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CITIZEN SCIENCE

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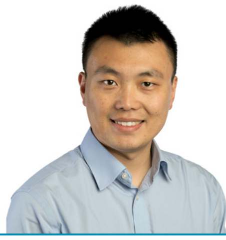
EDITORIAL



The term citizen science is broadly used to describe the engagement and participation of members of the general public in different aspects of scientific research such as data collection or processing. The last thirty years have seen an increasing use of the concept of citizen science in many fields of research ranging from astronomy to environmental science. Almost every week there are stories in the news about various citizen science projects. For example looking at the news from early December 2022, we find a story about volunteer amateur astronomers comparing images of the sky from the 1950's and today to determine whether some objects have vanished over the last 70 years; a project in Kangaroo Island in South Australia engaging tourists and locals in collecting data on koala behavior and observations on bee activities; plans for citizen science butterfly monitoring projects in New Hampshire to provide information on habitat needs and associated risks, timing of life cycles, and species range shifts over time; a citizen science project funded by the National Aeronautics and Space Administration of the United States to capture photos of sprites and other optical phenomena that flash above thunderclouds after a lightning strike.

A growing number of citizen science projects have been supporting hydrologic and water resources studies. The number of published papers on such projects has been growing exponentially over the last twenty years. This issue of Hydrolink includes five papers discussing different aspects of using citizen science in hydro-environmental and water resources studies.

The first of these articles, by Wouter Buytaert, presents an introduction to the different types of citizen science projects based on the level of and nature of citizen involvement in them, ranging progressively to greater engagement from simple data collection to their interpretation, problem definition and analysis. The article discusses the importance of creating partnerships that would enhance transparency to ensure that the knowledge generated by citizen science projects will be used in decision making. It also discusses the conditions for ensuring the sustainability of citizen science projects and the importance of embracing local knowledge.

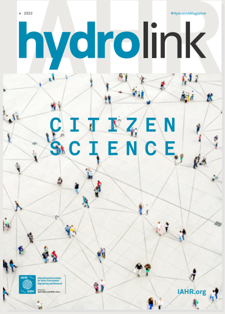
The article by Pan Yang, Geng Niu, Erhu Du, and Yi Zheng discusses different aspects of weather data collected by citizens and other public sources, especially in the context of urban hydrology. This includes data from personal weather stations, surveillance cameras, social media and sensors in portable devices, vehicles, mobile phones, smart home equipment, and telecommunication infrastructure. Quality control of large-volume data coming from diverse sources has been recently facilitated by machine learning methods. An interesting observation made in this article is that stormwater management models using high density crowdsourced rainfall data can provide more accurate estimates of rainfall intensity than models based only on more sparse conventional meteorological station data.

Closely related to citizen science is the concept of community observatories introduced in the European Union a few years ago, aiming at developing community-based environmental monitoring with innovative and novel earth observation applications and combining it with monitoring by policy makers, scientists and other stakeholders. The article by Ioana Popescu presents a case of using community observatories for the collection of data to support flood modelling in a wetland of important ecological value located in the upstream central part of the River Danube Delta. In this case the crowdsourced data complemented data from conventional monitoring programs and the results of a numerical hydraulic model of the wetland, improving this way the ability to manage this part of the delta.

An article by Rick Battarbee describes a citizen science project in the River Wharfe in Ilkley in the United Kingdom, where coliform contamination by the discharge of untreated sewage was a health hazard for people bathing in the river. The project engaged local citizens in the collection of water quality samples and mobilized them in a campaign that raised awareness about the problem and drew the attention of regulators, leading to the designation by the UK Government of that part of the river as an official bathing site, which would require regular monitoring by the UK Environment Agency. The same project helped also identify agricultural activities as an additional source of faecal bacteria in the river.

Citizen science projects can be used to engage schoolchildren, contributing this way to their environmental education. Such an example is the project for the environmental restoration of the Osonoigawa Brook, part of an urban waterway in Tokyo described in the article by Takehiro Watanabe, Takizawa Kyohei, Nakamura Shinichiro, Satoquo Seino, and Yukihiro Shimatani. An elementary school adjacent to this waterway developed a river-centered environmental curriculum, which included water quality testing, biological surveys, and lessons by local experts and university researchers. Fifth and sixth grade students were asked to draw their design ideas for the waterway, which were submitted to the local mayor who accepted their proposal. This together with input from local citizens in a series of workshops formed the basis for the design of the restoration of the brook.

The articles in this issue of Hydrolink highlight only a few of the possibilities offered by engaging ordinary citizens and various stakeholders in the collection, interpretation, analysis and use of data supporting water resources and environmental decisions. The growing literature on citizen science offers many more such examples. Key challenges are the issue of how to motivate wider citizen participation in science projects and how to ensure data quality. More innovation should be encouraged in this direction. In addition, greater use of AI tools and methods can help deal with the challenges of data collection, cleaning, and analysis in the foreseeable future.



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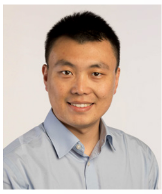

GUEST EDITOR

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Citizen science to support decision-making on water resources

By Wouter Buytaert

Introduction

Citizen science is becoming increasingly common in many environmental disciplines, including hydrology and other water sciences [1, 9]. Many citizen science projects have as their main purpose the generation of new scientific knowledge. In such projects, the participation of citizens is mostly driven by the desire to learn something new, and to be part of a collective scientific endeavour.

However, a growing number of citizen science projects has an applied dimension and aim to generate scientific knowledge that can be applied to address specific societal challenges or problems. This type of citizen science is particularly common in environmental contexts, because of the growing pressure of global environmental problems such as water contamination or climate change, but also because of an increasing awareness that classic scientific approaches are unable to produce the scientific evidence base to support decision-making and action.

This type of applied citizen science can be driven by the citizens themselves, as an activist approach to tackling an environmental issue where they perceive insufficient or inadequate action from relevant authorities, such as local water pollution issues. However, there is also an increasing interest from policy makers to use the concept of citizen science to foster the inclusion and engagement of the general public in the policy process. For example, the European Commission is actively examining the use of citizen science to support EU policies [6], and the UNESCO Intergovernmental Hydrology Programme has incorporated Citizen Science as a key method to support inclusive water governance [12].

Although the knowledge-generation aspect of citizen science is increasingly well understood and documented, its application to support decision-making is more novel and has received less theoretical attention [2]. Here, I identify some specific opportunities and challenges that require further scientific development and understanding.

Analysis framework

Citizen science is a concept that covers a very broad range of activities, both in terms of the nature of the scientific activity, as well as the modality of citizens' involvement. Several theoretical frameworks for the analysis and characterisation of citizen science activities exist [9]. However, I will use here the framework of Haklay [8] which is one of the earliest and most parsimonious frameworks to analyse citizens' involvement in citizen science projects (Figure 1).

The Haklay framework identifies four main types of citizens' involvement, depending on the stage of the knowledge production process in which citizens are involved. This typology ranges from involvement in only specific stages of scientific enquiry, such as data collection ("crowdsourcing") or interpretation of specific pieces of information ("distributed intelligence") to a much broader involvement in the knowledge production process, including problem definition, data collection, and analysis and interpretation ("participatory science" and "extreme citizen science").

It should be noted that this typology is not normative, and some of the most successful and sustainable citizen science projects are focused on crowdsourcing or distributed intelligence (e.g., Earthwatch Freshwater Watch [4]; Crowd-water [5]). However, as argued below, a clear understanding of the nature of citizen involvement is crucial to leverage citizen science in the context of environmental decision making.

4 Extreme	Collaborative science: problem definition, data collection, analysis
3 Participatory science	Participation in problem definition and data collection
2 Distributed intelligence	Citizen as basic interpreters
1 Crowdsourcing	Citizen as sensors

Figure 1 | Typology of citizen science projects according to the nature of citizens' involvement[8].

Challenges and opportunities

Generating quantitative evidence of appropriate quality

Water science, like many other environmental sciences, still struggles with generating a solid evidence base to support decision making. Many crucial variables, such as precipitation, river flow, and water quality parameter are very sparsely monitored in space in time, resulting in major data gaps and very large uncertainties. The potential workforce that can be unlocked via citizen science can create a step change in data collection. This is not just the case for manual sampling, but also for automated measurements. The robustness and ease-of-use of automatic equipment is improving constantly, bringing the operation of such equipment within reach of non-experts[11]. For example, the Weather Underground project[13] deploys thousands of weather stations in citizens' gardens worldwide.

However, ensuring that the data are complementary to statutory networks can be challenging. This requires appropriate designs, for example to determine sampling locations and timings. This does not necessarily mean that citizen science generate data need to be of the same quality as scientific observations – even lower quality data can be useful, for example for the interpolation of spatiotemporal patterns if analysed and interpreted using correct assumptions about uncertainties and qualities.

Generating knowledge that is useful, useable, and used

To ensure that citizen science generated evidence is used in a decision-making context, it needs to be actionable and accessible to decision-makers, but also trusted by these users. This goes beyond technical specifications and challenges. It also requires a co-creation process that generates credibility and trust between the partners and ensures that the produced evidence maps onto the specific management questions. Long-term partnerships between the stakeholders will often be necessary to achieve this. For example, in the United Kingdom, the Catchment Based Approach (CaBA, n.d.) is a recently established partnership between local water authorities, water companies, civil society, the UK Government, and business to promote an inclusive approach to river basin management. Around 40% of these partnerships implements citizen science activities to generate local evidence. Water funds, such as the Water Fund for the city of Quito, Ecuador (FONAG) partner with local commercial, governmental, and civil society partners to create an open and transparent environment for evidence-based decision making[7].

When implemented properly, citizen science can contribute to enhancing the openness and transparency of the evidence-based decision making. However, citizen science activities may also incur a risk of creating or exacerbating conflicts. This is especially relevant in the context of critical environmental issues, such as water pollution or allocation of scarce water resources. Citizen science activities inevitably change the dynamics and power balances of negotiation processes, which need to be carefully managed to ensure an optimal outcome and avoid conflicts[3].

Enhancing participation in a sustainable way

Citizen science relies on the impetus of voluntary participation. This process is inherently prone to the loss of momentum and interest of participants. This poses a challenge to the sustainability of citizen science projects, which can only be solved by finding a "win-win" arrangement in which the non-scientific participants extract sufficient value from the engagement.

The motives for participation in action-oriented citizen science projects can be highly diverse, and very different from that of pure science-oriented projects. While some participants may still be driven mostly by curiosity and a desire to generate new science, others may be keen to be involved in setting the agenda and direction of the research, leading to more extreme forms of citizen science[8]. Other participants may be driven by the relevance of the evidence for their own professional or personal activities. The latter emphasises the importance of "closing the knowledge creation loop" between all involved actors. Such projects evolve towards communities of practice around specific topics or interests. One example is the participatory hydrological monitoring network iMHEA (imhea.org) in the tropical Andes, which generates information about land-use impacts on water availability (**Figure 2**).

Valuing local knowledge

As most citizen science projects are designed by professional scientists, their methodology is often strongly based on the empirical scientific method. However, citizen science opens opportunities to implement a knowledge co-creation process that transcends specific knowledge paradigms and also assimilates local and indigenous knowledge. Projects that achieve such integration are necessarily of the "extreme citizen science" type in the Haklay framework, as they require full and equitable participation of all involved parties.

For example, over centuries, mountain communities in the tropical Andes have developed local water management practices based on so-called “water sowing and harvesting practices”. These artificial recharge systems that divert water from local streams onto hillslopes. These practices have been used at a local scale, but few of them have been integrated in basin-scale water management plans. Participatory hydrological monitoring has the potential to strengthen the quantitative evidence base of these practices and to integrate them in formal water resources management[10].

Figure 2 | Community engagement activities of a participatory monitoring initiative in the Bolivian Andes, which is part of the iMHEA network.
Photos by Cinthya Torrez, Universidad Mayor de San Simón, Cochabamba.

Wouter Buytaert
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Citizen's observatories: contributions to the improvement of flood modelling for management

By Ioana Popescu and Andreja Jonoski

Crowdsourcing of environmental data has recently been pro-posed as a possible alternative to augment and enrich available datasets for managing environmental systems. In water-related studies, it could supplement the data available from existing monitoring networks. This article presents experiences from research in collecting and processing crowdsourced data for use in flood modelling studies. The work has been carried out in a past European research project (of the H2020 Research Programme), where data collected by citizens were used to support the development, calibration and validation of hydrodynamic models used for flood analysis. The data were gathered by a dedicated game-like mobile phone app in the form of images and videos that were later post-processed to provide data on e.g. land use/land cover, river geometry, water levels and water velocities.

In water related problems models are important tools that support decision-makers for management in the their water resources. One of the important topics studied through modelling are the river floods and their related risks. Due to the impact that floods have on the environment, either in a positive or negative way, various types of models are used in order to understand and predict their behaviour. For adequate representation of floods in models, data is a critical requirement, as the quality of the developed models depends on data quality[6]. Continuous efforts are being paid for acquiring data, however still many rivers lack the amount and quality of data and existing data access is not always possible[4]. Limitations in data acquisition are due to several reasons: difficulty to reach the location, high cost of complex instrumentation, lack of technical knowledge of the data collection stations, etc. Alternative technologies, such as remote sensing and/or drones can provide complementary data, however these technologies are not available everywhere and they may be expensive. In this context, data collected through crowdsourcing can be relevant for modelling, if robust mechanisms for ensuring data quality are used.

De Sherbinin *et al.*[3] emphasize the critical importance of data as an output of citizen science projects, and their contribution to the collection of scientifically relevant information, due to the advantages of being low-cost and abundant. For flood related projects data is most often collected through citizen observatories (COs), in which participants together with scientists are involved in all stages of a project, from research design to processing of data collection and/or interpretation[2]. This approach, as part of the citizen science field, has often been used in the past decade in diverse projects for different purposes related to floods analysis and management. COs have been explored in the field of flood modelling and management as a monitoring tool, for data assimilation in modelling, and for mapping floods[1]. When used in modelling, all collected data through CO need to be benchmarked and integrated into models, for model set up, calibration, validation, simulation and potentially for forecasting.

In this article we are presenting the experiences in collecting data for flood modelling, through CO, for the particular case of a wetland in the Danube delta in Romania. The work was carried out as part of SCENT research project.

The Sontea Fortuna wetland and CO data collection

The SCENT project was one of the research projects funded by European Union under Horizon 2020 programme, exploring how citizens can be engaged in data collection such that they become the 'eyes' of the policy makers. The project developed a gamified smartphone application dedicated to collect data on land use, water levels and velocities in the form of photos and videos. The main research question was whether such collected data can contribute to the improvement of a flood model. One of the case studies where data was collected is the rural area of the Sontea-Fortuna wetland in Romania. Located in the upstream central part of the Danube Delta, the Sontea-Fortuna wetland is an important lacustrine complex for maintaining the good ecological status of the delta, both from hydrodynamical and morphological point of view (**Fig. 1**). The wetland covers a total surface area of 246.36 km^2. Main canals with total length of 106 km convey water to an inside secondary network of canals, which are 153 km long in total[5]. The canals in the wetland area are interconnected with 11 major lakes. The wetland is only accessible by boats.

Currently the Sontea-Fortuna wetland is well-preserved, however tendencies of increased discharge due to climate change, decreased sediment supply due to upstream interventions (dams and reservoirs) and modified eutrophication rates threaten the maintenance of the ecosystem. Thus, a river management that sustains a proper monitoring network, with real-time capabilities, together with modelling of the flooding patterns, is a necessity.

Flow properties in the studied area, depth and velocity (or depth and discharge), change with time, hence a hydrodynamic model of the Sontea-Fortuna wetland was build using the open source modelling suite developed by the Hydrologic Engineering

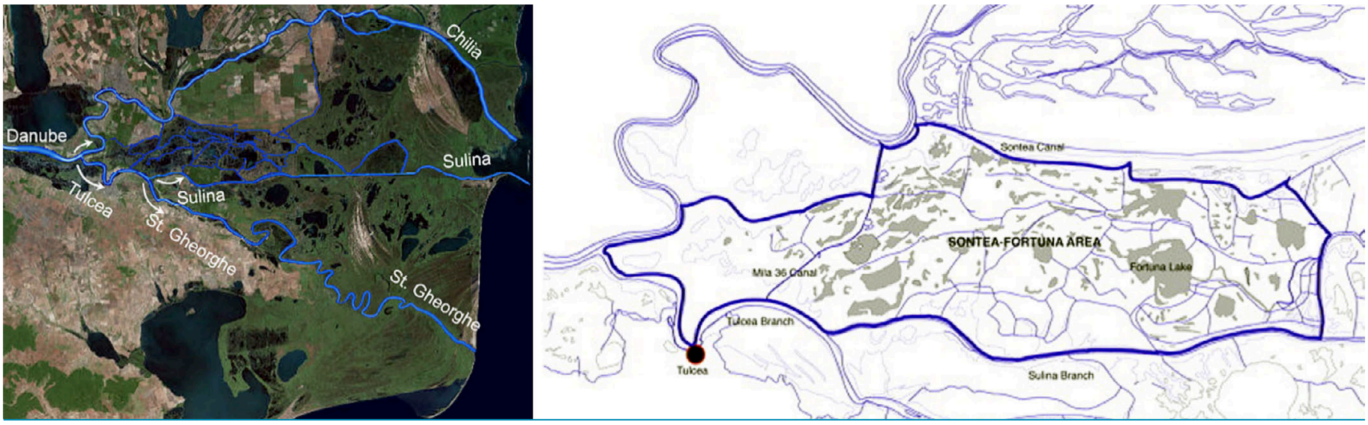

Figure 1 | Main branches of the Danube River (Left) and the Sontea-Fortuna area (Source: Popescu *et al.*, 2015) (Right).

Center (HEC) of the United States Army Corps of Engineers (USACE), the River Analysis System (HEC-RAS). The 1D/2D HEC-RAS model of the Sontea Fortuna area (**Figure 2**) calculates the value of depth and discharge in a spatial grid of computational points, defined by the modeller, over a simulation period of interest. The model build using traditionally available data (obtained from the Danube Delta National Institute) was tested for improvement by adding data collected through COs.

Data collection in the Sontea-Fortuna area entails defining boat routes to follow, when CO campaigns are organised. The approach for defining pathways for data collection, though not specific to the Danube Delta case study, was developed during the SCENT research and its applicability was tested in the Sontea-Fortuna area. The principle of determining the data collection routes take into account the interest of local stakeholders and the characteristics of the study area, such as navigability of canals in terms of minimum water level, boat velocity and maximum available time for a route completion. The generated possible pathways were given scores based on a set of criteria, allowing for their prioritisation and choice. **Figure 3** presents several determined routes, along with the boat position at the location of the measurement. Several possible pathways were determined and followed during data collection campaigns. However, some of these pathways were changed during the data collection due to the need of adjusting the pathway parameters, as it is, for example, the time needed to make an observation. Collected images for measuring water depth and videos (of floating objects for measuring flow velocity, not discussed here), with the phone, contained metadata on location coordinates, date and time. These were pre-processed and made available in the SCENT database. In order to use the crowdsourced data in the flood model of the area, the quality of photos of water depth were first visually analysed and the images with no gauge, very low resolution and no water surface were discarded. **Figure 4** shows images that are bad or good for model usage. The water depth values from filtered good images were manually interpreted.

In order to check the validity of the collected data, during the campaigns, measured data were collected through an Acoustic Doppler Current Profiler (ADCP) instrument, in the same locations where citizens were collecting data. The ADCP data had a series of measurement points along cross-sections of canals.

Modelling results

Three datasets were available to determine the quality of collected data after the processing step: crowdsourced data, measured data and model results. The water depth data of the three datasets were qualitatively compared and classified as good, average and bad matches. It was found that there was a shift in the location of model cross-sections with respect to the measured and crowdsourced data. The measured depths by citizens were aligned to the model cross-sections for analysis and visual comparison with the ADCP data, classifying them as good or bad, depending on how well they matched. The ones

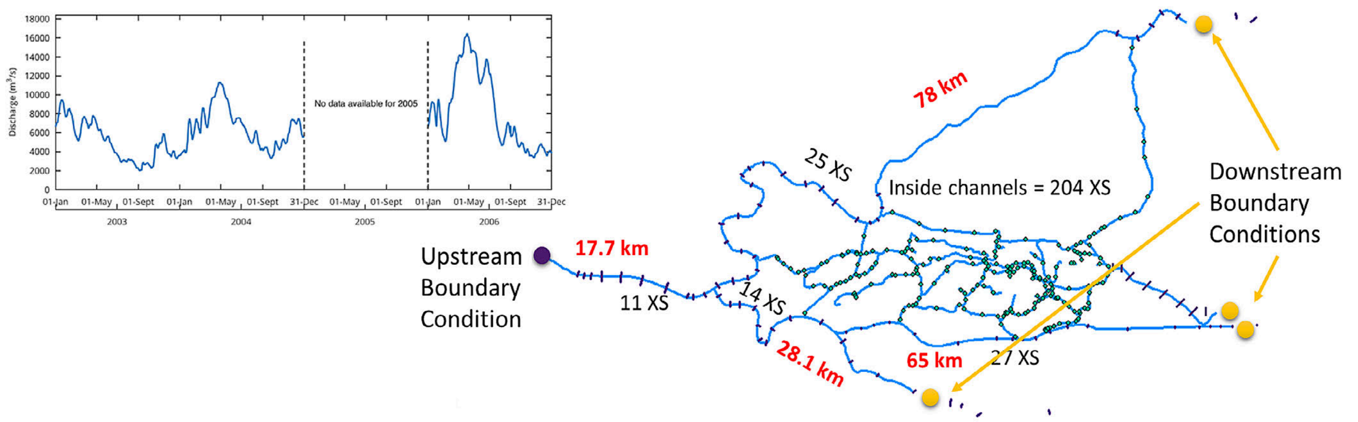

Figure 2 | Schematic of the 1d/2D RAS model of the Sontea-Fortuna area.

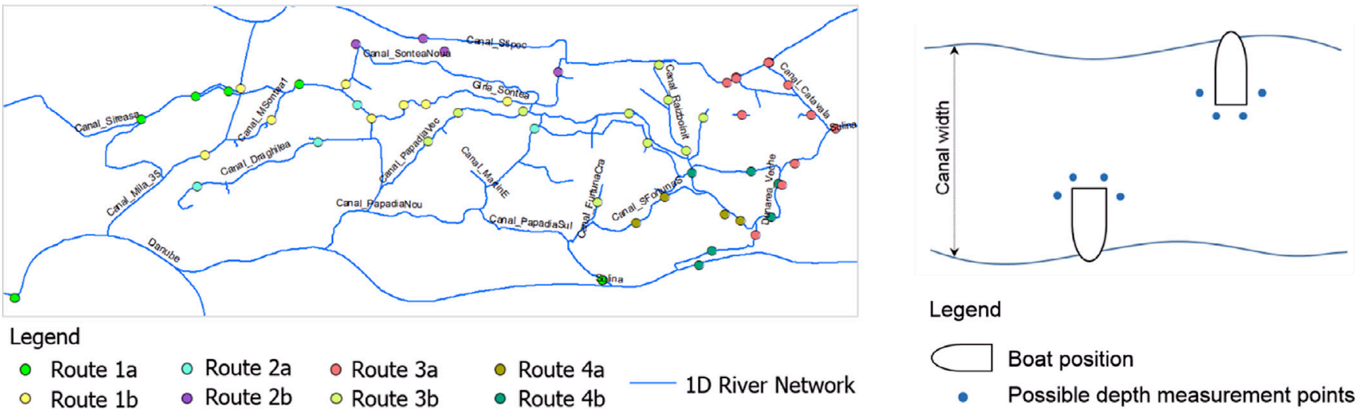

Figure 3 | Example data collection pathways to be followed by boats (Left) and boat position and data collection points (Right).

classified as bad were eliminated. There were two factors which led in crowdsourced data points to be discarded. One was the location of crowdsourced data itself, and the other was the representation of the terrain in the HEC-RAS model. The crowdsourced data locations were derived the GPS of the mobile phones. Sometimes the signal quality was weak resulting in locations potentially to be less accurate. The second factor was that eve though there were locations where, the crowdsourced data had proper spatial position, the spatial locations of crowdsourced data did not match the inundations shown in the model results (**Figure 5**).

In order to understand better how well the model is performing, without the uncertainty of the crowdsourced data, the maximum water depths in a cross-sectional profile and maximum discharge on the day of measurement were compared with the model results at all locations. It was found that the maximum depths in the 1D canals were approximately equal to the measured data. In 2D flow areas, they were close, but not as much as in 1D (**Figure 6**).

The comparisons of the model profiles with the crowdsourced and measured data indicated better matches in the 1D canal networks than the 2D flow areas, because the model was calibrated mostly for 1D networks. The good correlation of crowdsourced water depths with respect to the measured water depths indicate that the crowdsourced data represents valid information and may be used in modelling.

Figure 4 | Collected water levels of bad quality (upper row) and good quality (lower row).

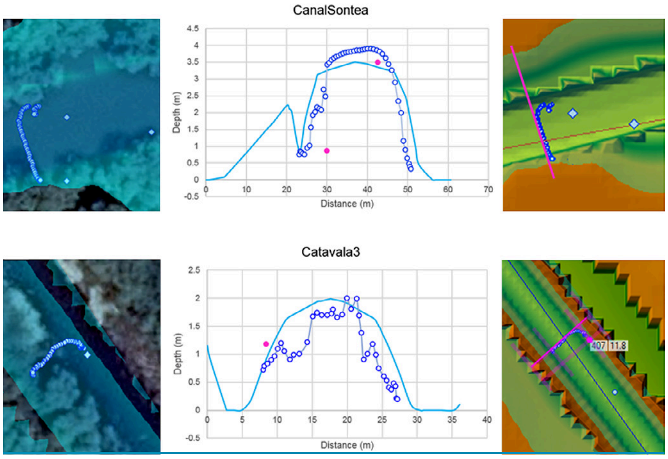

Figure 5 | Example of bad located crowdsourced data as compared with model inundation results.

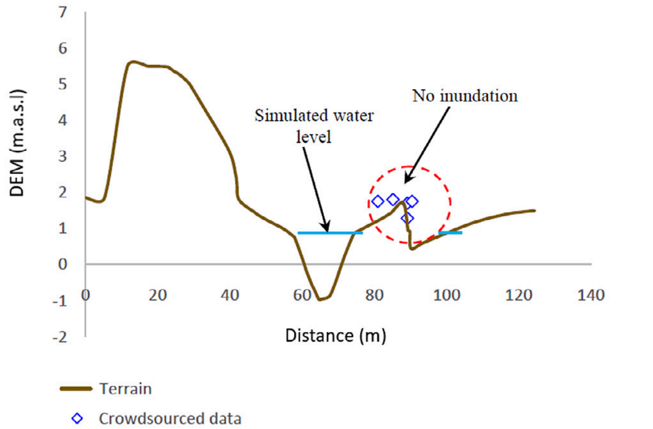

Figure 6 | Water depth comparison between measured, model simulated data and ADCP collected data, on two different canals inside Sontea Fortuna area.

Conclusions

The collected citizen data in SCENT proved that such data is effective as there is enough amount and well distributed data available from crowdsourcing. The comparative analysis carried out on different data sources indicated the value of crowdsourced data, complementing the limited data available from classical sources in the modelling context. Possible usages of crowdsourced data in the modelling of floods are validation datasets, when calibrating the model with the measured data, or vice-versa. Tuning the model using both measured and crowdsourced datasets in combination does improve its performance, and also shows the contribution of crowdsourced data as valid dataset in the modelling process.

Despite being challenging, the implementation of citizen observatories in the Sontea-Fortuna area has demonstrated its usefulness and that it can contribute to the improvement of many aspects of environmental area is better protected and managed. These initial results are promising, however many challenges remain open in crowdsourcing approaches, regarding gathering sufficient amount of data at the right time and on the right locations, as well as the sustainability of applying these methods for collecting data after the main project funding stops. There is a need for better involvement of the citizens in these actions, by having the authorities investing in actions and in continuous organisation of campaigns, in projects that address the concerns of the local communities engaged in COs.

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The role of citizen science in the campaign to designate UK's first official river bathing water

By Rick Battarbee

This article describes the citizen science project that helped establish a stretch of the River Wharfe in Yorkshire as the first running water site in the United Kingdom (UK) to be designated as a bathing water. The objective was to raise local awareness about the impact of sewage discharges on faecal bacteria concentrations in the river as it flows through the small town of Ilkley. With funds from local councils and charities we conducted surveys of *Escherichia coli* abundance along the river. It was shown that high faecal bacteria concentrations were not only caused by discharges of untreated sewage but also by treated effluents and by runoff from agricultural land. As a designated bathing water, the Environment Agency is now required to monitor the site, identify specific pollution sources, and ensure control measures are put in place.

Discharging untreated or partially treated sewage into rivers to prevent sewage treatment works (STW) becoming overloaded is standard practice in the water industry. In the UK such discharges are allowed under "consent to discharge" licences issued by the Environment Agency (EA). The relevant legislation implicit assumption is that untreated discharges would occur very infrequently, only during or directly after exceptionally heavy rainfall. In recent years, however, there has been an upsurge in pollution incidents reported by members of the public and data from event detection monitors, now fitted to combined sewer overflows (CSOs) throughout the UK, show that untreated sewage spills occur not exceptionally but very frequently and in many cases over 100 times per year.

The residents of Ilkley, a small town in West Yorkshire, have been in the forefront of the campaign to halt sewage spills. Initially complaints made to the EA and to the local water company (Yorkshire Water) about spills from the local STW into the local river, the River Wharfe, fell on deaf ears. Both organisations sheltered behind the site's "consent to discharge" licence held by the company.

Figure 1 | Untreated sewage discharge from the Ilkley sewage treatment works. Photo credit: Karen Shackleton.

Enter citizen science

Some of the initial anger in Ilkley centred on the unsightly nature of the untreated sewage discharges especially those that occurred in summer when river flow was too low to wash away solid matter. But the key concern was the health risk to river users from waterborne faecal pathogens. The local campaign group consequently went in search of data on pathogen concentrations. However, requests for information revealed that monitoring faecal bacteria concentrations on rivers did not occur. Faecal bacteria are only monitored at designated bathing water sites, which in Yorkshire only occurred on the coast.

We consequently devised our own protocols and set up a citizen science project to monitor faecal bacteria *(Escherichia coli* and Intestinal enterococci) both above and below the Ilkley STW and along the full length of the River Wharfe. We raised funds from a multiplicity of local councils, charities, and other organisations including crowdfunding and trained local citizens to collect samples. The samples were analysed by a fully accredited commercial laboratory.

Our objective was to raise awareness about the issue, locally and nationally, and provide our own advice to residents and visitors about the dangers of swimming in the river, especially at sites downstream of storm overflows.

Our data showed that high concentrations of *E. coli* not only occurred downstream of the storm overflow during spills, but also downstream of the final (treated) effluent outfall on occasions when the storm overflow was not spilling. For example, the *E. coli* concentration on the 10 July 2019 was 35,000 cfu/100 ml in the river at Beanlands Island, a site downstream of the final effluent outfall, compared with just 350 cfu/100 ml between the storm overflow and the treated outfall (**Figure 2**).

As treated effluent flows into the river continuously, day and night, we could conclude that *E. coli* concentrations downstream of the STW would always exceed safe limits for bathing, whatever the weather, and these concentrations would be further boosted in wet weather by discharges from the storm overflow.

The UK's first designated river bathing water site

Despite the strength of local opinion and despite the clarity of our data the campaign to clean up the river made little headway. Things changed when it was decided at a town meeting to apply to the UK Government for the stretch of River Wharfe in Ilkley to be designated as an official bathing water site under the EU Bathing Water Directive, now, post-Brexit, absorbed into UK legislation. If successful, such designation would require the EA to begin a monitoring programme and conduct a site investigation.

The frequency of storm overflows was not a barrier for the application as the principal criterion for designation depended on the visitor popularity of the proposed bathing water site (**Figure 3**) rather than water quality. In December 2020, after long delays due to the covid pandemic and an extensive consultation process, the site was awarded bathing water status, the first of its kind for a running water in the UK.

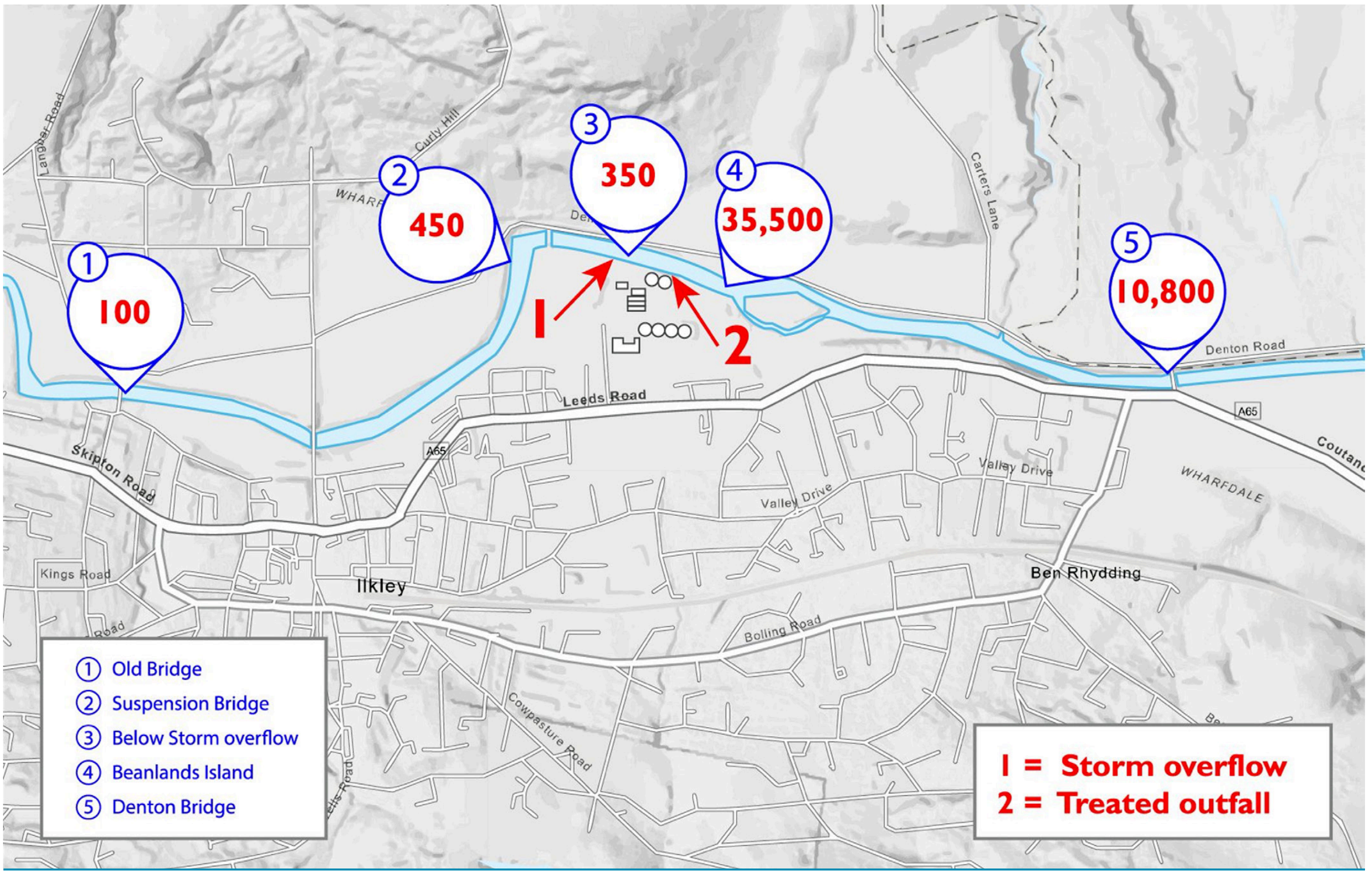

Figure 2 | *Escherichia coli* concentrations (cfu/100 ml) for sites on the River Wharfe upstream and downstream of Ilkley sewage treatment works on 10 July 2019. Drawing: Bruno Vincent.

Figure 3 | Visitors at the designated bathing water site on the River Wharfe in Ilkley.

Architecture versus sewage

The application for bathing water status shifted the emphasis of our citizen science project. Whereas sewage effluent, both untreated and treated, was indisputably responsible for the high concentration of faecal bacteria downstream of Ilkley STW (Figure 2), we needed to identify the sources of faecal bacteria arriving at the proposed bathing water site from sources upstream. These sources potentially included outfalls from small village STWs, a sewage pumping station storm overflow serving the village of Addingham, septic tanks, urban surface water runoff and agricultural livestock in tributary catchments.

For dry weather conditions, the data showed that *E. coli* concentrations in the main river were relatively low. In wet weather, however, we identified two scenarios that elevated *E. coli* concentrations in the main river and at the designated bathing site.

First, on two occasions after heavy rainfall the capacity of the storm tanks at Addingham Pumping Station was exceeded and untreated effluent was discharged into the local stream (Mill Stream) and thence into the main river. Despite the dilution provided by the main river in spate, the injection of *E. coli* in such high amounts increased its concentration in the Wharfe from 300 to 2,800 cfu/100 ml (Battarbee & Secrett 2020).

And second, on 23 August 2021, the day after a long spell of dry weather followed by a prolonged rainfall event, we observed *E. coli* concentrations in the main river rising to over 2000 cfu/100 ml (Figure 4) but at a time when the storm overflow at Addingham Pumping Station was not operating.

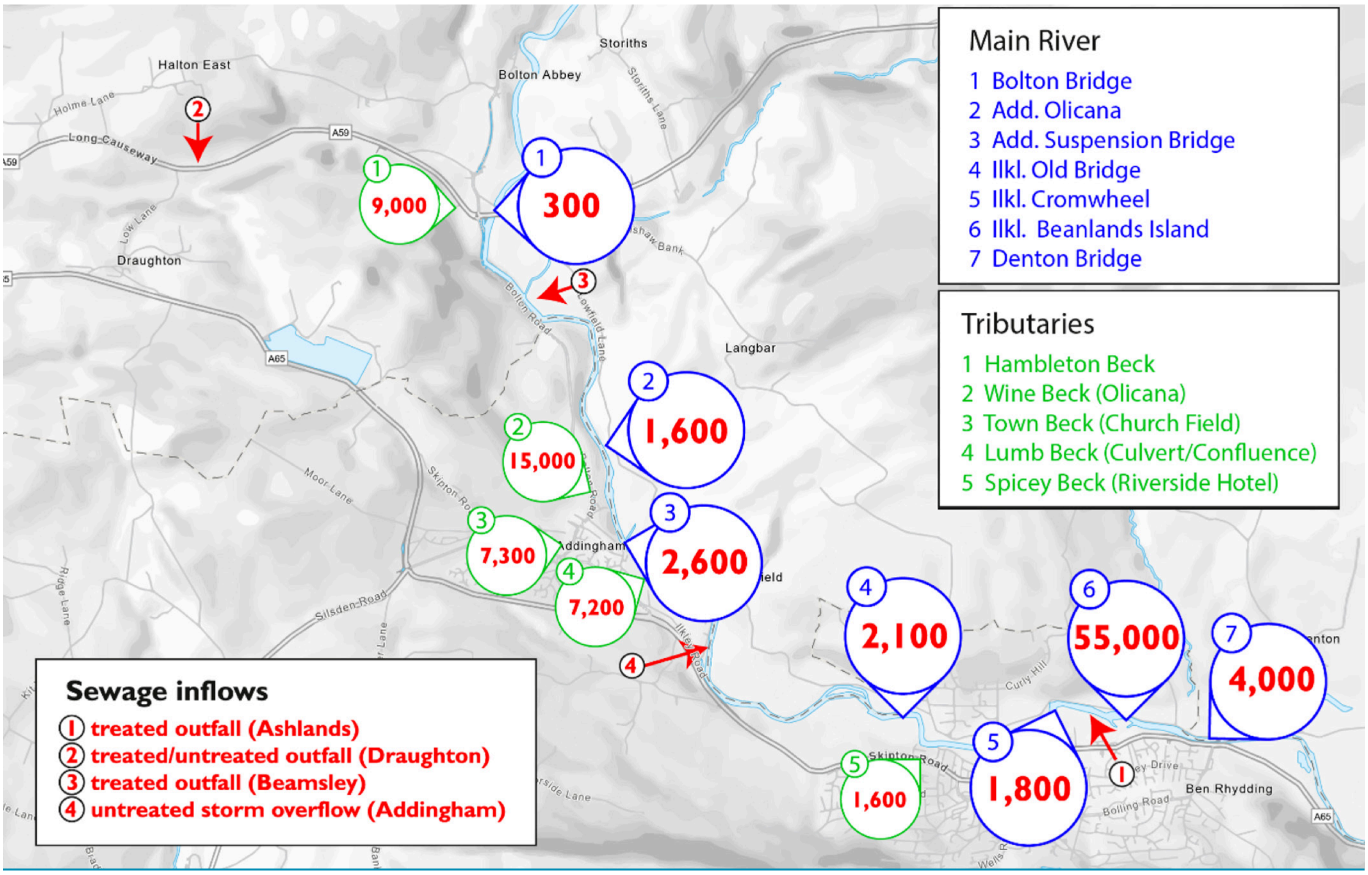

Figure 4 | *Escherichia coli* concentrations (cfu/100 ml) for sites on the River Wharfe (red numbers in blue circles) and tributary streams (red numbers in green circles) on 23rd August 2021. Drawing: Bruno Vincent.

The concentrations of *E. coli* in the tributary streams on that day were the highest recorded, indicating that the high concentrations in the main river were mainly of agricultural origin. We surmised that increased flow following the earlier rainfall had resuspended faecal bacteria from streambed and riverbed sediments and caused soil contaminated with livestock faeces to be inwashed from the banks (**Figure 5**).

Control measures

Following its designation as a bathing water site, the EA began monitoring faecal bacteria in Ilkley in 2021. Based on results for the 2021 bathing water season (May to September), the site has been classified as "poor", i.e. a 90 percentile value for *E. coli* greater than 900 cfu/100 ml.

Lifting the Wharfe from "poor" to "sufficient" status as defined by the legislation will require control of a number of different sources of faecal bacteria. Reducing spills of untreated sewage from CSOs is a priority not just in Ilkley but nationally in the UK —a priority now enshrined in the 2021 Environment Act. The solutions, however, although easy to identify will be slow to implement. For Ilkley, reducing groundwater infiltration into the sewer network, de-combining foul and surface water sewers and retrofitting sustainable urban drainage systems in the catchment are all needed but will take decades to complete.

Moreover, in the Wharfe catchment and other areas with extensive livestock farming, diffuse sources of faecal bacteria require control by better land and animal management, especially in riparian zones (Kay *et al.* 2018).

Although some of these solutions inevitably require hard engineering, for example the de-combination of old combined sewer networks, others are nature-based solutions that provide multiple environmental benefits. Constructed farm ponds and wetlands can be used for effluent treatment, rain gardens in urban areas reduce surface water runoff into sewers and fenced riparian buffer zones in agricultural catchments limit livestock access to river banks. Each of these solutions reduces both faecal bacteria contamination and nutrient pollution in watercourses, creates wildlife habitat and mitigates carbon emissions. Such co-benefits need to be taken into account when considering the cost of cleaning up.

The future

Following the Ilkley designation, a second river site (on the River Thames at Port Meadow) has now also been designated. Many more such designations are likely in coming years as campaign groups spring up throughout the UK and as the 2021 Environment Act, which requires water companies to reduce discharges from CSOs, takes effect. However, investment by water companies will materialise only slowly, diffuse pollution from agricultural land may be difficult to control and if climate change causes more frequent and intense rainfall events, the problem may well become much worse before it improves.

Citizen scientists have a major role to play in local monitoring schemes, raising public awareness and holding polluters, regulators and politicians to account.

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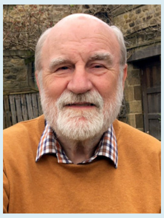
Figure 5 | Cows on the River Wharfe at Bolton Abbey. Photo credit: Jonathan White.



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How to design a river with children: community participation and stream restoration in Tokyo

By Takehiro Watanabe, Takizawa Kyohei, Nakamura Shinichiro, Satoquo Seino and Yukihiro Shimatani

This article gives an account of the planning of Osonigawa Brook, a stream restored in Tokyo, Japan in 2018. Local children, whose elementary school ran a river-centered curriculum using this stream restoration as a project-based learning program, participated in the design process. Years of cooperation between community volunteers, outside experts such as river engineers and hydrologists, and government agencies ensured the project's success. This case adds to the growing number of nature-based solutions being implemented in Tokyo, a mega-city seeking new ways to manage climate challenges.

A ribbon-cutting

On a summer day in 2018, an opening ceremony for a new brook took place in a small Tokyo park. On stage, six white-gloved figures stood side by side: the Suginami Ward mayor, a council member, two local elementary school children, and two community group co-chairs. Behind them was Osonoigawa Brook purling over riffles, its clear water shimmering in the sun.

This celebration showcased the children and many community members who worked to revitalize this urban waterway. Before the restoration, the brook had been fenced off and neglected, for good reason: it was dark and overgrown, its waters stagnant and knee-deep in semi-decomposed litter. But when a group of schoolchildren submitted a request to restore this waterway to the mayor, the community sprang to action to realize their dreams. After a series of participatory design workshops, the ward cleaned the stream and a new community group was formed to help maintain, monitor, and coordinate programs for this new blue space.

In cities such as Tokyo, rivers, ponds, and wetlands have captured the imagination of water experts due to their potential as spaces for biodiversity conservation and nature-based climate solutions. Yet many of Tokyo's rivers are cast in banks of ferro-concrete, fouled with combined sewage overflow. Many of Tokyo's inland waters are on life-support with pumps and by-passes, offering poor habitat for aquatic life. With rivers no longer directly linked to people's livelihoods, most Tokyoites are uninterested in the water cycle and unaware of the vast infrastructure that supports and protects their lives.

Osonoigawa Brook is an example of an urban water infrastructure project that was designed around the principles of ecological soundness and community participation. Behind the planning was a local elementary school that served as a hub of citizen science and river advocates who cooperated with the local government to reimagine a forgotten waterway.

A forgotten waterway

Osonoigawa Brook flows into the Zenpukuji River, which connects to the Kanda River – an important river system in Tokyo's history. Temples and shrines that visitors may find in the area tell of its historical importance as a spring pond. At the time of the capital's seventeenth-century founding, this river supplied water for rice paddies, urban residents, and the castle moat. Until the twentieth century, the area surrounding the river's headwaters remained mostly agricultural.

But starting in the 1920s, urbanization transformed the area into a commuter town, adding new stresses to the river. Hydrologically, the population increase resulted in greater use of ground and surface water. When farming declined, so did night soil demand, creating fecal sludge disposal problems. Furthermore, the completion of a modern water supply system, spurred by the cholera outbreak, meant that the Zenpukuji River was no longer needed to be clean. Even so, citizens and officials

Figure 1 | Osonoigawa Brook today. Photo by H. Watanabe.

Figure 2 | Opening ceremony for Osonoigawa Brook. Photo by H. Watanabe.

Figure 3 | Osonoigawa Brook before restoration, April 2018. Photo by K. Takizawa.

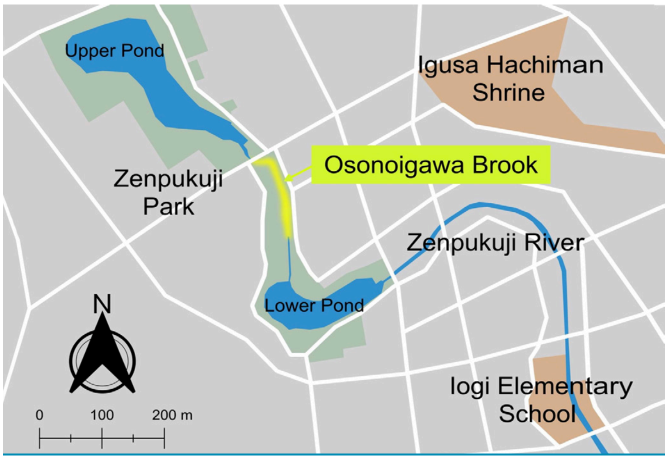

Figure 4 | Map of Osonoigawa Brook. Created by T. Watanabe, based on OpenStreetMap.

campaigned for public parks and green spaces. In 1930, the city designated Zenpukuji Pond and its surroundings as a "scenic area" and local landowners formed a conservancy, which worked to widen the pond for rowboats. In the 1950s, a second pond replaced rice paddies with an iris water garden. Efforts to refashion this spring-fed marsh into a recreational area for suburban families connected the former (upper) pond with the new (lower) pond, thus creating Osononigawa's modern shape.

During this transitional period, rivers in Tokyo became dirtier and flashier as they were channelized, culverted, and turned into sewage canals. Yet, as Japan entered an era of middle-class consumerism and gentrification, the public again called for improving urban environments. In the 1980s, a local group fenced off the waterway to protect fireflies, but this initiative faded as the springs dried up and the waterway fell into obscurity. In 1989, the River Revitalization Project, a government effort to revive desiccated waterways with treated wastewater, gave Zenpukuji River a second life. In 1997, the national government amended the River Laws, Japan's premiere law on inland waters, making environmental concerns and community participation top policy priorities.

By the 2000s, due to a renewed community interest in the Zenpukuji River, local river advocates devised community-led programs that included citizen monitoring and environmental education with the river as an outdoor classroom. Local elders, recruited by the school as volunteers, used this opportunity to teach children about a bygone era when Zenpukuji River wove through farm lots and rice paddies through braids of irrigation dikes. These programs also helped expose issues such as non-point pollution, biodiversity loss, and watershed-wide drop in surface permeability, and allowed the participants to connect these issues to more immediate problems such as flooding and the heat-island effect.

Children's hopes for a better river

Of the many schools along the Zenpukuji River, Iogi Elementary became an activity hub for the local advocacy of the river. Iogi has a rare feature: a river runs through it. With the help of these advocates, the teachers set up a river-centered environmental curriculum. Instruction now includes several trips in and around the river, including river clean-ups, birdwatching, a river monitoring routine consisting of water quality testing and biological surveys, and lessons by local experts and university researchers.

Iogi's program entered a new phase when the head of the school's community liaison office and a key volunteer organizer of this curriculum developed an interest in the waterway as a potential site for environmental programming. The two noted that unlike the river proper, the waterway did not suffer from sewage effluents, was accessible from the park, and was managed directly by the ward government, thus lowering the jurisdictional bar. To explore this idea further, the duo began consulting experts in 2013 and invited river engineers, hydrologists, and ecologists to conduct classes for the schoolchildren.

These activities gave shape to the hopes of stream restoration and inspired the school to bring the children's activities to the local government's attention. In a series of classroom activities, 113 children in the fifth and sixth grades each drew, with crayon and color markers, their design ideas for the waterway. While the drawings varied in style and content, they revealed that the students were concerned about accessibility, habitat restoration, daylighting, and multifunctionality.

In July 2014, four students visited the local government office to submit these drawings to the Suginami Ward mayor and asked him to "change the waterway so that we can enjoy it." In attendance were the students' teachers, the community liaison officer, and a television crew. Perhaps because this project was aligned with the ward's push for more ecologically-healthy water spaces as well as greater civic participation, the ward earmarked the children's proposal.

With the project approved, the river advocates prepared the community for active engagement in the planning. Community leaders met with officers and asked to hold a design workshop to guarantee the inclusion of community voices – especially those of children. The leaders also teamed up with outside experts to hold events, such as citizen science opportunities, a public panel with elders about local history, and a symposium about community-driven stream restoration projects. These events allowed local stakeholders to identify and resolve conflicting interests, while also building excitement for the project.

From design to construction

In October 2015, a year after the children submitted their drawings, the planning process began with a series of design workshops. Held meetings four times over two months at Iogi Elementary with 35 participants, the workshops were coordinated by a landscape architecture firm hired to draft the new waterway plan.

In the first workshop, the participants identified key desired outcomes. The schoolchildren launched the workshop with a presentation about their drawings and a survey that they had conducted to learn about the local residents' concerns. The participants then created a wish list of four key features: A | better accessibility, B | chances to observe nature, C | sites for water play, and D | habitat conservation. The session also exposed contentious issues, such as differing approaches to habitat protection.

In the second workshop, which was held outdoors, participants conducted field observations and shared their findings on four themes: 1 | water, 2 | light and greenery, 3 | people, and 4 | the surrounding area. In the third workshop, participants were divided into four groups and plotted the four desired features onto the waterway's ground plans. All groups proposed zoning a habitat conservation area in the upstream section, followed by a midstream nature observation area and a recreational area downstream.

In the fourth and final workshop, the landscape architects unveiled their plan, to the general satisfaction of the participants. There were, however, several design concessions. First, while the city approved a wider channel and a riparian slope, which required an expansion into the city's jurisdictional area, the culverted section could not be daylit, thus limiting the restored stream's length. Second, water testing revealed that the upper pond's water was unfit for both recreational use and aquatic life. Suggestions from participants, such as improving the water quality of the upper pond through dredging and culling invasives, were all deemed impractical, costly, and too time-consuming. Instead, a two-part solution was devised: reroute the unwanted water to the lower pond through an underground pipe and draw clean groundwater via a nearby pump into the stream head. Despite these setbacks, the workshops ended with a consensus on the design principles for the waterway.

Toward a partnership

During the two years between the workshops and the opening ceremony, the ward held meetings to develop a co-management partnership with the river advocates. Since the 1980s, as a response to the decline of neighborhood associations, irrigation cooperatives, and 'scenic area' conservancies, the ward had experimented with new governance arrangements. This was on the mind of participants who during the process had called for greater community participation.

The earliest meetings began with unresolved issues from the workshop. For example, the river advocates, with the advice of engineers, proposed design changes that remedied the channel's straight and fixed lines in the ward's plan by including nature-oriented features such as stream meandering, weir-induced pools and mid-channel bars, and adding variety to the stream width for slower and faster flows. These new design details were not only intended to foster greater habitat diversity, but also to entice children to "play river engineer" – changing the movement of water with stones – in their new blue playground. Another issue, which was raised once the meetings became public, was the name. Instead of "Dream Waterway," which was criticized for sounding too bureaucratic and divorced from local history, participants suggested "Osonoigawa." This was an old toponym that, according to one interpretation, is linked to a legend about a samurai who drank from the spring, and according to another interpretation, is an allusion to river otters. Participants also proposed replacing the suffix "-suiro" (waterway), which connotes an artificial canal, with "-gawa" (river), to convey a more natural and folksier image. The suggestion was well received, and Suginami officially adopted this new name. These meetings led to the founding of Osonoigawa Kappa Club, which was launched in 2017 by 13 members. Started with a ward partnership agreement, the group helps monitor the brook, conducts small-scale maintenance, and coordinates educational programs. Its charter explains the word kappa, a water trickster from Japanese folklore, as "someone who protects rivers and its waters." The group helped create rules of use for the new brook and ran programs during construction, such as enlisting schools in the effort to revive local flora from the soil seed banks of excavated layers.

Figure 5 | A student explaining drawings for the new brook. Photo by T. Takizawa.

Figure 6 | Osonoigawa Brook on opening day. Photo by T. Watanabe.

In closing

Four years after the children submitted hand-drawn blueprints to the ward mayor, a ceremony was held to open Osonoigawa Brook. Its banks stabilized by native flora that the children themselves planted, the new water space is a testament to the years of community-government cooperation, exchanges between local and outside experts, and the river advocates' insistence that children's experience remain at the heart of this project.

The new brook, now flowing clearly, is also lucid about the lessons it holds for community engagement and urban stream restoration. In this case, children's participation through the public school system was essential for its success. Like many schools, Iogi Elementary is connected to a range of stakeholders: children and their families, teachers and the board of education, neighborhood associations, volunteers, local businesses, and government offices. As a network hub, the school was able to mobilize resources across different sectors and bureaucratic barriers. As an institution of learning, it served as a bridge between local knowledge, embodied by community volunteers, and expert knowledge, typified by professionals and researchers.

One way, then, to involve communities in stream restoration projects is to develop field-based, problem-driven educational curricula that embrace both local knowledge and global expertise. Although a tall order, this model encourages communities to develop innovative solutions to today's water challenges. If schools and communities continue to nurture the children's connection to water, then perhaps a sense of stewardship, one that reaches deep into local neighborhoods and wide across the entire planet, will grow with them.

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Emerging challenges and the future of water resources management

By Angelos Alamanos and Phoebe Koundouri

Water managers are facing new challenges: more evident climate change impacts, Covid-19, recession, wars, population movements, increased energy and resources demand. These affect water management and several related sectors such as energy, fuels, industry, agriculture, international relations and trade, economy, resources, including water, human and natural capital. This situation creates an ambiguous context (deep uncertainty) that suggests reconsidering the traditional management approaches and leaves limited space for management failures and delays.

In this article, it is discussed three research questions/areas of focus for the future:

1 | Redefining multi-disciplinary science and innovative collaborations to analyze and solve complex problems.

2 | Efficient communication and continuous engagement to create the culture for science-supported policies and speed up the response of policymakers to grasp and adopt research and technological advances.

3 | Deciding under deep uncertainty.

Emerging challenges and connection with Water Resources Management

Most policy bodies and stakeholders involved with water management issues have started to face new challenges, increasingly associated with complex problems, that suggest reconsidering the traditional management approaches. The increasing needs accompanied by resources overexploitation and the inten sification of production have created conditions of scarcity, environmental degradation, and increased emissions of Greenhouse Gases that enhanced climate change. The rapid expansion of various human activities that rely on energy also contributed

to increased energy demand. Among the multiple consequences of climate change, there were lower intensity winds that prevailed in regions of north Europe – which have invested a lot in renewable (wind) energy systems, but do not have the respective energy storage capacity[1]. The global changes in energy supply and demand patterns brought us before big demand increments, reductions of supply and available stocks, thus an overall increase of prices (electricity, natural gas, etc.), and inflation. Covid-19 and the subsequent war in Ukraine made those effects more evident and much more stressed, initially in Europe[2]. This situation constitutes an unprecedented phenomenon of diverse challenges that interact, and are extremely difficult to predict, so they create a context of ambiguity. This affects systems that are interconnected with water resources, and the respective decisions on management, infrastructure, and investments (**Table 1**).

The water sector (and its relevant systems) has to cope with these challenges, additionally to any existing issues of infrastructure, water scarcity, water quality deterioration, and mismanagement in human, economic, institutional terms. Thus, it is crucial to identify the knowledge gaps, and apply innovative solutions to accelerate the adoption of science-supported policies, to tackle these challenges by sustainable ways (**Figure 1**).

Complex crises may create conflicts, treating the different systems (water-food-energy-fuel-resources-economy) as competitive, missing thus any opportunities for improvements. Below, we discuss some research areas/future research questions, as opportunities for improving the management of such systems.

Fields	Description
Disaster Management (floods, droughts, pollution, pollution events)	Forecast, protection, warning, prevention, evaluation, restoration, awareness, under changing conditions and behaviors
Transboundary management Water rights	Control and fair management of different demands and pressures, under changing conditions and conflicts
Resources allocation	Covering competitive demands with limited and deteriorating available surface and groundwater resources
Water infrastructure (storage, distribution, land, reclamation works, hydropower, etc.)	Different strategies considering different objectives and investments for design, operation, performance and efficiency of infrastructure
Water quality	Planning, decision-making, management, performance, protection, warning, prevention, restoration, control of point and non-point pollution sources from all uses
Interconected physical systems with water resources (soil, land, landscape, air, atmosphere, climate, oceans, biodiversity, ecology, etc.)	Monitoring, forecast, protection, warning, prevention, evaluation, restoration etc. management actions considering multiple effects, costs and benefits
Social and economic aspects (behavioral, dynamics, environmental economics, investment decisions, etc.)	Different strategies, methods and applications to cope with changing objectives of rights and shares, distribution of costs and benefits, social acceptance
Other cross-disciplinary, interconnected dyynamic systems (Ecohydrology, Socio-hydrology, Water-Energy-Food Nexus, Water Ethics, etc.)	Identification – implementation of 'best' management practices, optimizing efficiency and performance under specific criteria
Policy and Governance	Combining all the above into strategies, education, Public Participation and stakeholder engagement, strong institutional and financing mechanisms and regulations

Table 1 | Indicative fields of water management facing increasing challenges.

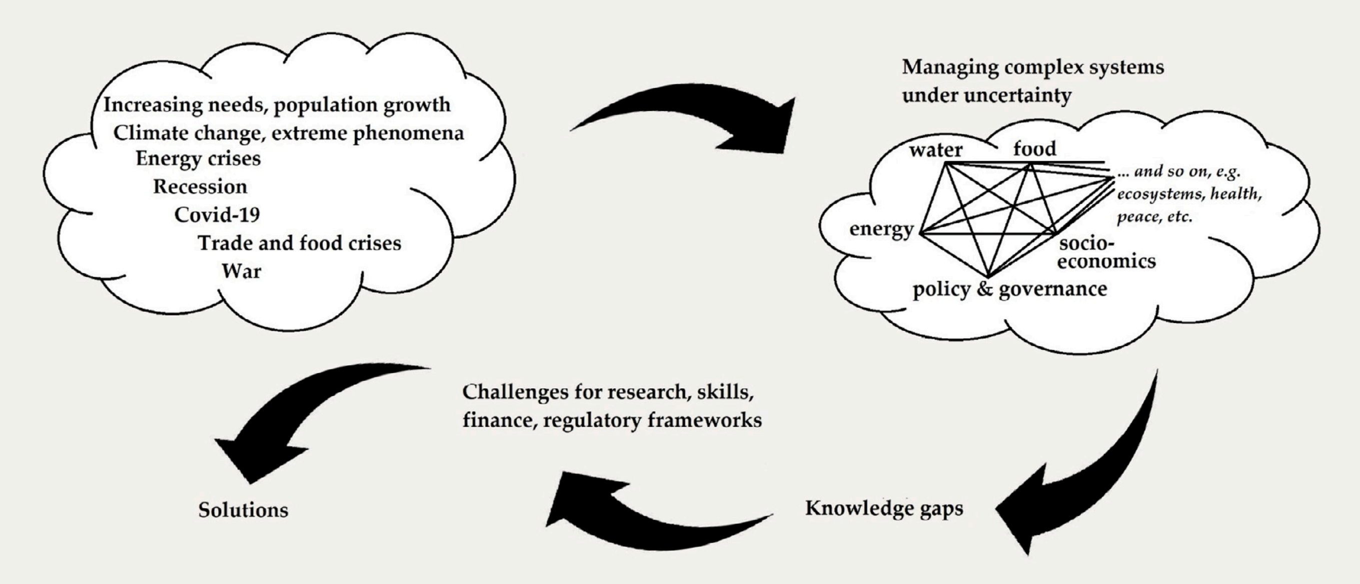

Figure 1 | Complex, interconnected problems, create deeply uncertain conditions that challenge the management of human-environmental systems, demanding thus innovative solutions.

1 | Redefining multi-disciplinary science and innovative collaborations to analyze and solve complex problems

During the last years the transition to a multi-disciplinary water systems management is evident. Redefining multi-disciplinarity should be built on the equal contribution of the different disciplines, their harmonization into modelling and implementation (coupled scientific areas rather than just add-ons to a main body of work based on a single discipline). Such an approach could bring fundamental advances in practice. The knowledge base has been developing, preparing the ground for this transition.

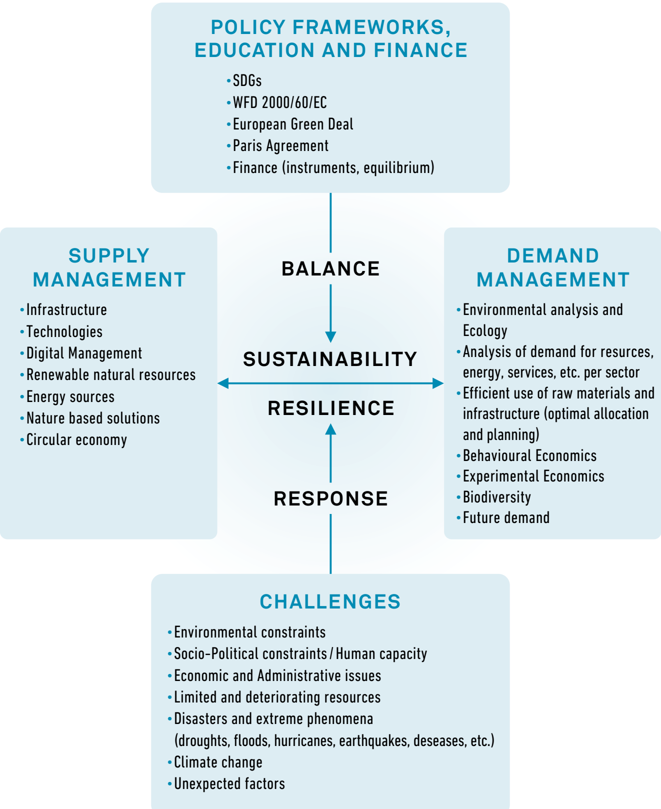

Figure 2 | Sustainability and resilience through balancing supply and demand and addressing various challenges in integrated systems[4].

This is justified by several examples on sophisticated integrated models represen-ting system dynamics, multi-disciplinary approaches, including more social and political aspects. Culture is seen as a missing to build this culture for all actors involved is by learning, from their discipline and other disciplines that can trigger innovative solutions and approaches to the current problems.

Analyzing the natural, human (social and behavioral), and economic sub-systems requires the consideration of all their supply and demand components, in order to develop and/or modify the institutional/policy-regulatory sub-system appropriately and proactively. A high-level example is presented in Figure 2: The supply side includes environmental, social, and economic factors that need to be analyzed, and assessed as assets, either to the degree that we can control or to manage better. Supply can be increased sustainably through more efficient and smarter use of our assets. The demand side includes also multiple parameters and disciplines (environmental, social, economic) that can be optimized and used efficiently. The institutional/policy-regulatory sub-system aims to (and is required to) balance supply and demand in order to make systems operate sustainably (both environmentally and economically). Thus, the ground is prepared, and more solutions can be provided to address the various challenges, and thus achieve resilience.

2 | Efficient communication and continuous engagement to create the culture for science-supported policies

The whole process described cannot operate in a healthy and integrated way without the necessary involvement from policymakers. Like the other actors, they should be part of a two-way informational process towards the development and the implementation of solutions. By informing researchers and being informed, the policymakers could develop the necessary culture for seeing tangible actions and steps towards an improved management of human-environmental systems.

The pace of technological and scientific advances is much faster than the pace managers need to grasp that information, adopt the appropriate advances and solutions, and develop flexible regulatory frameworks to support them. A simple example of this pace-difference phenomenon is Digital Water Management, where the policy makers' response has been slow compared to the private sector, and still, the solutions provided have not been fully exploited.

As researchers are making efforts to provide scientific results, policymakers should make respective efforts to efficiently exploit those outcomes, and overcome any socio-political barriers. Their response to the new challenges, information, and available solutions and technologies should be an area of focus in the future in order to place societies ahead of the challenges.

3. Deciding under deep uncertainty

The combination of challenges and crises described from the beginning makes the work of decision-makers more complex, since it is difficult to predict changes, how long they are going to last, how they interact, and successfully explore the trade-offs of many factors in future scenarios. Moreover, there is another factor that adds further uncertainties, and that is the (unknown) way that policymakers will respond, both to the new challenges and the new information, as mentioned above. Future research could provide more ideas on how to endogenize the reactions to new information, when analyzing complex systems.

As mentioned in the introduction, such conditions create a context of deep uncertainty – or ambiguity according to the economics terminology[5], namely, having unknown probability distributions for representing uncertainty and its key parameters, and/or asynchronicity effects (given state variables not updated simultaneously in response to changes in their "cause" variables).

Deciding under deep uncertainty is a topic of broader concern, with no clear answer yet. The roots of this problem can be found in the (already proven) weaknesses of the existing approaches to understand problems and designs where the rationality of the decision-maker cannot be justified. In particular, the standard economic and engineering approaches (originally developed to deal with risk) are insufficient in explaining problems involving (deep) uncertainty[6]. The classical frameworks of expected utility theory (typically used to explore rational decision making), or social Cost Benefit Analysis (welfare-maximizing sustainable investment allocation decisions), and other optimization approaches are not adequate, because the complex challenges we are facing can make people perceive risk and certainty in different ways that deviate from the 'rational' assumptions. The standard engineering design and decision-making approaches are built on the assumption of rationality (where actors decide in dispassionate, consistent and purely self-interest ways), which does not apply under ambiguity[7].

This is being observed in real-life applications, often with high-stakes, where policymaking does not act as a clear mechanism or process where researchers know in what stage of the process can step in with the scientific evidence to influence decisions.

The literature has several examples on how to explain how this concern significantly affects issues of water management (e.g. Water-Energy-Food nexus) or climate decisions[8,9].

The message so far is that the current approaches are still inadequate to address deep uncertainty and underline the need for complementary use of current approaches and critical thinking for policy flexibility and adaptiveness to uncertain paths, including water-related investment decisions.

The capabilities of Artificial Intelligence (AI) might be able to provide some insights on how policymakers would react to new information, e.g. by considering the outputs of a model as new input to re-train the algorithm, partially endogenizing thus a response to new evidence or decision outcomes, when analyzing complex systems. However, we believe that such problems (including water management, investment decisions, and governance) cannot be solved only by relying on new technologies and computing advances, but we must achieve a human-technological efficient cooperative intelligence[10]. That would require deeper reflections on the multifactorial character of each decision, as well as the local to regional scale effects. The other two research areas discussed above, interdisciplinarity and communication for science-supported policies, can only act in support of this direction.

Conclusions

Knowing our future challenges does not tell us how to meet them in ways that will change for the better how we plan, manage, and model. Our role as researchers, is to understand the ways that complex systems and challenges function and interact, and adapt our approaches to analyze and address them. It is difficult to have the answers on how to cope with deeply uncertain conditions and create sustainable and resilient human-environmental systems, and it is also naïve to believe that these answers are simple and can work for every case. Maybe we will always have such challenges and as science and technology evolve to help us meet them, we (perhaps in respon-se to world events or other externalities) will be introducing and facing new sets of challenges. A shift of focus towards sustainability, and the development of sustainably designed systems, combining insights from the three research areas described in this article could help accepting overall optimum decisions. The research areas described above are complemen-tary, and their future findings are expected to assist reaching closer to the answers we seek.

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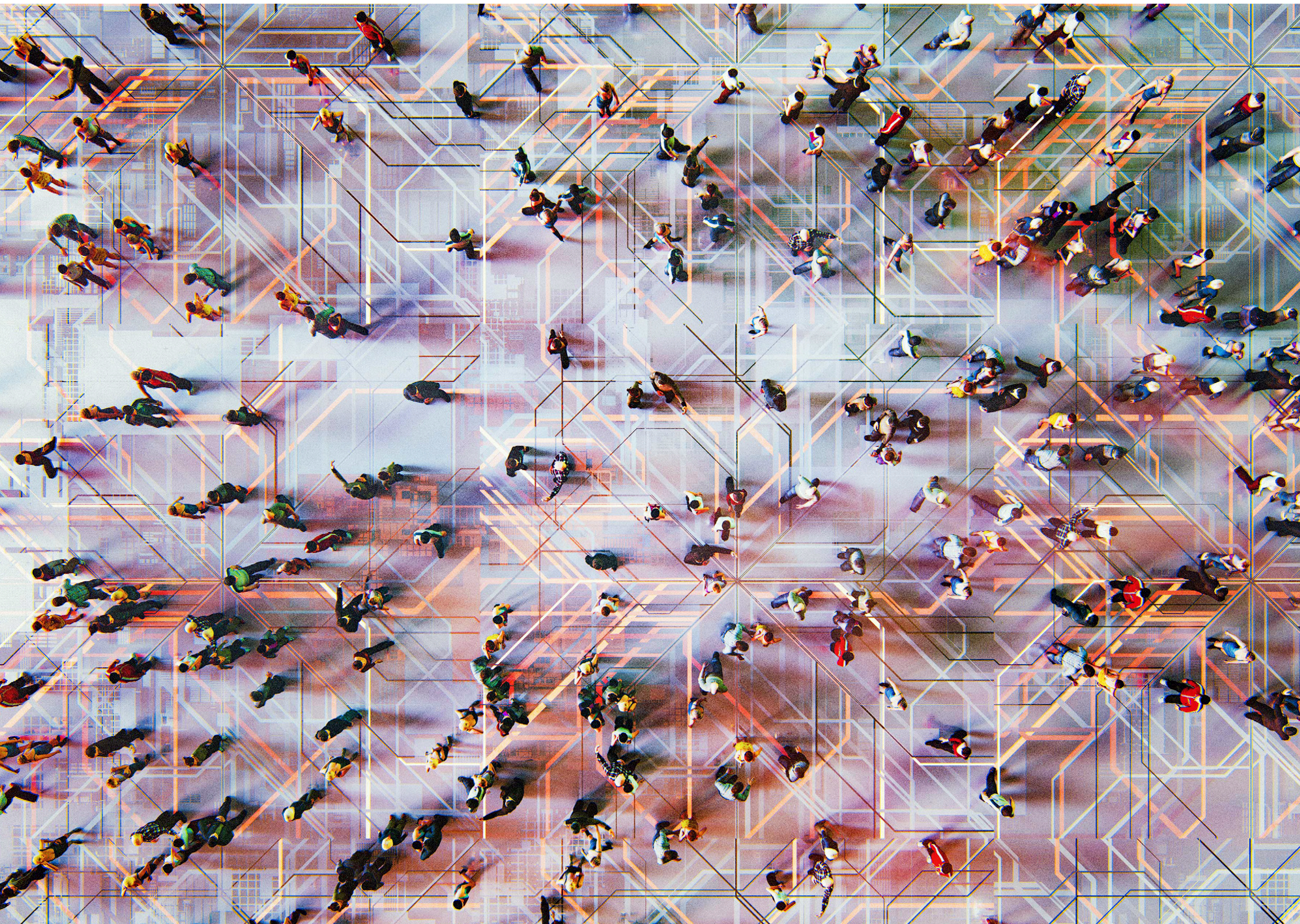
Boosting urban hydrologic research with citizen collected data

By Pan Yang, Geng Niu, Erhu Du and Yi Zheng

Citizen science, described as the method that involves citizens or communities in the scientific research process, has been used in a wide range of studies since the term was first introduced in the 1980s. In the era of big data, citizen science is increasingly attracting attention across a wide variety of scientific disciplines, as indicated by the appearance of vast reports, projects, and peer-reviewed publications. It significantly expands data collection means and scope across temporal and spatial scales, especially in urban hydrologic research.

With the dramatic popularity and implementation of social media apps and IoT (Internet of Things) in recent years, the crowdsourcing approach has been an emerging method to collect hydraulic data at a fraction of the cost of traditional ways. Through various applications in water-related issues, the crowdsourcing approach facilitated the observation of traditional methods that were difficult to quantify and thus improved the statistical power of datasets. It offers a new research paradigm and has been an important component of citizen science.

In urban hydrology research, more specifically, crowdsourcing has been seen as an innovative and promising method of environmental monitoring and data collection through the general where individual citizens or groups are encouraged to provide uploaded data through social media, mobile applications, or IoT platforms. While crowdsourced data is usually associated with a relatively high level of observation error, its tremendous volume of data could largely offset this disadvantage and provide useful information for hydrologic research. Crowdsourcing methods are thus considered to have the potential to provide high-density measurement data and augment related project scope across temporal and spatial scales. This is critical for studies such as flood management or urban stormwater modeling in which high spatial-temporal resolution monitoring data are required.



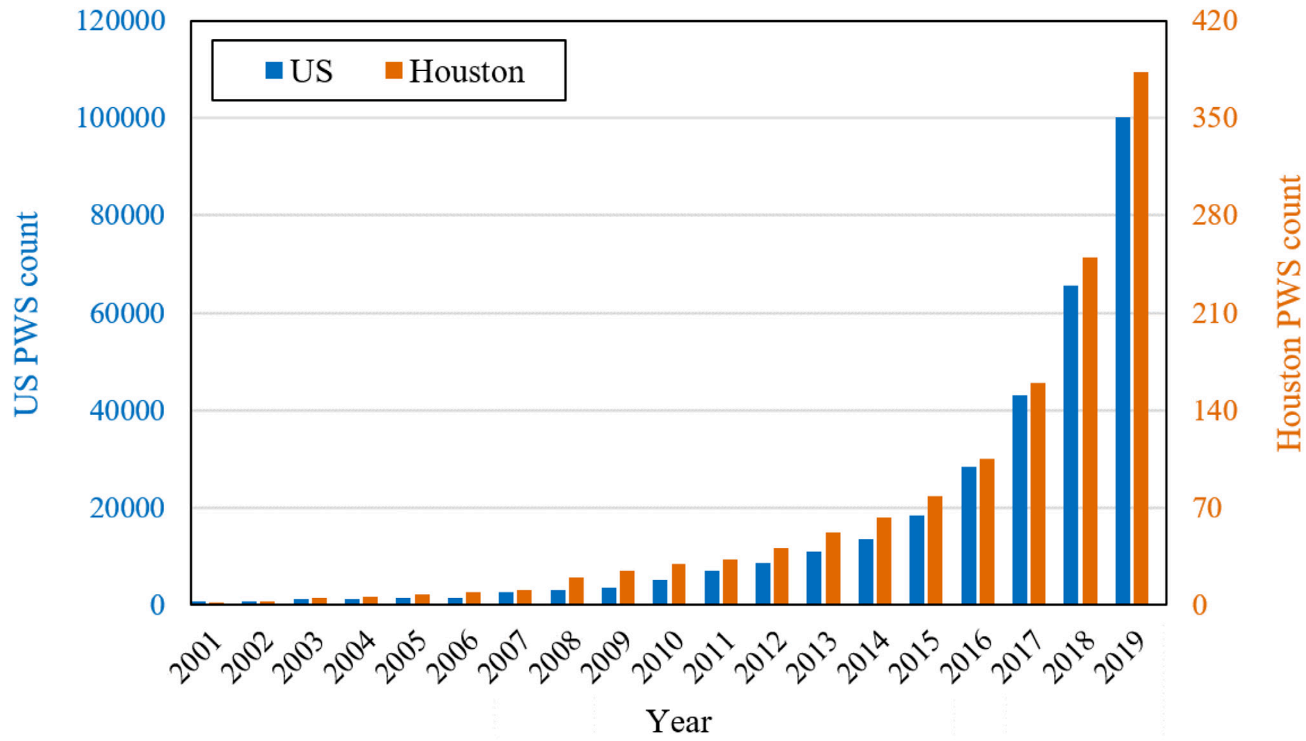


Figure 1 | In the past two decades, the number of Personal Weather Stations (PWSs) in the US and Houston has been growing exponentially. (Reproduced from Chen *et al.*, 2021)[1].

1 | Data acquisition methods

The contribution of crowdsourced data for urban hydrologic research is maximized when the data volume is large, which depends heavily on the choice of method for data acquisition. Ideally, the data acquisition method should have the potential to reach a large number of citizens or to be integrated with other existing devices (e.g., smartphones or surveillance cameras).

I Citizens

Collecting and reporting by individual citizen participation represent the most straightforward manner for sourcing data. Crowdsourced data collected via citizen participation usually is qualitative or quantitative regarding weather conditions, geospatial data, and stream stage via low-cost or homemade sensors. Take rainfall estimation as an example, during the past two decades, the number of personal weather stations (PWSs) in the US has increased exponentially from nearly 7,000 in 2010 to almost 100,000 in 2019 (**Figure 1**). Data collected from those PWSs have contributed to a much-improved estimate of rainfall in urban regions.

II Images/Videos

In recent years, image/video-based methods have been widely used in urban hydrology research. Based on report by IHS Markit[2], this planet is estimated to have over one billion surveillance cameras by 2021. With the aid of various data processing techniques, images captured by ordinary surveillance cameras or in-vehicle cameras have been undertaken to extract information about rainfall[3], flood inundation[4], and water pollution.

III Social Media

With the widespread use of various social media apps, it has been employed to assist urban hydrology research with the aid of data mining techniques. Crowdsourced data from social-media is usually attributed to unintentional type, as the information source is not shared for purposes of hydrology research. Examples include mining text information from social media, such as geo-tagged tweets about floods and water, to map flooding extents and estimate water levels.

IV IoT sensors

Crowdsourcing weather data can be collected from sensors integrated with portable devices, vehicles, mobile phones, smart home equipment, and telecommunication infrastructure. For instance, audio clips from built-in sensors of smartphones have been utilized to detect precipitation intensity. Moreover, wireless antenna signals could be used to monitor a variety of weather data, from fog to precipitation. Based on the principle that precipitation will attenuate the electromagnetic signal between antennas, the precipitation intensity is measured according to the relationship between electromagnetic signal attenuation and precipitation intensity.

Currently, there is not enough study showing the exact figures of the data volume contributed by each of the data acquisition methods. However, it is considered that passive crowdsourcing methods (where sensors can passively collect data without human interference) could potentially provide a much larger size of data than active crowdsourcing methods (where active data collection actions are needed to procure the data).

2 | Data processing

Despite their large data volume, crowdsourced data are usually heterogenous and unstructured in nature, and prone to a variety of noises (including observation and sampling error, incorrect data report, equipment failure, etc.). Adequate data processing is necessary to ensure the quality of crowdsourced data for urban hydrologic research.

Different data processing and cleaning approaches have been proposed. Some compared crowdsourced data with gold-standard data sets or by expert judgments; some assessed the trustworthiness of crowdsourced networks by reputation system; others identified noisy data from crowdsourced observations with preset rules[5]. More recently, a machine learning-based crowdsourced data quality control model was proposed to identify and filter noise from general crowdsourced rainfall observations automatically[6]. Since crowdsourced data is usually in large volume (e.g., obtained from PWSs) and discontinuous in both time and space, a machine learning-based processing method can automate the noise detection and removal process. As shown in Fig. 2, the machine learning based method can detect noisy data in spatially and temporally discrete crowdsourced observations coming from both fixed points (e.g., surveillance cameras) and moving sensors (e.g., moving cars/pedestrians), and can significantly reduce the overall rainfall estimate errors.

3 | Data utilization

Crowdsourcing can be used directly, or indirectly via urban stormwater models, to assist urban water management, flood evacuation, and other urban hydrologic management practices. Since performances of stormwater models rely heavily on the quality of input data (i.e., 'garbage in, garbage out'), a concern regarding their use of crowdsourced data is the relatively poor data quality. However, researchers have shown that low-quality crowdsourced data could contribute positively to these models, via specific mechanisms[7].

Specifically, the error propagation property of the stormwater model and the error structure of crowdsourced data ensures 'gold' (good stormwater modeling result) derived from 'garbage' (low-quality crowdsourced data). As shown in Fig. 3, because of the relatively low observation density, rain gauge estimated rainfall fields are usually associated with systematic under-estimation/overestimation of rainfall intensity at the storm center, where the hydrologic response is most sensitive to errors in rainfall data. In contrast, though the individual errors of crowdsourcing rainfall data are high, their high spatial density avoids systematic error at the storm center. As a result, stormwater flow simulated with erroneous crowdsourcing rainfall data can outperform that of more accurate traditional rain gauge data[7].

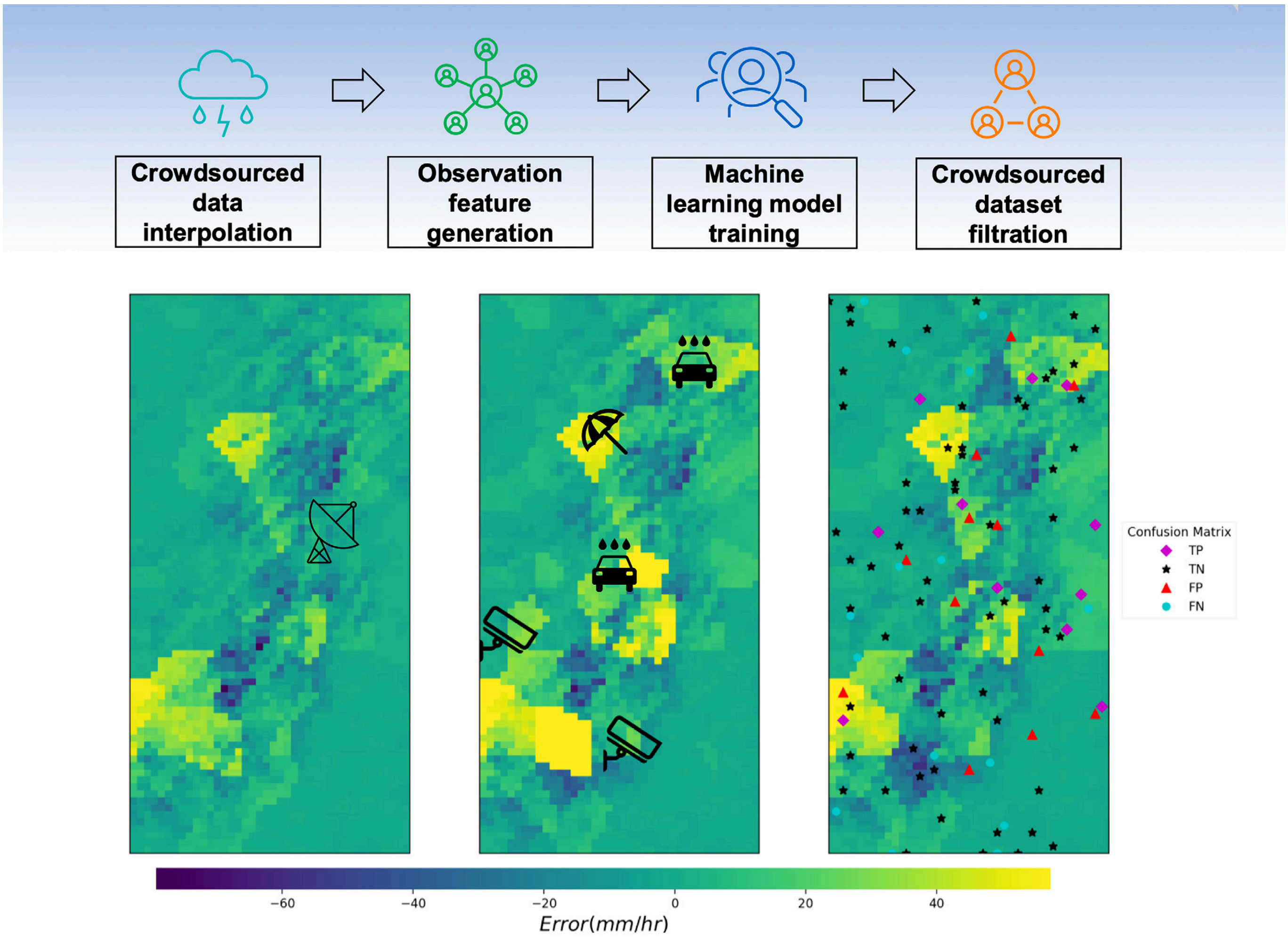


Figure 2 | Machine learning-based processing approach for automatic crowdsourced data quality control. (Modified from Niu *et al.*, 2021)[6].

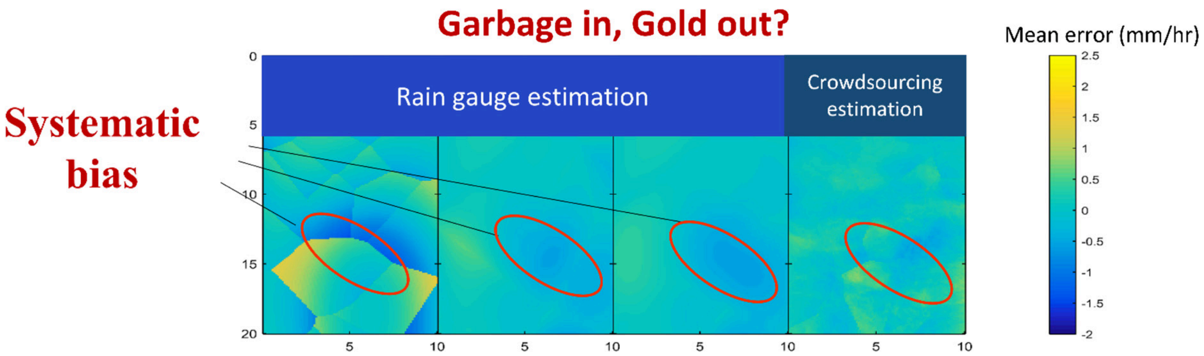


Figure 3 | Comparison of rainfall estimation error structure (derived from a synthetic but realistic rainfall simulation with known rainfall intensities) between rain gauge and crowdsourced data explains the superior stormwater modeling performance of the crowdsourced data. (Modified from Yang and Ng, 2017)[7].

The higher density of data and improved performance of high-resolution stormwater modeling enhance our ability to manage complex urban drainage systems, which are interrelated with many other urban infrastructures such as traffic networks, power grids, and water supply systems. A simple application crowdsourcing urban hydrological data is flash flood management, in which the real-time control of pumps and weirs can be improved with crowdsourced data. For the secondary damages caused by urban flash floods (e.g., traffic jams and power outrage), crowdsourced hydrological data can be used to develop early warning and management systems. An example is the planning of flood evacuation, which can be greatly improved with precise information on the location and timing of flood inundation provided by crowdsourced data. Such efforts can be integrated to assist the development of the smart city and digital twins of urban infrastructures, which aim to improve government service and citizen welfare with information and communication technologies.

4 | Citizen involvement

Crowdsourcing hydrological data can be broadly categorized into passive and active types, and active crowdsourcing is considered more challenging in terms of ensuring enough data volume and adequate data quality as continuous efforts from participants are needed. Based on past experiences, it is suggested that the simplicity of the application and immediate feedbacks are critical elements for a successful crowdsourcing project. The design of feedback must relate to the primary motivators for participating in a crowdsourcing project, which may include monetary reward, the expectation of reciprocal activities by others, the feeling of competition, and pure altruism. Passive crowdsourcing is considered less challenging in citizen involvement, but it may also bring inequality problems. As passive crowdsourcing projects usually require citizens to own specific sensors, e.g., personal weather stations, wealthy communities benefit more from such projects as they can afford more sensors to improve the monitoring quality. Researchers have now started combining efforts from both social science and hydrological science to improve participation in crowdsourcing projects. For example, Yang *et al.* (2019)[8] developed an agent-based model (ABM) which integrates individual participant behavior rules regarding crowdsourcing reward-action relationship with a rainfall field estimation model, and the integrated model was further applied to investigate the performances of several reward allocation strategies.

There can be ethical or legal barriers to the collection of crowdsourced data, especially regarding the data privacy issue. The use of personally owned sensors in crowdsourcing projects, especially smartphones, raises concerns regarding the collection and use of sensitive personal data. Currently, such an issue has not been widely discussed by the research community, which poses a challenge in the development of laws and regulations regarding the use and governance of citizen science data. Recently, the European Union (EU) developed a General Data Protection Regulation (GDPR) for citizen data privacy protection, which highlights and regulates the risks of accidental or unlawful destruction, loss, alteration, unauthorized disclosure of, or access to, personal data. To avoid ethical and legal issues regarding data privacy, anonymous task distribution, anonymous data reporting, privacy-aware data processing, as well as access control and audit of data utilization, can be used as suggested by relevant researchers.

Conclusions and outlook

Data acquisition remains challenging in urban hydrologic research. With the fast development and exponential adoption of low-cost sensors, citizen science, especially crowdsourcing, provides a promising direction to (at least partially) address the data challenge. Developing crowdsourcing in urban hydrologic research requires efforts from electronic engineering, hydrology, computer science, and social science. This article briefly introduces four aspects of crowdsourcing: data acquisition methods, data processing, data utilization, and citizen involvement. To move forward, there still exist many research opportunities in this relatively new field, e.g., the motivation of citizens, the integration with smart city development, and the development of standardized protocols. Among them, the integration of crowdsourcing hydrologic data with professionally collected data can be a promising direction. Combining both sources of data could overcome their disadvantages of low coverage (professional data) and low accuracy (crowdsourced data) (see an example in Yang and Ng, 2019)[8], and it provides an opportunity to re-design our urban hydrologic monitoring system with the aids of both professionals and amateurs. Another promising field is the development of digital twin modeling of urban watersheds, which can be substantially benefited from the vast volume of crowdsourcing hydrological data.

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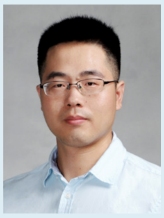

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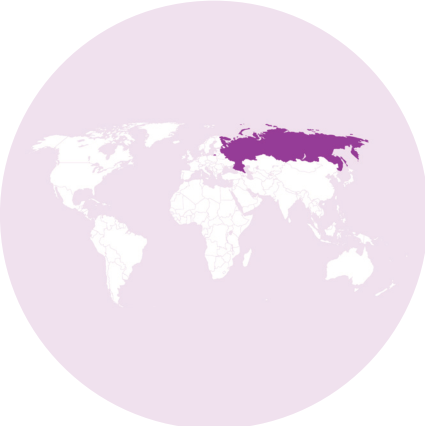
FAMOUS WOMEN IN HYDRAULICS

The IAHR task force on Strengthening Gender Equity intends to raise the profile and visibility of women who made major contributions to hydraulics.



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Olga Ladyzhenskaya
1922–2004, Russia

Olga Aleksandrovna Ladyzhenskaya graduated as a mathematician from Moscow University in 1946 and in 1947 started a PhD thesis directed by S.L. Sobolev. From 1949, she was a Lecturer at Saint Petersburg University and from 1954, she was a staff member of the Steklov Mathematical Institute.

Ladyzhenskaya was appointed in 1961 head of the Mathematical Physics Laboratory LOMI. She was a Corresponding Member of the Russian Academy of Sciences from 1981 and there became Academician in 1990 in the Division of mathematics.

She was also awarded membership of Leopoldina Academy of Germany in 1985, the Italian Academy Dei Lincei in 1989, the American Academy of Sciences and Culture in 2001, and was a recipient of the Honorary Doctorate from Bonn University in 2002. Ladyzhenskaya acted also as president of the Saint Petersburg Mathematical Society.

Biography extracted from the IAHR book *Hydraulicians in Europe 1800-2000 (Vol. 2) A biographical dictionary of leaders in hydraulic engineering and fluid mechanics* by Willi H. Hager. ISBN: 9789078046066 p. 1405, 2003.
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She received a number of national awards both from the Soviet Union and Russia.

Ladyzhenskaya's scientific interests were in the general solution of functional spaces. She further provided estimates for boundary value problems of systems of partial differential equations, and she devised a general approach for hyperbolic differential equations in 1955. In 1953, she had explored the mixed problem for hyperbolic differential equations.

She also presented solution paths for these equations by using the Fourier, the Laplace and the finite differences methods.

She further investigated the regularity behavior of multi-dimensional problems, and she had a particular interest in the stability of hydrodynamic and mechanics problems where energy dissipation is of relevance.

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Impacts of river basin changes on deltas and coasts
River - estuary - sea interactions
Coastal hydraulic engineering structures
Inland and coastal lake management

Sediment Transport and Morphodynamics

River sediment management and morphodynamics
Coastal and estuary morphodynamics
Sediment transport, deposition and remobilisation
Sediment (dis)continuity
Sediment management in reservoirs and river basins

Integrated Management of Extremes, Climate Change

Rainfall-runoff processes and modelling, remote sensing
Integrated flood risk management
Drought risk management
Climate change and water management

Environment and Society

Ecohydraulics in rivers coasts including hydropeaking
Ecological status and eco-engineering
Plastics and emerging contaminants in waterbodies
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Water education and innovation
Unconventional water resources

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