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# Sensing Impacts: Remote Monitoring Using Sensors



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# Sensing Impacts: Remote Monitoring using Sensors

*Sensing technologies are ubiquitous in most developed markets, where they are used for industrial process monitoring, product tracking, and information services. More recently, non-governmental organizations (NGOs) have begun leveraging sensors for supply chain management, remote monitoring, and consumer product testing. This report describes how sensors work, and how they can be harnessed for data collection in low-resource settings.*

## A Sensing Revolution

Sensors are all around us; you can find them in most modern homes, phones, and cars. A speedometer is a sensor, as is a water meter or a security alarm. At its essence, a sensor is simply a device used to measure a characteristic of its environment—and then return an easily interpretable output, such as a sound or an optical signal. Sensors can be relatively simple (e.g. compasses, thermometers) or more complex (e.g. seismometers, biosensors).

Recent advances in sensing and wireless networking have expanded the range of sensors available off-the-shelf; they have also made it easier for non-experts to experiment with the technology. These trends have been accelerated by the popularity of do-it-yourself (DIY) electronics, open-source hardware and software, and the Internet of Things, in which everyday objects are wirelessly connected to the cloud for sending and receiving data. Today, it is easier than ever to deploy sensors and remotely collect data.

And while many sensors are deployed in the environment, wearable sensors are an important trend for those studying human behavior. Wearable devices are placed on individuals to record movements or measure biological and physiological changes over time. They can be integrated into clothing, enabling rescue teams to quickly locate people after an environmental disaster. Or they can be used by health workers to monitor the movements of individuals undergoing physical rehabilitation.<sup>17</sup> They also can connect and exchange data with other objects. Numerous applications of wearable sensors are under development for health care, smart homes, fitness, and entertainment.<sup>18,19</sup>

Indeed, the market for sensor-based services is exploding—and while the social sector is a relatively new entrant to the market, there are great examples of NGOs and public agencies that are using sensing technology to improve service delivery. Table 1 outlines a range of applications for sensors in the development sector, with links to specific examples; and a 2016 report by [Cisco and ITU](#) details a number of examples.

For example, organizations in the water and sanitation sector have used accelerometers and motion sensors to monitor household water consumption, community adoption of latrines, and the use of handwashing stations.<sup>6,25,26</sup> Environmental monitoring programs have used geographically dispersed networks of sensors to capture real-time data on floods and other environmental threats.<sup>10-12</sup> NGOs have generally collaborated with researchers and community groups to deploy sensors in the field; however, there is an increasing role for private companies that directly support sensor deployments in low-resource settings (see Appendix).

Table 1. Applications of Sensors by Development Actors

<b>Applications</b>	<b>Examples</b>
Energy	Power grid conditions <sup>20</sup> , energy consumption <sup>21,22</sup>
Clean Water	Handpump functioning
Technology Adoption	Latrines <sup>6,25</sup> , handwashing, <sup>26</sup> water filters, cookstoves <sup>23,24</sup>
Environmental Pollution	Particulate matter, ozone, SO <sub>2</sub> , NO <sub>2</sub> concentrations indoors or outdoors <sup>27-31</sup> , mercury <sup>32</sup>
Ambient Environment	Temperature <sup>33</sup> , relative humidity <sup>34</sup> , noise
Water Management	Water quality (pH, turbidity) and safety <sup>35,36</sup>
Agriculture	Soil moisture <sup>34,37</sup> , fertilizer in soil <sup>38,39</sup> , water salinity in shrimp farming <sup>40,41</sup> , crop monitoring <sup>42,43</sup> , pests management <sup>44</sup>
Disaster Surveillance	Landslides <sup>10</sup> , Fires <sup>45</sup> , Floods <sup>11,12</sup>
Transportation	Monitoring surface conditions of roads, <sup>46</sup> pedestrian footbridges
Health	Monitor vital signs <sup>47</sup> , monitor effectiveness of home-based rehabilitation interventions <sup>17</sup>
Structural Health	Monitor bridges, aircraft, buildings for safety <sup>48</sup>

## Why sensors?

If designed and used appropriately, sensors can play a valuable role in “right fit” M&E systems. They have several features that support the CART principles:

### **Credible**

*Collect high quality data and accurately analyze the data.*

Sensors generate unbiased, frequent, and replicable measurements that are not prone to the inherent limitations of human-based data collection methods. If properly calibrated and maintained, sensing data can be far more reliable than self-reported information from surveys, focus groups, or polls. They can be less subject to fraud or errors in reporting and data entry, and they can be configured to generate a time stamp, geocode or other auditable trail for each observation, providing useful data-quality checks.

### **Actionable**

*Commit to act on the data you collect.*

One substantial advantage of sensors is their capacity to remotely capture and report data continuously, in near real-time. Traditional data collection methods, such as surveys and focus groups, require trips to field sites, long interviews, data entry and cleaning. Sensor systems can be

set up to automate many of these processes, providing information on program effectiveness in a more granular, timely, and actionable fashion. Most commercial providers of “sensors for development” offer dashboards that allow users to track performance over time.

### **Responsible**

*Ensure the benefits of data collection outweigh the costs.*

Sensing systems can be designed to collect data in a cost-efficient manner, through careful maintenance and reuse (even if the cost of individual sensors is significant). In fact, for routine or repeat monitoring of certain indicators, sensors can be less costly than human monitoring using enumerators or other staff. In some cases, remote sensing technology can increase the cost-efficiency of interventions themselves, for example by rapidly identifying components of a program or service that require repair (such as a vaccine refrigerator or water pump). As the market for these technologies matures, costs will drop further. When deciding whether to integrate sensing systems into data collection strategies, it is important to first determine if they will provide high-quality, actionable information, and then to weigh the upfront and recurring costs against the cost of other forms of data collection.

### **Transportable**

*Collect data that generate knowledge for other programs.*

While sensors are ubiquitous in developed countries, their use in low-resource settings is just beginning. As a result, the use of sensors for M&E can create two kinds of transportable knowledge:

1. Unbiased observations of phenomena that development actors care about—from community behaviors, to infrastructure performance; and
2. Lessons from the deployment of sensors in new contexts, which can be used to inform M&E strategies for other organizations.

## **Practical Considerations**

Sensors used in low-resource environments are usually designed to be low-power, small, rugged, and user-friendly. Their relative affordability allows organizations to deploy sensors over large areas of interest, and their small size makes them less intrusive (which is particularly useful when monitoring individuals or communities). They can be easily transported to remote settings; and once deployed, some classes of sensors can be maintained and used with minimal technical expertise.

In general, sensing technologies can be broken into three classes: 1) add-on sensors, 2) modified off-the-shelf, and 3) purpose-built standalone technologies that use pre-fabricated circuit boards.

**Add-on sensors** operate as “plug and play” devices. They rely on existing hardware, such as smart phones, for power and data management. These sensors are typically small, cheap, and portable; as a result, they are frequently used in decentralized, citizen-driven data collection exercises. Examples include devices for air pollution monitoring, water quality monitoring, or soil moisture analysis.<sup>13,14,50,51</sup>

**Modified off-the-shelf sensors** use commercially available sensors, but with customization for specific needs. For example, the Particle and Temperature Sensor (PATS) was engineered by adding a data logger to a commercial smoke detector.<sup>27</sup> On the one hand, relying on readily available

technology decreases design, development, and testing time. On the other hand, these sensors are affected by the cost and quality of the “parent” technology. As a result, relative to custom-build sensors they may be less flexible, have shorter battery lives, or require substantial end-user interaction.

**Purpose-built sensors** are integrated platforms built from scratch using electronic components. Compared to modified off-the-shelf, these sensors can be designed for minimal end-user interaction and ease of remote control (e.g. through Wi-Fi or cellular networks). They can also be designed to have fewer maintenance requirements. They can be engineered to last up to 24 months in the field on a single pair of batteries – sometimes longer, when harvesting power through solar panels or other means.<sup>52</sup> However, custom-built sensors can be difficult to manufacture at scale, and the scale-up itself can be costly. They also require longer timelines to allow for prototyping, field piloting, and iterative redesign.



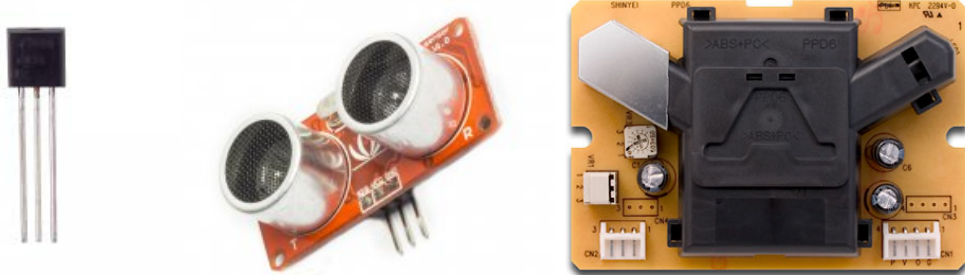
**Figure 1.** Three types of sensors (left to right): Add-on to cell phones (Project Hijack)<sup>53</sup>, Modified off-the-shelf (UCB-PATS)<sup>54</sup>, and purpose built standalone using existing circuit boards (solar-powered water sensor).<sup>55</sup>

## How do sensors work?

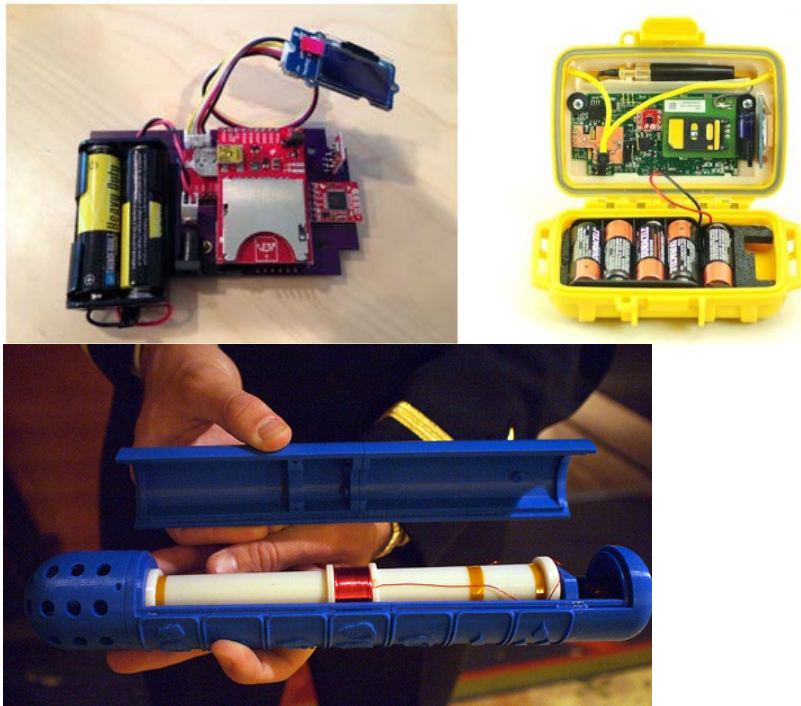
Every sensing technology includes a series of interlinked components that each carry out a specific function:

- **Sensing device:** the tool that measures and reports the variable(s) of interest, often available through retailers in the U.S. or Europe (e.g., RadioShack, SparkFun Electronics, RobotShop, Parallax, Shinyei). Cost varies anywhere from less than \$10 to over \$100 per unit, depending on the precision of the device, its size, and the quantity purchased.
- **Microcontroller module:** a chip that stores the program (software) that determines how often the sensor will collect data, how the data will be stored, processed, and transmitted. Commercially available controller modules (e.g., Netmedia's BX-24, Phidgets, Arduinino, Parallax Basic Stamp, MIT's Handyboard) can cost anywhere from \$20 to \$100.
- **Data Logger and micro SD (secure data) card:** a memory card that either stores the data collected or acts as backup when the data are transmitted wirelessly. SD cards can be password protected and data encrypted for security.
- **Telemeters (e.g., Wi-Fi, Bluetooth, cellular):** a device that allows remote transmission of the data. While data can be manually collected from an SD card or other storage device, this requires a trip to the field site. Wireless transmitters are essential for high-frequency, real-time data collection in remote settings.
- **Power supply:** stored power (e.g., batteries), harvested power (e.g., solar equipment), and/or a power adapter.

- **Other hardware:** printed circuit boards (PCB) that connect components together; switches/buttons for user input; digital displays; clock (to add date and time stamps to data); protective enclosure to prevent against tampering, theft, or other damage.



**Figure 2.** Examples of sensing devices (left to right): Parallax temperature<sup>56</sup>, Arduino distance meter<sup>57</sup>, and Shinyei particle sensor<sup>58</sup> (air pollution).



**Figure 3.** Examples of sensor hardware: Noise monitor<sup>59</sup> (left), SweetSense™<sup>60</sup> (right), and HealthyShrimp<sup>40,41,61</sup> (bottom).

## Design Trade-offs

Most sensors are built in engineering labs and are meant for deployment in industrialized settings, with network connectivity and infrastructure. For organizations working in less developed regions of the world, there are trade-offs between the quality and quantity of data required for measurement, and the ease of operating within local constraints.

### 1. Accuracy and Precision

Sensors vary in their accuracy. Users need to determine the level of precision required to credibly measure the variable(s) of interest. Manufacturers often provide a sensor specification data sheet, which contains information about sensor sensitivity, range, energy requirements, and operating conditions. Yet users should always field-test sensors in the actual location of deployment, as lab and field conditions may vary. For example, a popular particle counter that has an approximate 25 percent error rate saw this number increase to 50 percent at low particle concentrations.<sup>62</sup>

Users should also consider the level of data precision needed for meaningful decisions. For instance, the DeAGua water sensor, which measures usage of water dispensed through filters, was motivated by the need to precisely measure consumption for the carbon credit market. Cheaper water sensing alternatives are available, but they may not be as precise.<sup>63</sup> Temperature loggers that provide a binary (yes or no) signal if the temperature exceeds a threshold can be used to track adoption of fuel-efficient cookstoves, but a more accurate sensor would be needed to monitor temperatures of packaged products such as vaccines, which require highly controlled environments during transport.<sup>64</sup>

### 2. Frequency and Duration

Another trade-off is frequency (how often) and duration (total period) of data reading and logging. High frequency monitoring—for example, with samples taken multiple times per minute—can be costly in terms of power, data storage, and data transmission. In general, there are two methods for logging data:

- **Continuous logging:** Collecting data throughout the sampling period. Example: Measuring environmental conditions, such as temperature or noise pollution, at regular intervals until the sampling period ends, or the device fails.
- **Trigger-based logging:** Logging data only if a parameter reaches some threshold value. Example: To monitor hand washing behaviors *after* latrine use, you would design a water flow meter that is activated only when an adjacent latrine use monitor is triggered. The water flow sensor would then return to “off” mode once a zero value is logged.

Most off-the-shelf sensors offer little flexibility in choosing sampling frequency, while purpose-built sensors can accommodate near real-time sampling rates (e.g., several times a second or a minute) and complex triggering sequences. Yet *more* data does not always equate with *better* data for program monitoring or impact assessment. Higher sampling rates do generate more data, but this comes with higher processing and energy requirements. For example, an air pollution sensor that collects and logs pollutant concentrations every minute, although technically feasible, might not be necessary. Changes in concentrations may be slow, and the user may only need daily average values to draw a clear picture of pollution trends. Reduced sampling will expand battery life and simplify on-chip data storage and analysis.

### 3. Data Retrieval

There are two primary options for storing and retrieving sensing data: manually or remotely. Manual data storage and retrieval is usually done through a micro secure data (SD) card incorporated into the sensor. This is relatively cheap and minimizes the size and cost of sensors being deployed. This option requires end-user interaction on-site to manually download the data, either through data cables or through Bluetooth, RFID or near field communications (NFC). Relying purely on a SD card for storage may be sufficient in projects with easily accessible field sites, and with relatively brief logging and reporting periods (so that data can be stored for one-time retrieval). However, users run the risk of losing the data should the sensor hardware be vandalized or stolen, since no backup copies of the data are maintained.

Data can also be retrieved remotely using long-distance telemetry such as cellular networks, Wi-Fi, Bluetooth, or radio. In this case, data are generally transferred to a server or cloud database where they can be accessed anywhere via the internet. Some microcontroller modules already include telemetry capabilities, but pre-made circuit boards with these components are typically available and can be added to or removed from a device, depending on needs. The table below provides a snapshot of telemetry technologies available for wireless data retrieval.

Telemetry Technology	Description	Range	Pros	Cons
Bluetooth	Connects the sensor to a Bluetooth enabled device (e.g., smartphone, tablet, or computer) and transmits data via radio waves.	From less than 10m up to 100m depending on the type of devices (10m for mobile phones, 100m for computers).	High transmission rates (1-2 Mbps); ubiquitous in existing devices; does not require line of sight; low interference by physical objects or other devices.	Not the cheapest; energy intensive; short range; limited number of sensors connected.
Zigbee	Uses small, low-power radios for data transmission. <sup>52</sup>	10-100m.	Reliable; low power requirements; cheaper than Bluetooth or Wi-Fi; more than 65,000 Zigbee devices can be connected to overcome short range.	Low transmission rates (20-250Kbps; best for intermittent data transmission); short range.
Wi-Fi	Wireless Internet	10-100m (depending on indoors or outdoors)	Fast data transmission.	Expensive; limited by range of Wi-Fi network and potential for intermittent connectivity.
Cellular	3G/4G/GPRS	Wherever there is cellular reception.	Fast data transmission; can be used wherever there is cell reception.	Can be expensive because requires data plan (e.g., \$50 per unit per year <sup>65</sup> ); poor connectivity in some remote areas; energy intensive.



In resource-constrained environments, selecting an appropriate data retrieval technology requires detailed knowledge of the field site: Will the sensor be placed outdoors or indoors? Will Wi-Fi or cellular networks be reliable at these locations? How much data will need to be transmitted? Is intermittent data transmission feasible (and acceptable)? Many online resources provide detailed performance comparisons for each technology in different environments.<sup>66-69</sup>

In practice, engineers often choose to combine sensors into *Wireless Sensor Networks* (WSN) to improve range and power capacities. WSNs are small systems of sensors deployed in close geographic proximity, often with a single node that collects data from each sensor in the network. In deploying a WSN, you will use short-range wireless communication technologies (Bluetooth, Zigbee, or Wi-Fi) to relay data from the individual sensors to the local gateway, which then transfers the aggregate data over cellular networks or the internet.

Sensors and WSNs can be designed to process or analyze logged data before or after transmission. For example, in flood surveillance programs, sensor networks can be programmed to give warning signals (sounds or light) or send out SMS alerts when pre-determined levels of flood risks are reached (e.g., temperature, rainfall, water level, etc.).<sup>11</sup>

#### **4. Power Requirements**

In resource-constrained environments, where access to continuous power is challenging or impossible, sensors often rely on stored power (AA batteries<sup>24,26,59</sup>, lithium ion<sup>28,29,40</sup>, or solar salvaging methods<sup>55</sup>). For users, there is a clear tradeoff between measurement frequency and energy consumption: the lower the frequency, the higher the battery life. Since field trips to replace batteries can be time-consuming and expensive, organizations and engineers often design innovative methods to decrease the sensors energy requirements.

One option is to log data only after a particular event is triggered (e.g., once the temperature of a cookstove reaches a certain threshold, or when the door of a latrine is being opened<sup>26</sup>) or following a user-defined schedule (e.g., once every 24 hours). Trigger-based data logging has the advantage of providing users only with the data they need. Another option is to rely on a backup energy source, such as a solar panel or the power grid whenever available. Computer scientists have also developed algorithms to compress sensing data before transmission, thereby minimizing retrieval time requirements. Transmitting data only intermittently (rather than streaming data, with persistent transmission) can substantially reduce power consumption.

#### **5. Remote Monitoring and Calibration**

Sensors can be programmed to transmit data to the cloud for sharing and visualization in real or near-real time, using services like Xively or Open.Sen.se. Some platforms provide custom dashboards to view streaming data, create instant reports, or update sensor calibration and reporting parameters remotely.<sup>24,64</sup> This can be particularly useful when many sensors are deployed over a large area and the data collection strategy is expected to change after a period of time.

#### **6. Cost**

The price tag for any sensor or sensor network will include fixed costs (materials) as well as expenses for operations and maintenance, including data transmission or retrieval, batteries or other power supply, and labor. In addition, technical support may be required to deploy, calibrate, troubleshoot, or repair sensors in the field. Sensors deployed in resource-constrained environments

may require additional packaging to protect against precipitation or extreme heat; this can also drive up costs.

As discussed earlier, certain classes of sensors require very limited engineering expertise to deploy and maintain, but they might include unnecessary features and have a higher price tag to account for labor costs, software licensing, and technical support. Commissioning engineers or researchers to build custom sensors (tailored to specific needs) can be lower in cost, but requires additional time and piloting.

If an organization decides to build custom-made sensors in-house, it will need to acquire relevant engineering expertise and manufacturing capacity. Using pre-made components, engineers can develop lower-cost sensors that contain only essential features. Yet these will also need to go through a longer phase of prototyping and field-testing. Most of the NGOs that have followed this path with success were working closely with academic or private partners. Three examples of custom-made sensors with the breakdown of costs are provided in the appendices.

## **7. Community Response**

When deploying sensors for M&E, organizations need to consider closely how the community will react to the devices, and how this can affect data quality. Are you measuring human behaviors, or capturing environmental data? Where will the sensors be placed: in homes, or outside in public areas? How does the monitored population interact with the devices? Are you carrying out participatory measurement, with individual community members helping to collect the data?

Several research projects have sought to estimate how awareness of being monitored (through a sensor) changes individual behaviors. In most cases, awareness results in limited to intermediate reinforcement of positively perceived behaviors. For example, in a mobile sensing project in Ghana, some taxi drivers became concerned with the sounds of a sensor that was monitoring pollutant thresholds and decided to have their cars serviced.<sup>76</sup> In some cases, the presence of a foreign object in people's environments can arouse suspicion and even lead to vandalism and theft.<sup>28</sup> To overcome these issues, organizations can carry out a reactivity study that compares data from a group with knowledge of the sensor, to one that does not know when the sensor is being deployed. It is also possible to triangulate between different data collection methods (e.g., comparing sensing data with survey data that measure the same variables) to estimate the bias in each data generating process.

## **Privacy Protections**

When sensors are designed to collect information from private individuals or households, for example as part of a study, it may be necessary to obtain prior approval for your data collection protocols from a qualified Institutional Review Board (or local equivalent).<sup>75</sup> The approval process requires detailed descriptions of how the sensors will interfere with people's lives, how individuals' consent will be obtained, and how privacy and confidentiality will be maintained after data are collected. IRB approval is generally only necessary for research conducted to create generalizable knowledge, rather than the regular M&E activities of NGOs. However, thinking critically about these issues (interferences, consent, and privacy) is a valuable exercise for any NGO using sensors for data collection.

Sensors themselves can also be used to protect the public interest. There are several examples of citizen engagement and participatory science projects, in which people use portable sensors (either

as external attachments to consumer electronics like smartphones, or as standalone devices) to collect and share data about phenomena that matter in their lives. Examples include environmental noise, air pollutants, and water quality—all of which can be observed in public spaces, without intrusion on individuals' privacy.<sup>13-15</sup> Sensor technology is also playing an important role in investigative journalism. This is especially true in developing countries, where high quality data are often limited or inaccessible. Groups such as Internews' Earth Journalism Network are partnering with academics to train journalists around the world in the use of sensors for environmental reporting.<sup>16</sup>

## Case Studies

**Case 1:** Latrine use and hand washing behaviors in Indonesia<sup>25,26</sup> (MercyCorps)

*Status:* Completed

Mercy Corps' RW Siage Plus+ project aimed to improve access to and use of water and sanitation infrastructure in Indonesia. From September 2009 to September 2011, latrines with hand washing stations were installed and demonstration programs conducted. At the end of the program, Mercy Corps conducted a survey to monitor desired behavior changes with regards to latrine use and hand washing, yielding encouragingly high compliance rates (58-100 percent for latrine use, 44.6-60.3 percent for hand washing). However, when the team installed sensors on the latrines and flow meters on the hand washing stations to independently monitor behavior, the data revealed much lower levels of compliance (2-25 percent for latrine use, 0-40 percent for hand washing), indicating bias in the self-reported survey results.

**Case 2:** Maintaining Water Pumps in Rwanda (CellPump)

*Website:* <http://www.sweetsensors.com/applications/cellpump/>

*Status:* In progress (2015)

Studies show that on average, 30 to 80 percent of water pumps installed in developing countries break within the first year of use and are left in disrepair due to lack of monitoring by funders. To address this issue, the CellPump project is testing three models of water pump operation: a first allowing communities to self-report outages; a second group equipping 200 pumps with sensors to directly notify technicians of service interruption; and a control group. The study will test whether the introduction of sensors is the most effective approach for maintaining water pumps results.

**Case 3:** Water Filters and Clean Cookstoves in Rwanda (DelAgua Health)

*Website:* <http://www.delagua.org/projects/rwanda>

*Status:* In Progress (2015)

Partnering with the Ministry of Health, DelAgua Health is providing 750,000 households in western Rwanda efficient cookstoves and water filters as part of a randomized control trial. Five hundred of these will be equipped with SWEETSense™ sensors to record and report performance of the water filters. This deployment of sensors also contains a reactivity study to determine if and how the sensor impacts behaviors when people they are being monitored.

**Case 4:** Clean Water Projects (charity: water)

*Website:* <https://www.charitywater.org/pipeline/>

Status: In Progress (2015)

charity:water has been fundraising for and building clean water projects in over 20 countries. With funding from Goggle's Global Impact Award in 2012, the organization aims to install 4,000 remote sensors on existing and new water projects (e.g., water flow meters on hand pumps) over the next few years to monitor how their water facilities are being used.<sup>77</sup>

## Conclusions

Recent technology developments have increased the usability and scope of sensors in everyday life. Whether they are custom-made or purchased directly off-the-shelf, sensors have become cheaper, more robust, portable, and easier to use. This is true in sectors as diverse as energy, water and sanitation, environmental protection, agriculture, disaster surveillance, transportation, and health. For development organizations, this presents a unique opportunity to collect useful data with minimal human interaction. Compared with traditional methods for M&E, like surveys, sensors can lower risks of reporting errors; reduce expenses (by eliminating costly trips to project sites); and provide information at much higher frequencies—with data points recorded every few seconds, if necessary. In this way, sensors can play an important role in designing an M&E strategy that reflects CART principles.

At the same time, integrating sensors into an organization's M&E infrastructure is not without challenges. Users need to decide how to acquire the necessary engineering skills for sensor network management and data analysis. This can be achieved through staff training or external consultants; but regardless, budget must be allocated to system development and operation. Users must also work closely with vendors, field partners, and beneficiaries to ensure effective infrastructure maintenance and support for the technology. Partnering with research institutions or government agencies can help address the challenges of deployment and can absorb some of the costs of system development. While upfront investments can be pricey, it is important to keep in mind that program money diverted to sensor-based monitoring can contribute to organizational learning—and ultimately introduce efficiencies in program implementation that reduce costs over the long-term.

In infrastructure-constrained environments, sensing data collection raises several trade-offs in terms of data accuracy, frequency, and timeliness. Under defined budgetary constraints, the choice of the appropriate sensing device, retrieval technology, power supply, and network infrastructure will ultimately depend on the type and quantity of data required for monitoring and measuring impact. While sensing solutions are expected to improve in the coming years, the data generated will always be only as good as the inputs: a well-designed study or monitoring strategy—with realistic expectations, awareness of the local context, and understanding of data requirements—are key to effective M&E.

Finally, sensors should be seen as complementary to (and not substitutes for) other data collection methods. NGOs that have successfully relied on sensors have frequently used them to supplement other data sources, confirm initial observations, or identify questions to ask in interviews and focus groups. While sensors can be very useful for generating reliable high-frequency quantitative data on intervention outcomes, they may not provide answers on *why* programs are (un)successful or *how* they could be improved. Therefore, organizations might want to start by deploying sensors on a

small sample of program recipients, to answer a well defined question, and in conjunction with other data sources, to help benchmark or validate sensor outputs.

## APPENDIX 1: Commercially Available Sensors

Name	Application(s)	Capabilities	Locations Used	Status	Cost/Unit*
NexLeaf Analytics	- Vaccine cold chain monitoring - Cook stove use - Water and sanitation access and maintenance	- Generates reports and SMS messages - Web accessible dashboard	Haiti, Kenya, India, Indonesia, Mozambique, Philippines, Tanzania	NGO	\$
SWEETSense	- Latrine use - Hand washing behaviors - Water services (use, maintenance)	- Networked (cellular, Wi-Fi) - Remote web-based management	US, Haiti, Rwanda, India, Indonesia, China, Nepal, Kenya, Guatemala	Commercially available	\$\$\$ to \$\$\$\$
Lumkani	Early warning to prevent fire spreading in slums	Networked to provide to provide community alerts (devices within 60m radius alerted)	South Africa	Commercially available	\$
Glen Canyon Corp. Smart Meters	Monitor electricity usage	- Networked - Remote data access	US, China, India	Commercially available	\$
Berkeley Air Monitoring Group's PATS+ (upgrade to UCB-PATs)	Indoor air pollution (particulate matter, CO2, black carbon) monitor	- Portable 9V battery operated with data logger - Lower detection limit of 25 ug/m <sup>3</sup>	Guatemala, Mexico, India, Nepal, Mongolia, Ghana, Ethiopia	PATS+: Expected to be available in 2015	\$\$\$
Berkeley Air Monitoring Group's Stove Use Monitoring System (SUMS)	Thermal sensor to monitor cook stove use	-Li-ion battery lasts 6 months to 3 years -Can log every sec -No wire transmission		Commercially available	\$-\$
Edyn	- Garden sensor to monitor light, humidity, temperature, soil nutrition and moisture - Water valve controlled waster system based on data from Garden sensor	- Alerts and data sent to smart phone - Solar powered	Consumers, plans for use in developing countries in the future	Commercially available	\$\$ to \$\$\$

wimoto	Ambient sensors (temperature, humidity, light, soil moisture)	Alerts and data sent to smart phone (Bluetooth)	Consumers	Commercially available	\$\$
Maxim Integrated's iButton®	Ambient monitoring (temperature, relative humidity)	- Rugged, small design - Able to add data logging, clock, security, memory	Consumers	Commercially available	\$\$
MicroPEM™ Sensor	Wearable air pollution monitor	-light (0.24g) -AA batteries (40 hours)	12 countries	Commercially available	\$\$\$\$
University of Washington's PUWP <sup>28</sup>	Indoor or outdoor air pollution (particulate matter) monitor	- Also logs noise, temperature, relative humidity (modifiable) - Can sample every 15 sec	US, China	Field tests	\$\$\$
Odyssey Sensors' HealthShrimp	Salinity sensor for aquaculture	Lithium-ion battery charged unit by shaking (magnet and solenoid within device)	Bangladesh	Commercially available	\$
temperature@lert	Temperature and environmental monitoring	Can be networked, remote access to data	Consumers	Commercially available	\$\$\$
Air Quality Egg	Ambient air pollution (NO2, ozone, radiation, particulates, VOC's, and CO) monitoring	- Data delayed to base station and then uploaded online - Data can be viewed and shared remotely through Xively	Global	DIY	\$-\$\$\$
DustDuino	Indoor and outdoor real-time air pollution (particulate matter) monitor	Data can be viewed and shared remotely through Xively	Global	DIY	\$\$
Invisible Tracck	Detects illegal logging	- Placed on select trees - Connects with mobile network after logging to alert authorities - Tracked remotely by protection agencies	Brazil	Piloting	Unknown

\*Approximate cost per unit (hardware): \$: less than \$50; \$\$: \$50-100 USD; \$\$\$: \$100-500 USD; \$\$\$\$: more than \$500.

## APPENDIX 2: Materials & Other Fixed Costs

### (a) Noise Monitor<sup>72</sup>

Purpose	Part	Cost (\$ USD)
Microcontroller Module	Arduino Pro Mini 3.3V	9.95
Sensing Device	Breakout for ADMP401 MEMS Microphone	9.95
Data Logger & Storage	OpenLog	24.95
Power Supply	2 AA batteries	10.95
Data Transmission	Electric Imp Breakout (Wi-Fi)	12.95
Data Transmission	Electric Imp	29.95
Clock	Deadon Real Time Clock	19.95
Display	Grove OLED Display 128x64	19.00
Protective Enclosure	Hammond 1591XXCBK case	6.00
<b>TOTAL</b>		<b>\$143.65</b>

### (b) World Water Project<sup>73</sup>

Purpose	Part	Cost (\$ USD)
Microcontroller Module	Arduino Uno	25.00
Sensing Device	DHT22 Temperature & Relative Humidity	12.00
Power Supply	6W Panel + 15 W-hr Battery (Solar)	85.00
Data Transmission	Sim 900 GPRS Board (Cellular)	40.00
Protective Enclosure	Pelican 1050 Micro	15.00
<b>TOTAL</b>		<b>\$177.00</b>

### (c) DustDuino<sup>74</sup>

Purpose	Part	Cost (\$ USD)
Microcontroller Module	Arduino Uno	25.00
Sensing Device	Shinyei PPD-42 Dust Sensor	15.90
Power Supply	9V DC power supply	3.90
Data Transmission	Sparkfun Roving Networks RN-XV WiFi module	34.95
Data Transmission	Arduino Wireless Proto Shield	19.95
<b>TOTAL</b>		<b>\$99.70</b>



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