Environmental Science & Technology: Critical Review

Moving beyond the technology: a socio-technical roadmap for low-cost water sensor network applications

Feng Mao* [1,2], Kieran Khamis [1], Julian Clark [1], Stefan Krause [1], Wouter Buytaert [3,4], Boris F. Ochoa-Tocachi [3,4,5], David M. Hannah [1]

1. School of Geography, Earth and Environmental Sciences, University of Birmingham, UK

2. Present address: School of Earth and Ocean Sciences, Cardiff University, UK

3. Department of Civil and Environmental Engineering, Imperial College London, London, UK

4. Grantham Institute - Climate Change and the Environment, Imperial College London, London, UK

5. Regional Initiative for Hydrological Monitoring of Andean Ecosystems, Lima, Peru

*** Corresponding author:** Feng Mao

Email: MaoF1@cardiff.ac.uk

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Abstract

In this paper, we review critically the current state-of-the-art for sensor network applications and approaches that have developed in response to the recent rise of low-cost technologies. We specifically focus on water-related low-cost sensor networks, and conceptualise them as socio-technical systems that can address resource management challenges and opportunities at three scales of resolution: (1) technologies, (2) users and scenarios, and (3) society and communities. Building this argument, first we identify a general structure for building low-cost sensor networks by assembling technical components across configuration levels. Second, we identify four application categories, namely *operational monitoring*, *scientific research*, *system optimisation*, and *community development*, each of which has different technical and non-technical configurations that determine how, where, by whom and for what purpose low-cost sensor networks are used. Third, we discuss the governance factors (e.g. stakeholders and users, networks sustainability and maintenance, application scenarios and integrated design) and emerging technical opportunities that we argue need to be considered to maximise the added value and long-term societal impact of the next generation of sensor network applications. We conclude that consideration of the full range of socio-technical issues is essential to realise the full potential of sensor network technologies for society and the environment.

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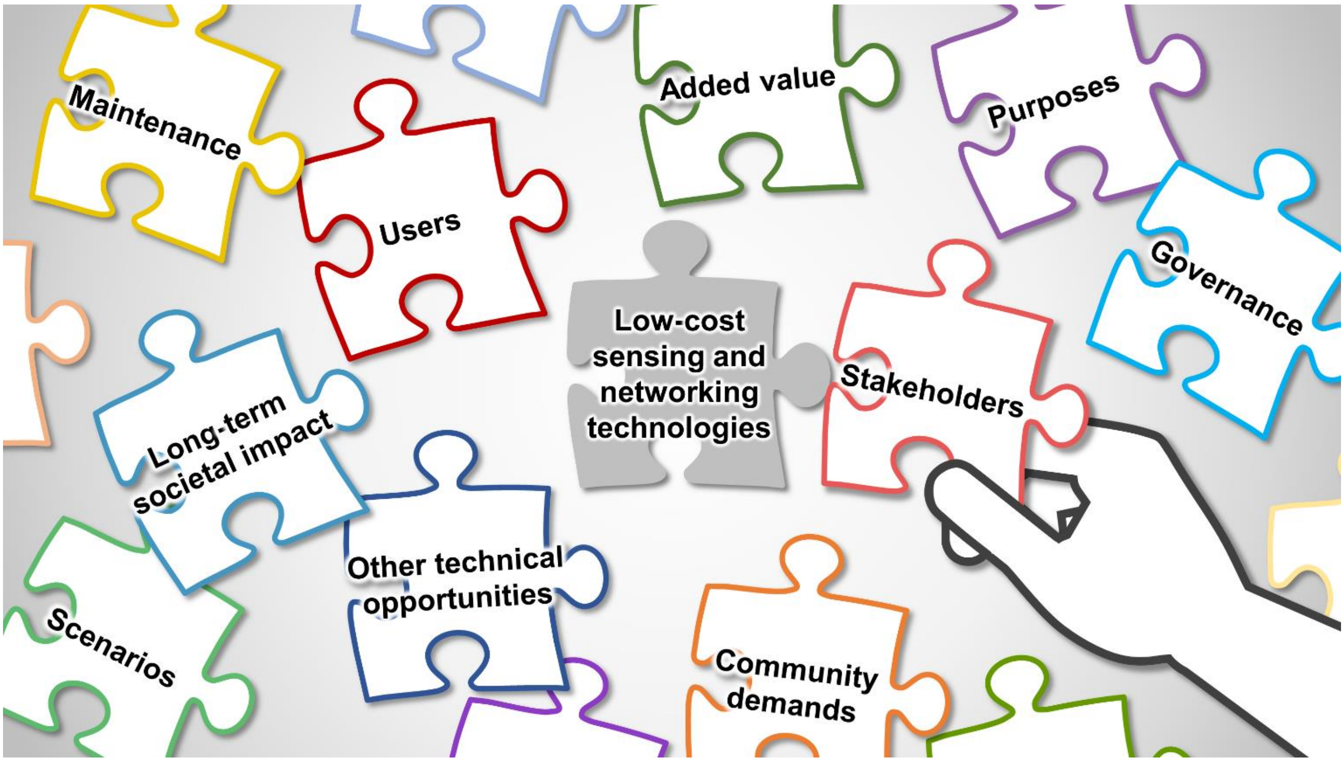
Maintenance
Added value
Purposes
Users
Governance
Low-cost sensing and networking technologies
Stakeholders
Long-term societal impact
Other technical opportunities
Scenarios
Community demands

1 Introduction

Rapid development of environmental sensing and networking technologies has altered radically the challenges associated with monitoring network design and implementation [1]. Historically, the focus was on where and when to sample to maximise coverage of spatial-temporal variability [2], often requiring physical sampling from specific locations. With the move towards automated environmental sensor networks (i.e. a collection of sensor elements that monitor and communicate measurements back to a central storage location), technical aspects of sensor networks became the main focus, such as how to design and build both sensors and the underlying network architecture, and also how to collect data with satisfactory quality [3]. However, technological progress, specifically miniaturisation and mass production of electronic components, has caused a proliferation of low-cost sensor networks across a range of applications, opening up new non-technical challenges (often related to network governance) that we argue now need urgent attention. These emerging challenges represent a major obstacle to the successful and effective delivery of sensor focused applications [4]. For example, in the information and communication technology for development (ICT4D) context, many initiatives fail after being deployed – not because of technical defects or faults, but rather because the technologies used require high maintenance or are not accepted by local communities [5,6].

Hence, we contend there is a pressing need to conceptualize sensor networks more holistically, comprising social and technical elements [4,7]. In doing so approaches to enable better design of tailored low-cost water sensor networks using existing technologies can be developed. In particular, there is a need to better consider the monitoring context, scenario and stakeholders, to deliver sensor networks which add value to conventional hydrological data collection activities. These considerations enable the full potential of low-cost information and communication technologies (ICTs) to be realised and used as a tool to build a more sustainable and resilient future for water sensor network applications.

This paper provides a critical review of the literature on low-cost senor networks (i.e. a collection of sensors operating autonomously that collect data, and with a low overall cost of the whole network), before considering their application in participatory monitoring networks used by different stakeholders for specific purposes. In doing so we aim to systematically bridge the gap between technologies and the current state-of-the-art in network design, implementation, and governance. More specifically we assess what recent technical advancement means for implementation and governance of current and future low-cost sensor networks. To make the critical review and constructive discussion more specific, we focus here on low-cost freshwater sensor networks as applications that have reach and significance for the global earth and environmental system, and thus have potential for generalisation in the broader physical field beyond freshwater.

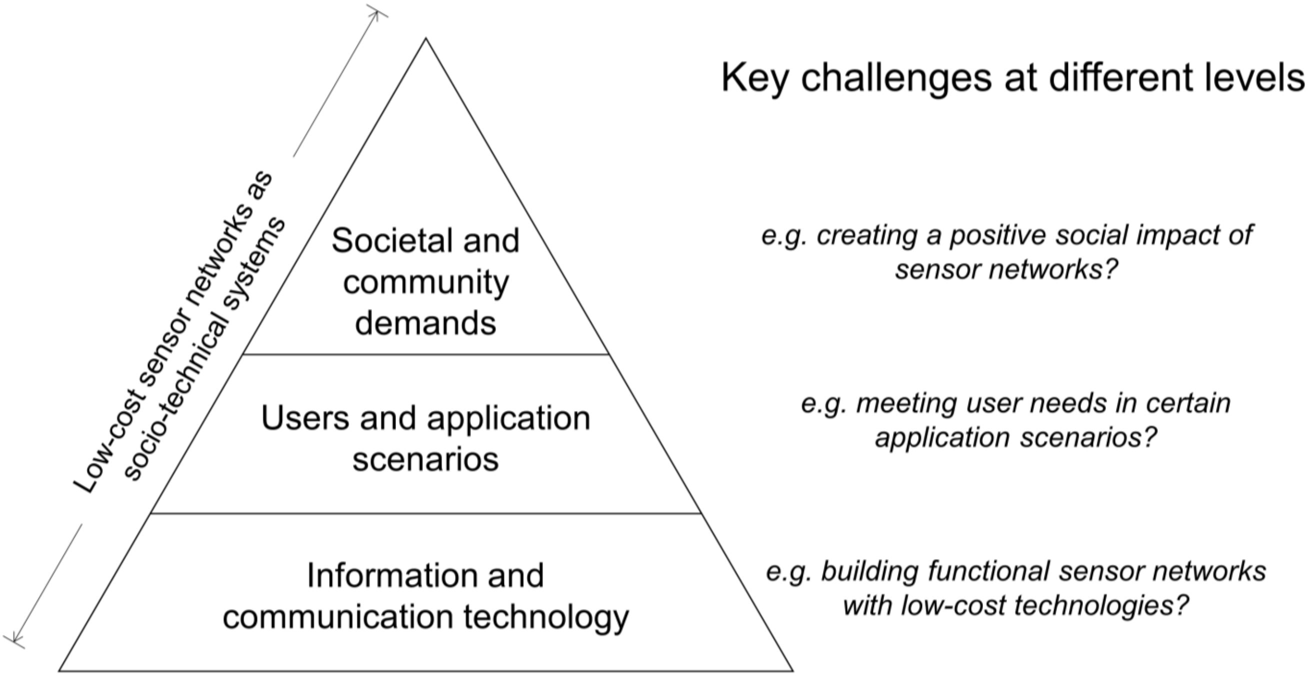

Figure 1. Low-cost sensor networks as socio-technical systems and example challenges at different levels.

In our review, low-cost water sensor networks are therefore viewed most appropriately as socio-technical systems [8] whose effectiveness depends on addressing socio-hydrological functions (e.g. monitoring in real time attributes of water quality or quantity for specific users), rather than as more conventional technical systems (Figure 1). Crucially, the success of socio-technical systems relies on optimising both its technical and social parts [9,10]. This socio-technical perspective enables us to consider factors which cross disciplines and scales, spanning technical aspects such as hardware, software, data transmission and processing, to higher socio-technical levels such as users and application scenarios, and societal and community demands [11–13]. In contrast to human-computer interaction that emphasises user experience and usability, the socio-technical approach encourages us to incorporate human, social and organisational dimensions into system design [9].

Here we provide a vision and future direction for this research field by considering recent rapid technical developments, increasing awareness of user and scenario needs, and how these now need to address wider societal demands (i.e. three levels of the pyramid in Figure 1). We do so by synthesising the literature and associated projects focused on low-cost water sensor networks to answer three main questions posed by the socio-technical 'pyramid' of Figure 1, namely: (1) What is the established mainstream model for building sensor networks (Section 2)? (2) How are low-cost sensor network applications currently used by stakeholders to tackle specific monitoring tasks and scenarios (Section 3)? And building on (1) and (2), what are the governance challenges and research opportunities for creating pervasive and long-term societal impact of low-cost sensor networks (Section 4)? In this review, we demonstrate that the potential of low-cost technologies and the range of possible sensor network monitoring configurations are yet to be achieved, particularly in the context of resource-constrained regions. Hence, we argue significant scope remains for expanding and improving the utility of low-cost sensor networks, providing their socio-technical attributes and challenges are given the required credence.

2 Towards a general structure for sensor network assembly

Here we offer a concise history and background of sensor networks, and investigate the flexibility and potential of low-cost ICTs in a wide variety of operational and policy contexts and resource-constrained settings. By reviewing the current options, we identify a general structure for assembling technical components (environmental sensing and networking technologies) across multiple configuration levels (e.g. unit, node, network), and demonstrate how these can be considered as building blocks that can be structurally organised into sensor networks.

2.1 Development of sensor network technologies

There has been significant progress in environmental ICTs over recent decades, with sensor networks gaining new features and becoming increasingly important for environmental monitoring, research and management. Automated and wireless environmental monitoring can be traced back to the early 1940s, when automatic weather stations were developed to replace repetitive labour-intensive manual data logging [14]. This enabled recording of environmental data at predefined intervals using automated loggers which could then be transmitted via radio to remote receivers. By wirelessly connecting multiple sensors, loggers or stations together, sensor networks make it possible to manage and synchronise environmental monitoring over large spatial areas, and so obtain data remotely [15]. Given these benefits, there have been moves towards the routine use of sensor networks for environmental data collection by environmental monitoring agencies globally (e.g. Environment Agency of England, National Oceanic and Atmospheric Administration of the United States).

Recent innovations in smart technologies (e.g. automation tools, internet of things (IoT), and the open-source movement) have provided numerous opportunities to develop and implement environmental sensor networks. There is now a wide range of highly modularised sensing and communication technologies available, which represent an array of technical components of reliable quality and increasing affordability [16,17]. This has fostered a rapid increase in the research, development and implementation of low-cost sensor networks for environmental monitoring and, in the case of water-focused applications, are increasing as a relative fraction of all sensor networks (Figure 2). The increasing popularity of sensor network research coincides with the global growth of low-cost or open source hardware movements, such as those centred around the Arduino microcontroller board (established 2004) and the Raspberry Pi single board computer (established 2012) see 7 (Figure 2).

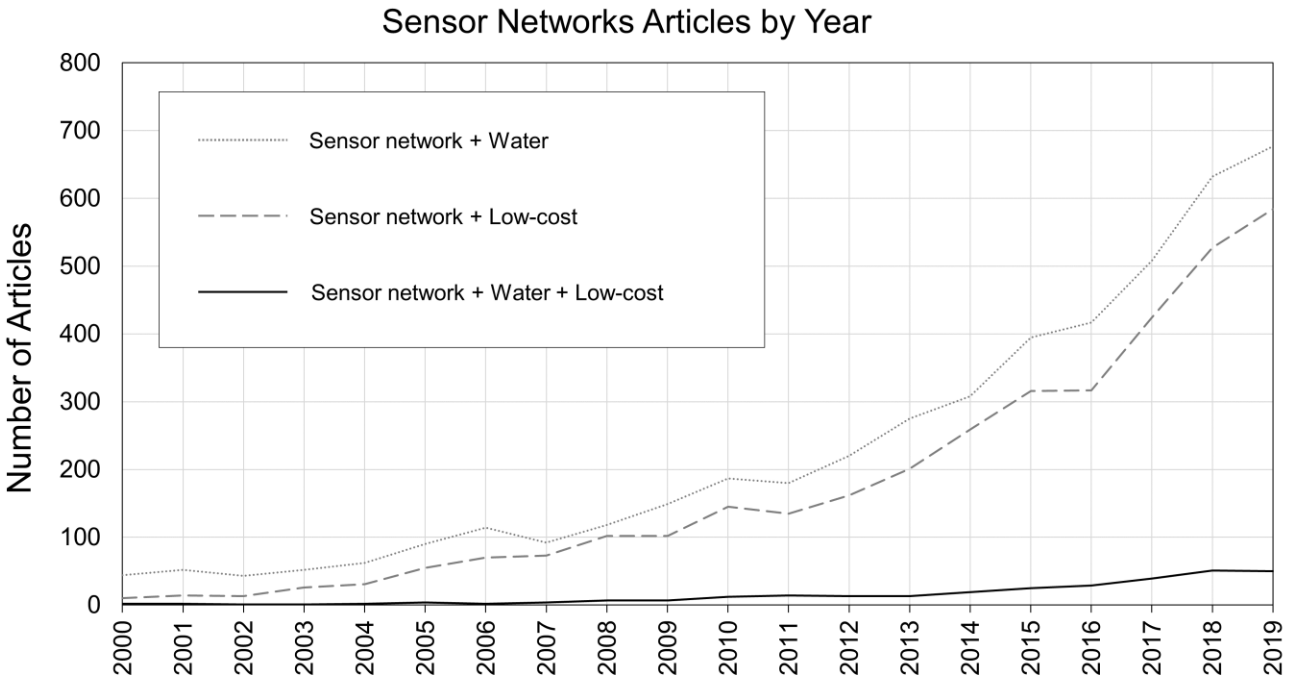

Figure 2. The number of articles on sensor networks per year since 2000. The light grey dotted line denotes articles of low-cost sensor networks, the dark grey dashed line denotes articles of water-related sensor networks, and the black solid line denotes articles of low-cost water-related sensor networks. Articles were identified using Web of Knowledge search queries: Sensor network: Topic = ("sensor*" AND "network*"); Water: Topic = ("water" OR "hydrology" OR "hydrological" OR "freshwater" OR "river" OR "rivers" OR "lake" OR "lakes"); Low-cost: Topic = ("low-cost" OR "low cost" OR "opensource" OR "open source" OR "inexpensive"); Document types: (ARTICLE).

These technical advances have greatly extended the potential application areas, purposes and scenarios in which low-cost sensor networks can be adopted [18]. For example, customised hydrological monitoring systems can now be built by researchers, water practitioners, and even hobbyists for whom expensive commercial hardware is out of reach, or have more tailored data and system[i] requirements. Especially for scientific research and environmental management, low-cost sensor networks can potentially mitigate the uneven distribution of monitoring sites – they are more likely and economically possible to cover data-scarce areas such as developing countries [19], rural regions, mountainous/upland headwater river systems [20] , and extreme environments e.g. 21 in a meaningful way.

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[i] An example: http://www.freestation.org/

2.2 Technical building blocks

Within a local sensor network, there are three main types of nodes. The *coordinator node*, or 'base station', is the centre of the network, coordinating the rest of the nodes in the network, and acting as a data sink, and sometimes a gateway that transmits the data out of the local network. The *sensor node,* also called 'mote', collects and sends environmental / hydrological data to the sink. The *relay node* does not collect or sink data, but is used to relay the data between the sensor and sink nodes when their distance is beyond the transmission range [22]. In addition to these three main types, a *human-computer interface node* is sometimes constructed to provide a direct communication channel to enable users to operate sensor networks.

Network nodes are comprised of several functional units that vary depending on unit selection and combination. The power of nodes may come from active sources (e.g. batteries and alternating current), or passive sources (that are usually used to charge the active sources; e.g. solar panels). A *processor unit* usually includes a micro-controller and local memory for data processing. The *Arduino* and *Raspberry Pi* platforms are the two examples of popular low-cost options for the processor unit. They have different features and are therefore suited to slightly different applications but have both used in many sensor networks. The *Raspberry Pi* is a series of inexpensive single-board computers and can be used as a general-purpose computer with potential for edge computing and advanced analytics locally as it was originally designed for basic computer science teaching in developing countries. The *Arduino platform,* a family of open-source single-board microcontrollers, was originally designed for building IoT and automation applications. Arduino has its own integrated development environment (IDE). Due to the nature of open-source hardware, with schematics readily available, many Arduino-compatible or -derived boards are provided by third-party manufacturers, some with enhanced or tailored features for different purposes (e.g. Adafruit feather series and Seeeduino series). Some sensor network builders may opt for other customised processor units with additional features, such as neoMote [23], Mayfly [24], ALog [16], Cave Pearl data logger [25], DIY environmental microcontroller units [17], or other commercial options [c.f. 26,27].

There is a large collection of low-cost hydrological *sensors* available covering a wide range of parameters. Commonly used *sensor units* include water quality sensors (e.g. turbidity, temperature, electrical conductivity and pH), soil moisture sensors, tipping bucket rain gauges for precipitation measurement, and water level sensors using pressure, radar or lidar technologies [28–31]. The cost of a sensor varies between parameters (e.g. temperature vs pH) but also for a specific parameter – from more professional yet expensive options to low-cost alternatives [32,33,e.g. 34] depending on required mechanical and accuracy / precision specifications.

The *data transceiver unit* is a prerequisite for wireless sensor networks that can communicate collected data back to a central storage location without cables. There are many available options for wireless communication, which have their own features, strength or scope of applications. For example, *Zigbee* is a set of communication protocols for creating wireless networks with low-power consumption but a low data transmission rate. *WiFi* technology involves the creation of wireless local area networks (LANs); while this facilitates high bandwidth there is a significant expense in terms of high energy consumption and short transmission range [e.g. 35]. The mobile phone links have sufficient bandwidth for most environmental monitoring scenarios particular as we move to 5G technologies. The *LoRa* technology, low-power radio frequencies is gaining popularity in IoT applications but coverage outside large urban areas is currently limited [36]. It is worth to note that the above technologies are just some common examples used in low-cost sensor networks, and a more complete list of wireless communication technologies and their features can be found in technical reviews [see 37,38].

Sensor network structure is a particularly important design aspect that can be approached at different scales with significant impacts on governance (see Section 4.2). A single wireless sensor network at the local scale requires a base station, to act as the network coordinator and data sink. At the regional or global scale, a local sensor network can be connected to either the internet or other sensor networks [39,40]. The connections between the local network and the internet represents the exchange of data and information between base stations/gateways and online servers (Glasgow et al 2004), while the connection between multiple local sensor networks involves links between base stations/ gateways from several local networks (Zia et al., 2013; Figure 3a). Depending on the monitoring context and purpose, different network architectures can be constructed with these connections to meet specific monitoring requirements (See section 3). For example, if the sampling sites are sparsely distributed in the landscape or barriers to communication exist (e.g. mountainous terrain) then local networking is not feasible, thus data collected by each sensor node can be uploaded directly to a cloud server (Figure 3b) [41,e.g. 42]. Alternatively, in more remote regions with limited human infrastructure the data collected by a local network can be stored in the base station and downloaded manually (Figure 3c) which in some development contexts may be the only feasible option. Alternatively if suitable infrastructure is in place data can be automatically uploaded to the internet via the base station (Figure 3d) [e.g. 33,43]. Recent approaches have advocated managing several networks remotely via the internet (Figure 3e), even if they are hierarchically structured this can make governance more efficient but requires a more top-down approach to network design (Figure 3f) [e.g. 23]. This approach may open opportunities for locally organised and community-led monitoring networks (see Section 3.4).

To summarise, we have identified a general structure for low-cost sensor network design which can be applied as a technical basis across varied application scenarios in Section 3, and can be further upgraded into participatory sensor networks that have social factors fully incorporated (Section 4).

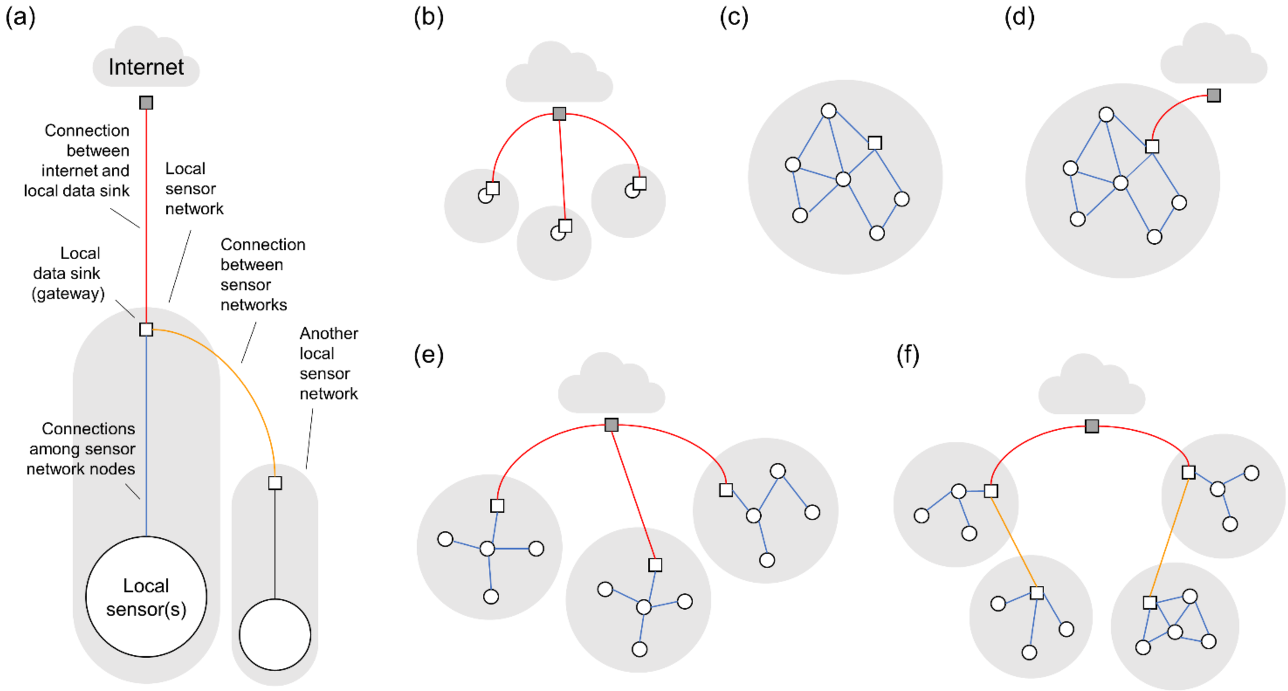

Figure 3. Example network architectures. (a) A schematic diagram of general network architecture, showing three types of connections: (i) connection between the internet and a local data sink (red line), (ii) connections among local sensor network nodes (blue line), (iii) connection between multiple sensor networks (yellow line). (b) An architecture with internet but no local networks. (c) An architecture with a local network but no internet connection. (d) An architecture with internet and one local network. (e) An architecture with internet connection and more than one local network. (f) An architecture with an internet connection and several local networks at different levels. Squares denote base stations or gateways; circles denote other network nodes such as sensors or relays.

3 Key categories of water-related low-cost sensor network applications

Low-cost water sensor networks are designed and developed as monitoring solutions that operate within certain hydrological scenarios. In this section, we identify from the academic literature four main application categories in which low-cost water sensor networks are currently or could feasibly be deployed. Typical examples are highlighted (Table 1), and the relationship between technology and properties of the monitoring category are discussed (see Figure 1). We identify four categories from the literature: (1) operational monitoring, (2) scientific research, (3) system optimisation, and (4) community development, though we should make clear that this does not by any means represent all existing application types and that these are not mutually exclusive. However, the classification captures a general pattern of how and where low-cost sensor networks are used. In each scenario, low-cost sensor network applications are situated in similar socio-technical niches and have corresponding technical configurations. We highlight four category elements thereof that determine and are determined by the application of sensor networks.

- Purpose: What is the main purpose of the network?
- Stakeholders: Whom the sensor network is built for? Who is involved in managing the sensor network? Do the stakeholders have multiple purposes?
- Management: How is the sensor network operated and maintained? What are the roles and incentives of different stakeholders in managing the sensor network?
- Scale: What temporal and spatial scales does the sensor network cover, the stakeholders interact, and management take place?

For example, within each category, the applications are designed for similar purposes and contexts; they are managed and participated by similar groups of users and stakeholders at similar scales; and in most cases have similar technical features and attributes.

Table 1. The main application categories suitable for the deployment of low-cost water sensor networks.

Scenario	Main purpose	Key stakeholder	Technical features	Scale	Management/governance	Typical context	Examples
Operational monitoring	Monitoring and water-related data collection	Monitoring agencies; water resource managers; scientists	Technologies that support long-term and large-scale monitoring	Regional - national scale; long-term	Led by single stakeholder; Adherence to international standards; Sometimes participated by citizen scientists	Regional - national monitoring programs	Weather Observation Website (wow.metoffice.gov.uk);
Scientific research	Problem-oriented research	Scientists	Data quality and network reliability are the primary concerns	Temporary set-up; generally small spatial scale	Led by single or few stakeholder; Tailored to the research problem	Variable and dependent on research question but can be in an extreme biophysical context	HiWATER [44,45]; SoilNet [46]; CAOS [47]; American River Hydrological Observatory [23]
System Optimisation	Management and control of water-related systems to optimise their status. e.g. irrigation and agriculture, aquaculture, stormwater management	Water managers, agricultural managers, farmers	Real-time or near real-time data processing; data visualisation for decision making. Often linked to actuators for system control	Local spatial scale; long-term	Led by few stakeholder	In an urban, agricultural, or indoor environment	Gutiérrez et al. [33]; Simbeye et al. [43]; Open Storm [48]
Community development	Sustainable development in rural areas	NGOs, local community members	Application of cellular networks and mobile phones	Local spatial scale; short or long term	Collaboration between external NGOs and local community members	Rural areas particularly in developing countries, usually covered by cellular networks	SmartPump [49]; SWEETSense [50]; iMHEA [51]

3.1 Operational monitoring

Operational monitoring is one of the most established applications of hydrological sensor networks. The main purpose of this category is to collect high-quality hydrological or meteorological *data* that contribute to long-term datasets often stored in regional or nationally curated databases, with the focus largely on meeting legislative monitoring requirements (e.g. the EU Water Framework Directive) rather than data collection to answer a specific scientific question. Water utilities, which have a long history of maintaining sensor networks to assess water resources, water quality, and more recently water consumption [52], could also be considered in this category. However, given the focus has largely been on monitoring of specific assets / infrastructure, with commercial sensor network solutions [53], we will not consider them specifically in this section but will explore some lessons learned / approaches used by the water utilities in Section 4.

The value of data collected for operational purposes and their potential for a variety of application possibilities is widely acknowledged, particularly for assessment, research, and decision-making [54]. Usually, these networks follow well-established international standards, such as those of the World Meteorological Organization [55,56]. Currently the use of low-cost sensor networks is limited as the focus is on high reliability, standardization, and long-term consistency. However, there is significant potential for low-cost sensor networks to support long-term and large-scale hydrological observation, especially in data-scarce or remote regions that are not covered by conventional monitoring systems, and are initiated and operated by public or private monitoring bodies [57].

These networks can benefit from the participation of the general public and citizen scientists. For example, the Weather Observations Website (WOW) was launched by the UK Met Office in 2012 and is an online platform for the meteorological monitoring community to upload, share and view their observation data [41]. Private owners of compatible automatic weather stations are encouraged to be involved in the activities. They usually install the stations in their gardens or on the rooftops, which are in close proximity to home WiFi routers [58], hence, collected data can be sent directly to the server through this WiFi connection (see

Figure 3b), and updated hourly on the Met Office site (http://wow.metoffice.gov.uk/). All the stations collectively form a large UK-focused global weather observation network which can, if measurement bias is adequately accounted, provide data that can augment existing networks of professional weather stations [59], being an alternative and cost-effective solution to achieve global and large-scale monitoring.

3.2 Scientific research

Scientific research driven sensor network applications differ from the operational/single purpose monitoring scenario as they are always hypothesis driven or challenge led. The data are collected by a single research group or through multidisciplinary research collaborations, and are used to answer certain scientific questions. For example, the CAOS project regards catchments as organised systems, aiming to provide a new modelling framework for complex intermediate-scale catchments, and to understand distributed dynamic hydrological processes [47]. To do so requires considerable amounts of highly resolved data (e.g. precipitation, humidity, soil moisture, water level, water quality) at a scale matched to the spatiotemporal pattern that is being investigated. Low-cost water sensor network applications are becoming increasingly used as they can provide a customised and flexible solution for diverse research purpose [47,60]. Similar demands and situations can be found in projects such as HiWATER [44,45] and SoilNet [46]. They both developed wireless sensor networks based on Zigbee and cellular network technologies to gather soil moisture data for hydrological research.

The selection of monitoring technologies in this category is, perhaps more than in other categories, determined by the scope of research questions and constrained by the nature of research projects. This is a function of the great diversity of monitoring applications within this category. For example, the installation of monitoring nodes is usually on a non-permanent basis and are planned to only last for the duration of the project, or until sufficient data are generated to answer the particular research question of interest. Hence, a low-cost solution with suitable accuracy, longevity and reliability may be preferable.

For example, in order to understand streamflow generation in meltwater dominated river systems, a wireless sensor network of 12 stations was deployed to monitor meteorological variables and river discharge in the Swiss Alps for 4 months in 2009 [61]. In the HiWATER project, 3-month data collected by sensor networks were used to explore the strengths and weaknesses of a particular hydrological analysis method [44]. While for the SoilNet project, sensor networks collected date from August to November 2009 to explain the spatial and temporal patterns of soil water content [46].

For scientists and their research projects, data quality (e.g. data accuracy, precision and drift) and network reliability are usually on the top of the list of concerns and in certain projects only more professional sensors or highly optimised nodes are suitable. At the same time, it is common within the scientific community to take advantage of newer technologies and leverage innovative methods [62]. More recently there have been projects combining a range of equipment from low-cost to expensive commercial kit. For example, the American River Hydrological Observatory (ARHO) covers an area of ~5000 km^2 in California, USA, and consists of 14 clusters or sub-networks of wireless sensor nodes organised in a hierarchy (see Figure 3f). Each sub-network has a mesh topology with one base station as the network manager and ~10 sensor nodes and 7 - 35 relay nodes. To support a smooth operation of a research sensor network at this scale, the NeoMote (see Section 2.1) was tailored to be used as the sensor and relay notes while Dust Networks Eterna radios, claimed as a low-cost industrial level ultra-low power wireless network platform, was used for data communication [23].

Maintaining data quality and network reliability can also mean that certain features of low-cost sensor networks features have to be compromised to assure the data meet these criteria. In some scientific applications, sensors are not wirelessly connected but organised as networks of isolated automatic loggers. These data are not transmitted to the internet automatically or in real-time but have to be downloaded from the local sensors or data sinks manually on a regular basis. For example, Pohl et al. [63] developed a network of snow monitoring stations (SnoMoS) across three river basins in Southern Germany. Between 2010 and 2012, during two winters in low-temperature and remote condition, nearly a hundred low-cost sensors collected data that was stored locally and then downloaded manually by direct connection using a laptop. While these compromises can be labour intensive, they can help to optimise limited power with a focus on data collection rather than transmission. This does, however, represent a trade-off between routine visits for data download and targeted visits when maintenance is required which can be identified remotely via wireless connection. These issues, along with others, need to be carefully considered as the optimal data transmission strategy will likely depend on the types of sensors used, how remote or hostile the monitoring environment is, GSM signal coverage, and power availability.

3.3 System optimisation

In addition to operational monitoring and scientific research, low-cost sensor networks have also been extensively used in water resources management, especially related to agriculture [64,65]. The main purpose of this application type is to control, maintain and optimise system conditions, such as water quantity, quality and usage.

Although the collected data can be used to inform water managers of parameters in near-real time enabling proactive response to system change, this feedback action is most effective when conducted via automation with actions taken according to predefined trigger thresholds. To achieve this, actuators need to be incorporated into the network, which turn the ‘wireless sensor network’ into a ‘wireless sensor and actuator network’ (WSAN) [66]. The data collected by sensors are processed at regular intervals (i.e. near real-time), and transformed into commands that are sent to actuators to control the system. For example, Gutiérrez et al. [33] developed a network to optimise water use for agricultural irrigation using nodes of soil-moisture and temperature sensors connected by Xbee and Zigbee technologies. The collected data were then transmitted, stored and analysed in a sink node. The local network had a two-way connection to the internet using the cellular network. This allowed routine irrigation schemes to be examined and activation thresholds adapted using a on graphical user interface. Two pumps for irrigation were controlled via a micro-controller and were activated when the threshold values of soil moisture and temperature were reached. The initial test result showed that this automation system has potential to reduce water usage by 90% compared to conventional irrigation practices [33]. A similar WSAN application was presented by Simbeye et al [43] for aquaculture. Here, sensors were used to monitor variables including dissolved oxygen, temperature, water level and pH, and multiple nodes were connected using Zigbee technologies. The fishponds oxygen levels were controlled by water valves and aerator pumps based on the real-time water quality data inputs. A local computer was used as the data sink, processor and controller. However, this differed from the operation of Gutiérrez et al [33] setting, as this application was not connected to the internet, but still provided sufficient functionality for improved aqua-culture management. This non-internet-dependent feature has good potential for promoting better agricultural practices in resource-constrained and remote communities.

Sensor networks can also be applied for management in fields other than agriculture, for example, Bartos et al. [48] introduced an ‘open storm’ platform for sensing and controlling watersheds. The WSAN collected distributed hydrological data such as rainfall, water level, soil moisture and water quality, and transmitted records to an online server in real-time. These data are then available for global processing to enable dynamic regulation of water levels across watersheds using a network of automated sluice gates and valves on stormwater drainage infrastructure. This activity supported flood protection, riparian ecosystem preservation and distributed stormwater treatment.

3.4 Community development

Low-cost water sensor networks have also been used for social development purposes that encourage collective actions. The environmental sensing activities in this scenario are not only a useful source of information for management, but more importantly can be seen as interventions to provide new livelihood, improve living standards, or as catalysts to create new pathways to more sustainable and resilient futures, especially for developing regions [67]. As a result, the applications in this scenario usually involve the participation of both external and local stakeholders and collaborations between developed and less developed countries. For example, around 200 million people in rural sub-Saharan Africa rely on groundwater and locally managed hand-pumps for all water usage [49] . However, the maintenance of these pumps has been the bottleneck of sustainable water service supply. Nagel et al. [50] developed a sensor network experiment based on affordable technologies in Rwanda in which the water level of 181 hand-pump overflow basins was measured using pressure transducers, and the information then transmitted to an online dashboard via the cellular network. This study highlights how an automatic sensor network can be used to manage water pumps and significantly decreased the number of non-functional pumps. Koehler et al. [49] highlight the need for good maintenance of water infrastructure, which can be underpinned by automatic sensors, as it dramatically increased willingness to pay for water services among communities in rural Kenya.

Community-based monitoring can achieve optimal complementarity with existing monitoring networks by national authorities of hydrology and meteorology. The iMHEA network in the Andes [51] is based on the assumption that civil society-based institutions can contribute with local scale monitoring of headwater river systems in remote areas, thus supporting sustainable development of remote mountain areas [68]. The network consists of more than 30 headwater catchments covering four major biomes in more than 10 locations of the tropical Andes (Venezuela, Colombia, Ecuador, Peru, and Bolivia). Precipitation and streamflow are monitored at high temporal resolution (5 min interval) using relatively low-cost sensors in small micro-catchments (between 0.5 to 8 km^2) with contrasting land management. The high spatiotemporal resolution of their data is aimed to support evidence-based decision making on land management, and has been made compatible with the usually long-term and low-spatial density of national monitoring networks [69].

The sensor network applications in this category are compatible with and are often built upon the existing mobile networks in developing regions facilitating the potential for participation by a much broader range of stakeholders. In many low- and middle-income countries, mobile cellular networks have developed rapidly as the key communication technologies, which are more accessible, reliable and thus, popular than traditional communication networks such as landlines [70]. For example, in 2015 some countries in Africa and Asia (e.g. Nigeria, Ghana, China, Malaysia, etc.) have experienced a significant increase in the proportion of the population (>10%) accessing the internet multiple times per day via smartphones when compared to the previous year [71]. It was estimated that the number of people with mobile network assess in Africa even overtook the number with improved water supplies in 2012; and in India the number of people with mobile network subscriptions is twice the number with piped water connections [72].

The coverage of cellular networks not only helps to transmit locally collected data to the internet, but also enables delivering the information to direct network end-users via mobile phones or other visualisation approaches. For example, Duncombe [73] also points out that mobile phones play an important role in disseminating information which determines the range and combination of people's choices and has great impacts on livelihoods. Zennaro et al. [74] introduce a case that applies wireless sensor networks to remotely monitor water storage tanks in Malawi. This application has a low-cost mechanism for water tank maintenance and sends alerts via short message services (SMS) to technicians when tank levels reach a critical point.

4 Opportunities for maximising societal impact

Thanks to the rapid advancement of low-cost technologies, sensor network applications have been changing the nature of active participation in data generation and increasing spatial coverage of monitoring sites. As highlighted in previous sections, flexible and versatile low-cost sensor technologies are now used in different applications for a wide range of purposes, and these have begun to generate impact at a wider societal level (Figure 1). At the same time innovative approaches (e.g. those addressing stakeholder engagement, financial incentives, application scenarios) rooted in the social sciences and specifically governance can contribute greatly in amplifying and strengthening this impact, by unlocking challenges around *inter alia* varied user roles and involvement, the needs of diverse geographical contexts, nuanced approaches to stakeholder engagement, and alternative incentive mechanisms and application scenarios. There is great potential here to learn from advances in the social sciences. Consequently here we examine these approaches and opportunities in societal and human dimensions that so far have been largely overlooked by researchers focused on low-cost sensor networks [4]. We contend these need urgent consideration if we are to leverage the maximum added-value from the next generation of hydrological sensor networks: namely, using these networks as key governance mechanisms to navigate towards more resilient and politically sustainable human-water relationships.

4.1 Stakeholder roles and interests

Affordable technologies are now enabling more stakeholders to participate in hydrological monitoring activities, especially in resource-deprived settings [69]. These stakeholders have widely differing roles, ranging from software developers responsible for sensor network design and development, funders supporting hardware installation and operation, users who co-produce or otherwise benefit from the outcomes of sensor networks, and ICT staff managing day-to-day maintenance issues. Given these stakeholder roles and their varied socio-technical contexts, involving them directly in the co-production of sensor design is imperative [75], not least because they have different goals and interests. For example, monitoring agencies conduct long-term and large-scale hydrological observations; researchers need evidence to answer scientific questions; and water users require information to achieve effective and efficient resource management. Moreover due in part to the open science movement [18], individual stakeholders can now play multiple roles as software designer and developer, sponsor, and data user.

In the monitoring categories outlined in Section 3, we identified multiple stakeholder roles particularly in two situations: water projects with public participation and citizen science elements (see Section 3.1 *operational monitoring*) [57], and those focussed on community development (see Section 3.4 *community development*) [50]. For example, public participation in water management often involves citizen scientists enrolling in sensor networks for monitoring and research, while sensor networks deployed in rural community development are usually sponsored and technically supported by external stakeholders.

4.1.1 Citizen science

The general public is playing an increasingly important role in low-cost monitoring activities, acting as citizen scientists participating in data collection and research, activities more often undertaken by scientists or professionals [76]. Volunteers can participate in operating and managing in-situ sensor networks, or in mobile crowdsensing by contributing water-related data using their own mobile phones [77,78]. Citizen science activities can offer a novel long-term source of hydrological information. Haklay [79] identifies four levels of citizen science, ranging from crowdsourcing of data, through to distributed intelligence, participatory science and collaborative science. This implies community involvement is not restricted to maintaining sensor networks and monitoring water parameters, but can encompass collective problem solving, information interpretation, knowledge co-generation, and decision-making. For example, in supporting community-based environmental management, citizen scientists might identify locally-specific problems and formulate research questions, maintain continuous data generation, make data generation useful and relevant to their everyday activities, and synthesise traditional and indigenous knowledge with newly generated knowledge to support decision making [80].

4.1.2 User-centred design

Divergent demands for specific sensor network features strongly suggest a user-centred and co-produced design approach is required. Instead of trying to apply blanket or standardised technical solutions in all cases, the user-centred approach starts from users' bespoke needs and tries to meet their requirements, daily routines, socio-economic conditions and socio-technical contexts by choosing appropriate tools from the technology pool.

Although some citizen scientists and researchers may set up and manage their own local sensor networks, this is not always the case. For example, in community development and for participatory monitoring at a larger scale, the network developers, users and managers may not be the same people and can have different perspectives, experience and understanding of sensor networks and the monitoring system of interest. Thus, high levels of communication are needed between these groups to reduce misunderstandings in the early stage of design. For example, the same concept can be understood differently by developers and potential users; so a ‘low-cost senor’ to a scientist may be a device costing ~$100 but many rural communities would find $100 unaffordable without subsidies [4]. Zulkafli et al. [80] therefore introduce a *user-driven* framework for designing decision support systems and other relevant technical applications. The aim is not only to guarantee meeting user demand, but more importantly to underscore the usefulness of building user involvement and keeping user-designer collaborations throughout the development process, from actor and requirement analysis to iterative testing and refining until the final delivery of the application [81,see 82].

4.2 Network sustainability and maintenance

Sustainability is a key requirement in designing and implementing low-cost sensor networks. As already discussed, the scope of scientific monitoring activities is often restricted by available research funding, which is not ideal for large studies needing long-term observations. Technical innovations developed by scientists or engineers may not be sustainable in the ‘real-world’ if challenges, such as power supply, management, finance and socio-political contexts have not been considered [4]. Therefore, alternative sustainability mechanisms, such as governance models, funding schemes, stakeholder engagement approaches need to be considered in these circumstances.

4.2.1 Governance

Prevailing patterns of governance (spatially distributed patterns and processes of decision-making and decision-taking among actors that takes account of existing power relations) are often decisive to how stakeholders participate and interact in monitoring networks [83–85]. The three most common patterns of governance for managing sensor networks are hierarchical (‘command and control’), grassroots (‘bottom-up’) or collaborative in their orientation.

Hierarchical governance typically commits significant resources to fund top-down structures and management tools required for sensor networks; this is often only undertaken if state agencies are the direct beneficiaries of network operation. Most projects in the first three categories (i.e. operational monitoring, scientific research, and system optimisation) are arranged this way.

In the grassroots governance approach, sensors or sensor networks are set up at the local or community scale or even by individuals to meet their bespoke requirements. Some actors aim to use the collected data as evidence of geographically-specific environmental problems with which to draw down resources for future action from the state or from other external stakeholders [83]. The funding, management, and organisation of these grassroots sensor networks are often provided in part by a range of local actors instead of being dominated by a single major sponsor. The locally managed sensors may be connected and contribute their data to a shared platform. Examples of such approaches include the citizen science-based WOW project [41] or the community-based iMHEA network [51].

Collaborative governance involves participation by diverse groups of stakeholders which cross the boundaries of public agencies, scales of government, and/or the public, private and third sectors to implement monitoring activities that cannot be achieved by one sector alone. This can involve organizing polycentric structures with multiple decision-making centres across scales, sharing decision-taking responsibilities and information [69]. For example, the TAHMO project demonstrates how different sectors work together to achieve long-term hydrological and metrological monitoring in Africa [86]. Here researchers developed low-cost weather stations which were installed and managed in local schools, with data generated being used as in science teaching activities. Collected data were then sold to insurance companies, with local farmers benefiting from improved weather forecasting services and better insurance cover for agricultural production. In addition, there were new opportunities to integrate sensor network approaches into other funding models in the environmental context, such as payment for ecosystem services.

4.2.2 Incentive mechanisms for sensor network implementation and operation

Citizen science-based monitoring poses substantive challenges to the collection of reliable and accurate data. Moreover citizen scientists participate in monitoring activities for many reasons, for example, learning new techniques, helping scientists conduct research, collaborating with others or just for personal enjoyment [87]. Increasingly therefore incentives are being used to encourage stakeholders and the general public to participate in data collection and sensor network maintenance, including monetary rewards, gamification, and developing large-scale communities of practice [88–90]. Monetary rewards usually incorporate an auction system. Here citizen scientists compete with each other over the characteristics of their data sets, for example data quantity, data quality, data frequency and geographic coverage, with the provider of the ‘best’ or most relevant data receiving payment [91]. Gamification involves stakeholders participating for recreational purposes instead of monetary reward. Citizen science application developers can build gaming elements into the monitoring systems to attract continuous contributions [92]. The communities of practice method [93] encourages citizen scientists to maintain or improve their social relations and status around the quality of their monitoring activities. For example, hydrological and meteorological monitoring volunteers in Nepal only receive a small wage from the Nepalese Hydrology and Meteorology Office, in this case the main motivation for them to participate in data collection activities is the national pride and social connections that inhere from assisting the Nepalese state through compiling accurate and authoritative data sets [67]. Although most of these methods are being discussed for mobile phone-based crowdsensing, they have great potential to be used alone or in hybrid ways for low-cost sensor network contexts.

4.3 Application scenarios and integrated design

4.3.1 Hybrid scenarios for multiple purposes and stakeholders

As discussed, one of the more promising strategies to ensure sensor networks are socially useful and politically sustainable is to build mutually beneficial collaborations among stakeholders, and thus fulfil multiple purposes with combined technical features in hybrid scenarios. For example, scientific research may require long-term hydrological monitoring data to identify trends or specific process dynamics, or require a larger spatial coverage to facilitate better calibrated global models. Optimisation of water usage for agriculture can also involve instilling improved water use in domestic contexts, especially in less-developed regions. In addition, the real-time and adaptive approaches which have been used in the management scenario can contribute in a community development scenario as early warning systems for local resilience building to defend water-related disasters [29]. These approaches can also be applied to hydrological monitoring and research [94]. This enables sensor networks to increase the frequency or temporal resolution of monitoring programmes responsively in real-time to adapt to and capture the hydrological changes in temporal and spatial patterns during extreme events such as floods and droughts [95]. This approach can help facilitate a better understanding of non-linear and dynamic hydrological processes that have been understudied to date.

4.3.2 Designing monitoring networks for multi-purposes

Designing these hybrid scenarios requires careful planning, and here we outline a generic framework for designing participatory sensor networks across scales to illustrate the key collaborations needed among stakeholders and technologies (Figure 4). A local sensor mesh network is adopted as an indicative example, although the network topology or architecture can be different (see Figure 3).

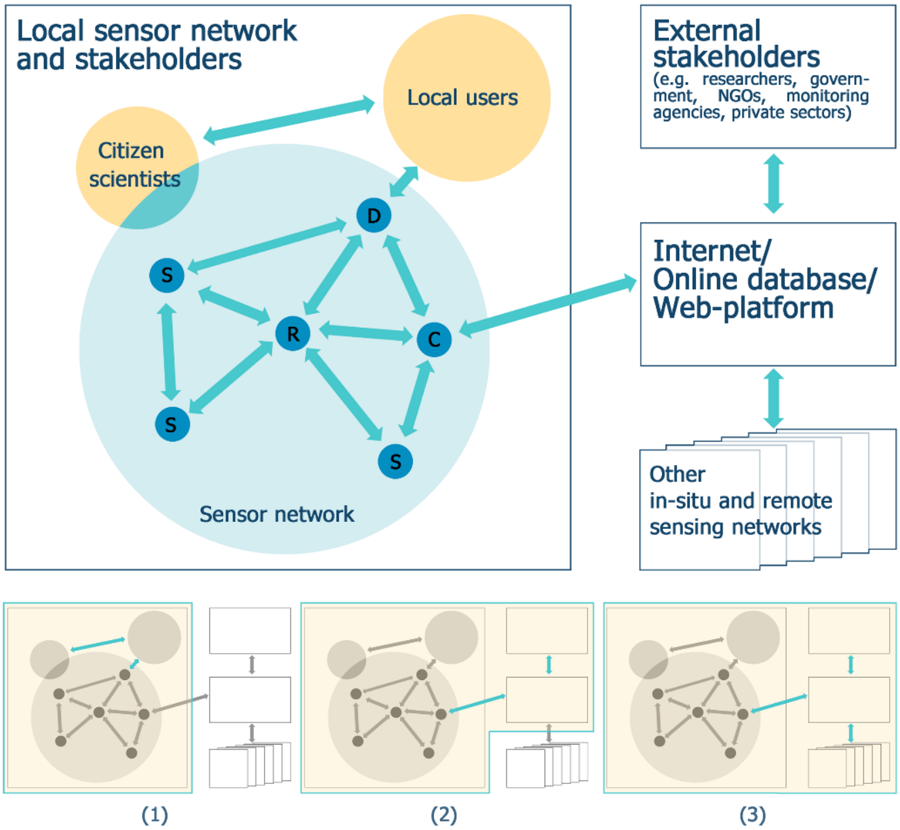

Figure 4. Sensor networks and stakeholders across scales. In the local network, C denotes a coordinator node, R denotes a relay node, S denotes a sensor node, and D denotes a display node. Three levels of participatory sensor networks are presented: (1) making data locally relevant, (2) connecting local and external stakeholders, (3) linking multiple networks and sensing data sources for larger impacts.

The first goal of any hybrid system is to ensure collected data is made locally relevant (Figure 4-1). At the local scale, high levels of cooperation are needed between users in developing the participatory sensor network. This is especially so when sensor network technologies are introduced to developing regions by external stakeholders (e.g. NGOs and researchers) with the aim of support indigenous communities with environmental challenges locally. The collected data should always be relevant to the livelihoods of local users [c.f. 96], and be readily accessible to them in terms of format and retrieval mechanism [97]. For example, if community members are convinced that novel hydrological data will improve their day-to-day water usage and agricultural practices and participate in designing a sensor network for this purpose, it is much more likely that they will use output from this network [51]. Co-produced network goals and design can substantially increase the probability of long-term community commitment to data collection and curation.

In addition, citizen scientists are not only responsible for maintaining the sensor network and data collection activities, they should also actively interpret and disseminate the information to the local community members and collect feedback from them.

Second, hybrid systems need to bring together and ensure the participation of local and external stakeholders (Figure 4-2). Local sensor and participatory networks generally fashion close connections with the outside world via technologies such as GSM or WiFi. Such networks enable external stakeholder involvement by facilitating remote access to locally collected data and thus justifies, their financial or technical support. In addition, this data communication also helps to raise awareness of external communities to local environmental problems, which may lead to potential external intervention.

Third, hybrid systems offer the possibility of linking multiple sensor networks for greater impact (Figure 4-3). Connecting multiple sensor networks helps expand the coverage of monitoring, to build larger databases and therefore to support more reliable outcomes, even if these sensors or networks have different purposes or are managed by different groups of people. For example, the Mountain-EVO project [67] installed a set of water level sensors in the upper tributaries of the Kali Gandaki River in Nepal, to support participatory monitoring of water resources for local irrigation practices. These data are at the same time complementary to the national hydrological monitoring network, and help to understand the hydrological processes of the river in the mountain regions. However, as these data are from different sensor networks and may not be stored in a central server, or managed by the same organisation it suggests potential future development in open data sharing protocols, unified data standards are required to ensure polycentric monitoring and water governance.

4.4 Further opportunities for improving participatory monitoring networks

Besides the three categories of opportunities outlined above, there are additional socio-technical approaches and considerations worthy of discussion. Below we identify four key points that have so far been neglected in the emerging literature on low-cost sensor networks but which we argue could, in the future, help to maximise their societal impact.

Data privacy and ownership has become increasingly important in recent years as more information is generated about our movement, activities and health [98]. Information collected on water quality and quantity is likely to become increasingly politically sensitive, particularly as human activity increasingly perturbs the climate and water cycle. Given this increased risk of cyber-attack, and potential implications for resource management and decision making, low-cost sensor networks for such applications may need to embed privacy and security for future data generation, transfer and storage activities [98]. Encryption of sensor data is a necessary future network design consideration, particularly when considering the link between sensor and cloud based server systems [99,100]. For data storage there are promising developments associated with block chain technologies which can improve security and are both scalable and cost-effective [101] and significant potential to utilise existing procedures developed for IoT applications, in the context of low-cost sensor networks [102].

Direct links to downstream data analytics, visualisation and other applications are currently lacking for most low cost sensor networks [7]. For water resource management and community participation the advantage of a bridge between raw sensor data and interpretable information is clear and is essential for timely decision making. For example, a recent study from Tasmania, S. Australia highlighted how real-time data from river flow and water quality sensors can be combined with 3rd party data (e.g. meteorological data) to provide a dashboard to inform a community water user group [103]. Machine learning provides numerous techniques to facilitate dynamic fault detection and data integrity assessments along with data aggregation / node clustering, real-time routing, power management and event detection which can greatly enhance functionality and reliability of sensor networks [104,105]. For a low-cost sensor network to conduct the dynamic behaviour previously described, bandwidth and connectivity to a cloud / central server can become problematic, however, the development of single board computers (e.g. Raspberry Pi) has made edge computing or processing a viable, cost effective option for most LCSN [106]. Thus, the combination of edge computing and deep learning has the potential to reduce time spent on the technical challenges of low-cost sensor network operation and enable users to focus on governance and decision making [107].

The integration of in-situ monitoring networks and remote sensing technologies is a fruitful avenue requiring further exploration (c.f. Figure 4). Satellite data are currently being used to help inform site selection of in-situ sensors (e.g. LandSat) [108] and assess: water balance, river network extent (global surface water – google earth engine), crop production, a suite of meteorological variables and even water quality for large water bodies [109,110]. These data can be incoporated into data analytics, visulisations (e.g. inputs to dash boards) or machine learning algorithims, and when combined with information from in-situ monitoring nodes can create better models and forecasts of water avialbility, water related hazards and could be utilised in low-cost sensor networks to inform descions at a societal level [111]. Data from novel satelitte monitoring missons (e.g. GRACE - ASA Gravity Recovery and Climate Experiment), if suitably calibrated/ground truthed, may provide spatially distrubuted measures of groundwater levels, albeit at a coarse - regional scale (Niyazi et al., 2019; Thomas et al., 2019). In addition the reduced cost of drone technology now makes it feasable to combine targeted catchment or river corridor surveying with in-situ sensing to help calibrate spatially ditributed models or improve understanding of spatial heterogeneity (Dugdale et al., 2019).

Network optimisation needs to be considered as low-cost sensor networks for water monitoring increase in occurrence, scale and scope. In an idealised situation the physical configuration of nodes, relays and sinks will be based purely on information capture, however there are often landscape based constraints or case specific considerations which influence node locations, such as security and accessibility (Chacon-Hurtado et al., 2017). Using network theory, entropy and value of information approaches network configurations can be established to ensure resilient data transfer, reduce data uncertainty, inform models and estimate signals for unmonitored locations (Chacon-Hurtado et al., 2017; Curry & Smith, 2016; Rathi & Gupta, 2016). Using these approaches dynamically and accepting node mobility can greatly enhance network performance, stability while ensuring sensors provide the data necessary to address the specific monitoring requirements (Chacon-Hurtado et al., 2017; Rathi & Gupta, 2016).

5 Concluding remarks

This critical review scrutinises the recent development of water-related sensor network applications and approaches through a socio-technical lens. By doing so, we are now able to directly address the research questions outlined in Section 1.

First, it is clear there is a general structure for building low-cost sensor networks which can be applied across a range of monitoring applications. In particular, we highlight how ICTs are now modularised, flexible, low-cost and are increasingly being used in water monitoring at different geographic scales for a variety of purposes. This enables us to develop sensor network applications by assembling low-cost technologies across pre-defined configuration levels, rather than developing a framework from scratch. Second, we identified four main application categories for low-cost sensing from the contemporary literature, namely operational monitoring, scientific research, system optimisation and community development. These categories are defined by different configurations of technologies, monitoring purposes, stakeholders, management strategies and spatial-temporal scales. Third, we call for continued evolution in water-related low-cost sensor network applications, and while technological advances hold great potential (e.g. edge computing and machine learning), bringing governance issues to the forefront of sensor network design and applications. Analysing the general building model and the application configurations leads us to conclude that the potential of hydrological sensor network has yet to be fully realised. We have argued that to do so requires us to expand our focus from designing better sensor network applications and optimising their technological operation (i.e. sourcing more energy efficient and effective electronic components), to embrace questions arising from the geographical and socio-technical contexts within which monitoring takes place.

Low-cost sensor networks can be used for a range of applications in developing and remote areas around the world. For example, there is significant potential for low-cost technologies to create greater social impact through community-driven assessment of water quality and quantity, by helping communities transition to more resilient and sustainable futures. However, to achieve this goal, we have to work more closely with stakeholders. Increasing collaborative engagement and co-design processes is crucial, as is increased attention to identification of the most appropriate governance models and incentive mechanisms for sustainable sensor network operation. This can only be achieved by considering the full range of socio-technical issues from the outset of the co-design process, to ensure the technologies used are better placed to meet the social needs and expectations of stakeholders.

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