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The how tough is WASH framework for assessing the climate resilience of water and sanitation

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Climate change presents a major threat to water and sanitation services. There is an urgent need to understand and improve resilience, particularly in rural communities and small towns in low- and middle-income countries that already struggle to provide universal access to services and face increasing threats from climate change. To date, there is a lack of a simple framework to assess the resilience of water and sanitation services which hinders the development of strategies to improve services. An interdisciplinary team of engineers and environmental and social scientists were brought together to investigate the development of a resilience measurement framework for use in low- and middle-income countries. Six domains of interest were identified based on a literature review, expert opinion, and limited field assessments in two countries. A scoring system using a Likert scale is proposed to assess the resilience of services and allow analysis at local and national levels to support improvements in individual supplies, identifying systematic faults, and support prioritisation for action. This is a simple, multi-dimensional framework for assessing the resilience of rural and small-town water and sanitation services in LMICs. The framework is being further tested in Nepal and Ethiopia and future results will be reported on its application.

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INTRODUCTION

Climate change is the defining challenge for the 21st century. The increase in global temperatures, changing patterns of precipitation, and more frequent extreme events caused by a changing climate will directly impact water and sanitation services, affecting all aspects of service delivery and undermining the achievement of Sustainable Development Goal 6[1,2]. As climate changes are increasingly felt, there is growing interest in how the resilience of systems and communities can be built to cope with climate threats[3]. The Inter-Governmental Panel on Climate Change defines resilience as "*the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning, and transformation*"[3].

Despite the critical importance of water and sanitation services in protecting public health[4], the resilience of these services in rural communities and small towns in low- and middle-income countries (LMICs) has only been considered recently[1]. The Vision 2030 study provided the first global assessment of vulnerability and resilience of water and sanitation technologies and management systems[5]. Following this, there have been global assessments of the likely resilience of commonly used sanitation systems[6] and the tools from Vision 2030 have been applied in studies of adaptation strategies for water and sanitation in African cities[7] and the resilience of sanitation in small island states[8]. The potential for Water Safety Plans (WSP) as tools to manage future climate risks to water supply has been identified[9], leading to revised guidance[10] and some evidence of integration of climate into WSPs in a number of settings, although relatively few from LMICs[11]. None of the work cited above, however, presented a framework to assess resilience that could be applied more widely.

The increasing attention on resilience in water and sanitation services raises important questions regarding how resilience should be measured and assessed[12]. GWP & UNICEF[13] developed a toolkit for climate-resilient water and sanitation, including recommendations for monitoring and evaluation. They provide a long list of potential indicators to consider across multiple domains, but do not offer a simple tool that could be readily deployed in LMICs. Frameworks have also been developed for large systems in England and Wales[14] and small systems in New Zealand[15]. However, neither of these two approaches can be immediately deployed for water and sanitation services in rural areas and small towns in LMICs, which operate in far more resource-constrained conditions and where simpler technologies, often managed by volunteers with little or no technical skills, are common.

Monitoring frameworks that can support action to prioritise communities, regions, technologies, or management systems are of particular importance in resource-poor environments. A parallel can be drawn with surveillance of the safety of water supplies. Studies in rural and urban areas of LMICs have demonstrated that simple robust measures of water supply performance can be developed that are effective in supporting decision-making at local and national level[16–19].

Given the lack of available simple tools to assess resilience, an interdisciplinary team of engineers, environmental and social scientists was brought together to investigate how to improve the measurement of resilience. This paper reports on the outcome of this work and presents a proposed framework for assessing the resilience of rural and small-town water supplies and sanitation systems in LMICs.

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Table 1. Domains of resilience for application to WASH.

Domain	Assessment method	Scale of assessment
Infrastructure	Assessment of sanitary integrity and protection, water quality, and yield analysis	Individual water supply, sanitation systems at community level
Environmental setting (catchment)	Geospatial analysis of remotely sensed images	Catchment/regional scale
Water and sanitation management	Focus group discussion and key informant interviews	Community water user committees and associations
Supply chains	Focus group discussion and key informant interviews, infrastructure assessment, geospatial analysis of remotely sensed images	Regional level
Community governance and engagement	Focus group discussion and key informant interviews	Community level
Institutional support	Focus group discussion and key informant interviews	Local government level

RESULTS

Five climate-related hazards that may threaten water and sanitation services in rural communities and small towns in LMICs were identified: floods, droughts, windstorms, storm surges, and sea-level rise. Of these hazards, the current literature is only strong for floods and droughts and these became the focus of this study. These were also the principal hazards that threatened the systems in the field sites in Nepal and Ethiopia. Flooding represents a particular threat to infrastructure integrity which may lead to water and environmental contamination or cause complete failure of the infrastructure, while drought may lead to a reduction in the water available in sources or degrade their quality[1].

We identified six key domains that influence resilience to floods and droughts shown in Table 1. Each domain was defined if it was considered to have a distinct and specific influence on resilience which was not subordinate to other domains. The literature review and expert opinion identified how the different domains could be assessed and the field assessments verified whether these were practical.

Water supply and sanitation infrastructure

Resilience requires that the infrastructure designed to support the delivery of services remains functional when under stress or subjected to shocks with the design based on a thorough initial risk assessment[1,20]. This requires an assessment of the ability of the infrastructure to withstand identified threats, which has been shown to be most effectively undertaken through a sanitary inspection[16–19]. Previous work has shown that analysis of sanitary inspection data combined with water quality and meteorological data demonstrates how water supplies respond to current and likely future weather events[21]. Assessments of risk from droughts were found to be better based on diagnostic data on water supplies related to factors such as depth of boreholes, yield assessments, and flows[22]. This assessment may be supplemented by data from key informant interviews with operators and managers on seasonal and temporal trends in yield.

Environmental setting (catchment)

The importance of catchment protection is well-documented for water supplies in LMICs[23,24]. Poorly managed catchments that encourage rapid overland flow may increase the risk of damaging floods. Degraded catchments with extensive bare soil, steep, managed forests, or farmland that do not promote infiltration and natural water storage may increase the risk of reducing yields of water sources during droughts. Remotely sensed images provide key information related to topography and land use, particularly vegetation cover, that are key to understanding how a catchment may respond to heavy rain events, prolonged rainfall, or prolonged dry periods[25–28]. They also provide useful information regarding likely sources of point and diffuse pollution within the catchment related to land use and population density[29–31]. For Nepal and Ethiopia, we found that Google Earth™ provided remotely sensed images that provided sufficient detail to develop likely scenarios of how these would react to climate events and to assess the exposure of communities to current and future threats.

Water and sanitation management

Adaptive management is critical in building resilience[32,33] and the importance of management tools to cope with the likely threats of future climate change has been noted[9,34]. Strong adaptive management is typified by WASH management structures that are representative of the communities they serve, with substantive participation by women and marginalised groups; sustainable financing (through user fees or similar community contributions) including access to emergency funds for rehabilitation; operator(s) in post with the requisite skills; and transparent decision-making processes[35]. Both formal and informal systems of governance were identified as important and often the latter proves to be the strongest drivers for good governance as they are rooted within the culture of the communities. The assessment of the resilience of service management was considered most effectively achieved through key informant interviews with managers of services and community members.

Community governance and engagement

Community governance and engagement are important when considering active engagement in climate adaptation activities for WASH[36]. Efforts to improve engagement in WASH without dealing with wider issues of how decisions are made within communities and who holds and uses power will undermine progress in developing resilient services. How communities respond to the challenges brought about by climate change will be dictated, to a significant extent, by their existing power and social structures[37–39]. Communities with well-established, responsive, and representative civic structures were considered more resilient to environmental change. The building blocks of such civic structures include local families, local self-help groups, local religious groups, local decision-making forums (both formal and informal), and local elites. A strong sense of community engagement was associated with higher levels of disaster preparedness and the likelihood of sharing information with neighbours[40,41]. Communities also coped with environmental stresses by coordinating the use of limited resources. In the context of water and sanitation, this may involve scheduling collection from public sources during a water shortage, transfers, or 'gifts' of water between neighbours with unequal access and contributing to building community facilities[42–45]. Social governance and engagement are best analysed through assessing the evidence of established social bonds, social networks, levels of interdependence, levels of conflict (latent or active), and cooperation over the use, maintenance, control of services, and evidence of previous collaboration on successful projects. This evidence is best collected through focus group discussions with community members.

Institutional support

The literature on WASH shows that support from the local or national government to WASH committees and managers from the local or national government helps ensure better management and operation[46–48]. Such support may cover different aspects, including technical support, financial assistance, support with purchasing spares, and water quality testing[49]. Rapid response to requests for urgent help, particularly for specialist repairs, and a transparent and simple system for accessing materials and spare parts are critical for communities to be able to effectively manage WASH services. Proactive visits by the government demonstrate a wider commitment to support communities, improve management, and help them to anticipate, absorb and accommodate events. Data on local government support is best collected from both local government and communities because this provides an understanding of both what should happen and what does happen in practice and the constraints that determine what support is given.

Supply chains

Supply chains are critical in ensuring that WASH services continue to function[50]. This is a separate issue to service management because supply chains are heavily influenced by where goods and services are sold and the condition of supporting infrastructures such as roads, bridges, and telecommunication[51]. Supply chains can get overwhelmed or disrupted after a severe weather event because of changes in supply and demand, damage to supporting infrastructure from a flood or landslide, and lack of contingency plans[52,53]. It is particularly important to assess whether there are critical points within the infrastructure, for instance, parts of roads prone to landslides or key river crossings at risk of flooding, which could impair the timely supply of spare parts, tools, or access to specialist support. Collecting data on supply chains requires a combination of interviews with WASH managers and spatial analysis of the critical infrastructure (roads, bridges, communications) used by the supply chain.

Scoring the indicators

After identifying the domains of interest, a Likert scale for each domain was developed based on a set of scenarios that the team considered demonstrated different levels of resilience for each domain. The scenarios were then given a score ranging from a score of 1 (very low resilience) to 5 (very high resilience).

The scenarios defined are based on the likelihood that the water supply or sanitation system will be able to cope with climatic events and so prevent adverse impact. Table 2 shows how each level of resilience is defined for each domain for piped water supplies and Table 3, for sanitation. The team also developed additional modules for assessing the infrastructure domain of point water sources and for water treatment (see supplemental data).

A final score for an individual system can be calculated by adding the scores for each domain as shown in Table 4. In this approach, the score under each domain is simply summed to provide an overall score, similar to the calculation of a total sanitary risk score when using sanitary inspection forms[18]. By providing a single score for each water supply or sanitation system, the likely resilience can be compared to other systems, thus supporting decision-making about where to prioritise efforts to increase resilience. Table 5 provides the scores for two water supplies in both Ethiopia and Nepal, with details on the rationale for each score provided in the supplementary information. The scoring system can also be used to calculate average scores for each domain, thus identifying whether systemic problems in particular domains exist. Finally, the scores for each domain may be used to analyse a single system to identify where weaknesses may lie and where the action is required.

The framework is now being tested with detailed data from study sites in both Nepal and Ethiopia to test how well the framework works in practice. We aim to report the details of this testing in the near future.

DISCUSSION

The impacts of climate change impacts on water and sanitation services have not received the attention it deserves to date in LMICs, and the sector must address this more systematically. An indicator framework for resilience of water and sanitation is important in helping the sector understand and cope with climate change. The feedback from our external consultation with representatives from UN agencies and NGOs noted the utility of a simple framework for assessing resilience as a useful addition to sector tools. How such a framework would integrate with assessments of sustainability was raised as being important to address within the guidelines developed to support the use of this framework.

To effectively understand and measure resilience, we have proposed a scoring system based on an assessment of resilience in six different domains. Resilience requires action across multiple aspects of water and sanitation services[34] and the concept of domains is useful in capturing the multi-faceted nature of the influence on resilience[54]. Combining the data from the six domains identified provides a multi-dimensional assessment of resilience. This approach not only allows a comprehensive evaluation of resilience, but also encourages a greater analysis of where weaknesses lie and the need to invest in multiple aspects of service delivery. This is particularly important when considering some of the broader aspects, such as social cohesion, institutional support, and supply chains, as they are often not given sufficient attention when supporting efforts to make water and sanitation service delivery more resilient and effective.

The absence of finance as a specific domain may be questioned given its acknowledged importance in increasing and maintaining access to water and sanitation services[55]. Finance in the framework is captured under management and institutional support domains as a tool to support the delivery and management of services. If, however, there were finances available solely dedicated to climate resilience and adaptation, including for emergency repairs after a major climatic event, then a domain could be developed to capture variation in its uptake.

The study team also developed a policy domain that is not presented here because it is assumed that national policy would apply equally to all water supplies and sanitation within a country. Scoring the policy domain and integrating it into an overall resilience score would be useful in making inter-country comparisons as a way of benchmarking how the water and sanitation sector was supporting adaptation to climate change.

For catchments, using satellite images from publicly available platforms was the only viable way to assess quality given the limited availability of maps and limited gauging of rivers. Where more accurate maps and gauged catchments exist or more detailed local remotely sensed images are available, it may be more appropriate to substitute these measures when assessing catchment quality. Time series of images would be useful to understand how changes in the catchment may have driven changes in water supply yield or in flood risks, but in many LMICs a sufficient historical record of images is absent. This limitation may be overcome, to some extent, through collecting qualitative

Table 2. Scoring framework for Resilience domains: piped water supply.

Score	Domain					
	Infrastructure	Catchment	Water supply management	Community governance and engagement	Institutional support	Supply chain
1 (very low)	No protective measures against the risk of damage and inundation in place, no data on trends in yield or evidence of declining yield, very high sanitary risks at source and within the distribution system, major damage and leaks in the distribution network, numerous raised tanks at risk from wind	The source is downhill of extensive, steeply sloping built-up land/bare soil, or is in an area frequently (annually) inundated with river or seawater, with no flood protection measures, and/or is in a densely populated setting with open defecation and pit latrines at high risk of inundation, other water users severely impact on water availability	No effective management, including financial, with no action taken to resolve problems in supply, no understanding of climate-adaptive management, no participation in risk assessments, untrained and unskilled operators, no representation of women	Minimal social cohesion, civic engagement, interpersonal trust, participatory behaviour demonstrated by lack of involvement of community members in decision-making; exclusion of marginalized groups from WASH decision making	No formal risk management programme in place in local government, no steps taken to support water supply managers to develop adaptive measures, substantial delay in procuring parts or technical support after an emergency	Only one source of consumables and parts, only one route exists between the community and the market with a high risk of damage to roads, bridges, or mobile communication networks from natural hazards, user committees do not store surplus parts needed to carry out repairs
2 (low)	Limited protective measures against the risk of damage and inundation, substantial seasonal declines in yield and an overall decline in yield, high sanitary risk at source and within the distribution system, some damage and leaks in the distribution network, some raised tanks at risk from wind	The source is downhill of some steeply sloping built-up land/bare soil, or is in an area regularly (once every 3–5 years) inundated with river or seawater, with partial flood protection measures, and/or is in a densely populated setting with some open defecation or pit latrines at medium risk of inundation other water users impact on water availability	Management is weak, including financial, with actions to address problems ad hoc and rarely in good time, a basic understanding of climate change and adaptive management, no participation in risk assessments, operators with limited partial training with limited skills, minimal representation of women	Limited social cohesion, civic engagement, interpersonal trust, and participatory behaviour demonstrated by only occasional involvement by community members in decision-making; limited inclusion of some marginalized groups in WASH decision making	No formal risk management programme in place in local government, but ad hoc support for water supply managers is provided to develop and undertake adaptive measures, some delay in procuring parts or technical support	Limited sources of consumables and parts, only one route exists between the community and the market, medium risk of damage to roads, bridges, or mobile communication networks from natural hazards, user committees do not store parts needed for repair
3 (medium)	Partial protective measures against risks of damage and inundation in place, relatively small seasonal declines in yield but evidence of overall decline, medium sanitary risk at source and within the distribution system, minor damage and leaks in the distribution network, few raised tanks at risk from wind	The source is downhill of moderately sloping managed or cultivated land, or is in an area occasionally (once every 10 years) inundated with river or seawater, with flood protection measures, and/or is in a densely populated area with no open defecation but pit latrines at medium risk of inundation, other water users have limited impact on water availability	Management is reasonably good, including financial, with actions taken when problems arise although not necessarily in good time, limited understanding of climate change and adaptive management, limited participation in risk assessments, operators with basic training with a moderate range of skills, moderate community engagement, and support, some representation of women but none in a leadership position	Intermediate social cohesion, civic engagement, interpersonal trust, participatory behaviour demonstrated by a regular but limited involvement of community members in decision making; limited inclusion of most marginalized groups in WASH decision making	The local government has a limited risk management programme and provide limited risk management training to water supply managers, but does not provide support to implement adaptive measures and no coordination with other sectors, slight delay in procuring parts or technical support after an emergency	Limited sources of consumables and parts, multiple routes exist between the community and the market, medium risk of damage to roads, bridges, or mobile communication networks from natural hazards, user committees have some surplus parts needed to carry out repairs

Table 2 continued

Score	Domain					
	Infrastructure	Catchment	Water supply management	Community governance and engagement	Institutional support	Supply chain
4 (high)	Protective measures against risks of damage and inundation in place, little seasonal decline in yield and little evidence of overall decline, low sanitary risk at source and within the distribution system, limited leakage, no raised tanks at risk from wind	The source is downhill of gently sloping managed or cultivated land, or is in an area rarely (once in 20 years or more) inundated with river or seawater, with flood protection measures, and/or is in a densely populated area with no open defecation but pit latrines at limited risk of inundation, other water users may have minor impact on water availability	Competent management, including financial, with actions taken in a timely manner to address supply problems, moderate understanding of climate change and adaptive management, moderate participation in risk assessments, operators with extended training and skills, good community engagement and support, equal representation of women on committees but few in leadership positions	Good social cohesion, civic engagement, interpersonal trust, general participatory behaviour; demonstrated by regular engagement of community members in decision making; moderate inclusion of most marginalized groups in WASH decision making	The local government has a developed risk management programme and provides risk management training to water supply managers and some limited support to implement adaptive measures and has limited coordination with 1–2 other sectors, no delay in procuring parts or technical support after an emergency	Multiple sources of consumables and parts, multiple routes exist between the community and the market with low risk of damage to roads, bridges, or mobile communication networks from natural hazards, user committees store most surplus parts needed to carry out repairs
5 (very high)	Comprehensive protective measures against risks of damage and inundation in place, no evidence of a seasonal or overall decline in yield, no evidence of reducing yield, very low sanitary risk at source and within distribution system leakage within national limits, no raised tanks at risk from wind	The source is downhill of gently sloping natural land, has flood protection measures and is in an area never inundated with river or seawater, and/or is in an area with no open defecation and pit latrines at no risk of inundation, other water users have negligible impact on water availability	Strong management, including financial, system able to anticipate problems and prevent these from disrupting supply, a good understanding of climate change and adaptive management, active participation in risk assessments, well-trained operators with a range of skills, women take an equal number of leadership and decision-making roles	Strong social cohesion, civic engagement, interpersonal trust, participatory behaviour demonstrated by active engagement by community members in all decision making; inclusion of all marginalized groups in WASH decision making	The local government has a comprehensive risk management programme and provides risk management training to water supply managers and ongoing support for adaptive measures with cooperation with all other sectors, no delay in procuring parts or technical support after an emergency	Multiple sources of consumables and parts, multiple routes exist between the community and the market, no risk of damage to roads, bridges, or mobile communication networks are from natural hazards, user committees store most or all parts needed to carry out repairs

Table 3. Scoring framework for resilience domains: sanitation.

Score	Domain					
	Infrastructure	Environment	Sanitation management	Community governance and engagement	Institutional support	Supply chain
1 (very low)	No protective measures around infrastructure to prevent damage or inundation from surface water flooding, pits very likely to flood, superstructure absent or at risk of damage from floods or high winds, water supply not sufficient for demand for water-based sanitation, very high sanitary risk	Toilet/sanitation system is outside and downhill of steeply sloping built-up land or bare soil, or is in an area frequently (annually) inundated with river or seawater, with no flood protection measures, and/or is in an area with high groundwater table	Pits are not emptied or new ones dug, protective measures against flooding or damage not maintained, flooded or damaged latrines abandoned, water for water-based systems very unreliable and frequently insufficient	Minimal social cohesion, civic engagement, interpersonal trust, participatory behaviour demonstrated by lack of involvement of community members in decision-making; exclusion of marginalized groups from WASH decision making	No formal risk management programme in place in local government, no steps taken to support sanitation users/managers to develop adaptive measures, substantial delay in procuring parts or technical support after an emergency	Only one source of emptying services, only one route exists between the community and the market with a high risk of damage to roads, bridges or mobile communication networks from natural hazards, products for simply repairs not available in the community
2 (low)	Limited protective measures around infrastructure to prevent damage or inundation from surface water flooding, pits likely to flood, superstructure at risk of damage from floods or high winds water supply unlikely to be sufficient for demand from water-based sanitation, high sanitary risk	Toilet/sanitation system is outside and downhill of steeply sloping built-up land or bare soil, or is in an area regularly (once every 3–5 years) inundated with river or seawater, with partial flood protection measures, and/or is in an area with high groundwater table	Pits not emptied, users may dig new pits, protective measures against flooding or damage not maintained, flooded or damaged latrines rarely repaired or reinstated, water for water-based systems unreliable and frequently insufficient	Limited social cohesion, civic engagement, interpersonal trust, and participatory behaviour demonstrated by only occasional involvement by community members in decision-making; limited inclusion of some marginalized groups in WASH decision making	No formal risk management programme in place in local government, but ad hoc support for sanitation users/managers is provided to develop and undertake adaptive measures, some delay in procuring parts or technical support	Limited sources of emptying services, only one route exists between the community and the market, medium risk of damage to roads, bridges, or mobile communication networks from natural hazards, products for simple repairs rarely available in the community
3 (medium)	Partial protective measures around infrastructure to prevent damage or inundation from surface water flooding, pits sometimes flood, superstructure at limited risk of damage from floods or high winds, water supply may not be sufficient for demand from water-based sanitation, medium sanitary risk	Toilet/sanitation system is outside and downhill of moderately sloping managed or cultivated land, or is in an area occasionally (once every 10 years) inundated with river or seawater, with flood protection measures, and is not in an area with high groundwater table	Limited pit emptying service, users dig new pits where needed, protective measures against flooding and damage moderately well maintained, at least half of flooded or damaged latrines are repaired or reinstated, water for water-based systems unreliable but rarely insufficient	Intermediate social cohesion, civic engagement, interpersonal trust, participatory behaviour demonstrated by a regular but limited involvement of community members in decision making; limited inclusion of most marginalized groups in WASH decision making	The local government has a limited risk management programme and provide limited risk management training to sanitation users/managers, but does not provide support to implement adaptive measures and no coordination with other sectors, slight delay in procuring parts or technical support after an emergency	Limited sources of emptying services, multiple routes exist between the community and the market, medium risk of damage to roads, bridges, or mobile communication networks from natural hazards, products required for simple repairs not always available in the community
4 (high)	Protective measures around infrastructure to prevent damage or inundation from surface water flooding, pits unlikely to flood, superstructure at little risk of damage from floods or high winds, water supply likely to be sufficient for demand from water-based sanitation, low sanitary risk	Toilet/sanitation system is inside or, if outside, is downhill of gently sloping managed or cultivated land, or is in an area rarely (once every 20 years or more) inundated with river or seawater, with flood protection measures and is not in an area with high groundwater table	Pit emptying available, new pits dug when required, protective measures against flooding and damage are well maintained, most flooded or damaged latrines are repaired or reinstated, water for water-based systems is generally unreliable but sometimes insufficient	Good social cohesion, civic engagement, interpersonal trust, general participatory behaviour; demonstrated by regular engagement of community members in decision making; moderate inclusion of most marginalized groups in WASH decision making	The local government has a developed risk management programme and provides risk management training to sanitation users/managers and some limited support to implement adaptive measures and has limited coordination with 1–2 other sectors, no delay in procuring parts or technical support after an emergency	Multiple sources of emptying services, multiple routes exist between the community and the market with low risk of damage to roads, bridges, or mobile communication networks from natural hazards, products for simple repairs available in the community

Table 3 continued

Score	Domain					
	Infrastructure	Environment	Sanitation management	Community governance and engagement	Institutional support	Supply chain
5 (very high)	Comprehensive protective measures around infrastructure to prevent damage or inundation from surface water flooding, pits do not flood, no risk to superstructure from floods or high winds, water supply is sufficient for demand from water-based sanitation, very low sanitary risk	Toilet/Sanitation system is inside or, if outside, is downhill of gently sloping natural land, has flood protection measures and is in an area never inundated with river or seawater and is not in an area with high groundwater table	Pit emptying undertaken regularly, new pits dug when needed, protective measures against flooding well maintained and upgraded when required, all flooded or damaged latrines are repaired or reinstated, water for water-based systems is reliable and always sufficient	Strong social cohesion, civic engagement, interpersonal trust, participatory behaviour demonstrated by active engagement by community members in all decision making; inclusion of all marginalized groups in WASH decision making	The local government has a comprehensive risk management programme and provides risk management training to sanitation users/managers and ongoing support for adaptive measures with cooperation with all other sectors, no delay in procuring parts or technical support after an emergency	Multiple sources of emptying services, multiple routes exist between the community and the market, no risk of damage to roads, bridges, or mobile communication networks are from natural hazards, products to support simple repairs available in the community

data from communities although this may come with some caveats regarding knowledge of larger catchments.

It may be argued that indicator frameworks should rely on more specific quantitative measures, for instance, detailed hydrological modelling of flood risks or specific measures of water supply service functioning such as maintaining positive pressures in pipes. However, such approaches are data-intensive and the amount of data required is rarely available in LMICs, particularly within rural communities and small towns. It is also not certain that greater use of such data would yield better decision-making given it would inevitably be bounded by significant uncertainties particularly in relation to future hydrology given the disruptive nature of climate change[56].

Developing indicator frameworks also requires consideration about the extent to which an indicator should be based on precise measures of an attribute or require a degree of subjective assessment. For instance, sanitary inspection forms are an example of using precise measures with a binary response in relation to the presence or absence of a hazard or risk[18,21]. However, as resilience is a very broad concept, using precise measures tends to result in very large numbers of indicators because each measure must be tightly defined[13]. We believe the approach to define each domain broadly allows for greater flexibility whilst maintaining comparability and that differences in individual judgement in each assessment can be easily overcome through training and peer review between assessors.

The framework presented uses existing data collection methods. Using tried and tested tools is more likely to encourage wider uptake than developing new data collection methods. In the context of LMICs, the limited availability of quantitative data requires an approach that allows for expert judgement. The advantage of using a semi-quantitative and flexible framework is that it avoids reliance on data-intensive approaches and can be modified as conditions demand, while still supporting the key objective of transparent monitoring.

This framework is not linked to specific projections of climate change, but rather takes a broader approach to understand likely resilience to anticipated impacts. Linking to more specific changes in climate is likely to be best achieved through climate storylines[57] that provide a more narrative-based approach to describing climate impacts. Climate storylines for Nepal and Ethiopia have been developed and the influence of these on the framework is being assessed.

The framework is designed to operate at a community scale. It does not capture individual or household actions, which could increase or decrease an individual's resilience to climate change. Household action is a greater issue for sanitation than water supply, particularly in rural areas where households take primary responsibility for service provision. However, we believe that understanding community level threats to sanitation is important to define resilience and identify actions required to support communities. For water supply, household interventions either focus on household water treatment or additional self-supply, for instance, rainwater harvesting. Such interventions may improve water quality, but rarely increase the amount of water available. The available evidence indicates that providing higher levels of water supply service through community scale services delivers the greatest public health benefits[1]. A focus on community scales is therefore warranted when considering resilience.

Many of the domains identified are inter-linked, with failures in one domain potentially compromising or compensating for resilience in other domains. The framework as developed does not capture these effects and this is an area requiring further analysis. However, it is unlikely that high resilience in one domain can ever fully compensate for low resilience in another domain and thus the framework indicates where the action is required.

The framework can then be used in multiple ways and at multiple scales to support action. It can be used to rank

Table 4. Total resilience scores.

Total score	Resilience	Priority	Qualifier	Action
25–30	Very high	Low	If score reduces because of failure on one domain, action required in that domain	Maintain performance
19–24	High	Low	Action focused on specific indicator failures	Limited improvements
13–18	Medium	Medium	Likely to be across multiple indicators	Substantial improvements
7–12	Low	High	Action required across all indicators	Large-scale improvements
6	Very low	Very high	Action required across all indicators	Systemic improvements

Table 5. Example scoring for four water supplies.

Domain	Nepal		Ethiopia	
	Piped system from a borehole	Gravity-fed scheme from spring	Gravity-fed scheme from spring	Protected well with a handpump
Environmental setting	4	4	4	3
Infrastructure	4	3	3	2
Service management	4	2	2	2
Community governance and engagement	2	3	2	3
Institutional support	4	1	3	3
Supply chains	4	1	3	3
Overall score (out of 30)	**22**	**14**	**17**	**16**

communities within a country or sub-national region, providing a transparent means by which priority areas for action can be identified. The framework will also allow the assessment of consistent failures in domains requiring systemic action such as changing technology design codes or improved institutional support. At the local level, the framework can be applied as a scorecard for a community-focused activity to support local community engagement and action to improve resilience.

The framework we have developed focuses specifically on water and sanitation services. In the future, it is important that this framework is integrated with other metrics of resilience to build a comprehensive picture of the resilience of basic services.

Testing the usefulness and applicability of the framework at a larger scale in Ethiopia and Nepal, including at sites recently affected by an extreme event, as well as extending the application of the framework to other critical service systems are important next steps in the face of a changing climate.

METHODS

The study employed three approaches to identifying potential components of a measurement framework: literature review; expert opinion; and limited field assessments in two countries, Nepal and Ethiopia, that are broadly representative of LMICs facing challenges both in the provision of water and sanitation and from future climate change. The field sites in Ethiopia and Nepal had not suffered recent extreme events, but were communities already experiencing the consequences of climate change and under threat from likely future events.

Literature review

The literature review focused on the reasons why water and sanitation services fail in response to climate variability and extreme events. Searches were undertaken in Scopus, Web of Science Core Collection, and PubMed using the following key search terms: 'climate change' and 'sanitation', 'climate change' and 'drinking water', 'climate resilience' and 'sanitation', 'climate resilience' and 'water supply', 'climate resilien*' and 'indicator*'. No limits were set on the date of publication, but only papers published in English were considered. In addition, documents identified from the IPCC 5th Assessment Report were reviewed. As this search was not a systematic or scoping review, we did not set formal inclusion/exclusion criteria or formally assess the quality of different papers.

Expert opinion

Expert opinion of resilience in practice was solicited from the members of the research team who came from the UK, Ethiopia, and Nepal using their experiences over the past 30 years, supported by discussions with other sector professionals.

Filed assessments

Limited field assessments were undertaken in Nepal and Ethiopia (see supplementary materials for details). Field assessments identified: the technologies used; recorded the location of services using GPS; collected details on how the services are managed; the level of support from local government; and, where spares and services were obtained. Sanitary inspections of water supplies and sanitation facilities were undertaken using forms modified from the examples provided by WHO[18]. Satellite and aerial images of the catchments containing the communities selected were analysed in Google Earth™ for information on landforms, land use, pollution sources, and activities that could disrupt or affect water supplies.

Weighting data from methods

The relative importance of the data derived from the three approaches varied somewhat by domain, but the overall equal weight was given to all three approaches to collecting the evidence. Field assessment data was given more weight when it demonstrated variance with evidence from literature or expert opinion, or where the evidence from other sources was limited or contradictory.

Framework development

We developed a framework to capture attributes that influence resilience and devised a scoring system using a Likert scale. The draft framework was shared with a selected number of international partners and a virtual consultation held to gain their opinion on the framework and specifically: (i) whether the framework sufficiently captured the different aspects of resilience, (ii) whether it was of use in planning and programming, and (iii) whether it provided a comprehensive assessment of resilience.

DATA AVAILABILITY

All the data used in this paper is provided within the tables and supplementary data.

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AUTHOR CONTRIBUTIONS

G.H., A.F., M.P., E.L., M.B., S.S., and T.W. conceptualised the project and G.H. secured the funding; G.H., A.N., A.F., M.Pr., M.B., M.P.O., and T.W. developed the indicator framework; T.W. & A.Ge. managed fieldwork in Ethiopia and M.B. and A.Gh. in Nepal; A.N., M.P. O., E.L., B.M., and DMA undertook field data collection and analysis. All authors contributed to and reviewed the final paper.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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