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Equitable technology development: A framework and methods for scientists and engineers

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ABSTRACT

Equity requires a rethinking of the processes and methods that applied scientists and engineers work through as they develop solutions that are simultaneously technical and social. By bridging insights from science and technology studies with critical analysis of participatory development practice, we propose a framework for understanding equitable technology development. We explore this through an illustrative case of water monitoring technology development, undertaken with scientists, engineers and communities in Vanuatu. Analysis suggests a typology of five methodological considerations that are significant for the practice of equitable technology development, locating equitable technology development as both a technical and an ethical challenge.

1. Introduction

This paper aims to provide applied scientists and engineers with practical approaches to technology innovation that delivers benefits that are equitably distributed among users. By focusing on equity, we recognise that there are diverse ways in which some users are disadvantaged in conventional approaches to technology development and that the benefits of innovation accrue unevenly within society. Responding to this requires attention to how innovation processes are delivered, by whom and on what terms. Concerns have long been raised that engineers and scientists anchor their practice in an inadequate understanding of how innovation leads to impact [1–4]. The imagery of technology delivered to end users in a linear process, transferred from researchers and engineers to recipients at the end of the development pipeline, is surprisingly persistent [5,6]. While highly influential [7], this description has been widely criticised for the central assumption that technologies are mobile, immutable 'black boxes', that are adopted, managed and valued in ways that are effectively fixed and independent of the wider social or cultural context in which designers and users function. Detailed analysis from multiple perspectives has revealed that this assumption rarely holds [4,8].

With this paper, we ask: can those concerned with technology development be supported by a more nuanced understanding of how science and technology produce outcomes? We refer to 'technology development' as a process that engages applied scientists and engineers in the production of products and/or solutions to identified problems. As Gilliam and Mehta [9, p10] point out, "there are a myriad of technological, infrastructural, and operational challenges that hinder the successful design and sustainable commercialisation or deployment" of technology. These challenges are suggestive of complex ways in which the outcomes of technological change are generated. Cases document the rapid disappearance of apparently effective technologies [10], or how very different long-term consequences emerge for people in apparently similar use cases [11]. While often reported on in developing country contexts, and frequently in relation to agricultural science and technology, equitable technology development is a universal issue, as illustrated by challenges with scaling point of care diagnostics [12], the emergence of the 'digital divide' [13] or recent popular interest in the effects of gender bias in science and technology development [14]. There is now a breadth of literature making it clear that, if the potential for equitable value and sustained use is to be understood, it is inadequate to consider science and technology in isolation from the setting in which it is to be applied [15–17].

In this work, we look to build on but move beyond this critical

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engagement with the inequities that emerge from technology development. As an interdisciplinary team that has been involved with technology development alongside highly marginalised communities since 2016, we recognise the need for a shift in how applied scientists and engineers conceptualise their engagement with societal problems, and for methods that allow them to engage productively in the development of solutions that are simultaneously technical and social. Like Glover and colleagues [8], we work from the principle that there is now wide body of critical social science in which to anchor technology development; however, we also draw on experiences and critiques of knowledge, power and participation in development studies [5]. As such, we respond to an emerging concern with democratising engineering practice [17] and contribute into a strand of participatory technology development literature that historically has sought to narrow the gap between users and researchers in the agricultural sector [18–21].

By fusing insights from science and technology studies with critiques of participatory development practice, we offer a framework for unpacking the challenge of equitable technology development (Section 2). We present the application of this framework in a case of water monitoring technology development, undertaken through interdisciplinary engagement with communities from the Pacific island nation of Vanuatu (Section 3). Our analysis of this case suggests a typology of methodological considerations that should be central in attempts to design innovation processes that drive towards equitable technology (Section 4). Before concluding, we offer a discussion of our findings (Section 5).

2. A framework for equitable technology development

In this section we draw from literature from within science and technology studies and the critical analysis of participatory development practice to propose a framework of three methodological considerations for equitable technology development.

2.1. Technology and society

Technology is not simply hardware that can be understood separately from society. Seminal contributions have long established how science and technology ideas, investments and methods are informed by the values of society, yet at the same time shape what society values [22]. The production and use of technology occurs in and interacts with its social context. Analysis of these interactions allows understanding of whose interests the outcomes of technology development will serve. The early design phase is imbued with decisions that reflect the underlying opportunities, incentives, training and experiences of scientists and engineers. This may close down opportunities for alternative visions of the social good to frame the focus of science and technology endeavours [23] and most certainly produces "different outcomes depending on the social circumstances of development" [24]. Technology adoption, moreover, is more complex than the delivery of finished products to users. Far from being a simple "exercise of choice among readymade technological packages", it is best understood as "an intricate and complex reconfiguration of various social and technical components": the technical and social are intertwined during the introduction of new technologies, and both are altered in the process [15, pp170–171].

The central argument is that there is no clear boundary between technology and society, or between design and use. An individual user will respond to a technological device in a particular place and time, drawing on their existing knowledge and creativity, the resources that are available to them, and in the context of social and cultural norms that regulate their behaviour. Mosquito nets may be fishing tackle, window coverings, storage devices or (perhaps) insect barriers. Water monitoring devices may be understood in relation to health and sanitation, or (as we found for some peri-urban community members in Vanuatu), assessed as a business opportunity. While new technologies bring with them new forms of practice and knowledge (such as the taking and interpreting of water quality samples), users put this to use (or not) in ways that reflect and resonate with their needs, interests, opportunities and constraints - and not necessarily in the manner intended by the designer [25,26].

Moving from an engineer's workbench to a community of end users means more than just the introduction of a new object: it is the bringing of the knowledge and practices shared by one social group (engineers), embodied in the technology object, into contact with alternative, established ways of doing and knowing. This transition is likely to change the technology - not necessarily as a material object, but in terms of the knowledge and practices that are associated with it [27]. This situation becomes more complex when one considers that this reconfiguration of knowledge and practice occurs in a particular social context, replete with its own norms, rules and cultural cues [28]. How water quality results are understood may be influenced by pre-existing beliefs about dirty water; the status and significance of the technology might depend on whether the device and the consumables it requires align with local economic, social and cultural norms of production and consumption; the results of water testing will likely re-shape rather than replace local rules for the management of water resources. Together, these technical and social effects will inform what constitutes 'safe water', and this will be different for different groups of people.

In sum, it is insufficient to think of technology as a single abstract black box that is unproblematically transferred between settings [17]. Rather, it is necessary to think in terms of the "coevolution" of the material object and the rules and practices associated with it [29, p864], and ask, at the outset, how a given piece of hardware might manifest as a specific socio-technical configuration in a particular context [30]. We need to think less about mobile technological devices, and more about the emergence of context specific socio-technical objects.

2.2. Knowledge and power

If technologies emerge through the interaction of material designs and social context, then significant questions arise around how new technologies should be developed and who should be involved. Different groups who are (or could be) engaged in the development and use of technology bring different bodies of knowledge, anchored in their experiences and/or training. However, they also differ in their capacity to influence how technologies are designed and used. This dual concern – that we should appreciate and work with different forms and sources of knowledge, and yet are challenged in doing so by the degree of power and control enjoyed by different actors – is the second consideration that informs our framework.

Multiple literatures set out arguments in favour of widening the group of stakeholders that participate in defining and resolving societal problems. For many working in global development, the rationale for participation is framed in terms of efficiency (securing better project outcomes) or empowerment (individuals gain an improved capacity to improve their own lives), although both claims are contested [31,32]. However, the case for participation is also made in work demonstrating that diverse perspectives are required to address the complexity of societal problems [33,34]; in response to the diverse value systems that are implicated in real-world settings [35]; as an imperative for responsible research and innovation (RRI) [36,37]; and in recognition of the ethical implications of selecting between alternative future pathways (see for example De Schutter [38, p349], who observes that scientific progress "cannot be conceived independently of the views of the intended beneficiaries"). These perspectives all question why legitimacy is exclusively afforded to knowledge and expertise anchored in formal science [39], and have underpinned calls for widening participation in innovation in agricultural science and technology [40,41], business studies [42] and in a broader shift towards "open innovation" [43]. In each case, there is a recognition that multiple stakeholders, often with diverse perspectives, are implicated in defining and resolving problems. While not suggesting the presence of rigid boundaries between the knowledge of scientists and other stakeholders [44], what is common among examples of multi-stakeholder innovation processes is a recognition of the expertise of people that live and work in the problem settings that science would otherwise objectify [45]. Collaborative and co-development approaches are proposed in which joint knowledge production takes centre stage.

Yet while participation holds significant promise for opening up innovation processes, implementation is fraught with risk. Participatory processes inevitably occur against a backdrop of uneven power relations among participants, with the effect of elevating the voice of some and marginalising others [46]. This can play out in multiple ways, such as through familiar patterns of authority (where deference is given to the views of, for example, senior staff or village elders [47,48]), perceived legitimacy of knowledge (where the expertise conferred by formal training is recognised, while experiential or tacit knowledge is not [45,49]), experience and skills (where those with training and confidence are more effective in presenting their views [47,50]), or deep rooted social norms (where gender, age or ethnicity, for example, lead to discrediting, devaluing or silencing of some voices [48,51]). While seeking to respond to these challenges, it is important to recognise that assumed categories of relatively powerful and vulnerable people (such as those linked to gender or age) may not align with local patterns of marginality [31,52]. Participation alone is no panacea for social and cultural relations, which need to be recognised and understood before any effort is made to ameliorate their assumed effects. A focus on informed and skilled facilitation and diverse approaches may be needed to engage different groups, with consideration given to, for example, providing different forms of support to different groups; changes to the timing, language or location of facilitated processes; or the use of creative methods alongside spoken or written communication [50,53]. A failure to address the context in which interventions take place not only undermines the purposes of participation (by overlooking relevant knowledge or silencing minority perspectives); it also provides a forum for the reproduction of existing inequitable power relations (further entrenching patterns of power and marginalisation in knowledge production) [46,48,54].

Attempts to bring scientists and communities together must address not only the imbalance that arises from their very different knowledge, skills and experiences, but also recognise the authority and norms of respect that might be offered to scientists as outsiders or perceived experts [46,49]. A long history of development interventions demonstrates the need to be wary of emancipatory language that promises greater control for marginalised groups through their involvement in participatory approaches. These methods can all too easily fall back into established relations of power, recruiting local people into projects or agendas defined by external actors [55–57], while studies underscore the potential to reinforce existing power relations through efforts intended to co-produce knowledge and generate shared learning [50,51]. The questions raised by a critical lens on co-production are not only who is involved and with what support, but: what are they being asked to co-produce? How does the identification of a development challenge occur, and how does this influence and reflect who is included and excluded? How might these choices shape the types of solutions that are developed and their social consequences [5,21,58,59]?

2.3. Actors and institutions

Third and finally, actors and institutions at multiple scales are implicated in technology development and use. Communities of technology users are themselves embedded in networks of actors and institutions that influence opportunities and constraints and are consequential for how knowledge and practices are reconfigured by new technical devices.

Systems approaches to the study of innovation emphasise the embeddedness of technology development within networks of diverse stakeholders, highlighting how innovation emerges from multiple sources, through partnerships and via learning between and within differently situated actors and organisations [60]. From this perspective, facilitating the development and spread of technologies means understanding the different actors involved and their differing interactions, freedoms and capabilities [15]. Neither developers of technology nor end users function in isolation from wider actors and organisations, or from the regulating effect of institutions that shape behaviour and choice. Institutions, in this sense, are distinct from organisations, and define the "underlying rules of the game" by which individuals and organisations operate, shaping incentives, behaviour and choice in ways that are relatively stable over time (although may be contested and are not immutable) [61, p3]. Crucially, they may be formal (such as codified laws or policies) or informal (such as social norms, customs or traditions) [62]. As such, informal institutions will inform behaviours within formal organisational settings (such as committees or participatory processes), raising questions about the potential of introduced norms, such as gender inclusion, to overcome wider and more deeply embedded incentives and behaviours that may limit equitable representation [48,63].

Networks of actors, organisations and institutions are, therefore, significant in the co-evolution of material technical objects and the rules and practices associated with them, leading to the emergence of context specific socio-technical objects. However, while the focus may be on, for example, relatively poor communities, it is important to recognise that the idea of a community is itself an incomplete description of the relationships, associations and dependencies that connect to the wider world. Just as the language of 'community' can lead to overlooking the complexity of social and cultural relationships and hierarchies, so too can it project an image of a coherent, bounded group with shared values and unfettered agency [31]. In reality, communities are made up of individuals, households and groups that are connected through local institutions, networks or relationships, and at the same time are connected to wider rules and norms that may operate at the scale of the state (e.g. nationally regulated markets), the landscape (e.g. norms, laws or regulations that distribute natural resource access), or via caste, clan or religious associations. Equally, schools, private sector actors, government extension officers, or non-governmental organisations may be a significant source of material or knowledge resources for a community. Patterns of access to these resources may vary within and between communities, shaping wider socio-economic opportunities. Together, these connections to wider networks at different scales will be significant in how end users respond to a technological device at a particular place and time, shaping their knowledge, the resources that are available to them, and the social and cultural norms regulating their behaviour.

2.4. Equitable technology development

In this section, we propose a structured approach to co-design that responds to the framework set out above. Fig. 1 provides an illustrative design heuristic that guides our approach. Relations between technology and society are central, captured through an iterative development process that allows for the emergence of science and technology solutions alongside institutional arrangements; here, the opportunities and constraints offered by existing institutions inform the technical choices, while the potential and limits of technical solutions shape the institutional arrangements required for sustainable and equitable deployment. This iterative approach is community-led, anchored in contextual analysis of the social and environmental conditions as experienced at the community level. This analysis informs facilitated engagement of local and higher-scale stakeholders, enabling the navigation of knowledge and power relations through an appreciation of the forms of difference within communities, and between communities and national and international stakeholders. Similarly, facilitated engagement of the project team is required to address knowledge and power differences within the interdisciplinary team and between the team and stakeholders.

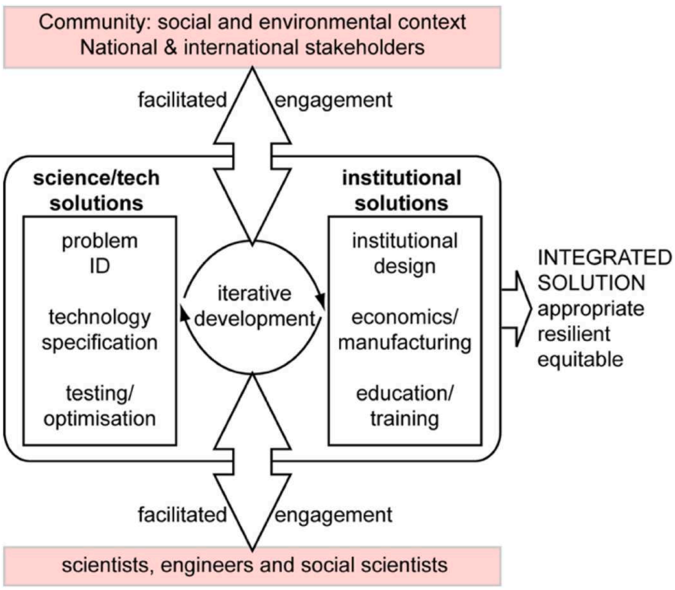

Fig. 1. heuristic model to guide equitable technology development.

Contextual analysis is also required to identify the networks of actors and institutions that shape community access to knowledge and to material and cultural resources, informing the selection of national and international stakeholders and building understanding of how they condition opportunities and constraints at the local level.

We applied this design heuristic to the problem of water quality monitoring in Vanuatu. Vanuatu is an island nation with many communities living in rural villages which, outside of the main island, can be highly isolated and very challenging to access other than by rudimentary road or sea landings. Vanuatu remains an Overseas Development Aid (ODA) recipient country and lacks resources to support water treatment infrastructure across the 80 remote islands. Communities in rural areas account for around 77 % of the population and rely on some form of piped water (39 % of rural households), rain water (42 %), river, stream, creek, lake or spring water (7 %) and underground borehole or well water (10 %) [64]. The piped water in rural areas usually originates in a spring, river or stream located above the village and reaches the village through a gravity fed system using one or more storage tanks. Overall, there are >2000 informal community water supplies and high rates of diarrhoea: for example, 14 % of under-fives had diarrhoea in a two-week period immediately prior to surveying in a Vanuatu Multi Indicator Cluster Survey [65]. According to the World Risk Report, Vanuatu is also one of the most disaster prone countries in the world, with a high susceptibility to natural hazards [66]. After Tropical Cyclone Pam (2015, at the maximum category 5 strength), half the population was reported to be without clean drinking water for one month after water and sanitation infrastructure was destroyed or contaminated [67]. In March 2023 consecutive cyclones affected 46 % of the population at strength category 3 or 4, leaving no access to water in the main impacted areas [68]. Climate change is set to increase the frequency and intensity of extreme weather events and research suggests a significant risk of diarrhoea following natural disasters and the need for control measures that can be implemented rapidly [69].

Scarce water resources are routinely relied on regardless of safety (in the absence of water quality monitoring) or being abandoned as unsafe (following unreliable and infrequent testing). Point-of-use water treatment, such as boiling or addition of germicidal agents (e.g. chlorine), can be effective; however these have proven too expensive and disruptive to employ routinely [cf. 11]. Tools that enable communities to better assess, preserve and manage their water supplies are an attractive solution to protect and empower communities by:

- Enabling routine, community-led assessment of water sources.
- Providing tools to assess the cleanliness of water storage tanks and rainwater cisterns.
- Identifying sources of contamination to empower communities to take remedial action.
- Enabling rapid monitoring of local water quality following emergencies and natural disasters.
- Determining the efficacy of water treatment processes, such as natural filtration systems.

The broad aim of our work was to engineer effective, equitable and appropriate technologies for testing of water quality in remote and rural communities in Vanuatu. We note, prior to engaging with the communities, the technology developers associated with the project had perceived potential concepts for the water quality monitoring technology. These imagined technologies were highly ambitious (exploiting novel biophysical technologies for the detection of bacterial biomolecules) and based entirely on technological solutions with no consideration of the inter-linked institutional arrangements required to operate, support and respond to the technology. The final device was based on colorimetric sensing of a solution-based culture which was shown in laboratory trials to have a limit of detection of a single *Escherichia coli* cell in 100 mL of liquid (as required by WHO specification). The technical and institutional specifications that this device responded to were developed through the phases of the project, and are summarised for one of the participating communities in Table 1.

2.5. Phases of engagement

The design heuristic in Fig. 1 was translated into five phases of engagement for implementation in Vanuatu context (Fig. 2). The interactions between the participating communities (five) and the project team were arranged across five phases of work (2016–2020; Fig. 2), each

Table 1
Specifications for water monitoring technology arising from co-design in Vanuatu.

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 panel systems 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.

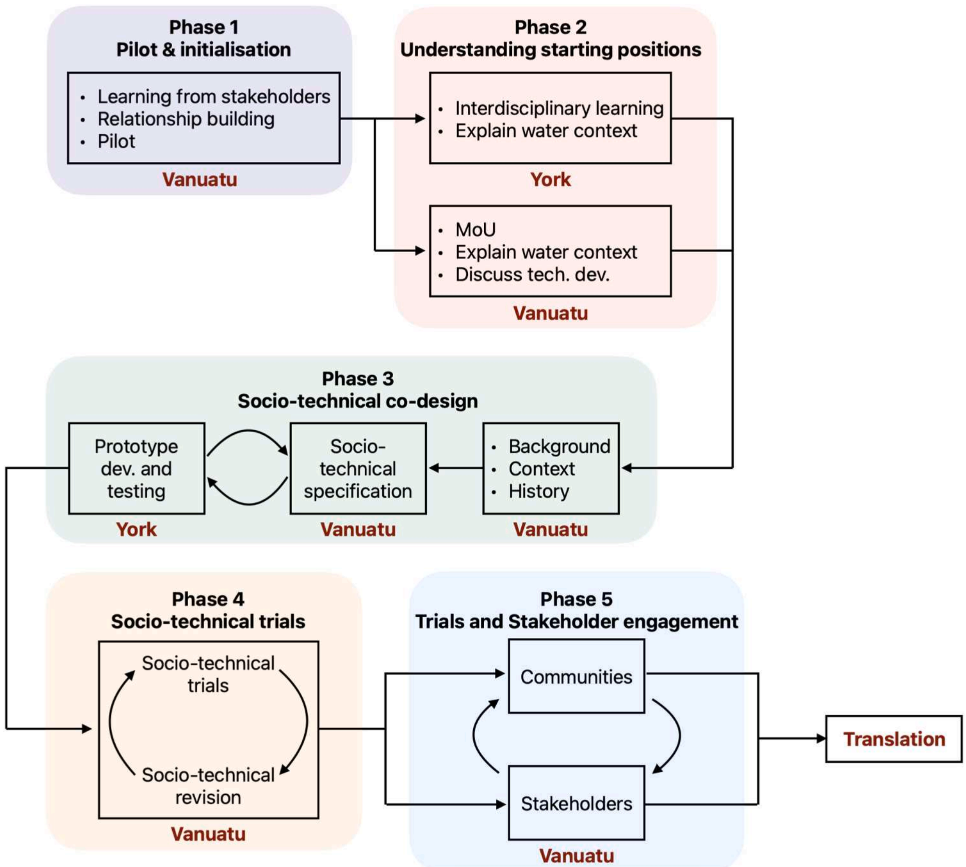

Fig. 2. five phases that structured engagement in Vanuatu. Phase 5 was not completed due to Covid.

with distinct goals, that together were intended to provide a structured approach to equitable participatory technology development. Broadly, phases 1 and 2 explored the starting conditions for the facilitation between the project team and communities (anticipated in the vertical arrow at the bottom of Fig. 1); phases 3 and 4 translated these insights into an iterative process developing social and technical solutions (anticipated by the 'iterative development' wheel in Fig. 1); and phase 5 facilitates relationships and learning between community and national stakeholders (anticipated in the vertical arrow at the top of Fig. 1). Prior to phase 1, our local partner, Oxfam in Vanuatu, had worked for many years with the project communities, establishing relationships of trust and mutual respect that opened a space for the project to be well received during initial introductions, and enabling access to settings that differed in terms of population, geographical isolation and available water sources. Similarly, national government and NGO stakeholders were already known to our local partners and relationships were mediated via the national coordinating mechanism for water, health and sanitation.

2.5.1. Phase 1: Piloting and initialisation

The pilot phase provided a period of knowledge, methods and relationship development. This was essential for engaging in the complex social, ecological, institutional and technological context within which technology development was intended to take place. The goal was threefold: first, to understand the problem of water quality from different perspectives, anchored in community perceptions but also exploring the views and activities of government and NGO actors. Second, the process was designed to enable relationship building, introducing the project and project team to these different stakeholder groups. Third, the pilot phase was an opportunity to trial methods for co-producing technologies with community members. Informed by these activities, the pilot phase concluded with initialisation of future action and research phases.

2.5.2. Phase 2: Understanding starting positions

This phase was structured with parallel activities for the research team and local communities, aimed at securing a foundation of common understanding in a complex, interdisciplinary and stakeholder-centred research and development project. For the natural and social scientists, with differing experiences of working in applied research projects, this meant moving towards a shared language and developing a shared understanding of what co-development means and involves. For the communities, this was an opportunity to be introduced to the project and to develop a shared understanding of what a research project entails and to agree aims, expectations and objectives. In preparation for the scientists and communities coming together in Phase 3, this phase opened space for both to explore and prepare explanations of the context in which they understand water, water infrastructure and water contamination issues. This phase also introduced how institutional arrangements interact with technology 'hardware', and a discussion of technology innovation through cycles of design, implementation, test and review.

2.5.3. Phase 3: Co-design

This phase brought the project scientists and community members together for intensive activities focused on, first, building a shared understanding of each other's context, interests and circumstances, and second, the development of interconnected technical specifications and institutional arrangements for a prototype technology. Significant time was provided for the community and project scientists to introduce the background and context within which they engage with questions of water quality, supported by the use of photo-elicitation exercises, and the building of a simple microscope with the community members. A novel method developed for the project, referred to as SHTEPS, was used as the entry point for discussing potential water quality monitoring technologies, and for a process of defining technology specifications (both quantitative and qualitative) that engaged the expertise of both the community members and the project team. SHTEPS draws on conflict resolution methodologies [70] and structured investigations across six categories: Social, Health, Technical/ financial, Environmental, Political/ institutional, Sustainability. The specifications were the basis of a prototype device that was developed by the project scientists between Phases 3 and 4.

2.5.4. Phase 4: Socio-technical trials

This phase provided the communities with an opportunity to test the institutional specifications developed in Phase 3 through role-play, facilitated on dummy prototype devices that mimicked the possible outcomes of a water quality sensor (i.e. water contaminated, water not contaminated). The aim was to provide an opportunity to reflect on and refine the design specifications developed in the previous phase, embedding the participants in a process of ongoing institutional and technical development.

2.5.5. Phase 5: Long term trials and stakeholder engagement

Covid-19 prevented planned activities in Phase 5, which would have delivered the device to the participating communities for long term trials and undertaken multi-stakeholder engagement. The goal of this phase was to bring the project team, communities and wider water system stakeholders into deeper dialogue, exploring the significance of socio-technical design; the potential for widespread use of technologies that better integrate with local context; and how a socio-technical design process can support alignment with and realisation of the Government of Vanuatu's emerging National Water Policy goals.

2.6. Methods for engagement

A combination of methods was used across the phases (Table 2) integrated into a process that was facilitated by a dedicated member of the project team (an experienced former senior staff member at an international development NGO with local language skills). Process design centred on the development of facilitation guides for each meeting, with the emphasis at each stage being on securing opportunities for the emergence of new understandings. The task for the facilitator was thus to support coordination and momentum, interaction, deliberation and critical reflection within and between the project team and the participating community members. This led to what Colvin et al. [71, p767] refer to as a "part preconceived, part emergent" design praxis: our goal was to create spaces for dialogue within and between the project members and participating Ni-Vanuatu communities, while working within project time and travel constraints, and guided by an overarching goal of enabling new understandings to emerge in relation to water quality monitoring [41].

The diversity of methods used across the phases are illustrated in Figs. 2& 3 and Table 2. The Supplementary Material offers additional detail for those looking to adopt these methods. The contribution that the overall process of engagement makes towards equitable technology development is assessed in the results section below. With the permission of participants, data was gathered throughout the process, principally in terms of facilitator notes taken during each discussion, augmented by subsequent triangulation and additional reflection between members of the facilitation team. Hard copies of drawn media were collected after each session and catalogued alongside digital objects (photographs, video of plays and presentations). For the purposes of this paper, our interest was not in providing a rich description of the entire dataset, but to undertake a broadly deductive thematic analysis in which coding was informed by the analytical categories of our framework [72]. One author was both researcher and facilitator, allowing the

Table 2
Complete toolbox of methods used during the four project phases.

Method	Phases	Summary
Inter-disciplinary workshops	1,2	• Bring natural and social scientists together to build shared understanding of project conceptual starting points, goals and methods. • Avoid hegemony of a particular field while working towards disciplinary integration.
Ground rules and memorandum of understanding (MoU)	All	• Agreement with communities around acceptable behaviours and how conflict would be handled within project meetings. • Agreement with communities of the outcomes that the project will, will not and might be able to achieve.
Group discussions	1,2	• Community disaggregated into groups representing people with similar social standing and/ or experiences of water access and use. • Discussions facilitated to support all group members to represent their views in relation to discussion topic. • Broad discussions, and provision of resources for drawing or sketching, help to elicit diverse perspectives.
Plenary feedback	1,2,3	• Groups supported to share conclusions in a facilitated plenary discussion. • Raises awareness and understanding within the community of the different needs, attitudes and challenges faced by groups.
Stakeholder workshop	1	• Support provided to small group of participants to represent community knowledge and raise demands. • Stakeholders reflect on their role in community water systems. • Raises awareness of water quality monitoring among stakeholders.
Photo-elicitation	1,2,3	• Individuals are supplied with a camera or tablet and invited to take photographs in relation to a particular topic or theme. • Photographs are used as the basis for subsequent discussions with individuals or in groups. • Discussions are frequently richer and different to those without images.
System and stakeholder mapping	1,2	• Participatory mapping process documenting physical, relational and decision-making nodes and connections from community outwards. • Process facilitated to stimulate discussion and document findings.
Community and scientist presentations	3	• Provide opportunity for the community and scientists to prepare presentations to deliver to each other. • Emphasis on ensuring community and scientists learn from each other.
SHTEPS	1,2,3	• Facilitated discussion of direct and indirect impacts of technology structured by six themes: Social, Health, Technical/ financial, Environmental, Political/ institutional, Sustainability. • Supports engagement with socio-technical understanding of technologies and the diverse outcomes that they produce
Socio-technical trials & action planning	4	• Testing of a dummy device in community setting embedded in agreed institutions arrangements. • Role-play enables testing and review of proposed institutional arrangements.

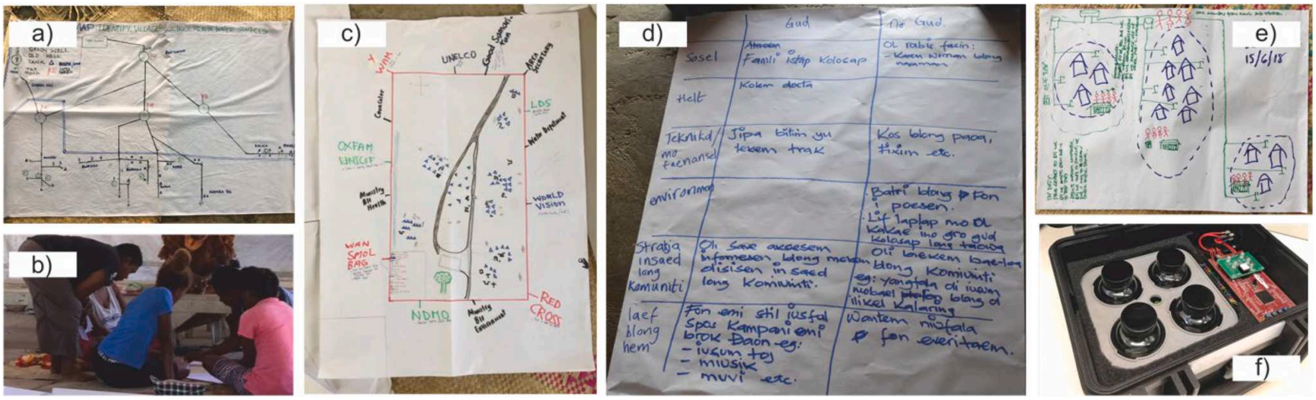

Fig. 3. Initial interactions with communities (phases 1 and 2) employed methods to establish a shared understanding of the project including community-led mapping of water systems (a) and facilitated workshops to agree aims, expectations and objectives (b) and stakeholder mapping (c). Phase 3 focussed on the development of a prototype water quality monitoring technology using the SHTEPS method (d), that revealed institutional arrangements (e) and technical specifications that were the basis of the socio-technical trial (Phase 4) and the prototype device (f).

distance between participants and the researcher to be minimised and therefore providing additional access to information and insights during the project activities [73]. This dual role does not, however, come without challenges [74]. The potential for bias or selectivity in the voices foregrounded in analysis was reduced by working with transcripts and digital objects in collaboration with the author team, after the completion of the project. This helped to secure distance for the research role, while the use of multiple methods (meeting transcripts, interview notes, diagrams, participant observations) provided opportunities for triangulation. The themes described in the following section were ultimately arrived at by consensus during a series of analysis meetings between the author team.

3. Results

Qualitative thematic analysis of when, how and with what effect the phases of activity addressed the underlying framework of equitable technology co-development, either individually or in combination, revealed five central methodological considerations, explored below.

3.1. Recognising and legitimising knowledge diversity

Community engagement was premised on separately identifying participants from different groups: young women and men (aged 18–25 years); members of the community water committee; adult women; adult men; single mothers; and elderly and disabled people. Through discussion with Oxfam in Vanuatu staff and local community leaders, these groups were identified as being likely to exhibit differences in perspective between groups, and similarities between group members, in relation to water access, use, quality and decision making. These differences in perspective were clear from the first set of discussions in Phase 1 of the project. For example, while all groups identified the river, rainwater tanks and village taps as sources of water, single mothers, mothers and the elderly & disabled groups also relied on streams (creeks), a well, and a spring near the village edge (mothers group). Differences between group responses provided the project scientists with an early indication of the need to consider both technical configuration and rules of use in order to address the problems of all, rather than only some, of the community (and thus starting to appreciate technology and society concerns).

In a methodology that was adopted in Phase1–3 of the project, project facilitators worked with each group during discussion sessions, supporting a conversation between group members and developing a shared view in relation to the topic in question. In a plenary feedback session, this perspective would subsequently be shared (by the group members) with the other groups. This approach offered multiple benefits in relation to knowledge and power: building confidence of group members in the legitimacy of knowledge held between them (for example, supporting the women's group members to articulate a shared, rather than individual, experience of poor water quality); developing an appreciation and understanding of alternative perspectives that exist between groups (for example, the community plumber declaring that he had "no idea" of the difficulties faced by women in his community accessing water); and building the confidence and skills of all in presenting their knowledge and representing their views. The group-wise methodology, as an approach to acknowledge the diversity and legitimacy of community knowledge and address differences in power, was reinforced through agreement of ground rules for discussions within the community (Phase 2), which set the stage for respectful interactions, while in Phase 3, the opportunity to prepare presentations consolidated group identities and opened creative space for them to express their experiences of community water history, access and use.

The multi-stakeholder workshop, at the end of Phase 1, moved on from differences within the community, to centre on knowledge held among government and civil society actors working at the provincial and national level. Participants were identified through explicit discussion of the actors and institutions that communities engage with in relation to water access and quality, as well as through the expert knowledge of NGO and governmental project partners. The workshop was in two parts: the first half day with only provincial and national level stakeholders present, and the second half with community members also participating. This allowed time to introduce the project and elicit views from government and NGO stakeholder groups on community water quality challenges. In the second part, the community presented their water perspective, drawing on the analysis they had undertaken with the project team. This provided an opportunity for the community to emphasise the problems that they had identified as most significant, and frame demands for support from the stakeholders where they felt it was appropriate to do so.

This process surfaced underlying tensions between groups. For example, the morning session highlighted assumptions held particularly by some government level stakeholders that communities were "lazy" or "ignorant", and largely at fault for the problems they face in water and sanitation. While these views were not explicitly articulated to communities in the afternoon, they contrasted starkly with the community presentation and group discussions that demonstrated the clarity with which community members understand their situation and the support required to resolve the challenges they face. The workshop format thus centred on and highlighted uneven knowledge and power relationships between communities and the higher-level stakeholders, and provided a mechanism through which the deep understanding of context held locally could be represented to more powerful stakeholders. The structured engagement ensured space was opened between differently situated stakeholders and provided the first steps towards an acknowledgement by each group of the legitimacy of the different bodies of knowledge. At the same time, by introducing the project and framing the discussion around the context specificity of technology development, the workshop repeatedly reinforced the technology and society imagery and sought to anchor new relationships between participants in this understanding.

3.2. Valuing community knowledge

These processes - of identifying and working with groups, and opening space for each to express their views - explored the plurality of knowledge within and between communities, stakeholders and academic participants, and sought to build legitimacy for views that are routinely marginalised (for example, women or youth by community leaders; communities by national or provincial stakeholders). While these methods focused on the legitimacy of diverse knowledges, the knowledge and power perspective also highlights countless examples of the marginalisation of community knowledge within development projects. Activities were therefore designed to explicitly demonstrate the value of community knowledge to the project, adopting methods that centred on community perspectives (discussions about different understandings of the project that centred on the development of a memorandum of understanding (MoU) between the community and project team; photo-elicitation, walking tours, and discussions of water in everyday life; and the development of presentations to the project scientists by the community groups; see Annex A). In each of these cases, the project team were learning from – and were seen to be learning from – the community, using methods that anchored discussions in the knowledge held locally and emphasising that the project team were in the community to listen and learn, rather than to tell community members how to behave or think. In Phase 3, each group decided how they would like to present their understanding of their context to the scientists, and had the freedom to choose methods that reflected local preferences and familiar forms, including short plays, drawings on different media, songs and speeches.

The project scientists were taken through a process that deliberately mirrored those taking place within the communities (facilitated discussion of project goals; scientist photo-elicitation; deciding how to present their understanding of their context) as an explicit demonstration of the equality of community and scientific knowledge in the eyes of the project. At the same time, these exercises supported the sharing of scientific knowledge and set the stage for the combining of science and community insights in Phases 3 and 4. Regular communication was central to sustaining respectful relationships, facilitated by the project team being hosted in the communities (opening space for informal interactions) and regular opportunities for the community to pose questions to the project team. For example, during the period between Phases 3 and 4, the project scientists developed a prototype water quality monitoring device informed by the specifications agreed in Phase 3. Workshop participants were provided with an update on this progress through a combination of video clips recorded by the project scientists and through inspection of a prototype device. Questions or comments were sent back to the project team in the UK by email, with responses shared next day by the facilitators.

3.3. Understanding context

Activities across Phases 1–3 provided important opportunities to understand the context into which new technologies would need to operate, including identification of relevant actors and institutions and insights into how aspects of technologies and society interact and inform each other. The different roles of actors and institutions within the community (community water committee, community disaster committee, community plumber) and beyond (NGOs, local and national government, donors) emerged in responses to questions around governance and institutions connected to water and health in Phase 1, and through the systems mapping undertaken in Phase 2. The Phase 1 discussions provided a starting point for the project team to understand local water and health challenges, and the context within which they are embedded. In the photo-elicitation phase that followed, community group members were able to lead the discussion, narrating their experiences to the project team scientists, who would listen and ask questions. These sessions, when repeated in the following phases alongside the walking tours, group discussions and community presentations, were significant in each community, revealing the social embeddedness and complexity of water infrastructure. Significant time invested in these steps; for example, Phase 3 entailed two-day workshops in each community. During this time the project team were hosted locally, enabling interaction informally outside of the structured process, providing additional opportunities for deepening mutual understandings of context.

Together, these activities provided insights into local interconnections between technology and society, through demonstrations of how perception, access and use was connected to social position, and the water-related rules, norms and processes at play. Equally, the scientists' photo-elicitation opened up important aspects of the UK context, including the rules and norms regulating scientific method and water monitoring standards. Workshops within the project team revealed the different epistemological starting points that underpin each discipline and agreement over the key insights being developed or applied through the project. As such, methods during Phase 2 were as much focused on the academic project team as they were on the communities and local project partners. Among the academic team, informal opportunities for discussion were seen as being as important as formal, structured activities. In this vein, travelling as a project team to Vanuatu provided concentrated periods of interdisciplinary working between the natural and social scientists, anchored in and continuously informed by experiences of being in the context and environs of the focus of the research.

3.4. Grounding socio-technical analysis and design

In Phases 1 and 2, the SHTEPS analysis explicitly focused on the relationship between technology and society, surfacing and deepening understanding of this aspect of the wider context. By first undertaking analysis of the impacts of mobile phones, community members and the project scientists were familiarised with the structured approach offered by SHTEPS, and developed an appreciation for the deep interconnections between technical devices and social context and the central role played by institutions in regulating performance. Examples were relatable and energising: cases of private solar panel owners levying a fee for charging phones; discussion of disruption caused by young people playing music or accessing pornography and the new community rules developed to address these problems; the advantage of being able to contact family members or medical professionals based in the main island. These examples grounded real-world discussions of co-production, helping provide meaning to abstract concepts and setting up the subsequent discussion of water quality monitoring technology.

In Phase 3, the SHTEPS categories yielded explicit examples of the consequences of different configurations of a new water quality device for the social context, such as the potential for individual device ownership to undermine community cohesion and promote rent-seeking; the need for results to be understandable for everyone and for mechanisms to communicate across the community if everyone is to benefit; and the potential for regular testing to inform and incentivise water infrastructure maintenance and repair - and to underpin lobbying of regional actors to support these services. Equally, these discussions revealed important contextual factors that would inform the technical specification: for example, power supply being limited to a car battery or solar charging sufficient for a mobile phone; cost of supplies and repairs limited by a monthly fee of 100vt (around 0.8USD) per household per month (requiring management); overnight test results acceptable; and the ability to test multiple water sources simultaneously would be a significant advantage.

Facilitated through the sketching of alternative local system maps to help describe potential design arrangements, these discussions integrated technical and social-institutional considerations. For example, there was an evolving appreciation that the portability of the device was not a priority, running counter to project team preconceptions and intersecting with discussions on technical constraints on power and weight (which were able to be relaxed when the requirement for portability was lifted), and in turn opened up new considerations around the provision of secure sampling vessels that would enable water collection from remote sites. Reference back to the SHTEPS categories ensured this co-design process retained a holistic and contextualised view of the opportunities and constraints of these design considerations. At the same time, this process opened up discussions of the limitations of existing technologies, and the rules, norms and practices of scientific disciplines (for example, in relation to sampling protocols or testing and verification of prototypes) and the applicable national and international water monitoring standards. As such, while SHTEPS was predominantly a mechanism for addressing technology and society interactions, when embedded in the overall methodology it also reinforced positive knowledge and power relationships.

3.5. Prototyping and socio-technical trials

The socio-technical trials in Phase 4 can be understood as the culmination of the process of engagement with the community, as it enabled them to move forward together with their assessment of how the device would perform in their setting. The assessment process was anchored in and reinforced understanding of the co-constituting of technology and society, as it supported iterative technical and institutional testing, with the community members reflecting and feeding back on both: through recommendations for device improvements (e.g., increasing the number of water sources/ samples that could be tested simultaneously) and through the refinement of their management and governance arrangements, culminating in the development of an action plan to integrate the device into the community.

Prior to community engagement activities, the scientists and engineers associated with the project developed potential concepts for the water quality monitoring technology based on highly innovative photonic and electrochemical biosensor technologies. The specifications and mode of operation of these systems was informed by WHO standards and peer reviewed literature on water quality testing in resource-limited settings [10,75], which emphasises the need for portable devices that are low cost, rapid and simple to use with minimal user training. In contrast, the phases of co-development revealed a set of characteristics that were quantifiable (e.g., time-to-result <10 hr, 100 vt per household per month), aligned with local technical infrastructure and experience (e.g. powered using widely available 100 W solar panel coupled with 65 Ah dry cell battery) and, in some cases that contradicted this accepted view. For example, a centralised and fixed sensor technology to enable individual community members to see the results of a test for themselves, and thus address issues of trust; be more robust (including against cyclones) than a portable technology; and less likely to create envy and discontent within and between communities where ownership of a portable technology would vary between households. A centralised system would further enable the cost of the technology and consumables required for testing to be spread across the community and simplify training needs (restricted to only those in the community water committee).

Treatment of technology as a combined socio-technical object allowed engineering of the 'hardware' to reflect community context and co-developed institutions. For example, the ability to perform multiple tests simultaneously enabled testing of the multiple water sources used by each community. Moreover, the method by which the result was reported to the community was informed by community needs; most communities requested a simple, binary readout (safe, not-safe) for each water source, while one community also requested a quantifiable measure of faecal coliform concentration for members of the community water committee to help identify the source of contamination and to evaluate remediation measures. In this way, designs were not only embedded and evaluated in context, but were developed through a process that reinforced the central role of community knowledge in technical development.

4. Discussion

Innovation systems and participatory perspectives on technology development recognise the importance of users' particular forms of expertise in aligning socio-technical innovations with local contexts [15,76,77], requiring methods that combine the knowledge of technology users, researchers and other key stakeholders [78,79]. Our experiences suggest this involves an ongoing commitment to carefully designed processes of engagement that over time allow different stakeholders to build an appreciation for unfamiliar forms of knowledge. Here we emphasise that, in our findings, there are clear differences in knowledge, power, values and experience within a given 'community' or end-user setting. Combining the knowledge of multiple users demands a depth of contextual understanding sufficient to move beyond assumed forms of similarity or difference (such as simplistic assumptions that homogenise communities and their knowledge and experiences [31,80]). Facilitation must be designed to respond to this context. Similarly, our experience highlights the need for specific methods and approaches to respond to histories of marginalisation from knowledge making, centring engagement processes on heterogenous local groups to reinforce the value and standing of their knowledge. Overcoming the tendency for community-based practice to defer to identified experts and outsiders requires explicit attention in its own right, including, in our experience, a focus on relationship and trust building alongside sustained efforts to communicate expert understandings and appreciate local knowledge [45,49].

In Vanuatu, facilitation was anchored in working with differently situated groups, recognising that culture, context and established practices influence – and are influenced by – their situated understandings of problems and potential solutions [81]. Structured processes were used to manage the interface between differently situated forms of knowledge and expertise (within and between community groups, between the community and project team, within the interdisciplinary project team, and between the community and wider stakeholders), emphasising mutual respect and joint learning, and in the process expanding the boundaries of understanding among those stakeholders who were engaged [82]. This perspective draws close parallels with literature connecting social learning and innovation [41,71,83,84], which puts the focus of facilitation on "enabling new meaning to be found through interaction with those who have a different perspective, in a process of shared 'sense-making' around particular issues or challenges" [50 p510]. As we have seen in Vanuatu, where facilitation emphasises the legitimacy of competing knowledge and potential for learning from each other, relational changes emerge that bring together those with different – and sometimes antagonist – backgrounds as they explore shared problems and seek new solutions [41]. As Rodriguez et al. [77] note, participatory design processes may provide benefits to participants that go beyond the technology development intervention, supporting community organising and policy engagement.

Rodriguez et al. [77] stress the need to focus on the impact of technologies in and on the social context of users, including how new technologies can lead to unexpected inequalities. Writing in the context of healthcare technologies, the authors argue that technical specifications are rarely sufficient for technologies to succeed. They critique the failure to explore contextual factors, power dynamics and researchers' positionality and argue that engineers must recognise the importance of contextual and socio-technical considerations to improve equity in outcomes [see also, 85]. Our experiences reinforce this position, and we argue for the necessity of building an understanding of the context in which technology development is intended to solve problems as a first step. This requires diverse methods to surface both differing appreciations of the multi-scale and multi-sectoral setting, and to recognise the nature of relations within communities, and between communities and the actors, organisations and institutions that they come into contact with. In Vanuatu, participatory mapping of these relationships revealed not only key stakeholders and their relative powers, but also the complex technical and social interconnections that define existing water infrastructure, and how perception, access and use is connected to social position and institutions. While systems approaches emphasise how innovation emerges from within multi-scale networks [60], here we also draw attention to how engaging with contextual understanding provides the foundations for subsequent co-design: informing facilitation and capacity support needs; grounding understanding of the social, environmental and technical context; and building relationships.

Finally, we emphasise that only after these foundational activities – which themselves help develop appreciation of how technology hardware and the local social and institutional context intertwine – can attention turn to socio-technical design. Analysis of a familiar technology (mobile phones) confirmed that the introduction of technologies produces “an intricate and complex reconfiguration of various social and technical components” [15, pp170–171], opening space for iterative socio-technical design. Locating this process in the different groups within the community revealed (through their alternative designs) how water monitoring technology differentially shapes knowledge and practice [25,28] and, crucially, how equitable outcomes can be supported through a specific socio-technical configuration in a particular context [30].

5. Conclusion

Niels Röling was not optimistic about the prospects for scientists to “make a first step from technology-supply-push”, suggesting that expertise in how science generates impact is weak within the profession [1], p92. While recognising and building on the considerable efforts that have been made towards rethinking technology change, as a group of scientists, engineers and social scientists we suggest that more emphasis is needed on the processes, tools and methods that scientists and engineers can work through if a sustainable shift in the contribution of science to societal problems is to be achieved.

Here, we propose a framework for understanding the challenge of equitable technology development, drawing attention to the depth of connection between technology and society; highlighting the different forms of knowledge that can or should be involved in technology development and the associated, uneven distribution of power and control; and the necessity to locate end users in wider networks of actors and institutions that influence opportunities and shape technology outcomes. Through our engagement in Vanuatu, we have illustrated one approach that explicitly responds to this framework, harnessing a diversity of participatory and creative methods through multiple phases of engagement. Analysis of this experience suggests a typology of methodological considerations that, we suggest, may have more general significance for scientists and engineers with ambitions for equitable technology development. First, we draw attention to methods capable of revealing and legitimising knowledge diversity. This involves an ongoing commitment to carefully designed processes of engagement that over time allow different stakeholders to build an appreciation for unfamiliar, overlooked or maligned forms of knowledge. Similarly, and second, specific methods and approaches are required to respond to histories of marginalisation from knowledge making, centring engagement processes on communities to reinforce the value and standing of their knowledge. Overcoming the tendency for community-based practice to defer to identified experts and outsiders requires explicit attention in its own right. Third, methods are required to build an understanding of the context in which technology development is intended to solve problems. This requires diverse methods to surface differing appreciations of the multi-scale and multi-sectoral setting. Fourth, methods are required to enable technology development to progress as an iterative process of material and institutional development that is anchored in the local context. We refer to this as grounded socio-technical analysis and design, recognising that the development of a technical device is entirely insufficient without engagement with the social and institutional circumstances that will condition its operation, management and sustainability. Fifth, and finally, prototyping and socio-technical trials open space for and show commitment to ongoing dialogue between communities and scientists while enabling incremental re-shaping of technical and institutional arrangements to better suit the needs and circumstances of end users.

This redefines technology development as an ethical problem and a deeply transdisciplinary endeavour. As the Vanuatu case example demonstrates, an overarching framework opens space for diverse, overlapping methods. This adds layers of complexity and therefore opportunities for ethical risk. While the framework helps to simplify and communicate the nature of the problem of equitable technology development, it does not foreclose the possibility of misinterpretation, inappropriate method selection, or poor implementation. While the risks of inappropriate technology development are significantly diminished compared to conventional innovation pathways, awareness and reflexivity among research and development teams will be essential to ensuring equitable outcomes.

Ethics and informed consent statement

This study was reviewed and approved by the University of York Department of Environment and Geography Ethics Committee with the reference ‘Sensors for clean water: a participatory approach for technology innovation’, dated 3 December 2018. All participants gave their informed consent for inclusion before they participated in the study.

CRediT authorship contribution statement

Jonathan Ensor: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steven Johnson:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniel Vorbach:** Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **James Moir:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.100451.

Data availability

The data that has been used is confidential.

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