IAHR White Paper Series

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To catalyse thinking, inspire debate and better apply scientific knowledge to global water problems, the IAHR White Papers seek to reveal complex and emerging issues in Hydro-Environment and Engineering Research. They are written for researchers, engineers, policy-makers and all those who are interested in the latest developments for a better water future.

HYDRO-ENVIRONMENT > DATA

Pathways towards democratization of hydro-environment observations and data

This White Paper grew out of the collaborative work conducted by several IAHR Technical Committees, with a focus on the Technical Committee on Experimental Methods and Instrumentation.

The outcome is a community vision on future pathways aimed at leveraging conventional and emerging (unconventional) methods to facilitate access to hydro-environment observations in the near future. It has been formulated in collaboration with a broad spectrum of experts from different backgrounds.

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Pathways towards democratization of hydro-environment observations and data

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A need for decision makers, a challenge for the empiricists

Water-related problems affect several billion people's lives and represent an annual challenge assessed at multitrillion US dollars (WEF 2019), which substantiates their core role in the UN Sustainable Development Goals (UN 2020). Preventing direct and indirect impacts associated with water excess or water scarcity events requires expert judgement based on reliable information.

Observations and measurements are fundamental prerequisites for making scientific progress. Measurements may challenge or consolidate theories with empirical evidence. Even the most conservative rationalist rejoices when new observations provide congruent values for the theoretically-driven von Kármán constant. Empiricism is embedded in scientific progress, with the latter intrinsically linked to the development of measuring capabilities.

In this White Paper, we provide a community-based discussion of the latest technological developments in flow measurement techniques and instrumentation. We highlight key future developments that contribute to the democratization of hydro-environment observations and data, considering democratization as the transition towards more shared and affordable access to information by the scientific community, stakeholders, and society in general. A natural example of democratization can be found in the increasing application of citizen science to monitor flow and in the emergency response to natural hazards. Nevertheless, many other types of flow observations can also benefit from recent innovations to enhance their accessibility and outreach potential.

Measuring water

Measuring water quantity, quality, and dynamic behaviour does not only serve academic and research needs, but it also contributes to new ways of public and stakeholders' perception and awareness of water-related problems, and creates new opportunities for better governance and management of water resources.

Contemporary management of water systems, in built and natural environments, requires accurate, fast, and synoptic measurements, together with processing of large amounts of hydro-environment data. Real-time measurements are essential to manage water systems, which directly impacts the production of food and energy, and to inform flood warning systems. Investment in instrumentation and the science of measuring water quantities is essential to manage water in a context of continuous change and exacerbation of extreme situations, such as scarcity or excess of water (Ranzi 2020).

To advance the knowledge of fluid processes, high frequency and high-definition measurements are required in most cases, for example, the study of the interactions of flow and biota, or air-water flows. On the other hand, to understand the dynamics of large-scale water bodies or catchment systems, the scope for data acquisition may extend over large areas, often at the cost of lower spatial resolution and acquisition frequencies.

A twenty-first century laboratory

In the twentieth century, Yeh and Cummins (1964) were working in the Columbia Radiation Laboratory at Columbia University (New York, USA) when they realized that their research on laser spectrometers could be applied to determine flow patterns in fluids.

Laser Doppler Velocimetry would then advance from a Do-It-Yourself (DIY) enterprise to a profitable commercial product in the 1970s. However, highly specialised state-of-the-art DIY instrumentation developments require multidisciplinary teams and elevated costs, which impedes their widespread development other than under exceptional conditions. Obsolescence or lack of funding can also be additional obstacles to the broader use of instrumentation.

Sustainability of such development efforts may be attained through collaborative synergies across multidisciplinary end users (for instance the EU INFRAIA programs including Hydralab/Hydralab+, Figure 1). When advanced research is supported by collaborative efforts, not only should the acquired data be made accessible, but clear mechanisms should be in place to also allow access to research infrastructures, thus ensuring entry opportunities for researchers of low and mid-income countries.

> Multidisciplinary collaborative synergies will enhance the sustainability of high-technology instrumentation and large-scale experimental developments.

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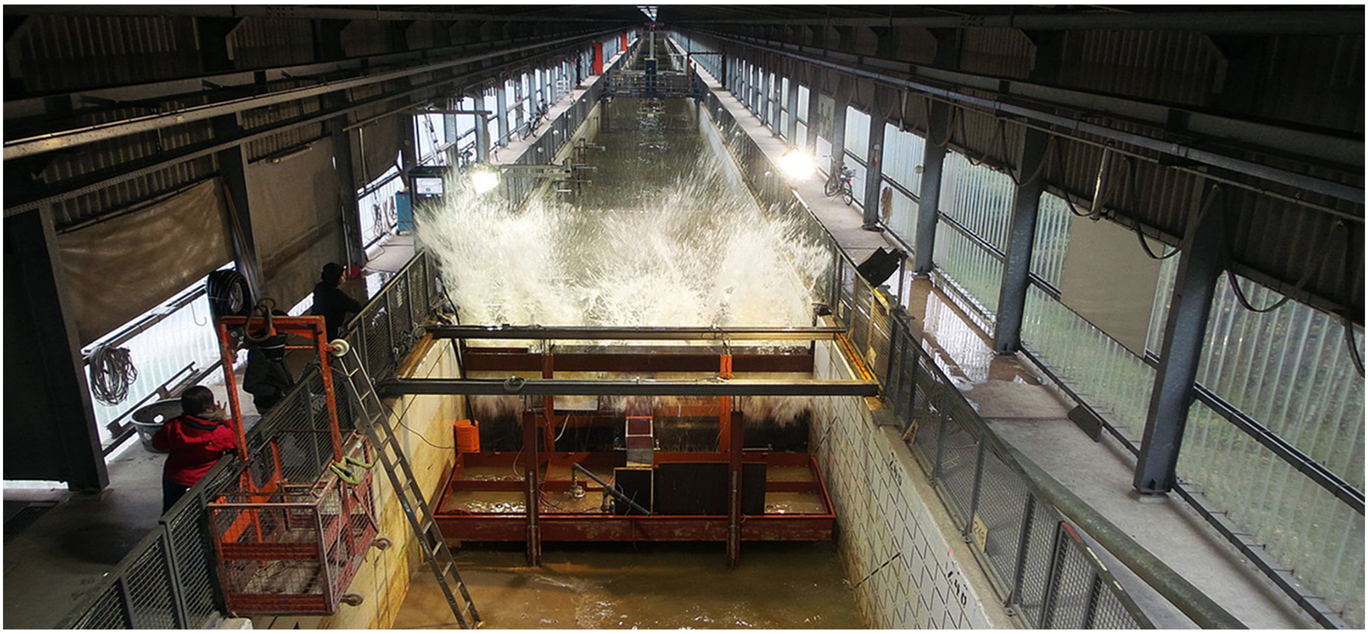

Figure 1 | Large-scale testing at the Large Wave Flume at Forschungszentrum Küste (FZK), Germany. Image courtesy of FZK, joint institution of Leibniz University Hannover and Technische Universität Braunschweig.

The third industrial revolution brought a wide generalization of the usage of digital means, fostering, in developed countries, a ubiquitous access to affordable and high-quality technology.

Internet and fast computing are no longer exclusive to high-tech laboratories, with big data processing made nowadays possible even on laptops. The unprecedented use of non-scientific equipment for flow measurements is driven by the unparalleled progress and affordability of everyday equipment for leisure and communications, such as smartphones or action cameras. The use of equipment not developed specifically for scientific purposes can reduce the cost of data collection and avoid the complications of dealing with complex hardware. For instance, through the combination of small single-board computers and camera modules with adjusted resolution, affordable rolling shutter camera recordings of up to 1,000 frames per second can be achieved. Using the Structure from Motion technique, we may reconstruct a vegetation patch in a river using a mobile phone camera. The fast-growing measurement community may benefit from common protocols in terms of setup conventions and accuracy testing, to ensure that appropriate quality standards are met.

Whether high fidelity or consumer equipment is used, data post-processing requires often highly specialised analysis tools. Open software can make the required routines accessible to a larger number of laboratories, while also enabling higher transparency. User-friendly, well-documented, and long-term maintained open software is still rare, but exceptions exist (e.g., the community-driven effort to develop free and open-source software for Particle Image Velocimetry, OpenPIV: https://github.com/OpenPIV/).

Multiple efforts often lead to several identical codes, instead of identifiable advances in the available tools. When contributing to open software, priority should be given to codes with an identifiable, transparent, and collaborative organisation, and with proven scientific soundness, which should guarantee future applicability, reliability, and maintenance. A greater convergence of community efforts should result in changing the motivation for using that software, from 'because it is freely available' to 'because it is of the highest quality'.

The field as a laboratory

Monitoring of rivers, oceans, reservoirs, lakes, and hydraulic infrastructures, including the measurement of fluxes of water, sediment, instream wood, biota, and plastics, underwent a revolution over the past decade. Global high-resolution topographic and hydrologic data are now available (for instance, hydrologic data can be found at the Global Hydrology Resource Center of NASA: https://ghrc.nsstc.nasa.gov/hydro/), gradually replacing expensive and time-demanding ground gauging of catchment processes.

Non-intrusive, high-resolution remote sensing techniques provide researchers and practitioners with ever-increasing quantities of high-quality data that are not yet completely explored. This development is especially beneficial for large river basins, such as the under-gauged Amazon, to avoid costly and time-consuming field campaigns in remote areas. Unmanned Air Vehicles (UAV), such as drones equipped with measuring equipment (with resolutions of millimetres and ranges of a few kilometres), can be combined or complemented with satellite products (with sub-meter resolutions and ranges of thousands of kilometres) to quantify the spatial and temporal evolution of storage and transport of sediment or wood within the landscape and river networks.

Figure 2 | Setup of instrumentation for a full-scale measurement campaign in the tunnel spillway of Luzzone dam (Switzerland), where flow velocities of 30 to 40 m/s were sampled (courtesy of VAW, ETH Zurich).

Furthermore, UAV solutions are emerging to monitor the state of hydraulic structures, including dams, navigation canals, and flood protection dikes. Radio Frequency Identification (RFID) tags and Global Positioning System (GPS) trackers add a new dimension to the time-dependent monitoring of wood or sediment through a river reach or a basin. Satellite data enable the monitoring of water levels, ocean waves, water quality, land cover, and other features. Drones support river and coastal characterization, hydraulic modelling, habitat mapping and monitoring, and safety assessment and monitoring of hydraulic structures, with the possibility to measure water levels, waves, topography, and roughness as well as river and sea bed topography and granulometry. Single and multi-beam acoustic instruments are quasi non-intrusive and have seen an expansion of their measuring capabilities below the water surface, from flow velocity to sediment fluxes and bed morphology. Flights equipped with LiDAR with water-penetrating capabilities allow the non-intrusive simultaneous survey of shallow rivers and coastal areas and the contiguous landscape. These are examples of unprecedented capabilities to validate models, to develop real-time monitoring and early warning systems, to implement real-time management measures and to inform governance and policy.

Measurements in the field or in full-scale hydraulic structures can provide the ultimate, direct validation of a theory or ground truthing for engineering design. These can take place, for instance, in water infrastructures (Figure 2) or in barely accessible coastal areas (Figure 3). In-situ campaigns are subject to special challenges, require meticulous and exhaustive planning, and may be subject to larger uncertainties than sampling under controlled laboratory conditions. Safety can be a problem, especially for measurements during extreme hydrological events, such as floods. The risk of destruction of the measuring setup is always present, and may require several iterations in the design of the measurement campaign. Nevertheless, full-scale measurements are of unmatched value, and sharing raw signals, as well as information on unsuccessful experiences, may have benefits beyond the initial research goals.

> Novel capabilities are emerging in real-time monitoring and early warning systems, and also in the implementation of real-time management measures that can inform governance and policy.

Enabling technologies and new data sources

Miniaturization of sensors and fast computing environments are the two key drivers to the dissemination of drones as a survey tool. The Internet of Things provides a useful set of sensors that can be accessed remotely; drones equipped with data receivers can fly over the location of the installed sensors and download their data. Likewise, the development of satellite internet constellations and low-power wide-area networks will allow sensor connectivity even in the most remote areas of the world.

The European Space Agency Copernicus and NASA/USGS Landsat programs provide public access to satellite imagery with global coverage and revisiting times of days, enabling access to nearly 50 years of multi-petabyte archives. Additionally, recent developments of cloud-based platforms for planetary-scale geospatial analysis provided tools to process these large amounts of data (e.g., Google Earth Engine, Gorelick *et al.* 2017). The combination of these developments enables Earth Observation (EO) applications to study the Earth's water processes either at high spatiotemporal resolution (Figure 4), or at global scale (Figure 5), such as water surface cover (Pekel *et al.* 2016), bathymetry (Murray *et al.* 2020), or coastal dynamics (Luijendijk *et al.* 2018).

Figure 3 | Drone inspection of Warriewood outfall (Australia), observations of algae coverage and dye dispersion tests. Safety issues would significantly challenge in-person inspection (courtesy of Chris Drummond, WRL, UNSW Sydney).

Freely available satellite products provide limited revisiting times (1 to 10 days) and spatial resolution (10 to 30 m) with sun-synchronous orbits, which may not be sufficient for many water-related applications, such as flood modelling of urban environments. In recent years, multiple private companies have started operating micro- and nano-satellite constellations with passive optical and active radar sensing capabilities. These constellations can allow multiple revisits per day, higher spatial resolutions (0.3 to 5 m), and alternative orbiting paths, consequently increasing the modelling and monitoring scope in remote areas, where no gauging stations exist. Additionally, on-demand video acquisition from space and new types of sensors are expected to become available in the near future, which will trigger new forms of monitoring. These EO datasets are expected to generate a wealth of raw data and should allow sensing surface water and hydraulic infrastructure at unprecedented resolutions. However, efficient and accurate Artificial Intelligence (AI) algorithms need to be developed to turn this raw EO data into relevant, quarriable, and well-structured information.

Figure 4 | Intertidal bathymetry with 10 m resolution of the Dollard bay in the Wadden Sea between the Northern Netherlands and Germany, derived from two years (2017-2018) of multi-spectral Sentinel-2 and Landsat 8 satellite data (courtesy of Deltares).

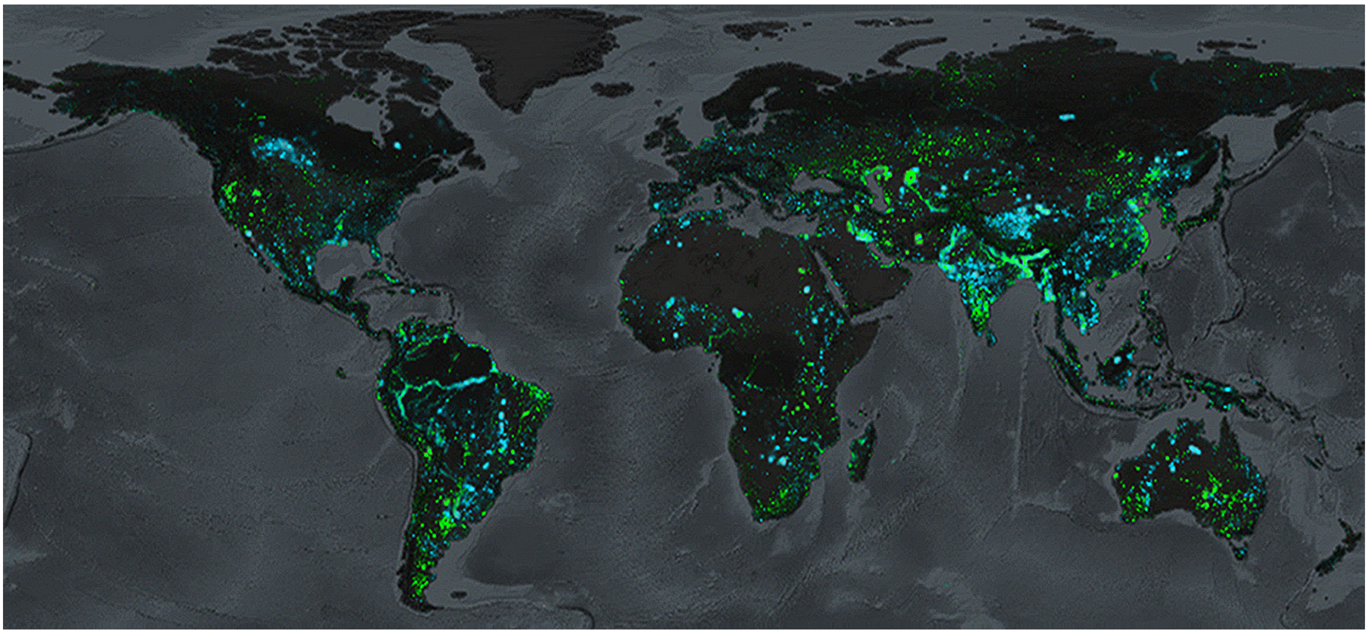

Figure 5 | Long-term surface water changes (1985-2016) derived from NASA/USGS Landsat missions (Donchyts *et al.* 2016). The colours depict transitions from water to land (light green) and land to water (blue). Satellite imagery was processed in the Google Earth Engine parallel processing environment.

Artificial intelligence techniques are receiving growing interest from the hydro-environment community (Savić 2019), where the number of applications is expected to increase considerably in the next years. For this reason, IAHR's quarterly magazine Hydrolink recently published a special issue with several articles on applications of AI in water management and hydro-environment engineering.

Instrumentation-wise, deep-learning allows extracting information from large and high-dimensional data streams (e.g., video, radar, sonar). More specifically, it enables deploying robust algorithms that cope with varying conditions in the field. Also, progressively generalized detection and classification algorithms will likely facilitate transference between similar applications. Another promising feature of AI lies in the possibility to enhance the derived data and information beyond the instrumentation resolution, by learning from physical properties of the monitored systems (e.g., super-resolution and compressed sensing).

Advances in UAV control and automation are a potential game-changer for large-scale or hazardous monitoring campaigns. The way we measure and what we measure may experience a disruptive change that will pose organisational and transference challenges.

Every day, the internet and social media offer us hundreds of videos, tweets, shares, likes, and comments, which include implicit and explicit information about floods, storms, lakes and reservoirs, rivers ecosystems, and waves, among others. These unconventional data sources provide a large volume of sourceable real-time data. Researchers have made meaningful and rewarding attempts to harness this emerging data wealth (Le Coz *et al.* 2016). An example is the series of intensive data mining studies around Hurricane Harvey (2017, Texas, USA). A database of over 7 million tweets was collected and analysed, demonstrating that the mined data can be used to inform disaster management, to improve the timing and location for emergency rescues and responses, and to optimize evacuation routes.

Besides the added value in increasing citizens' awareness, citizen science has also been used to validate remote sensing and numerical models to provide coverage beyond the traditional fixed gauging stations. For example, the water level of several lakes in the US is actively monitored by volunteers and citizen scientists.

Despite steady growth, the field is still facing several technical and social difficulties. Firstly, the data quality of citizen science is still challenging. Unstructured data found in social media requires advanced data processing to extract useful information. Smartphone app-based photo collection usually lacks consistency in photo quality and context control. This requires the designer of citizen science projects to create strict and practical data quality control protocols. Secondly, data processing is still a bottleneck to scale up applications.

Citizen science will play an important role in countries that lack monitoring infrastructures. Research is exploring methods of protecting privacy-sensitive information to avoid ethical, legal, and policy conflicts.

Processing large and rapid data stream often has to involve AI, especially in real-time or near real-time tasks.

Thirdly, data security and privacy issues are new challenges in dealing with citizen-science data. Active research is being conducted to explore methods of protecting privacy-sensitive information to avoid ethical, legal, and policy conflicts. Citizen science is believed to play a more important role in countries that lack monitoring infrastructures.

Key elements for discussion: openness, collaboration, and coordination

A new world is offered by digitalization, but also by new paradigms of access to information and of organisation. We discussed current developments in novel data acquisition methods, and for each we highlighted the main directions towards a more communal access to hydro-environment observations and data; openness, collaboration, and coordinated actions are important elements for this.

The current policy trend towards open-science (open-data repositories, open-software communities, open-access publications), is an opportunity for data democratization. However, it must be affordable and sustained by trusted researchers and scientific institutions to become a real instrument of progress towards common access. Furthermore, easy access to information may contribute to the false perception of assurance. Experts capable of interpreting the data and aware of their limitations, should always be involved to avoid ill-informed governance and policy-making processes.

Communication and collaborative processes are essential among researchers, but they should also involve the stakeholders of any shared data. Communication across disciplines and communities is essential to progress the science of measurements, as shown by the above-mentioned example of the development of Laser Doppler Velocimetry in the 1970s. Specifically, among the hydro-environment community, transparent communication should necessarily include unsuccessful attempts for a shared learning process. Conversation may also be strengthened by adapting the language to a non-specialized audience, and a first step could be the inclusion of plain language summaries on scientific literature to reach more effectively the broader public.

> Adapting the language to a lay audience will strengthen the conversation, and a vital first step could be the inclusion of plain language summaries to reach the broader public more effectively.

> IAHR was founded by 66 directors of hydraulic laboratories, making the science of measuring entrenched in the origin of our Association. Over time, IAHR became a common umbrella to a larger, more international, and more diverse community of hydro-environment professionals. With the emergence of new, disruptive technologies, we believe that coordination and collaborative actions across our communities can lead to a transition towards a sustainable and inclusive access to earth and water observations.

Figure 6 | Left: Testing smartphone cameras to monitor instream wood in the Sorge stream in the Dorigny forest (Lausanne, Switzerland); Right: RGB aerial image acquired with a fixed-wing eBee senseFly RTK Drone in the Sense River (Fribourg, Switzerland).

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About IAHR

The International Association for Hydro-Environment Engineering and Research (IAHR), founded in 1935, is a non-profit, global, independent members-based organisation of engineers and water specialists working in fields related to the hydro-environmental sciences and their practical application. Activities range from river and maritime hydraulics to water resources development and ecohydraulics, through to ice engineering, hydro-informatics, flood risk management and continuing education and training. IAHR stimulates and promotes both research and its application, and by so doing contributes to sustainable development, the optimisation of world water resources management and industrial flow processes. IAHR accomplishes its goals through a wide variety of member activities including working groups, congresses, specialty conferences, workshops and short courses, journals, monographs and proceedings.

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