HYDROLOGICAL SCIENCES JOURNAL
https://doi.org/10.1080/02626667.2020.1849707

SPECIAL ISSUE: HYDROLOGICAL DATA: OPPORTUNITIES AND BARRIERS

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Citizens AND HYdrology (CANDHY): conceptualizing a transdisciplinary framework for citizen science addressing hydrological challenges

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ABSTRACT

Widely available digital technologies are empowering citizens who are increasingly well informed and involved in numerous water, climate, and environmental challenges. Citizen science can serve many different purposes, from the "pleasure of doing science" to complementing observations, increasing scientific literacy, and supporting collaborative behaviour to solve specific water management problems. Still, procedures on how to incorporate citizens' knowledge effectively to inform policy and decision-making are lagging behind. Moreover, general conceptual frameworks are unavailable, preventing the widespread uptake of citizen science approaches for more participatory cross-sectorial water governance. In this work, we identify the shared constituents, interfaces, and interlinkages between hydrological sciences and other academic and non-academic disciplines in addressing water issues. Our goal is to conceptualize a transdisciplinary framework for valuing citizen science and advancing the hydrological sciences. Joint efforts between hydrological, computer, and social sciences are envisaged for integrating human sensing and behavioural mechanisms into the framework. Expanding opportunities of online communities complement the fundamental value of on-site surveying and indigenous knowledge. This work is promoted by the Citizens AND HYdrology (CANDHY) Working Group established by the International Association of Hydrological Sciences (IAHS).

ARTICLE HISTORY
Received 11 May 2020
Accepted 13 October 2020

EDITOR
A. Castellarin

GUEST EDITOR
Not assigned

KEYWORDS
citizen science; crowdsourcing; volunteered geographic information (VGI); human sensors; human behaviour; Citizens AND HYdrology (CandHy); unsolved problems in hydrology (UPH); transdisciplinarity

1 Introduction

Interest in citizen science is growing in several disciplines (Kullenberg and Kasperowski 2016, Njue *et al.* 2019), including the hydrological sciences (Fig. 1). State-of-the-art citizen science approaches, achievements, and caveats in hydrology and geosciences are currently being discussed and reviewed (Conrad and Hilchey 2011, Assumpção *et al.* 2018, Zheng *et al.* 2018, Njue *et al.* 2019, Paul *et al.* 2019, See 2019). Crowdsourcing, a specific type of citizen science (Haklay 2013, Paul *et al.* 2018), is expected to gain momentum as well as play a bigger role in water resource and risk monitoring (Mazzoleni *et al.* 2017, 2018), management (Uprety *et al.* 2019), communication, and awareness-raising (Mukhtarov *et al.* 2018).

Citizens' involvement is beneficial for studies assessing human impacts on the hydrological cycle (Abbott *et al.* 2019), as well as for assessing the interlinkages between hydroclimatic dynamics, especially extremes, and society. This is a relevant and timely societal challenge, as evidenced by the International Association of Hydrological Sciences (IAHS) launching the hydrological decade 2013–2022 with the theme "Panta Rhei: Change in Hydrology and Society" (Montanari *et al.* 2013, McMillan *et al.* 2016). Coupled water–human socio-hydrology studies interlinking the environmental, social, and economic sciences have matured,

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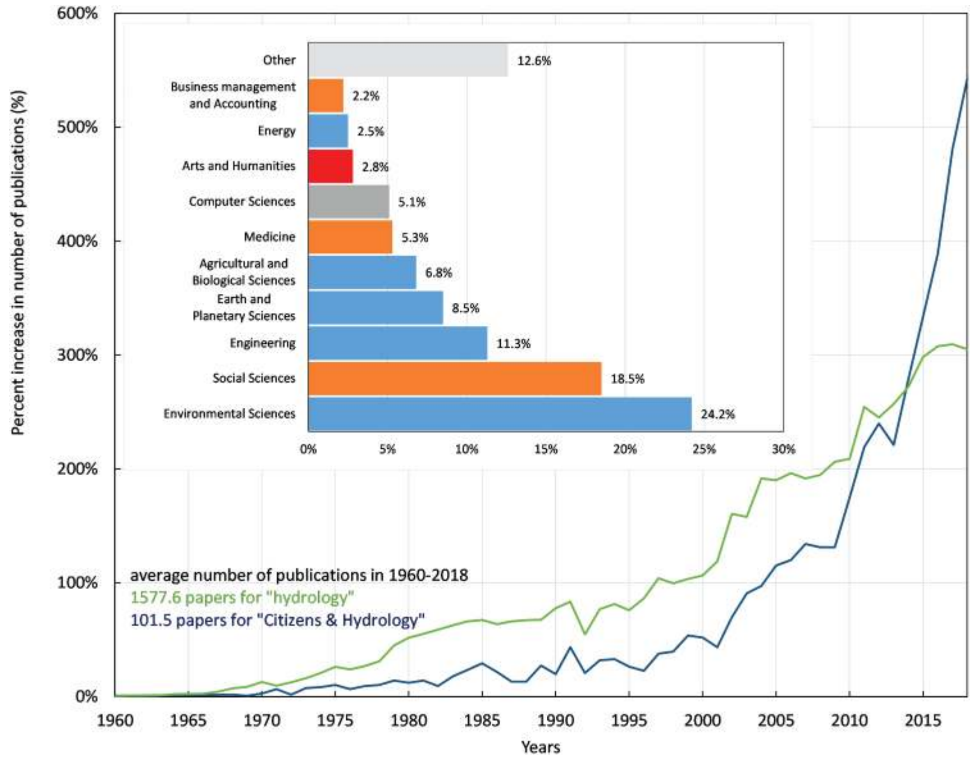

Figure 1. Bibliometric analysis using the Scopus database (for the period 1960–2018) filtering journal papers referring to hydrological studies [Scopus search string *TITLE-ABS-KEY (hydrology OR hydrological OR floods OR droughts OR water)*] (briefly referred to as "Hydrology") or papers where citizen science and hydrology (briefly referred to as "Citizens and Hydrology") are investigated by filtering keywords that are used as title, abstract or keyword (Scopus search string for citizens and hydrology is [*TITLE-ABS-KEY (hydrology OR hydrological OR floods OR droughts OR water) AND TITLE-ABS-KEY ("citizen science" OR crowdsourced OR crowdsourcing OR citizen)*]. The curves shown for "Citizens & Hydrology" (blue) and "hydrology" (green) represent the ratio of the number of papers published in each year as respect to the overall average number of publications in the reference period (1960–2018), expressed as a percentage increase. The horizontal bar chart inset shows the breakdown of percentages of publications per scientific sector (as categorized by Scopus) related to the blue curve.

providing additional clues to achieving water security and sustainable development (Di Baldassarre *et al.* 2013b, 2019, Young *et al.* 2015, Brondizio *et al.* 2016, Ceola *et al.* 2016, Mård *et al.* 2018). At the same time, awareness of major water, climatic, and environmental issues has stressed the importance of citizens' engagement (Hayward 2012, Liu *et al.* 2014, O'Brien *et al.* 2018).

Hydrology is therefore poised to become a major field of activity for citizen science, which may lead both scientists and citizens to better understand the complexity of hydrological phenomena. Citizen science constitutes, for hydrologists, an opportunity to join efforts integrating scientific, social, economic, cultural, political, and administrative processes. Moreover, citizens' observations and behaviour are not bounded and biased by disciplinary preconceptions. Crowdsourcing can fill the need for more distributed and diverse observations of the multiple sets of land, water, atmosphere, and energy variables (e.g. geology, soil type, vegetation, soil moisture, surface and groundwater discharge, sediment yields, soil chemistry, microbial community, air temperature, and energy consumption). In this regard, transfer of hydrological knowledge, data, and tools is particularly important for addressing knowledge gaps linked to most studies that have investigated only one of the Earth's spheres (i.e. hydrosphere, biosphere, lithosphere, or atmosphere). Citizen science projects could address scientific challenges prompted by Critical Zone (CZ) investigations (White *et al.* 2015, Brantley *et al.* 2016, Bui 2016), which require the interfacing of hydro-meteorologic, hydrologic, hydrogeologic, ecohydrologic, and biogeochemical sciences (Banwart *et al.* 2013, Cudennec *et al.* 2016, Loiselle *et al.* 2016, Guswa *et al.* 2020). Moreover, pressing scientific and societal challenges linked to water, energy and food security cannot be dissociated from humans and the role they play in the water–energy–food–ecosystem (WEFE) nexus (Liu *et al.* 2017, Carmona-Moreno *et al.* 2018, Cudennec *et al.* 2018, D'Odorico *et al.* 2018, Connor *et al.* 2020, Rosa *et al.* 2020) or in any attempt to address global environmental challenges in the Anthropocene (Palsson *et al.* 2013, Wu *et al.* 2013, Brondizio *et al.* 2016).

The following section introduces the main definitions and concepts and the challenges and opportunities linked to citizen science for hydrological sciences.

1.1 Citizen involvement in hydrology: from knowledge to action

The heterogeneous nature of citizen participation in water research projects allows multiple ways for citizens and scientists to interact. As a consequence, there are also multiple definitions of citizen science (See *et al.* 2016, Eitzel *et al.* 2017). Most literature defines citizen science as a method applied in research, designed and coordinated by scientists, which includes the involvement of citizens. Common theoretical schemes and definitions of citizen science are based on varying levels of participation by citizens. For instance, Haklay (2013) proposed four increasing levels of involvement: (1) crowdsourcing, (2) distributed intelligence, (3) participatory science, and (4) extreme citizen science. Another consequence of this heterogeneity is that citizen science overlaps with community-based participatory research, public participation in science and research, participatory research, or participatory action research (Eitzel *et al.* 2017). Table 1 summarizes the most relevant definitions used in this manuscript. We also introduce definitions of *human sensors* and *citizen science for hydrological sciences*, based on concepts explained later in this work.

Citizen science is dedicated to developing scientifically organized data–information–knowledge workflow performed through scientist–citizen cooperation (Wiggins and Crowston 2011, Aulov *et al.* 2014, Geiger and Schader 2014, Morschheuser *et al.* 2016, Smith *et al.* 2017, Vicari *et al.* 2019) and may also include citizen-designed experiments of scientific interest (Puri and Sahay 2003). The value of public engagement in research projects goes beyond the pure extension of the scientific observation capacity (Gura 2013). Directly involving citizens is an effective way to account for social, economic, educational, and behavioural dynamics (Chawla and Cushing 2007, Palsson *et al.* 2013, Jollymore *et al.* 2017). Together with more informed communication strategies (Aulov *et al.* 2014, Rutten *et al.* 2017, Smith *et al.* 2017, Pandya and Dibner 2019, Vicari *et al.* 2019), citizen science leverages multiple voices and local culture and conditions, which bring critical indigenous knowledge to hydrological studies (Sivapalan 2005). Citizens' engagement may, thus, have multiple beneficial outcomes, from knowledge development and awareness raising to encouraging more informed actions by concerned citizens. A large number of citizen science projects in environmental and hydrological sciences have demonstrated their positive impacts on the sustainability and safety of natural and anthropogenic ecosystems (Buytaert *et al.* 2014, Njue *et al.* 2019, Federal Crowdsourcing and Citizen Science Catalog 2020, Joint Research Centre 2020).

1.2 Citizens' intelligence for hydrological observations

Technological advances enabled scientists to capture hydrological processes at finer spatial and temporal scales. However, hydrology remains a data-scarce science, with many important variables (such as river flow, water quality, sediments, rainfall/snow depths, and groundwater levels) being severely under-sampled. This has decisive implications for our ability to assess and manage water resources, deal with challenges, and forecast events (Beven *et al.* 2020, Cudennec *et al.* 2020, Pecora and Lins 2020). Also, variables that are less used in practical applications can be crucial for the scientific understanding of complex processes and systems. Examples include interception volumes and their partitioning, snowmelt and sublimation fluxes, and phenomenological and social indicators affected by hydrological processes.

Citizens using mobile devices in urban and non-urban ecosystems are generating an unprecedented amount of data. Opportunistic sensing (definition in Table 1) is an emerging frontier for the hydrological sciences, gaining novel insights from citizens' distributed monitoring networks of hydrological processes (McCabe *et al.* 2017, Tauro *et al.* 2018). Social and demographic, behavioural, and human dynamics data are also voluntarily (or non-voluntarily) produced and shared by citizens through their handheld devices or digital platforms (Smith *et al.* 2019). Those data are commonly referred to as crowdsourced data (Howe 2006) or volunteered geographic information (VGI) (Goodchild 2007, Haklay 2013) (definition in Table 1). The terms "informal" or "unstructured" data are also used to refer to data produced by citizens, since this data often does not conform to existing standards (Stork 2001, Melville *et al.* 2012, Gandomi and Haider 2015).

Participatory monitoring approaches and crowdsourcing (definition in Table 1) of citizen scientists are increasingly tested to fill this data gap in hydrology and related disciplines, thanks to distributed volunteers using manual instruments such as the raingauge or more complete personal weather stations and other affordable environmental sensors (Buytaert *et al.* 2014, Follett and Strezov 2015, Kullenberg and Kasperowski 2016, Cunha *et al.* 2017, Mao *et al.* 2019, Trouille *et al.* 2019). Widely accessible technologies allow non-experts to easily gather, analyse, visualize, and share a wealth of Earth system data (Breuer *et al.* 2015, Michelsen *et al.* 2016, Starkey *et al.* 2017, Tkachenko *et al.* 2017, Njue *et al.* 2019, Sermet *et al.* 2019) that complements those from traditional monitoring networks and field surveys (Starkey *et al.* 2017, Etter *et al.* 2018, Davids *et al.* 2019). The interest and proactive attitude of the general public can lead to new discoveries and improved modelling of hydrologic phenomena (Yang and Ng 2017).

At present, affordable electronic devices (smartphones, cameras, microcontrollers, smart watches, drones, etc.) are able to monitor not only the environment, but also biometrics (e.g. temperature, heart rate), geolocation i.e. Global Positioning System (GPS), and communications (Stefanidis *et al.* 2013, O'Grady *et al.* 2016, Yu *et al.* 2017, Tauro *et al.* 2018, Wang *et al.* 2018, Mao *et al.* 2019, Seibert *et al.* 2019, Sermet *et al.* 2019, Dixon *et al.* 2020). Geospatial models, data, and tools are also more accessible to a larger number of users (e.g. researchers, professionals, students) than ever before thanks to open-source licensing (e.g. GNU General Public Licence), volunteer developers, user-friendly interfaces, geospatial data processing, and web platforms (Ames *et al.* 2012, Goodchild *et al.* 2012, Gorelick *et al.* 2017, Dallery *et al.* 2020).

1.3 Online communities: a wealth of data and opportunities

Web-based digital platforms aggregate a growing number of users, enabling scale and performance in crowdsourcing (Fohringer *et al.* 2015, Le Boursicaud *et al.* 2016, Jollymore *et al.* 2017, Li *et al.* 2018, Sit *et al.* 2019). A group of crowdsourcers who share a common platform to cooperate for a common goal form an online community (OC) (definition in Table 1). OCs are used in several settings to manage the relations among organizations and their stakeholders (Dellarocas 2006, Leidner *et al.* 2010), for mobilising people to lobby for common interests or causes (von Krogh *et al.* 2012, Braccini *et al.* 2019), for engaging individuals in the cooperative production of knowledge and innovation (Ma and Agarwal 2007, Faraj *et al.* 2011, Hutter *et al.* 2011, Majchrzak *et al.* 2013, Braccini *et al.* 2018), or for sharing knowledge and information of public interest (McLure Wasko and Faraj 2005). OCs can also increase engagement in and awareness of water-related challenges. At the same time, OCs present the risk of drifts in the understanding and practices of citizens in water management issues.

Table 1. Definitions of major concepts or newly introduced (in bold) used in this manuscript.

Name	Definition
Crowdsourcing	A sourcing strategy in which resources (goods, data, information) are produced or made available through the cooperative effort of several individuals (Estellés-Arolas and González-Ladrón-De-Guevara 2012). "Online, distributed problem-solving and production model that leverages the collective intelligence of online communities for specific purposes" (Brabham *et al*. 2014, p. 179). Crowdsourcing represents the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call. This can take the form of peer-production (when the job is performed collaboratively), but is also often undertaken by sole individuals. The crucial prerequisite is the use of the open call format and the large network of potential laborers. (Howe 2006).
Crowdsourced data	Any data (e.g. measurements, photos, videos, etc.) produced by crowdsourcing.
Online communities (OC)	A persistent group of people that share common or complementary interests and use internet-based digital technologies to communicate and coordinate their actions (Preece 2000).
Volunteered geographic information (VGI)	"A remarkable phenomenon . . . has become evident in recent months: the widespread engagement of large numbers of private citizens, often with little in the way of formal qualifications, in the creation of geographic information, a function that for centuries has been reserved to official agencies. They are largely untrained and their actions are almost always voluntary, and the results may or may not be accurate. But, collectively, they represent a dramatic innovation that will certainly have profound impacts on geographic information systems (GIS) and more generally on the discipline of geography and its relationship to the general public. I term this volunteered geographic information (VGI), a special case of the more general Web phenomenon of user-generated content" (Goodchild 2007, p. 2).
Opportunistic sensing	"The concept of utilizing signals from often unrelated measurements to inform upon hydrological processes. Inferring hydrological properties by making use of signals of opportunity (e.g. cellular network signals)" (McCabe *et al*. 2017, p. 3897) or "unconventional sources" (Jiang *et al*. 2019, p. 3005).
Transdisciplinary research	The development of transdisciplinarity studies including the following principles: cross-disciplinarity, shared goal setting, integration of diverse disciplines and non-academic participants, and development of integrated knowledge and theory among science and society (Tress *et al*. 2005).
Scientific communication	"The use of appropriate skills, media, activities, and dialogue to produce one or more of the following personal responses to science: Awareness, Enjoyment, Interest, Opinion-forming, and Understanding" (Burns *et al*. 2003, p. 183).
Human sensors	Citizens empowered by digital technologies with the bidirectional capacity for producing and receiving data, information and knowledge about the environment.
Human behaviour	The individual or collective physical and non-physical actions (e.g. emotions, rules of conduct) performed by citizens when processing information or reacting to forcing stimuli, conditions or events (Strickland 2011). A function of compatible intentions and perceptions of behavioural control in that perceived behavioural control is expected to moderate the effect of intention on behaviour, such that a favorable intention produces the behaviour only when perceived behavioural control is strong (Ajzen 1991).
Citizen science for hydrological sciences	The scientific organization of citizens' actions that produce knowledge about the water cycle from collecting to processing data on both natural and anthropogenic features and phenomena, as well as living or non-living entities.

These risks are significant especially when OCs adopt a social media presence which may be influenced by opinion biases, low scientific literacy, and/or organized forms of misinformation (e.g. "fake news") (Baccarella *et al.* 2018).

Online communities allow citizen science programmes to facilitate the interaction among selected groups of citizens, such as users from a particular geographic region (e.g. country, municipality, river basin, or coastal zone), demographic category (e.g. gender, age, religion, social status), recreational (e.g. river fishing, sailing, hiking), or professional activity (e.g. engineers, educators, sociologists). The number of OCs, empowered by online tools and communities (Federici *et al.* 2015) and digital social networks (Liberatore *et al.* 2018), is significantly increasing. However, offline communities still play a major role in many issues in both developed and developing countries, and the two settings can also overlap.

Online communities can be applied to different aspects of water management. Engagement of OCs in emergencies constitutes one relevant framework in which crowdsourcing of hydrological information could be helpful for early detection, rapid response, and efficient recovery (e.g. See *et al.* 2016, Ernst *et al.* 2017).

1.4 Citizen science for water emergency management and regional planning

Several examples exist where crowdsourcing activities have become pivotal components of real-time emergency and post-disaster management actions (Poser and Dransch 2010, Albuquerque *et al.* 2015, Huang and Xiao 2015, Le Boursicaud *et al.* 2016, Yadav and Rahman 2016). In concordance, crowdsourcing is used in the field of natural hazards (Fig. 1). For instance, during the floods in South India in 2015, citizen science observations were used for real-time emergency management (Naik 2016, Pandey and Natarajan 2016, Yadav and Rahman 2016, Anbalagan and Valliyammai 2017). Furthermore, some citizen science projects successfully investigated and tested the technical and procedural implementation of well-informed, educated, and organized groups of citizens (named citizen observatories in most cases) as effective risk mitigation measures (Wehn *et al.* 2015, Montargil and Santos 2017, Paul *et al.* 2018).

The added value of citizen science is also leading to the integration of citizen observations and feedback into decision-making frameworks for participatory regional planning (Aretano *et al.* 2013, Kleinhans *et al.* 2015, Kahila-Tani *et al.* 2016). Citizen-driven efforts support effective cooperation and mutual trust among stakeholders. For instance, misunderstandings and conflicts that arise between water users and managers (e.g. disputes in water allocation among different geographic regions or economic sectors, as in the WEFE nexus) can be anticipated and mitigated with citizens' involvement (IMoMo 2018). Citizens' consensus, behaviour, perceptions, and social dynamics in general – all difficult to measure – can be quantified (or at least assessed) and integrated into environmental and urban resource planning through crowdsourcing (Lee *et al.* 2011, Huang and Xiao 2015, Xiao *et al.* 2015, Beigi *et al.* 2016, Michelsen *et al.* 2016, Tkachenko *et al.* 2017, Arthur *et al.* 2018, Witherow *et al.* 2018).

1.5 Citizen science to achieve transdisciplinarity in hydrological sciences

Citizen science approaches can enlarge the scale, impact, and "ground-truthing" of hydrological sciences (Buytaert *et al.* 2014, Afshari *et al.* 2018), fostering unique opportunities to develop transdisciplinary research (definition in Table 1). Transdisciplinary hydrological research is a fundamental asset of studies aiming to address water challenges (e.g. water quality, water accessibility) and extremes (e.g. floods, droughts) while considering the interplay between socio-environmental factors that govern human–water systems (Ceola *et al.* 2016, Di Baldassarre *et al.* 2019).

While the technology that facilitates citizen science is mature with ready-to-use equipment and software broadly used across diverse disciplines (Wan *et al.* 2014, Mazzoleni *et al.* 2017, Tauro *et al.* 2018, Blöschl *et al.* 2019), standardization procedures are not. New policies are also needed that recognize citizen science as a cross-cutting priority, to support and regulate opportunistic sensing and unstructured information gathering, sharing, and use (Palsson *et al.* 2013, Wehn *et al.* 2015, Weber *et al.* 2019).

Conceptual transdisciplinary frameworks that integrate technical, administrative, and societal aspects to support the development of citizen science projects are lacking in the hydrological sciences. Some investigations developed such frameworks for citizen science methods, but, even if general, they lacked some aspects (e.g. administrative and policy assessment in Kieslinger *et al.* 2018), or referred just to data quality (Antelio *et al.* 2012) or were limited to specific disciplines and scopes and lacked generality and flexibility (Chase and Levine 2016). This hinders the progress of transdisciplinary research, limits the accumulation of knowledge, hampers a consistent implementation of the research results, and also makes the development of comparative assessments and evaluations of different citizen science projects challenging and inconsistent.

1.6 Outlook

In this study, we identify and introduce a conceptual framework that integrates crowdsourcing and behavioural mechanisms, to enable transdisciplinary interlinkages and assessments. The proposed framework aims to support the development of accumulated knowledge, avoid pitfalls, and maximize the effectiveness of joint efforts between citizen science projects. Such a conceptual scheme, therefore, is intended to foster advancements in the hydrological sciences by supporting the merging of outcomes from various citizen science initiatives and by allowing synergies amongst different sectors dealing with water challenges.

2 The topology of a transdisciplinary framework for citizen science in hydrology

2.1 Conceptualizing the topological framework

The diversity of concepts, definitions, data, models, tools, and procedures poses a challenge to designing a conceptual framework for citizen science in hydrology. Nonetheless, we propose a topological space to aid in the definition of such a framework and to initialize the discussions with the hydrological community. Four main elements, that are commonly shared by citizen science efforts addressing water issues, were identified: (a) citizens, (b) the hydrological sciences (hydrology, for simplicity), (c) technology, and (d) society. These four elements include different components whose interplay governs the development of citizen science projects in hydrology. The proposed elements and components are therefore topological properties shared by citizen science analysis, modelling, and assessment efforts for hydrological applications. The proposed citizen science topological space is schematically depicted in Fig. 2.

2.2 The dual value of citizens' involvement: human sensors and human behaviour

Two new major components emerge, together with *education* and *innovation*, in the proposed topological space as representative of the main facets of the citizens–hydrology–technology–society interface: *human sensors* and *human behaviour* (definitions in Table 1).

In the data–information–knowledge creation and sharing process, citizens are both data producers while participating as observers, and data receivers while working as nodes of a distributed network (Paul *et al.* 2018). The term "human sensor" may, unintentionally, dehumanize the citizen; however, we advocate for this term because in many studies, the human component of citizen observations is largely neglected. It should be noted that, although we choose to use the "human sensors" terminology, we acknowledge that citizens can be engaged in citizen science to varying degrees (see Section 2.3). Nonetheless, to provide a schematic organization of the "human sensors" component, we identify two main categories:

- *Direct citizen observations*: Information produced by involved citizens who utilize custom-made applications for the observation of predetermined phenomena or landscape features to develop specific modelling or monitoring activities. An increasing number of web and smartphone applications were recently established that fall within this category, as in the case of citizens collecting images and videos to monitor water parameters, land cover, or other geophysical parameters (Assumpção *et al.* 2018, Zheng *et al.* 2018, Seibert *et al.* 2019);
- *Indirect citizen observations*: The gathering and processing of information shared by citizens for other purposes, such as citizens spontaneously posting videos and images in online social networks of unusual river conditions (floods, droughts, pollutants, debris, etc.). These pieces of information may then be, instantaneously or subsequently, used by scientists for real-time water monitoring or post-event fluvial studies (Mazzoleni *et al.* 2017, Tkachenko *et al.* 2017, Annis and Nardi 2019).

This classification was also introduced by Craglia *et al.* (2012), as implicitly and explicitly contributed data, and by See *et al.* (2016) as active and passive crowdsourced geographic information. Thus, the human sensors concept implies that in hydrology, citizen science data are not always generated for a scientific purpose, in opposition to traditional monitoring practices. The human sensors component, representing a human–machine–environment interface, provides qualitative and quantitative observations that can be used within quantitative hydrological studies, with careful attention to the accuracy and scale of these observations (Buytaert *et al.* 2014, Kosmala *et al.* 2016, Seibert and Vis 2016, Mazzoleni *et al.* 2019). See Table 1 for the definition of "human sensors."

Citizens' behaviour (i.e. human conduct related to technical and social norms) and actions (i.e. activities performed in developing a task or accomplishing a goal) are a function of social, cultural, educational, psychological, and economic conditions. The "human behaviour" component refers, thus, to the subjectivity of human habits, motivation, perceptions, and dynamics concerning the input citizens receive or concerning the output (or actions) citizens produce. In particular, "human

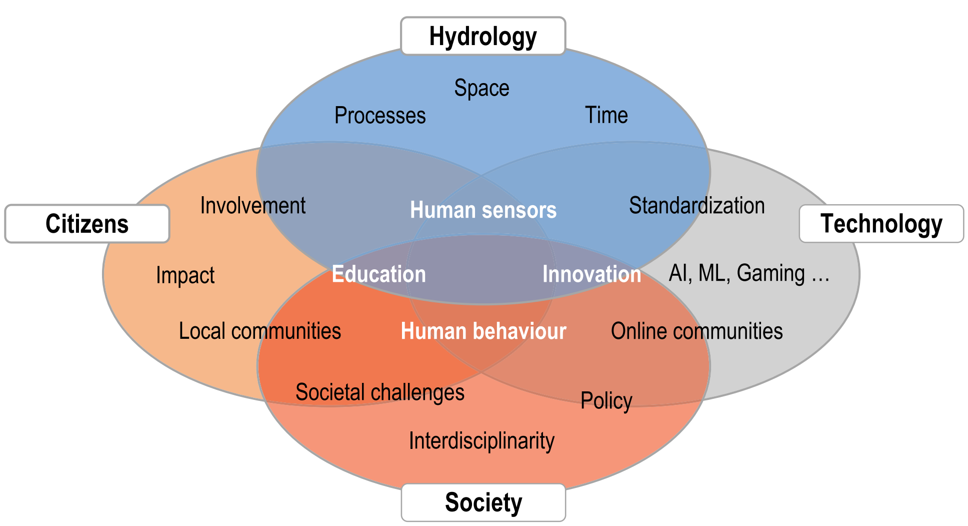

Figure 2. Topological space of a transdisciplinary framework applied to citizen science projects in hydrological sciences. The ellipses show the areas of interest and interfaces of the four main sub-spaces (related to the four main elements (bold): citizens, hydrology, technology and society). In bolded white are the four components (education, innovation, human sensors and human behaviours) that lie at the interface of all the four-element sub-spaces. The position of the components and the information included in each sub-space depict the relationships and shared spaces among the components, but are meant to be illustrative, not exhaustive.

behaviour" refers to how citizens subjectively extract knowledge from the data, modify their actions, or change their behaviour as a result of the gathered knowledge. See Table 1 for the definition of "human behaviour."

The "human sensors" component is widely explored in citizen science projects for the hydrological sciences (Zheng *et al.* 2018). In contrast, the "human behaviour" component represents an unexplored potential for hydrology. The interaction of hydrological sciences with social sciences, cognitive sciences, and psychology, among other disciplines investigating human behaviour, represents a pivotal asset of transdisciplinary citizen science projects. Hydrological models, supported by citizen science, should consider the quantitative integration of human behaviour for understanding and simulating water processes influenced by humans. The "human sensors" and "human behaviour" components are both essential for better understanding and forecasting hydrological dynamics in river basins, where human–water interactions govern water cycle variables and determine short- to long-term hydrological change (Di Baldassarre *et al.* 2013b, 2016, Pande and Sivapalan 2017, 2019).

The proposed characterization of the "human sensors" and "human behaviour" components suggests the depiction of an iterative cycle associated with citizens' engagement: data–information–knowledge–behaviour–action. This concept is derived from the data–information–knowledge–wisdom framework (Bernstein 2011). Considering that actions also support data production, this looping iteration applies whenever citizens' behavioural mechanisms are triggered by citizen science (i.e. observation) methods, supporting information and knowledge production and exchange. We posit that this iterative cycle is involved for all citizen science-driven workflows, and therefore also includes hydrological studies (Fig. 3).

2.3 Thematic areas of a transdisciplinary framework for advancing hydrological sciences

In this section, we explore the most relevant research prospects and gaps that should be addressed for advancing and connecting the hydrological sciences with academic and non-academic disciplines. Seven thematic areas are proposed, and the related transdisciplinary interlinkages are identified in Fig. 4 and described below.

2.3.1 Theme 1. Crowdsourced data and collaborative monitoring/mapping tools

This theme is discussed in terms of: (a) the tools and methods used by citizens for crowdsourced data gathering and processing; and (b) the crowdsourced data accuracy, quality, and specifications (e.g. spatial and temporal scale, resolution).

The first factor deals with existing or novel technologies used for monitoring that are available to citizens. While it is still possible to use analogue tools (Breuer *et al.* 2015) (e.g. interviews performed by volunteers, notes taken during field surveys, etc.), crowdsourcing tools are now mainly related to the use of mobile devices and web-based applications. In particular, significant advancements in the field of data collection and processing, involving the exploitation of information derived from crowdsourced data, are rapidly progressing in computer sciences. These also include methods for crawling indirect citizen observation data from online sources or methods for transforming qualitative or indirect data into quantitative hydrologically relevant information (Le Boursicaud *et al.* 2016, Michelsen *et al.* 2016, Restrepo-Estrada *et al.* 2018). Both tools and methods are gaining momentum provided by artificial intelligence (AI), and, in general, the rapidly advancing field of big data science, mining, and analytics (Kamar *et al.* 2012, Jeschke *et al.* 2018, Sermet *et al.* 2019).

The second factor pertains to the accuracy, quality, and technical specifications associated with crowdsourced data. The technical specifications associated with crowdsourced data define the reliability, robustness, flexibility, and scalability of the data. All these properties need to be considered and evaluated (Jollymore *et al.* 2017, Kieslinger *et al.* 2018). The spatial and temporal scales, the resolution, and several other parameters should also be defined before using such informal datasets. The main trade-off is having increasing volumes and frequency of data, but having to characterize crowdsourced data, vs using standard monitoring stations that can lead to

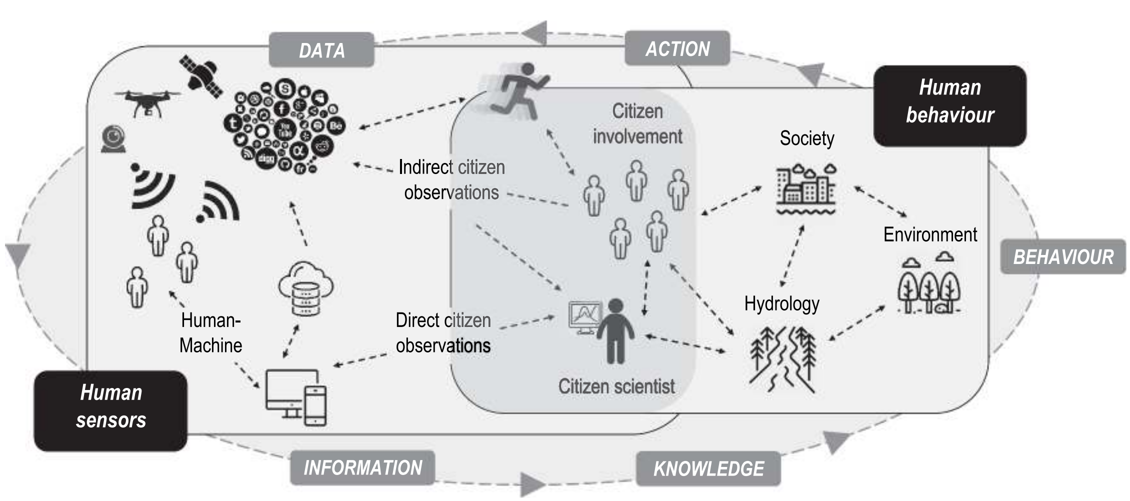

Figure 3. Schematic representation of the "human sensors" and "human behaviour" components supporting the data–information–knowledge–behaviour–action workflow characterizing citizen science projects for hydrological sciences.

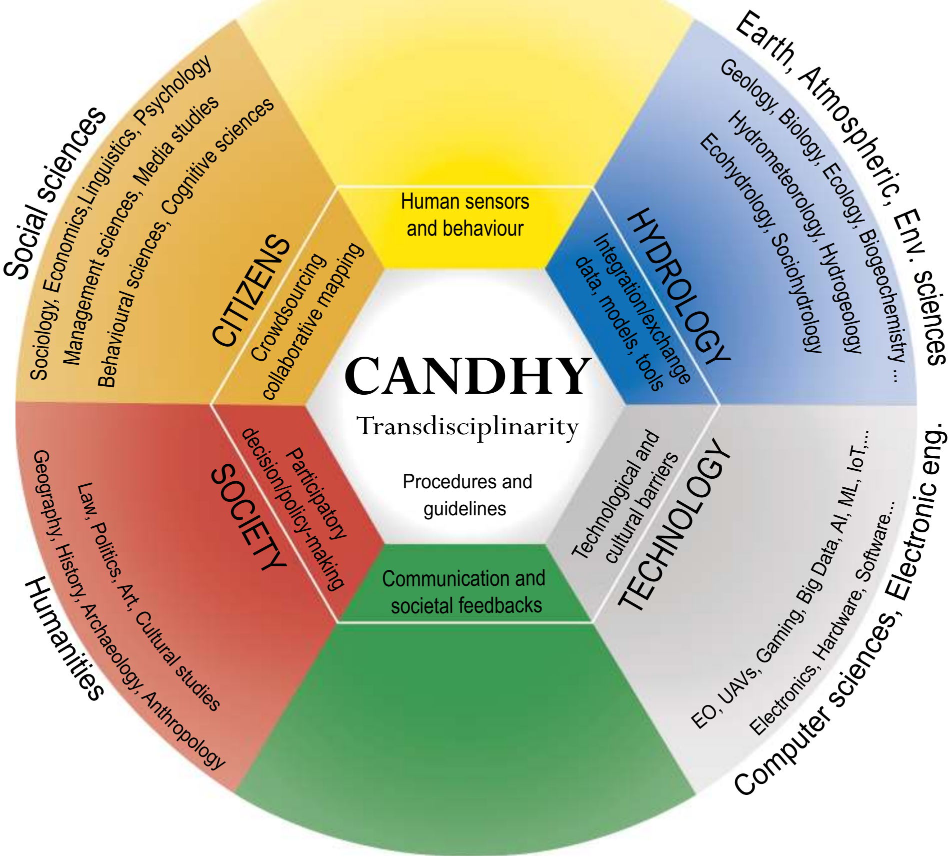

Figure 4. The Citizens and Hydrology (CANDHY) transdisciplinary research framework, with the disciplines of interest categorized into the four main elements (citizens, hydrology, technology and society) of the topological model and the seven selected thematic areas (in the coloured boxes).

limited discrete records (Davids *et al.* 2017). The data gathering, processing, production, and dissemination chain of crowdsourced data should follow quality standards, and these should be analysed and reported (Antelio *et al.* 2012). Standardization procedures that actually characterize traditional monitoring networks require innovations to include and exploit the opportunity offered by such data. Standard metadata structures are required to accommodate the heterogeneity of specifications associated with crowdsourced data. Finally, the design of online platforms to share and visualize crowdsourced data, implemented independently or jointly with traditional monitoring networks, should include optimal procedures for combining and/or assimilating each specific dataset, taking into account its quality and properties (see Theme 3).

2.3.2 Theme 2. Human sensors and behaviour analytics

Effective implementation of the "human sensors" and "human behaviour" components, to be jointly considered, represents the main value but also the major challenge of citizen science in hydrology. Citizens' observations are influenced by diverse non-technical (e.g. social, cultural, psychological) conditions pertaining to the "human behaviour" component. Analogously, research aiming to examine or influence *human behaviour* should always consider environmental factors, as perceived and observed by citizens, and thus, interface with the "human sensors" component.

As a result, the joint "human sensors–behaviour" characterize the multiple and diverse instances of citizens' participation and the varying influence of citizens' behaviour on the data collection or on the participation process itself. At the same time, a change of human behaviour as a reaction to the gathered observation or knowledge will be analysed as well. It is, thus, crucial to analyse interactions between the "human sensors" and "human behaviour" components to understand their combined effects on the data–information–knowledge–behaviour–action workflow.

Nonetheless, while the randomness and subjectivity of human-derived observations and actions are valuable for citizen science projects in hydrology, obtaining different information from the same crowdsourcing methodology also represents a challenge, as hydrological data require consistency over space and time (Strobl *et al.* 2019a). This thematic area is, thus, also suitable to investigate how the hydrological sciences should connect with knowledge, expertise, and scientific reasoning from other disciplines. For example, transdisciplinary studies are needed to understand how conditions of observations vary with changing climatic and demographic settings such as country, education, gender, age, income, and migration status or with fatigue conditions and other biases linked to diverse socio-cultural conditions. This theme also promotes research on cognitive and psychological sciences, to analyse individual life conditions especially related to people at risk, under stress, and in critical situations, which is the case for both water security and hydrological risk management challenges (Sheth 2009, Resch *et al*. 2015).

The interface between "human sensors–behaviour" and hydrology represents a cross-cutting topic that requires transdisciplinarity, where natural, social, and computer science experts should join efforts. In particular, we see the behavioural and cognitive sciences, focusing on motivation, learning, and communications, as relevant to this theme (Oliveira *et al*. 2017). Moreover, gaming technologies, which can integrate advanced hydrodynamic simulations (Zadick *et al*. 2016, Jeschke *et al*. 2018), are also expected to provide transdisciplinary testing environments and favour the engagement of non-traditional audiences (Newman *et al*. 2012, Morschheuser *et al*. 2016, Radchuk *et al*. 2017, Aubert *et al*. 2018, 2019, Den Haan and Van der Voort 2018).

Citizen science faces several challenges related to the integration of the human sensors and *human behaviour*. Theme 2 inherits the issues identified in Theme 1, in particular those affecting the operational use of crowdsourced data. Additionally, the confidentiality and the heterogeneity of data related to behavioural mechanisms provide further complications. Privacy and security concerns become more relevant and impactful in establishing long-lasting, consistent, generalized, and scalable citizens' engagement processes (Quinn 2018, Anhalt-Depies *et al*. 2019).

2.3.3 Theme 3. Integration and exchange of hydrological data, models, and tools

Although on-ground and remote sensing monitoring contribute to an increasing volume of hydrological data (Tomsett and Leyland 2019), large parts of the world suffer from water data scarcity, e.g. due to the degradation of traditional gauge networks and a lack of resources and commitment (McCabe *et al*. 2017, Manfreda *et al*. 2018, Tauro *et al*. 2018, World Bank Group 2018, Dixon *et al*. 2020). The usefulness of this scarce amount of data, if any, strongly relies on the accessibility, organization, and distribution of derived information for supporting research and innovations.

The availability and performances of water information systems have flourished in recent times (Demir and Krajewski 2013, Swain *et al*. 2015, Vitolo *et al*. 2015, Shukla *et al*. 2019). Water information systems are generally equipped with GIS and web–GIS interfaces implementing geospatial data models representing morphometric, environmental, hydrological, and socio-economic parameters associated with river basins and networks (Singh and Fiorentino 1996, Maguire *et al*. 2005, Whiteaker *et al*. 2006, Silberbauer 2019).

A number of regional and local water management agencies are investing relevant economic resources to extend their monitoring networks and develop ad hoc hardware and software for data gathering and sharing (e.g. web GIS, dashboards). Notably, examples exist of hydrological information systems covering large spatial scales and a wide variety of data sources (Addor *et al*. 2020), such as WMO Hydrological Observing System (WHOS), United States Geological Survey National Water Information System (USGS Nwis), Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) HydroShare, Water Information System for Europe (WISE), UNESCO-IHP Water Information Network System, World Resources Institute, and Global Runoff Data Centre (GRDC) databases. However, these systems rely solely on existing institutionalized data collection, and therefore reflect the uneven global distribution of observations, with significant gaps especially in low- and middle-income countries (World Bank Group 2018, de Bruijn *et al*. 2019, Crochemore *et al*. 2020). Moreover, satellite-based Earth observation (EO) systems are also improving considerably, capturing high-resolution spatial and temporal coverages of major Earth and water dynamics, with major efforts from governmental agencies (e.g. European Space Agency The Soil Moisture and Ocean Salinity (ESA SMOS), National Aeronautics and Space Administration Surface Water and Ocean Topography Mission (NASA SWOT)). EO services also provide readily available expert-use solution-oriented data and models for managing, monitoring, and mapping floods, droughts, land use, and urban change, among other things (Hewitt *et al*. 2012, Demeritt *et al*. 2013). EO platforms could also benefit from the integration of citizens' observations (Fritz *et al*. 2017), from global to local crowdsourcing projects. Nonetheless, major obstacles and issues still impact the integration of unconventional citizen-driven information and tools with standard hydrological and EO information systems.

This theme describes the role of citizen science in the integration and exchange of heterogeneous data sources and in the development of software for hydrological sciences and across the wide spectra of disciplines interested in water issues.

2.3.4 Theme 4. Technological, institutional, and psychological/cultural barriers for the uptake of citizen science projects

Implementing citizen science projects for innovation in hydrological sciences is a scientific challenge, but psychological and cultural barriers also need to be considered (Elliott and Rosenberg 2019). The water resource and risk management sector is bound by diverse laws and norms developed by international, national, regional, and local authorities. They are designed to make the different parties (e.g. managers, professionals, scientists, governments, etc.) cooperate consistently and efficiently to monitor, protect, and allocate water resources while guaranteeing sustainable and safe human activities (Kallis and Butler 2001, Bubeck *et al*. 2017). However, such rules often do not include citizen science activities explicitly. The use of informal data and community engagement in policy and decision-making may even contrast with some of the current approaches, where government authorities are not used to cooperating and interacting with laypeople. As a result, in existing highly hierarchical top-down approaches, a psychological and cultural shift is needed to overcome and move towards greater collaboration and participation (see also Theme 6). It is also necessary to investigate how to benefit from existing local participatory methods that are not related to citizen science.

This theme investigates regulatory frameworks that support the effective integration of new technical and administrative specifications, including citizen science. Adaptive and flexible, yet consistent and robust, regulations are needed to support the transfer of hydrological science innovations in operational water information, policy, and decision-making systems empowered by citizen science. Three major factors are investigated in this theme: (a) regulations and norms about the tools and methods for collecting, sharing, using, and validating hydrological data from informal sources; (b) evaluation of participatory approaches as mechanisms for more inclusive decision-making; and (c) cost–benefit analyses of citizen science projects.

The first factor deals with the issue that specifications of crowdsourced data and crowdsourcing platforms for hydrological monitoring and modelling are not consistent with existing standards. Pictures taken from cell phones as compared to water level measurements gathered from standard flow gauges is a good example of the lack of consistency that hampers the impacts of citizen science on fostering technological innovations for hydrological sciences. For example, evacuation decision-making during flooding conditions only considers validated data from official standard flow monitoring gauges. Crowdsourced data may complement standard data used for disaster risk management, especially if supported by proper legal frameworks, norms, and quality control.

The second factor pertains to research on the impacts of including public participation in decision-making. Some studies indicate positive correlations between participation, awareness, compliance with the law, and improved management (Von Korff *et al.* 2012, Buchecker *et al.* 2013); therefore, European directives (e.g. Water Framework Directive, Floods Directive) incentivize participatory approaches. Nevertheless, most national and regional regulations do not consider participatory approaches, and significant political and cultural barriers impact citizen science uptake for more inclusive water governance and decision-making. To overcome these barriers, official authorities may benefit, by means of citizen science projects, from increased and wider involvement of citizens and stakeholders.

The third factor is linked to studies that address other reasons hindering the uptake of regulations supporting citizen science. These reasons are rooted not only in the reliability of the data but also in the lack of understanding by authorities of the costs of citizen science projects and how to adapt existing practices. Understanding the technologies used by scientists and citizens is fundamental, but not sufficient. Indeed, cost–benefit analyses that consider the entire technological and administrative burden associated with citizen science projects are needed. This theme, thus, also includes research on how to create locally adapted citizen science projects, to facilitate adoption, paving the way for parsimonious citizen science project implementation (Assumpcao *et al.* 2019).

2.3.5 Theme 5. Communicating water science and societal feedbacks

Scientific communication (definition in Table 1) has moved from being solely the dissemination of scientific knowledge and research outcomes to the general public to encompassing public awareness, scientific literacy, and culture (Burns *et al.* 2003). This new purpose may stimulate behaviour change and actions from affected citizens and stakeholders. The scientific communication workflow includes multi-directional feedback between scientists and society, which can be further enhanced by citizen science (Bonney *et al.* 2009, Le Coz *et al.* 2016, Montargil and Santos 2017).

Communication and dissemination have become an integral part of research projects addressing hydrological issues. Citizen science constitutes a valid method for testing novel ways to exchange information between scientists and communities, particularly those affected by societal, climatic, and hydrological challenges. Citizen science projects represent a testbed for processing and conveying, to both experts and the general public, the transdisciplinary value of water as a resource, and disaster risk management.

This theme extends the proposed transdisciplinary framework to include studies on communication strategies for knowledge exchange and public feedback. It seeks to investigate, test, and discover new forms of visualization, infographics, and mapping, as well as new engagement models (e.g. demographics-targeted communication campaigns, online communities and social networks, and gaming technologies) that are explored and tested by scientists to reach a wider audience, from children to senior citizens (Schwabish 2020).

2.3.6 Theme 6. Collaborative and participatory efforts supporting decision-making and policymaking

Citizen science can help decision-making in many forms, most obviously by providing relevant data to authorities or by increasing participation levels in addressing societal challenges linked to water issues. The level and scale of citizens' participation (Haklay 2013) determine the effectiveness and impact of citizen science projects in supporting or prompting a change in water governance (Buytaert *et al.* 2016), but are not the only possibilities. Challenges due to the segmentation and diversity of participatory approaches are identified. These have various implications for the uptake of citizen science for decision- and policy-making. Four major factors to be investigated include: (a) diversity of approaches and scales; (b) diversity of participants; (c) the working conditions (behaviour, safety, productivity, etc.) characterizing citizens when deploying data as *human sensors*; and (d) the trustworthiness and authoritativeness of citizen science data and projects.

The first factor relates to the collaborative process. Differences in citizen science approaches depend on the spatial and temporal scale of the phenomenon of interest. For example, different scales apply to participatory projects aiming to manage extreme events, that usually require high frequency and low data latency (i.e. real-time conditions), as in disaster risk management and emergency response (Eilander *et al.* 2016, Ernst *et al.* 2017, Sy *et al.* 2019). This last example contrasts with urban and regional monitoring activities that are characterized by low-frequency and long-term response times (Albano *et al.* 2015, Lisjak *et al.* 2017). The dynamics of the phenomena of interest also affect the behaviour component, since different citizen science approaches are implemented for emergency management, such as extreme river flows vs water sampling of regular river flows.

The second factor is linked to the diversity and often random, unpredictable behaviour of the participants. In this regard, we emphasize that human sensors–behaviour interactions not only vary from citizen to citizen but also vary in time and depend on the specific context. The same citizen in the same time frame may behave and operate differently depending on motivation, availability, and the technical and engagement methods used for prompting and implementing their involvement. In this regard, uncertainty analyses in crowdsourcing benefit from transdisciplinarity. In particular, the hydrological sciences are linking with statistical and demographic studies, as well as with social and psychological sciences, to deal with the randomness and bias associated with observations of natural and human phenomena (Seibert *et al*. 2019, Strobl *et al*. 2019b).

The third factor refers to the working conditions of humans "working as sensors". In particular, there are diverse sensing conditions and processes that affect the quality and quantity of crowdsourcing records. The behaviour, safety, and productivity that impact the "human sensors" component need to be appropriately designed and managed. Research investigations should also consider the behaviour related to the use of dedicated tools for crowdsourced data production (e.g. the different effectiveness of information generated by citizens previously properly and purposely trained or by the volunteer data-gathering of untrained participants) (Strobl *et al*., 2019a). Further working conditions are represented by the analysis of potentially hazardous situations affecting citizens when sensing extreme phenomena and the potential risks of implementing citizen networks that may involve improper use of mobile devices in dangerous conditions.

The fourth factor deals with the operational use of crowdsourced data and crowdsourcing programmes for policy- and decision-making in water resource and disaster risk management. The previous factors, once addressed, may support the inclusion of crowdsourced data for integrating (or surrogating) traditional monitoring data. Nevertheless, policymakers and decision-makers may still be impacted by bounding conditions linked to actual standardized procedures that often avoid the full exploitation of the value of crowdsourcing. This bounding factor generally relies on the trustworthiness and authoritativeness of data gathering using citizen science methods. As an example, data gathered from a citizen science project supporting hydrological observations using a mobile application (e.g. Crowdwater – Strobl *et al*., 2019b or Scent project – Tserstou *et al*. 2017), even if consistent with standard river flow observations, may be disregarded for policy- and decision-making. In the context of flooding, direct observations, even if transmitted in a timely manner, cannot be used for evacuation planning (with some exceptions, e.g. Naik 2016, Pandey and Natarajan 2016, Yadav and Rahman 2016, Anbalagan and Valliyammai 2017).

It is expected that policymakers and decision makers will increasingly integrate citizen science in their decision-making, but how exactly this will happen remains unclear. This theme explores how hydrological scientists will collaborate with jurisdictional and policy experts, as well as with communication experts, psychologists, and other non-hydrologists, to support the operational use of crowdsourced data. It is therefore crucial to test shared procedures (i.e. shared among the plethora of heterogeneous components discussed earlier) and, consequently, identify and test novel guidelines allowing trans-sectorial participatory decision- and policymaking.

2.3.7 Theme 7. Procedures and guidelines for the integration of citizen science into hydrological research

New procedures and guidelines are needed for valuing citizen science in hydrology. Citizen science projects are lacking comparable data gathering, modelling, and integrated assessment schemes (Haywood and Besley 2014, Burgess *et al*. 2017). The many examples of diverse citizen science projects confirm that these schemes are hard to find. It is difficult to even analyse and compare different methodologies within similar projects sharing the same goal (e.g. water level monitoring) in hydrological sciences. The integration of the full range of heterogeneous and diverse water-related citizen science data in a robust assessment framework is challenging, but essential to achieve. From a technical point of view, comparative considerations on the quality and quantity of data, plus quality assurance, should be made to support transdisciplinary research programmes that aim to use such diverse data and tools. Also, it is necessary to evaluate data models and fuzzy methods that can incorporate multiple datasets into modelling frameworks (Malczewski 2006). Comparative assessments are fundamental to building knowledge from diverse citizen science models and outcomes. Additionally, heterogeneity, gaps, flexibility, interoperability, scalability, and data assimilation should be evaluated. Investigations on model calibration and validation procedures are also needed to accommodate the varying formats, uncertainties, and availability of crowdsourcing data. In turn, models optimized for crowdsourced data can be compared with models built with expert-sourced observed data, standard observations, or previously validated simulated variables.

This theme seeks to define and develop procedures and guidelines – as set out in the proposed conceptual transdisciplinary framework – and establish synergies among, as well as take into account the opportunities and caveats characterized in, the previous six themes. It constitutes a synthesis of the technical and non-technical, methodological, and procedural challenges and solutions introduced in this section. It aims to develop consistent assessments of citizen science projects and frameworks and accumulated knowledge towards the maturing of transdisciplinary citizen science projects in the context of finding integrative solutions to water challenges.

3 The CANDHY Working Group at the International Association of Hydrological Sciences

The Citizens and Hydrology (CANDHY; logo in Fig. 5) Working Group (WG) was established in July 2017 by the International Association of Hydrological Sciences (IAHS). The principal aim of the CANDHY WG is to support the use of citizen science in hydrology and harmonize research in this context, promoting the value of citizen science for advancing the hydrological sciences and finding answers to the most pressing open scientific, technical, and societal challenges in this field of expertise. This paper identifies the fundamental components, thematic areas, and specifications of citizen science projects giving them structure and direction to advance research and achieve scientific breakthroughs in hydrology.

The citizens and hydrology topic is aligned with major programmes and efforts of the IAHS. IAHS launched and catalysed

Figure 5. The logo of the International Association of Hydrological Sciences (IAHS) Citizens AND HYdrology (CANDHY) working group.

the Predictions in Ungauged Basins (PUB) Decade (2003–2012) (Blöschl *et al.* 2013, Hrachowitz *et al.* 2013) and the ongoing Panta Rhei Decade (2013–2022) (Montanari *et al.* 2013, McMillan *et al.* 2016) for promoting and coordinating scientific efforts for achieving improved hydrological data and models. CANDHY WG cooperates with the IAHS Measurements and Observations in the XXI century (MOXXI) WG, whose mission and goals are to address Panta Rhei science questions 1 and 5 that focus, respectively, on the identification of key gaps in the understanding of hydrological change, and on advancing monitoring and data analysis capabilities, also through opportunistic sensing, to predict and better manage hydrological change (Tauro *et al.* 2018). The CANDHY WG contributed to the Unsolved Problems in Hydrology (UPH) initiative, defining the UPHs of the "Measurement and data" section (UPHs 16, 17, 18) as well as the questions about "Interfaces with society" (UPHs 21, 22, 23) (Blöschl *et al.* 2019).

The CANDHY WG aims to promote the development of citizen science projects linking Earth, environmental, atmospheric, and hydro-sciences as well as humanities, social, and computer sciences, to synergistically define methods, procedures, and guidelines for the effective use of informal data and to foster participatory solutions for water challenges.

4 Citizen science in hydrological sciences: the way forward

While citizen science initiatives show promising results, there are still several challenges to be addressed. Evaluations of effective costs and benefits of citizen science projects need to be critically debated. Technology becomes obsolete very quickly and data infrastructure needs to be maintained. Short-term financing schemes and fragmentation affect the sustainability and long-term achievements of citizen science projects. Intellectual property, licensing, and data protection are serious challenges that need to be managed (Quinn 2018). Relevant opportunities offered by citizens' distributed monitoring networks and affordable opportunistic sensing require government and financial support, multi-sectoral coordination, and long-term vision (Dixon *et al.* 2020).

The impact of citizen science in hydrology depends on drivers and involvement from actors and stakeholders of participatory outcomes. It is not only a matter of extending the participation. What is needed is a commitment to co-generate citizen science programmes so that stronger links, mutual trust, and shared beliefs among researchers, citizens, and policymakers are developed (Stahl *et al.* 2017, Njue *et al.* 2019).

Citizen science is expected to reinforce the value and mission of socio-hydrology in understanding and addressing sustainable development and environmental issues (Pande and Sivapalan 2017, Di Baldassarre *et al.* 2019, Fritz *et al.* 2019). Approaches for connecting citizen science and socio-hydrology are still not well defined, but initial investigations on this topic are emerging (Buarque *et al.* 2020).

The next steps needed to allow citizen science to reach its full potential for hydrological sciences are through the following major research lines of action:

- Understand how crowdsourced data and actions generate hydrological knowledge and how this should be formalized in models and hydrological studies. Research and standardization efforts are needed to address data quality, data validation, and data interoperability.
- To date, most of the hydrologic information systems seem to be developed as top-down programmes (e.g. USGS Hydrosheds; Australian Water Observations from Space – WOfS; EU Global Surface Water Explored – GSWD) and do not allow for the integration of informal data processing methods resulting from citizen science. It is necessary to learn from successful examples, such as collaborative mapping projects like OpenStreetMap, involving thousands of volunteer mappers daily updating street/urban features. Hydrologists should seek a common, inclusive, and open platform fostering the integration of crowdsourcing with standard hydrologic monitoring and geospatial mapping data.
- A growing number of hydrological studies use data from social networks, but most of the crowdsourced data used in research are still indirect citizens' observations. Hydrological scientists may need to focus on creating efficient tools and resources (e.g. smartphone apps, web platforms, training, awareness, and communication campaigns) to incorporate the data collected through social networks. Novel paradigms and disciplines may be needed to support an increasing volume and effectiveness of social media content for hydrological sciences.
- Gaming technologies have successfully integrated numerical algorithms developed by hydrologists. Advanced hydrodynamic simulations of water dynamics are, in fact, now embedded in commercial gaming console applications and used daily by millions of users of any nationality and age. Hydrologists should take advantage of the growing interest, audience, and skills raised by the gaming industry, big data, artificial intelligence, machine learning, and augmented reality technologies. Collaborative virtual gaming and big data environments represent a great opportunity for citizen science in support of hydrological sciences.
- Citizen science represents an opportunity for discovery and testing novel educational programmes to be proposed at different levels (from doctoral research to elementary schools). Hydrological sciences should focus on the opportunities offered by citizen science for innovating and proposing transdisciplinary multi-level education methods and programmes.

- Engaged, informed, and concerned citizens are essential for managing the crucial natural resource that is water. Eventually, in this era of increased risk of disinformation, citizen science also represents a way to rebuild trust between citizens, science, and authorities. Trustworthiness and authoritativeness issues are, and will continue to be, a critical topic where scientific knowledge and methods should play a governing role in support of well informed decision- and policymaking.
- There are close analogies between the diversity, heterogeneity, and complexity of human beings and hydrologic phenomena. Human and water systems will continue to shape each other and interplay. The knowledge, studies, and solutions that have separately emerged from social and hydrological sciences will need to merge. Disciplinary boundaries of any further discipline able to understand, monitor, and influence the coupled human–water sensors and behaviour should be more permeable. Novel water governance solutions and strategies can be investigated through citizen science projects, and this represents an opportunity for scientists, stakeholders, decision makers and policymakers to develop and learn together.

We think that the proposed transdisciplinary framework may pave the way for a conceptualization and assessment model for citizen science projects addressing water challenges. The proposed CANDHY framework, with its elements, components, and interfaces, may be used to evaluate and compare the completeness, effectiveness, scalability, and replicability of citizen science projects. The CANDHY transdisciplinary framework is a first step towards new knowledge and the integration of crowdsourced data, tools, procedures, and policies produced in diverse academic and non-academic settings. We posit that the CANDHY transdisciplinary framework is a suitable means for valuing citizen science projects in hydrological sciences, with even broader applicability across many natural and social sciences.

Acknowledgements

Two anonymous reviewers provided ideas and comments that greatly helped to improve this paper. The IAHS CANDHY Working Group is continuously welcoming new members, citizens and hydrologists, interested in joining efforts and contributing to the CANDHY mission. To become a CANDHY friend – a member of the working group – and stay up to date, please visit the webpage https://iahs.info/Commissions–W-Groups/Working-Groups/Candhy.do

Disclosure statement

No potential conflict of interest was reported by the authors.

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