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EDITORIAL

Low-cost sensors for monitoring water resources

On 19 June 2019, 'Day Zero' was declared in Chennai, Tamil Nadu, India. The four main water reservoirs had cracked open with dryness – there was no water left in the city. The news shocked and surprised many because as late as 2015, Chennai was flooded and more than 300 lives were lost. These flood and drought disasters in the city did not occur suddenly; rather they happened gradually through depleting groundwater, drying rivers and vanishing wetlands, much like a predator closing in, openly visible, yet invisible by its apparent quiescence.

It may appear that we are weak at anticipating dangers, but this is not true. We can easily sense imminent dangers that generate visual stimulation. Unfortunately, the signals relayed from the existing water resources monitoring network in the country are shrouded with uncertainty due to spatially and temporally sparse observations. Therefore, while we hear about environmental and water issues, and vaguely sense something is going wrong, yet strong steps are not taken because our minds do not visualize them as imminent dangers. The key to handling such issues therefore lies in making the 'predator' more visible. Fortunately, we are now living in an age where we can monitor our water resources effectively. The last decade has seen a rapid improvement and significant price reduction in sensor technologies. These technologies are now accessible to scientists and managers from low- and medium-income countries for effectively monitoring their water resources.

The water resources monitoring primarily consists of measuring hydrological fluxes and storages such as precipitation, streamflow, evapotranspiration, soil moisture and groundwater levels. It also includes monitoring water supply from rivers, reservoirs, lakes, wells and canals, and water consumption in agricultural, industrial and domestic sectors. With increase in water contamination problems, the monitoring now encompasses water quality parameters as well. In India, water resources monitoring is mostly manual, which limits the density and accuracy of the data. Automatic instruments are being used, but owing to high cost they are sparsely installed. Moreover, lack of integrated monitoring across different regions, scales and variables renders the collected data to be of limited value for scientific analysis.

A monitoring system consists of a sensor, an embedded system, a data communication system, a power source and management system, and a data analysis and visualization system. The term 'low-cost sensors' is typically used when the initial purchase price of the monitoring system is at least an order of magnitude lower than the conventional or standard monitoring system.

In addition to the initial low purchase price, an ideal low-cost water resources monitoring system should be: (i) low in power consumption and maintenance, and self-sustained in power generation so that once installed it can run uninterruptedly for years; (ii) robust so that it provides reliable data in the harshest of environmental conditions (from sub-zero temperatures in the Himalayas to the scorching heat of the Thar Desert); (iii) smart so as to take its own decisions and also recuperate on its own in case of failure (e.g. in case of network outage, it should stop attempting to transmit data but rather log the data, conserving battery power); (iv) aesthetically invisible so that it blends into the environment, making it less prone to theft and vandalism, and (v) functionally invisible so that it leaves no harmful wastage (like plastic and battery residue) in the environment.

Advances in sensor and ancillary technologies have enabled fabrication of such ideal monitoring systems. Improvements in terms of accessibility, cost, quality and usability have been observed in all the components of a monitoring system. These advances and improvements are briefly discussed here.

A sensor senses changes in the physical environment and converts them into measurable signals. A vast range of sensors is available that can directly or indirectly measure almost all the elements of a water resources system. Examples include temperature, pressure, humidity, light, radar, ultrasonic, infrared, piezoelectric, turbidity, pH and capacitance sensors. Advanced microfabrication techniques are considered in mass-producing sensors that are compact, light weight, inexpensive and energy-efficient. Further, these sensors are mostly digital, making them more reliable (less prone to noise) and smarter (no separate calibration).

An embedded system controls the functioning of the sensor, and thus acts like a brain for the monitoring system. A revolution in the embedded systems started in 2005 with the birth of open-source Arduino platform. While earlier an engineer would have to solder a microcontroller to a printed circuit board along with other necessary electronic components, Arduino provided a ready-to-use board with microcontroller and other components pre-soldered and an open-source software to program them. Since then, with the development in electronics and embedded hardware, the microcontrollers have been evolving in their capabilities, cost, accessibility and standardization. Today, embedded systems have gained the capabilities of computers, running full operating systems (like Raspberry Pi). Parallel developments in open-source software and firmware have made microcontrollers more accessible to users, as they can now be programmed in high-level languages (like C++ and Python).

Water resources monitoring systems are often installed in remote locations where data transmission is possible only through long-distance wireless communication technologies. An ideal wireless technology should promote longer battery life and communication range, and higher scalability (i.e. greater number of devices per tower). Three technology options exist in long-range wireless communication – satellite technology, cellular technology (like 2G, 3G, 4G and 5G) and LPWAN (low power wide area network) technology (like Sigfox, LoRa, NB-IoT and LTE-M). Data transmission through satellite technology is quite expensive, but may be the only option in remote locations. The cellular technologies operate in licensed frequencies and are geared towards fast data transmission, but with relatively high power consumption. The LPWAN technologies belong to a new class of long-range wireless communication. These technologies have high scalability and low power requirements, but have relatively low data transmission rates. Some of the components of these technologies lie in the open-source and/or de-licensed domain, which make them relatively inexpensive. In the Indian context, cellular networks have gained wide coverage and LoRa is making inroads. Together they provide a cost-effective wireless communication solution to water resources monitoring systems.

The monitoring systems are traditionally powered by non-rechargeable batteries as they are convenient to use, easily available and relatively inexpensive. However, the need for frequent replacement and the resulting environmental implications make them less popular. On the other hand, rechargeable batteries charged with energy harvested from external sources (like solar power) are becoming increasingly viable. A power management system that selectively activates parts of the monitoring system when required and switches them off when not required can significantly reduce power consumption. Thus an efficient energy harvesting system with a rechargeable battery and a smart power management system can provide complete solution to the power requirements of a monitoring system.

Dense network of low-cost sensors will generate large amount of data that need to be stored and analysed. Owing to the progress in computer hardware technologies (like processors, storage devices and memory), servers have become cheaper and ever more powerful. While this has made handling of large data efficient, it has also enabled the use of high-level programming languages (like Python and JavaScript) for analysing data, which was not considered earlier owing to performance issues. Lately, Python is gaining traction as the popular language for writing data analytics algorithms, and JavaScript is gaining popularity for its back-end and front-end development capabilities. Further, cloud computing has provided a cost-effective means to use shared storage and computational resources over the internet for data analysis and visualization. Improvements have also been made in data formats for transmitting data over the web. JSON (JavaScript Object Notation) has gained universal acceptance as the web data exchange format. Smaller, simpler and quicker alternatives to JSON, e.g. Google Protobuf or Apache Thrift are now being explored.

The low-cost sensor technology is maturing fast, but it still has to overcome many challenges before being accepted by the scientific community and water managers. Long-term comparison of low-cost sensors with the reference/conventional monitoring methods is required to evaluate their reliability and stability under different environmental conditions. Characterization of their measurement uncertainties in terms of errors and biases is needed to assimilate them with other *in situ* and remote sensing observations. Specialized algorithms for data analysis and visualization would be required to extract useful information from the large volume of datasets collected by low-cost sensors. Further technological advancements would be needed to reduce the cost of sensor calibration, installation and maintenance, data transmission, analysis and visualization, and result dissemination.

The water resources monitoring in the country is primarily done by state and central government agencies. With the availability of reliable low-cost sensors, such monitoring can be decentralized to local government agencies like Gram and Nagar panchayats. Even local communities and citizens can participate in data collection, enabling citizen science (Silvertown, J., *Trends Ecol. Evol.*, 2009, **24**, 467–471). Such endeavours will raise awareness about water issues and increase civic participation in the decision-making.

Like the two young fishes in the famous parable of Wallace (Wallace, D. F., *This is Water: Some Thoughts, Delivered on a Significant Occasion, About Living a Compassionate Life*, Little, Brown and Company, USA, 2009), who were oblivious to the water in which they were living, we too have difficulties in perceiving important realities that are obvious and ubiquitous; the waning of water resources being one such reality. The low-cost sensors for monitoring water resources may provide the power of 'observation' with which the potential dangers can be seen and averted, and the healing process of already depleted water resources can begin.

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