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Water impact assessment

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This study helps ensure rural communities can maintain safe and reliable drinking water under climate stress. By identifying which resilience assessment and evaluation methodologies work in low-capacity settings, it informs more realistic investments and policies. The findings support practitioners and governments in advancing long-term, community-centred water sustainability.



Review of methodologies to assess and evaluate the climate resilience of rural community-managed drinking-water supply systems in low-income contexts

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In 2024, approximately 1.37 billion people worldwide living in rural and peri-urban areas remain without safely managed drinking water, with rural populations in Least Developed Countries (LDCs) being disproportionately affected, where 69.7% lack access. In these contexts, water supply is predominantly provided through self-supply systems, household- and community-managed, due to the absence of consistent government service provision. While these systems play a critical role in ensuring access, they are particularly vulnerable to climate change. Ensuring water safety and security in developing countries therefore requires the promotion of resilient water supply systems and empowered communities. Water system resilience depends not only on technological solutions but also on social, institutional, environmental, economic, and anthropological dimensions. Although a variety of tools and methodologies have been developed to assess and enhance the resilience of drinking water systems, few are specifically designed for rural, community-managed systems in low-income countries or adequately address the skills and enabling environments required for their effective implementation. This study presents a critical review of peer-reviewed literature, published guidance, and case studies focused on rural drinking water systems in developing countries. The review systematically organizes and analyses existing resilience frameworks and tools, highlighting significant gaps in contextual relevance. The findings underline the need for tailored, context-specific approaches that integrate elements from multiple methodologies and are grounded in an in-depth socio-cultural understanding of rural communities. These insights provide practical guidance for researchers, practitioners, and decision-makers seeking to move beyond risk diagnostics toward resilient, community-centered water service transformation.

1. Introduction

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Access to safe drinking water is a fundamental human right¹; however, it remains a major challenge in many low-income countries^{2,3}, particularly in rural and peri-urban areas where centralized service provision is often limited or absent. In 2024, only 30.3% of the rural population in the 46 countries classified as LDCs by the United Nations had access to safely managed drinking water⁴, remaining far from the achievement of SDG 6⁵. In these contexts, water supply is frequently ensured through self-supply and community-managed systems⁶, which play a crucial role in meeting basic needs but are often characterized by intermittent functionality, limited technical and economic capacity, and weak institutional support⁷⁻¹⁰. While climate change is increasingly recognized as a significant stressor on water supply systems¹¹⁻¹⁸, affecting availability, quality, quantity and infrastructure, many rural water systems already struggle to provide reliable services under current conditions. In such settings, immediate challenges related to system functionality, maintenance, and financing may take precedence over longer-term considerations such as climate resilience. As a result, the translation of resilience-oriented planning into tangible improvements in service delivery remains uncertain¹⁹⁻²¹.

Over the past decade, a range of methodologies, tools, and frameworks have been developed by international organizations, research institutions, and development agencies to assess and strengthen the climate resilience of water supply systems^{7,22-33}. These approaches typically aim to identify risks, evaluate system vulnerabilities, and support the design of adaptation strategies. Notably, these methodologies are not mutually exclusive and can be effectively combined for greater impact^{8,15,34}. However, most of these methodologies have been designed for urban utilities or systems with higher levels of institutional, economic and technical capacity, and their applicability to rural, community-managed contexts in low-income countries is often limited.

Moreover, the effectiveness of such methodologies in practice remains insufficiently documented. Although case studies demonstrate that these tools can support risk identification and planning processes, there is limited empirical evidence showing that their implementation leads to sustained improvements in system performance or resilience. This raises important questions regarding the conditions under which these approaches can be effectively applied, and the extent to which they can address the complex socio-economic realities faced by rural communities. In addition, the climate resilience of rural water supply systems is a multidimensional concept, encompassing not only technical and environmental aspects but also social, institutional, and economic dimensions⁷. The integration of these components into assessment frameworks varies widely, and the ability of existing methodologies to capture context-specific challenges, including financial constraints, governance limitations, and community dynamics, remains limited.

In this context, this paper presents a critical review of existing methodologies used to assess and evaluate the climate resilience of rural, community-managed drinking water supply systems in low-income countries. The objective is not only to identify and compare the main approaches currently available, but also to examine their structure, applicability, and limitations, with particular attention to the gap between methodological design and real-world implementation. By highlighting both strengths and constraints,



this review aims to contribute to a more grounded understanding of how resilience assessment methodologies can support broader efforts to improve water service delivery in rural, resource-limited settings.

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2. Methods

Searches were undertaken in peer-reviewed database of Scopus and International Water Association Publishing. Article selection began with the determination of keywords: 'resilien*' and 'drinking water' OR 'water supply' and 'safety' OR 'security' and 'tool' OR 'plan' OR 'framework' OR 'approach' and 'developing countr*' OR 'low income countr*'. The terms 'rural' and 'community-managed' were excluded from the research as they significantly narrowed the results. The database search yielded a total of 1125 records. After removal of duplicates, 1107 records were retained for screening. Titles and abstracts were independently screened by the authors to assess relevance to the topic. This screening phase resulted in the selection of 46 records for full-text assessment. In addition, the WHO/IWA Water Safety Plan (WSP) Portal was searched to capture relevant technical guidance and case studies. This process identified six additional documents eligible for full-text review. Grey literature was also systematically searched to reduce publication bias. Relevant documents were identified from the World Bank, World Health Organization, U.S. Environmental Protection Agency, Water Resources Institute, United Nations, United States Agency for International Development, Pacific Institute, World Resources Institute, Global Water Partnership, the NDC Partnership database, and other institutional sources. Additional publications were identified through reference list screening. This grey literature search resulted in nine additional documents being included in the full-text review. Overall, 61 documents underwent full-text review to assess eligibility. Studies were included if they described methodologies for assessing or improving the resilience of rural water supply systems in low-income countries, or if they presented case studies documenting the application of such methodologies. Based on the predefined inclusion and exclusion criteria (Table 1), 21 documents, comprising peer-reviewed articles, guidelines and technical reports, were included in the final synthesis. The literature review was limited to documents published in English, which may represent a potential source of bias and have led to the exclusion of relevant studies published in other languages. Guidelines and technical reports were included as sources of evidence, as they often present methodological frameworks and document applied case studies. The selected publications range from 2015 to 2024. This timeframe reflects the growing attention to climate resilience following the adoption of the Sustainable Development Goals and the Paris Agreement in 2015. One of the earliest official documents addressing climate-resilient methodologies for water supply systems in rural areas was published by the Government of Ethiopia in 2015³⁵, followed by the WHO Guidelines¹² subsequently informing the development of context-specific manuals and case studies across different countries. In Figure 1 is reported the flow diagram illustrating the different stages of the literature search and selection process, along with the number of records included at each stage. Full results for the data extraction fields are included in Supplementary Information file.

Table 1 Inclusion and exclusion criteria for documents selection.

INCLUSION/EXCLUSION	CRITERIA
Inclusion	Published in English
Inclusion	Dated within the past ten years (2015-2024)



Inclusion	Focus on rural areas in low- and middle-income countries	View Article Online DOI: 10.1039/C6EW00063K
Inclusion	Risk-based and resilience assessment methodologies for enhancing the resilience of water or WASH systems and communities	
Inclusion	Integration of climate resilience aspects into the tool or framework	
Inclusion	Both case studies and guidance documents	
Inclusion	Relevant to the topic and providing useful insights, even if not strictly focused on climate resilience (e.g., String et al. ³⁶ , WHO Regional Office for Europe ³⁷)	
Exclusion	Methodologies without applied case studies	
Exclusion	Specific water adaptation technologies (e.g., groundwater storage, rainwater harvesting)	

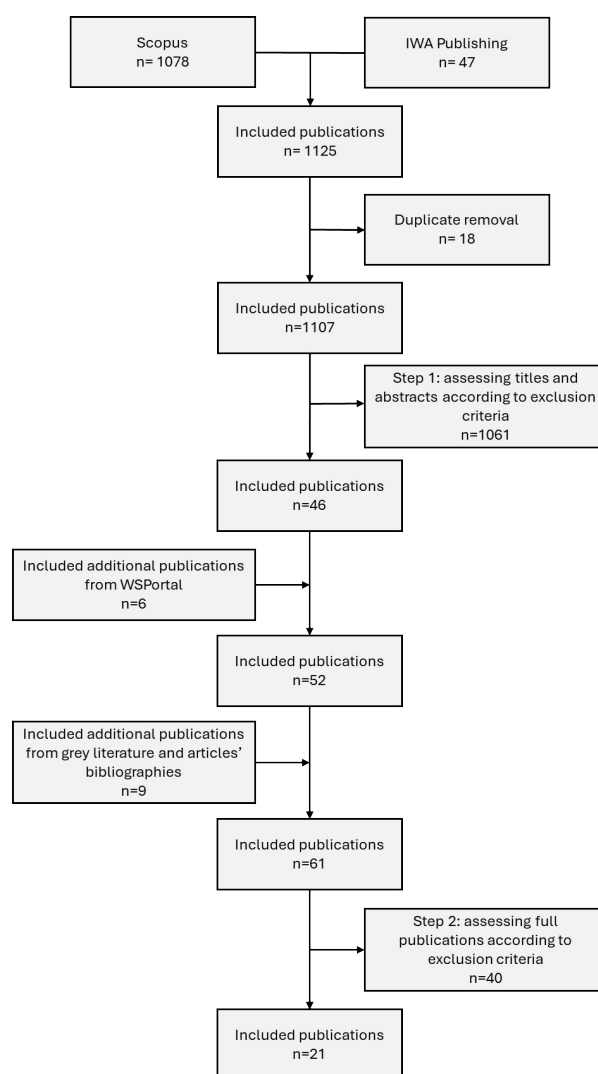


Fig. 1 The flow diagram representing the results of literature search

3. Results



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Analysis of the selected publications shows that they can be classified into four main methodologies to assess and improve the climate resilience of rural drinking water supplies in community-managed drinking-water supply. The methodologies selected from the review for the analysis are four: the Water Safety Plan, the How Tough Is WASH framework (HTIW), WASH Climate Resilient Development: Risk Assessment for WASH and the Rural Water Supply Climate Resilience Monitoring and Assessment Tool (RWS-CRMAT). In the reviewed literature, risk and resilience are often treated interchangeably, yet they represent distinct but complementary analytical constructs. Risk-based approaches focus on the probability and severity of adverse events (hazards, exposure, vulnerability), whereas resilience-oriented approaches emphasize system capacities to anticipate, absorb, adapt to, and recover from such events while maintaining service delivery. This distinction is critical in rural, community-managed water systems, where reducing risk does not necessarily translate into increased long-term resilience. The methodologies were selected in line with the objective of the research, which focuses on methodologies used to strengthen the climate resilience of rural drinking water supplies in developing countries during the period 2015-2024. The literature review showed that only limited information has been published so far on this type of methodology. Figure 2 reports the number of papers published by year of publication. The research interest on this topic is still high in recent years, as evidenced by the number of publications between 2022 and 2024. In the research 21 papers have been considered, including guidelines and case examples (Table 2). Rickert et al.¹³ present the diffuse integration of climate change aspects in the Water Safety Plan approach while IWA reports implemented methodologies, tools and approaches that have been useful for resilience planning to ensure sustainable and durable water supply systems in various context of the world¹⁰.

All the four methodologies analysed in this study have been implemented in the field at least once. The guidelines related to these methodologies are 14 and are available from Africa, South-East Asia, Pacific Islands and for global application (Table 2) while 10 sources report case examples from few countries of the world (e.g. Ethiopia, Indonesia, Nepal, Pacific Islands countries and South Africa).

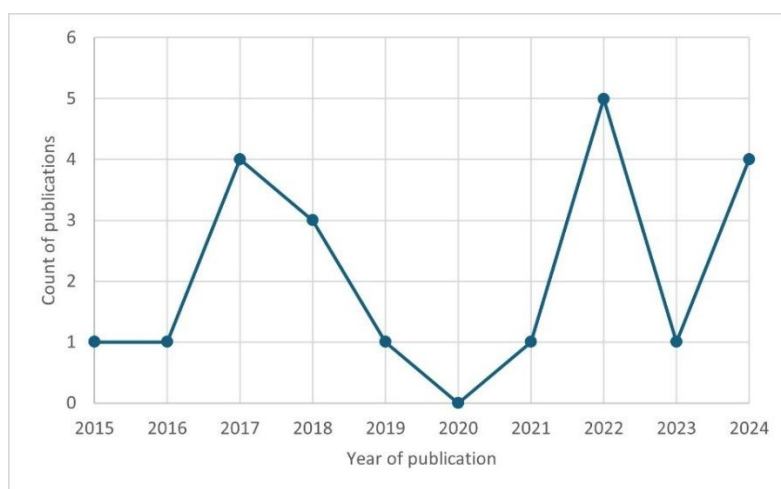


Fig. 2 Graph showing the number of publications that matched the search criteria published per year. [View Article Online](#)
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Table 2 Results of literature review on methodologies considering resilience of small rural drinking water supply systems in developing countries.

METHODOLOGY	REFERENCE	COUNTRY*	MANUAL/ GUIDELINES	CASE STUDY
Water Safety Plan (WSP)	Ministry of Water and Energy ³⁵	Ethiopia	X	
	String et al. ³⁶	Pacific Islands (Fiji, Vanuatu)		X
	WHO ¹²	Global Ethiopia Nepal Pacific Islands	X	X
	GWP-UNICEF ³⁸	Global	X	
	Government of Nepal ³⁹	Nepal	X	
	McKeown ⁴⁰	Tanzania	X	
	Rickert et al. ¹³	Ethiopia		X
	WHO Regional Office for Europe ³⁷	Global	X	
	Government of Vanuatu ⁴¹	Vanuatu	X	
	UNICEF Pacific ⁷	Pacific Islands	X	
	Rand et al. ⁴²	Vanuatu		X
	Love et al. ⁴³	Pacific Islands	X	
Souter et al. ⁹	Pacific Islands (Solomon Islands, Vanuatu, Fiji)		X	
How Tough Is WASH (HTIW) framework	Howard et al. ²⁴	Ethiopia Nepal	X	X
	Nijhawan et al. ⁴⁴	Ethiopia Nepal		X
	Nijhawan et al. ⁴⁵	Ethiopia Nepal	X	
Rural Water Supply Climate Resilience Monitoring and Assessment Tool (RWS-CRMAT)	University of Technology Sydney ³²	Indonesia	X	X
	Daniel et al. ⁴⁶	Indonesia		X
GWP-UNICEF WASH Climate Resilient Development: Risk Assessment for WASH	GWP-UNICEF ²⁵	Global	X	
	Kapwata et al. ⁴⁷	South Africa		X
	Ministry of National Development Planning ⁴⁸	Indonesia	X	

* According to the DAC List for 2024-2025 ⁴⁹, Ethiopia is classified as a Least Developed Country (LDC), Fiji as an Upper Middle-Income country (UM), and Vanuatu as a Lower Middle-Income country (LM). Nepal, Tanzania, and the Solomon Islands are also categorized as Lower Middle Income. Indonesia and South Africa fall under the Upper Middle-Income group. These two countries, along with Ethiopia, have recently joined the expanded BRICS grouping.

3.1. The methodologies

3.1.1. The Water Safety Plan. The Water Safety Plan (WSP) methodology, developed by WHO in 2004, is the one more represented in literature and comprehends several manuals and guidelines ^{50,51}. Water Safety Plans (WSPs) are proactive and comprehensive risk assessment and management tools that cover the entire water supply chain, from catchment to consumer.



WSP is an iterative approach developed in 7 steps, adaptable and flexible and includes modifications to prescribed WSP to adapt it to the local context as well as small systems ^{37,51,52}. The implementation of WSP approach in small rural water supply systems in low-middle income countries has increased in recent years ⁵³. Inclusion of climate change factors in the plan led to the revised guidance of WHO for Climate-Resilient Water Safety Plan (CR-WSP) published in 2017 ¹², meant for all the types of water supply systems in developed and developing countries, including also two related to rural areas in Nepal and Ethiopia. In 2022, WHO published a WSP guideline for rural communities ³⁷ that includes guidance on climate change aspects. Between 2015 and 2018 some governments (e.g. Ethiopia, Nepal, Tanzania) published modified CR-WSP guidelines for rural drinking water supplies adapted to their context, according to WHO guidelines ^{35,39,40}. In 2015, updated than in 2017, the GWP and UNICEF published a technical brief about modified water safety plans to enhance local participatory water supply and climate change risk assessment ²⁵, thought as a part of a broader framework for WASH climate resilient development ³⁰. The paper of String et al. ³⁶ shows a panoramic of the WSP implemented globally in small rural drinking water systems. Rickert et al. ¹³ present a review of CR-WSP implemented in small drinking water systems all around the world and also consider rural communities. Few countries, especially in Pacific Countries (e.g. Fiji, Kiribati, Solomon Islands, Tonga and Vanuatu) implemented the Drinking Water Safety and Security Planning (DWSSP), a facilitated risk-based planning method created on the principles of water safety planning, integrating climate resilience and adapted to the context ⁷. It was introduced in 2013 by the Department of Water Resources (DoWR) of the government of Vanuatu ⁴¹ and has been modified during the years resulting in a follow-up implementation guide ⁴³. A review of the implementation in rural communities in Vanuatu of 199 WSP and DWSSP developed from 2013 to 2019 is presented in Rand et al. ⁴², while Souter et al. ⁹ propose evidence and lessons from rural community's water safety planning implementation in Solomon Islands, Vanuatu, and Fiji. Furthermore, in recent years, the potential for WSP as a tool to manage future climate risks to water supply has been identified as an effective approach for climate resilience ^{13,16,20,54}.

3.1.2. The How Tough Is WASH (HTIW) framework. The How Tough Is WASH (HTIW) is a simple, multi-dimensional framework resulting from a two-year project funded by the University of Bristol in collaboration with Kathmandu University (Nepal) and Haramaya University (Ethiopia). The aim is assessing and scoring the climate resilience of rural and small-town water and sanitation services in Low- and Middle-Income Countries (LMICs). The framework considers resilience along six interconnected domains of service delivery: environment, infrastructure, service management, institutional support, community governance & engagement and supply chains. The first publication dates back to 2021 ²⁴ where the methodology and the general outputs from the implementation in Ethiopia and Nepal are presented. The specific results of the two case studies are discussed in the paper of Nijhawan et al. ⁴⁴ while in 2023 the field guide of the framework has been published ⁴⁵ (Table 2).

3.1.3. The Rural Water Supply Climate Resilience Monitoring and Assessment Tool (RWS-CRMAT). The Rural Water Supply Climate Resilience Monitoring and Assessment Tool (RWS-CRMAT) is one of the results of the two-year research project "Future proofing a basic social service: climate-resilient community-based rural water supply" started in 2023 and conducted by the University of Technology Sydney - Institute for Sustainable Futures (UTS-ISF) in collaboration with three research institutions



from Indonesia and in partnership with the Indonesian planning ministry, Bappenas. The climate resilience monitoring and assessment (CRMA) tool is a simple, easy to use tool to measure the climate resilience, monitor and assess the level of readiness of the rural water supply system in Indonesia to design more climate resilient systems; it was initially intended as a self-assessment by the local communities. The tool has been developed after confirming with literature and other climate-resilient frameworks⁴⁸ and after comparison with national stakeholders. As reported in Table 2, the project methodology and tools templates are shown on the website³² and a conference abstract has been published⁴⁶. The implementation of this tool has been proposed in rural areas in which an effective governmental program on community-based rural water supply and sanitation (i.e. PAMISIMAS) has been active since 2006. RWS-CRMAT includes two tools, the Rural Water Supply Climate Resilience Assessment Tool (RWS-CRAT) for detailed understanding of risks and constraints to climate resilience, and the Rural Water Supply Climate Resilience Monitoring Tool (RWS-CRMT) for system resilience assessment. The RWS-CRAT has been applied in 7 locations while the RWS-CRMT has been tested in 34 locations in 7 provinces.

3.1.4. The GWP-UNICEF WASH Climate Resilient Development: Risk Assessments for WASH. UNICEF in collaboration with GWP developed in 2014, revised in 2017 and updated in 2022 the Strategic Framework for WASH Climate Resilient Development⁵⁵, a sector-wide tool on climate resilient WASH systems and on investments to manage current and long-term climate variability³⁰. It consists of a stepwise, iterative and participatory approach, divided in 4 main steps: understand the problem, identify and appraise options, deliver solutions, monitor and move forward. For each step it provides different toolkits with technical briefs to sustain the step, as the local water safety plans³⁸. The Risk Assessment for WASH guidance note²⁵, sits under the 'Understand the problem' quadrant, which covers the various elements that help to understand the risks facing the WASH sector. This guidance note is intended to assess hazard, exposure, vulnerability and capacity and bring these together to provide an overall scoring of risks. The GWP-UNICEF methodology can be used for national-level assessments but also at sub-national levels/ local level. An implementation of the GWP-UNICEF risk assessment tool at a local level is available from a South African case study researching the risk of WASH-related exposure and vulnerability of a community⁴⁷. In 2024 the Indonesian government in collaboration with UNICEF has published a WASH climate resilient framework adapted from the GWP-UNICEF framework to the local context⁴⁸.

4. Discussion

4.1. Methodologies structure analysis

The selected methodologies are risk-based approaches which, according to Ludwig et al., represent promising measures for climate change adaptation in the water sector⁵⁶. The selected methodologies implemented in the case studies follow fundamental, systematic steps in the assessment process. From the analysis of these steps, six were identified as particularly relevant:

1. Team formation and community engagement
2. System description
3. Risk assessment



4. Improvements implementation
5. Improvements monitoring and evaluation
6. Resilience evaluation

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Table 3 summarizes the inclusion of these analytical criteria in the practical field implementation of the methodologies.

4.1.1. Team formation and community engagement. In community-managed drinking water systems, the involvement of users in assessment and implementation programs is essential for successful and sustainable interventions. In the WSP methodology, the role of the community is central to the effectiveness of the process and is highly emphasized in case studies. The presence of at least one community representative in the multi-stakeholder team overseeing plan implementation is therefore required^{9,12,13}. Guidance on who and how to involve community members in the team is provided in WSP-DWSSP case studies. Generally, teams include women, men, youth, religious groups, health workers, water committee members (if present), local institutions^{9,36}, technicians and/or community members with knowledge of water supply systems and their seasonal reliability^{9,13}. Of particular interest, especially for water management during critical periods, is the involvement of landowners who do not reside in the area, but whose water resources are used by or influence community supplies⁹. The inclusion of external experts, such as climate change specialists, disaster risk reduction experts and technical experts (e.g. hydrologists), is encouraged either from the initial stages³⁶ or during later phases of WSP implementation^{9,12,13}. However, in some case studies, these teams proved weak, inactive or poorly representative and ceased to function after methodology implementation⁹. The RWS-CRMAT methodology was initially designed as a self-assessment tool for community water committees holding clear responsibilities, including disaster response established through community-based rural water supply programmes that have been implemented by the government for many years³². Due to the limited effectiveness of the self-assessment strategy, the tool was later redirected toward local governments to inform targeted actions. For the WSP-DWSSP methodology, the role played by local water committees is crucial to successful implementation^{9,43}. However, difficulties related to the establishment, sustainability and representativeness of these committees in rural contexts have been reported in Nepal and Pacific Islands case studies^{9,44}. The HTIW and GWP-UNICEF methodologies suggest the involvement of external expert teams, while community engagement is focused on complementary activities^{24,44,47}.

4.1.2. System description. Data collection and a detailed description of the water supply system are essential for identifying system problems and exposure to climate risks. Collected data usually focus on community WASH behaviours and climate data, but also include socio-demographic information^{12,44,47}. All the methodologies analysed emphasize the importance of a participatory approach at this stage. In rural contexts, where data availability is limited²⁴, community knowledge and memory can complement scientific evidence^{9,13,38}. During field visits, commonly used data collection tools include household surveys, semi-structured interviews with key informants, focus group discussions, participatory mapping exercises and conceptual diagrams involving all community members and management authorities^{9,32,44,47}. Photographic documentation⁴², inspection of sanitation facilities and water sampling for microbiological analysis are also recommended⁴⁷. Meteorological, historical, socio-demographic and health



data from previous scientific studies, government or municipal documents, NGO reports and other available sources are considered useful ^{44,47}. The use of tools such as Google Earth™ for geospatial analysis of satellite and aerial images is also regarded as effective ^{24,44}. For data collection and system description to be adequate, data collectors must possess the necessary skills, given the technical complexity of acquiring and analysing certain information (e.g. water availability and consumption calculations, identification of control points and actions) ^{9,32,44,57}.

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Table 3 Results of literature review on methodologies considering aspects of climate change in rural communities: case studies.

METHODOLOGY	REFERENCE	ANALYSIS CRITERIA					
		TEAM FORMATION AND COMMUNITY ENGAGEMENT	SYSTEM DESCRIPTION	RISK ASSESSMENT	IMPROVEMENTS IMPLEMENTATION	IMPROVEMENTS MONITORING AND EVALUATION	RESILIENCE EVALUATION
WSP	String et al. ³⁶	✓	NA	✓	✓	✓	X
	WHO ¹²	✓	NA	✓	✓	✓	X
	Rickert et al. ¹³	✓	✓	✓	✓	X	X
	Rand et al. ⁴²	NA	✓	✓	✓	✓	X
	Souter et al. ⁹	✓	✓	✓	✓	✓	X
HTIW Framework	Howard et al. ²⁴	X	✓	✓	X	X	✓
	Nijhawan et al. ⁴⁴	X	✓	✓	X	X	✓
RWS-CRMAT	University of Technology Sydney ³²	X	✓	✓	X	X	✓
	Daniel et al. ⁴⁶	X	✓	✓	X	X	✓
GWP-UNICEF: Risk Assessments for WASH	Kapwata et al. ⁴⁷	X	✓	✓	X	X	X
Legend:							
✓ criteria discussed in the document							
X criteria not discussed in the document							
NA not enough information available to detect the discussion of the criteria in the study							



4.1.3. Risk assessment. Climate change affects water availability, water supply infrastructure and water quality ^{12,13,42,47}. To better understand potential infrastructure failure points and climate change impacts, it is therefore important to include climate projections and their consequences for water supply in risk assessments ⁴², considering how past climate events have influenced water supply systems ^{12,42}. The climate events considered in the case studies (refer to Table 4) are closely linked to local geography and context. Floods and droughts are the most common events ^{12,13,24,32,42,44,47}. Sea-level rise is reported in Ethiopia, Indonesia and Pacific Islands ^{24,32,42,44}; landslides in Ethiopia, Nepal and Pacific Islands ^{13,24,42,44}; and intense rainfall threatening water supply in Nepal, Pacific Islands and South Africa ^{12,42,47}. Once collected the data, quantitative and qualitative risks assessment methods are commonly used across all the methodologies, as the WHO sanitary inspections ⁵⁸ adapted to local contexts and microbiological water quality analysis ^{9,24,32,36,44,47}, even if with some differences.

The WSP methodology focuses on the risk assessment from the source to the point of use, as household water storage and treatment

are common in these contexts ³⁶. DWSSP extends risk assessment to sanitation and waste within the WASH system. The analysis and inclusion of other dimensions of resilience (social, economic, institutional, etc.) are integrated across all stages of the plan through, for example, the involvement of the team and the community in implementation, as well as through the planning and assignment of specific responsibilities. In the WSP methodology, risk is associated with a hazard (e.g. microbiological, chemical or physical contamination) or a hazardous event and corresponds to the combination of the likelihood that the hazard or event will occur and the severity of its consequences. In the implementation of the DWSSP in the Pacific Islands, risk identification was simplified into a

checklist of risks related to the quality and quantity of water from commonly used sources. Subsequent risk level determination was based on a qualitative assessment using standardized severity definitions for common hazard types and the likelihood of exposure. Risk assessments are recommended to include considerations of the impacts of climate change and demographic variations on the water supply system ⁹.

Table 4 Climate events considered in the case studies and countries of application.

CLIMATE EVENTS	COUNTRY	REFERENCE
Flood	Ethiopia, Indonesia, Nepal, Pacific Islands, South Africa	WHO ¹² , Rickert et al. ¹³ , Howard et al. ²⁴ , Nijhawan et al. ⁴⁴ , Rand et al. ⁴² , Kapwata et al. ⁴⁷ , University of Technology Sydney ³² , Daniel et al. ⁴⁶
Drought	Ethiopia, Indonesia, Nepal, Pacific Islands, South Africa	WHO ¹² , Rickert et al. ¹³ , Howard et al. ²⁴ , Nijhawan et al. ⁴⁴ , Rand et al. ⁴² , Kapwata et al. ⁴⁷ , University of Technology Sydney ³² , Daniel et al. ⁴⁶
Sea level rise	Ethiopia, Indonesia, Pacific Islands	Howard et al. ²⁴ , Nijhawan et al. ⁴⁴ , Rand et al. ⁴² , University of Technology Sydney ³² , Daniel et al. ⁴⁶
Landslide	Ethiopia, Nepal, Pacific Islands, South Africa	Rickert et al. ¹³ , Howard et al. ²⁴ , Nijhawan et al. ⁴⁴ , Rand et al. ⁴² , Kapwata et al. ⁴⁷
Heavy rainfall	Nepal, Pacific Islands, South Africa	WHO ¹² , Rand et al. ⁴² , Kapwata et al. ⁴⁷
Cyclone	Pacific Islands	Rand et al. ⁴²
Heatwaves	South Africa	Kapwata et al. ⁴⁷



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The Rural Water Supply Climate Resilience Assessment tool (RWS-CRAT) is meant for detailed understanding of risks and constraints to climate resilience. It has been implemented by local government experts in conjunction with in-field visits of the water supply system, is structured around open-ended questions and physical observations. It is used to gain a detailed understanding of the risks and constraints affecting the climate resilience of community-level rural water supply systems, with a particular focus on supply infrastructure and its management. Questions cover topics such as system design, availability of documentation, information on recent climate events and their impacts, community-based management arrangements, and asset ownership³².

The objective of the HTIW framework is to assess resilience. Resilience is grounded in a risk analysis and in the relationship between identified risks and the capacity to be prepared for and respond to them. Therefore, in order to evaluate resilience, the HTIW framework necessarily includes a risk assessment component. For example, within the infrastructure resilience domain, sanitary inspections are used as a risk assessment tool and are scored using a binary system (0/1). For the other domains, similar risk assessment templates are applied, using weighted scores for each question or categorical scales such as 0/1 (No/Yes) or 1/3 (Low/Medium/High).

GWP-UNICEF guidelines provide an extensive list of potential indicators across six domains (physical, social, environmental, human, financial, political and institutional). They include an initial high-level risk screening for all hazards and a detailed assessment for

specific climate risks. The GWP-UNICEF methodology⁴⁷ assesses risk using a three-point Likert scale (low, medium, high), considering three aspects: the hazard/threat (e.g. high temperatures/heatwaves, heavy rainfall/flooding, drought periods), the frequency and intensity of disasters, exposure (e.g. the population likely to be exposed), and vulnerability (calculated across environmental, human, physical and political-institutional components).

However, in the case study⁴⁷, risk is operationalised only as a function of hazard, exposure, and vulnerability, without explicitly accounting for capacity. This represents a key limitation, as capacity, defined in the GWP-UNICEF guidelines²⁵ as the ability of infrastructure, institutions, and society to prepare for, respond to, recover from, and learn from hazardous events, is a crucial determinant of overall risk. The inclusion of capacity allows for a more comprehensive understanding of risk, making this definition (hazard, exposure, vulnerability, and capacity) complete and more informative compared to other approaches. Furthermore, due to the limited number of hazards considered, no final overall risk classification was produced in this case study.

The interpretation of the collected data requires the involvement of experts for risk evaluation and classification^{24,47}, and it has been shown that consulting published studies and national health surveys is also useful for assessment purposes⁴⁷.

4.1.4. Improvements implementation. Within the WSP methodology, improvements correspond to control measures aimed at ensuring safe drinking water and managing risks arising from climate variability and change. The methodology promotes the



use of so-called “no-regret” measures, which generate benefits regardless of whether climate change impacts materialize or not^{12,25}. The literature provides comprehensive lists of examples of such measures implemented in case studies in Nepal, Ethiopia and the Pacific Islands^{12,39,42}.

These lists also serve as databases for other regions experiencing similar climate change impacts¹³. Examples of control measures implemented to reduce climate change impacts include demand management, the use of alternative water sources, flood-proof infrastructure, treatment barriers, and increased water storage capacity^{9,12}. In addition, preparedness plans addressing risk management from social, institutional, managerial and financial perspectives recommend improving road network efficiency, ensuring easy access to spare parts, and providing community training on risks and climate change⁴⁵. In developing contexts, the most common measures are low-cost or no-cost interventions that can be implemented through collective community action, such as water conservation behaviours, minor maintenance activities, agreed operational practices and the payment of water tariffs^{9,42}. However, studies in the Pacific Islands have shown that, despite the prevalence of infrastructure improvements such as source repair and decontamination³⁶, corrective measures are often not completed, and implementation rates remain low^{9,42}. Challenges related to community engagement, local living conditions, limited institutional capacity, and economic constraints, alongside priorities driven by immediate needs, may hinder effective implementation⁹. The HTIW framework provides results that can be used to identify the most vulnerable water systems and to identify actions to improve resilience, based on the descriptors of the “very high resilience” level for each sub-indicator⁴⁵. However, none of the case studies applying this methodology^{24,44} propose specific corrective actions, except for modifications to well design and source protection measures to reduce flood risk and damage⁴⁴. Within the RWS-CRMAT methodology, improvement measures related to water sources and disaster preparedness are recommended, such as the use of alternative water sources, backup power supply, site accessibility, source protection, and spare parts stockpiling³². However, there is no evidence that these measures have been implemented in practice. Regarding the GWP-UNICEF methodology, although the identification of solutions is recommended, the case study⁴⁷ focuses on risk assessment and does not present proposals for corrective measures.

4.1.5. Improvements monitoring and evaluation. Monitoring and evaluation of implemented control measures are key steps for the long-term success of interventions and their replicability in other projects. The Water Safety Plan provides the most extensive guidance on the evaluation of improvement plans; however, there is limited research on monitoring the outcomes of control measure implementation, particularly in relation to climate change¹³. According to WHO, climate-resilient WSP pilot projects in Nepal demonstrate that the WSP process is effective in addressing risks to water supply systems caused by climate change¹². Nevertheless, monitoring and verification of WSP implementation remain problematic and insufficiently documented in the literature. In the Pacific Islands, for example, WSP audits are carried out sporadically, usually shortly after implementation⁹. The difficulty in ensuring regular oversight and follow-up with water committees by governments and other enabling actors^{9,42} justifies the introduction of trained local facilitators who partially substitute national governments in monitoring activities^{36,42}. However, there is insufficient evidence to determine whether such follow-ups have improved community implementation of low-



cost or no-cost activities in the Pacific Islands⁴². Case studies applying the other two methodologies (the HTIW framework and the GWP-UNICEF WASH risk assessment) do not address this aspect in their analyses.

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4.1.6. Resilience evaluation. The overall evaluation of resilience is useful for identifying the most vulnerable water supply systems among multiple systems, by considering all domains of resilience (social, environmental, institutional, technical, and financial), to prioritise implementation actions. The analysis reveals that a part of the methodologies prioritizes risk identification over resilience evaluation. Only the HTIW framework and the RWS-CRMA tool are two methodologies specifically designed for resilience evaluation. The HTIW framework defines six resilience domains: environment, infrastructure, service management, institutional support, supply chains, community governance and engagement, system resilience and actions to improve resilience. Each domain has its resilience indicators validated through literature review, expert opinion and field assessments. The HTIW framework uses a three- or five-point Likert scale to evaluate each indicator across the six domains, where 1 represents the lowest level of resilience and 3 or 5 the highest. It provides different scales to be used according to the goal of the assessment (local or regional comparisons). This scale was developed based on the likelihood that water supply systems or sanitation services can cope with climate events and demonstrate varying levels of resilience²⁴. The final score for each individual water system, including sanitation facilities assessed through sanitary inspection forms, is calculated by summing domain scores and is therefore comparable across systems analysed using the methodology. In the RWS-CRMA tool, the Rural Water Supply Climate Resilience Monitoring Tool (RWS-CRMT) is the one meant for system resilience assessment. The tool uses a closed-question approach across twelve domains related to human resources, finance, institutions, infrastructure, water management, social inclusion and climate resilience risk assessment. It includes between one and four yes/no questions per domain, with a score of 1 assigned to favourable responses and 0 to unfavourable ones, in terms of contribution to resilience. The average percentage score for each domain provides an overview of strengths and weaknesses^{32,46}. The WSP and the GWP risk assessment approaches lack an overall resilience evaluation. However, the data collected for the risk assessment, if complemented with information from other resilience domains, can be used to conduct a comprehensive resilience evaluation of the water supply systems.

4.2. Key critical aspects for methodology application

Although well-structured methodological frameworks are essential, a critical gap persists between methodological design and real-world implementation, particularly in low-income rural contexts where institutional, financial, and technical constraints limit their uptake. The following sections analyse the key critical aspects affecting the practical application of the methodologies reviewed in this study, as well as those more broadly influencing the implementation of climate resilience approaches in rural settings in low-income countries.

4.2.1. Evaluation of key critical aspects for methodology application

Table 5 highlights several characteristics that are useful for a synoptic approach of the methodologies. Based on experiential evidence derived from the case studies, the following aspects emerged as critical in the water management process in rural contexts of low-income countries: required data, scale of implementation, applicability in contexts with low institutional capacity,



ability to capture climate uncertainty, and relationship with community-based management. It was not possible, according to the available case studies, to quantify the economic costs of implementing these methodologies.

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Scores range from 1 to 3, where 1 indicates low suitability of the methodology with respect to the assessed criterion, 2 indicates medium suitability, and 3 indicates high suitability.

- Required data: each methodology relies on a data base; the more specific and extensive the required data, the greater the need for professional expertise, which is not always available in rural contexts.
- Scale of implementation: the intervention effort envisaged by each methodology gains additional value when it allows comparison across systems, the replication of experience, and therefore the use of results by administrations to prioritize interventions at community, municipal and regional levels.
- Applicability in contexts with low institutional capacity: as shown by the case studies, methodological strategies may conflict with the limitations of local realities, negatively affecting the applicability of the process.
- Ability to capture climate uncertainty: more recent methodologies structurally incorporate attention to climate change and resilience, whereas older approaches (e.g. WSP) have progressively adapted as scientific evidence on climate change has evolved.
- Relationship with community-based management: community involvement is undoubtedly necessary and represents the only pathway to ensuring autonomy. However, case studies show how challenging effective community inclusion can be within these methodologies, as it requires a long-time frame and substantial investment in capacity building.

4.2.2. Financial and economic constraints

Table 5 Evaluation of key critical aspects for methodology application in rural water supply systems.

Methodologies	Required data	Applicability in contexts with low institutional capacity	Ability to capture climate uncertainty	Relationship with community-based management	Scale of implementation
WSP	1	1	2	3	C - M
RWS-CRMAT	2	2	3	2	C - M - R
HTIW	2	2	3	2	C - M - R
GWP-UNICEF: Risk Assessments for WASH	1	1	3	1	R

Legend:

1 low suitability; 2 medium suitability; 3 high suitability

C community level; M municipality level; R regional level



The cost of implementing these methodologies, insufficiently addressed in the scientific literature, also reflects broader institutional capacity constraints, particularly with regard to securing and managing funding and engaging with potential donors^{7,59}.
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Furthermore, the intervention strategies derived from these frameworks may prove weak in setting priorities and planning long-term actions. Addressing these limitations would require context-specific analyses at the regional level, which are essential for practitioners operating in the field but fall beyond the scope of this study.

4.2.3. Climate change constraints

Climate projections are characterized by significant uncertainty, particularly regarding hydrological impacts at the local scale⁶⁰. The predictability of climate change remains complex, as robust analyses are typically conducted at broader, macro-level scientific scales⁶¹. While institutions may have access to such data, translating them into context-sensitive plans and ensuring their effective implementation at the local level remains challenging. At the same time, the experiential responses of local communities to climatic variability, along with their practical knowledge and adaptive practices, represent a valuable resource. These locally grounded strategies, often developed using limited available resources, can provide important insights for both practitioners and researchers, and could become more effective if supported by adequate financial and institutional backing⁶². Incorporating community knowledge and historical data thus represents a crucial first step toward understanding local dynamics and improving the basis for context-relevant projections and planning.

5. Gaps and recommendations

From the analysis of the selected methodologies, both strengths and limitations emerge in relation to rural drinking water systems in low-income countries.

- WSP is the most comprehensive and structured approach, incorporating risk analysis, control measures, implementation strategies and monitoring within a long-term cyclical process. It provides the establishment of a team in which the community is given a leading role throughout the entire development of the methodology, and it is highly adaptable to context and amenable to simplification. The approach provides guidance for a comprehensive risk analysis and establishes criteria for quantifying the magnitude of risk to the water supply system. However, its articulated and complex structure makes WSP difficult to implement in its original form where contexts are not ready to adopt such a management plan and require preliminary interventions to build awareness of water system risks. The methodology requires extensive data collection, which is gradually differentiated according to the level of plan implementation. Although the initial version of the plan⁵¹ required a reformulation in 2017 to incorporate climate resilience aspects, it still lacks a holistic assessment of system resilience.
- RWS-CRMAT uses language and a structure that are easily accessible to local experts and technicians. It focuses on climate resilience, with particular attention to impact assessment and the management of climate-related events, addressing multiple



dimensions of resilience. However, it does not place the community at the centre in an inclusive manner, as it is applicable mainly in contexts where basic organizational structures (e.g. water committees) and institutional support are already in place and functioning. Moreover, the tool is limited to a descriptive analysis of risks associated with climate change impacts on water supply systems, without providing a weighted risk assessment. System resilience assessment is also qualitative and non-quantifiable, as it relies on questions without clear indicators and with responses limited to yes/no/not applicable. RWS-CRMAT therefore functions as an approach for identifying risks and assessing resilience but lacks an implementation and monitoring plan and thus requires integration.

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- HTIW framework offers a useful methodology for assessing system resilience by structuring the evaluation across multiple scales and levels, and by providing greater analytical insights through comprehensive descriptors and a more precise and inclusive scoring scale. The framework addresses all domains related to resilience; however, it does not involve the community and requires external assessment. In addition, it does not develop implementation or monitoring plans and therefore requires integration.
- GWP-UNICEF includes an analysis of all domains related to resilience to climate change and provides tools to conduct a quantifiable risk assessment for water supply systems. However, it does not involve the community and relies on external evaluation. Furthermore, it is a highly complex approach that requires extensive data collection and is therefore difficult to apply in rural contexts. This tool, to be effective, must be implemented within the wider GWP-UNICEF WASH assessment methodology.

While the importance of collaborations between universities and institutions in the countries concerned (e.g., HTIW and RWS-CR) in the development of methodologies is acknowledged, a significant limitation remains the analysis of methodologies developed locally and formalized in native languages. These have been excluded for linguistic reasons, yet they may be particularly relevant and effective, as they are grounded in direct knowledge of local contexts, as well as of the constraints and resources of systems and communities. This gap is also reflected in the geographical coverage of known implementations of the methodologies analysed in this study: there is a clear lack of case studies from low-income countries in South America and francophone Africa. Further research in this field would therefore be valuable.

5. Conclusions

The findings indicate that these methodologies provide a structured and coherent theoretical foundation for efforts to enhance the resilience of water supply systems and communities and emphasize the pivotal role of management approaches in improving the climate resilience of drinking water services. Although this review includes only methodologies that have been applied in real-world contexts, empirical evidence demonstrating that the application of these methodologies has led to measurable improvements in system resilience remains limited.

The focus of this critical review is to evaluate the potential of existing approaches for assessing and improving the climate resilience of rural water supply systems in low-income countries, and to identify their strengths and weaknesses to explore possible



areas for improvement. From a formal perspective, this research faced constraints related to the restricted availability of relevant literature and the lack of consistently defined or commonly agreed terminology for the methodologies reviewed (e.g., framework, tool, plan, approach). An additional limitation relates to the comparison of methodologies that differ in structure and perspective, while nonetheless addressing similar objectives and, partially, employing comparable practices.

Among the methodologies reviewed, the analysis indicates that the WSP represents the most comprehensive approach, despite prioritizing risk identification over resilience evaluation and requiring a substantial amount of data. By contrast, the HTIW emerges as the resilience assessment framework best suited to this context; however, it focuses primarily on punctual resilience evaluations without providing guidance for long-term improvement or management planning.

The conclusions highlight: (1) the critical importance of field-based data collection and a thorough understanding of the local context, encompassing geophysical, climatic, developmental, and socio-cultural dimensions, as well as the need to prioritize interventions and plan both short- and long-term actions in relation to available financial resources and funding opportunities. In many rural settings, ensuring basic water supply functionality may take precedence over long-term climate resilience planning; (2) the need for tailored solutions, through the development of context-specific tools that integrate elements from multiple methodologies and are grounded in an in-depth understanding of rural realities in low-income countries.

To be effective, such approaches should consider all components of the water supply system exposed to climate change and adopt a cyclical strategy of assessment, improvement, monitoring, verification, and subsequent reassessment, reflecting the iterative process required to address evolving climate variability and change. While the uncertainty associated with future climate conditions remains a significant challenge, it can be partially addressed through scientific projections as well as through the integration of local knowledge and community-based experience. Bridging the gap between methodological design and implementation conditions across different contexts should be a key priority for future work. Future efforts should combine risk assessment with explicit resilience evaluation, scalable across institutional capacity levels, and embed long-term facilitation and monitoring mechanisms rather than one-off assessments. Such approaches may enable governments, NGOs, and donors to move from diagnostic exercises toward sustained transformation of rural water service resilience.

Author contributions

M. Pezzato: conceptualisation, methodology, formal analysis, visualisation, writing-original draft; D. Giardina: methodology, writing-review & editing; C. Valsangiacomo: writing-review & editing; S. Sorlini: conceptualisation, methodology, writing-review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability



Supplementary Information is available. See DOI:... The data supporting this article have been included as part of the

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Data availability statement

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The data supporting this article are included in the Supplementary Information.

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