

Mitigating flood risk using low-cost sensors and citizen science: A proof-of-concept study from western Nepal

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Abstract

The generation of hydrological data for accurate flood predictions requires robust and, ideally, dense monitoring systems. This requirement is challenging in locations such as the Himalayas, which are characterised by unpredictable hydroclimatic behaviour with dramatic small-scale spatial and temporal variability. River level monitoring sensors that are affordable and easy-to-operate could support flood risk management activities in the region. We therefore identify potential for a local participatory monitoring network that also serve to overcome existing data gaps, which represent the main bottleneck for establishing an effective community-based flood early-warning system. We have applied a citizen science-based hydrological monitoring approach in which we tested low-cost river level sensors. Initial results, collected over summer 2017 from two stations on the River Karnali, suggest that our system can successfully be operated by non-scientists, producing river level data that match those obtained from an adjacent government-operated high-tech radar sensor. We discuss potential opportunities to integrate these low-cost sensors into existing hydrological monitoring practice. Combined with an adaptive, community-led approach to resilience building, we argue that our low-cost sensing technology has the potential not only to increase spatial network coverage in data-scarce regions, but also to empower and educate local stakeholders to build flood resilience.

KEYWORDS

citizen science, early warning system, flood risk mitigation, low-cost sensors, resilience building

1 | INTRODUCTION

Managing natural hazards is an important regulatory public service that benefits poor and vulnerable people directly (Guenni et al., 2005). Such management is very important in remote, mountainous and resource-poor

areas, as communities and local decision makers rely on limited data and information in attempting to adapt to unpredictable natural disasters. Nepal is a global hotspot for multiple natural disasters: people's vulnerability to such disasters is exacerbated by poor infrastructure, insufficient preparedness and a lack of institutional

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capacity (Ministry of Home Affairs [MoHA], 2018). Most river basins along the Himalayan foothills are highly vulnerable to flooding; while regular floods during the Monsoon are very common in the country, they have become more severe and unpredictable in recent decades (e.g., MoHA & DPNet, 2009). An increasing trend of extreme rainfall patterns, influenced by weather and climate extremes, is the main source of concern for flood hazard in Nepal and South Asia (Mirza, 2011; Sheikh et al., 2015; Nepal & Shrestha, 2015). In addition, the potential risks of glacial lake outburst floods have significantly increased over the last few decades (e.g., Aryal, 2012; Bajracharya & Mool, 2009; Ives, Shrestha, & Mool, 2010; Mool, Bajracharya, & Joshi, 2001). The condition is further exacerbated by the geologically fragile Siwalik Mountains (i.e., the foothills of the Himalayas) and ongoing unsustainable development activities, mostly related to dam building and road network expansion. Moreover, the manifold impacts of the Climate Emergency and resulting hydroclimatic uncertainties may have further exacerbated this already-vulnerable situation (Devkota & Gyawali, 2015; Eriksson et al., 2009; Shrestha & Aryal, 2011).

In Nepal, hydrologically induced natural disasters, in particular floods and landslides, are considered to be the most devastating natural hazards, causing 7,341 loss of human lives between 1983 and 2007 and considerable economic damage (MoHA, 2010; MoHA & DPNet, 2009). In recent years, the severity of floods has significantly increased, which can be linked to burgeoning population growth and rapid development activities both in mountainous and lowland areas. For example, in August 2014, an unprecedented flood event hit the lower Karnali River basin, claiming 222 lives and affecting over 100,000 people who lost their homes, or suffered damage to their livelihoods and businesses (Zurich, 2015). An understanding of when and how changes in the river upstream cause floods in the downstream plains (the Terai) is therefore crucial (e.g., Gautam & Dulal, 2013; Vuichard & Zimmermann, 1986).

Globally, low- and middle-income countries tend to lack well maintained and sophisticated hydrometeorological monitoring networks (UNESCO-WWAP, 2003). Since the Himalayan region is known for its remote and largely unexplored terrain, there is a major hydrological data gap, which has become a bottleneck to improving local capacity against flooding. In Nepal, current flood forecasting and early-warning systems (EWS) rely on limited hydroclimatic data from sparse hydrometeorological stations that mostly operate at larger basin scale. Due to the relative inaccessibility and lack of sufficient resources, there is a sizeable deficiency of actionable data to establish efficient EWS at a local scale.

There is also limited institutional and investment capacity, both nationally and locally, to establish effective flood forecasting and EWS for minimising flood risks and building community resilience (e.g., MoHA & DPNet, 2009; Pradhan et al., 2007). Enhancing local flood resilience capacity through a pluralistic approach is therefore a necessity to protect human lives and to safeguard local livelihoods in such a highly diverse geographical and variable hydroclimatic and biophysical conditions (Dixit, 2003). Recent studies have also highlighted the need for community-based EWS, particularly in flood-prone areas (e.g., Dhakal, 2013; Gautam & Phaiju, 2013; Shukla & Mall, 2016; Smith, Brown, & Dugar, 2017).

The generation of locally relevant hydrological data is important for building an efficient flood risk resilience programme. Citizen science (CS), where non-scientists can be involved in the design and execution of a research project (Bonney et al., 2009; Buytaert et al., 2014), represents a potentially useful tool to enhance a flood risk reduction strategy, especially for remote and data-scarce areas (Pandeya et al., 2016; Paul et al., 2018; Walker, Forsythe, Parkin, & Gowing, 2016). The participation of local stakeholders in ecological and environmental resources management has a long history; scientific workers have noted the importance of incorporating indigenous knowledge in, for example, flood risk modelling and hazard maps (Miller-Rushing, Primack, & Bonney, 2012; Silvertown, 2009). At the same time, the rapid advancement of technology in recent decades has catalysed this trajectory; for example, apps and readily available smartphone sensors facilitating participatory monitoring programmes (Chong & Kumar, 2003; Hart & Martinez, 2006; Newman et al., 2012; Roy et al., 2012).

CS has arguably moved beyond participatory monitoring (“citizens as sensors”) towards the co-generation of new data and actionable knowledge for more integrated decision-making (Palacin-Silva et al., 2016). As such, CS approaches are increasingly widely recognised and accepted by government bodies and decision-makers in environmental monitoring (e.g., Guerrini, Majumder, Lewellyn, & McGuire, 2018; Haklay, 2015; McKinley et al., 2015). Now, with the growing acceptance of the veracity of CS-based data in water resources management, it could be fruitful to develop collaborative activities and standardised monitoring protocols (Carlson & Cohen, 2018).

The participation of local communities in hydrological data and knowledge co-generation can support water resources management at a local scale (Buytaert et al., 2014; Carr, 2015; Paul et al., 2018); however, evidence for the applicability and uptake of this approach to build flood resilience is still limited. Intensive

hydrological training is often an unavoidable prerequisite to be able to decode complex data like time series of discharge (Hersch, 2009), which may limit the scope of CS-related projects in hydrology (Carr, 2015). However, new technological developments can (to an extent) surmount these limitations (Cohn, 2008; Paul et al., 2018). Indeed, low-cost sensors can be an important part of flood risk reduction strategy. Recent advances in communication technologies such as wireless networks will eventually cascade down to the local level, becoming an important pillar of hydrological monitoring networks, especially in data-poor regions (e.g., Buytaert et al., 2014; Horita, Porto de Albuquerque, Degrossi, Mendiando, & Ueyama, 2015).

Although locally generated data and knowledge have the potential to contribute towards regional and national flood risk reduction strategies, the lack of a robust hydrometric network still represents the main challenge in establishing a community-based flood EWS. There are also practical challenges revolving around operational running, accessibility, and climate hostility; and obtaining necessary permissions may be essential to establish new sensor stations in highly remote locations.

This paper discusses a proof-of-concept study using low-cost river level sensors in western Nepal. We interrogate the ways in which such technology can be harnessed with a CS approach to yield enhanced local resilience to flood risk. Although we present initial trial results and only focus on two study sites in western Nepal, we describe the potential of our system to complement official government data, especially in other data-scarce regions of Southeast Asia. The remainder of the text is structured as follows: Section 2 describes details about the location and local stakeholder at each study site, and the CS framework developed for this study. We also describe the operation and installation of the lidar (laser)-based low-cost sensors, as well as the design of our CS activities. Local communities participated in all sets of research activities, including sensor installation, data cogeneration and discussion. Section 3 presents the results and discussion of our monitoring campaign at two locations on the lower Karnali River, and places them within the broader context of improving local flood resilience. Finally, Section 4 provides conclusions and a brief statement of future work.

2 | METHODOLOGY

We have used an integrated CS methodology in which low-cost sensors and CS-based participatory methods have been systematically applied. At first, a suitable research site was chosen in the lower Karnali River Basin

to test this proof-of-concept. We developed a theoretical framework interlinking our CS approach to building local flood risk resilience. Subsequently, with local stakeholder and stakeholder institutions' participation, we tested our low-cost sensors at local riverbank sites. Similarly, a number of local engagement activities such as group discussions, sensor demonstrations and stakeholder meetings were organised throughout the project period. Since this study is mainly a proof-of-concept, at this stage, our pilot project is limited to (a) community environmental and scientific training; (b) developing low-cost sensors and testing them as a complementary data source; and (c) densification of Department of Hydrology and Meteorology (DHM)'s national hydrometric network and contributing to their existing flood EWS.

2.1 | Study site

The Karnali River Basin is located in the southwestern region of Nepal, which is relatively remote and data-scarce from a hydrometric point of view; the basin is highly prone to flooding disasters (Zurich, 2015). The river originates in the high mountainous region of the Himalayas and incorporates numerous smaller rivers and streams when it enters the middle and lower mountainous region (the Siwalik Hills). A progressively shorter and more intense Monsoon has increased the unpredictability of the hydrological regime, which results in a "difficult hydrological environment," which has a negative impact on local people, their livelihoods and businesses (Grey & Sadoff, 2007). In the Himalayas, both temperature and precipitation are projected to increase in the future; increases in runoff and river flow could become even more unpredictable than at present (Bajracharya, Bajracharya, Shrestha, & Maharjan, 2018; Immerzeel, van Beek, Konz, Shrestha, & Bierkens, 2012).

We chose two sites located on the lower Karnali River basin of Nepal (Figure 1a), which is one of the most densely populated and yet highly vulnerable regions in the country (e.g., Gautam & Dulal, 2013). Once the river reaches the floodplain area of Chisapani, it bifurcates into two major channels for ~50 km before converging into one channel again downstream. Both river channels are much wider and deeper (up to 15 m) and, as a result, the river velocity decreases. Data scarcity is a major issue for the area, with only one hydrological station, operated by the Nepali government DHM, located at Chisapani (Figure 1b), representing the vast downstream region. This station measures changes the river water level at 15-min intervals using a radar-based water level sensor. Although it feeds data to a community-based flood EWS, it may not predict every potential flood risk to the

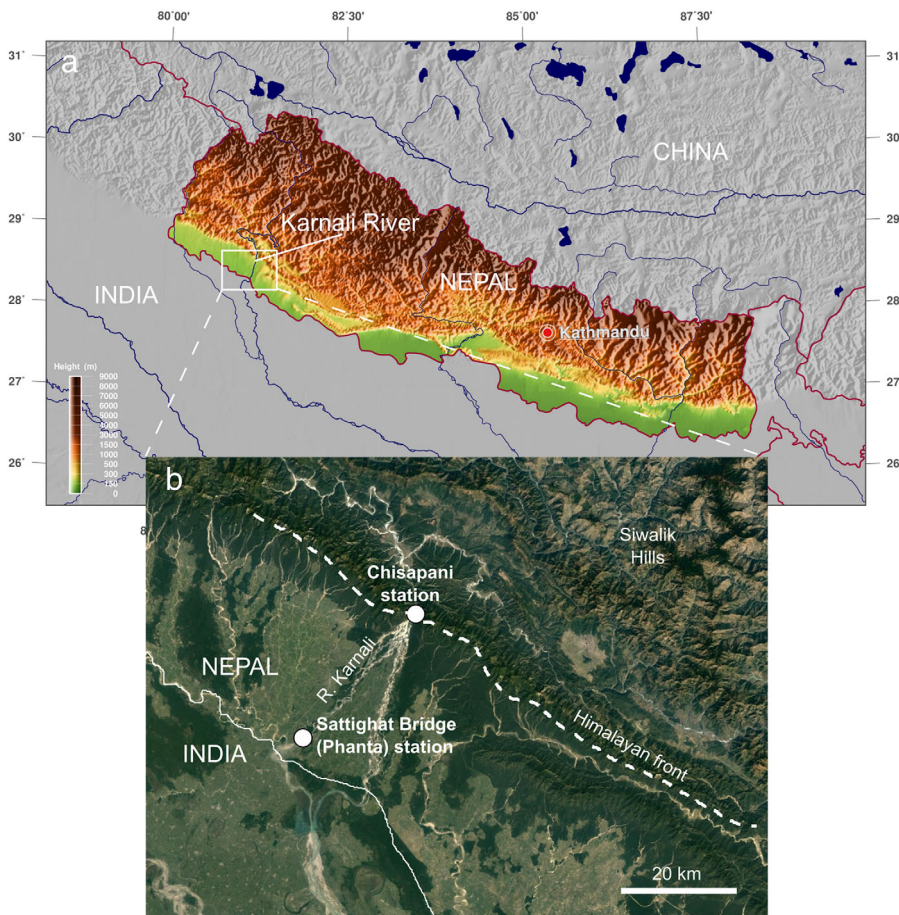


FIGURE 1 (a) SRTM DEM showing position of Karnali River in western Nepal. (b) Google Earth locations of two lidar stations: Chisapani (upstream) and Phanta (downstream) (Google Earth Map, 2018)

downstream plains, mainly due to the larger catchment area and frequently changing river channel in the downstream basin. There is also a manual staff gauge station alongside the radar station serving as a back-up measure should the system fail. A local gauge reader records the river water level three times a day and alerts local communities and relevant authorities (verbally) about any potential flooding.

The current EWS was set up in 2010; since then, DHM and the NGO Practical Action Nepal have worked together to operate the system alongside community disaster management committees (CDMCs) and District Emergency Operations Centre (DEOC) member organisations. The real-time data of the River Karnali level generated by the radar sensors automatically display on an LED display board at the district administration office. When the river water level crosses a certain “danger” threshold, the local gauge reader speaks to the District Disaster Relief Committee (DDRC), who then warn CDMCs about possible flood risks. Practical Action Nepal has been providing training and capacity building activities to CDMCs to understand the flood risks and build their resilience capacity for any such eventuality. Since 2017, DHM has started mobile messaging for smartphone

holders in vulnerable communities. Despite increasing efforts from national and local stakeholders, this community-based flood EWS relies on a sole hydrological station at Chisapani. If there were to be any technical failure within the monitoring system or any external damage occurred to the station, the existing EWS could become dysfunctional. This could represent a very serious problem during the monsoon season.

Cost precludes the installation of additional river level monitoring stations. The region’s few flood EWS rely on limited data availability from sparsely collected hydrological stations. To ameliorate this situation, we designed a low-cost lidar-based river level monitoring system (Paul et al., 2020), which has the potential to generate locally relevant hydrological data to support a flood risk reduction programme such as the current flood EWS in the Karnali Basin. We address two questions here: (a) can such a system reproduce existing government (DHM) radar data in time and space? And (b) can the system operate, and generate actionable data, within a CS framework? Our choice of locations for sensor deployment was motivated by accessibility and proximity to communities to the River Karnali. At ~40 km along the channel (Figure 1), we deployed lidar sensors at:

- Chisapani (upstream: Figure 1b). This town (population: around 1,000) hosts the aforementioned DHM-operated radar water level sensor.
- Sattighat Bridge (downstream: Figure 1b). This road bridge crosses the western distributary of the River Karnali (here, a small island is formed by the Karnali splitting into two channels just downstream of Chisapani, which subsequently rejoin ~50 km downstream). The small village of Phanta is situated at the point where the bridge reaches the west bank of the River Karnali.

The selected basin communities and key local stakeholders actively participated in all stages of the monitoring activities, including site selection, sensor installation, data collection and interpretation. We believe that such total engagement across the entirety of the project lifecycle have created a clear and positive impact in terms of generating actionable data and knowledge, improving risk reduction strategy, and building greater environmental awareness and community flood resilience.

2.2 | A theoretical framework for CS and flood risk resilience

CS is a valuable means of producing large and longitudinal datasets, often complementary to more localised data (e.g., Dickenson, Zukerberg, & Bonter, 2010; Paul et al., 2018). In disaster risk reduction, the role of civil society is immense, although relevant government agencies usually have overall responsibility to enact disaster risk reduction strategies (UNISDR, 2015). In this process, CS plays an important complementary role, particularly in data collection and the provision of new perspectives into flood risk assessment (Sy, Frischknecht, Dao, Consuegra, & Giuliani, 2018). CS-based data cogeneration can be broadly divided into two types of approach: “user-centric,” where users collect data and information on the spot; and “device-centric,” where sensor sampling occurs whenever the state of the monitoring device matches the specific monitoring requirements (Palacin-Silva et al., 2016). The latter approach is particularly useful for data-intensive environmental monitoring such as hydrological monitoring for flood EWS.

In recent years, participatory monitoring activities have become more viable because of the rapid advancement of Information and Communication Technologies (ICTs) and their uses in scientific research. Moreover, the availability of affordable technologies (including ICT applications) has also created a new avenue of opportunities in ecology and environmental monitoring (Dickinson et al., 2012). Despite growing interest in CS activities, the

concept is still not widely accepted within scientific and decision-making communities, mainly due to inconsistency in methodologies, lack of a well-defined data quality control mechanism, and ethical issues around CS practices (Bonney et al., 2014; Riesch & Potter, 2014). There are also manifold challenges in relation to institutionalisation and integration of such initiatives in conventional data generation practices (i.e., data and information uptake: Paul et al., 2018).

We have developed a CS framework for this study (Figure 2) and tested it during the project. The framework combines four key components: (a) a situation analysis of flood risks, (b) assessing any existing flood risk management activities, (c) adopting a CS approach and (d) improving participatory decision making. In the framework, CS plays a fundamental role in data cogeneration, implementing low-cost sensors and building flood risk-resilient communities. To implement this framework, we started with a situation analysis to define major flood risks to vulnerable communities, their livelihoods and economic activities in the downstream. This process requires a detailed understanding of flood trends and the way in which hydro-climatic variability influences flood risk dynamics. Thereafter, it is important to understand existing flood risk management activities including any local adaptive measures taken to deal with potential flood risks. Participatory discussions have helped us to identify which additional data and information could be helpful to local people (Section 2.4). We recruited key stakeholders from three local communities to discuss our planned CS approach. Our systematic analysis also allowed us to identify affordable and robust technology that could catalyse a CS approach to build community flood risk resilience in the long term (Section 2.3). As part of our CS activities, we also held sensor demonstrations, data collection and interpretation and local capacity building activities. Indeed, CS projects elsewhere have been shown to work best when there is demonstrated local buy-in (e.g., Buytaert et al., 2014). Sensor demonstration events at site and community levels were also essential for building local capacity to better understand sensors, data generation and interpretation. Finally, the framework also shows how the CS data and knowledge can lead to more participatory decision making at local scale.

2.3 | Low-cost water level sensors

The lack of a conventional hydrometeorological monitoring system constitutes a major challenge for data generation and the establishment of any flood risk regulation programmes such as EWS. This situation is exacerbated

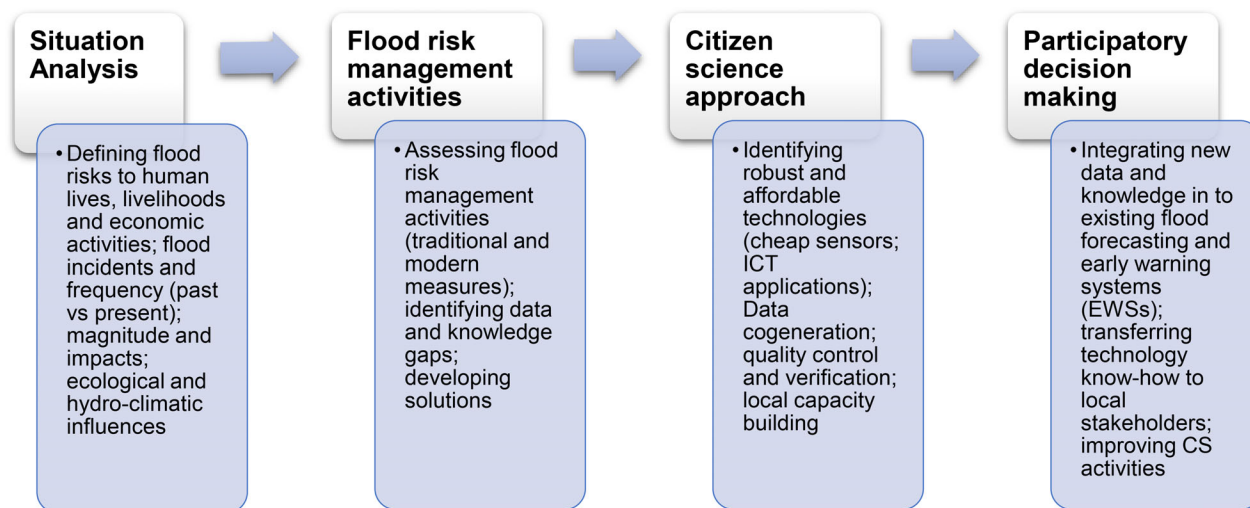


FIGURE 2 A citizen science framework for building flood risk resilience at a local scale

by a lack of investment at both institutional and infra-structural levels. In this way, affordable hydrological sensors could represent a complementary tool to generate locally relevant data and to support existing community flood risk resilience programmes.

The advent of affordable monitoring technologies has created an immense potential in the wider sector of environmental monitoring (Newman et al., 2012). The identification of apposite technologies for a given purpose is fundamental for a successful participatory monitoring programme. Affordable and non-complex, easy-to-use sensors could make for a good choice for basin communities, as they could easily learn about their operation and fundamental object. Indeed, there exists a need for local volunteers and participating stakeholders to understand key issues such as data gathering, quality control and sharing protocols (Geoghegan, Dyke, Pateman, West, & Everett, 2016). One common expectation is that data collected by affordable sensors will be sufficiently robust for integration within existing, more traditional data collection practices (e.g., DHM's radar water level monitoring network).

Although water level has been measured non-invasively (i.e., no water contact) for some time using ultrasonic or radar sensors (Neal, Atkinson, & Hutton, 2012), the use of visible or near-infrared (NIR) light to gauge distances has been restricted to the construction of digital elevation maps (mid-NIR: e.g., Özcan & Ünsalan, 2017), or measurements of bathymetry (green-blue visible light: Allouis, Bailly, & Feurer, 2007), using airborne or satellite-mounted sensors. We developed a lidar system, which has been successfully tested in the laboratory and under field conditions. It has a maximum range of 30–40 m and



FIGURE 3 (a) Chisapani (upstream) station location, facing north. Note deeply incised river valley. (b) Phanta (downstream) station, looking upstream. Here, the lidar system was clamped to the underside of Sattighat road bridge. See Figure 1 for locations. (c) and (d) Details of lidar sensor and installation on pole at Chisapani. Photographs taken November 2017

resolution of ± 2 cm (Paul et al., 2020). The sensor takes readings every minute, as a compromise between temporal resolution and power consumption. At Chisapani, we mounted the sensor next to the DHM radar (Figure 3a), in order to validate our data. Downstream, we clamped

the sensor to the underside of Sattighat Bridge, in a relatively inconspicuous location (Figure 3b).

We also tested ultrasonic sensors: the instrument failed to record river level data, as their maximum range was more limited (i.e., ~5–7 m). We then turned to constructing lidar devices, each one costing roughly USD 250–300, or one-tenth the cost of the nearby radar station. As well as being low cost, they are simple to install and operate (featuring a reset button and an SD card to store data, which can simply be taken out and read on a computer). Indeed, each installation was carried out by members of the local community, in under 30 min, involving cheap and readily available materials like concrete and makeshift steel clamps.

2.4 | Local engagement

The effective engagement between professional scientists and local stakeholders is fundamental for the success of CS-based monitoring activities (Riesch, Potter, & Davies, 2013). After an initial consultation with key local stakeholders including local community members, three vulnerable communities (viz. Chisapani, Karmi Danda and Phanta) were chosen for targeted CS activities such as participatory discussion, sensor demonstration, data collection and interpretation and collaborative decision-making. Key local informants were recruited from those communities and represented local elders, youths, an equal proportion of women, poor and disadvantaged people. Similarly, relevant institutions such as Practical

Action Consulting, DHM, key local government authorities and NGOs were also invited to discuss the potential of the CS approach working in tandem with low-cost, community-operated sensors. A series of participatory discussions was held in those three local communities. As most stakeholder institutions are based in the Tikapur and Guleriya municipalities on both sides of the river channel, we organised several stakeholder meetings in order to understand local perspectives and indigenous knowledge of existing flood risks and potential solutions. Since most local stakeholder institutions are based in both these locations, we also initiated data sharing and capacity building activities, in which the local stakeholders were trained to operate and download data from the sensors.

Basin communities and key local institutions actively participated across all stages of the project, including the choice of locations, sensor installation, data co-generation and participatory discussion (Figure 4a,c). Active and enthusiastic local stakeholders and NGOs participated in sensor demonstration and data interpretation at the site level (Figure 4a,b). Similarly, a wider range of local people including local elders, women, and children were invited to, and attended, community events to raise awareness and the implement CS activities effectively (Figure 4c). As better education and awareness at the community level have a positive impact on reducing flood vulnerability (KC, 2013), we explored how our approach to CS and low-cost technologies could improve disaster risk resilience at the community level.



FIGURE 4 Community engagement. Demonstration of LiDAR sensor operation over (a) Sattighat Bridge, near Phanta village; (b) a water butt with community disaster management committee (CDMC) at Karmi-Danda, Tikapur. (c) Community discussion at Phanta. (d) A stakeholder workshop at Gularia, Bardia: explaining the relevance of river level information to representatives from District Emergency Operations Centre (DEOC), district level government offices, municipalities, Red Cross, military, police and NGOs

We also convened policy dialogues among end-users, primarily DHM and the local NGO Practical Action Nepal, as well as basin-level stakeholders such as District Administration, DEOC members, sector-specific government entities, community leaders from project sites, and local government authorities (Figure 4d), to discuss the opportunities and challenges arising from this innovative approach. Since these local stakeholders have worked in current flood risk reduction/management activities in the basin, their involvement in such dialogues is crucial to the successful integration of any CS approach in the medium to long term. Local engagements were focused on the effective implementation of CS activities at various local levels. This took the form of:

- A series of structured dialogues (Figure 4) for which information had been disseminated in advance in the local language. Such sessions, whose format varied from classroom-style lectures and question-and-answer sessions to one-on-one discussion and active, participatory demonstrations, (a) lowered the risk of damage or theft of locally installed equipment; and (b) improved general environmental awareness such as typical frequencies and magnitudes of monsoon-related flooding (Cohn, 2008; Paul et al., 2018; Smith et al., 2017). During our preliminary discussion with local experts and NGOs, secondary schools were suggested as a useful entry point for a larger intervention, as teachers tend to be among the most educated locally, and children are likely to report on the research enthusiastically to parents and elders (Riesch & Potter, 2014).
- Identification of “local leaders” or “community champions,” amenable to the project aims, and helping to foster its long-term sustainability (Section 3; Walker et al., 2016).
- Sharing the lidar sensor data with DHM and discussing on the potential integration of these local data into their existing basin-scale flood EWS.
- Initiating a collaboration with a local start-up company to design a more sustainable monitoring system. Interactions with them have been focused on the sustainability of the monitoring plan.

To safeguard the long-term sustainability of our activities, we noted the importance of innovation and knowledge transfer between scientists and local stakeholders throughout the entirety of this pilot project (Hecker et al., 2018). Local engagement activities generated enthusiasm among local communities and key stakeholders about the operation and maintenance of our low-cost sensors. However, the challenge beyond this proof-of-concept study is to make such locally generated river level data actionable, that is, to identify ways in which

they could directly build local capacity and resilience to flooding.

3 | RESULTS AND DISCUSSION

With the active participation of stakeholder institutions and local communities, we installed the sensors at the beginning of the 2017 monsoon season—in early June—and measured local river levels then, such that we would obtain a time series for the entire monsoon season and would be able to convert these data into absolute water level, respectively. For the two upstream and downstream locations, these time series are presented in Figure 5. There is a clear agreement ($R^2 = .975$) with the independent radar measurements of river level at Chisapani, in both time and magnitude, implying that our low-cost lidar system is sufficiently robust in this instance. The highest peak in river level, for instance, is measured as:

- 8.80 m at 2230, 03/08/17 (DHM radar data);
- 8.84 m at 2221, 03/08/17 (lidar data).

Figure 5 shows that the temporal and spatial pattern of river level peaks and troughs is replicated between the two stations, albeit with a lag time. This correlation could allow for the calculation of flood wave speed: the along-channel distance between the two sensor stations is ~ 40 km (Figure 1), and the lag time for the highest peak mentioned earlier between the two stations is ~ 28 hr (Figure 5), giving an approximate flood wave celerity of 0.4 ms^{-1} . This value lies within the typical range of $0.2\text{--}1.0 \text{ ms}^{-1}$ given by Gautam and Dulal (2013) for rivers emerging from the Lower Himalaya onto the Gangetic Plain. The absolute river level variation downstream is much smaller than that upstream, while the variation through the monsoon season is less pronounced; this finding can be explained by the channel geometry that is

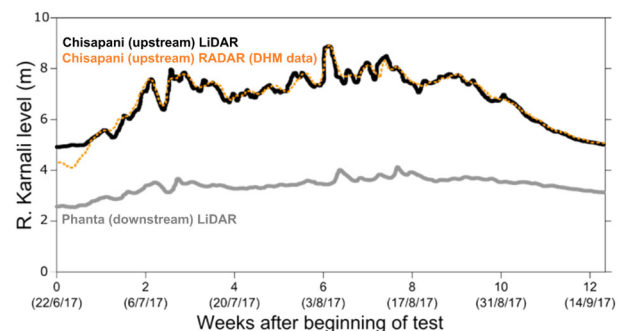


FIGURE 5 River Karnali water level, monsoon season 2017. Data were converted from distance to water level using mean depth values of the River Karnali, taken in June 2017

much shallower and wider downstream (Figure 2b), carrying a smaller volume of water (since, at this point, the River Karnali has split into two channels: Figure 1b).

Since the collected data can be directly used in DHM's operational flood EWS in the basin, an opportunity has been created to integrate both affordable technology and CS into existing hydrological monitoring practice. However, challenges remain in terms of the integration and sustainability of the entire practice. One of the main issues concerns the exact way in which river level data can be integrated. The development of user-friendly technologies has made a significant impact in hydrological monitoring; although emerging technologies and web-based interactive platforms could become a perfect match for streamlining data collection, quality control and communication, local capacities to take charge of those critical aspects of participatory data co-generation are rather limited (e.g., Newman et al., 2012).

3.1 | Data collection

Our main aim here was to understand, as part of a proof-of-concept study, how our low-cost sensors could form part of community-based data co-generation, thus improving data for flood EWS at a local level. It was suggested that the river level data be fed into real-time data displays at community centres; this could be a feasible extension to this proof-of-concept study. Our lidar water level sensor was able to replicate the DHM river level data, and at greater temporal resolution: this technique could therefore be scaled up to other areas across Nepal that lack official hydrological instrumentation. Integrating this new approach with local decision making could contribute to the better management of water resources, helping to adapt agricultural practices to changing water availability in the long term.

3.2 | Awareness and capacity building

Local engagement activities have had a useful impact on data collection, interpretation and a possible integration of lidar sensors in DHM's existing hydrological monitoring system. The main outputs of round-table discussions were:

- DHM shared their current practices on disaster risk reduction in different river basins in the country. For example, after implementing a community flood resilience programme in the West Rapti basin, the flood risk to basin communities was significantly reduced. Similarly, the Babai Basin (western Nepal) EWS is also

a successful example where it helped to build resilient basin communities.

- Graphical explanations of sensor operation (e.g., using a water butt to simulate the River Karnali: Figure 4b) were a useful tool when engaging local stakeholders, such as farmers and village leaders/politicians, as they reported that the link between action (i.e., changing water levels) and the data (on the graphical display) were easier to understand.
- Key local stakeholders, particularly DHM and Practical Action Nepal, asked about the robustness of our sensor equipment, data collection strategy, storage and its potential use in ongoing flood forecasting and community-based EWS.
- DHM stated that while they oversee national-level hydrometeorological monitoring, they currently lack capacity to carry out such CS-based monitoring at a community scale. DHM could, however, play a leading role in providing technical support to local authorities on how to conduct and operate hydro-meteorological monitoring activities in the future.
- DHM and local civil society organisations (CSOs) expressed views that local authorities (e.g., police and community groups) could take forward monitoring activities in the medium term (2–5 years), since Nepal has recently entered into a new federal system in which local governments have increasing resources as well as a sense of responsibility to take control of such monitoring practices and protect flood risk areas. DHM and Red Cross suggested that, after a period of successful data retrieval (e.g., 1 year), local stakeholders should formally own the lidar sensors and continue to monitor river water level semi-autonomously.

Such local engagements have been useful to raise awareness of low-cost sensors and participatory data and knowledge cogeneration activities directly beneficial to local flood risk resilience. Similarly, the CS activities have successfully transferred technical knowledge to Practical Action Nepal (a major local and national NGO) and have produced useful complementary discussions with both Practical Action Nepal and DHM on how to integrate low-cost sensors into their current monitoring system.

3.3 | Future potential of data cogeneration

Our community-led approach (i.e., local stakeholders install and maintain the equipment, and take measurements) has the potential to devolve water resource management decision making to lower (community) levels; such a polycentric model for water governance has been

shown to be more effective in remote and data-scarce areas than the currently prevailing top-down, mono-centric approach (Buytaert, Dewulf, De Bièvre, Clark, & Hannah, 2016; Paul et al., 2018). Beyond this study, we note the tremendous opportunity for affordable technologies to augment community flood risk resilience in the long term. Embedding such technologies in conventional hydrological monitoring practice requires a strong CS approach. In our Karnali basin project, various local engagement activities such as community discussions, stakeholder meetings and participatory monitoring and analysis have successfully raised local enthusiasm and interest in flood mitigation measures. Similarly, the eventual transferral of sensor ownership to the local government (under the technical guidance of DHM) would help to ensure the sustainable use of technology in the longer term. We suggest that future capacity building should focus not only on the generation of new data, but also on their efficient use in the existing basin scale flood EWS and ongoing risk reduction and resilience programme in the region; we are currently working closely with DHM to ensure data uptake and information dissemination to the vulnerable communities.

We identified several well-connected and educated individuals (mostly village leaders and local politicians) to help ensure the long-term sustainability of the project (a “community champion”: Walker et al., 2016). Then, continued data co-generation would have real potential to complement existing hydrological data and knowledge, especially in relation to the characterisation of process heterogeneity in other remote regions, as well as human impacts of the water cycle. For long-term viability, financial support is another major issue that should be clearly addressed; in other words, how and who will provide the costs of monitoring practices. Since local motivation for participation can be affected by personal interests and other external factors (Rotman et al., 2012), the initial collaboration could become less formal during (and by the end of) the project; and local volunteers may question whether to continue their involvement (Rotman et al., 2014). As a result, the monitoring practice could be compromised, which in turn could have direct consequences on data quality control. We have attempted to obviate these problems through the intensive sensor consultations described earlier, the designation of one or more “community champions” at each locality, and the limited provision of equipment like small stocks of replacement batteries. Further the recent federalization in Nepal opens up opportunities for us to collaborate with municipal authorities to leverage resources and capacities to sustain this local system.

The successful use of low-cost river level monitoring sensors could provide both robust and user-friendly

hydrological instruments for local stakeholders to generate data and knowledge that is directly applicable to community flood resilience programmes. The continuing collaboration between local communities, municipal authorities and DHM is crucial and could help to augment community resilience building efforts against Monsoon-related flooding. The successful integration of affordable technology is in the interests of all participating stakeholders, while an innovative and non-scientist-centric approach that can harness or catalyse this new technology should be placed at the heart of local flood risk reduction strategy.

4 | CONCLUSIONS

We conclude that integrating locally operated low-cost hydrological sensors into a CS approach holds real potential both for collecting robust hydrological data (especially in data-scarce areas), and for improving local, community-level flood risk resilience and capacity. The generation of actionable data and knowledge is crucial to many vulnerable river basins in Nepal, where flood risk management is closely linked to saving human lives and safeguarding local livelihoods. A lack of redundancy in DHM's conventional hydrometeorological monitoring system is a major constraint to predicting floods downstream, when existing sensors fail to transmit real-time data to flood forecasts and EWS. Since the lack of locally applicable data and knowledge has seriously hindered flood risk warnings to date in many parts of Nepal, the integration of CS and low-cost sensors could be highly valuable for flood risk reduction programmes.

We have described a pilot deployment of low-cost river level sensors, which have the potential to complement existing hydrological networks, while simultaneously involving local communities (whom these data are designed to protect) more closely. We recorded the variation in the level of the River Karnali across an entire monsoon season; our data match official Nepal government records. Successful sensor installation and project development have hinged upon the close collaboration between local partners, authorities, and communities, as well as the provision of local training on sensor use and data interpretation. If such projects proceed sustainably (i.e., with a clear plan of future operations at the local level), the new technology leveraged and partnerships created could represent a major step forward in predicting and adapting to floods in the Lower Karnali Basin and other vulnerable regions across Nepal. The major remaining challenge concerns the way in which these data can be made directly actionable to the local community, beyond the provision of LED boards

showing river level data in real time, or dissemination of the results through DHM's operational flood EWS in the Karnali Basin.

Although we believe that the successful integration of CS practices can provide both robust and user-friendly hydrological instruments for local stakeholders to generate locally relevant data, developing a locally tailored CS practice is a challenge for remote and data-scarce areas. If we can address these issues appropriately, the practice could improve local communities' adaptive capabilities to cope with increasing flood risk and potential damage. We conclude that facilitating CS-based hydrological monitoring could be an effective strategy to improve a country's flood risk management activities in the long term.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

- Aryal, K. R. (2012). The history of disaster incidents and impacts in Nepal 1900–2005. *International Journal of Disaster Risk Science*, 3(3), 147–154.
- Allouis, T., Bailly, J.-S., & Feurer, D. (2007). Assessing water surface effects on LiDAR bathymetry measurements in very shallow rivers: A theoretical study. Second ESA Space for Hydrology Workshop, Geneva, Switzerland.
- Bajracharya, S., & Mool, P. (2009). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region of Nepal. *Annals of Glaciology*, 50(53), 81–86.
- Bajracharya, A. R., Bajracharya, S. R., Shrestha, A. B., & Maharjan, S. B. (2018). Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Science of the Total Environment*, 625(1), 837–848.
- Bonney, R., Cooper, C. B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., & Shirk, J. (2009). Citizen science: A developing tool for expanding science knowledge and scientific literacy. *Bioscience*, 59(11), 977–984.
- Bonney, R., Shirk, J. L., Phillips, T. B., Wiggins, A., Ballard, H. L., Miller-Rushing, A. J., & Parrish, J. K. (2014). Next steps for citizen science. *Science*, 343(6178), 1436–1437.
- Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., ... Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, 2, 26.
- Buytaert, W., Dewulf, A., De Bièvre, B., Clark, J., & Hannah, D. M. (2016). Citizen science for water resources management: Towards polycentric monitoring and governance? *Journal of Water Resource Planning and Management*, 142(2), 01816002.
- Carlson, T., & Cohen, A. (2018). Linking community-based monitoring to water policy: Perceptions of citizen scientists. *Journal of Environmental Management*, 219, 168–177. <https://doi.org/10.1016/j.jenvman.2018.04.077>
- Carr, G. (2015). Stakeholder and public participation in river basin management: An introduction. *WIREs Water*, 2(4), 393–405.
- Chong, C.-Y., & Kumar, S. P. (2003). Sensor networks: Evolution, opportunities, and challenges. *Proceedings of the IEEE*, 91(8), 1247–1256.
- Cohn, J. P. (2008). Citizen science: Can volunteers do real research? *Bioscience*, 58, 192–197.
- Devkota, L.P., & Gyawali, D.R. (2015). Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. *Journal of Hydrology: Regional Studies*, 4, 502–515.
- Dhakal, S. (2013). Flood hazard in Nepal and new approach of risk reduction. *International Journal of Landslide and Environment*, 1(1), 13–14.
- Dickenson, J. L., Zukerberg, B., & Bonter, D. N. (2010). Citizen science as an ecological research tool: Challenges and benefits. *Annual Review of Ecology, Evolution and Systematics*, 41, 149–172.
- Dickinson, J. L., Shirk, J., Bonter, D., Bonney, R., Crain, R. L., Martin, J., ... Purcell, K. (2012). The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment*, 10(6), 291–297.
- Dixit, A. (2003). Floods and vulnerability: Need to rethink flood management. *Natural Hazards*, 28, 155–179. <https://doi.org/10.1023/a:1021134218121>
- Eriksson, M., Xu, J., Shrestha, A. B., Vaidya, R. A., Nepal, S., & Sandstrom, K. (2009). *The changing Himalayas: The impact of climate change on water resources and livelihoods in the greater Himalayas*. Lalitpur, Nepal: International Centre for Integrated Mountain Development.
- Gautam, D. K., & Dulal, K. (2013). Determination of threshold runoff for flood early warning in Nepalese rivers. *Journal of Integrated Disaster Management*, 3(1), 126–136.
- Gautam, D. K., & Phaiju, A. G. (2013). Community based approach to flood early warning in west Rapti River Basin of Nepal. *Journal of Integrated Disaster Risk Management*, 3, 155–169.
- Geoghegan, H., Dyke, A., Pateman, R., West, S., & Everett, G. (2016). Understanding motivations for citizen science. Final

- report on behalf of UKEOF, University of Reading, Stockholm Environment Institute (University of York) and University of the West of England.
- Google Earth Map. (2018) Location of the lower Karnali Basin in Nepal, 28°31'23.70"N and 81°19'35.09"E elev214m [Feb 2017].
- Grey, D., & Sadoff, C. W. (2007). Sink or swim? Water security for growth and development. *Water Policy*, 9(6), 545–571.
- Guenni, L. B., Cardoso, M., Goldammer, J., Hurtt, G., Mata, L. J., Ebi, K., ... Norgaa, R. (2005). Regulation of natural hazards: Floods and fires. In *Millennium ecosystem assessment. Ecosystems and human well-being: Current states and trends* (pp. 441–454). Washington, DC: Island Press.
- Guerrini, C. J., Majumder, M. A., Lewellyn, M. J., & McGuire, A. L. (2018). Citizen science, public policy. *Science*, 361(6398), 134–136. <https://doi.org/10.1126/science.aar8379>
- Hart, J., & Martinez, K. (2006). Environmental sensor networks: A resolution in the earth system science? *Earth-Science Reviews*, 78(3–4), 177–191.
- Haklay, M. (2015). *Citizen science and policy: A European perspective*. Washington, DC: Woodrow Wilson International Center for Scholars.
- Hecker, S., Haklay, M., Bowser, A., Makuch, Z., Vogel, J., & Bonn, A. (2018). *Citizen science: Innovation in open science, society and policy*. London, England: UCL Press. <https://doi.org/10.14324/111.9781787352339>
- Hersch, R. (2009). *Streamflow measurements* (3rd ed.). London, England: Taylor & Francis.
- Horita, F. E. A., Porto de Albuquerque, J., Degrossi, L. C., Mendiolo, E. M., & Ueyama, J. (2015). Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks. *Computers & Geosciences*, 80, 84–94.
- Immerzeel, W. W., van Beek, L. P. H., Konz, M., Shrestha, A. B., & Bierkens, M. F. P. (2012). Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climate Change*, 110((3–4)), 721–736.
- Ives, J. D., Shrestha, R. B., & Mool, P. K. (2010). *Formation of glacial lakes in the Hindu Kush–Himalayas and GLOF Risk Assessment*. Kathmandu, Nepal: ICIMOD.
- KC, S. (2013). Community vulnerability to floods and landslides in Nepal. *Ecology and Society*, 18(1), 8. <https://doi.org/10.5751/ES-05095-180108>
- McKinley, D. C., Miller-Rushing, A. J., Ballard, H. L., Bonney, R. E., Brown, H., Evans, D. A., ... Soukup, M. A. (2015). Investing in citizen science can improve natural resource management and environmental protection. *Issues in Ecology*, 19, 1–27.
- Miller-Rushing, A., Primack, R., & Bonney, R. (2012). The history of public participation in ecological research. *Frontiers in Ecology and the Environment*, 10(6), 285–290.
- Mirza, M. M. Q. (2011). Climate change, flooding in South Asia and implications. *Regional Environmental Change*, 11, 95–107.
- Ministry of Home Affairs. (2018). Nepal Disaster Report, 2017: The Road to Sendai, Government of Nepal, Kathmandu, Nepal.
- Ministry of Home Affairs Economic Survey. (2010). Government of Nepal, Ministry of Home Affairs (MoHA), Kathmandu, Nepal.
- MoHA and DPNet. (2009). Nepal Disaster Report: The Hazardscape and Vulnerability, MoHA (Ministry of Home Affairs), Kathmandu, Nepal.
- Mool, P. K., Bajracharya, S. R., & Joshi, S. P. (2001). *Inventory of glaciers, glacial lakes and glacial lake outburst floods, Nepal*. Kathmandu, Nepal: International Centre for Integrated Mountain Development.
- Neal, J. C., Atkinson, P. M., & Hutton, C. W. (2012). Adaptive space-time sampling with wireless sensor nodes for flood forecasting. *Journal of Hydrology*, 414–415, 136–147.
- Nepal, S., & Shrestha, A. B. (2015). Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basin: A review of the literature. *International Journal of Water Resources Development*, 31(2), 201–208. <https://doi.org/10.1080/07900627.2015.1030494>
- Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., & Crowston, K. (2012). The future of citizen science: Emerging technologies and shifting paradigms. *Frontiers in Ecology and the Environment*, 10(6), 298–304.
- Özcan, A. H., & Ünsalan, C. (2017). LiDAR data filtering and DTM generation using empirical mode decomposition. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 10(1), 360–371.
- Palacin-Silva, M., Seffah, A., Heikkinen, K., Porras, J., Pyhalahti, T., Sucksdorff, Y., ... Junntila, S. (2016). *State-of-the art study in citizen observatories: Technological trends, development challenges and research avenues*. Reports of the Finnish Environment Institute 28/2016, Finnish Environment Institute (SYKE). Retrieved from https://helda.helsinki.fi/bitstream/handle/10138/164810/SYKEre_28_2016.pdf?sequence=2&isAllowed=y.
- Pandeya, B., Buytaert, W., Zulkafli, Z., Karpouzoglou, T., Mao, F., & Hannah, D. M. (2016). A comparative analysis of ecosystem services valuation approaches for application at the local scale and in data scarce regions. *Ecosystem Services*, 22, 250–259.
- Paul, J. D., Buytaert, W., Allen, S., Ballesteros-Canovas, J. A., Bhusal, J., Cieslik, K., ... Supper, R. (2018). Citizen science for hydrological risk reduction and resilience building. *WIREs Water*, 5, e1262. <https://doi.org/10.1002/wat2.1262>
- Paul, J. D., Buytaert, W., & Sah, N. (2020). (in press). A Technical Evaluation of Lidar-Based Measurement of River Water Levels. *Water Resources Research*, 56, <https://doi.org/10.1029/2019WR026810>.
- Pradhan, E. K., West, K., Katz, J., Leclercq, S. C., Khattry, S., & Shrestha, S. R. (2007). Risk of flood-related mortality in Nepal. *Disasters*, 31, 57–70.
- Riesch, H., & Potter, C. (2014). Citizen science as seen by scientists: Methodological, epistemological and ethical dimensions. *Public Understanding of Science*, 23(1), 107–120.
- Riesch, H., Potter, C., & Davies, L. (2013). Combining citizen science and public engagement: The open AirLaboratories programme. *Journal of Science Communication*, 12(3), 1–19. <https://doi.org/10.22323/2.12030203>
- Rotman, D., Preece, J., Hammock, J., Procita, K., Hansen, D., Parr, C., ... Jacobs, D. (2012). *Dynamic Changes in Motivation in Collaborative Citizen-Science Projects, Civic and Community Engagement* (pp. 217–226). Paper presented at the Proceedings of the ACM 2012 Conference on Computer Supported Cooperative Work, CSCW 2012, February 11–15, 2012, Seattle, Washington.
- Rotman, D., Hammock, J., Preece, J., Hansen, D., Boston, C., Bowser, A., & He, Y. (2014). *Motivations Affecting Initial and Long-Term Participation in Citizen Science Projects in Three*

- Countries (pp. 110–124). Paper presented at the iConference 2014 Proceedings. <https://doi.org/10.9776/14054>
- Roy, H. E., Pocock, M. J. O., Preston, C. D., Roy, D. B., Savage, J., Tweddle, J. C., & Robinson, L. D. (2012). *Understanding citizen science and environmental monitoring*. Final Report on behalf of UK-EOF. NERC, Centre for Ecology & Hydrology and Natural History Museum.
- Sheikh, M. M., Manzoor, N., Ashraf, J., Adnan, M., Collins, D., Hameed, S., ... Shrestha, M. L. (2015). Trends in extreme daily rainfall and temperature indices over South Asia. *International Journal of Climatology*, 35, 1625–1637.
- Shrestha, A. B., & Aryal, R. (2011). Climate change in Nepal and its impact on Himalayan glaciers. *Regional and Environmental Change*, 11(1), S65–S77. <https://doi.org/10.1007/s10113-010-0174-9>
- Silvertown, J. (2009). A new dawn for citizen science. *Trends in Ecology and Evolution*, 24(9), 467–471.
- Shukla, Y., & Mall, B. (2016). *Enhancing Frontline Resilience: Trans-Border Community Based Flood Early Warning System in India and Nepal*. UNESCO Chair in Technologies for Development: From Innovation to Social Impact, accessed on July 10, 2018. Retrieved from http://cooperation.epfl.ch/files/content/sites/cooperation/files/Tech4Dev%202016/1125-Shukla-SE08-DRR_Full%20Paper.pdf.
- Smith, P. J., Brown, S., & Dugar, S. (2017). Community-based early warning systems for flood risk mitigation in Nepal. *Natural Hazards and Earth System Sciences*, 17(3), 423–437.
- Sy, B., Frischknecht, C., Dao, H., Consuegra, D., & Giuliani, G. (2018). Flood hazard assessment and the role of citizen science. *Journal of Flood Risk Management*, 12(S2), e12519.
- UNESCO-WWAP. (2003). United Nations Educational Scientific and Cultural Organization World Water Assessment Programme Water for People—Water for Life. The United Nations World Water Development Report, Berghahn Books, Oxford.
- UNISDR. (2015). *Sendai framework for disaster risk reduction 2015–2030*. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNISDR) Retrieved from <http://www.wcdrr.org/preparatory/post2015>
- Vuichard, D., & Zimmermann, M. (1986). The Langmoche flash-flood, Khumbu Himal, Nepal. *Mountain Research and Development*, 6(1), 90–94.
- Walker, D., Forsythe, N., Parkin, G., & Gowing, J. (2016). Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme. *Journal of Hydrology*, 538, 713–725.
- Zurich Insurance. (2015). *Risk Nexus: Urgent case for recovery: What we can learn from the August 2014 Karnali River floods in Nepal*. Internal Report. Retrieved from <http://www.55c198e8-5f10-4c30-9f1d-6dfe0a000047>.

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