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Editorial – Operational, epistemic and ethical value chaining of hydrological data to knowledge and services: a watershed moment

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Hydrological processes are fundamental contributors to ambient environmental conditions and planetary health (as geomorphological engines, vectors of dissolved and suspended compounds, and core properties of ecosystems), to the provision of water quantity and quality for direct and indirect human needs, and to the formation of hazards and security issues through their variations and extrema. Hydrological processes and patterns are highly diverse and undergo complex development across and along interfaces, landscapes, gradients and scales. Their emergence and intensity are often non-linear over a wide range of spatial, temporal and frequency scales, and their complexity is highly heterogeneous geographically and hydroclimatically, reflecting both geophysical and anthropogenic influences. Variabilities and changes in external drivers and internal characteristics of hydrological systems combine to induce shifts in the characteristics of hydrological dynamics, thereby producing multiple challenges for economic development and security.

They also occur within the broader context of emerging and accelerating challenges posed by the Anthropocene (Steffen *et al.* 2011, Bai *et al.* 2016, Brondizio *et al.* 2016), which underpin the goals developed for a sustainable future at the Rio+20 Conference (United Nations 2012) and, subsequently, for the 2030 Agenda for Sustainable Development (United Nations 2015). Within Agenda 2030, water is the focus of Sustainable Development Goal 6 (SDG 6). Its stature, therefore, has increased significantly from the United Nations (UN) Millennium Development Goals (MDGs) of 2000 where water was subsumed within a broader suite of environmental objectives. Moreover, water is a connector and integrator and SDG 6 is interlinked with many targets of other SDGs (ICSU 2017, UN Water 2018), which requires analysis through a nexus approach (Liu *et al.* 2017, Cudennec *et al.* 2018, Connor *et al.* 2020, Heal *et al.* 2021). The monitoring of progress towards SDG 6 targets and on interlinkages (UN Water 2018, and progress reports available at <https://www.unwater.org/publications/sdg-6-progress-reports>) indicates

that progress is not on a trajectory to meet the targeted ambitions in 2030.

Assessing, understanding, anticipating, and managing this complex convolution of hydro-meteorological/climatic and geographic dynamics, and of related development trajectories and security issues, are actual operational, epistemic and ethical challenges. These challenges range across a spectrum from global and continental questions (Eagleson 1986, Blöschl *et al.* 2017, Addor *et al.* 2020, Koutsoyiannis 2020, WMO 2021a, Caretta *et al.* 2022, Chagas *et al.* 2022, Kreibich *et al.* 2022) down to more localized issues, either in catchment/critical zone observatories and related networks (Bogena *et al.* 2018, Braud *et al.* 2022), or in diverse socio-ecosystemic/socio-hydrological settings, local scenes and arrangements (Di Baldassarre *et al.* 2019, WWAP 2021, Yu *et al.* 2022).

Given these essential features of hydrology, both as a science and as an operational field, and because of the multiplicity of water-dependent disciplines, sectors, stakeholders, methods and policies – all characterized by diverse land-/hydrospheres, problem-spheres and polycentric arrangements – one must address immense heterogeneity and fragmentation. This necessarily imposes limitations in terms of collecting, managing and sharing data; of knowledge and methodological development, synthesis, generalization and transposition; and of value adding and service delivery to end users.

The close partnership among the International Association of Hydrological Sciences (IAHS), the World Meteorological Organization (WMO – Commission for Hydrology and then Hydrological Coordination Panel) and the United Nations Educational, Scientific and Cultural Organization (UNESCO – Intergovernmental Hydrological Programme (IHP) and World Water Assessment Programme (WWAP)), further integrated within the UN Water mechanism, enabled synchronicity and complementarity in debates and initiatives surrounding the challenges associated with water-related data and in maximizing their utility. Accordingly, this Special Issue has been designed to gather and compile grassroots

contributions, results, innovations and progress from the scientific community (in the spirit of Cudennec and Hubert 2008, Koutsoyiannis *et al.* 2016, Quinn *et al.* 2018). It aims to do so in congruence with:

- (1) the diagnosis of operational gaps and improvement roadmaps (Rogers *et al.* 2019, Alliance for Hydromet Development 2021, Dixon *et al.* 2022, and the Integrated Monitoring Initiative for SDG 6, <https://www.unwater.org/our-work/integrated-monitoring-initiative-sdg-6>);
- (2) the lessons learned from the Prediction in Ungauged Basins (PUB) decadal initiative (Sivapalan *et al.* 2003, Blöschl *et al.* 2013, Hrachowitz *et al.* 2013) and the ongoing consolidation of the Panta Rhei decadal initiative (Montanari *et al.* 2013, Ceola *et al.* 2016, McMillan *et al.* 2016, and synthesis outcomes in preparation);
- (3) the community-based identification of the Unsolved Problems in Hydrology (UPHs) (Blöschl *et al.* 2019, Blöschl and Cudennec 2019);
- (4) the shaping of the UNESCO IHP IXth strategic plan (UNESCO 2022, itself strongly backing the UPHs; and related stock-taking deliverables, e.g. Arduino 2021, Mahé *et al.* 2021);
- (5) the data and information accelerator of the SDG 6 global acceleration framework (UN Water 2020, <https://www.unwater.org/our-work/sdg-6-global-acceleration-framework>);
- (6) and the WMO's hydrology-related strategy, initiatives and wider Earth System Approach (WMO 2014, 2018, 2021b, 2021c, Pecora and Lins 2020, Dixon *et al.* 2022, and the HydroSOS – Global Hydrological Status and Outlook System under development, <https://public.wmo.int/en/our-mandate/what-we-do/application-services/hydrosos>).

This Special Issue offers, in two instalments, an early 2020s snapshot of scientific methods, results, innovations and perspectives on data and data+ issues in hydrology, including across a broad suite of arrangements, settings, topics and scales. With both original substance and a curation dimension, the snapshot projects the actual challenges converging at the crossroads of:

- (1) the digital and related industrial revolutions (Rifkin 2011, WEF 2018);
- (2) the ideals of knowledge-based societies (OECD 2001, UNESCO 2005, Mansel and Tremblay 2013);
- (3) the reinforcement of open science mechanisms, behaviours and fluidity within the community and the society, including the reduction of possible weaknesses (Boulton 2021, UNESCO 2021, Hall *et al.* 2022, Cudennec *et al.* 2022b);
- (4) the reinforcement of scientific support for mainstreaming sustainable development and security issues into water-related policy, operational practices (Ceola *et al.* 2016) and future insights (Meadows *et al.* 1972, Oki *et al.* 2006, Cosgrove and Loucks 2015, TWI2050 2018) (including UPHs #21, 22 and 23 in Blöschl *et al.* 2019);

- (5) the implementation and assimilation of emerging methodological and technical innovations from observation to analysis (Tauro *et al.* 2018, Sermet *et al.* 2020, Zubezu *et al.* 2020, Ayzel *et al.* 2022, Dixon *et al.* 2022, Nair *et al.* 2022, Tessema *et al.* 2022, and UPHs #16 and 17 in Blöschl *et al.* 2019), and to hydroinformatics (e.g. web service protocols and interface ergonomics – Pecora and Lins 2020, Shukla *et al.* 2020, Silberbauer 2020; Dallery *et al.* 2022, Pozzoni *et al.* 2022);
- (6) data rescue (Yu *et al.* 2020a); the valuing of scarce data and design for improvement (Bolinches *et al.* 2020, Reynolds *et al.* 2020; Goswami 2022; Jiang *et al.* 2022; Pozzoni *et al.* 2022); quality assurance of shared datasets, products and services (Crochemore *et al.* 2020, Hunter *et al.* 2020, Ayzel *et al.* 2022, Merks *et al.* 2022, Tessema *et al.* 2022); the consolidation of specific datasets (large sample – Addor *et al.* 2020; high resolution – Aybar *et al.* 2020; multidisciplinary – Braud *et al.* 2022); the articulation of diverse data and heuristics to address complex systems, multidisciplinary issues and interfaces (including UPHs #17, 18 and 19 in Blöschl *et al.* 2019); and the reduction of, and accounting for, uncertainties (Strobl *et al.* 2020, Westerberg *et al.* 2022, and UPHs #20 and 21 in Blöschl *et al.* 2019).

The coincidence of the scientific snapshot presented in this Special Issue with the multilateral processes that led to the UNESCO recommendation on open science (UNESCO 2021) and to the WMO unified data policy resolution (Adrian *et al.* 2021, WMO 2021d) makes it all the more timely and relevant. This is particularly so as it provides context for many aspects identified in the multilateral processes, as well as a range of results, analysis and innovations which will be valuable when it comes to generalized operational implementation of multilateral principles. These latter activities will be facilitated not only by the noted coincidence, but by the continuing proactive dialogue and partnership between operational and policy experts at the national and multilateral levels and the scientific community. Indeed, the co-convening of this Special Issue itself, and some of its contents (in particular Pecora and Lins 2020, Dixon *et al.* 2022 with an original curating dialogue format, Nardi *et al.* 2022), are themselves tangible elements of the long-lasting partnership between IAHS, WMO and UNESCO (see also Young *et al.* 2015a, 2015b, Tauro *et al.* 2018, Yu *et al.* 2020b, and Amoussou *et al.* 2021 for recent examples).

As a result of the accelerating self-organization of the hydrological scientific community towards both the “open science frontier” and the hydrological front via networking, coordination and sharing mechanisms, agenda setting and synthesis facilitation shall be sought by all. And learned societies like the 100-year old IAHS (Rosbjerg and Rodda 2019, <https://iahs.info/About-IAHS/History-of-IAHS.do>) remain essential to that ambition as, for example, with the actual development of the Digital Water Globe platform (Arheimer *et al.* 2022), the consolidation of the Panta Rhei decade, and the design of next steps for the community, to be acknowledged and sustained by all stakeholders.

Furthermore, collaborations between the hydrological scientific community and multilateral programmes and initiatives should remain a priority to ensure convergence in:

- (1) setting standards, protocols, infrastructural platforms and outlooks (WMO HydrosOS; UNESCO IHP-Water Information Network System (WINS); Stewart 2015, Pecora and Lins 2020, WMO 2021d, 2022a, Arheimer *et al.* 2022); and consolidating good practices and guidelines (Addor *et al.* 2020, Shukla 2020, Acharya *et al.* 2022, Hall *et al.* 2022, Jiang *et al.* 2022);
- (2) translating field challenges into scientific questions, and scientific results into services, innovations and actions (WMO 2014, 2018, WEF 2018, Dixon *et al.* 2022, UNESCO 2022, Uhlenbrook *et al.* 2022), particularly in the SDG 6 global acceleration framework;
- (3) consolidating hydrological knowledge with wider aspects of the water-related challenges into the common good of knowledge (Blöschl *et al.* 2019, Boulton 2021, Misstear *et al.* 2022);
- (4) formulating capacity development referentials, resources and mechanisms (Nacken 2015, WWAP/ UN Water 2016, Kootval and Soares 2020, Jiang *et al.* 2021, UNESCO 2022, WMO 2022b, UN Water Capacity Development initiative in support of the SDG 6 Global accelerator framework); and
- (5) supporting a polycentric and subsidiary intelligence, to advance water-related development trajectories, mitigate water/systemic risks, and manage crises upon their emergence (UN Water 2013, Eliason 2015, Young *et al.* 2015a, Armstrong McKay *et al.* 2022, Sillman *et al.* 2022, WEF 2022).

Beyond the particular examples of improving hydrological understanding, products and services, particularly progress on data management, the snapshot of this Special Issue further contains overall lessons and avenues that should help shape priorities for the next steps of community self-organization and of science–operations–policy cooperation. These overall lessons and avenues relate to three dimensions in the value chain:

- (1) operational: data–product–service,
- (2) epistemic: data–information–knowledge, and
- (3) ethical: with multifaceted recognition of all involved parties.

These lessons also confirm how data and value-chain workflows must reinforce exchanges between different knowledge systems and engagement with societal elements, citizen science (Sermet *et al.* 2020, Strobl *et al.* 2020, Nardi *et al.* 2022, Seibert and van Meerveld 2022), equality–diversity–inclusion (Ali *et al.* 2021, Acharya *et al.* 2022, IAHS 2022), traditional and indigenous knowledge and wisdom (Carroll *et al.* 2021, UNESCO 2021, 2022) and user-oriented (i.e. fit for purpose) design (WMO 2014, Shukla 2020, Silberbauer 2020, Dallery *et al.* 2022 for end users versus De Lavenne *et al.* 2023 for modelling experts); how the data and workflows are

critical for trust in the substance and among stakeholders; and the necessity of respecting the following sets of principles:

- (1) FAIR – findable, accessible, interoperable, reusable (Wilkinson *et al.* 2016);
- (2) SQUARE – supporting quality action and research (Cudennec *et al.* 2020, and further development by Rau *et al.* 2020, Acharya 2022, Hall *et al.* 2022, and Kreibich *et al.* in preparation) – including a guarantee of the essential quality assurance procedures of scientific practices (e.g. peer review, transparency and replication) (ISC 2021), and of the additional value-adding comparative approach, synthesis building and agenda setting; and
- (3) CARE – assuring collective benefit, authority to control, responsibility, and ethics (Carroll *et al.* 2020, 2021; also consistent with WWAP 2019, 2021 and 2023 in preparation, respectively, on values, on leaving no one behind, and on partnerships and cooperation).

The synchronization of all these developments shows how the progression into the early 2020s is a watershed moment in terms of data and value chain management towards hydrological intelligence. Statements by member states of the UN and by stakeholders during the 24–25 October 2022 preparatory meeting and stakeholder consultation (e.g. Cudennec *et al.* 2022a, Rock 2022, Uhlenbrook 2022; and synthesis by United Nations 2022) confirm that awareness is mature enough globally for making informed and meaningful decisions at the UN 2023 Water Conference (<https://sdgs.un.org/conferences/water2023>) towards a game-changing data- and science-informed action plan.

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