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Overview

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In disaster risk management (DRM), an emerging shift has been noted from broad-scale, top-down assessments toward more participatory, community-based, bottom-up approaches. Arguably, nonscientist local stakeholders have always played an important role in knowledge risk management and resilience building within a hydrological context, such as flood response and drought alleviation. However, rapidly developing information and communication technologies such as the Internet, smartphones, and social media have already demonstrated their sizeable potential to make knowledge creation more multidirectional, decentralized, diverse, and inclusive. Combined with technologies for robust and low-cost sensor networks, a 'citizen science' approach has recently emerged as a promising direction in the provision of extensive, real-time information for risk management. Such projects work best when there is community buy-in, when their purpose(s) are clearly defined at the outset, and when the motivations and skillsets of all participants and stakeholders are well understood. They have great potential to enhance knowledge creation, not only for data collection, but also for analysis or interpretation. In addition, they can serve as a means of educating and empowering communities and stakeholders that are bypassed by more traditional knowledge generation processes. Here, we review the state-of-the-art of citizen science within the context of hydrological risk reduction and resilience building. Particularly when embedded within a polycentric approach toward risk governance, we argue that citizen science could complement more traditional knowledge generation practices, and also enhance innovation, adaptation, multidirectional information provision, risk management, and local resilience building. © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

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INTRODUCTION

Within the emerging trend of democratizing science, the participation of nonprofessional scientists in research projects that involve data collection, interpretation, and analysis is often termed 'citizen science.'[1–5] The constant demand for research to be societally relevant has helped involve more citizens in research projects.[4,5] As a practice, citizen science is receiving increasing attention in many disciplines. However, traditional citizen science applications are already well established in, for instance, aspects of biology like medical trials,[6–8] and the development of geographic information system (GIS) networks.[9–11]

Water science is not an obvious discipline for the use of citizen science because many measurements are technologically demanding. On the other hand, there are also several good examples, such as the citizen-led measurement of precipitation, river water, and soil moisture levels.[1] This process has been greatly aided by rapid technological development over the past 10–15 years, with small, cheap sensors now widely available in smartphones, which themselves are generally fully Internet connected and come with sophisticated cameras as standard.[9,10,12–15] Moreover, the management of flood risk through interaction with social media[9,14] and simple smartphone-based flow estimation,[10,13,15,16] is another common hydrological citizen science application.

At the same time, there is much interest and a need to explore new ways to create relevant knowledge. Hydrology remains a highly data-scarce science; in many regions, if data exist, the lengths of the time series are insufficient.[17] From a policy perspective, there is increasing interest in improving the risk perception by engaging all actors involved in Disaster Risk Management (DRM).[1,18] The 2015 UN Sendai Framework for Disaster Risk Reduction, for instance, states that '*[d]isaster risk reduction requires an all-of-society engagement and partnership [in which] special attention should be paid to the improvement of organized voluntary work of citizens.*'[19]

These points are highly relevant in the context of risk reduction and resilience building. These are areas where a major need for data persists, and they are of high societal relevance (as they have a direct impact upon livelihoods). Also, 'traditional' methods struggle to create locally relevant, 'actionable' knowledge. For instance, 'traditional' water level and discharge monitoring is usually based on a sparse network of gauges that require extensive and technologically complex maintenance, while legal issues over data ownership can frustrate community-level access.[1] Hence, this paper explores the challenges and opportunities of citizen science within a broader context of DRM and resilience.

THE CONCEPT OF CITIZEN SCIENCE

While the concept of citizen science is well established, several different definitions, both formal and informal, exist.[1] Citizen science is most commonly defined as science by nonscientists: it is '… *a form of science enacted and developed by citizens themselves*'[20,21] or '*[t]he participation of the general public in the research design, data collection and interpretation process together with scientists.*'[1] Other related terminology includes the 'public understanding of science and technology' (PUST) tradition, which focuses on outreach and enhances public knowledge and acceptance of science; and 'public engagement in science' (PES), which stems from community science approaches and focuses on participatory research, practice and policy.[22–25] True citizen science projects can be differentiated from more general stakeholder engagement by the active involvement of citizen volunteers throughout the project, which is underpinned by one or more motivational aspects.[1] Citizen science is thus distinct from participatory approaches in general, which have been defined as 'activities that engage the public and/or stakeholders.'[26] Such approaches have been encountered in river basin management since at least the 1970s, when a bottom-up approach was recognized as key in the sustainable management of water resources.[26,27] Elsewhere, in river quality restoration, a citizen science approach has been sought as an augmentation to participation alone, as citizen scientists became recognized as increasingly important actors in actively defining local monitoring practices.[27]

The historical starting point for citizen science was largely based on environmental data collection by volunteers.[1,26,28] With time, the focus has broadened, shifting from acquiring data to other phases of the scientific process, including problem statement, analysis, and interpretation. Within this perspective, it is the citizens who, as engaged stakeholders, define the problem at hand, and then collect relevant environmental information (viz. observation of water levels, rainfall and water availability etc.). This information is then processed by scientists into forecasting models, and fed back to the system.[29,30] A recent framework by Haklay refers to this mode of citizen science practice as extreme citizen science, or collaborative learning (Figure 1).[31]

'Extreme citizen science' (the fourth and highest level of Haklay's framework[31]) embraces collaborative science in its broadest sense: citizens are involved from problem definition to the dissemination of results. In this interpretation, the emphasis is not on the citizen as a scientist, but on the scientist as a citizen.[23,32] This method of practicing science is currently not widely accepted in the academic community: taking into account local needs, practices, and culture, it requires scientists to engage at a profound level with the social and ethical aspects of their work.[32]

Extreme citizen science is gaining popularity within environmental and conservation sciences in particular.[33–35] There are a number of information gaps that hamper effective environmental monitoring for evidence-based decision-making, including insufficient data, inconsistent metrics, weaknesses in predictive models, and a lack of real-time monitoring systems.[36] While increasing numbers of stakeholders—governments and large development organizations, research centers and private companies, and local and national NGOs—engage in data collection, their activities are mostly uncoordinated, and the resulting data often remain underutilized. Most worryingly, very rarely do those metrics translate into usable, actionable knowledge for the communities directly affected by the environmental change.[37]

Recent research[1,31,38] has demonstrated that community-based monitoring can provide reliable data to help fill data gaps, for instance in catchment and risk management.[1,2,39–43] Comprising both outreach (awareness raising, increased scientific literacy, community cohesion, and social capital) and research (robust and meaningful metrics) outputs, the participatory, community-led approach can be fruitful for policy development over a variety of geographical scales. This is conceptualized in Figure 2, which indicates the pervasive nature of citizen science across all spatial scales. Also, Figure 2 shows that the generation of new global-scale products could have an impact on both communities and science (e.g., improved precipitation data from merging citizen science gauge records and remotely sensed data sets).[44]

While the exact form that citizen science takes varies widely (Figure 1; from crowdsourcing[3] to active community participation in high-level decision-making)—and there is some debate over whether all projects that include nonscientists in scientific work constitute citizen science[1,3–5]—timely and accurate information can greatly assist the governmental organizations and emergency agencies involved in hazard risk management.[12,45–48] The participatory approach has been shown to work best when there is active buy-in from the local community.[1,4,21,49] That is, the benefits to local stakeholders should be highlighted. The best projects have their aims and objectives defined at the outset; project members have appropriate expertise (not just scientifically, but also in publicity and communication); and there is a clear willingness to listen and adapt as necessary. Several studies have discussed the motivation of volunteers for engaging in citizen science.[1–3,5,20] Motivational aspects are manifold and often highly

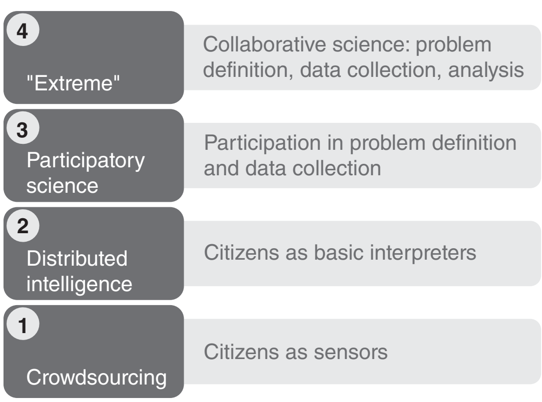

FIGURE 1 | Levels of participation in citizen science. After Haklay.[31]

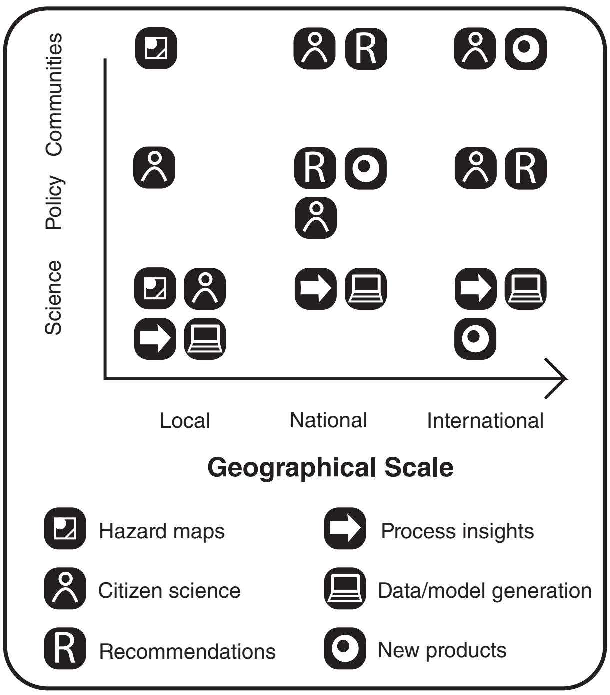

FIGURE 2 | Examples of the potential use of citizen science to deliver outcomes for communities, policy, and science, at different geographical scales.

complex, ranging from scientific curiosity to environmental concern and a desire for political empowerment.[1] A participant is only a citizen scientist when they actively volunteer (i.e., they are motivated by one or more factors) and maintain their activity (and contact with the professional scientists) throughout the duration of the project. In some citizen science projects, participants have lost interest and/or fallen out of contact with scientists,[9,11] or, as 'citizen sensors,' collect data passively without any obvious motivation.[10] However, the recent tendency is to involve volunteers in all intellectual aspects of the science, rather than capitalizing on them as a low-cost workforce.[1,2]

CITIZEN SCIENCE IN HYDROLOGY

Overview

The implications of the Internet, smartphones, and new developments in sensing technology on citizen science in a hydrological context have recently been discussed.[1] The increased availability of Information and Communications Technology (ICT)—in particular, mobile phone saturation across societal segments—opens up new ways of both gathering big data and accessing environmentally relevant information, having a profound impact upon the work of scientists and policy makers.[50,51] Today's mobile phones may be equipped with sensors that can be utilized for scientific observation, including transceivers, FM and GPS receivers, cameras, accelerometers, digital compasses and microphones.[52,53] Even in the absence of the sensors, mobile networks can still be used to transmit physical observations and measurements from users to the predesigned scientific domain.[52,54] Beyond smartphones, citizen science can also benefit from other newly emerging technologies[53]: examples include crowdsourcing rainfall data from personal weather stations,[55] or inferring precipitation by exploiting sensors attached to car windscreen wipers.[56]

The uptake of citizen science has, so far, been rather limited in terms of hydrological risk and resilience building, even though participatory projects have been noted in water resources management for some time.[1,27] Hydrological data are often difficult to interpret intuitively, while measurements tend to be expensive (e.g., using proprietorial software), complex, spatially sparse and temporally dense (for instance, long time series of discharge and precipitation). For these reasons, intensive scientific training and specialization is normally a prerequisite for data analysis and manipulation.[57] However, new technological developments can, to some extent, circumvent these limitations, paving the way for the more rapid uptake of citizen science[1,5] (Table 1).

Quantification of Hydrological Risk

Table 2 summarizes documented citizen science projects that involve risk reduction and/or resilience building against hydrologically induced natural hazards, such as flooding and landslides ('hydrohazards'). Many projects involve community-based responses to river flooding, either taking a preventative approach,[14,15,61] or offering the opportunity for real-time observation and mitigation.[9,10,13,16,60] In the majority of these studies, we note that the role of citizen scientists is strictly limited to information and data gathering, rather than leveraging the full potential of actionable knowledge co-generation.[2] Compared to citizen science applications in water resources science (e.g., measuring water quality parameters and biodiversity), there is less emphasis on training the project participants.[1] This could be a direct result of recent technological development, which allows data to be shared easily via social media.[9,10,12,13]

In building resilience, utilization of multiple data sources is particularly desirable. The installation of networks of robust and low-cost sensors (e.g., automatic rain gauges and river level distance sensors) has recently emerged as a useful approach that has the potential to provide real-time information for risk management.[1,10,16,58,62,63] However, considerable effort is required to ensure the effective operation of these sensors. Participatory monitoring can involve supervision and/or installation of such sensor networks; in high-risk, low-data availability areas, citizens can provide additional, often qualitative, information via various devices such as smartphones (Volunteered Geographical Information: VGI).[9–16,48,60,61]

The combination of a sensor network with VGI can act as a mutual support system to achieve hydrologically induced risk management, and significantly improve the coverage of monitored areas.[1,5,16,58,60] This can take the form of time-stamped and geolocated photographs,[9,10,12–15] social media updates,[12,14,15] or interviews and feedback to *ad hoc* hazard mitigation websites.[12,60,61] Smartphone apps have also been developed to this end.[9–11] On the other hand, a few projects have worked closely with local communities in order to explain to and train participants in the use of more complex monitoring principles, e.g., water level and flow[1,10,16] and rain gauges.[58]

TABLE 1 | Some Commonly Measured Variables in Hydrological Risk Reduction, and Challenges and Opportunities Emerging from Citizen Science Applications. Modified from Table 2 of Ref [1] which Contains Additional Details of Other Hydrological Variables

Variable	Opportunities	Challenges
Precipitation	Cheaper equipment (e.g., electronic tipping bucket rain gauges). Bulk analysis of environmental influences on rain capitation. Merging with remotely sensed observations.	Long-term data collection. Proper installation, maintenance, and documentation of local environmental conditions.
Soil moisture	Automatic measurements (e.g., Time domain reflectometry) becoming increasingly affordable.	Relationship to other soil properties; high spatial variability; dependence on local agricultural practices.
River level/stage	Low-cost, robust, and accurate measurements using latest range-finding technology (e.g., radar and lidar).	Proper maintenance and data download. Conversion to real-time transfer and display. Potential human interference with exposed sensors.
Streamflow (volume per unit time)	Collection of calibration data; cheap measurement technology; emerging image analysis techniques for stage and flow measurements	Proper installation and maintenance; technical support
Water use	Availability of electronic sensors; convenient data communication via the Internet in urban areas	Interpretation and extrapolation of generated data; potential human interference
Vegetation dynamics	Cheap and readily available technology (e.g., GPS, photography; remote identification	Hard to process and combine with remotely sensed data; systemization

The organization and degree of involvement of the citizen scientists varies widely. On one end of the spectrum (Haklay's[31] Level 1), so-called 'community-led' projects may in practice involve very limited direct community engagement, and as a result of this collect very little data, or utilize it sparingly or poorly. For instance, drainage and early warning systems to reduce the risk from glacial outburst floods in Nepal were constructed and monitored following a remote crowdsourcing approach, but little action was then taken, owing to funding concerns and lack of continuing interest from participants.[48] Moreover, the initial results of the Creek Watch program in the western USA did not greatly progress, perhaps because specific roles were not yet fully defined for the relevant actors in this flood resilience-building project.[10] Sometimes, governmental bodies or scientists do not recognize local actors as being able to produce high-quality, official information; furthermore, community interest or deliberation over possible solutions may be lacking.[1,14,48]

On the other end of the spectrum (Haklay's[31] Level 4: 'extreme' citizen science), extensive community-led engagement exercises have generated fruitful results for knowledge co-generation, from rural areas with multiple hazards as in western Nepal,[1,42,45] to urban areas at risk from repeated flooding.[14,15,59,61,64] The most effective projects (from the point of view that both scientific and citizen engagement objectives are satisfied) involve two-way information flow over the entire project lifecycle, which has been shown to improve citizen participation significantly, as well as their sense of situational awareness.[2,9,62] For instance, Liu et al.[9] describe how, using their flood resilience app, users can simultaneously upload geo-referenced tweets, and also instantly explore heterogeneous data sets and maps that have been processed by professional scientists. This process, in turn, can inform future participatory observation, ensuring that the citizen science project grows organically and sustainably.

However, it must be remembered that most citizen science projects in this context only involve monitoring and data submission ('citizens as sensors': a 'one-way street'[9]), with roll-out of citizen-to-citizen or citizen-to-scientist feedback (and more sophisticated information provision systems) generally lacking or at an early stage.[10,11,13–16] This makes it pertinent to analyze how citizen science concepts may be leveraged to turn collected data into actionable knowledge related to risk reduction, governance, and wider resilience building.

Hydrological Risk Management and Governance

The polycentric risk governance approach has recently gained traction in the context of climate change policy[65] and the generation of knowledge on ecosystem service processes of remote river basins, linking them into local and regional governance

TABLE 2 | Recent Examples of citizen Science Applications in Hydrological Risk Reduction and Resilience Building. A Summary of More General Applications in Hydrology/Water Resources Science is Given Elsewhere[1]

Study	Location(s)	Nature of hazard/program objectives	Activities/innovations	Citizen scientist engagement	Professional scientist role
Buytaert et al.[1]	Peruvian Andes, Lake Tana (Ethiopia), Mustang (Nepal)	Impact of changing land use	Rainfall, river level, soil moisture and stream flow data coupled to modeling approach	Hydrological monitoring	Design of monitoring program, training, data analysis
Malakar[58]	Central Nepal	Rainfall and landslide monitoring	New sensor networks installed at community level	Rainfall monitoring; geological studies	Enunciation of major landslide causes; training and data interpretation
Oven et al.[59]	Nepal	Flood, landslide, earthquake risk reduction	Community-based disaster risk reduction intervention	Semi-structured interviews and focus group discussion	Problem definition; design of engagement program
Borga et al.[60]	n/a	Resilience to flash floods	Integration of hydrological data with citizen science	Collection of eyewitness accounts and observations	Problem definition; design of interviews; data interpretation
Kattelmann[48]	East Nepal	Glacial lake outburst floods	Drainage and automatic warning systems	Soliciting political interest and funding	Design of drainage projects
Lane et al.[61]	Ryedale, North Yorkshire, UK	Building flood resilience	Improvements to local flood knowledge	Extensive engagement with scientists and policy makers	Extensive engagement with citizen scientists
Liu et al.[9]	Champaign, IL (testing)	Emergency management; urban flood response	New integrated Mapster app	Twitter and access to maps (two-way information flow)	Data protocol design only
Robson[10]	San Jose, CA	Building flood resilience	'Creek Watch': app and website	Simple observation of water level and flow rate; time-stamped photos	Top-down approach: complete oversight of program
Le Coz et al.[13]	Argentina/France/New Zealand	Building flood resilience	New crowd-sourced data sets	Photos and videos for flow estimation	Training, design of monitoring system, data dissemination
Uson et al.[14]	Santiago, Chile	Urban flood risk reduction	Role of citizen science on governance structures	Social media content, photos	None
Rosser et al.[15]	Oxford, UK	Flood probability mapping	Citizen science and remotely sensed data	Geotagged photos from social media	No active contact with citizens
Horita et al.[16]	Sao Carlos, SE Brazil	Integrated river flood risk management	Combination of wireless sensor network and citizen observatories	Observational monitoring	Provision of participatory website only

processes.[1,18,62,63] Moreover, the polycentric approach is particularly suitable for reducing disaster risk in remote environments where flooding continues to represent a major hazard. The combination of this conceptualization of risk governance with citizen science strongly suggests that a participatory approach to data collection can enhance multidirectional information provision and local resilience building.[1,2,18,62]

The multidimensional nature of hydrological hazards in remote regions, the acute scarcity of data on driving processes and vulnerability, and the high diversity and number of actors involved in disaster preparedness, response and recovery, make disaster risk reduction in this environment a formidable challenge.[66] Lack of scientific evidence is a major obstacle to improving local policy-making to deal with managing hydrological-based risk,[17] which is further hindered by the frequently observed combination of acute poverty and often poorly developed links between formal and informal institutions.[67] There is therefore real potential for the involvement of local actors and communities (i.e., citizen science), who may also be incentivized by a desire to improve living conditions and livelihoods, provide protection against hydrological-related hazards, or foster a sense of civic or national pride.[1]

The coupling of insights on risk management, disaster risk reduction, resilience building, and citizen science, is challenging. Multiple risks need to be considered at the same time; responsibilities cut across multiple governance scales and sectors of society; and the risks that need to be addressed are characterized by complexity, uncertainty, and ambiguity. Effective risk governance involves stakeholders at various levels; this includes the use of citizen science across all three phases of the disaster risk cycle:

1. Pre-disaster preparedness: since vulnerability is what turns hazards into disasters,[68] disaster resilience requires *ex ante* socioeconomic and physical vulnerability assessment to promote vulnerability reduction.[69] Governance capacity in preparedness and early warning is enhanced by involving and drawing on communities and their local knowledge, practices, and risk culture,[70] involving them in citizen science efforts that support early warnings.
2. In-disaster response: most efforts in risk research focus on the first phase. Yet in many cases, crisis management is the major factor in shaping how catastrophic disasters will turn out to be.[71] Individual citizens and their networks play an important role in in-disaster response: most people are saved by their kin, friends, or neighbors.[72] While real-time disaster monitoring by trained scientists will always be important, citizen science can be an indispensable tool to provide rapid initial assessments of damage, as well as areas and communities that are most at risk.[69,72] Such real-time, multidirectional risk communication between citizen scientists and disaster relief agencies can greatly improve the speed and effectiveness of the response.[72]
3. Post-disaster recovery and adaptation: this stage involves working at the community level to ensure that a return to the *status quo ante* (with the same vulnerabilities) does not happen (this is often physically impossible anyway). The efficacy and longevity of disaster resilience building projects is greatest when there is active community buy-in, e.g., through citizen science projects.[4,21,49]

It is therefore clear that the principles of hydrological risk governance and citizen science are very strongly aligned.

Building Resilience

The seminal work of Ostrom on polycentric governance[42,73] has triggered an increasing scientific awareness that managing natural resources and risks can benefit from a polycentric approach.[2,74,75] This acknowledges that social-ecological systems are often characterized by multiple centers of decision-making across different scales, thereby relying on a distribution of responsibilities, multiple sources of information, and cogeneration of knowledge. Even if they are less streamlined than tightly integrated centralized systems, polycentric systems tend to '*enhance innovation, learning, adaptation, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales*.'[73] Table 3 details the main advantages of a polycentric citizen science approach over a top-down, monocentric one. The former approach has become prominent in the context of climate change policy[65] and the generation of knowledge on ecosystem service processes of remote mountainous basins, linking them into local and regional governance processes.[1,18,62,63]

Polycentric approaches to hydrological monitoring and management could provide an extension or even possibly an alternative to Integrated Water Resources Management (IWRM).[74] The current discourse on IWRM is concerned with identifying potential entry points to scale up the local water management approaches toward the development of nested institutional setups.[74,76] Despite many achievements in DRM, problems with building resilience persist across many hydrological risk management projects.[69,71,77,78] Governing risks is concerned not just with minimizing the risks, but also enhancing resilience, in order to be able to withstand or even tolerate surprises and respond better.[43,45,79] Resilience is the capability of a system to (1) resist shocks, (2) adapt flexibly to constantly changing conditions, and (3) to transform, in order to keep fulfilling basic functions and services.[75,80] Polycentric disaster risk

TABLE 3 | Main Benefits of Polycentric Disaster Risk Reduction over a Monocentric Approach

Monocentric disaster risk reduction	Polycentric disaster risk reduction
Focus on individual hazards	Focus on multiple hazards and cascading effects
Dominant responsibility of public authorities	Distributed responsibilities across public, private, and civil society sectors
Pre-disaster preparedness	
Expert monitoring	Participatory monitoring networks and citizen science
Disconnected single hazard early warning	Polycentric multi-hazard early warning
Unidirectional risk communication	Multidirectional risk communication, including communities
In-disaster responses	
Top-down crisis management	Multilevel response capacities
Command and control responses	Resilience through adaptive responses and local self-organizing
Focus on single hazard	Focus on multiple hazards and cascading effects, relying on multiple sources of information
Post-disaster recovery and adaptation	
Focus on relief and recovery	Focus on adaptation to enable more resilient responses in the future
Focus on incremental improvement	Focus on updating risk information and adapting governance arrangements
Learning by dominant actors only	Learning by multiple actors and citizen science

governance should enhance the resilience of hazard-prone communities to fulfill basic functions through resisting, adapting, and transforming in anticipation and response to catastrophic natural hazards and still be able to pursue their social, ecological, and economic development objectives.

The combination of this conceptualization of risk governance with the opportunities brought by citizen science leads us to believe that a participatory approach to data collection can enhance multidirectional information provision, polycentric risk governance, and local resilience building.[1,2,48,62]

Polycentric Risk Governance and Citizen Science: A Framework for Sustainable Development

Polycentric governance principles therefore sit well within the concepts and technologies supporting citizen science activities. Figure 3 demonstrates this convergence and explains how citizen science is the single most important principle that underlies the entire workflow of actionable knowledge generation. This encompasses previously discussed terminology such as low-cost sensors and gadgets (e.g., in connection to smartphones) in data collection, as well as exploiting the Internet of Things (i.e., the Internet connectivity of such gadgets) and participatory modeling for data analysis. Figure 3 shows that the generation of actionable knowledge and polycentric risk reduction (gray boxes) is intimately connected to citizen science through three stages in a research project framework. In the next section, we discuss this tri-partite framework of data collection, processing, and provision, in greater detail. In this way, we envisage Level 4 ('extreme citizen science') of Haklay's framework[31] as the most fruitful avenue for the future development of citizen science. The link with sustainable development, as for instance evinced by the 2015 UN Sendai Framework for Disaster Risk Reduction,[19] can be usefully exploited as a means to move beyond the commonly held treatment of citizen science as data collection alone.

CHALLENGES AND OPPORTUNITIES

Information Collection

As argued above, the most straightforward (and widely documented[1,6,7,20,23,32]) aspect of citizen science, not just from the participant's point of view, is data collection. As stated earlier, typical hydrological measurements are not easily integrated within the citizen science framework: they are often complicated, expensive, and tailored to the specific needs of professional scientists. As a result, the monitoring procedure may need to be technically simplified to, for instance, basic visual observations of river levels and flow rate,[10] or geotagged photos and videos of flooding.[13–15]

In a hydrological risk reduction context, this relatively simple participatory approach can be augmented with the use of low-cost sensing equipment within a devolved monitoring framework.[2] This has the effect of improving the spatial coverage and sustainability of monitoring programs. In the last few years, citizen science has expanded rapidly with the

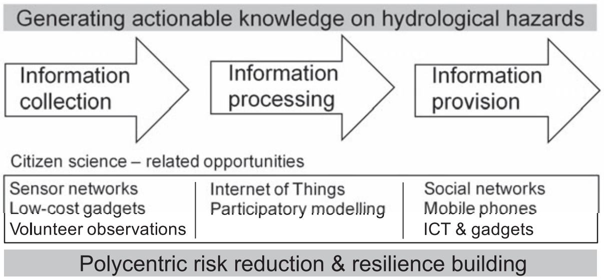

FIGURE 3 | Schematic overview of how a polycentric approach to risk governance may support a workflow of actionable knowledge generation, targeting risk reduction and resilience building. The Challenges and Opportunities section is guided by the three stages of our framework.

development of smartphones with built-in GPS receivers, allowing more information to be shared through digital media. It is likely that standard mobile phones will soon be able to host so-called smart sensors, which would let people measure and record environmental data beyond those required for risk reduction; for instance, air temperature and moisture content.[18,64,77]

The combination of distributed sensor networks, participatory monitoring, and citizen science holds great promise to complement official monitoring networks and remote sensing by generating site-specific information with local buy-in,[1,2] especially in data-scarce regions. Although the quality and availability of remotely sensed data is increasing, ground-based observations (such as rainfall, river flows, soil properties, strain data, and disaster damage) are still needed for calibration, and to resolve small-scale spatiotemporal patterns and processes, especially in complex mountain regions.

Information Processing

The increasingly low-cost availability of ICT, such as open-source data management platforms as well as rapidly increasing Internet and mobile phone coverage, represent major technological advances.[1,2,47] These advances could serve as the basis for multiple entry points in the expansion of citizen science beyond the concepts of the previous section. In hydrological risk reduction, the direct engagement of citizen scientists in the data processing stage is ripe for expansion: as noted earlier, very few studies feature true two-way information flow between the citizen and scientist throughout the life-cycle of the research project.[9,10,61] We believe that the joint analysis and interpretation of data represents a more fundamental means to enhance citizens' participation to the scientific objectives of a research project.

The emergence of open source, cloud-based risk analysis platforms supports the construction of a modular, distributed, and potentially decentralized (i.e., aligned with citizen science activities) data processing workflow. As such, they provide useful platforms for building polycentric early warning systems[77] that allow more diversified and tailored access. One specific example is the Zooniverse citizen science project and software framework, where scientists engage directly in virtual tasks with users; for instance, in interrogating how spatial patterns could reflect hydrological variables in a catchment model.[81] The citizen science approach strongly complements this emergence of new technology, emphasizing the fruitful approach of using citizens as basic interpreters, and placing renewed focus on data logging, quality control, and transmission. The open-source hardware platform Arduino enables the straightforward coupling of analogue hydrological sensors for water level, temperature, humidity, radiation, and precipitation with low-cost, robust data loggers. Web-based services allow for easy connection of sensors with online modeling tools to provide real-time data quality control, storage, and simulation. The use of data exchange standards such as the Open Geospatial Consortium sensor observation service facilitates the near-real-time integration of (citizen science-based) sensor data with other data sources (e.g., traditional monitoring and satellite products). From a technical perspective, regions with low internet penetration can benefit from far-reaching mobile phone coverage for sensor data transmission via text messaging.[1]

Information Provision

The final pillar of our framework for citizen science (Figure 3) involves the communication of results back

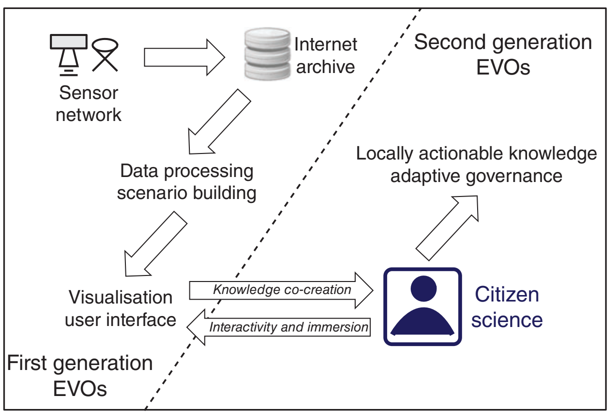

FIGURE 4 | Features of first- and second-generation Environmental Virtual Observatories (EVOs). After Karpouzoglou et al.[62]

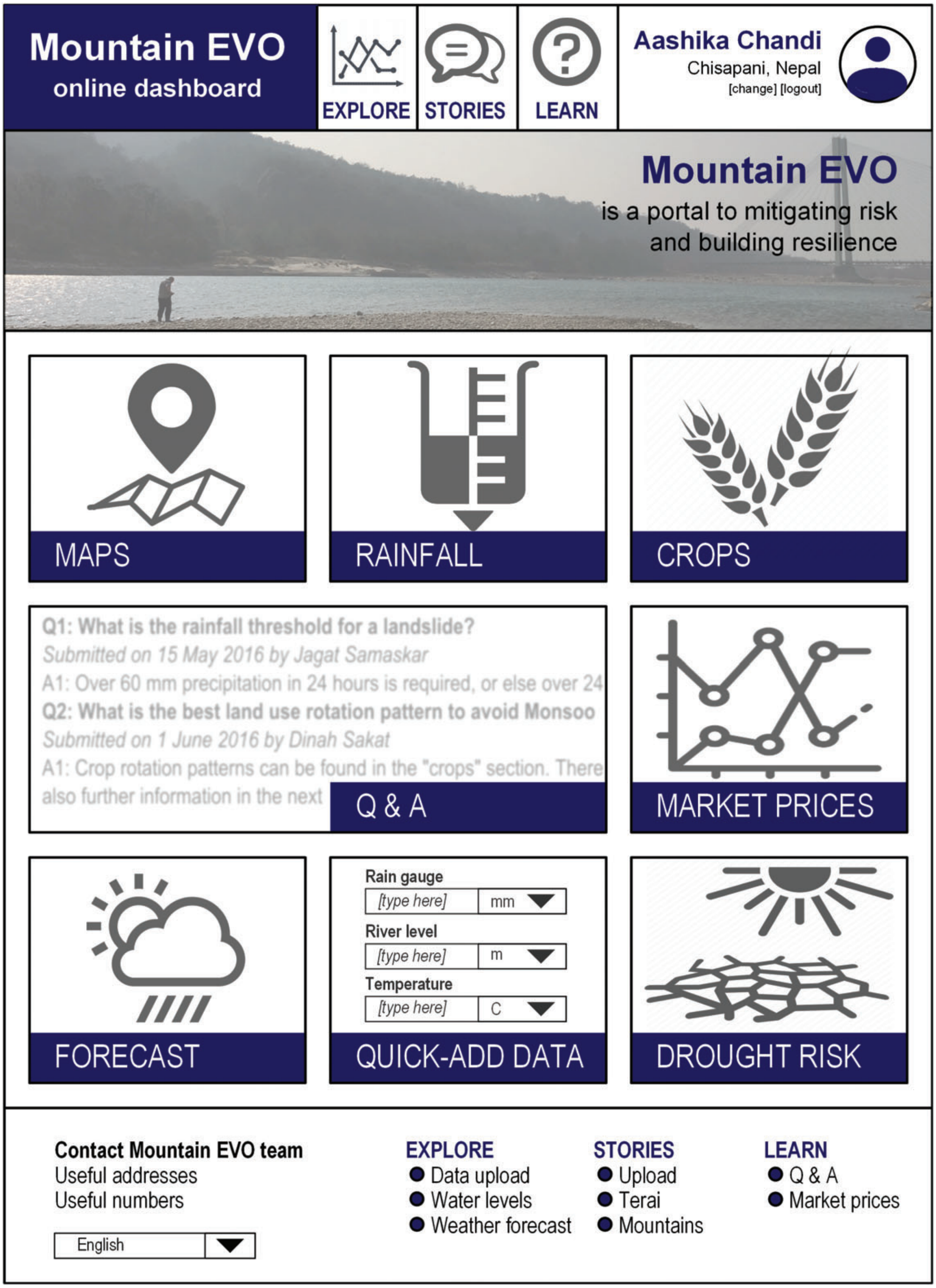

FIGURE 5 | Example of a prototype dashboard-style knowledge dissemination interface, co-designed with local stakeholders, using the methodology developed by Zulkafli et al.[18]

to the participants. This provision of information, in a manner that is comprehensible for a nonscientific audience, serves as an incentive for further citizen participation. Although this important aspect of citizen science is lightly developed[3,23,32] (especially in a hydrological context[1,14–16]), we believe that the recent growth of Internet technologies could create excellent opportunities for user feedback and communication beyond the scientific project itself. In the small number of cases where information provision and citizen feedback are integral to project development, the situational awareness and participation rates of participants, as well as levels of community buy-in, are high.[2,9,62]

As strongly advocated by the Sendai Framework on Disaster Risk Reduction,[19] linking data analysis platforms to social computer networks and ICT (such as mobile phones and tablets) allows tailored interfaces and people-centered decision- and policy-support systems to be constructed, which can effectively support a citizen science approach to information generation, visualization, and communication. Such technologies have been termed Environmental Virtual Observatories (EVOs),[1,62] which are open and decentralized, allowing information to flow freely between multiple actors. This is one of the salient points of citizen science. Given the potentially very different quality and nature of citizen science-collected data, a major outstanding challenge is the communication of inherent assumptions and new uncertainties that are difficult to quantify.[1,82]

Figure 4 shows the development of EVOs through time: while the first generation was constructed around scientists, the second generation is specifically designed in a participatory manner, i.e., around the principles of citizen science. It is also concerned with how co-generation/co-design potentially leads to political empowerment of marginalized individuals and communities. In this way, these more recent EVOs have broader implications for resilience building and knowledge co-creation.[62] Figure 5 shows an example of an interface that is built around the activities of the citizen participant in a recent research project.[1,18]

Future challenges in the realm of data provision include ensuring a user-centered approach, leveraging new technology, and recognizing the polycentric nature of systems. While it is sometimes difficult to quantify visual data, many EVOs now include a component of graphical support for participatory scenario building; for instance, 3D visualization and modeling of raw photographic and geospatial data using a gaming engine.[83] Zulkafli et al.[18] describe a four-stage citizen science approach to designing an information provision system. This approach involves: (1) discovery of user motivations and goals; (2) conceptual design of the system, based on user interviews and testing; (3) detailed design; and (4) system launch and feedback sessions with the local community. Clearly, the involvement of participants over the entire-life cycle of a research project (Figure 3) is the best way of creating locally relevant actionable knowledge (Box 1).

BOX 1

THE HISTORY BETWEEN CITIZEN SCIENCE AND WATER SCIENCE

The application of citizen science in hydrology and water resource science arrived rather late in the former's history, mainly because of the advanced technology required for monitoring many aspects of the water cycle, which precluded the active involvement of nonprofessional scientists.[1] Yet the rapid and widespread effects of inexorable global population growth and environmental change have stimulated scientific interest in the collection of hydrological data that are both spatially and temporally rich. Though citizen science is a relatively new term, people have been contributing to scientific projects for many years. The Christmas Bird Count, conducted by the US National Audubon Society in the late 19th century,[3] is sometimes noted as the first true citizen science project; though it is likely that meteorologists had been collating volunteer data for a long time hitherto. In terms of water, the earliest projects exploited economic gain as an incentive for community participation: for instance, in employing a village network to monitor annual spring discharge,[84] or mill workers to measure river flow.[85] As technology has progressed, citizens are now able to take part in sophisticated and extensive water quality monitoring networks, reporting data in real time.[26] In the realm of academia, there is extensive evidence that a former, rather dismissive, attitude among water scientists of citizen science has profoundly shifted in recent years.[4,49] There are now many publications that use citizen science data as primary core information, in fields as disparate as botany and ecology,[28,38,86] medical research,[6–8] and hazard risk mitigation and resilience building.[1,2,39,64,77]

CONCLUSION

The growth of citizen science in a hydrological risk context can be explained by the prior inaccessibility and sparseness of water-related datasets, as well as the development of new technology such as Internet-connected smartphones. The active involvement of citizen scientists across the entire project lifecycle (rather than participatory monitoring alone) can enhance local uptake, support local diagnostics, and increase decision capacity. Beyond the technical and communication challenges, this is an efficient way to enhance the culture of hazard risk and make communities more collectively engaged. In other words, the principles of polycentric hydrological risk governance and citizen science are very strongly aligned; and this alignment is expressed well in the form of polycentric monitoring approaches. Citizen science effectively bridges gaps between contextual science and adoptive knowledge.

One exciting future perspective would be to combine such 'measurement-oriented' and 'citizen hydrologist' approaches with the powerful tools developed in other projects for data mining the social media contents and conducting a spatial analysis of VGI. A participatory citizen science approach to data collection can enhance decentralized multidirectional information provision, polycentric risk governance, and local resilience building. However, we believe that the future of citizen science lies not in mere data collection, but rather in its integration with information processing and feedback (i.e., the complete research project life-cycle). Potential links to sustainable development in a hydrological risk reduction context offer the unique opportunity to shift the paradigm decisively away from 'citizen sensors' toward the much broader concept of 'extreme citizen science.'

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