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Co-Development of Technology for Measuring Faecal Contamination of Drinking Water

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Abstract. Participatory approaches to innovation aim to address persistent failures of technology to respond to end-user needs and context. Here, we present the results of a transdisciplinary project aimed at co-developing new technologies for water quality monitoring in remote locations in developing countries. Drawing from critical social science, we developed and implemented a suite of approaches to engage community members and other regional stakeholders in an innovation process that is simultaneously social and technical. Part of our community engagement activities involved the sampling and molecular analysis of drinking water sources from two communities on the island of Efate in Vanuatu. The results revealed evidence for temporal variations in the extent of faecal contamination from different sources. This analysis was used to help frame discussions about microbial contamination, water quality and health, which, along with other structured conversations, led to technical and institutional specifications for water quality sensing. These co-developed specifications were striking, contradicting widely assumed requirements for handheld, rapid, mobile devices. Informed by these specifications, a device for monitoring colorimetric changes in response to microbial growth was designed and built. This device was able to quantify growth of faecal coliform indicator species *Escherichia coli* inoculated into sterile media. Subsequently, we showed the device could detect *E. coli* inoculated into sterilised river water. The limit of detection was as low as a single *E. coli* cell in 100 mL of liquid. Detection at this low concentration was achieved in 16 hours, meeting a specification requirement established through the co-design process.

Keywords. Water quality monitoring technology, Vanuatu, Faecal coliforms, Participatory methods, Transdisciplinary engineering

Introduction

There is a breadth of literature making it clear that, if the potential for equitable value and sustained use of technology is to be achieved, it is inadequate to consider science and engineering in isolation from the setting in which it is applied [1,2,3]. Participatory

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approaches to technology development aim to embed communities in the innovation process from the outset, ensuring that technology is developed to meet the needs, skills and socio-economic context in which a particular community live, and deliver benefits that are distributed equitably [4,5,6]. We recently extended the analysis of participatory technology development and provided a framework that scientists and engineers can use to better address pressing societal problems [7].

Informed by this framework, we have been working with rural and periurban communities in Vanuatu, in a transdisciplinary project that aims to co-design new sensor technology for microbial contamination of drinking water. In collaboration with national NGOs and local communities, we developed a range of contextually appropriate methods for knowledge sharing about water sources, water usage and microbial contamination, attitudes to technology, and the importance of equity in technology use and distribution of benefits. The emergent shared knowledge was used to specify the requirements for a new sensor technology appropriate for use in and by local communities. Critically, our participatory approach recognises the importance of social, political and economic context in determining the acceptance, equity and long-term impact of a technology. This allows us to co-design solutions that incorporate technical design and institutional arrangements that govern access, use, financing and maintenance of the technology.

Here we present a summary of the methodological approaches deployed in co-development of the water quality monitoring technology, the technical and institutional specifications of the co-developed solution and the performance metrics of the water quality sensing apparatus. While the co-developed solutions are specific for our partner communities in Vanuatu, the transdisciplinary approach and methods described here are versatile and it is our hope that our methodological considerations will influence and support technology innovation that delivers benefits that are distributed more equitably.

1. Transdisciplinary methods for knowledge exchange

Interactions between the participating communities and the project team took place between 2017-2020. A variety of participatory methods were employed to generate a shared understanding of the use, access and quality of community water sources, and to co-develop the requirements for a socio-technical solution for sensing water contamination in Vanuatu. These methods allowed us to move beyond the power inequalities that routinely prevent joint knowledge production in technology development [4]. The conceptual framework underpinning our participatory approach and the full range of associated methods are described elsewhere [7]. Here, we focus on three, interlinked methods that allowed us to develop a set of technical specifications for a device to measure contaminated water, and the associated institutions required to provide a functional and sustainable solution for water quality monitoring.

1.1. Community and participant recruitment and engagement

We co-designed our water quality monitoring technology with four communities located on two islands of Vanuatu. Our interdisciplinary team, comprising natural and social scientists and experienced development professionals, identified communities that reflect the diversity across Vanuatu in terms of population, isolation and water access

challenges. All community interactions were facilitated by a dedicated member of the project team with local language skills and a thorough understanding of local customs. The task for the facilitator was to support interaction, deliberation and critical reflection within and between the project team and the participating community members enabling the emergence of shared understanding. At the outset, the aims, expectations and opportunities of being involved in the project were discussed with communities and explicit opportunities were given to opt-in/out of the process at intervals throughout our engagement. Participating communities subsequently identified individuals to participate in workshops. To ensure diverse and inclusive representation, we identified groups within each community likely to display different perspectives in relation to water access, use, quality and decision making. Through discussion with NGO partners and local community leaders, these groups were: young people (aged 18-25 years); members of the community water, sanitation and hygiene (WASH) committee; adult women; adult men; single mothers; elderly people; and people with disabilities. Four representatives from each of these groups were identified by the community to take part in all subsequent interactions. With the permission of participants, data was gathered in terms of facilitator notes taken during each workshop, augmented by subsequent triangulation and reflection between members of the facilitation team. Hard copies of drawn media were collected after each session and catalogued alongside digital objects (photographs, video recordings of plays and presentations).

1.2. Microbial sampling: Study design and sampling

To assess the microbiological quality of drinking water sources in Vanuatu, we undertook a longitudinal sampling and analysis campaign. Sampling was performed five times over a 9-month period from three different sources in the two communities (referred to as BL and EP) on Efate island. Communities were consulted to agree the key water sources to be sampled. In addition to providing key information on the quality and variability of water (by source and over time), this activity allowed us to (i) explore the challenges and hurdles of carrying out field analysis in these settings, (ii) engage communities in a conversation about water quality and sensing technologies, (iii) introduce communities to microbiological concepts through the campaign itself and via discussion of the key findings. These conversations were critical to inform a shared understanding of the social and technical specifications for water sensing technologies that would be appropriate for use in the context of communities in Vanuatu.

Research facilitators and community members were trained in water sampling methods during field visits to BL and EP (Fig 1a). Water samples, alongside control samples, were collected from the six drinking water sources, using sterilised sampling kits shown in Fig. 1a) that were prepared at the University of York, UK. Particulate material was collected on filters, then stored and transported to the UK for total DNA extraction. DNA sequencing, following amplification of 16S rDNA and inclusion of a control bacterial DNA (*Thermus thermophilus*) revealed spatio-temporal variations in prokaryote abundance and diversity. We used abundance of bacteria from the orders Bacteriales and Clostridiales as an indicator of faecal contamination. In river water from the periurban informal BL community, up to 30-40 % of the bacteria present were from these taxa at one particular time point, indicating intense contamination by faeces. Elevated contamination was especially observed at the September sampling point which

took place shortly after a period of heavy rainfall. Sequences from the archaeon *Methanobrevibacter* which is typically associated with mammalian gut microbiome, were also identified in BL river at this time. Other drinking water sources tested had > 100x fewer Bacteriales and Clostridiales and no *Methanobrevibacter* consistent with variable, but frequently low-level faecal contamination.

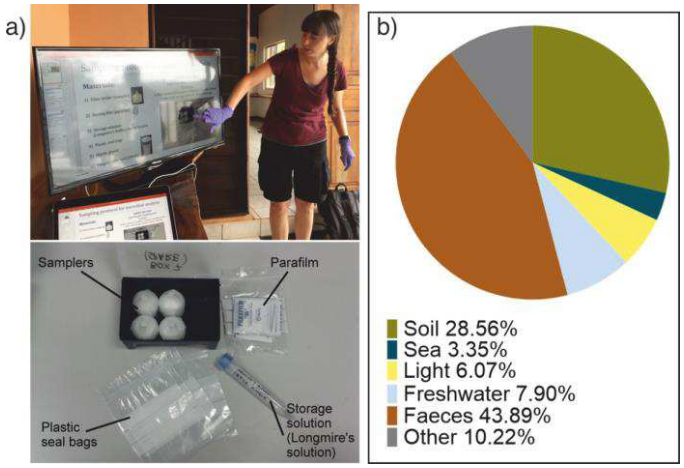

Figure 1. (a) A simple water sampling kit and associated protocol that could be deployed for microbial sampling in the field was developed and sterilised kits were shipped to Vanuatu where facilitators and community members were trained in aseptic water sampling. (b) Example pie chart (for the BL river sampled in September 2017) used to communicate results of the microbial sampling campaign with community members. The chart simply illustrates the relative abundance of microbial contamination as a function of origin (namely bacteria associated with soil, seawater and freshwater habitats, bacteria associated with faecal contamination, photosynthetic bacteria and others which could not be ascribed a specific niche)

A summary illustration in the form of simple, comprehensible pie charts was generated to show the key features for a discussion with the communities (example shown in Fig. 1b). These charts stimulated conversations about the seasonal and spatial variation in water quality in communities, detailed and nuanced discussions about the origins of microbial contamination and indicator species, and concepts associated with sensor technology, such as sensitivity, specificity and false positives/negatives. The microbial quality data for the two communities was also shared with the Department of Water Resources (DoWR) in Vanuatu.

1.3. Construction and use of a simple field microscope

To further build a shared understanding of the microbiology of water and the value of sensor technology to reveal microbiological contamination, we designed a simple microscope that could be constructed *in situ*, in a community setting in Vanuatu, to allow visualisation of microbes in local water samples. The direct construction of the microscope in front of a community audience demystified the technology, whilst allowing us to directly view magnified microbial components from water samples on an iPad screen (and on a projector screen for larger audiences). The microscope, constructed using wooden blocks, a ball lens, white LED light source and an iPad camera, allowed microorganisms in water samples collected in the community to be viewed on the screen. This opened up wide and deep conversations about contamination, the role of

technologies to reveal apparently 'invisible' contaminants and the nature of bacteria (including their positive functions for humans and the environment). Community members found this activity highly engaging and, for the most part, new and surprising. In half of the communities, the scientists were invited to construct the microscope for a second time to allow more community members to view the samples.

Considerable time was invested in this process as a shared understanding of microbial contamination alongside concepts associated with sensor technology was critical for subsequent technology co-development. Moreover, the performative and interactive nature of the demonstration helped build cooperation and trust between the participants and scientists. We note, while the aim was to exchange knowledge about contamination of drinking water, engagement in this process led to a wider appreciation of sanitation and hygiene. For example, in one community, the participants independently linked concepts of microbial contamination to the need for hand washing prior to eating or preparing food. This highlights an important observation; while knowledge exchange should adopt methods that are culturally sensitive and delivered at an academic level appropriate for the audience, with careful design and the support of skilled facilitators, these activities can support exchange of complex scientific or technological concepts and deliver new experiences and opportunities for learning both within the community and between community members and the research team.

1.4. Co-produced water quality monitoring technology: Specification acquisition

The field microscope and molecular analysis of water quality provided an arena in which the scientists and the communities could share their respective knowledge about water and water quality. This was subsequently built upon through structured workshops to define the specifications (quantitative and qualitative, technical and institutional) for potential water quality monitoring technologies. This was achieved using a new participatory method, that we refer to as SHTEPS, that enables acquisition of the specifications for a potential, 'imagined' technology [7]. Community participants were first supported to analyse the impacts (positive and negative) of an existing and familiar technology (mobile phones) across the six SHTEPS categories: Social, Health, Technical/ financial, Environmental, Political/ institutional, and Sustainability. The SHTEPS approach was then deployed again, this time to a hypothetical water quality monitoring technology from which technology specifications could be derived. It is important to note, the project scientists were not simply observers in the process. Rather, they were active participants, responding to questions raised by community participants and contributing their own knowledge when there were clear technical opportunities or constraints. This demands attentive facilitation by individuals cognisant of local context and able to understand and bridge power imbalances and different bodies of knowledge that exist between the community and the project team.

Conversations were facilitated in relation to each SHTEPS category using a series of prompting questions e.g. What might the technology look like? How will users interact with the technology and how will the result of a test be communicated and shared across the community? How will the sensor be powered, maintained and funded in the community? Questions were also posed that explore quantitative, technical attributes including, how fast should the test operate? How big/small should the sensor be? What is the acceptable power consumption? These conversations, supported by sketches, maps and role play, led to lists of positive and negative technical and institutional attributes,

that would be maximised or minimised in the final design. A summary list of technical and institutional specifications for a single community is shown in Table 1.

Prior to community engagement activities, the scientists and engineers associated with the project had perceived potential concepts for the water quality monitoring technology. The specifications and mode of operation of these systems was informed by academic expertise, WHO water quality standards and by peer reviewed literature on water quality testing in resource-limited settings. This literature widely emphasises the need for portable devices that are low cost, rapid and simple to use with minimal user training [8,9]. At first sight, this list of characteristics appears reasonable and appropriate, if lacking in quantitative detail. As shown in table 1, it is striking that our approach to technology co-development revealed a set of characteristics that were quantifiable (e.g., time-to-result <16 hr,) and aligned with local technical infrastructure and experience (e.g. powered using widely available 100W solar panel coupled with 65 Ah dry cell battery).

Table 1. Specifications for water monitoring technology from SHTEPS analysis

Technical specifications	**Institutional specifications**
Test time: Overnight during which time water is not collected i.e. ca. <16 hr	Management: Each community will establish a committee to oversee management, funding and maintenance of the water quality sensor
Power requirements: Current solar panels available in community have capacity to fully charge a standard smart phone but are insufficient for charging a laptop computer battery i.e. < 0.1 kWh.	Use: A single member of the committee will be responsible for collecting water samples, using the sensor and reporting results. Results will be visible to all through safe-/not-safe indicator lights and signage placed at each water source.
Physical design: Rugged, non-portable device that can be housed in a weather proof housing in a central location within the community.	Funding: Costs for purchasing the test and associated consumable items will be raised through a community tax (reflecting current tax raising responsibilities of local water, sanitation and health committee)
Test readout: Binary 'safe/not-safe' readout through red and green lights mounted directly on the housing. This will be coupled with signage installed at the location of the source that indicates the test result.	Maintenance: Each committee will possess an additional sensor unit enabling validation of technology operation through a comparative assessment. Materials, including chemicals must be able to be acquired in country and stored locally.
Multiplexing: All water sources in particular community (total of 4) to be tested simultaneously.	Water quality improvements: Informed by historical water quality test results, the committee will implement remediation measures to improve water quality e.g. cleaning of water storage tanks, relocation of cattle, or lobbying local, provincial and national stakeholders.

Table 1 also reveals that in some cases, the co-developed specifications contradicted the accepted view. For example, communities engaged in this project expressed a preference for a centralised, rugged and fixed sensor technology, in stark contrast to the established view of decentralised testing using portable water quality sensors. A fixed sensor would enable individual community members to see the results of a test for themselves, and thus address issues of trust, be more robust than a portable technology and less likely to create jealousy and discontent within and between communities where ownership of a portable technology could vary between households.

We stress, the preference for a centralised model of water quality testing emerged from communities reflecting their social context. It is likely this would have been neglected without a participatory approach to technology co-design. Furthermore, this preference not only informs the engineering and technological choices but also the institutional arrangements that shape the acceptance, use and long-term impact of a technology. For example, a centralised system enables the cost of the technology and

associated consumables to be spread across the community, while simplifying training needs and communication of results to all members of the community. This emphasises the need to understand technology as a socio-technical object in which both the technical solutions and institutional design are interlinked and need to be considered together in an iterative process of co-development.

2. Co-designed technology to detect faecal contamination

Informed by the technology specifications co-developed through the SHTEPS process and shown in Table 1, prototypes of a water quality monitoring technology were designed, tested and refined in the laboratories at the University of York. While much of this work was performed away from Vanuatu, the communities remained engaged in the process and were given updates through a combination of videos recorded by the project scientists and through inspection of a physical prototype. Questions, comments and recommendations from the community were sent back to the project team by email, with responses shared by facilitators.

2.1. Co-produced water quality monitoring technology hardware

The final technology (referred to as VBox and shown in Fig. 2) was based on colorimetric sensing of a solution-based culture using MacConkey Broth that is used widely for the enrichment of Enterobacteriaceae. The broth contains lactose as a carbon and energy source for Gram-negative, lactose-fermenting bacteria, such as *E. coli*. Bacteria degrade the lactose to lactic acid resulting in a pH change which is detected through a colorimetric pH indicator, here bromocresol purple which changes the colour of the media from violet to yellow. To increase the specificity and selectivity of the test, the broth was heated to 44 ºC to select for thermotolerant bacteria, including the so-called faecal coliforms. The colour change can be observed directly by eye (inset of Fig. 2b) however to increase the sensitivity and speed of the test and to explore quantification of the faecal coliform concentration, an electronic colorimetric read-out was designed and tested. A narrow angle LED (viewing cone angle 15º) operating at 590 nm (bandwidth 13 nm) corresponding to the maximum absorption wavelength of bromocresol purple was used as the light source. The LED was powered via a driver circuit to provide a stable current of 50 mA. The LED was mounted such that the emitted light was incident on a 100 mL capacity bottle (WHO standards for water quality are measured in terms of cfu/100 mL) and the light transmitted through the water sample was detected using a silicon photodiode with built in transimpedance amplifier mounted at 180º to the LED optical path. The output of the photodiode was connected to an analogue input of a microcontroller platform. A PID control loop implemented on the microcontroller regulated the temperature of the 100 mL sample using resistive heating foil and a temperature sensor IC, both mounted on the bottle holder using thermally conductive tape. Four identical systems (consisting of separate LEDs, photodiodes, heaters and temperature sensors), all controlled independently by a single microcontroller, were implemented in a single polypropylene, waterproof housing enabling simultaneous measurement of four separate water samples. The housing was thermally insulated using foam allowing each chamber to be maintained at 44 °C suitable to selective growth of thermotolerant bacteria such as those associated with the mammalian gut microbiome.

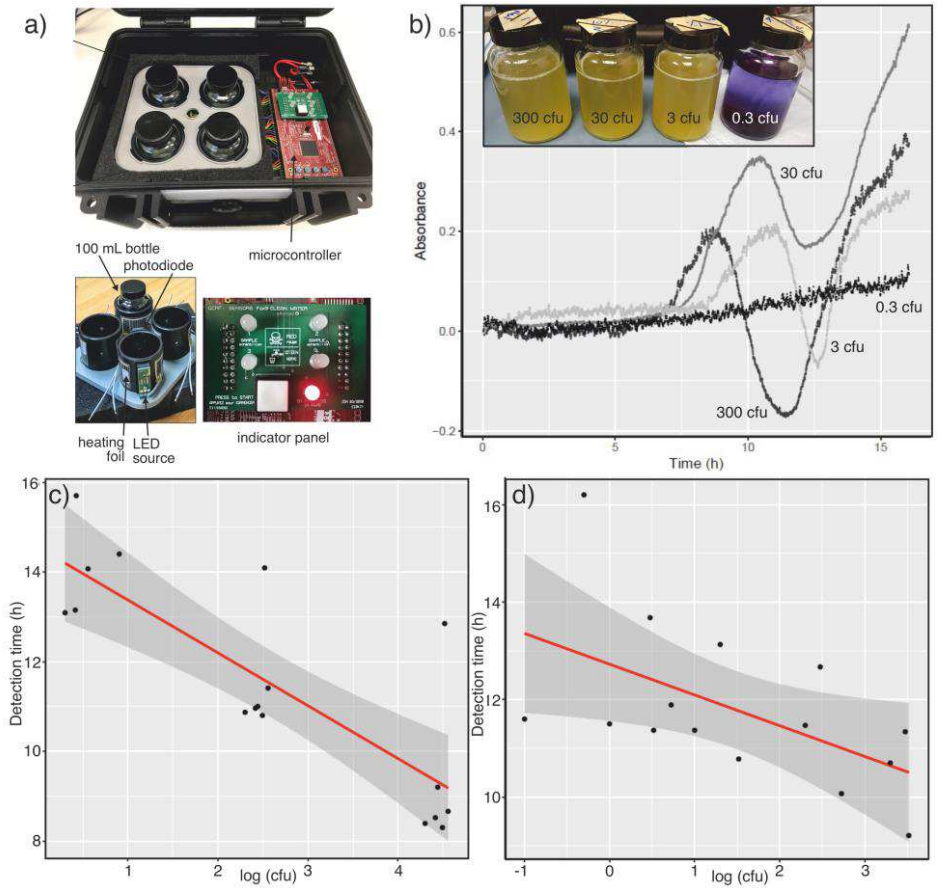

Figure 2. (a) The VBox consists of four separate colorimetric sensors. Each channel includes a 100 mL sample bottle containing the MacConkey broth and an LED and photodiode to monitor the colour and turbidity change resulting from bacterial growth. The broth in each bottle is heated to 44 ºC using heater foil to select for thermotolerant bacteria. An indicator panel reports the operational status of the system (on/off) and communicates the test result via a bi-colour (red/green) LED providing a comprehensible, binary read-out. (b) *E. coli* inoculated into 100 mL vessels in the VBox device and absorbance measured over 16 hours. The biphasic change in absorbance is readily observed following inoculation with > 3 cfu *E. coli* W3110. Inoculation with an estimated 0.3 cfu *E. coli* W3110 revealed no observable growth of *E. coli*. Inset: Visual observation after 16 hours growth of *E. coli* cultures used in the VBox. (c) Relationship between time for detection of growth as a function of concentration of *E. coli* W3110 inoculated into MacConkey media made using deionised water. (d) Relationship between time for detection of growth on inoculating *E. coli* W3110 into MacConkey media made using filter-sterilized river water as the aqueous matrix for the media.

2.2. Detection of cultured E. coli in laboratory and ground water samples

The four chambers of the VBox were inoculated with different concentrations of *E. coli*, to assess the time taken to measure *E. coli* growth and the limit of detection. Following inoculation, the device chambers were maintained at 44 °C, and the transmitted light intensity was measured for a period of 16 hours. Inoculation with *E. coli* led to a distinctive biphasic change in optical intensity (Fig. 2b), due to (i) optical absorption by the pH dependent bromocresol purple chromophore and (ii) optical scattering due to the

change in turbidity caused by *E. coli* growth. The time taken for the optical response to shift from being dominated by chromophore absorption to optical scattering, was observed within 16 hours of inoculation. Moreover, the optical response time was seen to be dependent on the initial concentration of *E. coli* (Fig. 2b). Fig. 2c illustrates the relationship between *E. coli* inoculum and the time taken for the characteristic optical response. As would be predicted, there is a negative and linear correlation between the log of the number of *E. coli* cells inoculated and the optical response. The device was capable of detecting >3 cfu in 100 mL using laboratory-cultured *E. coli* in MacConkey broth generated using laboratory-grade RO water as the solvent. Inoculation with < 1 cfu *E. coli* showed a nil response in the optical behaviour of the sample (which can also be observed by eye at the end of the experiment, inset of Fig. 2b).

To assess the potential to use this technology in a nearer to real world scenario, a series of tests were undertaken to measure the growth of *E. coli* in VBox in MacConkey broth using filter-sterilised river water (obtained from the River Ouse, York, UK). Freshly abstracted river water was sterilized and used as the matrix and made into culture media using powdered MacConkey broth. The optical response was monitored following inoculation with *E. coli* W3110. The relationship between log (cfu *E. coli*) and time remains linear and negatively correlated, and the VBox still maintains a capacity to detect *E. coli* to around the WHO expected standard of 1 cfu/100 mL (Fig. 2d).

To test further the capability of VBox to detect *E. coli* under real world conditions, we also developed a method to assess the *E. coli* content of raw river water. We found that VBox is able to detect any contamination of *E. coli* within the 100 mL media vessels. This meets the expectations for faecal coliforms detection set out by the WHO (detection of 1 colony forming unit in 100 mL water). In our experiments a lack of detectable colour change in VBox was always consistent with no detectable colony forming units of *E. coli.* This was the case when inoculating deliberately with a laboratory strain of *E. coli* and when detecting naturally occurring *E. coli* from raw river water samples. In this latter case, the VBox was approximately 10x more sensitive than the culturing method, which we ascribe to the greater level of stress imposed on *E. coli* abstracted from the water due to the filtration process and the shock of exchange into a different medium, compared to the VBox in which the only shock was the introduction of nutrients via supplementation with MacConkey broth. However, whilst we can confidently detect any quantity of *E. coli* in VBox, we cannot confidently quantify the level of contamination (at least between 1 – 1000 cells per 100 mL) when using raw river water, presumably due to the introduction of uncontrolled variables between different river water samples. We are thus in a position to use VBox to provide a presence / absence, safe / not-safe indication for detection of faecal contamination based on this indicator species, in line with the preferences expressed through the community engagement processes.

3. Conclusion

In this project we have developed and implemented a set of participatory and creative methods to support the co-design of a new technology for water quality sensing, appropriate to the setting of the chosen remote and rural communities. The process provided us with specific qualitative and quantitative specifications for a technology, both in terms of the technical component of the water quality sensor and the institutions that need to be implemented to ensure access, use and benefits of the technology are distributed equitably across the community. These specifications were tangible but also

surprising, cutting against conventional wisdom, such as the perceived need for handheld, rapid, mobile devices. Informed by these specifications, we were able to build and test a water quality monitoring device for detection of faecal coliforms in water. Work is still underway, engaging with community members and other stakeholders in Vanuatu around evaluation of the water quality monitoring technology in communities, user-led translation and widespread distribution of these socio-technical innovations into products that provide crucial and actionable information for some of the world's poorest and most marginalised communities.

The project has been eye-opening and inspiring for the scientists involved, and we would encourage other applied scientists and engineers to collaborate with social scientists and skilled facilitators to embed end-user and stakeholder engagement more thoroughly into technology innovation processes, from the outset and continuously throughout their projects. While this participatory approach requires sustained effort, cost and attention to methods of communication, this transdisciplinary approach to research yields solutions that better address end-user needs, respond to local context and deliver long-term benefits that are distributed more equitably across society.

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