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Designing citizen science for water and ecosystem services management in data-poor regions: Challenges and opportunities

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ABSTRACT

While the citizen science approach has gained prominence in water and ecosystem services management, methodological limitations, insufficient resources invested in monitoring practices and a lack of effective mechanisms for integrating the approach into existing monitoring and decision making processes means that its full potential has yet to be realized. Nevertheless, the concept offers a real opportunity to address data gaps and assist decision makers operating under a wide range of socio-ecological and environmental uncertainties. In this paper, we report findings from a project in which low-cost sensors were deployed to collect hydrological data in two study locations in Nepal. We found evidence that the citizen science has potential to generate locally relevant data and knowledge which can enrich a much more polycentric governance of water ecosystem services management. However, some major challenges need to be overcome, in particular developing locally-tailored monitoring sensors, standardizing monitoring and data sharing practice, improving local capabilities to collect quality data and making the approach more sustainable and adaptive to emerging environmental threats and uncertainties. If sufficient attention can be given to these key challenges, citizen science looks set to play a significant future role in water and ecosystem services management.

1. Introduction

A voluntary involvement of lay publics (non-scientists) in scientific research is generally termed ‘Citizen Science’- CS hereafter. There is a long history of citizen's voluntary participation in scientific enquiries in a variety of ecological and environmental resource management contexts (Irwin, 1995; Silvertown, 2009; Miller-Rushing et al., 2012). CS can be broadly defined as the voluntary participation of individuals and communities in research design, data co-generation and interpretation, often in association with or under the guidance of scientists (Bonney et al., 2009; Dickinson et al., 2012; Buytaert et al., 2014). In the last two decades, CS initiatives have made a significant contribution in ecological and hydrological research and data collection (Cohn, 2008; Dickinson et al., 2012; Bonney et al., 2014; and Njue et al., 2019). Community-based hydrological monitoring has also become a successful measure to generate quality data and enhance local people's understanding of key hydrological functioning (Walker et al., 2016). As a result, CS is becoming an important form of public participation in natural resources management and therefore is receiving increasing attention in public policies and decision making processes (Haklay, 2015).

CS-based practices have an ever increasing footprint in a range of ecological and environmental research activities, including species range shifts, water quality and quantity monitoring, spread of infectious disease, demographic changes, land use alternation and climate change impacts (Roy et al., 2012; Palacin-Silva et al., 2016). An immense level of data generated by citizen science projects suggest growing public enthusiasm and willingness to engage with environmental concerns. CS has also become an established research protocol for some large scale monitoring of biodiversity and ecological processes. For example, the Open-Air Laboratories (OPAL) project in the UK (www.imperial.ac.uk/opal) was designed for participatory monitoring of water, air, insects, birds and wildlife habitats (Davies et al., 2013). Similarly, the ‘*eBird*’ programme is a web-based volunteering programme (http://ebird.org/content/ebird/about/) for documenting presence or absence and abundance of bird species in North America all year round (Wood

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et al., 2011; Sullivan et al., 2014). These large-scale monitoring activities are supported by thousands of volunteers taking part in monitoring activities. The role of CS-based monitoring activities is now well-recognized in environmental education and research programme (Cohn, 2008; Bonney et al., 2009; Roy et al., 2012). All of that indicates a growing potential of CS in environmental research and education.

In relation to water ecosystem services (ES) management, rural and mountain communities have been effectively using their traditional knowledge to monitor and manage available water resources more equitably and sustainably (Buytaert et al., 2014). For example, in Mustang region of Nepal, local communities use traditional cooperative system to share available water resources in local irrigation system (Messerschmidt, 1986). Although traditional practices are still useful to manage water resources at a local scale, the rapid evolution of socio-hydrological processes (Shivapalan et al., 2012) has furthered the need for more local data and knowledge generation and exchange. This is particularly true of mountainous regions where increased socio-hydrological pressure and hydro-climatic variability have made water ES management increasingly unsustainable (McMillan et al., 2016). Lack of sufficient data is a major challenge and can potentially lead to an inaccurate decision making in water ES management. In this situation, we try to understand how CS based approach can help to cogenerate locally relevant hydrological data for better management of water–ecosystem services. Indeed, the role of local communities in managing and protecting water resources is already widely documented (Dickinson and Bonney, 2012; Buytaert et al., 2014; and Jollymore et al., 2017). However, contemporary water ES management at a local scale is facing many challenges since environmental, social and economic interests are closely intertwined and constantly evolving. Emerging CS activities, supported by innovative technologies, have begun to create a dynamic, decentralized and polycentric network of data collection process for more collaborative decision making (Buytaert et al., 2016). CS projects in ecological and environmental decision making are designed to address such complex socio-ecological and environmental questions (Shirk et al., 2012). They are also diverse in terms of sizes and scopes - some with a regional scope such as 'Freshwater Watch' (Loiselle et al., 2016) and 'Crowdhydrology' (Lowry and Fienen, 2012), others focussed on local scale practices such as the 'Mountain-Environmental Virtual Observatories' (Mountain-EVO) designed for remote mountainous areas of Nepal, Peru, Ethiopia and Kyrgyzstan (Buytaert et al., 2014) and a crowdsource approach in hydrological monitoring in a rural Kenya (Weeser et al., 2018). Similarly, local participation has been proven successful in Tanzania to establish an effective hydrological monitoring network and carry out participatory monitoring (Gomani et al., 2010). Projects with regional scope usually have more formalized monitoring structures in data cogeneration but less direct engagement with local volunteers (Haklay, 2015). In addition, the CS approach has emerged as an innovative tool for not only to enhance water ES but also to improve conservation efforts and natural resources management (McKinley et al., 2016).

The advent of affordable monitoring technologies now means that CS can be integrated into a wider range of environmental monitoring schemes (Newman et al., 2012). The rapid advancement of sensor technology has created waves of new applications from environmental monitoring to industrial sensing (Chong and Kumar, 2003). New sensor technologies have also made it possible to collect and analyse large quantity of data. Environmental sensor networks have now moved from passive (data logging and manual systems) to active (real-time and web-based) monitoring, and as a result, make a useful contribution in the understanding of earth and environmental processes (Hart and Martinez, 2006). Many CS projects are now increasingly using mobile apps and information and communication technology (ICT) solutions to facilitate data collection (Luna et al., 2018), whereas some CS projects are also using low-cost sensors, visual monitoring techniques and written methods to collect and disseminate data and results (Palacin-Silva et al., 2016).

Nevertheless, while technology has become an important factor in the expansion of environmental monitoring, it is not clear that participating stakeholders, especially locals, are aware of the potential use of their collected data in decision making. Despite an increasing use of CS practices within the hydrological and ecological disciplines, CS-generated data and knowledge has yet to be systematically integrated into local decision making (Carlson and Cohen, 2018). CS practices have been constrained by methodological challenges such as how to develop standardized methods for data collection and quality control, how to deal with technological limitations and sustainability issues and how to properly integrate CS data into local decision making processes (Palacin-Silva et al., 2016). It is more challenging for data-poor and remote areas where local capacity to integrate such practices at local scale is very low. In order to understand the effectiveness of CS approach in water ES management, we have tested a CS framework in two remote and mountainous regions of Nepal. In this paper, we analyse these two CS-based water resources monitoring practices and explain the potential role of CS in water ES management in remote and data-poor regions. We have explored what works and what needs to be improved in order to make the CS approach more holistic and integrated. The paper discusses key challenges and opportunities faced by contemporary CS practices in general, and by those two CS projects in particular. These include methodological practices such as the use of low-cost technologies, data collection and quality control, local engagements and the sustainability of monitoring activities. We assess the suitability of new and affordable sensor technologies in data co-generation processes in remote areas and the impact of citizen science in scientific scholarship and local decision making. The paper concludes by summarising key lessons learned and charts a way forward for optimizing CS benefits in water ES management.

2. Materials and methods

In this paper, we analyse data and evidence from two empirical CS projects that we implemented and monitored in parts of Nepal. The projects were designed to cogenerate hydrological data and information to improve water related ES management at local scale. One was focused on understanding water quantity available for agricultural production in a semi-arid high mountainous environment, the other to generate river water level data to improve community flood risk resilience in a flood prone area. We applied an integrated CS research methodology combining participatory data collection and analysis, case study investigation, use of low-cost sensors, community discussion, stakeholder meetings and the participatory evaluation of CS practices. In the analysis which follows, we compare key successes and challenges from those two case study investigations. We conclude that insights from these pilot sites, together with those from similar projects conducted in other settings, suggest considerable scope for policy and practice applications in currently data scarce locations around the world.

2.1. Designing a CS-based water monitoring practice

Previous work undertaken by the authors has involved the development of a polycentric monitoring approach involving local people and stakeholders to cogenerate actionable data and knowledge for more participatory water resources planning and management (Buytaert et al., 2014; Buytaert et al., 2016). There are three major interlinked activities within this novel polycentric approach: i) participatory observation and data collection; ii) data processing and knowledge extraction; and iii) knowledge dissemination and local interaction (Fig. 1). Since hydrological data gap is a major challenge to both study sites, this framework could act as an effective CS approach in reducing hydrological uncertainties and improving water resources management. At first, we held participatory observation and situation analysis in both sites to find out what data and information are currently available and what additional data could help to create new knowledge in support of

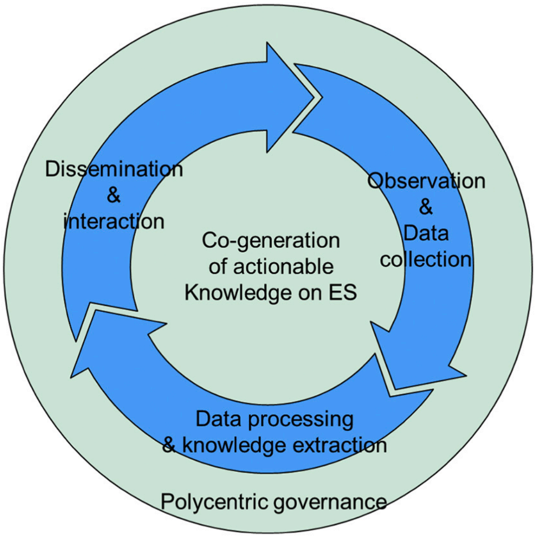

Fig. 1. A polycentric framework for CS-based data and knowledge cogeneration (Buytaert et al., 2016).

local decision-making. As part of participatory data collection process, we deployed low-cost sensors to collect water level data from both case study sites. In the Upper Kaligandaki Basin, we installed a pressure level sensor at the Lumbuk stream, and for the Karnali River Basin we designed and deployed two LiDAR Distance Sensors at Chisapani and Phanta to monitor river water level. Both sensors were designed using appropriate data logger systems. The temporal resolution of the LiDAR sensor was set for every minute. While designing low-cost sensors, key attention was given to what data do we need to generate and how do we identify right sensors to adapt with local hydro-climatic conditions. Local volunteers and relevant stakeholder organizations such as government's Department of Hydrology and Meteorology (DHM), Practical Action, local NGOs and local government authorities were invited in all stages of CS activities including sensor demonstration, sensor installation, data collection and community interactions. Then, collected data and information have been analysed and shared with local people and participating organizations. Throughout the project period, we regularly held targeted meetings with local volunteers, NGOs and key government organizations to discuss the strengths and weaknesses of CS practices within the polycentric governance-based water resources management.

In both case study sites, we adopted the polycentric framework (Fig. 1) to implement CS-based participatory monitoring activities. Since water resources management at local scale is heavily dependent on locally relevant hydrological data, innovative sensor technologies could make a significant contribution in data and knowledge co-generation (Buytaert et al., 2016; Palacin-Silva et al., 2016). While using low-cost sensors is crucial to generate water level data at case study areas, we also tried to understand how those low-cost sensors cope with local hydro-climatic conditions in a high mountainous area of the Upper Kaligandaki Basin (with approximate height of 3150 m.a.s.l.) and a big river system (a major tributary of the Ganges River Basin) in a low-land area of the Karnali River Basin (with approximate height of 180 m.a.s.l). Collected CS data and information from both sites were discussed with local people and key stakeholder organizations.

2.2. *Case study investigation*

Using the above polycentric framework, we developed two CS projects and deployed these within two contrasting locations. The trans-Himalayan mountain region of the Upper Kaligandaki Basin is an arid land with less than 250 mm per year of rainfall whereas the low-land region of the Karnali River Basin is a flood prone area with an approximate annual rainfall of 1500 mm (Fig. 2). Selected case study sites represent two major water ES management challenges of the region – 'too little or too much' water scenarios. On the one hand, local communities of the Upper Kaligandaki Basin are experiencing uncertainties over water availability which is crucial to local agricultural practices. On the other hand, increasing flood risk is a constant challenge to basin people along the lowlands of the Karnali River Basin. Nepal as a whole has been facing a 'difficult hydrological regime' for some time, with a higher degree of inter- and intra-annual rainfall and runoff variability and thus causing an array of water security challenges for people, livelihoods and local economies (Grey and Sadoff, 2007). In addition, a lack of sufficient hydrological data at local scale has become a major obstacle for the better water ES management such as agricultural water management and flood risk reduction in the long-term.

Located in a rain shadow of the Himalayas, the Upper Kaligandaki Basin receives very low precipitation of less than 250 mm per year, mainly contributed by snowfall. Due to a changing snowfall pattern in recent years, mountain communities are experiencing hydrological uncertainties to their croplands (Manandhar et al., 2012). On the one hand, an increasing uncertainty in water availability may have a significant impact on agricultural practices. On the other hand, a sudden and unpredictable glacial melting can create landslides and flooding disasters for downstream areas. The situation has been further exacerbated by cascading effects of climate change impacts in the Himalayan region (Xu et al., 2009). In addition, an unprecedented level of land use change and socio-economic transformation over the recent decades may have created significant impacts on sustainable water ES management.

A lack of sufficient local data is a major challenge for building an effective community flood risk resilience system. This is particularly a major issue for the low-land area of the Karnali River Basin. Although a single automatic Radio Detection and Ranging(RADAR) system at Chisapani area is generating valuable hydrological data at 15 min intervals for existing flood early warning systems (EWS), deploying a set of low-cost sensors (Paul et al., 2020) could generate locally relevant data and enhance existing flood EWS (Pandeya et al., 2020). This can not only become a redundancy measure to existing RADAR system but also play a complementary role in generating water level data. There is a major challenge in predicting floods downstream when existing monitoring sensors fail to transmit real time data to the EWS. In this circumstance, an integration of CS approach could provide both robust and user-friendly hydrological instruments to local stakeholders to generate locally relevant data and knowledge for better decision making (Buytaert et al., 2014; Pandeya et al., 2016). During the monsoon of 2017, river water level data was generated in the Lower Karnali River Basin using the low-cost sensors and scientifically analysed by comparing the data with the existing automatic-monitored data. The likely benefits of those data has been regularly discussed with local people at community level and with key stakeholder organizations. On this basis, it seems that a CS-based monitoring approach could play an important role in better understanding of hydrological regime and thus supporting local communities to manage flood risk at local scale.

2.3. *CS-based activities*

In both case study sites, local volunteers such as village elders, youths, women and disadvantaged people voluntarily participated in targeted CS activities such as participatory discussion, sensor demonstration, sensor installation, data collection and evaluation. Participatory discussions were regularly held to understand water resources management practices and what hydrological data and knowledge gaps exist and how we can improve the evidence base for better management of water resources. Such local level interactions were helpful to identify what additional data and information are needed to mitigate these challenges. At the early stage of project implementation, we organized two community level meetings in the Upper Kaligandaki Basin and three community level meetings in the Karnali Basin. Local volunteers and

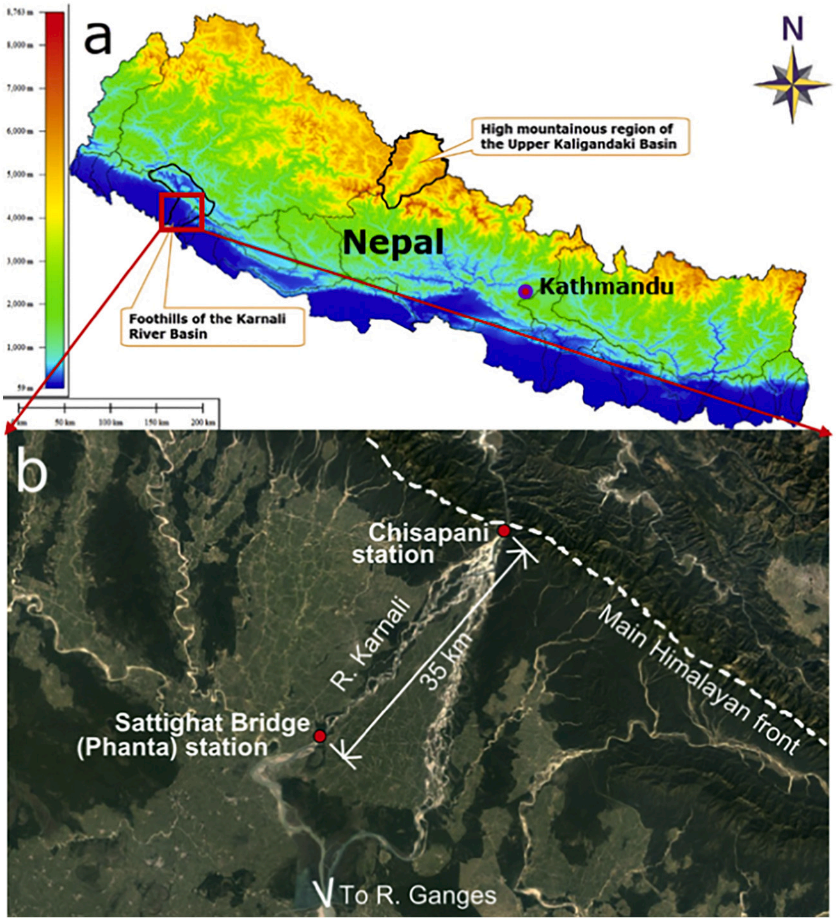

Fig. 2. a) Geographical location of study sites in a SRTM DEM map; b) Google Earth locations of two lidar stations in the River Karnali: Chisapani (upstream) and Phanta (downstream) (Google Earth Map, 2020).

stakeholder organizations shared their experience of water resources management challenges in those meetings. We also assessed existing data and knowledge gaps on water ES management which led us to identify appropriate low-cost sensors. Local people in the Upper Kaligandaki Basin have been using a traditional practice to share stream water among communities. On the one hand, changing water availability in the Upper Kaligandaki Basin has become a major challenge to basin communities to maintain their agricultural-based livelihoods. But at the same time, an increasing risk of flooding events has become a new normal for many basin communities in low-land areas of the Karnali River Basin. In both cases, local communities actively engaged in CS-based participatory monitoring activities to improve agricultural water management and building community flood risk resilience.

In the case of Upper Kaligandaki Basin, local communities and stakeholder organizations were invited in targeted CS activities such as community discussions, sensor demonstration, participatory data collection and interpretation. At the beginning of the project, community discussions were held in two selected villages (viz. Dhakarjhong and Phalyak) to identify what additional data and information could make their existing water resources management more equitable and sustainable. Local people shared their experience of increased hydrological uncertainties, especially unpredictable snow and rainfall pattern in recent years. They suggested that having an improved monitoring system at local streams local people can understand changing water availability and adapt their agricultural practices with new realities. Consequently, appropriate CS activities such as sensor installation, participatory monitoring, data collection, community discussion and interpretation were systematically implemented. Local people were involved in sensor installation and also took part in water level monitoring and data collection. Throughout the project, a number of participatory discussions and round table meetings were also held at community and local institution levels to share CS data and knowledge and to generate valuable feedback. Similarly, in the Karnali River Basin, targeted CS activities such as local consultation meetings, sensor demonstration, participatory monitoring and community interactions were organized from the beginning of the project. Three local villages (viz. Chisapani, Karmi Danda and Phanta) were selected for those CS activities. We identified two suitable sites in Chisapani and Phata to install LiDAR sensors. The sites are about 35 km apart within the lower region of the Karnali River Basin. Local volunteers participated in sensors' installation and subsequently in monitoring activities. Since the basin has an ongoing flood risk resilience programme, supported by the DHM, Practical Action Nepal and relevant local level organizations such as NGOs and local government authorities, the participation of these stakeholder organizations in various stages of research was crucial to make the entire CS project more effective. Alongside sensor data collection, we organized local interactions including community level discussions and basin stakeholder meetings in order to share CS data and research findings. In the next section, based on our empirical evidence on low-cost sensors and CS activities, we critically assess them and identify key challenges and likely opportunities in making them more inclusive and impactful.

3. Results and discussion

3.1. *Problem identification*

The identification of vital water ES challenges at local level that directly relates to improving local lives and livelihoods can make a real difference in data and knowledge cogeneration. Local people in remote mountainous regions of Nepal are struggling with unpredictable hydro-climatic behaviour coupled with a complex socio-hydrological environment. In both case study projects, we held participatory discussions with local communities and key stakeholder organizations such as Practical Action, DHM and local government authorities to identify water management challenges and underlying gaps in the knowledge and data. In the Upper Kaligandaki Basin, a higher degree of rainfall and snowfall uncertainties is causing an agricultural related water management challenge to local farmers whereas an increased frequency of high intensity rainfall during the monsoon has created growing flooding risk to basin communities in the low-lands of the Karnali Basin region. Such challenges are further compounded by human interventions in the catchment. These include land use change, riverine encroachment and unsustainable urbanization and infrastructural development activities. In the Upper Kaligandaki Basin, local communities shared their management challenges of continuing their traditional agricultural practices which require regular supply of water most of the year. Since it is very difficult to understand and predict changing water availability without scientific measurement, these communities were most interested in contributing to stream water level monitoring. A local participant put it clearly: '*since the Karnali river is frequently and constantly changes its course during the monsoon, which is further exacerbated by human interventions along the river channel such as sand mining and river encroachment, a community based river water level monitoring can improve flood EWS system and reduce any future flood risks*'. Local communities and key end users such as the DHM and Practical Action Nepal actively participated in both project design and implementation processes.

3.2. Local motivation and engagement

A strong local motivation is fundamental to any CS initiative as it helps to accelerate local people's participation in monitoring, data sharing and community engagement. However, local motivation is dynamically changing throughout the project duration as it is guided by personal interests and external factors such as technical support and acknowledgement (Rotman et al., 2012). In the Upper Kaligandaki Basin, once local farmers from both villages understood the benefits of water sensors and their role in participatory monitoring, they have shown their enthusiasm in CS-based monitoring of the Lumbuk stream (only water source available for local irrigation). Observations made on site took place with community involvement, cogenerating relevant data and information (Fig. 3). Local key informants were recruited to monitor water level. For instance, local people told us that potato and cereal crops used to be the main agricultural products but that due to water uncertainties and a lack of sufficient labour force, there had been a shift towards growing more resilient crops such as apples and walnuts, adopting water harvesting techniques and finding ways to share the resource more equitably (Manandhar et al., 2011). Water sharing is seen as particularly important, the communities we spoke to recording and allocating water to separate farmers according to an agreed protocol. This is a good example of the adaptability of communities who find themselves facing uncertainties about water supply. Such adaptive decision making can be further strengthened by the local involvement in CS-based monitoring of water resources, particularly their role in the adoption of low-cost sensors and participatory data collection methods.

In the Karnali River Basin, local communities and key stakeholder organizations such as DHM and Practical Action Nepal actively participated in local discussions on how CS activities including the testing of low-cost sensors could generate robust data to support community flood EWS (Fig. 4). Targeted local engagement activities generated local enthusiasm on effective operation of low-cost sensors and making data available to basin communities and existing flood EWS. We received valuable feedback from local people; for example, one important piece of feedback from villagers was to build a network of real-time data displays at community centres. This could also help to share water level data with community people and may significantly enhance local flood risk resilience capacity. As part of local engagement activities, we also organized policy dialogues with key end-users such as the DHM, Practical Action Nepal and local organizations including District Emergency Operations Centre (DEOC) member organizations, NGOs and government authorities to discuss opportunities and challenges arising from this innovative approach. Such interactions were very useful in identifying where low-cost sensors can most effectively be installed and how best to induct local residents in recording and relaying in a timely manner the data they generate. Regarding the latter, sensor data can be used during periods of very high water which warn authorities and communities to take actions before the flood strikes.

Although local people showed their continued enthusiasm in low-cost sensors, participatory monitoring and targeted local engagements, local motivation in CS activities can be easily eroded over time due to

Fig. 3. Water ES management in the Upper Kali-Gandaki Basin - a) agricultural land at Phalyak village; b) irrigation pond at Dhakarjhong village; c) apple farming at Ghyakar village, and d) a community discussion at Dhakarjhong village.

Fig. 4. Citizen Science activities - a) Local interaction with local volunteers in the Karnali Basin, b) Sensor demonstration at Phanta community c) A Pressure Level Sensor installed in the Lumbuk stream of the Upper Kaligandaki Basin, and b) A LiDAR Distance Sensor installed at Chisapani area of the Lower Karnali Basin.

people's time constraints and other competing interests (Rotman et al., 2012). Sometimes local volunteers begin to question the rationale for projects if they feel they lack ownership in the overall objective or framing (Rotman et al., 2014). Lack of citizens' long-term motivation may compromise the very nature of participatory monitoring, which in turn can have direct consequences on data quality control. Public engagement may also become less effective when the geographical scale of monitoring activities increases (Sheldon and Ashcroft, 2016). We were mindful of these challenges in designing the pilot projects in Nepal and achieved active and continued local participation in both cases. In the Upper Kaligandaki Basin where one of the CS projects was carried out in a small catchment, participatory monitoring and local engagement activities were occurred at community level. Whereas in the lower Karnali River Basin, local engagements were held both at community and at a larger basin level. We found that local people actively participated in both small and larger scale projects. This shows that the local enthusiasm in CS activities and their participation mainly rely on whether the CS initiative is trying to address a key local water ES management challenge. The experience from these two case studies assured us that the continued motivation and effective public engagements mainly relied on how successfully the local concerns are identified, what are the robust and easy to use low-cost sensors, and designing of effective data collection and sharing mechanism.

3.3. *Affordable technology and ICT applications*

Affordable technologies and the use of ICT applications are now common features of CS projects. In the current research project, we designed data logger based low-cost sensors (a pressure level sensor for the Upper Kaligandaki Basin and two LiDAR Distance Sensors for the Lower Karnali Basin). Data stored in SD cards can easily be read on computer and deposited in online data repositories. A rapid use of low-cost sensors has been transforming CS-based hydrological monitoring. At the same time, increased internet coverage (even in remote areas) can make these sensors accessible by linking them to online platforms. Although emerging low-cost sensors 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 cogeneration is still lagging behind. To address these challenges, CS initiatives might need to be more efficient in the way data are verified and applied in local decision making. Technologies with the least complexity and low maintenance costs could make participatory monitoring more sustainable. Since most conventional hydrological monitoring instruments are expensive and also require higher installation costs, affordable monitoring technologies have many applications, especially in remote and data-scarce regions and for those areas where investment in water resources monitoring at local level is low. In this situation, a successful use of low-cost monitoring sensors could provide both robust and user-friendly hydrological instruments for local stakeholders to generate data and knowledge directly applicable to water resources management (Buytaert et al., 2014). The use of low-cost sensors in hydrologic research and water ES is becoming increasingly popular (for e.g., Jollymore et al., 2017, Paul et al., 2018). However, their systematic use in water resources management is a new phenomenon. Crowd-sourcing of hydrological data has been playing an important role in generating supplemented hydrological data for research and public engagement (Lowry and Fienen, 2012). While low-cost sensors have made it possible to encourage local people in participatory monitoring of water services, it is not yet clear that local people and stakeholder organizations are fully aware of collected water data and their effective use in decision making.

In the Lumbuk stream of the Upper Kaligandaki basin, we installed pressure level transducers (sensors) for water level sensing (Fig. 4c), a type of technology that has already proven effective to monitor stream water level in high mountainous areas. For the Karnali River basin, we designed low-cost LiDAR Distance Sensors (Fig. 4d), which have proven robust and well adapted to the region's tough climatic conditions. The LiDAR sensor is suitable for large rivers as it can measure up to 40 m of distance. LiDAR sensor is also cost-effective (fully integrated loggers can be made for as low as US$250–$300), which is well below compared to existing RADAR system based automatic hydrological monitoring system. It is understood that the approximate cost for the existing RADAR system (including installation) could be around US$10,000. As well as being cheap, they are easy to use and install - which is useful for remote areas currently lacking data. This new sensor has been generating robust data comparable to DHM operated RADAR System data (Fig. 5). The use of low-cost monitoring sensors has also attracted local key informants, relevant government authorities, women and poor in both CS projects. It showed that the selection of the right monitoring technologies has a positive influence in hydrological data cogeneration. Once this monitoring system is linked to community early warning system, there is a good chance of improving community flood risk resilience capacity.

3.4. Data quality control

Sensor data needs to be systematically processed in order to prove the robustness of CS data and their use in local decision making. Since CS methodologies are diverse and often lead to varying errors and biases (Engel and Voshell Jr., 2002), data systematization is a major concern for many CS projects in terms of their effective re-usability and integration across disciplines (Schade and Tsinaraki, 2016). Local participation in both our case studies was self-motivated and there was a willingness to learn about local hydro-climatic uncertainties and the need to adapt to them. Fig. 5 shows the trend analysis of two LiDAR sensors installed at Chisapani and Phanta. At Chisapani station, LiDAR sensor data is comparable to DHM operated RADAR-based data. It proves the robust data quality of LiDAR sensors. Although CS generated data was scientifically verified, due to our flexible monitoring protocols, structural differences were apparent with conventional monitoring practices which could undermine the effective use of collected data and information in the long term. Current protocols for data logging system needed to be transformed into a real-time data logging and transmission system. Further adjustments would make the LiDAR sensor even more effective. These include solving power back-up with solar panel system, improving communication mode with real time data collection and displaying at community centres.

Participatory data collection and their rigorous analysis is fundamental for CS practices in order to prove their scientific robustness. This ensures the usability of CS data in resources management. In the Karnali River Basin, a new LiDAR water level sensor was able to replicate the DHM generated RADAR system data at a greater temporal resolution (Fig. 5). The LiDAR sensors are capable of collecting river level data in every minute compatible with existing RADAR data. This has proven the technical robustness and a better temporal resolution of low-cost LiDAR Distance Sensor. This technique could therefore be directly used in community flood early warning system in the basin. Although CS generated data can be reliably high quality equal to those produced by professional sciences, each CS data should be judged separately according to project design and application (Kosmala et al., 2016). Data quality control needs to incorporate data analytical and visualization tools that can correctly reveal patterns of data (Hochachka et al., 2012). Our CS projects also show that there is a need for increased emphasis on data quality control, including adopting rigorous protocols such as repeated sampling at predetermined intervals, improved strategies for reducing spatial biases, use of quizzes and games to evaluate observer skill, and tools for inclusion of data on observer quality in the database. A continuing collaboration between local communities and relevant hydro-climatic institutions can support in participatory data collection, quality check and their systematic use in decision making and resources management.

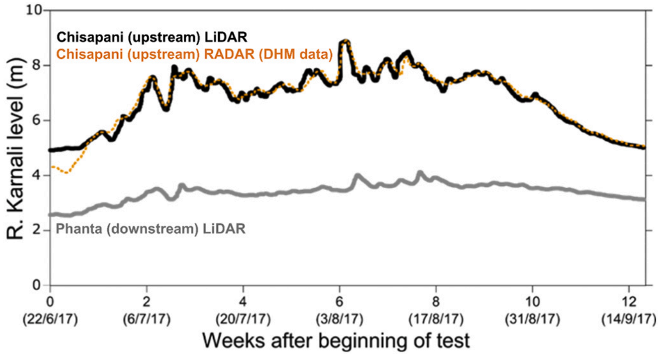

Fig. 5. LiDAR sensor based river water level data compared with existing RADAR system data.

3.5. Scientific and policy impacts

In the Lower Karnali River Basin, the data generated by the low-cost sensors has the potential to help existing community flood EWSs by increasing the lead-time of potential flood risks. Our efforts to identify the issues has helped to cogenerate essential but supplementary data to support such critical water ES management. The pilot case study also clearly indicates that appropriate CS initiatives can encourage local volunteers in data and knowledge cogeneration if sufficient attention can be given to identify community concerns at an early stage of project design. However, our research findings also raise a key question: the extent to which it is possible to incorporate these necessarily more locally tailored approaches to monitoring and reporting into established hydrological monitoring and management practices. With the advancement of user friendly low-cost sensors and online ICT technologies, CS practices could be an effective approach for remote and data-scarce Himalayan region. The experiments also show that the greater availability of data and simplified tools means that local stakeholders would be able to use such tools independently and integrate new data into their local decision making. Accelerating the use of CS practices requires a more formalized CS practices and their encouragement and promotion by local policy makers and practitioners (Newman et al., 2012; Hecker et al., 2018). While there is a strong innovative technological aspect to all this, further experimental research may be required before adopting the approach more widely. CS approaches also have potential to implement transformative research projects on coupled human and natural systems that can support ecological and environmental decision making (Crain et al., 2014). For remote and data-scarce environments where leveraging CS data and knowledge has crucial role to make water ES valuation more inclusive and policy-oriented (Pandeya et al., 2016). In the absence of an appropriate data sharing mechanism, CS practice could influence existing decision making negatively, mainly due to misusing of CS data by certain members of the public for their benefits. Despite continuing methodological challenges, CS approach has been effective in raising public perception on how water resources is functioning to produce services; what are major concerns; and how that can be remediated. Now, there is a real optimism that CS project can play a major role in water ES management.

3.6. Upscaling and sustainability

Despite some positive impacts of these CS projects in terms of data generation and policy advocacy, upscaling them is not an easy task. It requires designing more robust sensors and CS activities as policy and decision makers want more research and proven methodologies before adopting them into their existing monitoring and management practices. DHM's technical team expressed their concerns on how to maintain power back (such as solar or battery powered system), how to improve data logging and communication mode of sensors in the longer term. Key local stakeholders including the DHM and Practical Action have also emphasized that expanding such testing in different local settings could further improve the robustness of data and sensors. However, structural barriers such as the lack of long-term funding, inconsistency in methodological protocols and poor communication with local communities and end users means that current monitoring activities may not be sustainable in the long-term. Initial collaborations between local people, local authorities and scientific organizations could become less formal after project funding runs out. As a result, the robustness of monitoring sensors could be compromised and this will have consequences for data quality control. For the long-term monitoring, continuing financial support for any project is essential and the sustainability of funding sources needs to be clearly established. Strategic collaboration among participating scientific organizations and local volunteer groups is a necessity not only for maintaining project leadership but also acquiring necessary resources for running monitoring work, public engagements and database management (Dickinson et al., 2012). Enhancing local capacity to take in-charge of monitoring activities can only create a sense of community ownership over CS project. That will encourage local volunteers to acquire skills and knowledge and sharing that with peers.

The sustainability of CS approaches also relies on how well experimental monitoring work is led by end users after the project completion. A constant support to local communities in data collection and their verification and systematic integration is essential to strengthen the essence of CS-based polycentric framework. Our community-led, bottom-up approach has shown the potential for devolving water resource management decision making at 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, monocentric approach (Buytaert et al., 2016; Paul et al., 2018). Local communities and stakeholder organizations such as DHM, Practical Action Nepal and local government bodies have shown interests in developing a real-time monitoring system and linking them to a telemetry system. In terms of financial sustainability, local communities and stakeholder organizations have emphasized that local authorities could invest in CS-based monitoring which can make the CS projects more sustainable. Local authorities have got full responsibility to manage water and environmental resources at local scale. Success would depend on a close collaboration between scientific organizations, local partners, government authorities, NGOs and communities as well as providing training and capacity building on using the sensors and interpreting the data. If these hurdles can be overcome, the technology and CS approach could offer a long-term solution for water ES management at local scale.

4. The prospect of citizen science in integrated water ES management

While water and environmental research activities are becoming more data intensive and collaborative, sharing data has been proven a useful approach, not only for data verification purpose but also to optimize their use in research and policy-making (Tenopir et al., 2011). The research findings from both case study sites showed that the CS-based polycentric framework has a great potential in generating locally relevant data and knowledge. This also proves the fact that CS approach can play a valuable role in producing large and longitudinal data, often complementary to more localized data collection exercises (Dickinson et al., 2010). Although CS practices can be largely divided into two major types - ‘user-centric’ where users are collecting data and information on the spot; and ‘device-centric’ where sensor sampling occurs whenever the state of the monitoring device matches the application's requirements (Palacin-Silva et al., 2016), the latter approach has become more useful to data intensive water resources monitoring and management. In our both case studies, low-cost sensors have successfully generated locally relevant data and information. Sensor technologies played key role in data cogeneration and making it available to end users. However, the sustainability of these CS practices remain a major concern as they may need financial support to continue monitoring activities.

The use of sensors in both case studies has proved that emerging sensor technologies are opening up new opportunities in environmental monitoring and supporting long-term environmental stewardship (Ho et al., 2005). Newly developed low-cost monitoring sensors mean that CS observatories are capable of collecting large volumes of field-based data (Hochachka et al., 2012). A rapid advancement of ICT applications has further enabled CS initiatives to create user friendly online platforms for data storage and sharing; yet due to resources limitation and lack of local capacities, there is no guarantee for the higher level of public participation in monitoring and decision making (Wehn and Evers, 2015). There will remain some technical challenges in terms of developing suitable sensors and ICT platform to meet local requirements. We found that developing robust sensors for remote and mountain regions is a major challenge as the local hydro-climatic condition is highly unstable and could make data collection unreliable.

Both case studies primarily concentrated on critical water ES management challenges at community level – improving agricultural water management in the Upper Kaligandaki Basin and building flood risk resilience in the lower Karnali Basin. That helped to motivate local people and organizations in targeted CS activities. It supports the fact that CS activities are driven by not only to generate scientific data and knowledge of contemporary environmental issues but also to improve environmental decision making and building public awareness for greater societal benefits (Geoghegan et al., 2016). Highly motivated local individuals seek opportunities to participate in scientific enquires, gain skills and expertise in generating new scientific knowledge about ecosystem functioning and share that to local people for environmental awareness and policy advocacy (Johnson et al., 2014). We found that key stakeholder organizations are also enthusiastic in using CS approach including low-cost monitoring sensors. However, it is also the fact that getting desirable research impacts from CS initiatives is still a big challenge since there is an inherent suspicion about the data and results from public participation that it could take decades to positively affect the environment (Irvin and Stansbury, 2004). CS based monitoring practices are largely considered as a second-rate science, mainly because of improper scrutiny over data collection and validation process. Perhaps due to that reason, CS based research outputs are often placed under project outreach publications (Bonney et al., 2014). Nevertheless, many CS projects, mainly large scale monitoring activities, have been using established protocols for data collection and sharing practices. As a result, there is now an increasing number of scientific publications based on CS data (for example, Sullivan et al., 2017; Loiselle et al., 2016; Vincent et al., 2017). We have also noticed such suspicion in both cases, especially from some stakeholder organizations such as DHM and district level authorities. Their main concern was on how to maintain these monitoring sites in the longer term. DHM also suggested to carry our more experimental research in other parts of the country before adopting into their hydrological monitoring system. It is now crucial that CS data and knowledge need to be systematically used in improving water ES management.

Successful CS activities are typically cost effective, excellent in public engagement and often entail innovative technologies in monitoring activities (Pocock et al., 2014). This has been well demonstrated in the projects reported here, notably the potential for low-cost LiDAR sensors to be widely applied to monitor flood risk. Most large scale CS projects have established standard data collection and verification methods, for example, *ebird* and OPAL projects have been deploying systematic data quality verifying processes. CS activities have also created social benefits by raising public awareness about local environmental concerns and promoting local engagements (Palacin-Silva et al., 2016). Nevertheless, CS practices have yet to create real impact in policy and decision making. CS projects are particularly not coherent in scientific methodologies (Bonney et al., 2014) and also face ethical issues about data collection methods and their acceptance among scientists (Riesch and Potter, 2014). Maintaining conflicts of interests, data exploitation, data disclosure and intellectual property are crucial to prove CS practices scientifically robust (Resnik et al., 2015). Despite several concerns in contemporary CS practices, the concept offers a new opportunity in environmental monitoring as the public interests and willingness to participate has been increasing across the disciplines. Both case studies experienced these key challenges, especially gaining end users trust in sensors and CS data was a major challenge. There is a need for locally tailored sensors and continuing local engagement.

Despite the active local participation in both sites, we also found that CS projects are still facing multiple challenges in terms of the extent to which local volunteers can use scientific methodologies such as user practices, sensor technologies, data aggregation, data quality control, privacy issues, recognition of local contribution and data accessibility. Nevertheless, a systematic use of CS approach could generate locally relevant data and help addressing water resources management challenges at local scale. To achieve desirable outcomes, CS projects need to identify right technologies alongside a plan for empowering citizen's ability to use those technologies in monitoring and data management practices (Roy et al., 2012). Local volunteers and participating stakeholders need to understand key issues such as their access to the internet, time to do the CS work, ability to follow scientific data collection protocols and web-based data management practices (Geoghegan et al., 2016). Data generated by affordable sensors should be robust enough to use in scientific purpose, and it is also desirable that collected data can be useful in local decision making. Although the role of new and affordable technologies is immense, the methods used in data collection and visualization need to be scrutinized. A successful integration of innovative CS practices should also be the interests of all participating stakeholders. Since collaborative research is now progressing from its traditional role as awareness raising tool to generating new data, incorporating local perspectives and knowledge and then recognizing them as a norm for effective decision making (Palacin-Silva et al., 2016), CS could become a complimentary approach in that direction. Since public volunteers are generating sizeable data and local knowledge through collaboration with research institutions, CS practices could make positive impacts in water and ES management.

Although the citizen science is a promising approach for both agricultural water management and flood risk reduction, successful integration and its sustainability are key challenges at local to basin scale decision making. While there is a strong component of innovative technological aspect, further experimental research may be required before adopting the approach as a viable and alternative approach. The sustainability issue could be addressed by developing a close collaboration with local partners and communities. In addition, capacity building of end users is essential to ensure the successful embedment of the approach in local decision making. If these major challenges are properly addressed, CS based hydrological monitoring could be an effective strategy to improve water ES management in the long-term.

5. Conclusions and the way forward

From the case study investigations, it is clear that the CS approach and low-cost sensors can play a central role in the polycentric governance of water ES management if sufficient attention is given to the way in which projects are designed, tailored and implemented in community settings. A key challenge is to ensure that the scientific merit of low-cost sensors and collected data is reconciled with the monitoring practices and protocols of decision-making bodies such as the DHM and local authorities. Our work shows that the relevant government and management authorities want to see further experiments and tests of fitness for purpose before integrating them into their monitoring system. The result of such caution is that large scale deployment of CS-based water data within water ES management is still far from realized. However, the use of low-cost and easy-to-use sensors means that CS approaches are gaining in credibility among this stakeholder group. With the roll out of ICT applications and online platforms, CS is becoming more accessible to local enthusiasts who can voluntarily contribute in data gathering by texting or uploading to relevant data repositories. Issues of data quality control and issues to do with central versus local ownership continue to slow progress. Building a strong partnership with communities and securing financial resources to continue monitoring activities can ensure the sustainability of CS activities. Since the voluntary participation of local people is largely driven by how a planned CS project is addressing local concerns of ecological and environmental issues, identifying those concerns is fundamental to any planned CS project to succeed.

Hence, research experiments conducted in both of our study sites shows that key local stakeholders such as DHM and local government authorities are reluctant to either be involved in CS projects or directly use CS data in their decision making practices. We found evidence that an adaptive monitoring strategy may be needed to overcome such resistance, with a systematic integration of CS data and knowledge into decision making building strategic partnerships with stakeholder organizations and help securing necessary financial support and upscaling monitoring activities in other similar situations.

Despite several challenges and limitations, there are reasons to be optimistic that well-designed CS projects can be integrated in water ES management in remote and data-scarce regions. From our experiments in Nepal, we highlight three key ingredients for success: Firstly, affordable and easy-to-use technologies should be identified and tailored to locally relevant hydrological data and the scope for knowledge cogeneration. While integrating new tools and technologies, local volunteers need to be trained to use them in situations where professional scientists and technicians will not be available or reachable. In many CS practices, local people merely become passive witnesses to the monitoring process rather than directly involved in it as a social practice. Although the greater availability of simplified tools would eventually cascade down to local scale as with the ICT and other technologies, we need to empower local volunteers and stakeholder organizations by giving targeted training and make the whole monitoring practice more integrated. Local stakeholders should be able to use such tools independently to generate data. The key question still remains unanswered whether water management authorities would be willing to integrate CS practices and low-cost sensors into their decision making practices.

Secondly, the sustainability of CS-based monitoring activities needs to be clearly addressed upfront. This primarily means finding financial support to underpin CS activities over the long term and addressing issues such as how and who will provide the costs of monitoring practices, especially in poorer and remoter areas. Transferring the ownership of monitoring practice to local volunteer groups could encourage end users to source relevant financial resources. Incorporating local data and knowledge at the stages of both project design and implementation is also desirable. Similarly, maintaining local motivation is a major factor to improve monitoring activities in the long term. If CS projects should be more flexible and able to incorporate emerging environmental issues for the upscaling best practices and making them self-sustainable. Thirdly, robust data quality control and the integration of CS data into decision making are both essential. These conditions require standardized protocols for monitoring, data quality checks and early engagement and buy in by stakeholders and officials. Finally, when CS projects can establish a practice for quality engagements with local volunteers, professional scientists and decision makers, the approach could create a robust pathway for a citizen-centric environmental decision making. A robust and locally suited CS practice could offer reliable solutions to water ES management.

Author contributions

BP produced the first draft of the paper and conducted the majority of the fieldwork on which it is based. WB designed the LiDAR sensor system. WB and CP contributed valuable inputs to the drafting and editing of the paper.

Conflict of interests

The authors have no competing interests to declare.

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