Environmental Science
Water Research & Technology

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/d6ew00347h

Enabling data for decision making on drinking water safety through fit-for-purpose laboratories

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Received 31st March 2026,
Accepted 4th June 2026

DOI: 10.1039/d6ew00347h

rsc.li/es-water

In low resource and remote areas where billions of people lack safe drinking water, managers and users have limited access to regular operational water quality testing that can inform drinking water safety improvements. Increasing availability of methods enable operational monitoring in challenging settings, but approaches need to be embedded in operational activities to sustain implementation and affect change. We demonstrate how fit-for-purpose laboratories (FFPLs) operated to support water service providers can deliver data for operational and strategic water management decision-making (particularly *E. coli* data). Using an iterative action-research learning approach and implementation science framework we chart the development of FFPLs in Bangladesh, Kenya and Nepal over 5+ years, their pathways to sustainability and impact on water safety, demonstrating a shift from water quality testing to water safety improvements and management as capacity and knowledge increases. This is reflected in increased trust and legitimacy, built through reporting, that has helped leverage external funding for sustainability. We distil key considerations to guide the establishment of FFPLs in varied settings.

Water impact

Billions of people lack access to safe drinking water. Our analysis captures 5–10 years of experience implementing fit-for-purpose labs in three different contexts to advance water safety management through operational water quality testing. The learnings provide guidance for expanding water quality testing and water safety management to unserved populations, to close the gap on access to safe drinking water.

1. Introduction

Safe management of drinking water supplies depends on water quality data. Water Safety Planning, the predominant framework for safe drinking water management, relies on data to describe water supply systems, identify hazards, and validate and verify control measures.[1,2] One type of data needed is data for operational decision-making; this is distinct from the use of water quality data at aggregate levels for regulatory compliance, public health surveillance, and target tracking purposes.[2–4] Operational water quality monitoring establishes an information feedback loop that can guide managers to make rapid adjustments in response to threats and to invest in system maintenance and upgrades that improve water safety over the longer-term. Examples from small water supply settings include adjusting chlorine dosing based on chlorine residual monitoring[5,6] or using *Escherichia coli* test results to trigger action to improve the sanitary conditions of water supplies.[7,8] However, for small water supplies in resource limited settings, supporting structures for operational water quality monitoring are typically not in-place.[9–11] The majority of the 4 billion people without access to safe drinking water live in areas of lower population density[4] where smaller water supplies face operational challenges associated with having limited funds to overcome geographic barriers.

There are multiple approaches to generate operational water quality data, which can cover a range of direct measures and risk indicators, from physical observations and user reports to field tests and laboratory tests. Physical observations, for example sanitary inspections,[12] and user reports on organoleptic properties and acceptability are less

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resource-intensive but are subjective with limited reliability. Sanitary inspection surveys do not replace water quality measurement for identifying health hazards; therefore, they are best used as a complementary source of information for both identifying hazards and planning risk management.[13] The quality, reliability and costs of water quality measurements vary widely[14] and testing can be arranged in varied modalities: samples may be analysed onsite at the point of sample collection, in an internal lab affiliated with the water service provider, and/or in an external (third party) lab (Fig. 1). 'Service provider' is used here to reflect those responsible for maintenance and quality of the system, who lead on sampling, managing reporting of data, and will act on results to improve the quality of the water service.

External laboratories, which are often accredited and centralised, are expected to provide high quality of data from standardised methods for the widest range of parameters, based on rigorous quality control procedures and highly trained staff. This data source is most likely to be trusted and accepted by regulatory agencies, but reliable centralised testing can be difficult to access and costly. Field tests such as those that rely on colour change reagents (*e.g.*, for chlorine residual level) and electrochemical probes (*e.g.*, for physicochemical determinants) may be easier to implement but provide limited information. For operational purposes, a key criterion for water quality data is its ability to proactively inform changes in management of the system. Thus, in addition to the costs and benefits of different data types and sources outlined above, the implications for decision-making by water service providers or other water supply operators are crucial.[10,15] These may include how frequently tests can be conducted based on costs and logistics; the time taken to get results and how this compares to decision timelines; whether the results usefully inform decisions and whether they are sufficiently trustworthy to act upon. Often, trade-offs must be weighed; for example, the benefits of sending samples to an external laboratory for analysis by highly trained technicians with high-specification equipment must be weighed against potential loss of accuracy from delayed analysis while samples are subject to variable transport and storage conditions.

In this paper, we demonstrate how laboratories can be established to meet the specific needs and circumstances of different types of water service provider by: supporting robust application of a wider range of onsite and benchtop testing methods; enabling best practice for storage and transport of samples to external laboratories when necessary; and managing data for internal use and reporting to authorities, water users, and other stakeholders.[16] We refer to such laboratories as 'fit-for-purpose' when they enable operational adjustments and adaptation of data collection strategies over time in support of the delivery of sustained improvements in water safety.[17] They are not necessarily focused on accreditation nor on expanding data collection. The fit-for-purpose lab (FFPL) is more than just a physical room – it encompasses an enabling environment for both field-based (onsite testing) and lab-based analysis (internal laboratory) methods; systems to facilitate use of external labs where necessary; and systems to receive, manage, and report data. This paper addresses a key gap in the literature as, while there is literature on water quality testing, there is limited literature on innovation in implementation of operational

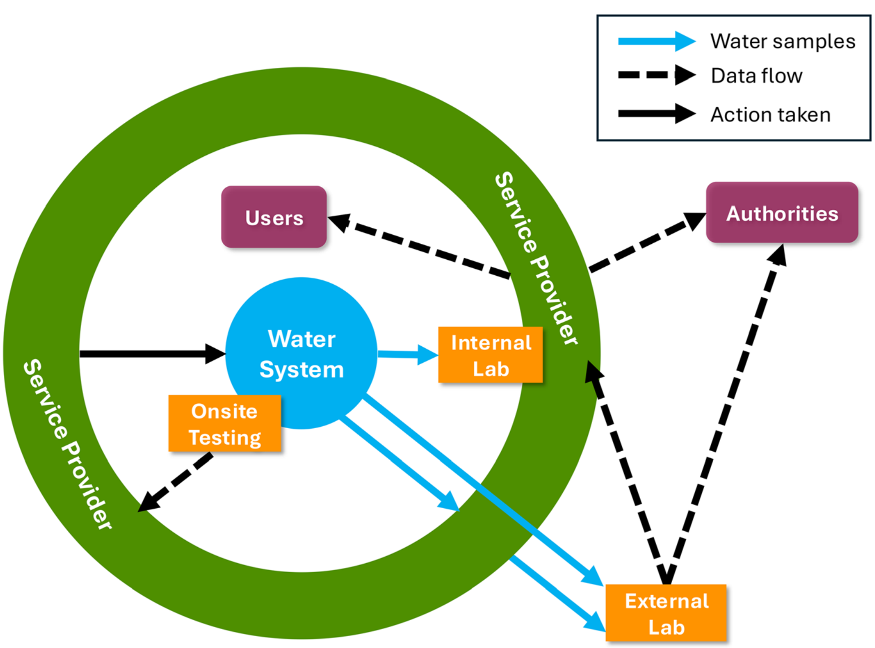

Fig. 1 Sample analysis modalities within a conceptual operational monitoring framework, where the water system (infrastructure, treatment processes and environment) is managed by a service provider (community or professional) responsible for the service quality and reporting results to users and authorities.

testing arrangements. FFPL approaches remain poorly defined and not yet well established, particularly for small and resource-constrained water service providers. There is limited guidance on how FFPLs can be implemented to support operational water management decision-making and sustained improvements in water safety.

This paper draws on three case studies of the establishment of FFPLs in Bangladesh, Kenya and Nepal. Each of the labs was developed to support a water service provider, to influence and inform their work to improve water safety, including both professional and community service provider models. Appropriate external laboratories were not available, particularly for *E. coli* analysis. The chosen case studies have (1) demonstrated improvements in water quality delivered by operators; (2) reported water quality data to communities and local and national authorities; (3) increased the reliability and reach of drinking water safety services; and (4) secured funding that has enabled them to remain sustainable after the research implementation phase. The laboratories have each developed tailored solutions to the contextual challenges presented by location, policy, and capacity. We develop a framework based on the similarities in the decisions that need to be made, particularly the trade-offs that are negotiated, to inform replication and scaling of these laboratories in rural areas.

2. Methodology

We applied a participatory qualitative action research approach to understand organisational learning in fit-for-purpose lab (FFPL) implementation. Grounded in a combination of organisational learning and implementation science theory, the project focused on case studies in Bangladesh, Kenya, and Nepal. We used an adapted learning history method and the implementation science RE-AIM conceptual framework[18] to develop a checklist for assessing the pre-conditions and trade-offs of initiating and sustaining FFPLs in varied rural contexts.

The project obtained ethical approval from the University of Oxford's Central University Research Committee (application number: SOGE1A2021-243) and from the Eawag Directorate (application title: Establishing "Fit for Purpose" Laboratories for Rural Water Supplies: A 3-Country Study). Ethical clearance was also granted by the National Health Research Council in Nepal (proposal ID: 333 2022) and the Daystar University Institutional Scientific Ethical Review Committee in Kenya (application ID: DU-ISERC/03/08/2022/00071). The research additionally was covered by a research license from the Kenyan National Commission for Science and Technology (license number: NACOSTI/P/22/21153 and NACOSTI/P/23/31555).

2.1. Case study background

Here we provide a brief introduction to the case study locations and lead implementation partners. Due to the nature of this work as an implementation science study, the Results and Discussion section includes substantive contextual detail, which is not duplicated here. The research focused on organisational learning from three case studies (Fig. 2): the REACH Water Security programme observatories in southeastern Kenya[19] and coastal Bangladesh;[19] and the REACH partnership funded collaboration with the Integrated Water Resource Management Program (IWRM-P) in mid-western Nepal.[20]

The IWRM-P has been working in the construction of drinking water schemes for rural populations in five districts of western Nepal in the hilly regions of Karnali and Sudurpaschim provinces since 2012. Implementation of the programme is led by Helvetas Nepal, the country branch of the international Swiss non-governmental organization (NGO), Helvetas, which focuses on development cooperation and humanitarian response. The establishment of labs under IWRM-P began in 2017 in the Dullu municipality, Dailekh district, as part of research to explore how community-led water quality monitoring can lead to improvements in drinking water safety.[21] Access challenges due to the hilly geography necessitated a decentralized arrangement with labs strategically placed close to water supply systems. The labs remain part of a supported community-based management model, with the role of service provider filled by decentralised water user associations. For the purposes of this paper, Helvetas were considered as part of the 'service provider' team due to their supporting role in the setup and ongoing management. By 2023 there were eight labs established across five districts served by IWRM-P.

In Kenya, a lab was initiated in 2018 in Kyuso Town, Kitui County, for research that queried how water safety activities could be incorporated into rural water maintenance service provision.[22] The nearest laboratory at that time was in Nairobi, at a distance of over 230 kms from Kyuso, with longer travel distances from sampling sites; the time and cost of this travel were prohibitive, which also required an additional journey to pick up the results by paper. This research was conducted in collaboration with the FundiFix Water Services Trust, a Kenyan-owned and registered social enterprise established in 2016 to offer maintenance services for rural water supply in parts of Kitui and Kwale counties in Kenya. The lab had fully transitioned to serve FundiFix's operational objectives by the end of 2019.

In Bangladesh, the lab was established in 2021 as part of the initial implementation of the SafePani model for safe drinking water service delivery in rural schools and healthcare facilities.[23] The lab was set up in Khulna City, Khulna District, to serve surrounding rural areas (travel times of up to 4 hours). Existing local laboratories in Khulna were focused on chemical parameters, and/or could not provide results for *E. coli* within two days, with results required to be collected in person. The lab was co-developed with HYSAWA, a non-governmental organization that focuses on mobilizing resources and capacity development for local governments and communities to improve management of decentralized water, sanitation and hygiene (WASH) services in Bangladesh. HYSAWA are the

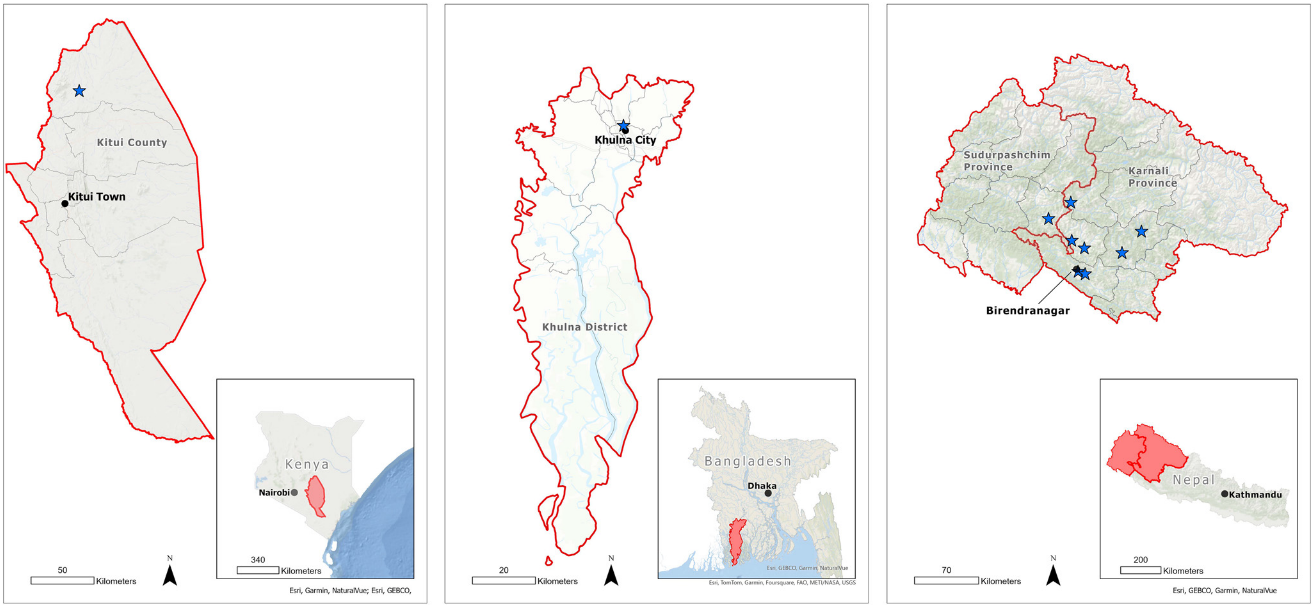

Fig. 2 Maps of case study locations, with established laboratories represented by blue stars, in Kenya (left), Bangladesh (middle) and Nepal (right). Insets illustrate remoteness from national capital cities.

lead implementing partner of the SafePani programme in Khulna.

2.2. Open system learning history

The learning history is a participatory action research method for organizational learning to support socioenvironmental change initiatives.[24,25] The method guides practical application of organizational learning concepts,[26] emphasizing the value of collective reflection, self-evaluation, and transdisciplinary interaction for planning interventions – including implementing novel systems of water supply service provision.[27]

We followed the open system learning history practice, an adaptation of the learning history method for settings with evolving or unclear organizational boundaries where the field of inquiry is structured by networked relationships between multiple organizations and individuals.[24] This approach conceptualizes the written format of a learning history as plural, provisional, and flexible.[24] In addition to internal case study reports and field reports, we produced a lab assessment tool,[28] lab operational manual,[29] and now this paper – which collectively serve the purpose of documenting and guiding FFPL improvement pathways. We worked through four stages: 1) establishing a team and engaging stakeholders to co-design data collection tools around notable results; 2) conducting insider/outsider reflective interviews and surveys; 3) data distillation and thematic writing, and 4) validation with participants and invited others. The last two stages were done iteratively, with reflections continuing over time capturing adaptations and expansions of the laboratories. Our use of the learning history approach means that we, the authors, have dual roles as both researchers and participants of the study – documenting our own reflective process while working to initiate and sustain FFPL implementation.

There are two 'teams' relevant to this study: the authorship team involved in formal analysis and the wider partnerships involved in implementing the laboratories. The authorship team is comprised of a) staff from the three case study FFPLs and associated service providers and supporters who have had leadership roles in implementing water safety activities, b) senior researchers who have worked with the service providers for more than a decade, and c) researchers who joined the team when this study began in 2021. The wider partnerships involved in implementing the laboratories are structured differently in each case study and further elaborated in the results section.

Formally, the authorship team began compiling information for the learning history in November 2021. Data collection is characterized in three phases: Phase 1 includes data prior to 2021 which were obtained from meeting notes and internal documents. Phase 2 (2021/22) was structured fieldwork in the three countries with insider/outsider reflective interviews with service providers, stakeholders and users, and surveys with users. Phase 3 includes ongoing reflective analysis incorporating additional data collection to track changes in sustainability and scale up phases.

2.2.1. Data collection. Briefly, the structured fieldwork in Phase 2 was carried out at lab locations in the three countries. Based on data from Phase 1 and experience conducting surveys and interviews in the case study locations[7,21,30] data collection instruments were developed: key informant interviews and a survey of water users. Semi-structured interviews were undertaken with key informants in each of the countries, including local laboratory staff, program managers, and water supply operators. Interviews were conducted by researchers independent from the service provider staff and senior researchers who were previously known to respondents. The informants were purposively sampled from the respective country water sector actors and stakeholders closely working with the laboratories. The service provider members of this paper's authorship team were among those interviewed. The interviews documented the monitoring strategies adopted, enablers and barriers to local laboratory functionality, logistical arrangements, and project origins. We interviewed a total of 57 actors in the three countries (with 27 participants in Bangladesh, 16 in Kenya and 14 in Nepal). Interviews were conducted in English, and after obtaining informed consent, each interview took approximately one hour. Multiple rounds of qualitative coding were applied to the transcripts, the inception fieldwork reports and other documentation compiled for each case study from Phase 1, facilitated by NVivo (version 14, Lumivero).

Surveys of water users were developed to capture their experience as each service provider was reporting water safety data and engaging them in water safety actions. The surveys of water users (n = 52 in Kenya, 50 in Nepal, and 75 in Bangladesh, for a total of 177 surveys) were conducted using Kobo Toolbox by researchers and service provider staff. The surveys probed household water management activities; perceptions about water quality; and involvement in water quality management. Respondents were randomly sampled from communities being served by service providers using FFPLs. Communities were purposively selected to maximize variation in users' degree of involvement in monitoring activities. All respondents were more than 18 years of age and belonged to different households.

Interviewees and survey participants were informed about the project background, the focus of the research, pseudo-anonymity and voluntary participation. Participants were given contact details in case of follow-up inquiries or complaints.

2.2.2. Analysis and validation. The final two stages of the learning history entailed iteration between data analysis, summative and thematic writing, and validation amongst the authorship team and with key informants. Internal summaries of analysis from data collection were developed and circulated, followed by discussion and refinement. Initial outputs from the analysis were circulated amongst the authorship team for multiple rounds of review and improvement. They contain a distillation of much of the practical learning from the case studies.

We used the five domains of the RE-AIM framework (Reach, Effectiveness, Adoption, Implementation, and Maintenance) to guide our reflective process to consider the enablers and barriers of effective FFPLs throughout the implementation cycle (Fig. 3) across the three contrasting case studies. The RE-AIM framework was developed to increase the generalizability of findings from implementation science research.[18] It has been widely employed to guide planning, evaluation and reporting of interventions within public and environmental health contexts,[31] including water supply service interventions.[32] The five domains provided the basis for focused inquiry by informing how we structured our first round of qualitative coding and organized the results and discussion in this paper.[29] Brief descriptions of each domain are provided in the corresponding results and discussion sections for ease of reference.

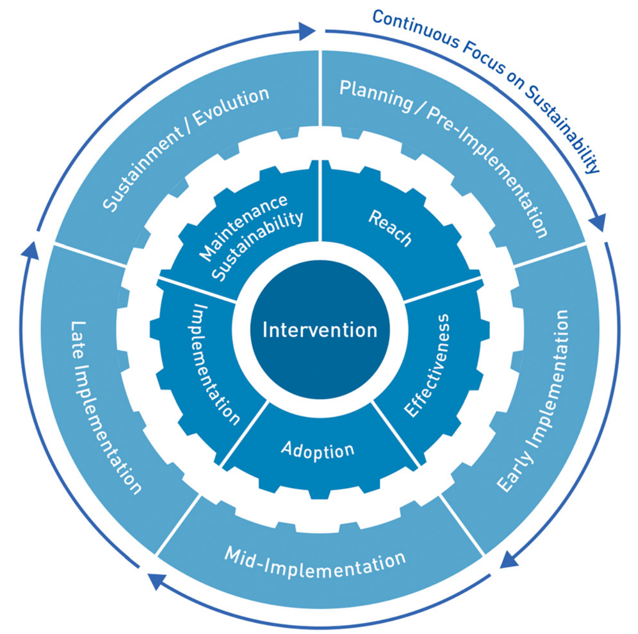

Fig. 3 Visual summary of the RE-AIM framework (adapted from ref. 33).

3. Results and discussion

The results and discussion are structured according to the domains of the RE-AIM framework. Firstly, we explain the intervention design and context upfront in the Implementation approaches. The following sections on Reach, Effectiveness, Adoption, and Maintenance explore in more detail how the programmes evolved and have scaled up, with key findings summarised in section 3.6.

3.1. Implementation

The Implementation domain focuses on the extent to which a programme is delivered as initially planned. Table 1 summarises the three cases (also see Table S1 in SI for a more detailed analysis of early implementation). Here we discuss the pre-implementation design, early implementation, and evolving approaches across the case studies.

3.1.1. Pre-implementation design. Each programme had different starting conditions: in Kenya and Nepal, labs were initiated through research projects, building upon previous research partnerships between the University of Oxford and FundiFix in Kenya and between the Swiss Federal Institute of

Table 1 Summary of early implementation approach (* physical assessment, # examples include an operator's office and a local health clinic)

	Bangladesh case	Kenya case	Nepal case
Location	Service provider field office	Service provider field office	Various#
Water system management	Professional service provider	Professional service provider	Supported community-based management
Lab management	Professional service provider	Professional service provider	Local government
Field tests	Temperature, pH, electrical conductivity, odour*, colour*	Temperature, pH, electrical conductivity, odour*, colour*	Temperature, pH, turbidity*, odour*, colour*
Internal laboratory tests	*E. coli* (IDEXX Quantitray), total coliforms	*E. coli* (IDEXX Quantitray), total coliforms, fluoride (ion selective electrode)	*E. coli* (membrane filtration with compact dry plates), total coliforms
External laboratory analyses	As, Mn, Cl, Fe	Major ions and trace elements	As, F

Aquatic Science and Technology (Eawag) and Helvetas in Nepal. In Bangladesh, the SafePani programme began as an implementation-focused partnership between Oxford researchers, the government, and UNICEF; the service provider, HYSAWA, was recruited after the initial design phase.[23] Implementation was supported by funding from the Foreign, Commonwealth and Development Office (FCDO), UK, *via* the REACH programme. All laboratories remain operational at the time of writing, covering a period of 5 to 9 years. Due to the differing origins of the three programmes, the planned use of water quality test results varied substantially in the beginning. The first labs were initiated in Nepal in 2017. Researchers worked with Helvetas and community members to set up water quality testing capabilities to verify an existing WASH strategy. At the time, water treatment was not included in the strategy and there was no structured plan for test results to inform water supply operation and maintenance (O&M). In Kenya, a lab was initiated at the end of 2018 to enable a baseline assessment of water quality risks across different infrastructure types in FundiFix's service area. Again, there was no structured plan at the outset for feeding data into O&M decision-making. Instead, alongside the baseline assessment, research explored how water quality monitoring could be incorporated into FundiFix's services without compromising their core mission: maintaining supply functionality. FundiFix were cautious about embedding water safety activities into their operations, recognizing that water quality monitoring and reporting would introduce new costs and new complexity into relationships with communities, schools, and the government. This concern is shared by water service providers in a range of rural settings.[34] In Bangladesh, learning from the work in Nepal and Kenya, a lab was initiated in 2021 as part of establishing a new service provision arrangement. HYSAWA were recruited with a mandate that foregrounded water safety. A plan for using water quality test results to guide O&M activities was established at the outset.

E. coli as an indicator of health risk from microbiological contamination was the priority determinand in all three case studies as the most precise indicator of recent faecal contamination.[15] The methods to test for *E. coli* were chosen based on trade-offs in availability and costs of consumables, sample processing times, technical skill requirements, power requirements, and safe disposal requirements. For example, the IDEXX Quantitray system used in Bangladesh and Kenya benefits from high credibility (according with ISO 11133:2014) with low technical skill requirements and fast processing, but has high cost and safe disposal requirements (because of larger plastic consumable components). In Bangladesh, the lab equipment cost around £8000 in 2022, with initial consumable costs estimated at £4.80 per sample for *E. coli*; office space, electricity, and staff time are not included in these costs. In contrast, the compact dry plates used in Nepal are less costly and easier to dispose of safely, but they require more processing time and technical skill. The lab equipment in Nepal cost less than £1500 for the most recent labs established, of which the majority (~£1000) was for *E. coli* testing equipment such as a filtration unit and incubator, while consumable costs are estimated at £2 per sample for *E. coli*. Both methods require power for incubation; this was achieved in Bangladesh with grid power and in Kenya and Nepal with solar power. Total coliforms were assessed because *E. coli* tests simultaneously produced results so no extra consumable costs were incurred; results only became useful for decision making once chlorination was implemented.

The consistent prioritization of *E. coli* testing across the case studies was largely driven by the ubiquity of microbiological contamination risk and the relative ease with which action can be taken to respond with either temporary or lasting measures to protect and treat supplies. In contrast, there was more variability in chemical determinands (Table 1) because chemical contaminants are a secondary health concern and capacity to act on results is highly constrained in all three settings. Determinands were chosen based on known geogenic health hazards and prior expectations in the service areas. In Bangladesh, external government labs were used because time was not a limiting factor (no immediate action would be triggered by results), government was the primary intended recipient of the results, and costs were built into the Safepani programme budget at the outset. In Kenya, baseline screening assessment of major ions and trace elements was completed using a university research lab, but probes were used for ongoing testing of F, pH, and conductivity to avoid the higher costs associated with sending samples to an external lab. In the hilly areas of Nepal, where geogenic contamination of groundwater was not a known health hazard, only a baseline screening of chemical determinands was undertaken using an external lab as part of a university research project.

3.1.2. Early implementation. Despite the differences in programme origin and design, there were substantial commonalities across the case studies (Table 1). Infrastructure, staffing, and protocol decisions were based on trade-offs in practicalities, regulations and guidelines, local expectations, and local capacities. Labs were situated where building space was accessible, affordable, and located close enough to water supplies to enable transport of microbiological samples for analysis within 6 hours. For each case study, the structure and quality of the implementation plan was determined by staffing and management decisions, from recruitment to training and quality assurance processes. In the first years of each programme, management support from external water safety experts was influential, particularly in establishing protocols and delivering training. Specific recruitment and staffing compositions varied based on initial programme designs, budgets and availability of skilled professionals, with specific roles differentiated accordingly. For example, the Nepal programme had the most decentralized design and, therefore, required more personnel. But due to the limited qualified human resources to conduct water quality testing in rural areas, teachers, health personnel and representatives of community drinking water committees were trained to handle microbial testing. In Kenya, sampling was initially managed by a water safety manager and a dedicated water safety field technician. As the water safety services evolved, the FundiFix maintenance mechanics (the *fundis*) have been trained to collect samples, thereby reducing transport costs and field time for the water quality staff. Similarly, in Bangladesh a wider range of staff have been trained to collect samples over time.

3.1.3. Evolving implementation. Implementation of the labs in all three case studies has evolved through learning by the service providers and through development of relationships with government and water users. Reporting to government and communities was integrated in the design of the interventions. Consideration was given to the potential benefits of reporting, such as use of safer sources or treatment, *versus* potential costs associated with psychosocial distress and destabilizing the politics of water supply projects. In each of the case studies, dialogues have been ongoing to navigate tensions[34] between government, water users, and service providers around the validity of water quality concerns and allocation of responsibility for ensuring management of water quality hazards originating from community activities (*e.g.*, microbial contamination) *versus* geogenic sources (*e.g.*, fluoride and arsenic).[34]

Prioritization of determinands, choice of test methods, and water safety improvement activities have evolved over time in response to these dialogues and wider learning as needs and conditions have shifted. For example, the FundiFix lab in Kenya changed their *E. coli* testing method after three years: replacing the Quantitray system with membrane filtration using M-Coli Blue 24 broth. This was done to reduce costs and waste; take advantage of enhanced technical skills of staff and established recognition by the county and sub-county governments; and because daily sample processing volumes had reduced in 2020 (Fig. 4) when the research phase gave way to focus on service delivery implementation. In Nepal, decreases in tests in 2020 marked a shift from research-driven towards operational monitoring, as well as Covid-19 disruptions. Sampling frequency has decreased over time as the operational teams have been able to make use of patterns and trends in the data to understand variability by system type, determinand, and season. Increasing samples in Bangladesh and Nepal reflect the expanding reach of the programme (Fig. 4), including establishment of more laboratories in Nepal. Beyond method changes, additional chemistry testing capabilities have developed in the labs in Kenya and Nepal to test for free chlorine. This has been a response to the introduction of water treatment services following community sensitization as further explored below.

Since the purpose of the labs is to support improvements in water quality, through evolution in Kenya and Nepal and from the planning phase in Bangladesh, implementation included use of the data to inform actions. In Bangladesh, protocols and initial agreements with government included roles and responsibilities to act on detection of *E. coli*, and to report data. Sanitary hazards and *E. coli* detection have reduced over time.[35] In Kenya, data informed awareness of hazards, which motivated uptake of regular sanitary inspections; maintenance to address sanitary hazards; and trials of treatment options. Implementation of water treatment evolved to become a priority for FundiFix, with monitoring consequently being adapted to provide operational data on chlorine residuals as well as *E. coli*. In Nepal, operational data challenged existing prioritisation of quantity and reliability, with only 31% of samples free from faecal contamination at the point of collection.[36] This led to actions including source protection measures, with further data motivating treatment interventions and integration of chlorine residual testing.[5] With passive chlorination at the point of collection, 93% of samples were free from faecal contamination.[5] In all case studies, the strong results and engagement have helped to leverage more sustainable funding beyond the research programme (see section 3.5).

3.2. Reach

The Reach outcome domain focuses on understanding the intended target population of an intervention and evaluates the extent to which they are served. In other words, it asks

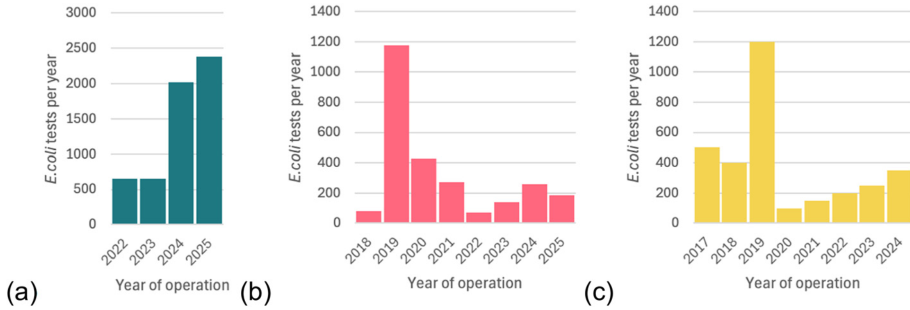

Fig. 4 Estimated annual *E. coli* test processing, including quality control tests (replicates and blanks) for FFPLs in (a) Bangladesh, (b) Kenya and (c) Nepal.

who is intended to benefit and who actually benefits from an intervention. Often, this is moderated by who chooses to participate in intervention activities, use promoted products, or subscribe to intervention services. FFPLs were intended to serve water users who are relying on existing water supply infrastructure that already had varying O&M arrangements in place. As the labs developed and influenced water safety management activities, there are consequences for the reach of the broader O&M programmes. In our three cases, the labs complement existing programmes that aim to improve water services. In all cases, water supply design and installation as well as the criteria for which supplies were included in the broader programmes went beyond water safety considerations. So, the design of the labs themselves was not a major determinant of the population reached. People who exclusively use surface water, dug wells and other self-supply arrangements that are not part of the WASH strategy (in the case of Nepal) or the O&M service delivery (in the cases of Bangladesh and Kenya) do not benefit from lab-supported water safety management activities. In Bangladesh, early implementation included community piped schemes, schools and healthcare facilities, but as the programme evolved, support was focused on schools and healthcare facilities.

Affordability is a moderator of inclusion, *i.e.* water supply usage, for community settings. In Nepal and Kenya, regular tariff contributions for O&M funds were made by water users. In Bangladesh, service was restricted to school and healthcare settings where water users were not paying tariffs. Tariffs are set with affordability as a key objective and none of the programmes have full O&M cost recovery from tariff income, all are supplemented with other financing streams. Nevertheless, people who cannot or choose not to pay tariffs for the serviced water supplies are relying on alternative supplies that are outside of the reach of the labs. There is a strong seasonality to this dynamic, with many water users relying on alternative sources in wetter periods, which has implications for health as well as for financial sustainability for service providers.[37] For example, in our survey in Nepal, 36% of users reported switching to an alternative water source in the wet season, which were primarily unprotected sources. If the inclusion of labs in rural water service provisioning drives an increase in user tariffs, there is a risk that the labs could contribute to widening inequity by reinforcing exclusion of people with the least ability to pay for services. Thus, it is important that the data and management activities supported by labs contribute to stabilizing and strengthening financing of O&M services, as further discussed in section 3.5 on Maintenance.

Implementation of FFPLs will also influence other factors, beyond affordability, that affect whether people choose to use serviced water supplies. Water source choices are complex, people weigh their understanding of and trust in water safety against other considerations such as distance, queuing, security, labour, livestock needs, personal relationships, functionality, *etc.*[7,38] Through our surveys and interviews, and in comparing experiences across the three country cases, we find that the visibility of water quality monitoring and management activities, the way that water testing results are communicated to water users (or not), and the degree of water user involvement in monitoring activities can influence how people value water safety management as part of broader O&M services. For example, in Bangladesh, where water quality testing is done by the service providers, water users are aware that their drinking water is being tested, and the work is visibly supported by government, there is increased user trust in the legitimacy of the testing. In Nepal, there is less visible government support, and instead community representatives are more involved in the sampling, analysis and responses to test results (42% in our survey), which engenders trust in a different way.[39]

In summary, Reach was mediated by the wider strategies and programmes, with affordability constraints offset by other funding. As we explain below, investments were key in expanding reach over time to more sites near laboratories (Bangladesh scaled up to additional unions) and expanding the number of laboratories (Nepal scaled from 3 to 8 laboratories, serving new areas).

3.3. Effectiveness

Effectiveness refers to both the positive and negative outcomes gained from an intervention. It describes the impact of the intervention experienced by participants and the behavioural outcomes realized. In terms of the desired outcome, here we focus on the ability of the FFPLs to inform actions that advance drinking water safety, but also highlight other relevant outcomes.

Increased awareness and accountability. The labs increased the awareness and transparency of water quality issues locally, leading to greater engagement and accountability among water users, service providers, donors, and governments. Reporting enhanced accountability from both the bottom up and the top down. For example, water users received water quality reports and attended meetings with the service provider to discuss follow up actions to improve the situation, both increasing the awareness of the community of their responsibilities and enabling them to hold the service provider or government accountable. Service providers have taken action to improve water in response to the results. In Nepal, the labs provided information on the effectiveness of household water treatment devices (*e.g.*, ceramic filters) that were being promoted through their WASH programming. This allowed the service provider to respond to specific situations in a timely manner, such as inconsistent or incorrect use, product malfunction, and material replacement. In Kenya, increased awareness of water quality issues led to implementation of chlorination. In Bangladesh, the service provider became aware of water quality issues in rainwater harvesting systems and has started investigating treatment options.

In addressing these issues, the labs have also had a role in managing the effectiveness of new treatment. For example, water quality testing of household stored water identified a need for residual disinfection to reduce recontamination, leading to the implementation of inline chlorination interventions in Nepal and Kenya. While the majority of households accepted chlorinated drinking water, some complained about the taste or smell.[5] In these instances, regular monitoring helped identify cases of over-dosing and enabled operators to adjust dosing to the desired range for both efficacy and consumer acceptance.[40]

Results were reported to government, but accountability of the service providers or laboratory to government was initially limited by weak regulatory environments for rural water supplies. Over time, the reporting of data and the development of expertise in the service providers have supported government advances in rural water, including collaborations with regulators[41] and in development of Nepal's NWASH reporting database. In Bangladesh, financial support from the government *via* Safepani's results-based funding[23] has created accountability directly to government.

Greater demand for safe water. The demand for safe water has been observed by the team to have increased as a result of the interactions described above, which in turn translated to a greater willingness to invest in water safety measures. This effect was apparent across multiple levels, from water users to service provider to government agencies. As it has coincided with a broader trend of appreciation for drinking water quality in the sector it is not possible to attribute the role of the labs, however there are indicative changes. These changes may reflect interest in viable solutions, rather than safe water *per se*. In Nepal, following the implementation of FFPLs, the service provider intensified its WASH promotional strategy and households had near universal adoption of household filters over the course of an 8-month monitoring period.[21] In Bangladesh, SafePani started as a pilot in 4 unions and was rapidly upscaled to 8 unions, with support from the government steering committee.[23] This was further expanded to district scale, with financial support from the government. The lab has supported this success, informing rapid service provider actions to deliver safe water, however, it should be noted that the demand for safe water is intrinsically linked with the maintenance work improving reliability of water services. Community demand for safe water has been expressed, with cases of requests to expand the reach of the services to new areas or requests to government for improvements based on results. However, community priorities continue to focus on service accessibility (fees, hours of operation, *etc.*) rather than the safety of drinking water.

For water service providers, operational monitoring has led to a greater awareness of seasonal changes in water quality that coincided with the shifts in quantity. In Nepal, a better understanding of these inter-linkages motivated the integration of water safety planning measures within their existing integrated water supply management approach. In Bangladesh, the seasonal impact on water quality in rainwater harvesting systems and the challenges of water quantity in the dry seasons have influenced the service providers work programme, cleaning and preparing rainwater catchments before the onset of the monsoon rains, and working with communities to identify how to better manage use of safe drinking water to ensure sources remain available through the dry season.

Career opportunities. The labs provide job opportunities, including in rural areas. The results of the interviews highlighted that lab staff were generally satisfied with their remuneration and terms of employment. Staff in rural areas and smaller urban centres are disconnected from educational opportunities, restricting their training and development potential. While they had opportunities for new training during the establishment of the labs and after purchase of new laboratory equipment, there were no other additional trainings being offered in the early years. Lab staff emphasized the importance of regular training to build confidence in new aspects and technologies in monitoring. Over time, those who were involved in establishing the labs have had opportunities to attend conferences and present their own work.

In summary, the effectiveness of FFPLs has seen positive outcomes in increased accountability and awareness and improvements in safety of drinking water, further creating demand for safe drinking water while building capacity in rural areas for water safety.

3.4. Adoption

The Adoption domain focuses on the uptake of an intervention by end-users or institutions in target settings. In this domain, evaluations seek to understand what drives initial decisions to trial and adopt interventions and how adoption then spreads, scaling out and up with expanded geographical and institutional range. Initial implementation of the labs in Nepal and Kenya focused on understanding and demonstrating water quality risks. When these activities began, water quality was not yet a priority for the water service providers and water treatment was not being implemented. Long-standing water sector programming norms in both countries were underpinned by assumptions about water safety hazards being introduced primarily at household level and by concerns about water quality monitoring destabilizing efforts to improve the quantity of supply from improved infrastructure.[34] In both cases, demonstration of water quality hazards motivated the service providers to explore water safety interventions. Water safety management has since become a substantial component of their operations through regular inspection and maintenance of sanitary conditions and roll-out of water treatment.

In contrast to Nepal and Kenya, improving water quality has been a high-profile priority in Bangladesh for longer due to abundance of water and the visibility of cholera epidemics and arsenic contamination.[42] This context, and learnings from the Nepal and Kenya cases, supported the SafePani programme design to prioritise water safety as part of O&M activities from the outset. Thus, the FFPL concept was adopted in an already-advanced stage. Following the SafePani pilot phase, which demonstrated the utility of the lab, investment from the Government of Bangladesh enabled the programme to scale to district level in 2024 to serve approximately 1100 schools and healthcare facilities[23] with further expansions planned in 2026.

Wider adoption of the FFPL approach is also ongoing in Nepal and Kenya, with less direct input from government and more uptake by sector partner organisations. In Nepal, the approach expanded from three, to five, to eventually eight labs across Karnali and Sudurpaschim provinces serving over 100 000 people in the Helvetas–Nepal programme area as of the end of 2023. The FFPL approach is being promoted internationally throughout Helvetas' operations and it has been adopted in western Nepal through the SuSwa programme, which is implementing monitoring to support O&M of in-line passive chlorination treatment.[5] In Kenya, FundiFix's experience has led them to develop internal capacity for in-line chlorination, including producing passive in-line chlorination devices inhouse, and has fed into training initiatives to expand professionalised water service delivery and results-based funding mechanisms in partnership with USAID, the World Bank, Uptime Global and others.[8] In summary, adoption is associated both with learning about the water safety challenge, and seeing the potential for solutions, both within the service providers and in external funders.

3.5. Maintenance

Maintenance assesses the level and length of time that the results of the intervention last and how long they will be sustained. As discussed, the FFPL approach has scaled up in all three case studies. In this section, we expand on the aspects of design, implementation, and context that have facilitated sustainability, considering both the motivators and challenges.

3.5.1. Reporting. Across all the programmes, transparency in results through regular reporting to government and users has generated reinforcing feedback mechanisms, creating legitimacy and ensuring accountability for testing and for actions. In Bangladesh and Kenya, support from Uptime Global has ensured validation and verification[43] of water safety data and laboratories that has further helped to create legitimacy. Although the labs were initiated by research projects, the co-production inherent in development of internal laboratories ensured service providers had ownership of the data and were engaged in the results. This led to expansion of water safety activities in Kenya and Nepal. In Bangladesh, the data has enabled co-creation of awareness of limitations of water supply technologies facilitating new design of new management approaches. The selection of parameters is important to inform positive feedback mechanisms as reporting of some parameters remains political,[34] and there is potential for generating distress where water quality hazards are reported with no action taken.[7,44]

3.5.2. Sustaining funding. The labs were established using external funding, *via* the REACH programme. This funding was used to establish and demonstrate the model, but each have demonstrated sustainability and scale beyond this funding. The cost of the labs and water safety components in each site were tracked, with significant fluctuations in costs noted in field reports. Alignment to service provider activities in Kenya and Bangladesh and the involvement of community members in Nepal have kept costs low. In Bangladesh, a water safety programme was projected to cost around a third of set-up costs and 20% of recurring costs for the service delivery, or around USD 0.20 per student in schools per year.[45] These programmes have seen investment from national government (Bangladesh, Nepal) and charities and donors (Bangladesh, Kenya, Nepal). This has included increased ability of service providers, and supporting organisations such as Uptime, to leverage investment from donors with demonstration of improvements to water safety. These FFPLs are intrinsically linked to the outcomes and benefits in reliability as part of the O&M programmes, which has undoubtedly supported the sustained investment. It is important to note that reliance on water users to pay increased fees for safer water has not been demonstrated to be viable in the rural communities the labs are serving; therefore subsidies are required.[38,46]

3.5.3. Organisational learning culture. Core to the sustainability of FFPLs has been the willingness across all levels to respond to the data, and to partner with researchers in learning about water safety. In Kenya and Nepal, the labs were developed with partners who initially did not consider water quality a priority or a viable part of their business. In Nepal, water quality issues were initially attributed to household behaviour, as is common where responsibility for water safety is left to communities.[34] The service providers have demonstrated a learning culture, establishing continuous improvement approaches in line with water safety planning approaches. Data is used to inform both immediate operational decisions and strategic planning. This has been facilitated through the focus on generating operational data *via* inhouse laboratories, rather than regulatory data, as it created an environment for learning and reduced pressure to produce 'good' results that can disincentivise learning. As part of changes towards sustainability, implementers have been able to reduce the frequency of sampling and range of parameters as they develop a deeper understanding of their system behaviour, as is expected in WSP approaches. This has enabled testing to reduce over time in all sites, with refinements to focus on data for decision-making, with implications for costs. Teams have also innovated to cut costs, building bespoke items from local materials, such as incubators in Nepal,[47] and chlorinators in Kenya.

3.5.4. Leadership and career development. FFPLs created job opportunities, but through the learning culture also provided a range of experiences and career development opportunities across staff at different levels, as has been discussed above. These helped to ensure sustainability in staffing and to build capacity. FundiFix initiated an internship programme to further build capacity for their work and the sector. With scale up, there are further decisions to be made on when to create additional laboratories and how to develop and maintain sufficient capacity across a decentralised team. Access to peer networks of research and implementation water safety professionals can support ongoing learning and development, such as the team have experienced and developed through Uptime partners, communities of practice, and donor programmes on results-based funding. Furthermore, innovation around the implementation of FFPLs, and the water safety interventions they have generated, have created opportunities for the teams to step into leadership roles in the sector, further incentivising individual commitment to ensuring the sustainability of implementation. For example, Y. S. Crider's work on in-line chlorination at the Nepal site[5] has led to a professorship, and B. M. Kunwar's work has him advising on implementation more broadly.[17,48] Co-production of the work and outputs has supported NGO partners in their promotional and fundraising visibility and in individual career development. These leadership opportunities are closely linked to the innovations developed, suggesting potential gains may reduce longer term. While there remain many opportunities to innovate to advance water safety, these may not always align to support sustainability of FFPLs.

3.5.5. Outside factors. There are numerous other factors that will affect ongoing sustainability. Two key areas are around availability of materials and regulatory environments. Experiences of disruptions to consumables access due to international supply chains and rapidly fluctuating exchange rates have created challenges, leading to delays in testing and changes in methods. To date, the results produced have been accepted by government in all three contexts, however water quality regulation has been limited in rural areas. Regulations that require use of accredited laboratories are unlikely to be viable in many rural contexts, and may reduce investment in FFPLs and operational data collection. Funding remains a key challenge within the water sector in the current context of large-scale cuts in international aid, which also affects the organisations involved in the FPPLs. To date, the labs remain valued by their organisations and the funders.

Across these projects, co-production between implementers and researchers has been critical to many of these factors that have supported the success and sustainability. A key challenge in the sustainability outlook will be the transition from co-production to the standard operational delivery of labs by implementers without research engagement. The role of researchers has evolved over the programmes as capacity has developed with the teams, with initiatives to develop peer water safety networks representing a shift to supporting wider networks and further developing leadership roles for implementers.

In summary, maintenance has been achieved through a combination of internal and external factors that have addressed many of the challenges of rural water supply: funding and staff retention, as well as building an evidence base for learning.

3.6. Learning to deliver impact on water safety

Our summary overview of the implementation journey (Fig. 5) draws together the interlinked threads across the analysis of the three case studies. A notable outcome is the transition from water quality assessment to water safety management, including implementation of treatment systems and new measures to reduce contamination. This shift has helped to leverage external investment. It has been possible because of the capacity built within country, in the service providers running the laboratories, the teams supporting them, and the government partners.

The opportunity to analyse and reflect on this implementation over years, in different countries and management contexts provides a unique perspective. As highlighted above, the learnings from Kenya and Nepal have helped to accelerate progress in Bangladesh, increasing the

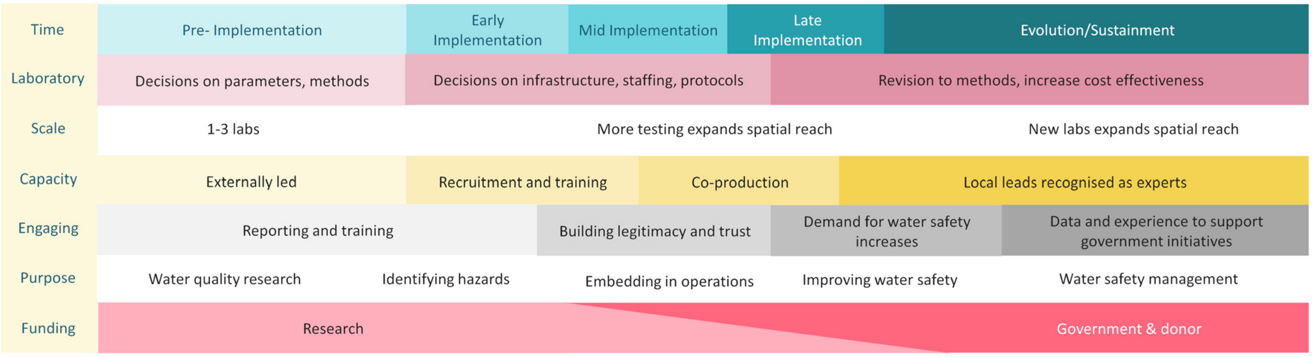

Fig. 5 Implementation pathways for FFPLs: from design to scale, and from research to water safety management.

reach and funding for the programme. The learning histories methodology has enabled this analysis of the process of implementation to be captured, documenting our own work to initiate and sustain FFPL implementation. While this has the potential for bias, we have tried to focus the results, particularly the outcomes in Fig. 5, on those that are verifiable.

4. Guidance for establishing FFPLs

Across the case studies, they have achieved expansion and sustainability based on the value to improved drinking water safety demonstrated. They have developed local capacity for drinking water safety – in the lab staff but also more broadly in the organisations and in the communities and

Table 2 Key considerations for implementing a fit-for-purpose lab

What actions will water quality testing inform?	Actions may include: adjusting treatment or performing maintenance, advising users of risks and response options, reporting results to government or community leadership to support their planning, and making strategic investments for water safety
What determinands are useful to test?	What determinands are practical to test and appropriate to understand changes and inform actions? Including: • What organoleptic measures can be used? • What feasible determinands best represent health risk? • What other determinands help contextualise results or actions? *e.g.*, iron which has implications for water quality perception/acceptability and for chlorination effectiveness; or pH which supports understanding the source of contaminants, risks of infrastructure degradation, and has implications for testing protocols How will testing support achieving effective regulatory requirements for testing and reporting? What are the potential risks to the reputation or operation of the water service?
When to test?	Is regular testing useful to inform operations, given the time period over which you expect to see variability in this parameter, *e.g.*, seasonal, random, related to failure of infrastructure integrity? Will this vary for different system types? How quickly can actions be done in response to an issue being identified?
Where to test?	Where in the water supply should samples be collected to inform particular actions? Should testing focus on water as collected by the user (*i.e.* the water as delivered, which provides an overall view of safety), or water leaving a bulk storage tank or treatment stage (to understand changes in water quality within the distribution system), or water close to the source (to understand source risk and protection interventions) Will this vary for different system types or under different conditions
How to test?	Will the available field or laboratory tests provide more useful information? Consider the type of data and time to access it, given travel times for samples and reliability of methods Are external laboratories available to do the tests and provide data that is timely, reliable, and cost effective? Are consumable supplies reliably available and cost-effective for sampling, field and laboratory needs to execute chosen methods? What additional services are needed to execute methods, *e.g.*, running water, alcohol for disinfecting, electricity? How can quality assurance and control steps be incorporated to ensure data are sufficiently reliable to act upon? Are there adequately skilled people available to implement chosen methods appropriately? What initial and on-going training is needed to maintain quality of test results?
How to inform actions?	How will data be processed to inform those who are taking water safety actions? How will results be reported to users and government in a timely manner? How can data be combined and presented to help contextualise results and actions? What tools and techniques can support this? How will data be analysed to understand trends, including to inform revision of sampling plans? Who will be involved to review these analyses? How will learning be encouraged? How can the team engage in peer networks to support ongoing learning?

governments to which they report. And they have developed and adapted to local conditions to ensure legitimacy of their services and data, including in different modalities as professional service providers and as supported community-based management.

Drawing from these experiences, we have developed a guide (Table 2) that synthesises the decisions that will guide the implementation of FFPLs to inform water safety actions. These labs should be designed to allow learning and development; thus, they may inform about what actions are needed (*e.g.*, Nepal and Kenya), trigger pre-agreed actions (*e.g.*, Bangladesh), and instigate creative or innovative actions (all three cases). The emphasis in this guide is to ensure decisions are focused on how to provide actionable information. Value for money should be considered for all data collection. For example, where actions are costly there is a need for reliable data to ensure actions are necessary and proportionate. Where actions are cheap and easy, there may be 'no regrets' options that are appropriate requiring no or limited data.

5. Conclusion

Billions of people lack access to safe drinking water, many of whom live in rural areas where advancing access to safe drinking water is hindered by low-resourcing, long distances, and difficulty accessing laboratories. Through case studies from three countries, this study has demonstrated that operational water quality testing in fit-for-purpose laboratories (FFPLs) can provide a foundation for sustainable water quality improvements. Despite differences in the origins and set-ups of the case study FFPLs, they have (1) achieved expansion and sustainability based on the value to improved drinking water safety, demonstrated through the shift from water testing to water safety management; (2) developed local capacity for drinking water safety – in the lab staff but also more broadly among service providers and in the communities and governments to which they report; and (3) developed and adapted to local conditions to ensure legitimacy of their services and data. The learning history discussed in this paper has drawn out key considerations that are common across the cases – from planning, early implementation, iterative learning, scale up, and sustained implementation. These considerations start from a focus on how water quality testing will inform actions, and from there progress to determine what, when, where and how to test, and how to implement systems to support data use. Furthermore, the case studies demonstrate how a learning history approach offers opportunities to co-produce evidence on implementation that supports scaling and adoption of impactful interventions.

Author contributions

Saskia Nowicki: conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing – original draft, writing – review & editing. Jackline Muturi: data curation, formal analysis, investigation, project administration, writing – original draft, writing – review & editing. Marisa Boller: project administration, writing – review & editing. Sital Uprety: investigation, writing – review & editing. Bal Mukunda Kunwar: investigation, resources, validation, writing – review & editing. Cliff Nyaga: investigation, resources, validation, writing – review & editing. Mary Sammy: investigation, validation, writing – review & editing. Md. Feroz Rahaman: investigation, writing – review & editing. Nurul Osman: resources, validation, writing – review & editing. Sara J. Marks: conceptualization, data curation, formal analysis, funding acquisition, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, writing – review & editing. Katrina Charles: conceptualization, funding acquisition, methodology, supervision, validation, writing – original draft, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data for this article that has been collected from human participants are not available for confidentiality reasons.

Supplementary information (SI): including photos of the labs and rural context, and further details of lab set up is available. See DOI: https://doi.org/10.1039/d6ew00347h.

Acknowledgements

This research was supported by the REACH programme funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) (Aries Code 201880). The views and information expressed in this document are not necessarily those of or endorsed by the funder; FCDO can accept no responsibility for them nor for any reliance placed on them. Maps and graphics were provided by Rosi Siber and Michael Vock.

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