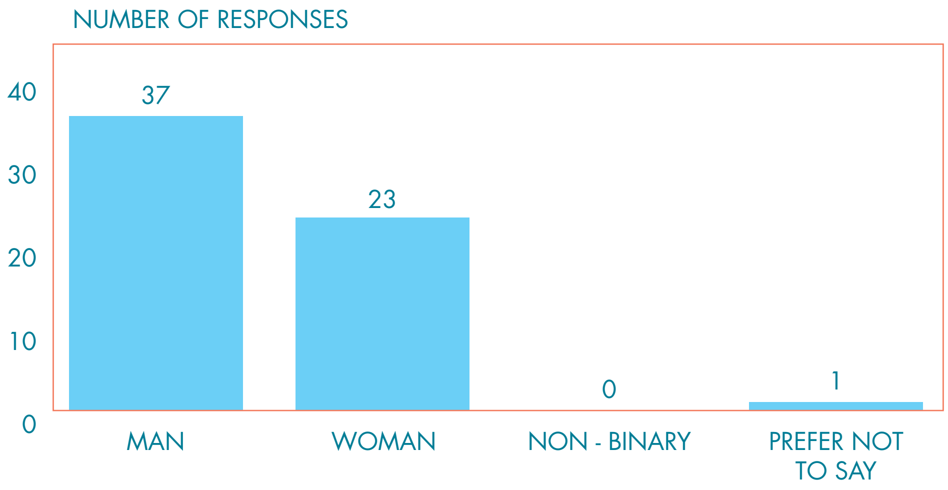
WHAT IS YOUR AFFILIATION AS PART OF THE UNESCO WATER FAMILY? (n=61)



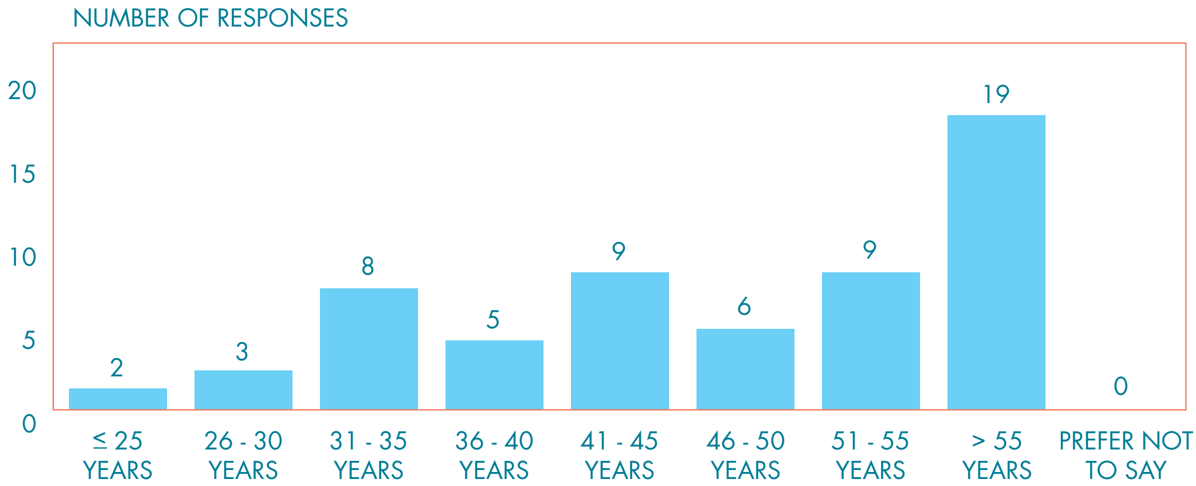
SURVEY IN LANGUAGES (n=61)



WHAT BEST DESCRIBES YOUR GENDER? (n=61)

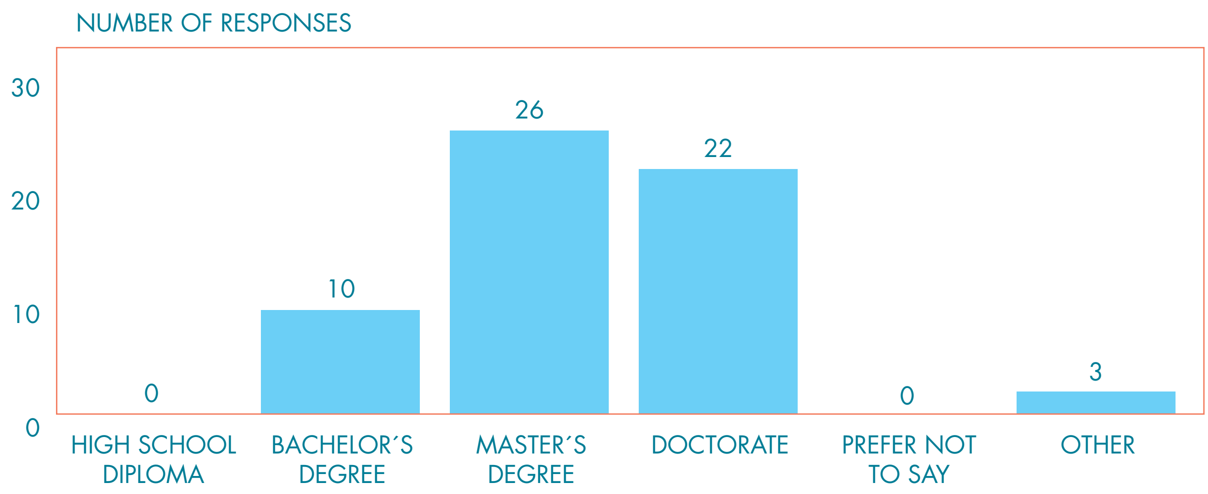


WHAT IS YOUR AGE RANGE? (n=61)

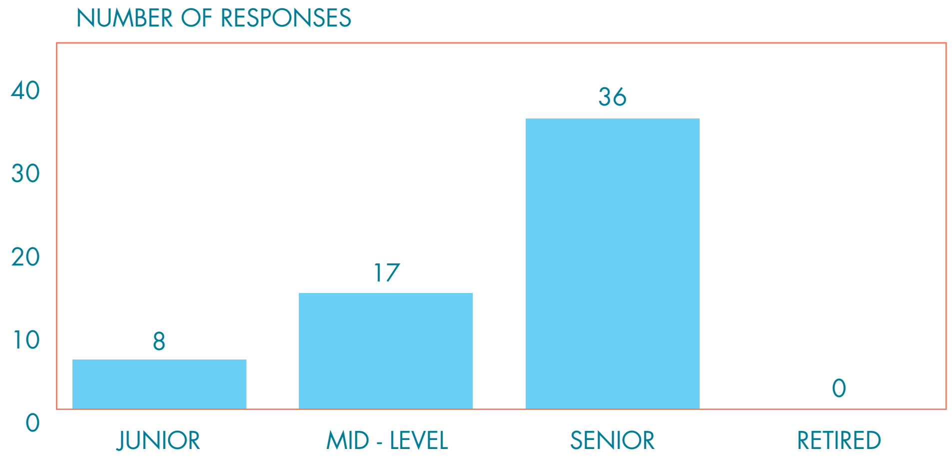


APPENDIX

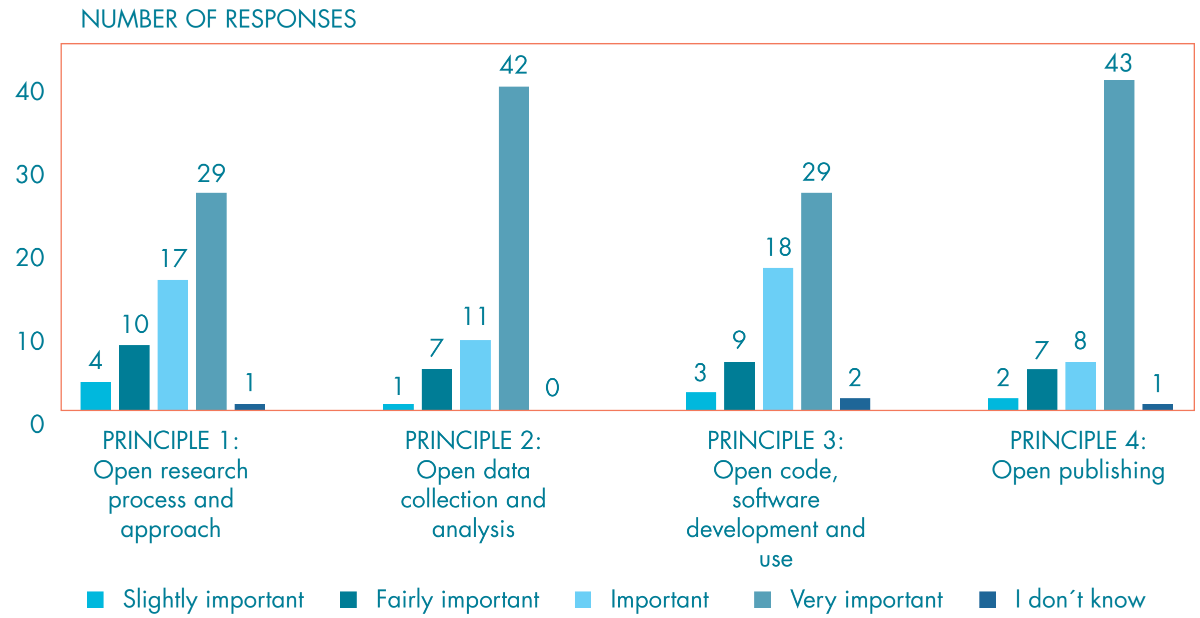
WHAT IS YOUR HIGHEST EDUCATIONAL DEGREE EARNED? (n=61)



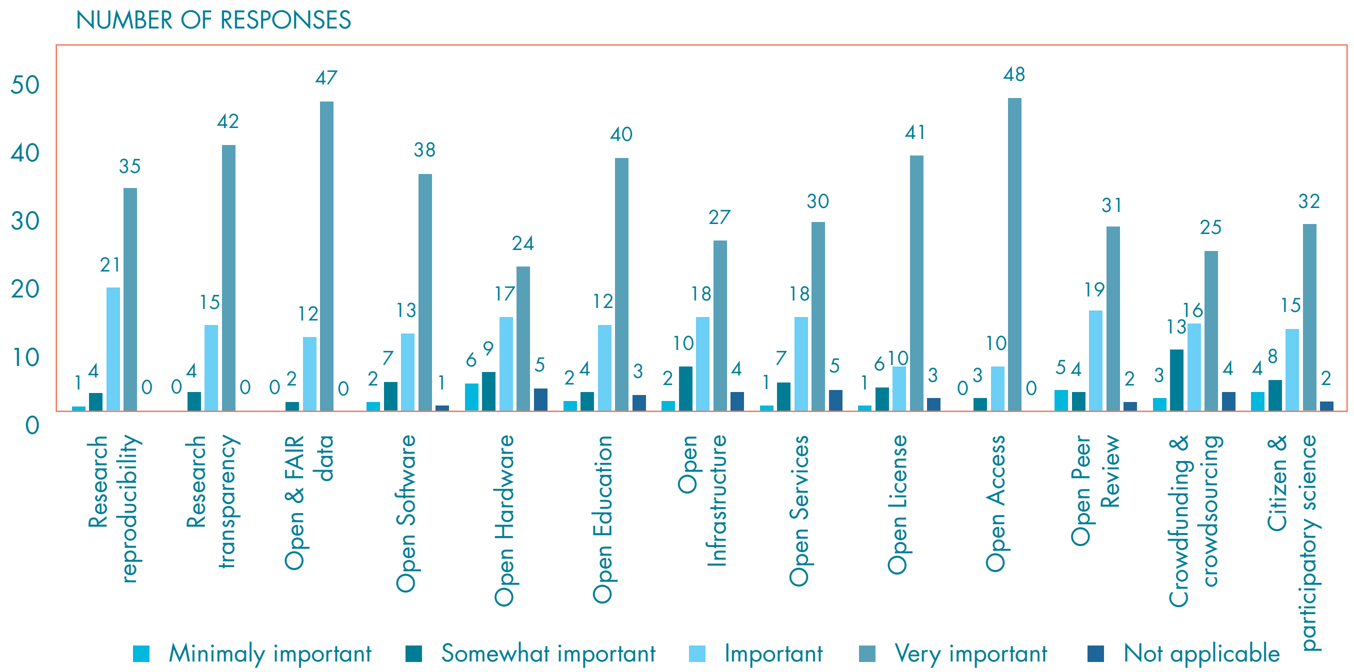
HOW WOULD YOU DESCRIBE YOUR CAREER STAGE? (n=61)



HOW WOULD YOU RATE THE IMPORTANCE OF OPEN SCIENCE FOR YOUR WORK ? (n=61)



HOW IMPORTANT ARE THE FOLLOWING ASPECTS OF OPEN SCIENCE TO YOUR INSTITUTION? (n=61)



Open Hydrology

The UNESCO Recommendation on Open Science has set an international standard for guiding principles that emphasize accessibility, inclusivity, equity, and sustainability in scientific research. This publication introduces the Open Hydrology framework, designed to integrate these principles into the field of hydrology through six foundational pillars: Open Data, Open Source, Open Publishing, Open Infrastructure, Open Education, and Open Participation.

By promoting transparency, collaboration, and accessibility, the Open Hydrology framework advocates for the broad dissemination of hydrological knowledge, technology, and tools. Ensuring free and equal access to this information is crucial for advancing FAIR science and addressing the intricate water challenges we face today.

This publication has been developed under the framework of the Hydro-Resilience Project 'Addressing Hydro-climatic Vulnerability through Citizen and Open Science', made possible with the support of the Flanders Fund-in-Trust (FUST) for the support of UNESCO's activities in the field of science.

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