Climate Resilience and Sustainability

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What Does a Climate-Resilient Rural Water Supply System Look Like? An Interdisciplinary Approach to Climate Resilience Mapping in Nepal

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ABSTRACT

Climate change significantly affects the water, sanitation, and hygiene (WASH) services, especially in rural areas of developing countries like Nepal. Erratic rainfall, extreme precipitation, and rising temperatures are key challenges impacting water and sanitation, making these systems less resilient to a changing climate. Understanding the importance of climate-resilient WASH systems enables local authorities to assess and improve them through targeted interventions. In this research, we examined 180 rural water supply systems (RWSS) of Dailekh district located in the middle hills of Western Nepal and mapped their resilience across five domains. The domains include community capital, environment, infrastructure, institutional support and governance, and WASH management of the systems. The results show that 6% of the RWSS in the district have very low resilience, whereas only 11% have very high resilience. Most systems (76%) are classified as very low to medium-resilient systems, highlighting the urgent need for enhanced efforts to strengthen RWSS against the impact of climate change. Among the five domains assessed, institutional support and governance systems emerged as the weakest, closely followed by WASH management. In contrast, community capital stands out as the strongest domain across all surveyed systems. This article presents a flexible indicator-based approach for mapping the resilience of WASH systems in Nepal. This approach can be adapted to other areas of natural resource management by customizing indicators and domains tailored to local social-ecological contexts.

1 | Introduction

Climate change significantly impacts the water, sanitation, and hygiene (WASH) services, particularly in countries like Nepal, by affecting the quality and availability of drinking water, disrupting essential sanitation services, and increasing the risk of contamination and hygiene-related health crises due to disasters (WHO 2015; Ahmad et al. 2018; GWP and UNICEF 2017). The WASH sector, particularly in rural areas of least-developed countries, is highly sensitive to both climatic and non-climatic risks. Climate change acts as a threat multiplier, worsening existing water-related risks. Disruptions in WASH systems can severely impact vulnerable and marginalized communities by hindering service delivery and increasing health risks (Sharma et al. 2021; Caretta et al. 2022). This leads to higher incidences of waterborne diseases such as cholera and diarrhea, disproportionately affecting vulnerable populations (Howard et al. 2016; WHO 2015).

Natural hazards such as floods, landslides, droughts, and wildfires further threaten WASH infrastructure by damaging water networks, drying up sources, and contaminating supplies (Ahmad et al. 2018). Floods can overflow latrines and sewers, whereas drought reduces water availability and quality, and rising temperatures also affect wastewater treatment and pose health risks (WHO 2023; GWP and UNICEF 2017). Erratic rainfall and extreme weather events, exacerbated by climate change, are particularly disruptive to water and sanitation services in rural areas (Caretta et al. 2022; Howard et al. 2010; Howard et al. 2016). These events disrupt domestic water availability and quality, affecting essential water supply and sanitation services (Ayanlade 2024).

In Nepal, climate change is visibly affecting WASH services and hindering progress toward Sustainable Development Goal 6: Clean Water and Sanitation (MoFE 2021; Calow et al. 2011; Poudel and Duex 2017; Howard et al. 2021). Damaged infrastructure due to landslides and altered rainfall patterns jeopardizes the water supply, whereas disasters frequently disrupt sanitation services. A recent example is from September 2024, when extreme rainfall (exceeding 300 mm in 24 h in some parts of central Nepal) caused significant damage across various sectors, including the water supply. The event affected more than 1600 water supply schemes, raising concerns about a potential disease outbreak and resulting in estimated losses of around NPR 5.73 billion (about $43 million) (NDRRMA 2024; UNICEF 2024). This highlights the sensitivity of the WASH sector to extreme climatic events and underscores the need for resilient water supply systems capable of withstanding and recovering such events.

Rural water supply systems (RWSS), especially in hills and mountains in Nepal, face climate-induced challenges like floods, landslides, drying sources, and droughts, whereas plains are affected by floods, sedimentation, pollution, and declining groundwater levels (WHO 2015; Ahmad et al. 2018). These impacts have compromised the infrastructure, disturbed service delivery, and posed health risks. Water supplies are contaminated with pollutants and pathogens during floodings, when infrastructure is not designed to handle such events. In hills and mountains, spring sources have either dried up or yielded less discharge due to various climatic and non-climatic factors (Adhikari et al. 2021), making the water supply more unreliable. In some areas in the hills, decreasing water supply has led to seasonal and permanent migrations (Joshi and Dongol 2018).

Intergovernmental Panel on Climate Change (IPCC) defines resilience as "the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity of self-organization, and the capacity to adapt to stress and change" (IPCC 2007). Climate-resilient development integrates adaptation and mitigation actions to advance sustainable development for all (IPCC 2022). Building climate-resilient WASH systems can help address several critical challenges, including rising demand from population growth, deepening socioeconomic disparities caused by limited access to safe water, and policy gaps that hinder the fair distribution of resources (Bishoge 2021; Zhang et al. 2020; Aksha et al. 2019). A clear understanding of how climate change affects the WASH services is essential for developing effective, resilient strategies that protect these vital services amid growing climate pressures (IPCC 2007).

Resilience is a complex and multifaceted concept that describes a system's ability to withstand and recover from stresses and shocks. Empirical measurement of the resilience of a system is always in the interest of researchers, practitioners, and policymakers (Cutter et al. 2014). Quantitative and qualitative measurements can provide baseline datasets and strategies for addressing climate change and extremes (Fan et al. 2021; Zaman and Raihan 2023). By combining social, economic, and environmental indicators, resilience mapping provides a comprehensive view of areas more vulnerable or resilient to potential climate-induced extremes, shocks, and stresses (Aksha and Emrich 2020; Cutter et al. 2014). This approach allows decision-makers, planners, and policymakers to identify at-risk populations and visualize the adaptive capacity of communities, systems, or environments, ultimately assisting efficient resource allocations and devising strategies for enhancing long-term resilience (Mavhura and Manyena 2018; Nijhawan et al. 2022).

Various resilience frameworks for the natural resource sector are proposed in the literature, like WaterAid (2021) for climate-resilient WASH systems, Tyler et al. (2013) for climate resilience and food security, and Howard et al. (2021) for mapping of WASH system's resilience. All these frameworks differ in the sectoral context and the scale in which the framework is applied. Similarly, various index construction approaches are developed to measure the inherent resilience at household, community or system levels (Aksha and Emrich 2020; Mavhura and Manyena 2018; Schipper and Langston 2015). For this study, we have adapted the framework suggested by Howard et al. (2021) for mapping resilient WASH systems. Their framework comprises six domains that assess the status of WASH system resilience: (1) environmental setting, (2) infrastructure, (3) service management, (4) community governance and engagement, (5) institutional support, and (6) supply chains. Originally developed for Nepal and Ethiopia, this multidimensional framework provides a simple yet robust approach to assessing the resilience of rural and small-town water and sanitation services. This approach was tested in community-managed water supplies (Nijhawan et al. 2022) and water safety plans (Poudel et al. 2024). In our case, we consider five key domains—community capital, environment, infrastructure, institutional support and governance, and WASH system management—aligned with the core functionalities of rural WASH systems. Our approach has combined institutional support and governance domains and removed supply chains as the latter is less relevant for RWSS. It is because such systems often rely on locally available materials, community-led construction, and maintenance practices rather than centrally procured components or complex distribution networks.

Given the risks of climate change and extreme events in Nepal, understanding how climate-resilient water supply systems are in the rural areas is crucial. The objective of the article is to assess the resilience of RWSS in Western Nepal. On the basis of these objectives, the article addresses three research questions: (1) What are the mountain-specific variables and indicators to assess the resilience of the RWSS? (2) How can these variables be empirically measured and mapped for the resilience of the water supply systems? (3) How does resilience mapping inform the decision-making process at the local level to build climate-resilient water supply systems? We selected 180 RWSSs from the Dailekh district in Western Nepal typically representing rural settings.

2 | Methodological Approach

To understand the distribution of climate-resilient WASH systems, we assessed and mapped climate resilience scores at the RWSS level. The following subsection describes the study area and methodological approach.

2.1 | Study Area

This research focused on RWSS in the Dailekh district, a representative mid-hill region in Nepal. Dailekh district is especially vulnerable to natural hazards, extreme climate events, and declining water sources, highlighting the challenges faced in similar mid-hill terrains of Nepal. Projections suggest that by the 2050s, Dailekh will move from its current "high" landslide hazard risk category to a "very high" risk category, driven by ongoing climate and environmental changes (MoFE 2021). The district also has one of the lowest Human Development Index scores (0.422) and is among the most deprived districts in terms of access to safe drinking water, with approximately 48% of the population lacking access to safe drinking water (GoN and UNDP 2014).

Dailekh district is located in the Karnali province of Western Nepal and covers an area of 1505 km^2 with elevation ranging from 550 to over 3500 m above mean sea level. Geographically, the district's landscape is predominantly hilly, with 80% of the landscape consisting of hills and the remaining 20% classified as mountainous, creating challenges for establishing and maintaining effective WASH systems. The annual precipitation is about 1700 mm, and the mean annual temperature ranges from 5°C to 34°C.

The district has a population of 253,319 (NSO 2021) and is divided into 11 municipalities (seven rural and four urban). The district has 588 water supply schemes registered in the National Water Supply, Sanitation, and Hygiene Management Information System (NWASH-MIS) (Figure 1). These schemes serve communities ranging from 5 households to over 300 per scheme.

2.2 | Resilience Mapping Framework

On the basis of the resilience measurement literature and guided by Howard et al. (2021), this study proposes a methodology for benchmarking climate-resilient WASH systems in the mountainous context of Nepal. Climate resilience is defined here as the capacity of WASH systems to absorb, adapt to, and recover from climate-related shocks and stresses through both social and infrastructural mechanisms. The framework encompasses five key domains: (1) community capital, (2) environment, (3) infrastructure, (4) institutional support and governance, and (5) WASH system management. The following steps were involved in assessing the resilience.

2.2.1 | Indicator Development for Each Domain

The indicators are primarily developed from the empirical assessment of resilience literature. We adapted Howard et al. (2021) and GWP and UNICEF (2017) for the RWSS in the mountainous context of Nepal. A total of 24 relevant indicators and associated measuring variables (Table 1) were identified for evaluating and comparing WASH systems representing rural areas (Nyaupane 2022; Barua et al. 2014).

Community capital domain (six indicators) refers to the collective capacity of a community to address the challenges in WASH systems, emphasizing democratic processes for resolving user challenges, active participation of WASH committee activities, enforcement of rules and decisions, and fostering cooperation and coordination among all users (Kyne and Aldrich 2020; Balaei et al. 2018).

The environment domain (five indicators) comprises the overall environmental conditions of the areas, including the catchment's conditions—topography, land use, historical hazards, and disturbances in the upstream area. The conditions help to evaluate the WASH systems' resilience to climate extremes as suggested by Zhao et al. (2024) and Sono et al. (2021).

The infrastructure domain (three indicators) comprises the physical infrastructure of the WASH systems such as condition of distribution networks, focusing on potential damage to intake areas, tanks, pipes, and taps; protective measures, such as the use of local materials (wire, cemented bricks, and concrete) for fencing at key locations like intake sites and reservoirs (Quitana et al. 2020; Mostafavi et al. 2018); and age of the systems.

The institutional support domain (five indicators) encompasses risk management programs, emergency WASH support, climate change adaptation initiatives, training for WASH support, and assistance in monitoring climate phenomena aimed at evaluating the system's capacity of climate resilience (Nijhawan et al. 2022; Jones et al. 2013).

WASH system management (five indicators) refers to the integrated approach ensuring the availability of toilets, proper handwashing practices with soap, designated responsibilities for repairs and reconstruction, the proximity of toilets to water sources, and user awareness of climate change and its impacts (Nijhawan et al. 2022; Sherpa et al. 2014).

2.2.2 | Survey Questions

To assess the resilience of the five domains, survey questions were designed to capture the contribution of several indicators. We developed 114 questions for 28 variables under 24 indicators as specified in Table 1. Each variable was measured through multiple close-ended questions, providing respondents with a list of options to choose from. All the questions and their associated

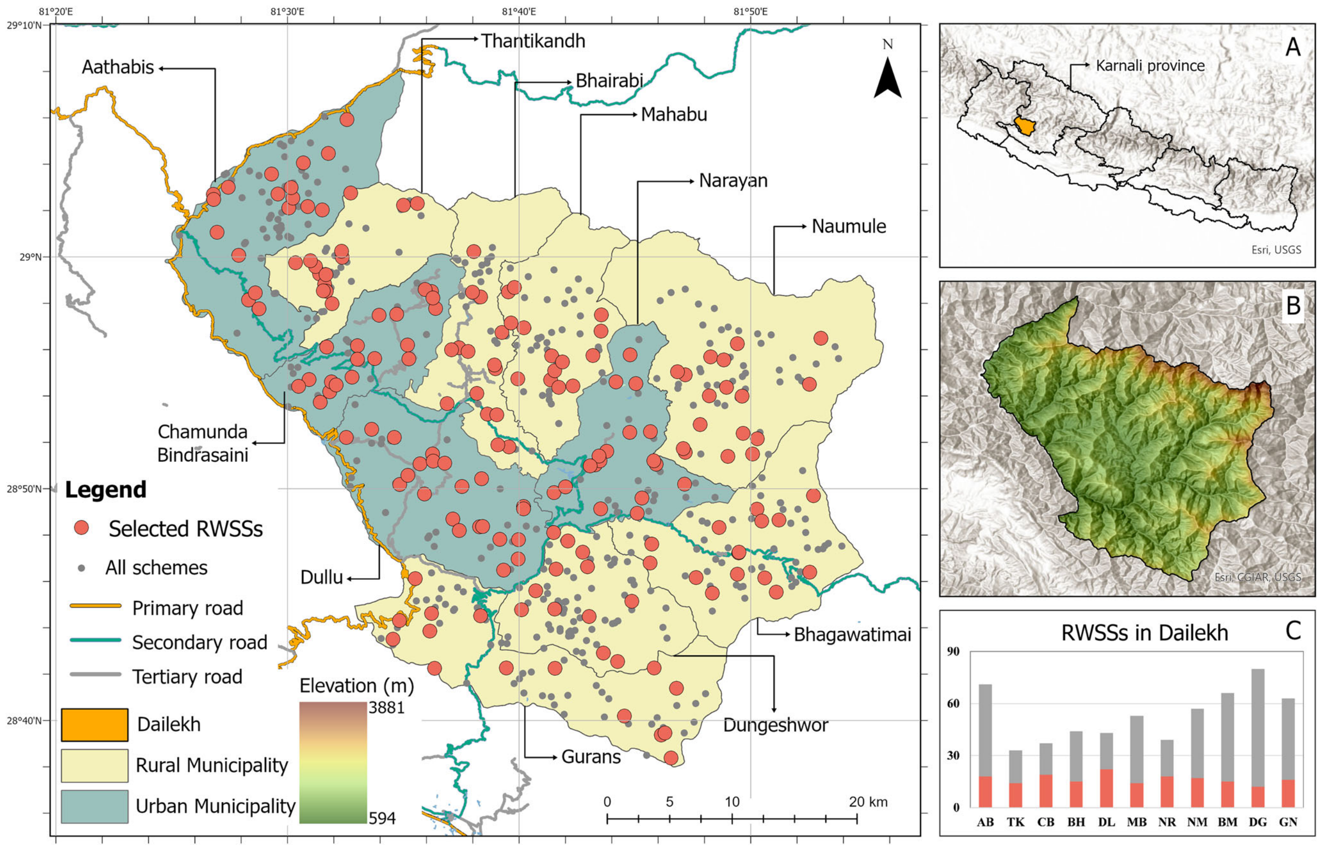

FIGURE 1 | Map of the study area and the existing Rural Water Supply Systems (RWSSs) (both selected and all existing schemes). The selected schemes are marked in red, and the existing schemes are marked in grey. Inset (A) shows the location of Dailekh district in Karnali province, and inset (B) shows the elevation within the Dailekh district in meters. Inset (C) shows the total number and selected RWSS in each municipality of the Dailekh district. AB, Aathabis; BH, Bhairabi; BM, Bhagawatimai; CB, Chamunda Bindrasaini; DG, Dungeshwor; DL, Dullu; GN, Gurans; MB, Mahabu; NM, Naumule; NR, Narayan; TK, Thantikandh.

scales are provided in Table S1. Table 2 provides a few examples of questions that were asked during the survey interview and how they were scored during the computation of climate resilience.

2.2.3 | Data Collection

We conducted a survey to collect system-level data on RWSS for resilience mapping. In this study, RWSS refer to registered water supply systems managed and operated by water supply users and sanitation committees (WSUSCs), which are constructed with the primary objective of protecting, conserving, and managing local water sources, ensuring a reliable supply of water to meet daily needs for drinking, sanitation, and hygiene, while also being responsible for the operation and maintenance of the systems for the functionality (MoWS 2024). Out of 588 systems in Dailekh district, we selected only registered systems from all 11 municipalities. Each municipality has 6–12 wards, and where multiple WASH systems existed within a ward, we selected them proportionally. To cover nearly one-third of the population size, we selected 180, ensuring that at least one system per ward is covered, as the sample size.[1] Within each ward, water supply projects were selected using simple random sampling based on proportional allocation. Ultimately, 12–22 systems were surveyed per municipality (Table S3).

Survey questions were coded on the Kobo platform (Kobotoolbox 2018), and local enumerators from Dailekh participated in a 2-day training to familiarize themselves with each question and practice mock exercises. The interviews were conducted in a group setting, which typically involved executive committee members of each RWSS, including the chairperson, secretary, or treasurer, and other committee members. The survey responses were collected using mobile devices. A communication channel was established to ensure timely database uploads and maintain data quality. Field challenges were addressed through evening meetings, whereas data inconsistencies were monitored and corrected as needed. Additionally, back-checks were conducted with selected respondents to verify accuracy.

2.2.4 | Analysis

We analyzed RWSSs using responses from nearly 100 objective questions across five resilience domains, scoring each on a scale of 0–5 where higher scores indicate greater resilience. To provide a more interpretable comparison across systems and domains, we applied the min-max normalization technique at the domain

TABLE 1 | List of indicators and extracted variables in each resilience domain.

Domains	Indicators	Measuring variables
Community capital	Water-sharing rules	Evaluation of water sufficiency; existence of water-sharing rules if deficient
	Alternate sources	Need and identification of alternate water sources
	Cooperation and coordination	Evaluation of the level of cooperation and coordination among members
	Enforcement of rules and decisions	The proportion of people who follow the rules and decisions
	Users' involvement in WASH	Attendance in WASH user committee meeting; discussion among WASH user committee members; discussion of issues/problems among WASH users committee members
	Decision-making process	Consensus/participatory decision-making process to find out solutions to issues/problems
Environment	Topography of the source area	Source type, slope of the catchment
	Land use in the catchment area	Land use type around the source area
	Exposure to natural hazards	Historic frequency of multiple natural hazard occurrences
	Source protection	The presence of source protection such as fencing, gabion walls, concrete structures, etc.
	Anthropogenic activities	Easy access of humans and animals to the source area
Infrastructure	Intake, reservoir, and distribution network protection	Presence of source protection such as fencing (just covered with local materials, wire fencing, cemented with brick walls), materials used for intake structure
	Intake, reservoir, and distribution network conditions	Intake, reservoir, and distribution networks, such as open pipes, disconnected services, and (frequently) damaged taps
	Age of the system	Construction year
Institutional support and governance	Risk management program	Resources for risk management
	WASH emergency support	Support received before, during, and after an emergency in the water system
	Climate Change related support	Participation in climate change awareness programs
	WASH support training	Training programs provided to users
	Measurement of climate	Measurement of water quality, availability, temperature, and rainfall
WASH management	Assigned responsibility for the repair/reconstruction	People responsible for the functioning of the water system
	Availability/construction of toilets	Users proportion who have access to toilets
	Proximity of toilets to water sources	Proximity of water bodies/sources to toilets; dead soil management
	Hand wash practices	Proportion of people who use soaps for hand washing
	Perception and awareness of the climate change among users	Perception and awareness of climate change among users

Note: The first column is the domains used to measure the resilience of the system, the second column is the list of indicators to measure the individual domains, and the third column is the list of variables to measure each indicator.
Abbreviation: WASH, water, sanitation, and hygiene.

level, which transforms the aggregated scores into a uniform range between 0 and 1. Using an additive index construction approach, the scores for each indicator were summed to calculate resilience scores for each domain for each WASH system (Balaei et al. 2018). Then these values were again normalized to ensure that systems can be compared equitably across different domains. Each domain and overall resilience scores are categorized using equal-width binning. This method transforms continuous data into categorical data by grouping values into discrete bins. Here, the range of the data is divided into five intervals (0–1), each of the same width (1), that is, [0–0.2] very low; [0.2–0.4] low; [0.4–0.6] medium; [0.6–0.8] high; [0.8–1] very high.

TABLE 2 | Examples of questions, responses, and their respective scores.

Domains	Indicators	Sample questions?	Methods	Scores (contribution to resilience) and options					
				0 (No contribution/Lack of resilience)	**1 (Very low)**	**2 (Low)**	**3 (Moderate)**	**4 (High)**	**5 (Very high)**
Infrastructure	Intake protection	Is there any protection system (fencing) installed in and around the intake area?	Directly scored	No. It is easily accessible to anyone	Partially protected, partially open	Simply covered with stone, plastic, or other materials	Fenced with mesh wires or nets	Dry stone walls with or without mesh wires or nets	Cemented walls with or without mesh wires or nets
Environment	Exposure to natural hazards	Did this WASH system experience these hazards (landslide, flood, erosion, wildfire, rock fall, snowfall, cloudburst, winter rainfall) in the past years? (Yes = 1 & No = 0)	The answers were summed up and then categorized based on the standard deviation (refer Table S2)	—	Significantly lower than average	Below average	Around the average	Above average	Significantly higher than average
Community capital	Involvement and discussion in the management process	How often does the user's management committee meet?	Directly scored	Never	Annually	Biannually	Quarterly	Monthly	Frequently and as needed

TABLE 3 | Number of rural water supply systems with their resilience category for each dimension in Dailekh district.

Category	Community capital	Environment	Infrastructure	Institutional support and governance	WASH management	Overall resilience
Very high	19 (10.6%)	14 (7.8%)	12 (6.7%)	2 (1.1%)	13 (7.2%)	11 (6.1%)
High	56 (31.1%)	53 (29.4%)	55 (30.6%)	15 (8.3%)	25 (13.9%)	32 (17.8%)
Medium	64 (35.6%)	70 (38.9%)	65 (36.1%)	3 (1.7%)	32 (17.8%)	65 (36.1%)
Low	39 (21.7%)	38 (21.1%)	42 (23.3%)	19 (10.6%)	80 (44.4%)	66 (36.7%)
Very low	2 (1.1%)	5 (2.8%)	6 (3.3%)	141 (78.3%)	30 (16.7%)	6 (3.3%)

Note: The different colors in the table indicate the intensity of resilience, with red being very low resilience and green being very high resilience. The number in parentheses indicates the percentage of the systems.

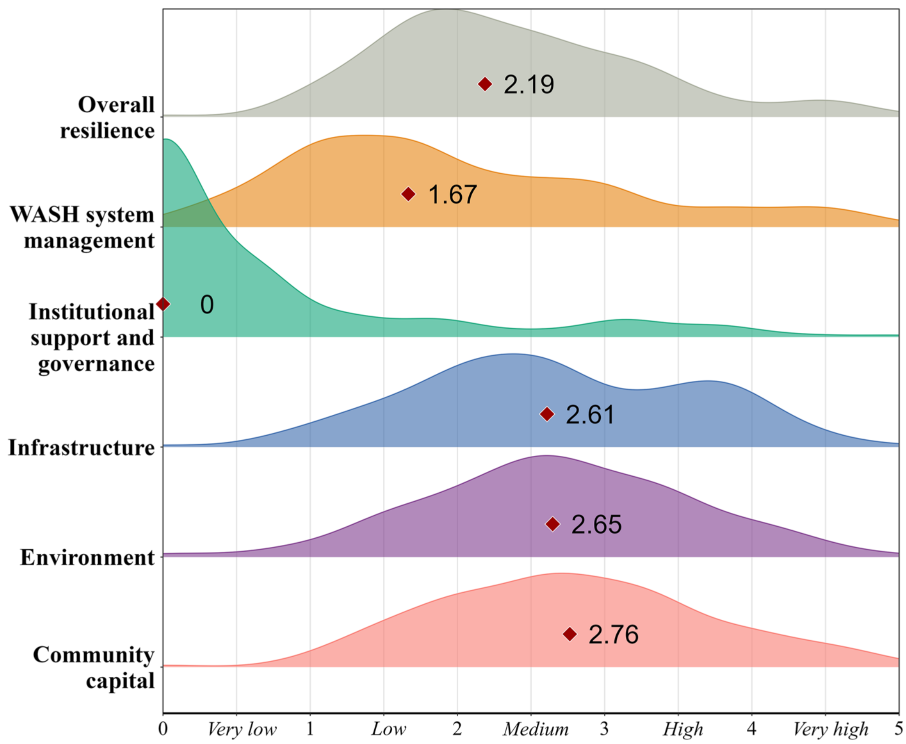

FIGURE 2 | Ridge plot showing the distribution of resilience score with the number of schemes (*y*-axis). The red diamond and the value indicate the median of the distribution of each domain.

3 | Results

3.1 | Overall Resilience

Table 3 shows the number of RWSSs that are grouped into five different categories from very low to very high, based on the normalization. The resilience mapping of the surveyed WASH systems shows that only 11 systems (6%) has "very high" resilience score, whereas 6 systems (3.3%) fall under the very low resilience score. The resilience of the WASH systems is also analyzed in different domains. Most of the domains show resilience scores that are normally distributed except the institutional support and governance domain, where 89% of the systems fall in the low to very low category (Figure 2). In contrast, only 9% of the systems show "very high" to "high" categories in this domain. Domains such as community capital, environment, and infrastructure have a median score higher than 2.5, indicating that a majority of the systems fall within at least higher or equal to median. However, the median score for WASH management (1.67) and institutional support and governance (0) reduced the overall resilience score of all domains to slightly below the 2.5 (2.19) threshold (Figure 2).

Table 4 and Figure 3 show the number of schemes of different resilience categories in 11 municipalities of the Dailekh district. Bhairabi rural municipality (RM) has 80% systems in the "high" to "very high" resilient category, whereas none of the systems in Aathabis and Chamundabindrasaini urban municipalities (UMs) have "high" to "very high" resilience score. In contrast, 72% and 63% of systems in Aathabis and Chamundabindrasaini fall

TABLE 4 | Number of rural water supply systems in each resilience category for all municipalities.

Municipality	Very high	High	Medium	Low	Very low	Total
Aathabis	—	—	5	13	—	**18**
Bhagawatimai	—	6	4	5	—	**15**
Bhairabi	6	7	2	—	—	**15**
Chamundabindrasaini	—	—	7	10	2	**19**
Dullu	1	7	11	2	1	**22**
Dungeshwor	3	3	4	2	—	**12**
Gurans	—	2	8	6	—	**16**
Mahabu	—	1	6	7	—	**14**
Narayan	—	4	7	5	2	**18**
Naumule	1	1	6	8	1	**17**
Thatikandh	—	1	5	8	—	**14**
Total	**11**	**32**	**65**	**66**	**6**	**180**

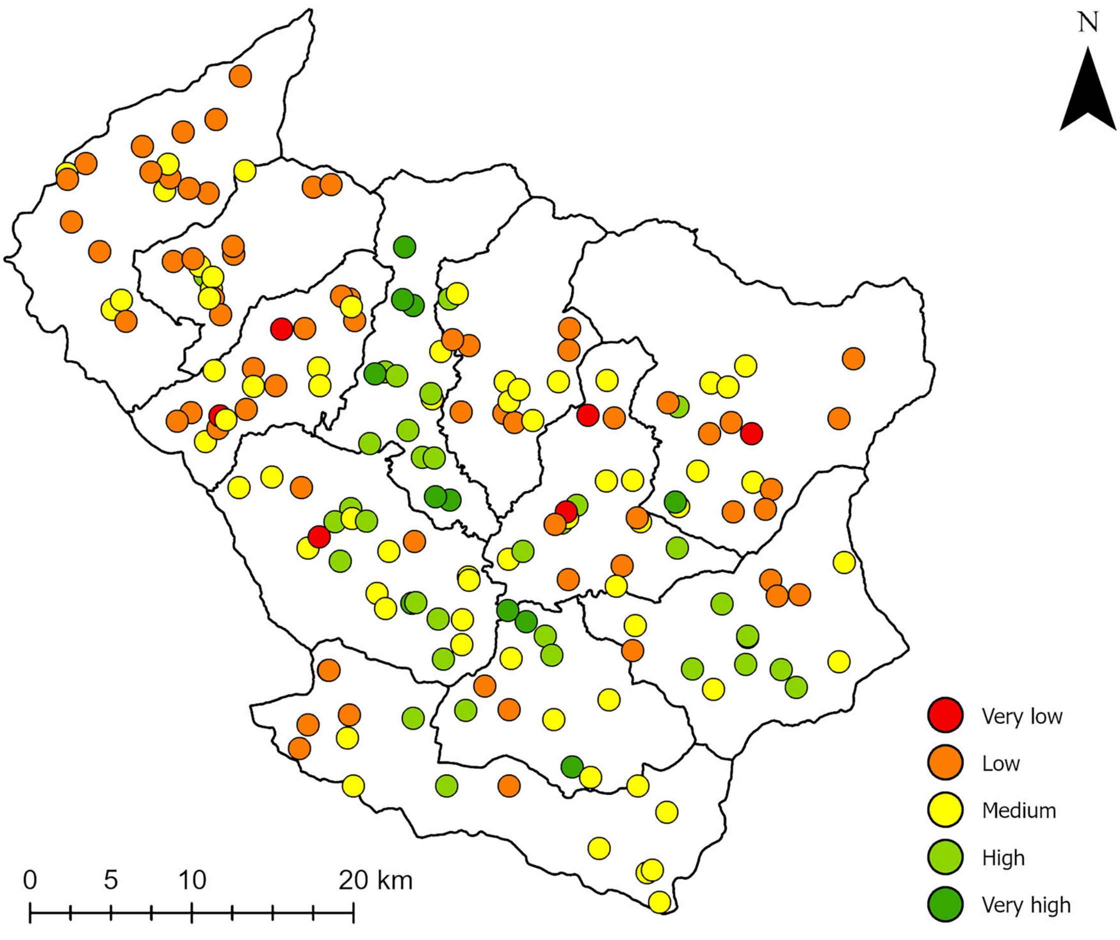

FIGURE 3 | Spatial distribution of the overall resilience of rural water supply systems in Dailekh district.

under the "low" to "very low" categories, respectively. Overall, only 24% of the systems are in the "high" to "very high" categories, whereas 40% are in the low to very low categories, and nearly one-third of the systems are in the medium category of resilience.

Our analysis indicates that the three systems with the highest scores are the Tallowadar Khola Khanepani Yojana and Karnali Solar Lift Aayojana in Bhairabi municipality and the Sisne Thakurkuna Khanepani Yojana in Dungeshwor municipality. Conversely, the three systems with the lowest resilience scores

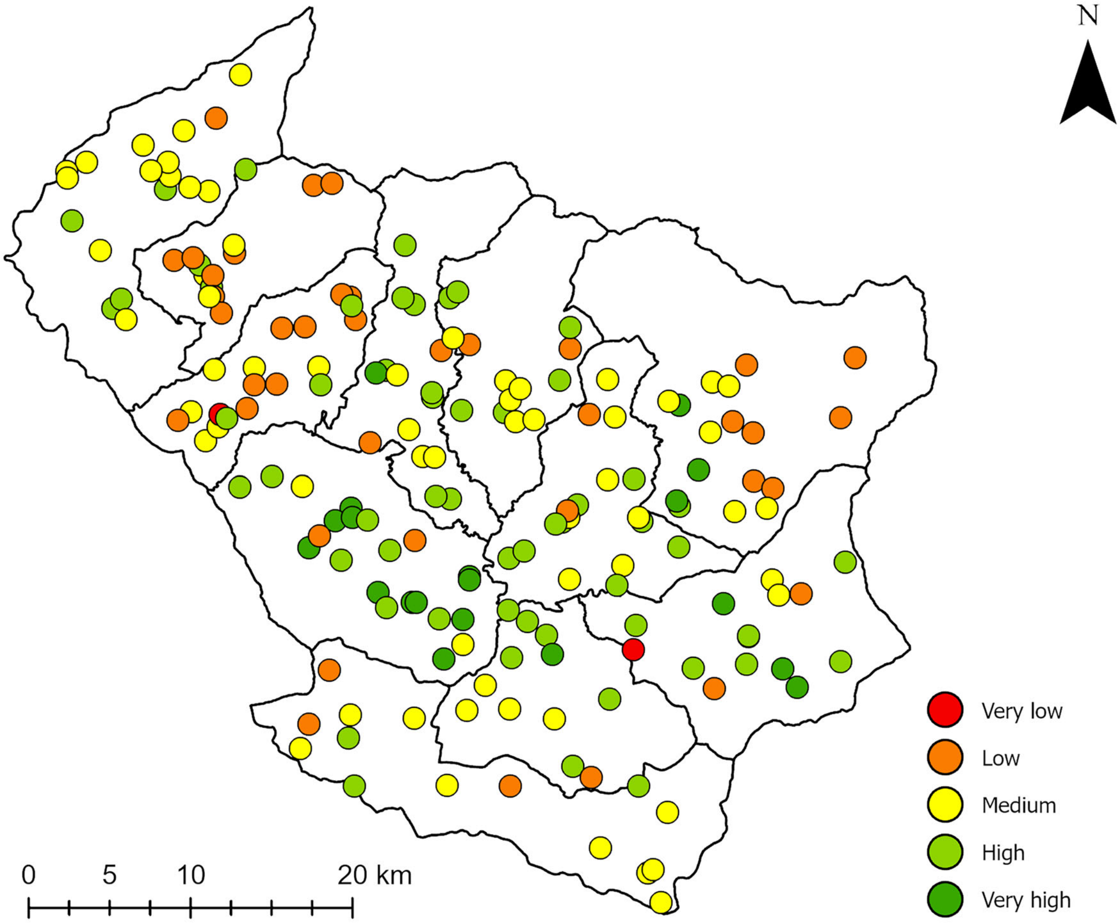

FIGURE 4 | Spatial distribution of the rural water supply systems resilience under the community capital domain in Dailekh district.

are the Bhatgaun Khanepani Yojana in Chamunda Bindrasaini municipality and the Dandakhoriya Chunkhani Khanepani Yojana and Dewalkada Khanepani Yojana in Narayan municipality. Table S3 provides a detailed list of all 180 systems across 11 municipalities, showing their resilience scores by domain as well as their overall resilience.

3.2 | Community Capital

The high scores in this domain are characterized by adequate water supply for the users for the whole year, the existence of water-sharing provisions if water is deficient, the need and identification of alternate sources, highly engaged users in meetings and committees' affairs, high enforcement of rules, and a participatory decision-making process. For example, about 69% of RWSSs have an adequate water supply for the whole year. About 17% (31 of 180) of RWSSs have water-sharing rules during deficit, and that rule was formed with inputs from all users through open discussion. Similarly, about 64% (114 of 180) of water systems reported "good" and "very good" coordination and cooperation among users for attending meetings, contributing to discussions, and taking roles in repair activities. Furthermore, about 76% of water systems mentioned that they meet at least once a year, and 32% stated that users meet the requirements of the WASH system management (Figure 4). The resilience scores of all systems across the five domains are provided in Table S3.

3.3 | Environment

In this domain, the catchment's environmental conditions, including topography and land-use pattern, the historical occurrence of multiple hazards and disasters, and the presence of disturbance in the upstream catchment area, were assessed to understand the RWSSs' environmental resilience domain to climate extremes. RWSSs that have inadequate source protection, systems that are exposed to animal grazing and other disturbances, proximity to agricultural practices, and systems that are located on slopes without fencing have lower resilience scores. Additionally, the systems with a high frequency of disaster occurrences and no alternate sources available have low resilience scores.

Among the surveyed systems, 8% were classified in the very high resilience category and 3% were classified as very low resilience. For instance, the survey included eight different hazards (landslide, flood, soil erosion, forest fire, rockfall, snowfall, winter rain, and monsoon rain) that could affect RWSSs in the study area. A total of 11 out of 180 WASH systems scored highest in annual exposure to these hazards in the study areas, making the systems vulnerable to continuous stress from disaster and diminishing the system's resilience. In 59% of systems, some sort of protection of intake (fencing by open wire and concrete wall) was found, whereas 32% of the systems have open intake without any protection (Figure 5).

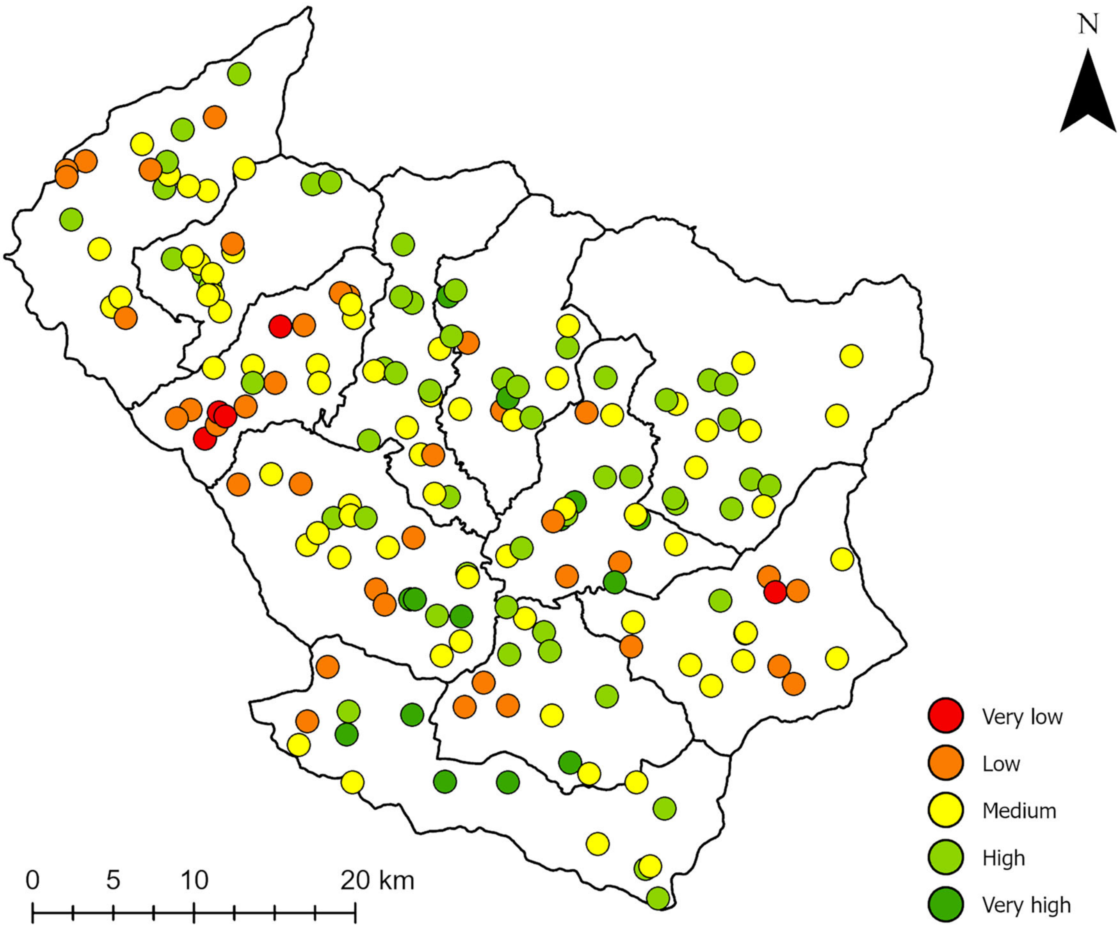

FIGURE 5 | Spatial distribution of the rural water supply systems resilience under the environment domain in Dailekh district.

The resilience score for all systems for this domain is provided in Table S3.

3.4 | Infrastructure

The assessment of the infrastructure domain examined various factors, including protective measures like fencing (ranging from local materials to wire fencing), cemented brick walls, and concrete structures at key locations such as intake sites and reservoirs. It also considered the age of the systems and the condition of distribution networks, focusing on damage to intake areas, tanks, pipe systems, and taps.

Among the evaluated water systems, 12 were classified in the very high resilience category, characterized by recent construction and strong protective measures, such as wired fencing combined with stone masonry or cement walls. These resilient systems showed no damage to their intakes, reservoirs, pipe systems, or taps. Overall, 107 out of 180 water systems had high-quality wired fencing or masonry walls at their intakes, and about 43% (76 out of 180) reported no damage to taps. In contrast, six systems fell into the lowest resilience category due to inadequate fencing, exposed pipes, and nonfunctional taps. Notably, 38% (69 out of 180) had exposed or improperly covered pipes, making them vulnerable to damage from human activity, animals, and disasters, which could lead to service disruptions.

Figure 6 shows the spatial distribution of RWSSs for the infrastructure resilience domain. A maximum number of low resilience systems in this category were observed in Aathabis UM, whereas the most resilient systems were observed in Bhagwatimai RM.

3.5 | Institutional Support and Governance

In this domain, indicators such as risk management programs, WASH emergency support, climate change adaptation, WASH support training, and support to measure climate phenomena were included to evaluate the system's climate resilience. The training and support play significant roles in the smooth functioning of the RWSSs, and these aids are primarily from governments and bilateral and multilateral organizations. The majority of the systems (119 of 180) users reported that they lack the capacity to test water quality, deal with disaster risk and management, repair the systems, and record bookkeeping of the systems. Similarly, 178 (of 180) systems mentioned that they have received no external aid and support for their systems (Figure 7).

3.6 | WASH Management

WASH system management domain comprises the availability of toilets, use of soaps forhand washing practices assigned responsibility for repair/reconstruction, proximity of toilets to water

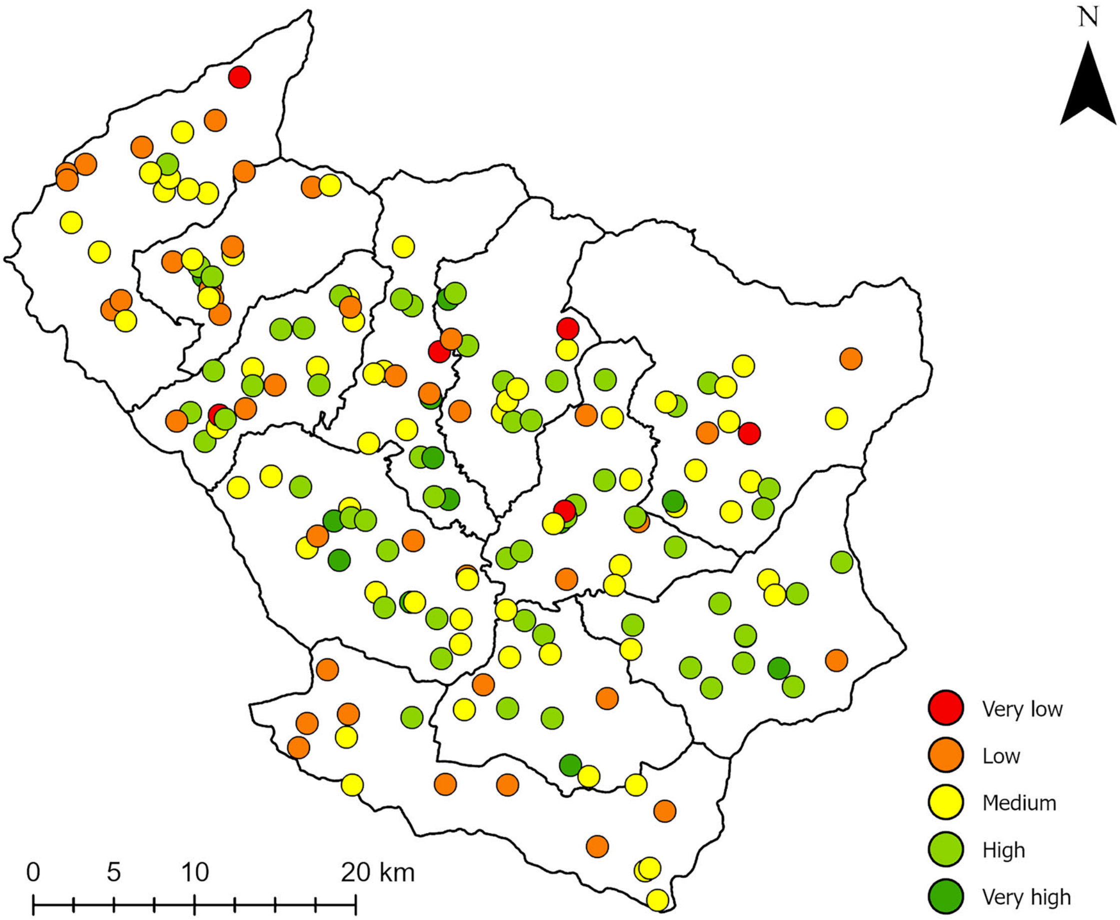

FIGURE 6 | Spatial distribution of the rural water supply systems resilience under the infrastructure domain in Dailekh district.

sources, and perception awareness of climate change (climate extremes) among users. Systems with a higher proportion of toilets, better hand washing practices, low proximity of toilets to water sources, and higher perception and awareness of climate change among users characterize the high scores in this domain.

Out of 180 RWSSs, only 43 (~24%) systems have been assigned a dedicated resource (a village maintenance worker or technician) to fix and manage the taps (Figure 8). Likewise, 62% (111 of 180) systems have reported that the majority of the users use soap to wash their hands, and in 76% of water systems, users use either soap or ashes or mud to maintain their hygiene and sanitation. About 97% of RWSS users have no toilets constructed in proximity to water systems. On the other hand, about 31% (56 out of 180) of system users reported having no or low knowledge of ongoing climate changes or their impact on WASH systems.

4 | Discussion

This article assesses the resilience of RWSS in Nepal's mountainous region by utilizing context-specific indicators under the five specific domains. Through a survey of representative systems, we used an additive index construction approach to benchmark their climate resilience. This research addresses the gap in local-level studies of climate resilience by providing a comprehensive list of relevant indicators for five domains of resilience derived from academic literature and practitioners' perspective.

The systems in the high resilience categories are typically supported by multiple positive factors, such as the presence of a safe intake structure, well-protected water sources, better sanitation services, strong hygiene practices, regular maintenance, active committee meetings and user engagement, preparedness for dry seasons through water-sharing rules, and minimal social disturbances. Conversely, systems classified as having low resilience commonly lack these elements. They often have unprotected water sources, broken distribution systems (e.g., damaged pipes and taps), a low proportion of toilets, and limited awareness of climate change and its impacts. These systems typically lack the capacity or experience to manage WASH services, receive little to no external support or training, and often lack water-sharing rules despite an inadequate water supply. In many cases, there is no identification of alternative water sources, no preparation for future challenges, and minimal discussion of issues within committees or with the community.

For instance, the Tallowodar RWS project has the highest overall resilience score among the 180 systems. It has a protected spring source (concrete wall with fencing and year-round availability), better condition of pipelines (fully buried), community-managed repairs, and full household toilet access near their houses and far from their drinking water source all support stability.

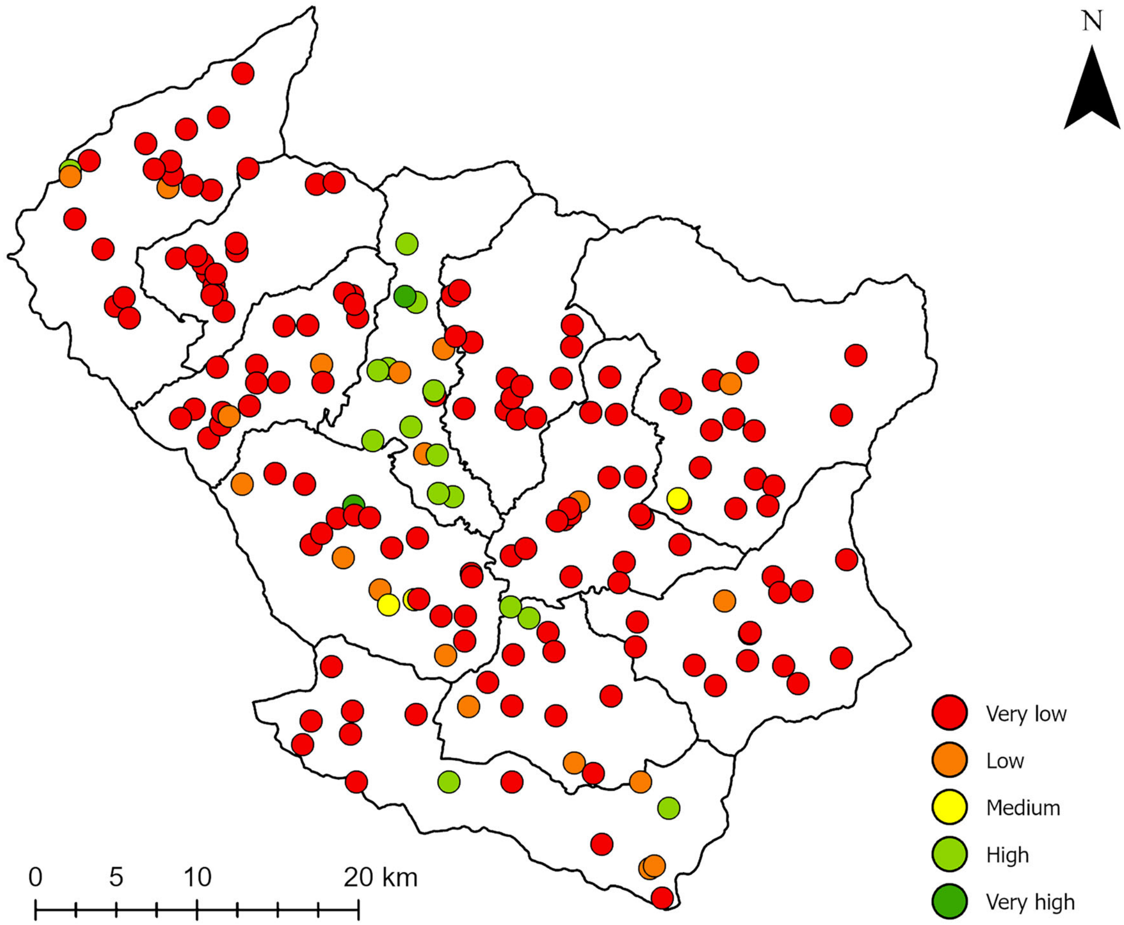

FIGURE 7 | Spatial distribution of the rural water supply systems resilience under the institutional support and governance domain in Dailekh district.

Regular trainings and meetings, inclusive decision-making, and climate awareness further enhanced their community capital. Each household has access to an individual tap for the whole community.

In contrast, the Bhatgaun RWS project has the lowest overall resilience score. Its primary source of drinking water is an exposed rivulet with high turbidity in drinking water during monsoon season and low flow during the dry season, and vulnerable pipelines (partially buried pipes that are regularly damaged by hazards like landslides), limited repair skills and equipment, and low institutional engagement (low support from local government) contribute to its fragility. In addition, they are still using community taps (8 community taps for 22 households), limiting reliable access to water. Though basic WASH infrastructure exists at the household level, lack of water quality monitoring, no identification of alternate sources, and less cooperative governance weaken their capacity to respond to hazards.

In the institutional support and governance domain, about 78% of the water supply systems are grouped in the very low resilience categories and ranked the lowest across all five domains. This finding corroborates the research of Nijhawan et al. (2022), which also identified institutional support as one of the weakest components of community-managed water supply projects in Nepal. Similarly, Khadka et al. (2023) observed that the systems in Nepal tend to prioritize water supply infrastructure and technical interventions over improvements in governance and institutional capacity. Our analysis further confirms these patterns: 66% of systems reported receiving no training or support in critical areas such as water quality measurement, disaster risk reduction, maintenance, climate change risk, and financial record keeping. Research by Vivekananda et al. (2014) on understanding climate resilience in western districts of Nepal also observed similar realities that a lack of governance and institutional effectiveness could significantly derail the survival and progress of a community after major environmental and social challenges.

Although the overall spatial distribution does not reveal a consistent trend across the entire study area, some localized differences are evident on the basis of the administrative boundaries. For instance, water supply systems in Bhairabi RM tend to be more resilient, with most systems falling in the medium to high resilience categories. In contrast, systems in Aathbis and Chamundabindrasaini UM are generally less resilient, categorized in the medium to low range. These variations suggest that resilience may be more influenced by local governance, institutional support, and community-level factors rather than by geographic location alone. This indicates a complex and context-specific nature of RWSS, where spatial risks may not always align with administrative or geographic boundaries.

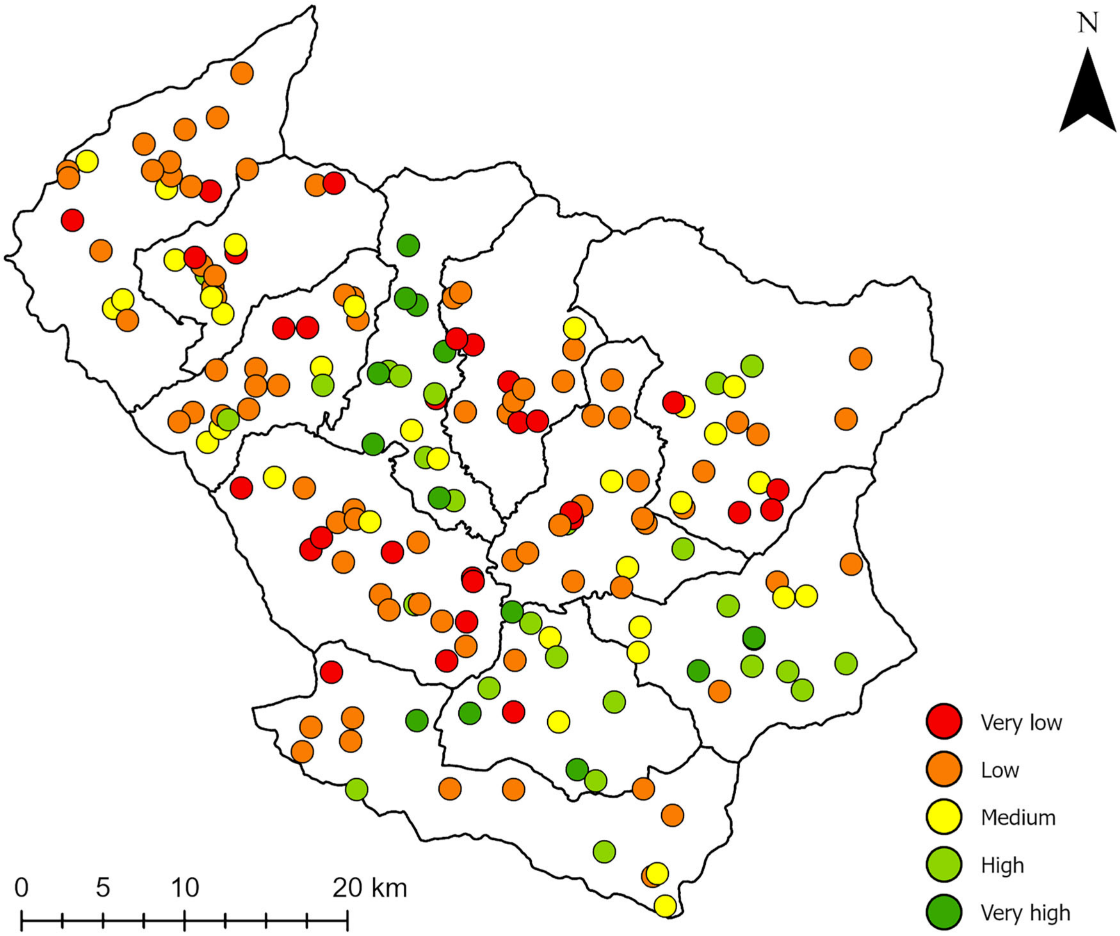

FIGURE 8 | Spatial distribution of the rural water supply systems resilience under the WASH system management domain in Dailekh district.

The RWSSs in our study area indicate that community capital enhances overall system resilience. Approximately 42% of these systems are classified in "very high" to "high" resilience scores, whereas about 36% fall into the medium resilience category. This finding aligns with a previous study on local-level risk and resilience-building processes in the mid-hills of Nepal, which highlighted those lower levels of social capital present significant challenges to risk reduction and resilience efforts (Jones et al. 2013). The study underscores that communities with a strong interest in risk reduction and active engagement in disaster preparedness tend to be more resilient to extreme events.

This indicator-based approach can also help establish baseline conditions for a system, enabling impact measurement to evaluate changes over time. Its flexibility also allows for adjustments to indicators and scoring based on the local context while exercising similar climate-resilient RWSS mapping efforts in other local areas, regionally and globally. Local governments can prioritize immediate interventions for the water supply systems with the lowest resilience scores, such as Bhatgaun Khanepani Yojana (Chamundabindrasaini Municipality), Dandakhoriya Chunkhani Khanepani Yojana and Dewalkada Khanepani Yojana (Narayan Municipality), and Gurgure Khanepani Tatha Sarsafai Yojana (Naumule RM), in order to improve their performance across various indicators (Table S3).

A limitation of this study is that interviews were limited to executive committee members, whose responses may reflect subjective judgments and institutional viewpoints. As a result, findings may not fully capture broader stakeholder perspectives. The primary aim of this study was to benchmark the resilience of RWSS, and therefore, field validation was excluded. However, future research could focus on field-level validation to strengthen these findings.

5 | Conclusions and Way Forward

This study applied a composite indicator approach to develop a water supply system's resilience index, allowing for the comparative analysis of climate resilience across the systems. Using 24 indicators and related variables from the literature, the research covered critical aspects such as environment, infrastructure, WASH management, institutional support and governance, and community capital. The resulting resilience mapping provides a baseline for future assessments of changes in resilience's components. Additionally, the indicators and variables reflect the specific context of Nepal's mountainous and mid-hill regions, making it adaptable for use in the systems in other mountainous countries.

Our research addresses what climate-resilient rural water supply systems look like by considering various aspects from physical to social dynamics in Nepal. This mapping guides local authorities in investing in and repairing the least resilient systems by targeting weak domains and indicators as well as learning from highly resilient systems. In the long term, this study provides a framework to build a climate-resilient system. The National Climate Change Policy (2019) of Nepal places strong emphasis on building a climate-resilient society (MOFE 2019), and WASH systems playa vital role in this development. The study reveals that institutional support and governance within the RWSS show the lowest resilience scores, highlighting a critical need for government intervention. Prioritizing the most vulnerable systems and focusing on their climate resilience would address significant gaps in risk management, emergency preparedness, and basic operational capacity.

This article presents a flexible yet robust indicator-based approach to climate-resilient mapping and is tested in the context of Nepal. Furthermore, this approach can be adapted to measure climate resilience mapping in other natural resources sectors, such as irrigation and forest management, by modifying the domains and relevant indicators to align with the unique social-ecological settings and local context.

Acknowledgments

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Data Availability Statement

The questionnaire used in this study is available in Table S1, along with the aggregated responses in Table S2.

Endnotes

[1] A ward is the smallest administrative unit within a municipality in Nepal.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Table S1 cli270014-sup-0001-TableS1.docx **Table S2** cli270014-sup-0002-TableS2.docx **Table S3** cli270014-sup-0003-TableS3.docx