PHOTO CREDIT: LAHORE UNIVERSITY OF MANAGEMENT SCIENCES (LUMS)
IoT sensors deployed in Pakistan as part of the Frontier Technologies Early Warning Forest Fire Detection System pilot

IOT Sensors for Social Impact:

April, 2023.

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FRONTIER TECH HUB

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Introduction

Scope of this report

Since 2016 the Frontier Technologies programme has supported 10 pilots to test the potential for IoT sensor based solutions to deliver social, environmental or humanitarian impact across a range of sectors and use cases.

This report is concerned with sharing findings from 4 of those Frontier Technologies pilots, on what's needed to effectively test and scale IoT sensor solutions for social, environmental or humanitarian impact. The pilots featured in this report are:

- Sustainable eWater supply in Tanzania
- Early Warning Forest Fire Detection System in Pakistan
- Informing community-based climate adaptation and planning in Nepal
- Validation of low-cost sensors for optimal insect protein production

Where relevant, it also shares insights from wider studies and pilots, including other FCDO investments. The report aims to primarily share insights from the perspectives of those involved in directly delivering early stage innovation projects. It shares insights on the types of solutions that have been tested (including details on 'what worked') in relation to three key use cases for IoT. It also seeks to share insights from pilots on the barriers and enablers to successfully testing and scaling IoT sensor solutions, and reflections from the Frontier Technologies Hub, on where the 'frontier' is, in terms of developing, testing and scaling IoT sensor solutions for impact.

What are IoT sensors?

For the purpose of this report we define Internet of Things (IoT) sensors as sensing devices which are able to take an input from the physical environment and convert this input into data (through in-built microprocessors) - such as a temperature reading. This data is then communicated over the internet (or other network), to other devices within their network, in ways that can trigger automated responses by other smart devices, and / or inform stakeholders to make more effective decisions.

Recent technical trends have seen a number of developments that could potentially support the proliferation of IoT sensors for social, environmental and humanitarian impact. This includes the emergence of lower cost and durable devices, as well as the deployment of Low Power Wide Area Networks, by mobile operators in many markets, into which devices can connect with lower power consumption - which supports the longevity and therefore viability of devices.[1]

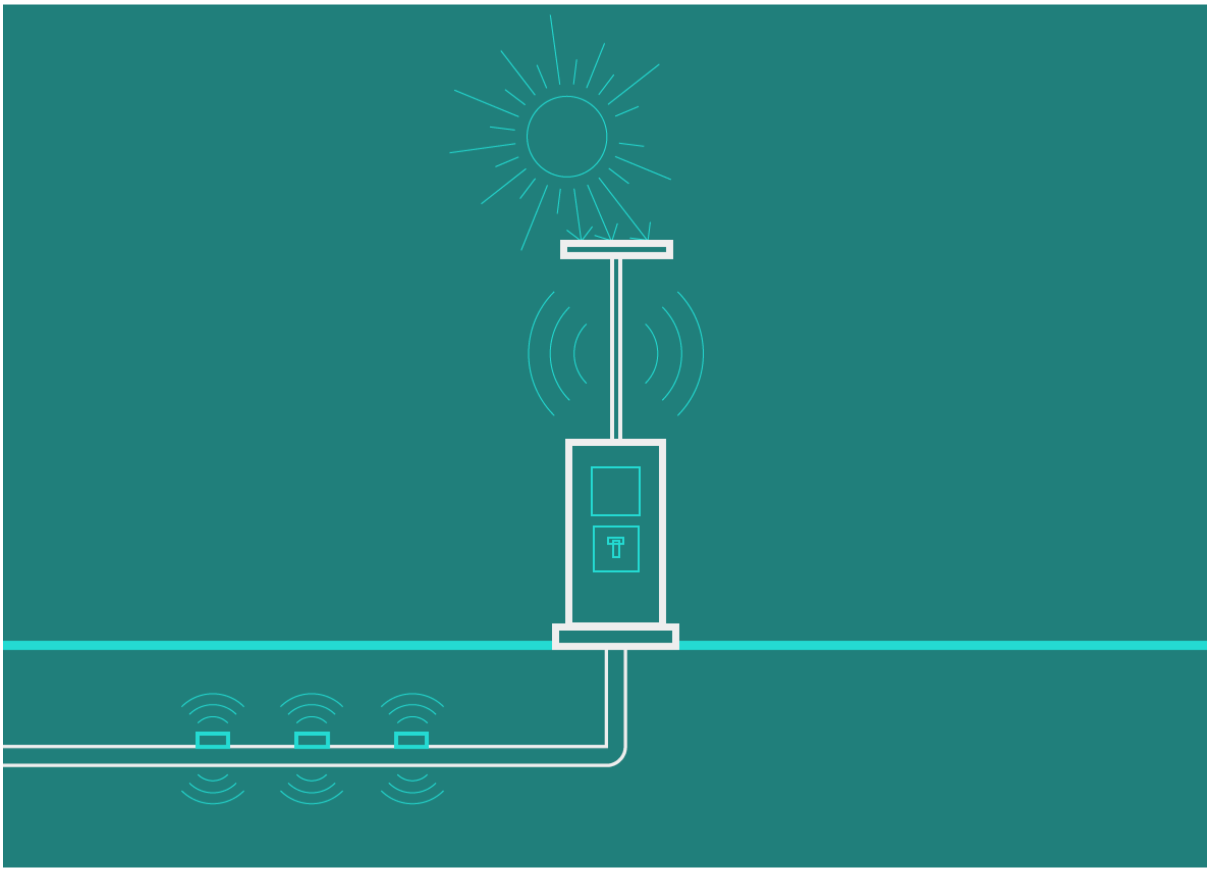
[1] GSMA, 2023

Use cases where IoT sensors have been used for Social Impact

Across Frontier Technologies pilots there have been three key use cases for which IoT sensors have been piloted for impact. Below we have outlined key findings in relation to each use case, in terms of the different ways that sensors can be used to meet end user needs. These use cases are:

1. Improving access to clean water and sanitation
2. Informing Disaster Risk Management (specifically in relation to natural hazards)
3. Improving agricultural productivity (especially for smallholder farmers)

1. Improving access to clean water and sanitation



GRAPHIC CREDIT: Dave Thomas - Picnic Films

eWater - using IoT sensors to improve access to clean water

Over the last decade, a number of different pilots have implemented IoT sensors in order to improve access to reliable water in rural WASH systems in Africa. A key problem that these solutions have aimed to fix is the unreliability of existing water infrastructure. It was estimated a decade ago that globally one in three handpumps in rural areas were broken.[2]

In 2016 the Frontier Technologies Hub worked with eWATER Services to pilot the use of IoT sensors within solar powered water systems in rural Tanzania. Sensors for monitoring the pressure of water in tanks and flow of water from individual taps were installed, and data from these sensors was transmitted over the internet and shared with engineers in eWATER's Smart Maintenance Teams. Through monitoring patterns in water flow and volume, engineers were able to identify issues and breakages in the WASH system and respond - increasing the uptime of water taps to 99% (up from around 66%). Wider impacts were also realised as a result of these improvements. In one village, the average time spent collecting water per household was reduced from three hours a day to just 10 minutes, with girls able to attend school as a result. Since finishing the pilot, eWater have also found that through supporting more functional water infrastructure,they have been able to eliminate incidents of water-borne diseases within communities, as well as help to deliver significant reductions in CO_2 emissions, by avoiding the need for communities to burn wood and charcoal to boil water from contaminated sources.

PHOTO CREDIT: Lil Patuck
An eWATER Smart Tap in use in Tanzania. By holding a pre-paid NFC tag to the tap water flow is initiated. Water flow sensors then determine consumption usage, and the amount to be debited from the users account

[2] Rural Water Supply Network, 2010

Through implementing sensors across WASH infrastructure, eWater engineers were able to monitor real time and joined-up views of the health of the individual WASH systems they are responsible for - with data made accessible via a Geographic Information System. This enabled eWATER engineers to better identify trends and patterns in both usage and issues across systems, in ways which supported smarter decisions on managing WASH assets. For example: in one instance sensors flagged that 6 taps were showing a low flow at the same time. Through analysing the data, the eWater team were able to identify that there was likely an issue upstream in the water provision network, and were able to more efficiently resolve the problem, than would have likely happened without the benefit of sensor data. Data from sensors also allowed eWater to more effectively target where to make future investments in the network - including data relating to the demand and usage of taps.

As part of the 2016 pilot, and with a view on delivering a sustainable solution, eWATER implemented and tested a business model whereby end-users pay for water via cash or mobile money. End users were able to upload mobile money onto a digital account (or have family members upload credit on their behalf), and they were able to access water by using an electronic tag (linked to their digital account) to turn taps on. Water flow sensors then monitored consumption and charged accounts accordingly. Through implementing this model, eWATER delivered a service based approach to water provision - whereby the money collected for water consumption was in turn used to pay for engineers time for maintenance activities, to ensure taps were functional and water was available at the point of need. Through implementing the smart taps, eWater was able to double the amount of revenue collected for water use in one village, and triple revenue collection in a second village. In the context of the pilot, this additional funding was sufficient to cover ongoing operation and maintenance costs for infrastructure, while also generating additional income which could be invested to support expansion of the approach to additional villages and water systems.

PHOTO CREDIT: Lil Patuck
An eWATER Smart Tap in use in Endanachan Tanzania. The tap is powered by a solar panel.

Since completing the Frontier Technologies pilot eWATER now operates over 700 taps across Tanzania. The service based model continues to demonstrate potential to offer a sustainable route to scaling access to water, although more work remains in terms of reaching sustainable scale, including in terms of overcoming upfront costs and complexities associated with accessing water systems, and acquiring and installing sensors within taps.

PHOTO CREDIT: eWATER
An eWATER Smart Tap in use as part of a demonstration in Endanachan Tanzania.

Wider initiatives adopting smart sensors for rural WASH systems

This potential for smart taps to help resolve the challenges experienced within rural WASH systems, has also been demonstrated through a range of other projects. In 2016, a separate trial of smart sensors in Rwanda, by an organisation called SWEETsense, identified that while sensors may add 10% to the cost of a hand pump, through significantly increasing tap uptime, they significantly reduce the cost per unit of water per 10,000 litres delivered.[3]

Similarly to the eWater pilot, other projects implementing IoT water flow sensors have also demonstrated their potential to combat the issue of non-revenue water (this includes water lost through leakages, or inaccurate meters before governments or water companies can collect revenue). Smart City Taps, a solution supported by UKAID via grants to the GSMA and GIF, combines smart water meters with a digital solution

[3] ITU / Cisco, 2016.

where customers can pay for their water with mobile money. In the case of the GSMA grant, CityTaps helped improve revenue collection by 100% in the part of the network where smart taps were deployed.[4]

In addition to improving the availability of water at taps and hand pumps, sensors are also increasingly being used to improve the quality of water in WASH systems. Traditionally water quality sensing technologies have suffered from long operation times (e.g. requirements to wait for samples to be tested in a laboratory) and high costs. However, a number of recent studies have demonstrated breakthroughs in water quality sensing - where sensors show potential for real time and continuous monitoring of divergence in water quality across a range of parameters, against baseline metrics.[5][6]

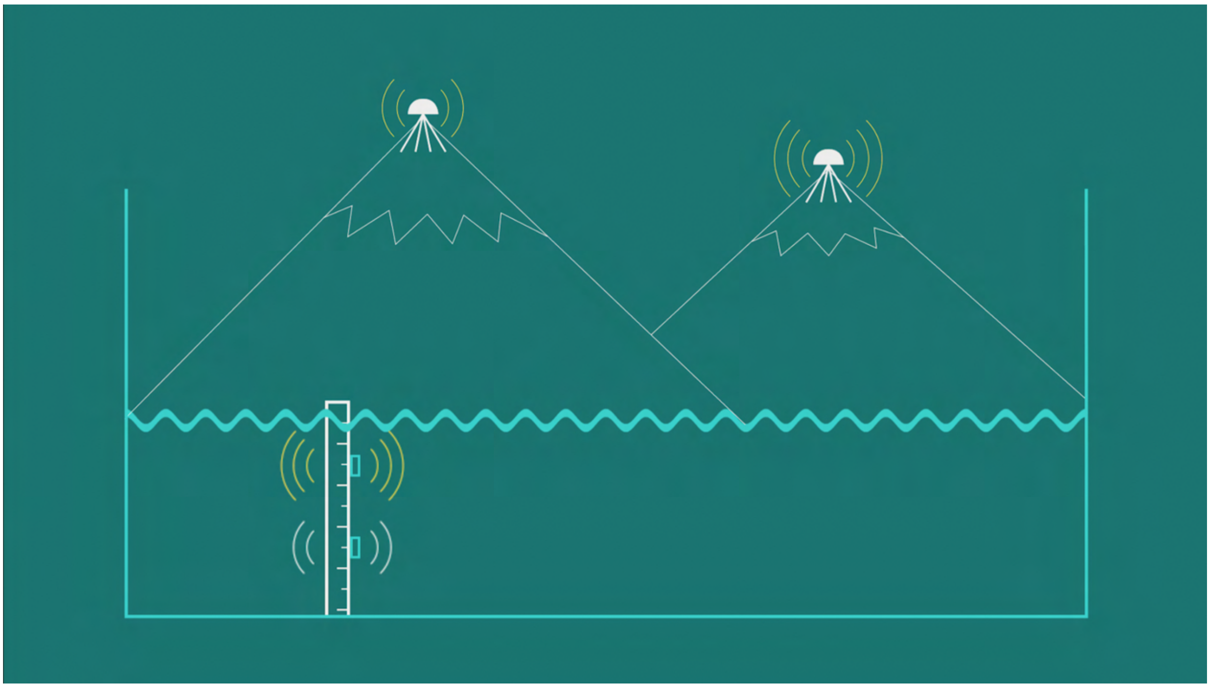
To what extent have IoT solutions been scaled for impact?

In addition to eWATER, a number of different projects have now demonstrated the effectiveness of water flow sensors, alongside service based business models, as viable routes to sustainably increasing access to water.[7][8] The data indicates that once installed and operational, sensors alongside service based models can be used to unlock sustainable access to water, via enabling revenue collection and supporting timely and ongoing maintenance of taps or handpumps. More recently, studies have also begun to demonstrate the potential for water quality sensors to unlock impact through providing real time data and insights on water quality.

However, despite these successes, remote monitoring of rural WASH systems through IoT sensors has yet to be taken up at significant scale in contexts where it is most needed.[9] As the eWater pilot and other projects have identified, outstanding barriers include the need for key stakeholder buy-in (such as governments who may continue to have a preference for supporting community, rather than service based models for WASH management), as well as high upfront costs to procure and install sensor technologies.

[4] GSMA, 2021
[5] Vargas et al, 2020
[6] Kavitha et al, 2021
[7] Smith School Water Programme, 2014
[8] Nagel et a., 2015
[9] Thomson, 2020

2. Disaster Risk Management - Natural Hazards



GRAPHIC CREDIT: Dave Thomas - Picnic Films

Through providing stakeholders with access to precise, comprehensive and real-time data on changes in the physical environment, IoT sensors can play a critical role in supporting disaster risk management. This includes decision making within the immediate response to a natural hazard, as well as decision making to prevent, mitigate and better prepare for natural hazards.

Early Warning Forest Fire Detection System - validating the potential for sensor networks to detect the presence of forest fires and trigger early warning

Through the Frontier Technologies Early Warning Forest Fire Detection System pilot in Pakistan, the World Wildlife Fund (WWF) and Lahore University of Management Sciences (LUMS) have worked together to deploy IoT sensors capable of detecting and alerting Forest Department stakeholders and community members to the presence and location of fires. Over the course of 2022 and 2023, the pilot effectively deployed and tested an IoT sensor network in a forest in Khyber Pakhtunkhwa Province in Pakistan, capable of collecting and sharing data on changes to temperature, humidity, CO_2 and carbon monoxide. The solution has proven effective at detecting the likely presence of fires within a close proximity to those sensors. The pilot has been able to overcome a number of technical challenges associated with deploying the sensors, including demonstrating the ability for IoT components to withstand harsh conditions, and finding creative solutions relating to local processing of data, in order to overcome data bandwidth challenges.

PHOTO CREDIT: LUMS
IoT sensors were deployed in northern Pakistan as part of the Frontier Technologies Early Warning Forest Fire Detection System pilot

Alongside sensors, the pilot installed cameras, each installed at the top of towers and connected to individual AI modules, which were able to use AI models to process images and visually detect the presence of a fire. The team was able to extract live streams from camera towers at high-definition video quality with a maximum delay of 15 seconds, and could receive bursts of images at regular intervals so that the AI module could identify the presence of smoke or fire within a given scene. In particular, the pilot established that a standard Pan Tilt Zoom (PTZ) camera was suitable for monitoring an area of up to 15 km in distance, and that through using AI to detect fires in the images, they were able to implement a solution almost 10 times cheaper than installing thermal cameras to detect the presence of fires.

Through the pilot, the team from LUMS and WWF have been able to validate the potential for IoT sensors to play a role in supporting forest fire detection as part of a broader systems approach which combines sensors with cameras and remote sensing. The team identified that a multi-pronged approach allowed for a more stable solution for early warning, where data from different sources was still available, even if one source experienced downtime. The team identified that this approach could also meet stakeholder needs for flexibility to scale different components independently – for example adding more sensors, fixed camera towers or weather stations in certain locations depending on the unique needs of specific regions and ecosystems. In particular a likely consideration for stakeholders will be around costs, and the practical benefit of different sensing technologies – with in situ IoT sensors only providing sensing capacity over very limited ranges (often meters), compared with cameras demonstrating potential to cover far larger distances, assuming clear site lines. In this regard sensors might be better placed in locations cameras cannot reach, or in areas where it's highly important to detect presence of a fire early (for example where there's higher risks around loss of life).

PHOTO CREDIT: LUMS
A camera installed in Pakistan as part of the Frontier Technologies Early Warning Forest Fire Detection System pilot. The camera is connected to individual AI modules, which is able to process images and visually detect the presence of a fire.

The pilot found that there were a range of challenges associated with integrating different types of sensors into the network, in terms of the costs, power requirements, ease of integration, and ease of sourcing. Temperature and humidity sensors were easily available, cost-effective, and power-efficient, making them a suitable choice for the network. TVOC (air quality) sensors had some low-cost and power-efficient options, but not many were not designed for outdoor scenarios. Smoke sensors were generally power-hungry and not easily available off the shelf, but they could be integrated relatively easily into networks using generic IoT nodes. Particle matter sensors had average power requirements and promising fire sensing potential, but they required customised IoT node development. CO2 sensors were easy to source and power-efficient, although somewhat expensive.

As well as deploying technology, the pilot progressed, it sought to explore how best to provide forest department and local communities with the real time information needed to react to fires and trigger early warning systems. As a result, the pilot developed and tested an SMS notification system for officials and community members. Further work is required to scale the solution, including ensuring greater forest coverage before this system is likely to 'go live' and start providing early warning to communities.

Early Warning Forest Fire Detection System - Informing ongoing response to a disaster

As well as supporting early warning, IoT sensors can also help inform the ongoing response to a disaster by providing stakeholders with up to date information on the location and severity of an incident. For the Forest Fire Detection System, a digital dashboard was developed for Forest Department officials, which shares real time information from multiple sources, including GPS enabled IoT sensors, and provides a central map which visualises readings from devices and highlights areas where a fire has been detected. This allows forestry officials to monitor the spread of a fire over time. Feedback received from the Kaghan Forest Division has included their desire to use the intelligence from these dashboards to not only respond to fires, but identify the culprits behind man-made fires, and monitor forest health more generally.

As part of this dashboard, the pilot team has sought to provide forest department officials with predictive models, which visually indicate the likely direction in which an active fire might spread, as well as ongoing visualisations of likely hot spots" (areas where fires are most likely to occur and the likelihood of occurrence). The intention is to provide the forest department and emergency services stakeholders with information to support decisions on how to safely tackle forest fires to preserve the environment and human life. The AI models are underpinned by historical sensor data, data on vegetation and weather data (live and historical) - including data wind speed and direction.

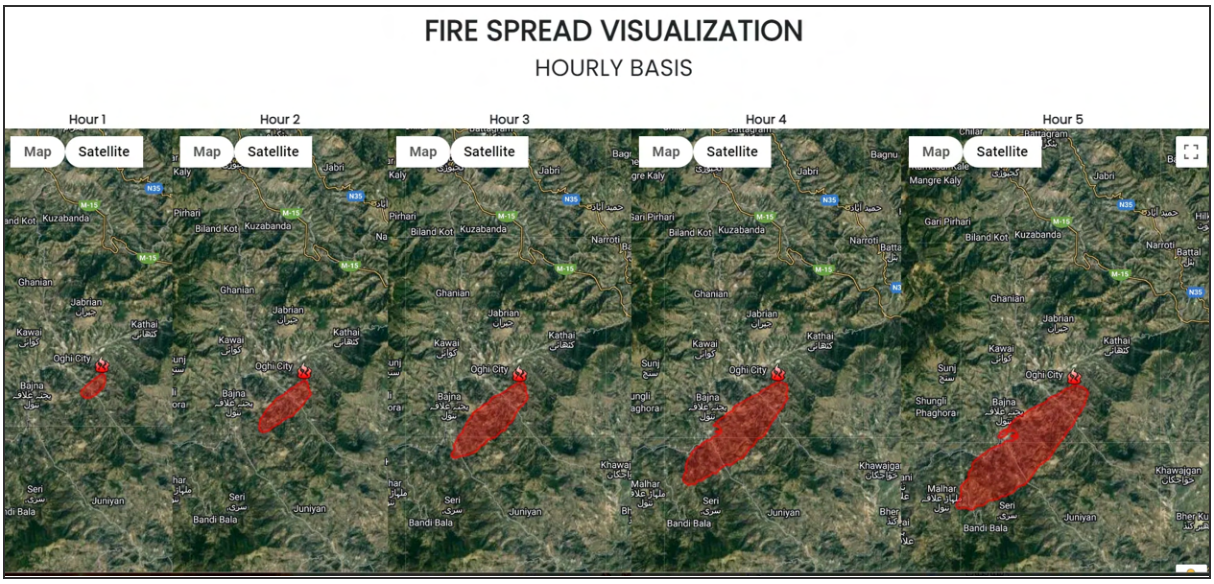


PHOTO CREDIT: LUMS
Screenshots from the dashboard created by the Forest Fires Early Warning System - this view uses an AI model to predict fire spread over time.

Using sensor data for longer term planning and mitigation activity

In addition to supporting stakeholders to respond to natural disasters, IoT sensors have also been deployed across a range of contexts to generate data to help stakeholders understand the likelihood, risks and potential impacts of different natural hazards, before they occur. IoT Sensor data is often collated with data from other sources (e.g. remote sensing, weather stations, seismology stations, socio economic data) and analysed to identify the areas at greatest risk from hazards. By combining environmental data with demographic, vulnerability and economic data, models can be created which can identify the areas where a potential disaster is likely to have the greatest impact. This could include areas which are highly populated or contain vulnerable individuals who may have less resilience to potential impacts. This information can support stakeholders to make smarter decisions on how best to mitigate the impact of disasters, including decisions based on the cost-benefit analysis of different intervention options, as studies on flood risk modelling have demonstrated.[10]

In Nepal, Youth Innovation Labs are working with the Frontier Technologies Hub on a pilot aimed at informing their next iterations to the Building Information Platform Against Disaster (BIPAD) platform. This is a platform that is owned by National Disaster Risk Reduction and Management Authority (NDRRMA), and provides Disaster Risk Management stakeholders (e.g. local governments, humanitarian agencies, NGOs) with real time and historical information on changes in the environment, as well as natural disasters and their impact. The platform is informed by a wide range of data collected from all over Nepal by a range of institutions, and through a range of methods, including the use of internet enabled sensors monitoring changes to the environment related to flooding, forest fires and seismic activity. The portal represents the first time nation-wide data sets have been integrated and aggregated into a single platform. The BIPAD portal also incorporates socio-economic data alongside sensor data and provides policy makers with risk profile data on different regions, including information on the damage and loss that has been experienced by communities over time. In doing so, it aims to support more effective risk reduction interventions.

[10] Ruckelshaus, 2020

PHOTO CREDIT: NISHANT GURUNG
A water level sensor installed in Chisapani, Nepal. Data on water level readings are populated on the BIPAD platform.

Currently, the portal is widely used by government stakeholders as a tool for actively monitoring natural hazard information. A daily bulletin shares information from the portal with users from across 700 local government municipalities and provides them with up-to-date information on natural hazards and risks within their locality. Through the portal, local government actors can also access a disaggregated view on their own natural hazard risks (past and present), with data intended to inform longer term formulation of policies and plans around natural disaster management.

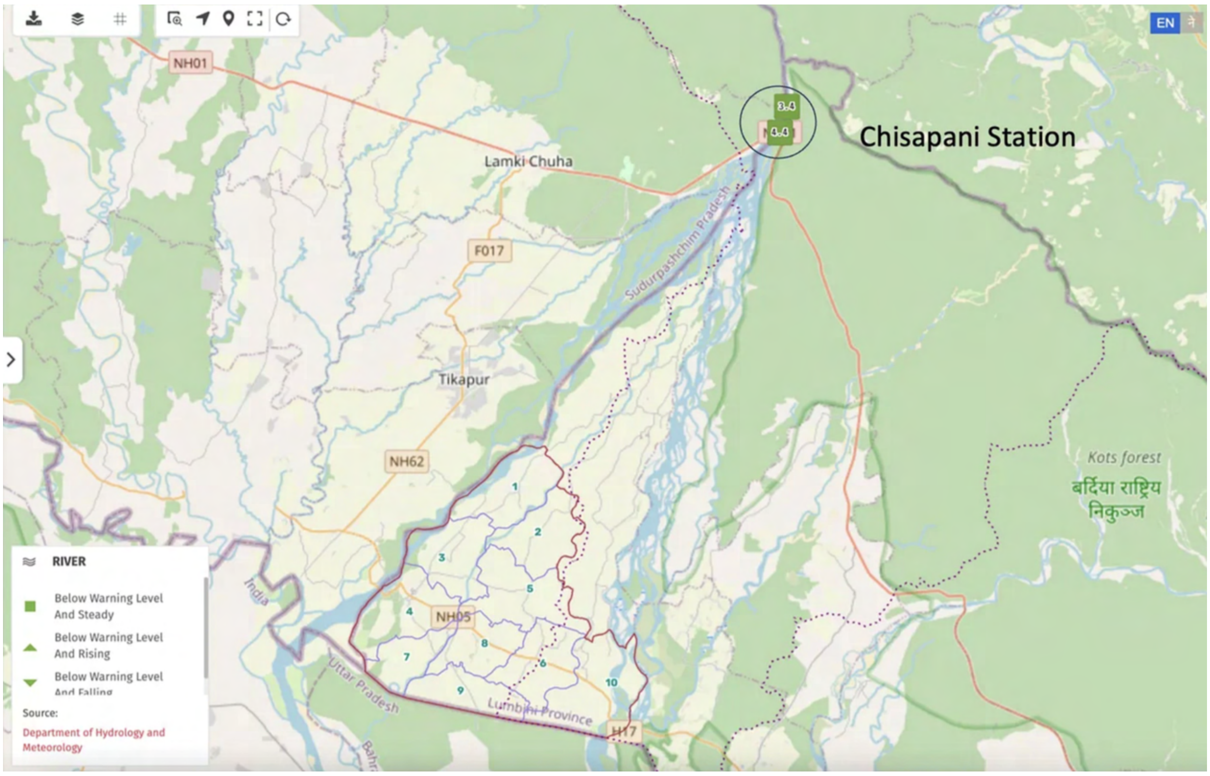


PHOTO CREDIT: Youth Innovation Labs
Screenshot of the BIPAD portal providing real time river water level data, taken from Chisapani Station in Nepal. This information helps inform those downstream, including local government actors in Rajapur of the likelihood of flooding.

Exploring strategies for data-driven community-based adaptation and planning in Nepal

Through working with the Frontier Technologies Hub, Youth Innovation Lab are conducting a pilot to explore how best to support local government stakeholders and local communities to effectively use the data available on the portal for longer term planning and risk mitigation. To this end, several strategies are being explored alongside the technology – including training up local planning officers in local municipalities and testing how and whether the provision of improved technical capacity can help local departments to better analyse and use information within their planning. In addition, the pilot has also developed toolkits, intended to help local government departments conduct risk assessments for natural hazard management, and better use data for decision making.

As well as working with government stakeholders, the pilot is also exploring how offline communication approaches might be used to translate and communicate data and information from the platform to inform the actions of community members. For one experiment, the pilot has tested whether murals might be used in one community to effectively communicate key messages on the local sites and areas that are statistically most at risk of landslide. They are testing to see whether this information can effectively influence behaviour – including around construction of buildings and homes on at-risk land.

Predictive models for natural hazard management

At the frontier of technical solutions which use sensor data to inform natural hazard prevention and mitigation, are solutions which use AI to predict where a natural hazard will happen next, based on detailed analysis of large volumes of historical data.

Recently, studies have demonstrated the ability for AI based models to react to real time data and predict the likelihood of a river flood happening, to within a 95% accuracy.[11] What has made AI based solutions particularly exceptional, is the ability to identify trends and patterns in data that might not otherwise have been observed using previous data analysis approaches. Indeed, one model that has recently been developed in Nepal was able to identify the causal relationship between different 'cascading hazards', whereby risk factors that lead to a single hazard, can also be used to predict the advent of a second natural hazard, which will be triggered by the first hazard.[12] In practice, AI models might soon be able to preempt future cascading hazards, in a way that can inform smarter risk mitigation measures.

To what extent have IoT solutions been scaled for impact?

While IoT sensors show strong potential for supporting disaster risk management, they have yet to be significantly scaled within the global south. Many applications of sensors, and particularly those applications which involve using sensor data with AI solutions to support predictive modelling, remain at a proof-of-concept stage, and have yet to be scaled for impact.

The cost of devices remains a barrier to scale, and ongoing maintenance of sensors is also needed for sensors to continue to provide data for decision making. It is worth noting that in the photo shared above of a water level sensor in Chisapani Nepal, the sensor in question was in fact broken at the time the photo was taken, and manual data readings and data entry was conducted in order to populate the BIPAD portal. This points to the need to find sustainable models for funding and implementing technology, so that the benefits of improved information for disaster risk management can be realised.

Recent technological breakthroughs offer great potential for overcoming barriers to scaling the use of sensors for natural disaster management. This includes advances in remote sensing technologies - not explored in this report - where sensors (e.g. cameras, multispectral and hyperspectral sensors, laser altimeters, radar, sonar) are installed on satellites, and where data sets are often made widely available at low / no cost over cloud platforms. As with the case of the two Frontier Technologies pilots referenced in this section, there's value in early innovation projects to continue to conduct research to explore what combination of data collection approaches and technologies show greatest potential for providing disaster risk management stakeholders with the information they need to make effective decisions, in a way which is also cost effective and sustainable. Research should also seek to investigate what the unique value add of sensors are within a given context. As evidenced by the Pakistan Forest Fire Early Warning system, in some instances IoT sensors, which only offer limited range of coverage of detection, may be far less cost effective as alternative solutions - e.g. long range cameras - at monitoring large areas of land. Alternatively, there are other scenarios where IoT sensors offer unique value add - for example in quickly detecting fires in built up areas, where alternative cameras might prove less effective.

[11] Boulouard, 2022
[12] Talchabedal, 2023

3. Improving agricultural productivity for smallholder farmers

GRAPHIC CREDIT: Bethan Thomas

Smallholder farmers make up 90% of farmers worldwide, yet suffer from lower productivity, increased vulnerability to shocks (e.g. extreme weather events) and often lack access to agricultural inputs, credits and markets.[13]

While not widespread, there are emerging examples where IoT sensors have been deployed to support precision farming for smallholder farmers. This is a practice where sensors are used to generate data on 'what works', which in turn is used alongside real time data to inform real-time decisions to optimise farming processes, inputs and growth conditions, to deliver benefits such as improved yields, environmental sustainability and reduced costs.

Using sensors to optimise insect production in Kenya

The Frontier Technologies Optimal Insect Protein Production pilot has tested an approach for using smart sensors to support precision farming, and optimise agricultural practices amongst smallholder farmers in rural Kenya. Led by Regen Organics (formerly known as Sanergy) and the International Centre of Insect Physiology and Ecology (ICIPE) in Kenya, the pilot explored how sensors could be used to increase yields of black soldier fly (BSF) larvae, which is used in animal feed. The pilot sought to identify whether and how this technology can replace existing methods for small-scale BSF farming which involve considerable manual monitoring of BSF growth conditions through complicated paper-based data collection and analysis.

[13] UNDP, 2021

Working directly with smallholder farmers, the pilot supported farmers to implement sensors capable of monitoring and sharing data on a range of parameters (temperature, light, humidity, PH / moisture content of the substrate, ammonia / CO2 levels in the air) within their BSF farms. Internet reliability and battery powering of sensors did cause some issues at early stages of the pilot. Through analysis of the data collected on site, the pilot was able to effectively identify and model the combination of data parameters that lead to increased yields of BSF larvae. For example, based on results from the pilot, the team believe the mating success of reared BSF can be dramatically increased by exposing adults to light that has wavelengths between 440 or 540 nanometers. The team believe that the sensors present a more efficient approach for gathering important data than existing paper based recording processes.

Farmers involved in the pilot also identified the benefits of sensors in helping them to optimise their processes. As Nicholas Ndekei, Chief Executive Officer at Zihanga LTD told us;

"Before we used to hatch our eggs in the traditional methods and would lose up to 40% of our production. The IoT forces you to quantify more things, and forces you to know what you need to do and how to do it. We saw an increase, we're getting 90% of production."

These findings align with those of wider studies on the potential for smart farming amongst smallholders in LMICs, which also report benefits such as shorter production cycles, reduced costs, lower use of inputs (including scarce resources like water), higher yields and fewer losses to crops from pests and disease.[14]

Optimising insect production - longer term goals

While the Optimal Insect Protein Production pilot was able to identify some of the optimal conditions for BSF larvae production, the longer term goals of this project are to build solutions and services which provide farmers with data and recommendations in order to guide farmers to help deliver these optimal conditions.

Currently the team is developing an online planning system that is accessible to farmers and helps translate key insights into prompts for action. Alongside this, they are looking to use data generated by sensor networks on the parameters most effective for BSF larvae production to develop predictive models which can preempt what changes are required to growth conditions in order to optimise productivity. The intent is to integrate this model into the online planning system, and provide prompts for farmers to undertake actions to deliver more optimal growth conditions.

In the longer term the pilot is also looking to conduct further work to identify what's needed to encourage farmers to adopt the solution as a whole, so that it can be scaled for impact. This includes identifying what additional support farmers need to effectively deploy and implement the solution. Over the course of the pilot, farmers benefited from technical assistance in installing sensor networks on farms, and farmers felt that this type of assistance would be essential if the approach was to scale to other farms.

[14] GSMA, 2022

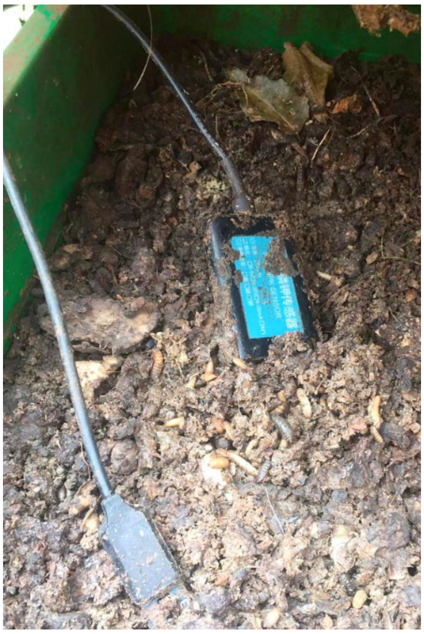


PHOTO CREDIT: ZIHANGA LTD
Photo 1: Sensors deployed at Zihanga Ltd, a small-scale BSF farm in the outskirts of Nairobi city.
Photo 2: Dried BSF Larvae as an end product of organic waste valorization.

Wider use cases for IoT sensors in agricultural production

Beyond Frontier Technologies pilots, there are many other IoT solutions which have been tested to support smallholder farmers to increase agricultural productivity. A major example is the use of IoT sensors alongside smart irrigation systems - which can be triggered automatically, or manually in response to sensor readings on changes to environmental conditions such as soil moisture. In addition soil monitoring, sensors have also been used by solutions which help farmers to optimise fertiliser use, and avoid degradation of soil quality - such as the Soil Health Cards solution in India.[15]

In pastoral farming, there have been some limited implementations of IoT sensors to help smallholder farmers implement smarter livestock management - including using sensors to detect diseases immediately in order to support a faster response.[16] In aquaculture, IoT sensors have been used by smallholder farmers to optimise the feed provided to their fish, such as the eFishery solution in Indonesia, which uses sensors to detect the appetite of fish and shrimp, as well as IoT automatic feeders, to provide fish with the optimal amount of food.[17] Sensors have also been used by smallholder aquaculture farmers to monitor water conditions in fish tanks, and in hydroponics farms to monitor and optimise environmental conditions.[18]

[15] UNDP, 2021
[16] GSMA, 2022
[17] GSMA, 2022
[18] Antony, 2020

To what extent have IoT solutions been scaled for impact?

While there has been a growth in the use of IoT sensors in farming globally, when it comes to smallholder farmers in the Global South, IoT smart sensors have yet to scale significantly. This is the case for insect production, smart crop management and livestock solutions, although there are some examples where aquaculture solutions have attracted 10,000 or more users, each paying monthly usage fees.[19] Within LMIC markets, there are few examples of IoT sensor solution providers actually developing and marketing solutions specifically for smallholder farmers.

For smallholder farmers, key barriers remain which inhibit their ability to adopt and benefit from solutions. Barriers include challenges around ease of use, digital literacy, cost of devices, costs of connectivity, and lack of mobile and IoT coverage.

PHOTO CREDIT: ZIHANGA LTD
Sensors deployed at Zihanga Ltd, to monitor optimal conditions for BSF production..

[19] GSMA, 2022

Cross-cutting findings - enablers, barriers and the frontier for implementing IoT sensors for impact

Across the three core use cases explored through Frontier Technologies pilots, there are common barriers inhibiting the effective scaling of IoT sensor based innovations, as well as common enablers. Below we have presented a summary of these findings, as well as details on the key 'frontier' areas of opportunity, where our research indicates further work should be carried out, in order to unlock opportunities for scaling IoT sensors and further explore emerging solutions for deploying sensors for impact.

What are the common barriers to testing and scaling IoT sensor technologies for impact?

Durability and resilience of devices

Even with significant advances in sensor technologies durability and resilience of devices has surfaced as a challenge across Frontier Technologies pilots, especially those that require sensors to work in harsh environmental conditions.

In the case of the eWater pilot for instance, the team faced multiple challenges, including in finding sensors capable of withstanding extremely high temperatures in Tanzania and strong UAV light, as well sensors which were able to withstand attacks from ants, which were prone to find their way inside devices and shortcut internal circuits.

Similarly, the Optimal Insect production pilot found that the organic material they placed sensors in was very acidic, and not all sensors were able to operate in these conditions.

Cost of devices

Although the price of sensors have significantly dropped over the last 5-10 years, the cost of devices and other materials required for the implementation of solutions continues to be a barrier for both technologists implementing IoT solutions as well as end users and customers of potential solutions. Across different sectors high upfront capital costs can stall the implementation of solutions, even where they demonstrate potential to deliver longer term returns on investment.

In the case of the eWater pilot, upfront capital costs for procuring and installing devices, and the time required for the solution to deliver a return on this investment, are an inhibitor to the rapid scale of the solution - even though the business model itself has proven sustainable once sensors are installed. Water quality sensors, in particular, remain very expensive for those implementing IoT WASH solutions.

The Forest Fire Early Warning System in Pakistan, identified that there was a distinct lack of commercially available sensors suitable for outdoor (as opposed to indoor) air quality monitoring, available in their market. This would likely significantly inhibit the uptake of those solutions as part of any IoT networks scaled for impact.

The Optimal Insects Production pilot also identified the cost of sensors as a potential barrier to encouraging adoption among farmers, and a farmer interviewed for this study identified that the current costs of a suite of sensors needed to operate a smart system, would be a barrier of entry. They estimated that up to 70% of farmers in Kenya will not be able to afford a sensors kit, especially marginalised farmers with difficulty accessing credit (and especially women and youth farmers). As Nicholas Ndekei, the Chief Executive Officer of Zihanga Ltd:

"Even if this increases your return, it increases costs, so it's a barrier to entry for a lot of farmers to adopt this. So it will be a certain class of farmers, the more commercially oriented, more profit maximizing than risk minimising that would be the early adopters of this."

Lack of maintenance of sensors

Broken and faulty sensors can be counterproductive for any sensor based solution, and can result in users being provided with inaccurate information, in ways that lead to detrimental consequences.

In the case of the BIPAD portal in Nepal, the solution is dependent on data from sensors which the implementation team has no control over. In some cases, actors (often NGOs) may have installed sensors many years ago, and handed them over to community members, without putting in place sustainable solutions (including skills and funding) for the ongoing maintenance of devices. This has potential to lead to sensors breaking, and either failing to provide information or providing inaccurate information. This implicates the ability for the BIPAD portal to deliver robust data for decision making, and more broadly, creates potential for situations where early warnings are not triggered, because sensors are not working.

Maintenance of sensors, and more importantly, models and approaches which sustain the maintenance of sensors in the longer term are therefore critical if sensor-based solutions are going to unlock impact. In the case of eWater, a business model in which end users pay for water, but proceeds are used to maintain sensors and water infrastructure more generally, has proven an effective approach, where community based approaches to WASH infrastructure management had historically failed.

Limited connectivity and / or high power requirements for devices

While improvements in connectivity have made possible the emergence of IoT sensors for the use cases explored in this report, limited connectivity continues to remain a barrier to scaling solutions and particularly in remote areas. Low and intermittent connectivity in hard-to-reach areas has presented as a major bottleneck, leading to loss of data in the Optimal Insects pilot.

Powering devices, especially in remote areas also posed a challenge for Frontier Technologies pilots implementing sensors. In the case of the Forest Fire Early Warning System, team members identified that many off the shelf products (designed for in-door use)were too power hungry for the needs of a solution working in remote areas, and custom solutions with longer battery life needed to be identified and implemented. The pilot also found that high data requirements for transmitting data could also limit battery life, and learned where it was important to tweak solutions, so that they only transmitted data once a certain detection threshold had been reached - so as to reduce data transmission and extend power.

Power also posed a challenge for the Optimal Insects production pilot. Initially the pilot intended to power ammonia sensors via batteries, but found that this was not possible due to the higher power requirements of sensors. Through the use of a mains connection and a 5V power adapter the pilot was able to find a solution to power the ammonia sensor and integrate it into their IoT solution, but this work around would not have been possible without access to mains electricity. More generally the pilot found that typical battery powered sensor nodes were not always well suited for BSF larvae farms, given that typical batteries, that were large enough to power a sensor node, would dominate the overall size of the node, and lack practicality in the relatively small-scale environments and insect farming infrastructure present within smallholder BSF farms. The pilot also found that batteries which required replacing were too expensive for this use case, and found that rechargeable batteries were much more appropriate.

While issues around connectivity and power were experienced by pilots, it is important to note that these are both areas where rapid progress in technologies and the installation of supporting infrastructures is underway - in particular in the emergence of low-power wide-area networks which are wireless telecommunication networks which are well suited in use cases where longer device battery life is important for sustainability, but data transmission requirements may be less onerous.

Lack of patient or longer term capital investment

Lack of patient or longer term capital investment is an inhibiting factor to the long term scaling of solutions. Many sensor projects are limited in duration and scope, and funding and monitoring activities usually stop once research is finished. In the case of disaster risk management, funding for technology tends to be prioritised towards response rather than mitigation - and therefore funding approaches aren't able to support longer term sustainability of technologies - which is critical for the ongoing running of IoT sensors. While pilots using sensors for WASH and agricultural use cases often show potential for return on investment- these are often coupled with high upfront costs for installation of sensors, and consequently longer term investment is required for these returns to be realised.

Lack of buy-in or understanding about the technology and its benefits

A lack of understanding around sensors and the value add created through implementing sensor based solutions can act as a barrier to implementation and scale.

In the Forest Fires Early Warning System pilot, implementers dealt with initial mistrust amongst those community members who would often act as first-responders to forest fires. Suspicion towards the use of technology as a form of surveillance was initially an obstacle to securing their buy-in which was an essential part to scaling the solution.

In the case of the eWater pilot, government support in particular has proven crucial for the longer term scaling of this solution, especially as government actors often have power to make key decisions around whether to include or exclude organisations like eWater from participating in WASH system, and accessing WASH infrastructure. In the WASH sector, government support can also manifest in changing policies or regulations that affect prices of water in a given country, and impact the ability for an organisation like eWater to scale their business model - as reductions in the price of water, even just for a short while, leave their model uncompetitive. Establishing buy-in to the approach and model for maintaining WASH assets, that eWater was seeking to implement, therefore proved critical to the viability and success of the pilot.

What are key enablers to testing and scaling IoT sensor technologies for social impact?

Engaging stakeholders and convincing them of benefits of adoption

Of the 4 pilots that feature in this study, 3 found that government support was crucial for both ensuring an enabling environment for piloting, and enabling scale.

In the case of the BIPAD portal, government stakeholders were both the end users and owners of the proposed solution – and the team found co-design, to ensure the solution responded to their needs and key areas of demand was essential from the start of the project.

In the case of the Forest Fires pilot, a close working relationship between the delivery team and the government helped to ease the process of finding and accessing land for installing sensors. Engagement with community members to explain the benefits of sensors was also critical – especially as many initially feared the sensors were a form of surveillance.

In the case of eWater, the pilot found government stakeholders were key decision makers, who needed to be bought into their approach, in order for them to be able to work with Community Owned Water Supply Organizations and essentially access the water infrastructure they wanted to help improve. Convincing government stakeholders that a pay-as-you-go model underpinned by sensors (and where any revenue was re-invested into the infrastructure and maintenance) is the most effective approach to ensuring sustainable access to water, was found to be critical.

Strong contextual knowledge

Across pilots, a strong contextual knowledge about the environments and communities in which devices were installed proved a critical enabler for effective deployment of devices. Existing knowledge supported pilots to customise solutions to local needs, and anticipate and plan for technical and contextual challenges before they emerged.

Contextual knowledge also helped pilots to identify the areas where sensors might be able to deliver the most impact. In the case of the Forest Fire Early Warning System, the goal was to place sensors in an area where the risks and potential impacts of a fire were higher. From the learning that human fires were much more of a hazard than natural fires, local contextual knowledge was required to place sensors near to locations with human activity. This required an understanding of the local context such as the areas that were near lands of farmers who burn their lands for farming purposes.

Based on an appreciation of the value of strong contextual knowledge for the longer term success of a pilot, the Frontier Technologies Hub has recently introduced a discovery phase at the start of the pilots – to encourage team to spend some upfront time ensuring that they understand the contexts and the needs of users, before advancing towards prototyping and lean testing of a proposed solution. This approach borrows many of the UK Government Digital Service principles around Discovery, and emphasises the need for pilots to investigate the users and user needs, the existing technical landscape, existing solutions in the context and globally, the broader legal / regulatory environment, the broader financial environment and the key contextual requirements for scaling the solution within a proposed pathway.

Service based business models

For IoT sensor-based solutions to have sustainable impact, pilots need to identify longer term models for scaling and sustaining the solution. The eWater pilot essentially implemented a service-based model, where rather than conduct one-off work to provide communities with working taps, sensors were used to collect payments which funded repair work and, ultimately, a service for users who could now access reliable water at the point of need. To collect payment, they integrated their solution with existing mobile money applications, further simplifying access for end users. Revenue was also used to train engineers and cover the material cost for repairs – with materials all sourced locally to keep costs low.

Service based approaches aim to solve a whole problem for end users (e.g. enabling ongoing access to water even when taps break), rather than simply providing a product alone (e.g. installing a tap). They aim to address underlying issues that can emerge over time that prevent user needs from being met (e.g. taps breaking), where a product approach may rely on the one-off delivery of a working product. The provision of an ongoing service can provide those who own a solution with the revenue stream needed to both continue delivery, but also expand and scale.

In addition to eWater, other pilots featured in this study have also also explore opportunities for adopting a broader service based approach as a route for scaling their solutions. The Optimal Insects Production pilot, for example, began to test what additional support they might be able to provide farmers, in addition to providing them with a functional technical product – such as installation, advisory or repair services.

Ease of use

Usability is crucial in ensuring uptake of both sensors, and related solutions (e.g. dashboards and services providing data) accessed by end users. User-centred approaches to design and implementation are critical for ensuring solutions are developed in a way that work for users within the contextl constraints they operate in, and ultimately help to meet their needs. Where sensors are designed to support decision making, projects benefit from working closely with end users in order to understand the key decisions they have to make and their incentives.

In the case of the Optimal Insects Production pilot, where sensors were installed within farms, the team found that plug and play capabilities were essential in order for farmers to be able to implement the sensors themselves. Here ‘plug and play’ refers to sensors which would be easy for farmers to install and set up themselves with minimum instruction. Without this, farmers involved in the pilot stated that the processes around configuring and setting up sensors would be too significant a barrier for them. According to Nicholas Ndekei, the Chief Executive Officer of Zihanga Ltd:

“Configuration of the IoT sensors took a significant amount of time and without the technical support from ICIPE and Sanergy, which came as part of the practical training in the use of Iot sensors, we wouldn’t have been able to do it on our own as Zihanga Ltd.”

Where is the ‘frontier’ for further work (especially early stage innovation projects) testing IoT sensors for impact?

Artificial Intelligence and predictive analytics

Across the use cases explored through this research, a common thread was the potential for AI, and particularly predictive analytics to unlock catalytic value - if used effectively alongside sensor based solutions. AI shows potential for informing preventative interventions before something goes wrong through effective analysis of real time and historical sensor (and non-sensor) data.

For WASH use cases, this can include using predictive analytics of sensor data to support preventative maintenance to issues in WASH systems before they manifest into serious breakages or leaks. Studies have already demonstrated the possibility of using machine learning algorithms alongside data from WASH systems, to pre-empt pump failure in advance.[20][21] As one study focussed on handpumps has found, given the advances that have already been made in using sensors to detect problems, the only way to significantly improve the response time to fixing faults to handpumps from days to hours, would be to use predictive analytics to repair breakages before they significantly materialise.[22]

Translation of data for decision making and capacity building for data analysis.

Across the pilots, a common finding was that the value of sensors is derived ultimately from the data they generate, and ultimately the types of early interventions and decisions this data can help to unlock – whether it is decisions to fix a faulty water asset, improve the productivity of a farm, or respond trigger a natural disaster early warning system.

However, a common finding was that there is often a need to translate data to make it easier for end users to make sense of the key insights from the data, make decisions and deliver interventions. Translation can take the form of presenting raw data in more user-friendly ways, or alternatively, identifying specific insights and recommendations and presenting those to end users.

Through implementing the BIPAD portal the team at Youth Innovation Labs in Nepal, have identified a range of strategies for effectively translating data for decision making, including developing dashboards which synthesise large data sets into maps which plot key environmental incidents, and the human and economic losses as well, in formats that allow government stakeholders to understand present and historical risks, and respond. Within the portal, users are able to access different modules depending on whether they are ‘disaster managers’ (i.e. individuals who help to co-ordinate the immediate response to a natural hazard) or ‘planners’ (i.e. individuals responsible for planning and delivering longer term

[20] Greef, 2019
[21] Wilson, 2017
[22] Thompson, 2012

mitigations). The modules translate the data in ways that make sense for different user types, as Pradip Kathiwada explains:

"The modules on 'Incident', 'Dashboard', 'Real Time' and 'Citizen Reporting' need focus on quick relay of information to drive "Response Decisions" whereas 'Damage and Loss', 'Risk Info' and 'Profile' modules need focus on data standards, accuracy, details, metadata, and references in order to drive "Planning Decisions"."

Prior to the BIPAD portal, key data on natural hazard risks was shared in excel, and as a result was more easily overlooked by staff. Comparatively, the transition towards intuitive dashboards has prompted more frequent interventions, and more informed decision making on natural hazards.

For local community members, the team in Nepal has experimented with new strategies such as murals, in order to intuitively communicate key points of information to community members on the specific environmental risks in the local environment. As Pradip Kathiwada, explains:

"After the 2015 earthquake there were areas where the number of landslides rose 400%. If we can present comparison data, starting in 2014, and showing the number of landslides growing over time within a specific area, if you can visualise that data in maps and murals, the impact is that you can then inform planning… You can inform local building development, based on an understanding of these kind of risk factors and the likelihood that if you build on high risk plots of land - you are going to run an economic risk and loss of life risk."

The Optimal Insects Production pilot found that users of the platform failed to effectively use data on the platform to make decisions and take actions to optimise productivity. The team discovered that this was because the farmers were questioning their own ability to understand what the data meant, especially in instances where data analytics revealed new insights that were contrary to their previous experience. Through capacity building on data analytics and additional information to translate information for farmers, and address their concerns, farmers were able to make much greater sense of the information, and use data to drive decisions and interventions.

For disaster risk management, LUMS in Pakistan learnt that it was pointless having the latest sensor technologies, if end-users (like forest department actors responsible for early warning of fires) couldn't use or understand the dashboards presenting data on forest fire risk. As the team explained:

"we realised we can do a lot of technological advancements, but if they [the users] cannot use it or they don't understand it, then, they don't want to scale it."

Effectively translating data for decision making provided additional benefits in the case of the Forest Fire Early Warning System, as the team found that once stakeholders were able to use dashboards and access data, they were able to identify additional use cases and benefits for the data that the implementation team hadn't considered.

Demand (rather than supply) led approaches to innovation.

More IoT sensor projects need to start with a demand-led approach - where multidisciplinary teams work with stakeholders, such as government service providers (e.g. Ministries responsible for the provision of clean water), in order to identify their needs and challenges, before identifying how IoT sensors, and associated solutions can be used to address these needs and improve service provision. To date, many sensor interventions have been supply rather than demand led - starting with a technical concept, rather than a clearly articulated policy priority, with underlying user needs.

One of the reasons the BIPAD portal has been able to effectively scale for impact in Nepal, was because the starting point for the solution was the government and their priorities. As Pradip Khatiwada explains:

"The government wanted to have this kind of platform. [When we started the work] there was nothing available, some organisations were developing solutions, but nobody was listening to the government about their actual priorities. I think it was quite easy [for the team to implement the solution] because it was not our plan or idea."

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Sensors installed in Chisapani, Nepal