Sensor Networks and Geohazards

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1 Introduction to sensor networks

Advances in communication technology and the miniaturization of electronics have led to the emergence of Environmental Sensor Networks (ESN). ESNs are typically arrays of devices containing sensors which are interconnected using a wireless network. These systems allow the study of fundamental processes in the environment, as well as providing vital hazard warnings (e.g., flood alerts). This is particularly important in remote or dangerous environments where many processes have rarely been studied due to their inaccessibility. Hart and Martinez (2006) argued that environmental sensor-network systems have the potential to produce a revolution in the Earth and environmental sciences similar to that generated by the use of satellite remote sensing in the 1970s, and will become a key part of geological surveys (Kimball et al., 2020).

The development of ESN requires a unique combination of technological and environmental understanding (Chong and Kumar, 2003; Martinez et al., 2004). The ultimate aim is to create a Global Environmental-Sensor Web that would provide analytical tools to understand Earth-System processes using near real-time data collected from sensors (especially *in situ* sensor networks) combined with other thematic information (e.g., geology, soil type, and topography), model-based data and predictions, and data sets from data fusion. Decisions and support systems can be built from these, as well as sending alerts and influencing emergency-infrastructure systems. Initial examples include the Geospatial Cyberinfrastructure for Environmental Sensing project (GeoCENS, n.d., www.geocens.ca) and Digital Earth (Gore, 1998; Stacey and Berry, 2018). There is a vision that this would be a globally integrated system of sensor systems (sometimes called the Sensor Web; Delin and Jackson, 2001)—One example is the Global Earth Observing System of Systems (GEOSS; GEO Implementation Plan Task Team, 2005; OGC, 2008; Zyl et al., 2009).

Although there has been increased development of ESNs over the last twenty years (many are discussed below), the number of projects that address large temporal or spatial scales are low. This is because most systems are custom built and there are technical challenges that need to be addressed. This includes power management, long-range communications, interoperability, standardization, robustness, scalability, management, usability, and security.

We first review the evolution from logging, to sensor networks, to the environmental Internet of things (IoT). We then highlight systems to investigate different geomorphological processes (i.e., glacial, periglacial, and coastal). This is followed by an investigation of sensor networks that have been used to investigate hazards (i.e., avalanches, landslides, volcanic, and tsunamis), with an examination of the role of Uncrewed Autonomous Vehicles (UAVs) and citizens as sensors, as part of an integrated alert system. Finally, we discuss the challenges of network design, communications, standards, data, and integration.

1.1 Logging

Environmental sensor networks have evolved from automated loggers that record data at specific intervals and require manual downloading by a maintenance team. The first automatic weather station was installed in 1939 by the Bureau of Aeronautics, US Navy (Brooks, 1940; Wood, 1946). It consisted of a Stevenson screen type arrangement mounted above a cabin that housed the electronics. The cabin was 2 m × 2 m × 2 m, weighed 1 ton, and was powered by a 1000 W 115 V petrol generator, with an 80 gal fuel tank, which was enough to obtain 8 observations a day for 4 months. Since then commercial loggers have allowed sensors to be plugged in, sampling rates set and left *in situ*, with data collection normally by laptop at intervals (e.g., Campbell loggers). Loggers have been used in many environments to collect data. Examples include the subglacial environment (Fischer and Clarke, 2001), periglacial (Matsuoka and Humlum, 2003), fluvial (Lawler, 2005), and soils (Grismer, 1992).

The evolution from passive logging to an active ESN can be illustrated by the Argus video system for near-shore monitoring (Holman et al., 2003), which began as video recording in 1992, but went on to use the intelligent processing of images, as the data volumes were too high for communications infrastructure. Loggers have also gained communication capabilities via Wi-Fi, mobile networks, satellite, and other radio links. This makes automatic data uploads easier, although it is not trivial to integrate multi-vendor systems.

1.2 Sensor networks

Environmental sensor networks comprise sensor nodes embedded in the environment, sending data via a radio network to a server, where the data can be accessed (Fig. 1; Martinez et al., 2004; Corke et al., 2010; Bakker and Ritts, 2018; Mao et al., 2019). Typical examples of use include: (1) habitat (Szewczyk et al., 2004); (2) glaciers (Martinez et al., 2004); (3) slope stability (Hasler et al., 2008); (4) agriculture (Wark et al., 2007; Rustia et al., 2020); (5) forestry (Hefeeda and Bagheri, 2009); (6) water quality (Wong and Kerkez, 2016); and (7) air-quality control (Elen et al., 2012; Lerner et al., 2019).

Although sensors can be wired together (e.g., Leo-15 Coastal Cabled Observatory, Glenn et al., 2006; NEPTUNE project; Phibbs and Lentz, 2006), most applications aim to use a wireless system, as cables are often impractical, obtrusive, and can disturb the

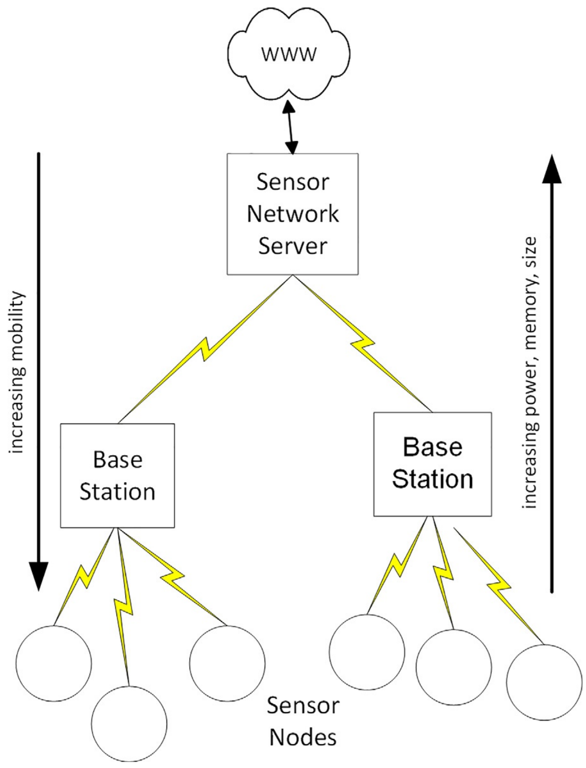

Fig. 1 Sensor network. Reproduced from Martinez K, Hart JK, and Ong R (2004) Environmental sensor networks. *Computer* 37 (8): 50–56.

environment being monitored. *Ad hoc* or *mesh networks* represent systems where the sensor nodes dynamically intercommunicate in order to establish a network. This more advanced network functionality can provide long range links as long as there are nodes spread across the route. Other systems typically use network infrastructure (e.g., cellular) or long-range radio links to a "base station" or "gateway," which is connected to the Internet. Once these data are collected from the sensor nodes, they can then be analyzed, used in a geographic information system (GIS), combined with satellite images, and published to give users seamless access to data and information. Fig. 2 shows an idealized sensor-network pipeline.

As shown in Fig. 1, there is generally an increase in computational power, data storage, and power availability from sensor nodes through to the server. In advanced systems, the sensor nodes can store data, make decisions about what data to pass on, and even make decisions about when and what to sense. This is typically done to save battery-draining communications, reduce data volumes, and tune the outputs to the user's needs. The term *edge computing* is often used for nodes (e.g., cameras or sound recorders) which carry out their own analysis, and they can send classifications, counts, or samples, thus avoiding overloading servers and networks.

If a large number of sensor nodes are needed, they would typically be organized in clusters with their base gateways communicating a cluster's data. Due to variations and incompatibilities in radio networks, this is sometimes necessary anyway. There may also be intercommunication between servers and sensor nodes, for example, to control actuators (e.g., water flow) or control sampling rates. In a landslide-prediction system, if the weather forecast predicts a storm, then the nodes could be tasked to sample at a higher frequency.

Martinez et al. (2004) suggest that Environmental Sensor Networks are a subset of sensor networks that are specifically tuned to applications in the natural environmental. It is important that before any system is designed and installed, a detailed understanding of the physical environment and deployment is acquired. The systems must be designed to withstand specific conditions such as temperature, weather, pressure, fine dust/ash, or vibration. Generally, the sensor nodes need low power and be housed in a weather-proof container. Ideally, they need to be designed to blend into the environment to minimize human interference and should not cause pollution. They may have to be lightweight (if they are being transported by backpack; Phillips et al., 2017) or a specific size related to their deployment (Martinez et al., 2004).

Nodes may be part of a large-scale system and have a single purpose (e.g., weather stations or the Global Seismographic Network, n.d., http://www.iris.edu), or they may be more localized multifunction heterogeneous networks with different sensors embedded in the environment (small-scale examples discussed above). Nodes do not necessarily need to be static, and some move within the environment they are monitoring and can be moved by aerial tramways (Rahimi et al., 2004), robotic vehicles (Melodia et al., 2005), animal-borne instruments (Kays et al., 2015; Ripperger et al., 2016), Autonomous Underwater Vehicles (AUVs; Ryan et al., 2002; Zolich et al., 2019), and Uncrewed Autonomous Vehicle (UAVs; Shahbazi et al., 2014; Wang et al., 2015; Budi et al., 2018).

Biosensors have a huge potential for environmental monitoring and there has been rapid development of cost-effective, *in situ*, and real-time lab-on-a chip analysis in the field as part of a sensor network. These can monitor various air, water, and soil pollutants (e.g., Justino et al., 2017; Pasternak et al., 2017; Halilović et al., 2019; Ahmed et al., 2019; Gupta and Kakkar, 2020).

1.3 Internet of things

Numerous authors have envisioned a future where more devices and objects are Internet connected, generally known as the Internet of things (IoT; Hodges et al., 2012; Feki et al., 2013; Hart and Martinez, 2015; Kocakulak and Butun, 2017; Čolaković and Hadžialić, 2018). A typical definition is "*The Internet of Things provides the necessary infrastructure to transparently access sensors, processes and actuators using standardised protocols regardless of hardware, operating systems or location*" (Presser et al., 2009; Roggen et al., 2012). It has been estimated that this will become an integrated into our lives (e.g., transport and logistics (Atzori et al., 2010; Sicari et al., 2019), healthcare (Vilamovska et al., 2009; Rajput and Gour, 2016), and built environments (Strohbach et al., 2004; Haase et al., 2016)).

Although IoT devices can directly use Internet protocols (IP) and have unique global addresses, many use non-IP links to gateways and a cloud infrastructure which represents them. The main difference between a "normal" sensor network and an environmental IoT system is that the nodes ideally have Internet protocol connectivity allowing them to directly send data to a server/cloud and users can interact with them more easily in the field. The use of IoT protocols allows for a mixture of equipment from different vendors. The communication system could be Wi-Fi, Zigbee, 6LowPAN, LoRaWan, NB-IoT depending on the power and connectivity. Some systems use GSM (mobile phone networks), satellite (e.g., Iridium), or the newly emerging micro/nano-satellites (CubeSats) to link to the Internet (Section 4.2 discusses this in more detail).

Most real-world systems will contain different communications elements depending on the application and devices. The Glacsweb project (Martinez et al., 2012) moved from an initial heterogeneous sensor network (using *in situ* probes and geophone nodes with a radio link) toward an environmental IoT system with surface nodes using more IP networking. In contrast, the

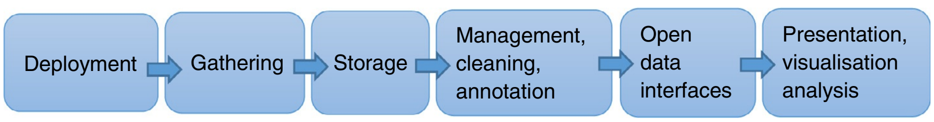

Fig. 2 Idealized sensor-network pipeline.

Table 1 Evolution from logging to environmental IoT.

	Logging	*Environmental sensor networks*		*Environmental IoT*
		Single function	*Heterogeneous*	
		Increasing "smartness"		
Sensor nodes	Normally one type per application	Normally one type or group of sensors	Heterogeneous, varied types	Heterogeneous, varied types
Communications	Usually none, sometimes IP and GSM	Always exist, mostly one way	Always exist, mostly non-IP, gateways usually IP	Mostly IP, some with gateways to IP
Communications standards	None	Custom and standard	Custom and standard	More open standards, e.g., 6LoWPAN
Node operating systems/ software	Simplified or proprietary	Custom, nonstandard	Custom, nonstandard	Emerging (Contiki, RIOT-OS) or Linux
Server protocols and data standards	Often proprietary	Custom to open data	Custom to open data	Emerging, more Web based

Adapted from Hart JK and Martinez K (2015). Toward an environmental Internet of Things. *Earth and Space Science* 2: 194–200.

Mountain sensing project (www.mountainsensing.org), monitored environmental conditions in the Cairngorm Mountains and was designed to only use IoT protocols from the beginning (Fabre et al., 2016; Bragg et al., 2016). It used the 6LoWPAN Internet protocol (an adaption of IPv6), which is tuned to low-power radios and allows normal Internet tools and development, together with the HTTP-like CoAP protocol which provides familiar web methodologies. This approach can dramatically simplify deployments because a mixture of devices can use a common radio network, and the methods to send/get data are uniform and familiar to Web programmers (Table 1).

2 In situ data collection

2.1 Glacial processes

The Glacsweb project (Hart et al., 2006, 2009, 2019a) was the first project to apply an environmental sensor network to study subglacial processes. The system comprised sensor nodes (probes and geophones), base stations, and a sensor network server in the United Kingdom (Fig. 3). The Glacsweb probes (0.16 m long) contained microsensors measuring water pressure, probe deformation, resistance, tilt, and probe temperature (Fig. 4). The system was initially deployed at Briksdalsbreen in Norway from 2003 to 2006 (Martinez et al., 2006; Hart et al., 2006) and then Skálafellsjökull, Iceland (2008–2012; Martinez et al., 2009, 2012). The probes (sensor nodes) were inserted in the ice and the till via a hot-water drill. The probe data were recorded every hour and transmitted to the base station located on the glacier surface. These data were sent daily via Wi-Fi or GPRS to a web server in the United Kingdom (Martinez et al., 2009).

The probes were housed in a polyester case. The initial probes in 2003 and 2004 ran on 433 MHz, while the 2006 and later versions used 173 and 151 MHz frequencies. Fifteen were installed at Briksdalsbreen and a further 15 at Skálafellsjökull, for a total of 3756 probe days of data received. The probes were designed so that if the data were not immediately accessed, then they were

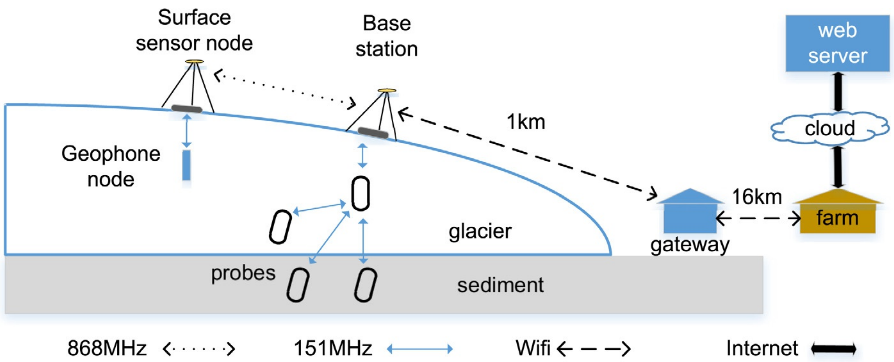

Fig. 3 Glacsweb system from Skálafellsjökull, Iceland. Reproduced from Martinez K, Hart JK, Basford PJ, Bragg GM, Ward T, and Young DS (2017a) A geophone wireless sensor network for investigating glacier stick-slip motion. *Computers & Geosciences* 105: 103–112.

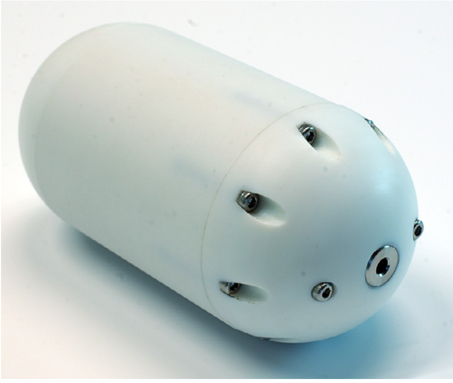

Fig. 4 Glacsweb probe (2012) showing end pressure sensor (length 0.16 m), two conductivity bolts and sealing bolts.

stored for later retrieval. There were some problems with communications between the probes and the base station, which unfortunately led to the probes filling their programmable memory (EPROM), resulting in some data gaps.

The results showed that deformation occurred throughout the year (Hart et al., 2011, 2019a), produced the first-ever measurements of tilt (Hart et al., 2009), and enabled the reconstruction of stick-slip motion (Hart et al., 2019b), as well as the amount of time for lodgement and deformation (Hart et al., 2011; Hart et al., 2019b).

Other examples of *in situ* sensors in a glacial environment include the cryoegg and ETracers to measure hydrological processes (Bagshaw et al., 2014). These comprise sensor nodes that are inserted into supraglacial rivers and the data are collected when they emerge in the glacier's proglacial rivers. There is also *in situ* lab-on-chip (LOC) technology to measure nitrates in supraglacial streams (Beaton et al., 2017).

The SEAMONSTER system is a sensor network that was used to instrument Lemon Glacier in Alaska (Heavner et al., 2008). Another sensor network monitored the Tsho Lake in the Himalayas, as an early-warning system for potential Glacial Lake Outburst Floods (Fukui et al., 2008).

There are problems, however, with the transmission of radio through ice, due to the scattering and absorption of high frequencies. For this reason, there have also been some investigations of other techniques such as acoustic (Lishman et al., 2013).

2.2 Periglacial processes

There have also been sensor networks installed in periglacial environments. The PERMASENSE project was set up at the Matterhorn to measure rock instability (Hasler et al., 2008, 2012; Beutel et al., 2009; Weber et al., 2016). A related project, the X-SENSE project, used a wireless network of global positioning systems to measure periglacial earth movements (Buchli et al., 2012).

Matsuoka (2006) proposed a global network to monitor periglacial processes (they assumed it would use loggers). This included growth of ice wedges and pingos (Mackay, 2000), rock glaciers (Haeberli et al., 1998), solifluction (Matsuoka et al., 2005), and earth hummocks (Gurney and Hayward, 2015). This has been achieved in part with a recent summary of permafrost melting (and carbon dioxide release) based on a global system of logged borehole temperature data from the Global Terrestrial Network for Permafrost (Biskaborn et al., 2019). The results from this network have shown that since 2007, permafrost temperature increased by $0.29 \pm 0.12\,^{\circ}\mathrm{C}$.

Eberhardt et al. (2014) developed a low-cost mobile-sensor system for measuring carbon dioxide in permafrost areas. Such systems would be ideal to integrate into an arctic-sensor network- monitoring system.

Another key area for sensor networks is the monitoring of snow packs (Malek et al., 2017; Zhang et al., 2020) for fresh water supplies, hydroelectric power, and avalanche forecasting.

2.3 Coastal processes

The study of coastal processes provides a series of distinct problems for sensor-network research, in particular, the problems of radio communications and water. In addition, since beaches are sites of recreation, it is important that monitoring is unobtrusive (Lucrezi et al., 2015).

An early coastal-sensor network was developed by Holman et al. (2003) (i.e., Argus Imaging System), who used video cameras to record wave and ocean-current conditions. More recent projects have been developed in Australia (Splinter et al., 2011; Bracs et al., 2016), and the Web Camera Application Testbed (WebCAT) in the United States (Jacobs et al., 2009; Dusek et al., 2019), to similarly measure these properties.

Albaladejo et al. (2010) and Xu et al. (2014) made a survey of ESNs to investigate oceanographic conditions. Most projects focus on water-quality control (O'Flyrm et al., 2007; Adamo et al., 2015; Pule et al., 2017), environmental parameters like air and water temperature (Sieber et al., 2008; De Marziani et al., 2011), wave height (Marin-Perianu et al., 2008), or oceanographic parameters in general (Pérez et al., 2011).

The Coastal Ocean Observation System of the Murcia Region (OOCMUR) is one of many national projects to monitor coastal environments using sensor networks (Pérez et al., 2017). The sensor nodes (mounted on buoys) measure depth, temperature, current, salinity, turbidity, dissolved oxygen, chlorophyll, and nitrates. Other examples are the UK Channel Coastal Observatory (Page et al., 2009), the Columbia River observation network (CORIE) project (Baptista, 2006), and the SEA-LABS system in Monterey Bay (Bromage et al., 2007).

A number of sensor networks have been used to measure coastal erosion. This includes estimating the depth at which there is little or no motion of sediments (Watt et al., 2019). Other researchers have attempted to measure beach-sediment transport by tracers, sediment traps, or sediment-volume changes. The recent development of radio-frequency identification (RFID) has allowed the identification of individual clast movement (real and artificial; Allan et al., 2006; Bertoni et al., 2010; Grottoli et al., 2015) and so enabled the quantification of the abrasion rate on a coarse-grained beach (Bertoni et al., 2016).

Techniques to measure beach transport by sediment traps include measuring by acoustic (Poortinga et al., 2012) or piezoelectric (Raygosa-Barahona et al., 2016) sensors. Pozzebon et al. (2018a) devised a sensor network to collect sand and relate this to the wind levels and direction, and transmitted these data in real time. In order to calculate volume changes, frequent topographic surveying is needed (Coco et al., 2014; Grottoli et al., 2017). Although this has been attempted by UAVs, light detection and ranging (LiDAR), and terrestrial laser scanning (TLS) imaging (e.g., Pye and Blott, 2016; Guisado-Pintado et al., 2019), these can only record before and after an event rather than in real time. Sensor networks which comprise a series of "sensing poles" have been suggested to make a live 3D map of the beach surface, using light-dependent resistors (LDR), although these cannot record at night (Pozzebon et al., 2018b) like ultrasonic and infra-red distance sensors (Bocci et al., 2020).

There are also underwater sensor networks that mostly use acoustic waves to transmit data (Pompili and Akyildiz, 2009). There are problems, however, in shallow water where transmission is governed by turbidity, ambient noise, salinity, and pressure gradients, and sound communications may affect marine life (Au et al., 1997). It is also possible to use optical-wave technology, but this requires line of sight (Reza and Harms, 2009). Other researchers have investigated the use of Electromagnetic (EM) communications (Che et al., 2010). This method was used in the Automated Sensing Technology for Coastal Monitoring (ASTEC) project which used a sensor network comprising underwater static buoys to measure the movement of sea-bed material to monitor coastal erosion. Jaffe and Schurgers (2006) discussed an acoustic underwater-sensor network of freely floating nodes to monitor effluents from sewers, three-dimensional features of coastal circulation, and ecological processes.

3 Complex systems and geohazards

Approximately 3 million people worldwide have been killed in the past 20 years due to natural disasters such as earthquakes, landslides, floods, cyclones, and snow avalanches (Adeel et al., 2019). Climate change has/will lead to an increased frequency and magnitude of many of these events (IPCC, 2012). Sensor networks are a key part of preventing further deaths in the future (Chen et al., 2013). Robust systems need to be built that not only monitor the environment but are also able to make decisions and alert emergency services and the public. The data need to be drawn from a wide range of heterogeneous sources; *in situ* sensors, remote sensing, UAVs, and human observers. In order for a sensor-network system to successfully operate in a complex environmental system, it needs to be able to analyze and synthesize large volumes of data. The use of self-organizing neural networks; swarm intelligence; self-configuring wireless networks; and cultural acquisition using a common language will all help (Collier and Taylor, 2004).

3.1 Avalanches

Although numerous factors contribute to snow avalanches, they typically occur when the weight of snowpack exceeds the shear strength, and about 100 people a year are killed in the European Alps (Alpine Tourism, 2018). Powder avalanches are generated from a single point, while hardened snow may fail along a fault plane within the snow (slab avalanche). Avalanches are traditionally measured either by placing sensors in the avalanche path, or by sensors outside the path (e.g., radar or video). Erlacher et al. (2016) devised nodes ("snowballs") which behave like snow and record during the occurrence of an avalanche. The moving node communicates with a fixed-sensor node (anchored base station) outside the avalanche. With enough nodes, it is possible to calculate the 3D trajectory (Fig. 5).

Henderson et al. (2004) planned a 50–100-node sensor network in the Wasatch Mountains in Utah. Their nodes were designed to measure snow density, snow thickness, and slope, to enable avalanche prediction. Carta et al. (2013) devised nodes that measure water content via the dielectric constant; these nodes were installed in the snow, or put out in summer before the snow arrives.

Marconi et al. (2012) reported on a European project on "Smart collaboration between Humans and ground-aerial Robots for improving rescuing activities in Alpine environments" (SHERPA) from 2013 to 17 to investigate the feasibility of an Air-Ground Collaborative Wireless Network (AGCWN). Rahman et al. (2018) proposed Collab-SAR, a collaborative avalanche search-and-rescue technique that includes a wireless-based network infrastructure and a collaborative search technique, based on the SHERPA project. This enables wireless communications between the rescue agents (robots and humans). UAVs (both short and long range)

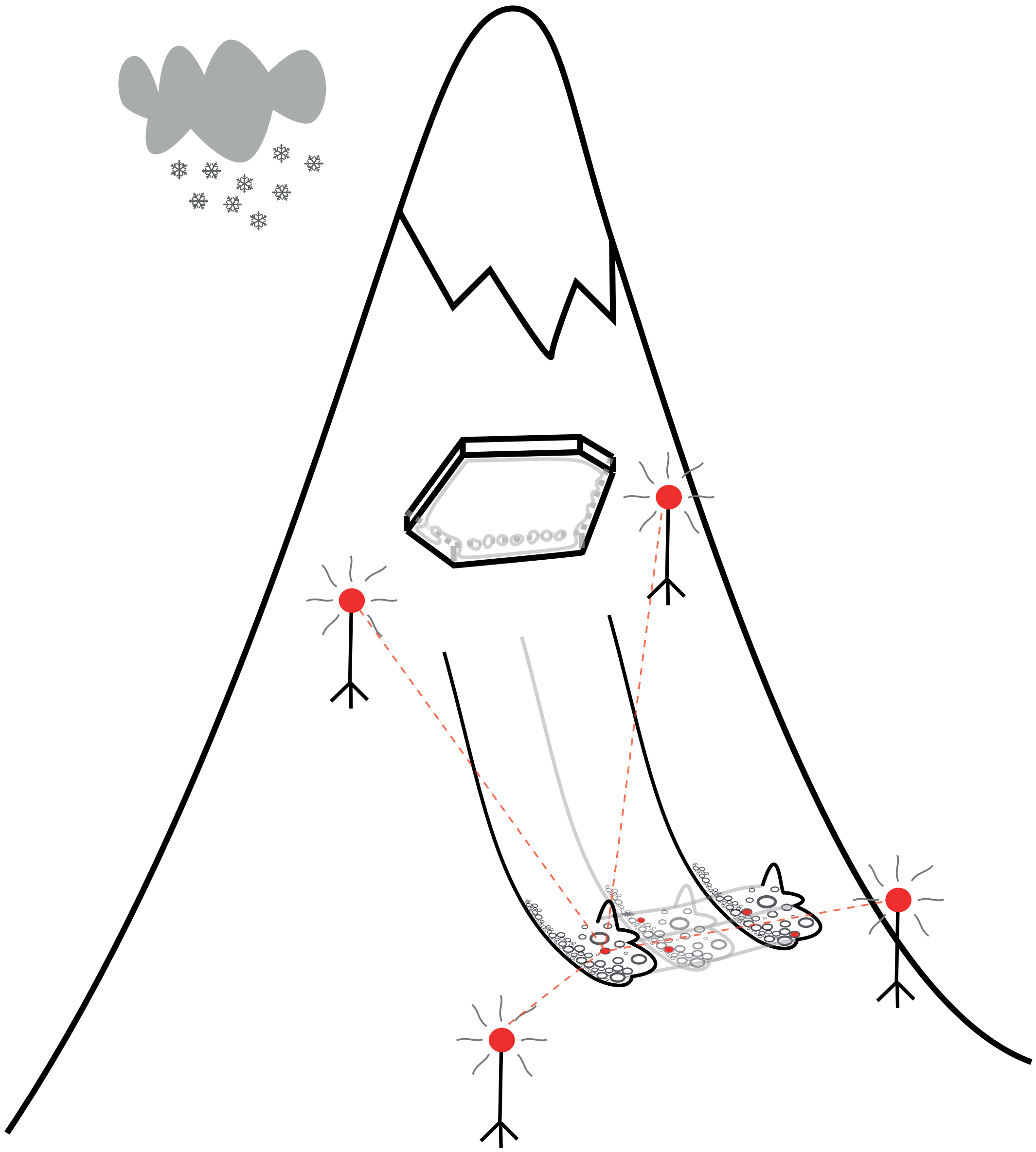

Fig. 5 Avalanche environmental sensor network. Reproduced from Erlacher F, Weber B, Fischer JT, and Dressler F (2016, January). AvaRange-using sensor network ranging techniques to explore the dynamics of avalanches. In: *2016 12th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, pp. 1–4. IEEE.

are used for surveillance and Uncrewed Ground Vehicles (UGVs) are used as base stations (and can be used as a docking/recharging for the UAVs, and protection for the human rescuers). More details about UAVs in disaster management are presented in Section 3.5.

Antolini et al. (2019) described an early warning system that can be used for both avalanches and landslides. They tested this in a gulley that opened out onto a road with a traffic light. They used data from wireless sensor nodes (inclinometer sensors; Giorgetti et al., 2016), weather stations, and a camera, which fed into a gateway sensor node (base station), then on to a sensor network server, which controlled the traffic lights on the road (and sent out SMS alerts) if an event was triggered (Fig. 6). On a larger scale, road-weather-information systems (RWISs) have the potential to be used for avalanche warnings. Sensors can be added to the existing infrastructure, or a local mesh network or Internet access could be installed around an established weather station (Idell-Sassi et al., 2016).

Another project used a public awareness campaign in the Pacific Northwest in 2011–2012 called "Are you Beeping?," asked backcountry travelers to test their avalanche beacons against a series of base stations. These stations also provided avalanche forecasts and can record the activities of travelers (Waller, 2014), and these data were fed back to the public via social media. Future plans were to connect the signs (base stations) to the Internet and each other. These mesh networks in a remote environment not

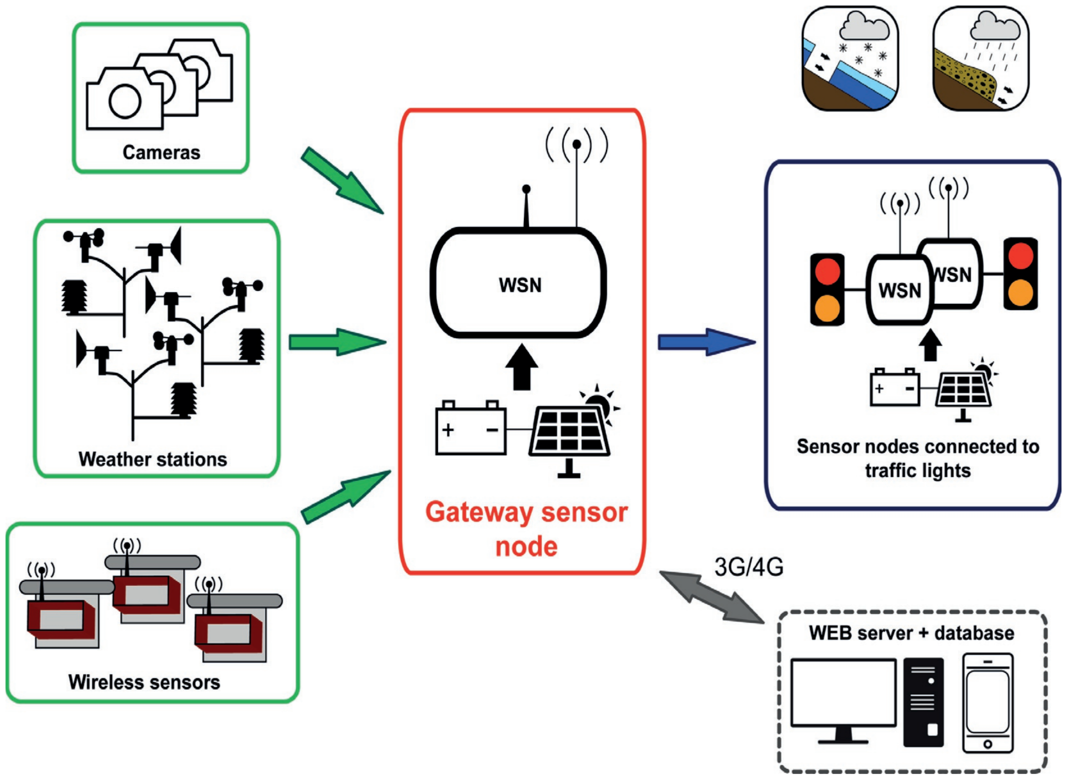

Fig. 6 Avalanche/debris flow alert system. Reproduced from Antolini F, Aiassa S, and Barla M (2019) An early warning system for debris flows and snow avalanches. In: *National Conference of the Researchers of Geotechnical Engineering*, pp. 338–347. Cham: Springer.

only extend Internet coverage but also enable new sensors, weather stations, or avalanche-forecast-notification systems to share the same network securely.

3.2 Landslides

The monitoring of landslides represents an ideal use of sensor networks, since they require long-term monitoring, and are usually triggered by precipitation events. The design needs to use low power (as battery replacement may be difficult), and operate remotely (Lee et al., 2010; Giorgetti et al., 2016).

Landslide monitoring typically consists of nodes with accelerometers to detect and measure vibrations caused by landslides (Kotta et al., 2011; Biansoongnern et al., 2016). Terzis et al. (2006) proposed a sensor column-based network to detect the slip surface location. Ramesh et al. (2009, 2017) and Ramesh (2014) installed distributed-sensor monitoring system based on 50 geological sensors and 20 wireless sensor nodes to monitor a local zone at high risk from landslides in India (Idukki, Kerala State; The nodes measured rainfall, moisture, pore pressure, and movement). The system was able to provide three-level alerts (low, intermediate, high) and its effectiveness was tested during the monsoon season (Fig. 7). Other systems have also been designed and implemented based on collecting a range of environmental data and sending an alert once a critical threshold was crossed (Hill and Sipple, 2002; Sheth et al., 2005; Fernandez-Steeger et al., 2009; Rosi et al., 2011; Yu et al., 2012; Fosalau et al., 2016; Perera et al., 2018). Sofwan et al. (2017) designed an IoT system to provide a landslide early warning.

3.3 Volcanic hazards

Volcanoes require remote monitoring since they are often hazardous, inaccessible, and in isolated locations. Typical measurements include: (1) seismicity, (2) surface deformation, (3) thermal changes, and (4) gas flux (Pyle et al., 2013). The first monitoring began in 1841 at Mt. Vesuvius followed by Mt. Etna 1881, Mt. Peleé 1902, and Hawaii 1912 (Tilling, 2003). There is now a global organization, the World Organization of Volcano Observatories (wovo.org), to collate volcano monitoring data. However, most volcanos of the world are currently not monitored, and a study in 2011 showed that only 13% of active volcanoes in developing countries were currently monitored (on the ground), even though many pose a high risk to large populations (Aspinall et al., 2011; Sparks et al., 2012).

Traditional broadband seismometers are expensive, bulky, and difficult to install. Consequently, very few can be deployed at a given site, and poor spatial coverage limits scientists' ability to study volcano dynamics and make accurate eruption predictions.

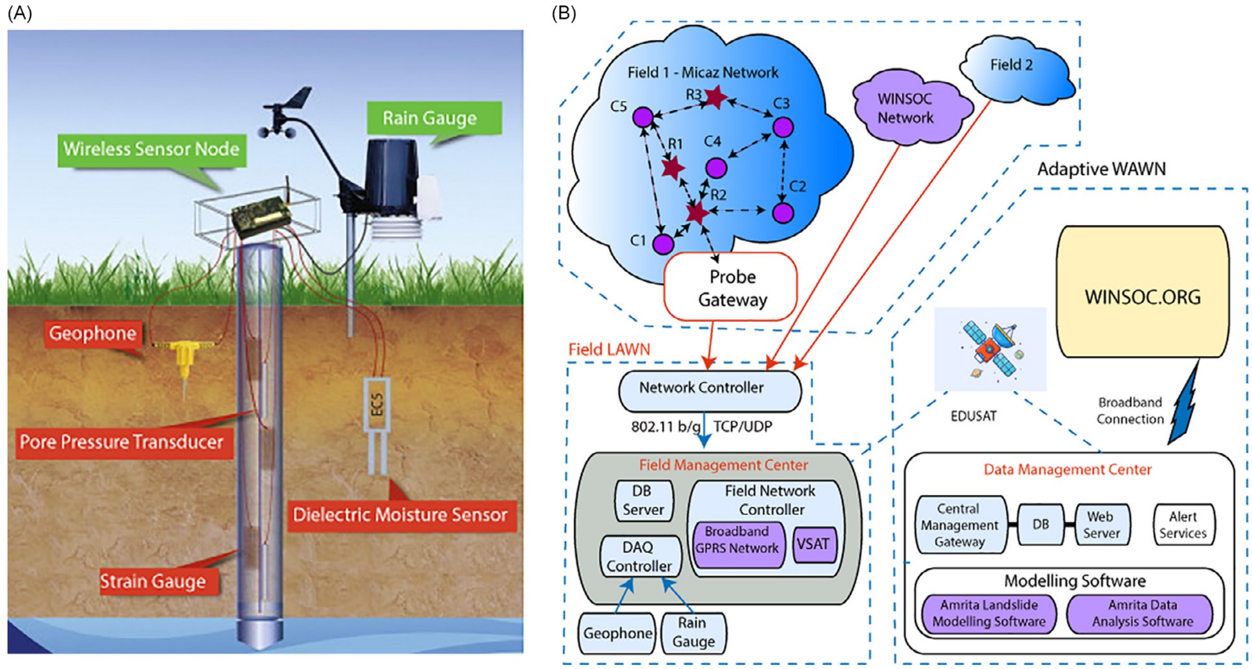

Fig. 7 Landslide environmental sensor network: (A) deep earth probe (with associated sensor shown) and (B) sensor network architecture. Reproduced from Ramesh MV (2014) Design, development, and deployment of a wireless sensor network for detection of landslides. *Ad Hoc Networks* 13: 2–18.

Werner-Allen et al. (2005) installed a sensor network at Volcan Tungurahua, Ecuador which consisted of 4 nodes, and collected 3 days of acoustic data, followed the next year by 3 weeks of data (Werner-Allen et al., 2006). A similar system was later deployed at Mount St. Helen's in 2008 (e.g., the Optimized Autonomous Space In situ Sensorweb—(OASIS) project; Song et al., 2010) with 12 sensor nodes operating for 6 months.

The problem with these systems, however, was that they generated a huge amount of data which required high power to transmit. Liu et al. (2013) used a similar system but only sent the data when events were triggered to save data transmission. This concept was also used by Martinez et al. (2017a) and Martinez et al. (2017b) to collect ice-quake data. This method allowed the systems to operate much longer. Rutakemwa et al. (2017) installed a similar system at Nyiragongo Volcano and used cloud computing for processing of aggregate query and storage of data. Scarpato et al. (2017) installed a heterogeneous-sensor network in Campi Flegrei, southern Italy, which included velocimeters, accelerometers, GPS receiver, tiltmeters, tide gauges, and thermal cameras. In addition, at Mount Singabung in Indonesia, a sensor network (measuring soil condition, water, and air quality) was set up after a major eruption in preparation for the next volcanic event (Sinulingga and Siregar, 2017).

Other systems have concentrated on measuring one particular aspect of the volcanic environment. Crawford et al. (2019) discuss a low-cost sensor network deployed during the summer 2018 Kilauea eruption on the Island of Hawai'i to measure volcanic gas emissions. Morales-Simfors et al. (2019) designed a system to measure radon levels, as it has been argued that radon is a precursor for earthquakes and volcanic eruptions (Nazaroff, 1992). Rainville et al. (2019) designed the Volcanic Ash Plume Receiver (VAPR) sensor network system at Mt. Etna Volcano comprising a series of GPSs. These were used to detect ash plumes, as they caused a sudden shift in the GPS position (Grapenthin et al., 2013). This effect was used to develop an ash-detection algorithm (Larson, 2013; Larson et al., 2017). Wang (2019) has devised a low-cost ultra-wide-band (UWB) radar sensor network to enable the discovery of people trapped in buildings combined with a fuzzy-pattern recognition algorithm.

Volcano tomography allows seismologists to visualize the internal structure of a volcano and this changes when an eruption is imminent (Lees, 1992). Phillips et al. (2017) designed a low-cost sensor network system capable of producing real-time tomography from seismic-event detection (Fig. 8). These were deployed in Tungurahua Volcano, Ecuador and Llaima Volcano, Chile. A similar system was also installed at St. Helens (Kamath et al., 2016).

Song et al. (2009) dropped air-borne sensors (by helicopter) at St. Helens to form a sensor network. Each node collected and sent real-time continuous seismic, infrasonic, lightning, and raw GPS data to a base station. More recently, Wood et al. (2018) described a "Dragon Eggs" system of sensor nodes deployed by UAVs at Stromboli volcano. Each node includes gas sensors (SO_2, H_2S), relative humidity, temperature, pressure, GPS receivers, and vibration sensors. To save power, data were only sent back when triggered by events.

Lara et al. (2015) discuss the concept of a Real-Time Volcano Early Warning Systems (RT-VEWS). They would have three elements: (1) volcanic activity monitoring, (2) event detection (since continuous monitoring produces a large amount of daily data), and (3) an alert system (they used Integrated Services Digital Broadcasting (ISDB-T), the standard for digital terrestrial

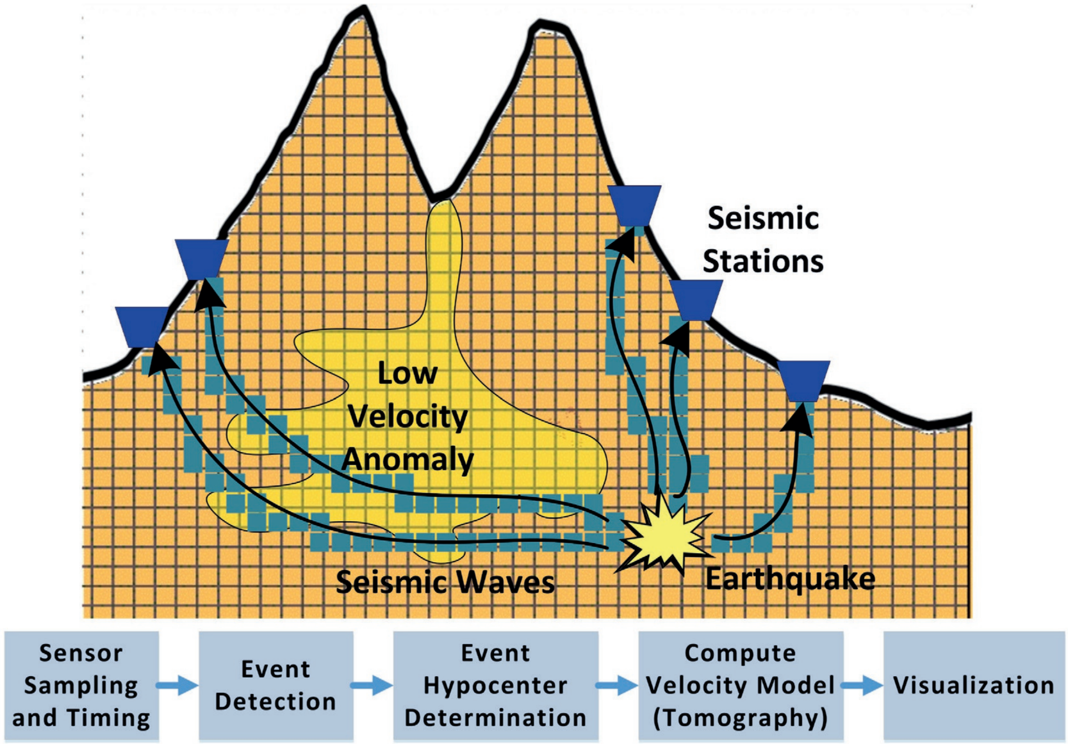

Fig. 8 Volcano tomography sensor network system. The tomography estimates a velocity model consisting of the seismic-wave propagation speeds in cubic blocks beneath the volcano surface. Reproduced by Phillips DE, Moazzami MM, Xing G, and Lees JM (2017) A sensor network for real-time volcano tomography: System design and deployment. In: *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, pp. 1–9. IEEE.

television). They tested this with 10 sensors at Cotopaxi Volcano, with 3 days of monitoring, with data sent by Wi-Fi to a laboratory located 45 km away.

It is worth noting that at least 70% of the volcanism on Earth occurs under the ocean, which is even more difficult to monitor. Therefore, some cabled networks have been established along the Juan de Fuca tectonic plate, with two networks which include over 1700 km of cable and 14 subsea nodes. Data and imagery are available in real to near-real time (Kelley et al., 2014).

The National Aeronautics and Space Administration (NASA) has a Volcano Sensor Web (VSW) which is a global network of sensors and applications for detecting volcanic activity. It uses software agents to detect volcanic activity alerts generated from a wide variety of sources on the ground and in space, and can be easily triggered manually (Davies et al., 2016). In the future, it will link with the World Organization of Volcano Observatories and other global-sensing systems to provide unified volcanic alerts.

3.4 Tsunamis

In the 1990s, a global system of offshore gauges called the Deep-ocean Assessment and Reporting of Tsunamis (DART) was installed (Gonzalez et al., 1998). This allowed the development of a Tsunami warning system in the Pacific Ocean (Titov et al., 2005). These instruments, however, are expensive (US$250 k) and so sparsely used. There is also a global network of fixed Ocean Bottom Seismometers (OBS) along with a denser array of Ocean Bottom pressure gauges (OBPG; locations shown in http://www.iris.washington.edu/gmap/#network=_OBSIP&planet=earth). The latter are not permanent stations (so can be moved to areas of interest) and have a high sampling rate, but they do not provide real-time data (unlike DART; Heidarzadeh and Gusman, 2019).

It has been suggested that animals can sense incoming tsunamis by sensing changes in marine conditions (Tiwari and Tiwari, 2011), and this could be utilized by using a sensor network (Virmani and Jain, 2016). The latter investigators devised a sensor network that measures these changes, which includes change in electric field (Manoj et al., 2006), electromagnetic force (Tyler, 2005), wave-energy gradient (Salmon, 2015), and heat/chemical energy emitted from the marine animals.

3.5 UAVs, sensor networks, and disasters

There is a growing research field involving the integration of sensor networks with UAVs (Mitchell et al., 2010; Maza et al., 2011; Gomez et al., 2015; Capitan Fernandez et al., 2015; Martínez-de Dios et al., 2017). Luo et al. (2019) argue that UAVs need to be embedded into the entire life cycle of disaster management. This includes data collection prior to the disaster, high-resolution real-time images during the disaster, and mapping post disaster. These are linked together into a network (Fig. 9), which consists of a

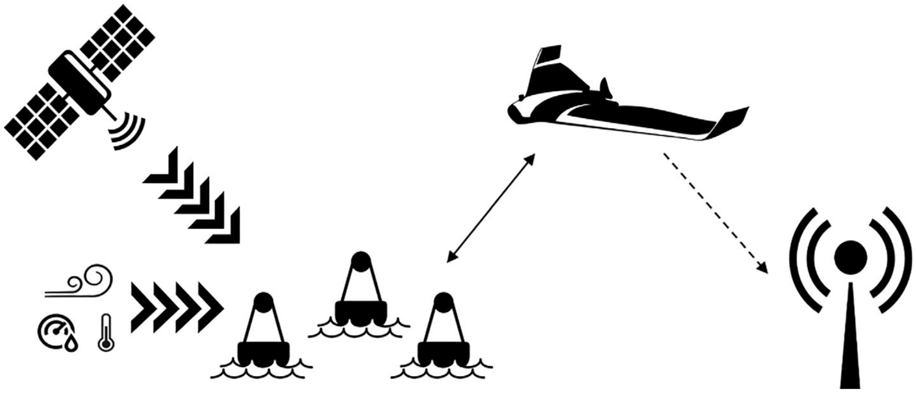

Fig. 9 UAV-based sensor-network system for a coastal monitoring (the straight-line arrow indicates the main data transmission flow, the dashed arrow represents the communications with the optional ground station and the others indicate the environmental input to the buoys). Reproduced from Trasviña-Moreno CA, Blasco R, Marco Á, Casas R, and Trasviña-Castro A (2017) Unmanned aerial vehicle based wireless sensor network for marine-coastal environment monitoring. *Sensors* 17 (3): 460.

Wi-Fi network, 2G/3G/4G/5G cellular network, UAV ad hoc network, and GPS-assisted satellite network. They can also be used as a flying base station (Morgenthaler et al., 2012; Mozaffari et al., 2016; Ullah et al., 2017). The UAVs can also be used as a data mule (Heimfarth and de Araujo, 2014). It has also been suggested that UAVs can be used as an aerial charger to fly to an exhausted node to recharge its battery (George et al., 2010).

Zolich et al. (2016) used a UAV to collect data from stationary low-cost and low-power buoys. Trasviña-Moreno et al. (2017) used a similar system but from freely floating buoys (Fig. 9) to monitor shoreline variables in the Sistema Multipropósito para Monitoreo del Medio Ambiente (SIMMA) research project in Mexico. UAVs have also been used as part of numerous wildlife surveys (Hodgson et al., 2013; Bevan et al., 2015).

3.6 Citizens as sensors

It has been shown that citizen science can be extremely useful in disasters and feed into a sensor network approach (Goodchild, 2007). "Citizen science" can be accomplished through structured programs (Theobald et al., 2015), or from information provided unwittingly via harvesting social media or location data (Becken et al., 2017). Becken et al. (2019) argue that a "hybrid" monitoring system of sensor networks alongside human volunteers is ideal for many environmental monitoring situations. Poblet et al. (2018) suggest that there are four disaster management phases: mitigation, preparedness, response, and recovery, and that citizen science can have a key role in each of these phases. In particular, they argue for 4 levels of crowdsourcing (see Fig. 10): (1) crowd as a sensor: the collection of data from multiple devices; (2) crowd as a social computer: collecting data from social media and engagement in social conversation if needed; (3) crowd as a reporter: people can offer first-hand information on events as they are unfolding; (4) crowd as a microtasker: the execution of specific processing tasks by users (requiring specific knowledge and training).

There can be real-time observations such as the "Did You Feel it" (DYFI) website from the USGS, which was used to monitor earthquakes (Crooks et al., 2013), or cetacean sightings (Lodia and Tardin, 2018). The latter results were tested against monitored data and showed acceptable levels of correlation. Other examples include flooding in Brazil in 2010 (Poser and Dransch, 2010; Degrossi et al., 2014), Pakistan in 2010 (Munro, 2010), Queensland in 2010/2011 (McDougall, 2011), Thailand 2011 (Kaewkitipong et al., 2012); as well as the Haiti earthquake in 2010 (Zook et al., 2010), Nepal earthquake 2015 (Imran et al., 2015) and forest fires in France in 2009 (De Longueville et al., 2009).

Any system that makes decisions in an emergency situation needs to take into account human responses and society as a whole (Perez, 2019). It needs to be trusted by the public, and the response must be appropriate to the nature and scale of the event (Croft, 2019; De Longueville et al., 2010; Laituri and Kodrich, 2008; Scott and Johnson, 2016). It may be possible to plan for disaster mitigation in terms of infrastructure, but there may be many associated societal effects such as shortages in goods (and panic buying), relative timing (during a school day), and differences in health/mobility/resources of citizens which need to be accounted for (Emrich and Cutter, 2011; Wang and Lin, 2018). Engagement and education are important (Roser-Renouf and Maibach, 2018) to enable an "intelligent" response from the public to an alert from a so-called smart sensor network.

4 Network design and challenges

4.1 Sensor nodes

The platform for sensor nodes has changed over the last twenty years. Many research-based nodes have been developed, and they are commercially available as well. The Mica2 mote (https://www.willow.co.uk/MICA.pdf) was popular during the early development of ESNs, while more recently Arduino (https://www.arduino.cc/)-based systems have been used. Libelium (www.libelium.com)

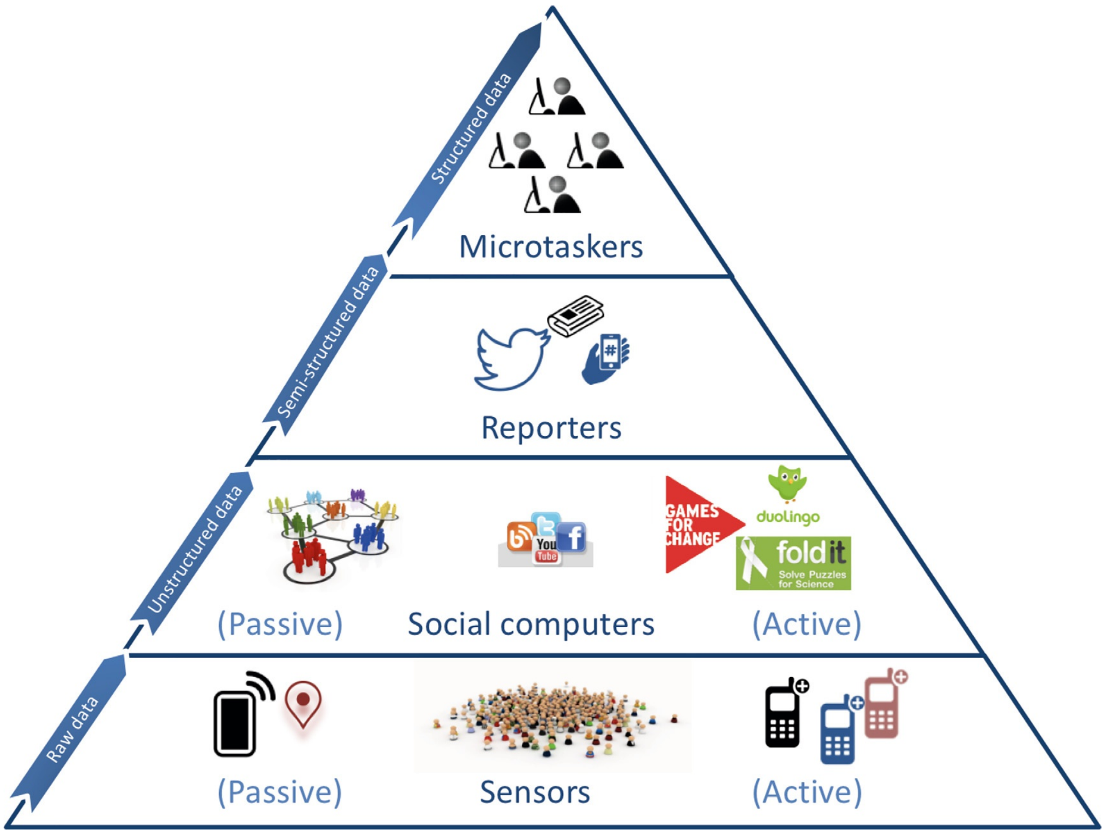

Fig. 10 Crowd-sourcing roles based on types of data processed and level of involvement. Reproduced from Poblet M, Garcia-Cuesta E, and Casanovas P (2018) Crowdsourcing roles, methods and tools for data-intensive disaster management. *Information Systems Frontiers* 20 (6): 1363–1379.

combines the easy-to-use Arduino environment with hardware, sensors, and libraries that allow a wide range of systems to be built. The agriculture industry has a range of suppliers, for example soilscout (soilscout.com) makes specialized ground-sensing sensor nodes. Similarly, the construction industry has sensor network products such as the Wisen systems which have been used to monitor tunnels (https://hmagrp.com/hma-wisenmeshnet/).

Students can learn a lot about sensing using Arduino or Raspberry Pi kits and in some cases this hardware can be used to run experiments. However, their power consumption and connectivity are not ideal for battery-powered sensor nodes. What distinguishes wireless sensor-node hardware is the range of radio communication and low-power modes so that sensing can be scheduled between low-power sleep states.

Most of the specialist nodes are configurable, but not so easily used for building a general sensor node for other purposes. The increasing spread of communication technologies such as LoRaWAN (see Section 4.2) has led to a dramatic increase in commercially available sensor nodes, typically single purpose, ranging from air quality and water level to rain gauges. There are around 100 outdoor devices that are currently available to buy to use with this communication system (https://www.thethingsnetwork.org/marketplace/). LoRaWAN has the advantage that all the sensor nodes can link to any certified base station.

4.2 Communications

A variety of radio communications technologies are used to send data back from the field. These range from Cellular networks (typically GPRS/3G) commonly available for commercial equipment such as meteorological stations, to specialized lower power technologies. Fig. 11 shows an estimate of the range and power use of some communication technologies. It should be noted that some are proprietary, so for example with LoraWAN, only one type of radio and base station can be used, but already several vendors sell different hardware. The more open standards make it easier to have a mixture of hardware and protocols within a deployment.

Each communication system develops over time so there are emerging systems related to cellular networks such as NB-IoT and LTE-M which use less power, cost less, and gain from the widespread coverage mobile phone providers can maintain. Wi-Fi is not an obvious method to use due to its short range, but it can be useful to link sensors in a small site to an outgoing gateway. It is also possible to use amplifiers and directional antennas to build fast links over 10-20 km. At the lowest range scale, Bluetooth has a Low Energy mode (BTle) which is useful for linking sensors at close range to a device with long-range communications, avoiding wires.

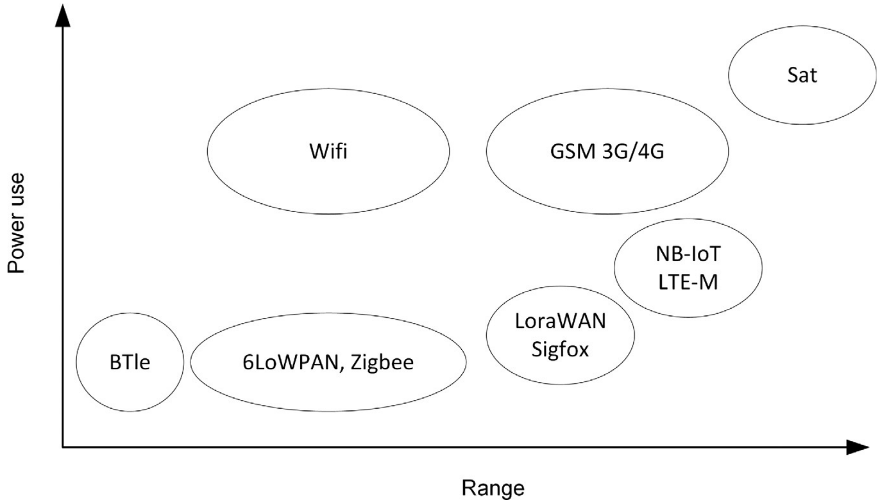

Fig. 11 Schematic diagram to show the relative range and power use of different communications systems.

BTle is mature and has wide technology support due to its use in home systems and mobile phones. Systems that have much lower power usage such as Zigbee and 6LowPAN, which use the IEEE 802.15.4 standard, have a lower data rate (e.g., 50 kbit/s). At 2.4 GHz, they have low range (<250 m) but at sub-GHz frequencies, (915–868 MHz) they can have over a 1 km range. Where high-power radio is allowed there are also "radio modems" available with a range of tens of kilometers.

Technologies that have been tested extensively are LoRaWAN and Sigfox, which represent the newer Low Power Wide Area Networks (LPWANs). They have reasonably low-power requirements but very low data rates (e.g., 1 s for a 50 byte packet) and limited duty cycle (e.g., 1% of airtime). They rely on a separate infrastructure of base stations installed by other providers, with the aim to cover wide areas with a low-cost network (at sub-GHz frequencies). They are particularly popular with smart city and agriculture projects where fixed base stations can be set up by individuals or organizations. Satellite-based communications have been used for years for devices such as Argo floats which need global coverage. The Iridium system is an example which allows short messages to be sent from anywhere and is ideal for very remote areas. Power use is high and transmission can take many seconds, but it has been used successfully (Martinez et al., 2017b). New networks are emerging which use nano-satellites (e.g., Vodafone, swarm, space), benefitting from lower deployment costs and newer technologies to provide global coverage.

4.3 Power management

Devices with long-range communications use a lot of battery power when communicating, so they usually only do so at intervals. When they rely on each other for relaying data they require a synchronization technique, which can increase complexity but can be as simple as using a GPS clock to turn on every hour precisely. Power-aware systems can monitor their battery life and avoid communications if the system is at risk.

4.4 Robustness

In the physical environment, communications have to be robust enough to retransmit lost packets or recognize that the signal strength is not sufficient at that time. This normally implies that the sensor data are stored in a large enough buffer that down-time on communications can be tolerated. These factors combine with the usual waterproofing and weather protection to increase system robustness. Many systems have a single point of failure such as a base station, but it is possible to include back-up communications (e.g., GSM or Satellite) because long-term failure of such a link could result in nodes overloading their data backup. However, no system is perfect, and monitoring mechanisms so that users receive some diagnostics when things fail can help with system management.

4.5 Scalability

Most systems that rely on a base station or a gateway can only connect to a relatively small number of nodes, which is normally sufficient for a research team. However, if the infrastructure is used by thousands of users (e.g., a smart city) there may be connection problems (contention; when the nodes all transmit at the same time), and protocols need to be established to avoid data loss (Kim and Choi, 2006). For mesh networks where nodes dynamically join and readjust routes, there is normally a high limit to the number of nodes that can participate. Low-bandwidth links can limit the scalability of the system though, particularly if some sensor readings create bursts of data.

4.6 Usability and management

Deploying complex systems can be frustrating due to the lack of simplified human interfaces, obscure terminology, and hidden behavior. This can affect being able to configure sampling rates for example, but networked devices will always have a hidden issue of connectivity: where can the sensor nodes be placed? Simple systems where data are pushed from sensor nodes to the cloud for example may not have any way of monitoring their "health" or configuring different parameters remotely. Systems which use Internet and Web protocols can often be managed with conventional tools and the channel back to the devices can be easier to use. Simplifying management requires a design from the outset that provides these mechanisms.

4.7 Security

Security, in terms of someone being able to hack into the system and cause disruption, depends on the nature of the communications system. Fully IP-based systems could be exposed if firewalls and encryption are not used correctly, and this has been documented for general IoT devices. However, shared base stations with proprietary links can still be subject to attacks.

4.8 Standards

One of the main benefits of networks based on IP protocols is the use of web and Internet technologies. While many sensor networks will use nonstandard ways to transfer their data to a server, once there are common Web and data standards, this will make data integration simpler and the software more future-proof. Some underlying network standards have been boosted by the growth of commercial Internet of things devices. For example, low-level radio packets can be interoperable across vendors (using IEEE 802.15.4) and various manufacturers use this to standardize access to products such as thermostats, switches, and lightbulbs. This has also led to low power standards to connect to devices which mirror the Web methodologies. The constrained application protocol (CoAP) is an example of the new standards which can allow a mixture of sensor hardware to behave like web servers so data can be fetched easily with scripts.

5 Software and network integration

Standards to format, describe, and publish observations and measurements have evolved and it is much easier to make data accessible on the Web. Sensor networks can transfer data to servers but the mechanism for uploading and downloading the data is generally nonstandard. This has led to each system having a specific upload technique to put the data into a database or other storage system for later use. Cloud-based information services can simplify the storage, management, and access to data. Examples of Earth-science-based systems run typically by government agencies including the UK NERC Data centers (https://nerc.ukri.org/research/sites/data/) and the US Earth Resources Observation and Space (EROS) center (https://www.usgs.gov/centers/eros). These provide a uniform way to upload data but typically expect data sets, not a continuous data stream. Data from sensor networks need to be managed, discovered, and integrated into web resources (Rennie, 2016; Wong and Kerkez, 2016; Petrić et al., 2018; www.copdess.org) to make it available for analysis. Data sets need to be designed to be FAIR: findable, accessible, interoperable, and reusable (Wilkinson et al., 2016). This is increasingly seen as a way to ensure data sets across the globe are more usable by researchers.

6 Conclusions

Environmental sensor networks have the potential to transform environmental and Earth science. They allow continuous monitoring of environments, which is particularly important in remote or hazardous locations. They can be combined with thematic information, satellite data, and simulated data and predictions to provide an understanding of environmental processes and systems, as well as being a vital component of emergency infrastructure systems.

Geomorphological systems that have particularly benefited from sensor networks include glacial and periglacial systems, where monitoring over-winter, or beneath glaciers is very difficult by traditional methods (Martinez et al., 2006; Hasler et al., 2012). This has allowed a far better understanding of glacier dynamics, and such properties as methane release which are vital for predicting temperature increases and sea-level rise (Hart et al., 2019a; Oberle et al., 2019). Another important area of research is in understanding coastal processes and dynamics. Sensor networks have brought together many innovative techniques (e.g., time-lapse cameras, buoy-mounted instruments, RFID-tagged clasts, automatic beach surveying) to measure the numerous dynamic processes effecting the coastal system and the stability of shorelines. This has allowed the quantification of the rate and nature of coastal processes, as well as setting a base line from which to measure change associated with both rising sea levels and other anthropogenic disturbances such as changes in land cover, land use, and pollution (Benveniste et al., 2019).

Sensor networks also play a critical role in understanding and assessment/monitoring of geohazards. They allow the integration of spatio-temporal data from *in situ* sensors, remote sensing, UAVs, and human observers, from which, geospatial big data can be analyzed rapidly using algorithms, artificial intelligence techniques, numerical models, and intelligence decision-support systems to provide live early warning and emergency relief information. *In situ* sensors can be deployed in remote and hazardous areas to monitor avalanches, landslides, volcanoes, and tsunamis. Robots, on the ground (UGV), air (UAV), and underwater (AUV), can be used for sensor/node deployment, data collection, and surveillance. Human agents are another important element (citizens as sensors), whether they carry a specific connected sensor during leisure/sport activities (in the case of avalanches; Waller, 2014), or become an active and/or passive "reporter" during disasters (via social media; Poblet et al., 2018). Human-induced climate change will lead to more extreme events which will mean that "intelligent" sensor networks will be even more important in emergency planning and operations, and so it is vital that any decision support-related system needs to take into account human responses to life-threatening situations.

Although there have been many technical advances over the last twenty years, there has been a relatively slow uptake of sensor networks. This is because most systems rely on bespoke nonstandard elements which require specialized expertise. Therefore, there is the need for standardized systems, and such an opportunity has been provided by the development of the Internet of things (IoT). Many of the sensing techniques discussed in this chapter are interchangeable between different environments and phenomena (e.g., avalanches, landslides, lahars), which enables the potential for the development of more generic monitoring systems. What is required is an optimized standard "toolkit" that can be used by any environmental monitoring team to gather data from the natural environment. This will allow the construction of heterogeneous systems by nontechnical specialists (using a building block approach) to allow seamless data streams from the field to be captured onto the web, to enable sophisticated analysis and modeling for both research and disaster planning, management and response. Over a longer time-frame, such localized systems could be linked together into a more comprehensive global integrated system that is essential for predicting and protecting environmental responses to climate change.

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