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WASH infrastructure in Nepal: vulnerability, resilience to disasters, and mitigation strategies

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ABSTRACT

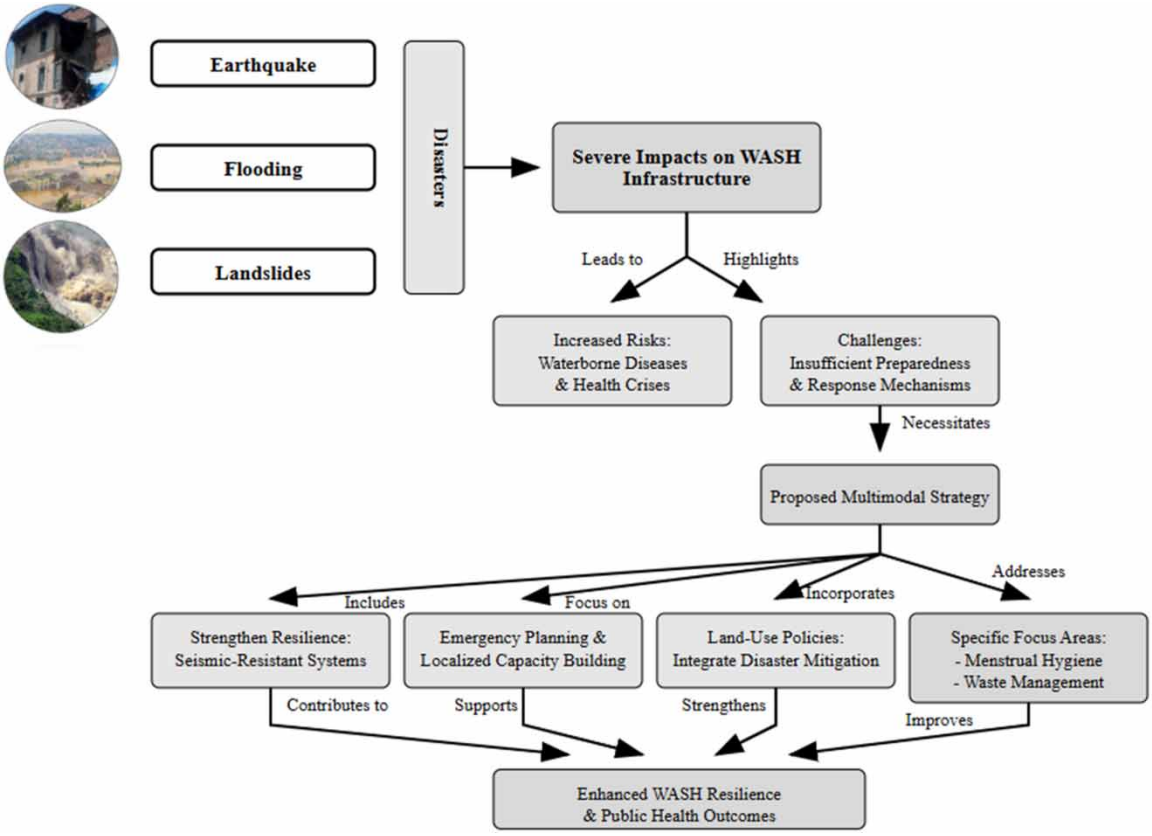
The infrastructure of water, sanitation, and hygiene (WASH) systems in Nepal is highly vulnerable to frequent natural disasters, endangering both socio-economic well-being and public health. This study employs a literature review approach to examine the intricate relationships between WASH systems and natural and human-induced disasters, including landslides, floods, and earthquakes. The results reveal severe consequences, including contaminated water sources, deteriorated sanitary infrastructure, and an increase in illness, disproportionately affecting marginalised populations. This research also sheds light on Nepal's remarkable resilience, showcasing innovative recovery programmes that combine indigenous knowledge with scientific approaches to enhance long-term preparedness. Key strategies include fortifying infrastructure resilience, distributing redundant facilities, enhancing institutional synergies through comprehensive emergency planning, localising capacity building, and incorporating disaster mitigation into land-use policies. Despite its contributions, this study is limited by its reliance on secondary data sources, which may include biases in reporting disaster impacts and resilience strategies. However, future research should aim at incorporating field studies and empirical analysis to enhance the accuracy and applicability of resilience frameworks. Despite these limitations, this study further proposes incorporating WASH resilience into sustainable development paradigms through multi-sectoral collaboration, strategic resource allocation, and ongoing implementation of the best practices. Globally, natural disasters pose a significant challenge to WASH infrastructure; however, in Nepal, the exceptional frequency and severity of disasters, such as landslides, floods, and earthquakes, necessitate a unique focus on innovative, context-specific strategies to enhance resilience and ensure long-term sustainability.

Key words: Disaster Impact, Water Quality, Resilience, Infrastructure Vulnerability, Climate Adaptation, Public Health Risk

HIGHLIGHTS

- Water, sanitation, and hygiene (WASH) infrastructure in Nepal shows high vulnerability to earthquakes, floods, and landslides.
- Environmental hazards, compounded by poor planning and infrastructure failures, severely impacts WASH services.
- Integration of multi-sectoral WASH resilience strategies with novel land-use and disaster risk reduction framework to strengthen infrastructure adaptation.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Despite encompassing an area of only 147,516 km^2, Nepal's geophysical structure is highly complex and prone to earthquakes, landslides, and floods disasters. The country is particularly vulnerable to these hazards, primarily due to its varied topography, diverse climatic conditions, and steep slopes, which increase its vulnerability to landslides (Government of Nepal 2018; Bajracharya *et al.* 2015). This uneven terrain's fundamental instability provides a perfect target for landslides, particularly during monsoon periods when the soil gets wet (Kayastha *et al.* 2013). Nepal's mountainous landscape adds to its complexity in terms of vulnerability due to inaccessibility and remoteness. Many communities reside in isolated areas, hindering timely response efforts in the aftermath of disasters. This isolation can significantly delay the delivery of critical aid and impede rescue operations (Gurung *et al.* 2012). The differences between the high Himalayas and the Terai lowlands result in varying climatic zones, from tropical to alpine, which increases the country's exposure to multiple weather-related hazards (Gautam 2017).

The impact of these natural disasters on Nepal's water, sanitation, and hygiene (WASH) infrastructure is significant, with many facilities destroyed. Earthquakes, landslides, and floods frequently damage water treatment plants, pipelines, and sanitation systems, leading to widespread contamination and outbreaks of waterborne diseases (Sekine & Roskosky 2018; Shrestha *et al.* 2017). Monsoon floods worsen these challenges by further contaminating water sources and increasing the risk of water-related illnesses (United Nations Office for the Coordination of Humanitarian Affairs (OCHA) 2015). Conversely, drought conditions intensify water scarcity, creating hygiene challenges and elevating the risk of water-related health issues. These impacts significantly compromise public health and impede post-disaster recovery efforts. With over 80% of Nepal's population exposed to such hazards, establishing resilient WASH infrastructure is critical to safeguarding public health and improving disaster response capacity (Gurung *et al.* 2012).

These vulnerability patterns are not unique to Nepal but are manifested across different regions globally with similar intensities. In Ethiopia alone, more than 1.1 million people were displaced between January and November 2023 due to climate-related events such as floods and droughts (UNICEF 2023). These displacements then

significantly disrupted the access to safe WASH services which then led to outbreaks of cholera and measles especially in the regions of Oromia, Somali and Amhara (UNICEF 2023). Similarly, the 2023 Kahramanmaraş earthquake in Turkey caused 450 km of surface rupture, displaced aquifers by 3 m and contaminated 78% of the groundwater sources with microbiological pathogens through damaged sewer networks (Öser *et al.* 2023). Furthermore, Iran's 2022 Imamzadeh Davood landslide triggered by flash floods also destroyed 56% of local water distribution pipelines and left 21% of households without sanitation access for more than 72 h (Takian & Raoofi 2023).

Although several studies have explored the impacts of natural disasters on WASH infrastructure, relatively few provide a focused analysis on Nepal's specific vulnerabilities and resilience needs, considering its unique geographic and socio-economic context. Additionally, a comparative analysis with regions sharing similar socio-economic and geographic characteristics, such as Bangladesh and Pakistan, reveals that Nepal's WASH infrastructure is highly vulnerable (World Bank 2022). This increased vulnerability stems from Nepal's rugged mountainous landscape, frequent seismic activity, and challenging terrain, which significantly hinder emergency response and recovery efforts (GoN 2018). In contrast, Bangladesh, although highly susceptible to flooding, benefits from relatively flat terrain and well-connected infrastructure, allowing for quicker disaster response interventions (World Bank 2022). Global frameworks, such as the Sendai Framework for Disaster Risk Reduction and the Sphere Association (2018), emphasise the importance of enhancing WASH systems through proactive planning. However, Nepal struggles to fully implement these guidelines due to geographic limitations and research shortages, making resilience-building a more complex challenge (UNDRR 2015; Sphere Association 2018).

Therefore, this study builds on existing literature by addressing these gaps and proposing targeted, context-specific resilience strategies. This study aims to explore the major factors that make Nepal's WASH infrastructure vulnerable to natural disasters and investigates ways to strengthen its resilience. Understanding the intricate dynamics between natural disasters and WASH infrastructure in this context is critical for developing robust approaches to safeguarding communities, ensuring sustained access to safe water and sanitation even in the face of disaster-induced disruptions. To fill this gap, this study employed a literature review methodology, focusing on secondary publication databases, to review the existing conditions of hazard impact on WASH infrastructure. The objective of this study is to (i) identify the multiple hazards in the context of Nepal, (ii) identify the vulnerability of WASH infrastructure in Nepal, and (iii) formulate proposed strategies for enhancing WASH resilience in Nepal.

2. METHODOLOGY

An extensive literature review was performed to identify relevant research on WASH, natural disasters and their interactions. This review spans the period from 2010 to 2023, utilising reputable academic databases such as Google Scholar and Scopus (Figure 1). A rigorous screening process was implemented to include only studies specifically relevant to Nepal. Priority was given to research focusing on WASH systems within Nepal or in regions with comparable geographic or climatic conditions. To ensure the relevance and applicability of the findings, studies unrelated to the topic were excluded from consideration. A combination of keywords was employed, including 'WASH practices', 'water quality', 'sanitation infrastructure', 'flood', 'earthquake', 'landslide', 'water supply', 'sanitation', and 'hygiene'. The collected data were selected based on relevance to WASH resilience in Nepal and comparable geographic or climatic conditions.

Inclusion and exclusion criteria: the inclusion criteria emphasised studies that discussed the direct impacts of natural disasters on WASH infrastructure, particularly those providing insights into resilience-building and best practices. Generally, most studies adopt this approach, which includes a generic impact on losses; however, the provision of specific impacts is lacking in those studies. Studies that did not address WASH-specific impacts or lacked empirical data were excluded. Additionally, grey literature from governmental and non-governmental organisations in Nepal was incorporated, including official reports from the Department of Disaster Risk Reduction (DDR) portal and a report detailing agency involvement in disaster mitigation. These include documents from government agencies and non-governmental organisations (NGOs) that are not peer-reviewed, such as government reports, technical manuals and reports, policy briefs, consultancy reports, and NGO publications.

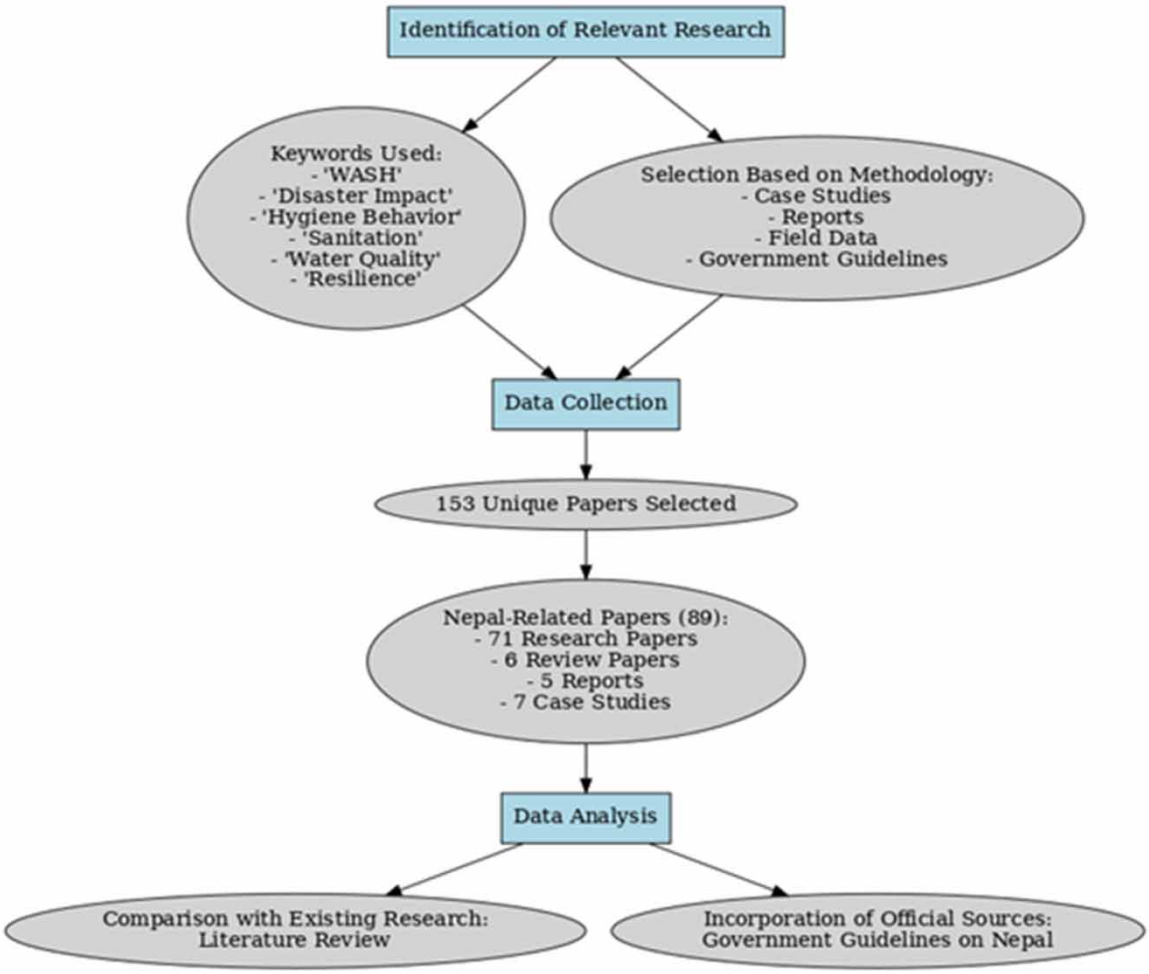


Figure 1 | Flowchart for literature review on WASH and natural disasters.

Data validation and analysis: secondary data from selected studies were analysed through thematic analysis, ensuring that findings aligned with the scope of this research. Grey literature was cross-checked with academic sources to ensure accuracy and relevance. The literature review is illustrated in Figure 1, which follows the PRISMA framework to outline the selection process, ensuring transparency in the study's methodology.

Limitations: The review is limited by its reliance on secondary data, which may not fully capture recent, field-based developments in Nepal's WASH sector. Additionally, the study's scope does not include primary data collection, which could provide deeper insights.

3. NATURAL DISASTER VULNERABILITY AND WASH

Natural disasters have a profound impact on human life, public health, and economic systems. . Globally, an average of 30,909 lives were lost annually to natural disasters between 1991 and 2020 (ADRC 2022). The 2004 Indian Ocean earthquake and tsunami resulted in approximately 280,000 casualties (Lavigne *et al.* 2013), while economic damages averaged $1.3 trillion between 2000 and 2011 (Barnes *et al.* 2019). In South Asia, disasters affected countries with limited adaptive capacity and fragile infrastructure. For instance, the 2011 floods in Pakistan, triggered by intense monsoon rains (Mahmood *et al.* 2021) and compounded by climate change (Ali *et al.* 2020), displaced 33 million people and caused damages exceeding $15 billion. The floods destroyed over 999,000 homes, illustrating the severe socio-economic and infrastructure challenges faced by developing nations (Hamid *et al.* 2011). Nepal also shares these vulnerabilities, exacerbated by its rugged topography, frequent seismic activity, and monsoon-dependent climate.

Similarly, a comprehensive UNICEF analysis identified 10 African countries, Benin, Burkina Faso. Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Nigeria, and Somalia where a 'triple threat' convergence creates extreme risk

conditions including inadequate WASH services, WASH-related diseases and climate hazards (UNICEF 2023). UNICEF (2023) also revealed that across these 10 countries, nearly one-third of children lack access to even basic water at home, and two thirds do not have access for basic sanitation services. The situation was further worsened by 2022 Nigerian floods that affected over 1.7 million people across multiple states and had also displaced 739, 322 individuals, destroyed 60,7554 houses and partially damaged 32,572 houses along with 440,000 hectares of farmland (IDMC 2025) The disaster had also triggered outbreaks of cholera and acute watery diarrhoea (AWD), especially in the northeastern states of Borno, Adawama, and Yobe to Bayelsa state (IDMC 2025). The 2023 Turkey earthquake also provide quantifiable comparisons for seismic WASH disruptions. Post-event analyses revealed turbidity levels in karst springs increased by 400 NTU, while 62% of coastal wells showed seawater intrusion from liquefaction-induced subsidence (Şimşek *et al.* 2024).

WASH systems are critical for safeguarding public health during and after disasters. They prevent the spread of diseases, promote hygiene, and ensure access to safe water and sanitation. However, disasters often expose the vulnerabilities of these systems. For example, during the 2010 Haiti earthquake, only 89% of the urban population had access to improved water sources, and less than 25% had access to adequate sanitation facilities pre-disaster (Denis 2015). Post-earthquake, only 3% of the population had adequate handwashing facilities with soap and water, contributing to a cholera outbreak that caused 8,534 deaths among 697,256 reported cases (Lantagne *et al.* 2013; Orata *et al.* 2014). Studies attribute the outbreak to pre-existing poor WASH infrastructure, overcrowding, and damaged healthcare systems (Andrews & Basu 2011; Gelting *et al.* 2013; Brown *et al.* 2012). United Nations (2010) reports that Asian and Pacific countries are especially vulnerable, with people in these regions four times more likely to be affected by natural disasters than those in Africa and 25 times more likely than Europeans or North Americans. According to UNDRR (2021), South Asia alone accounted for 58.6 million displacements due to weather-related disasters and 2.9 million from geophysical disasters between 2010 and 2021. World Bank (2022) reports that over the past two decades, more than half of South Asia's population, approximately 750 million people, experienced one or more climate-related disasters. Figure 2 summarises the impact of various categories of natural disasters over the specified periods globally. Each bar represents a specific category, showcasing the corresponding magnitude of impact measured in terms of deaths, economic damage, displacement, and other relevant metrics. The data highlights the significant toll that natural disasters have had on human life, infrastructure, and socio-economic well-being, emphasising the urgent need for effective disaster preparedness and mitigation strategies.

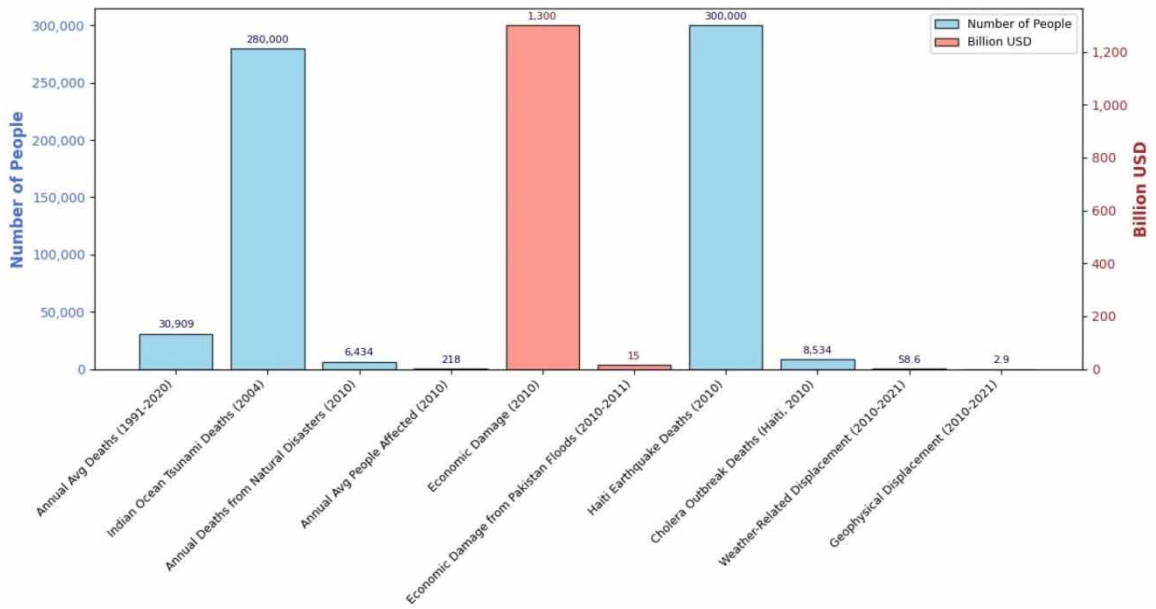


Figure 2 | The global impact of natural disasters (ADRC 2022[a]; Lavigne *et al.* 2013[b]; Wallemacq *et al.* 2015[c]; Barnes *et al.* 2019[d]; Barnes *et al.* 2019[e]; Mahmood *et al.* 2021[f]; DesRoches *et al.* 2011[g]; Lantagne *et al.* 2013[h]; UNDRR, 2021[i]; UNDRR, 2021[j]).

Nepal's WASH system noticeable exposure was recorded during the 2015 Gorkha earthquake natural disaster. The earthquake rendered 80% of water sources unusable, destroyed over 1,570 water systems, and led to

widespread contamination, thereby increasing public health risks (Uprety *et al.* 2017). These underscore the critical importance of disaster-resilient WASH systems in ensuring post-disaster recovery and long-term sustainability.

The increasing frequency and intensity of disasters, driven by climate change, intensify Nepal's risks. Rising temperatures accelerate glacial melt, increasing the likelihood of glacial lake outburst floods (Walsh *et al.* 2016), while more intense monsoons trigger landslides and flash floods that severely disrupt water supply and sanitation services. Urban encroachment into hazard-prone zones exacerbates these vulnerabilities by degrading natural buffers, such as forests and wetlands, which play a fundamental role in mitigating disaster impacts (Andreasen *et al.* 2022). Nepal consistently ranks among the most vulnerable countries globally to the impacts of climate change and natural disasters. The Global Climate Risk Index placed Nepal fourth in terms of climate risk and 30th in relative vulnerability to flooding (Thapa & Prasai 2022). The German Watch Climate Risk Index 2021 ranked Nepal as the 10th most affected country from 2000 to 2019. Nepal's climate vulnerability rankings from 1995 to 2021 highlight significant risks to its WASH infrastructure due to environmental hazards, limited economic resilience, and socio-economic constraints. Key findings include Nepal's high flood risk (as reported in the 1997 GVA report), exposure to climate change impacts (as per the 2021 Maplecroft index), and low adaptive capacity (as per the 2021 Notre Dame index), which collectively emphasise the critical need for strengthening the WASH sector's resilience. Detailed rankings and indices are summarised in Table 1.

Table 1 | Nepal's rank during various years based on the risk of climate change and the impact of flood

Year	Index	Nepal's rank
1995	Environmental Vulnerability Index (EVI)	47th
1996	World Resources Institute (WRI) Climate Vulnerability Index	49th
1997	Global Vulnerability Assessment (GVA) Report	30th
2021	Maplecroft Climate Change Vulnerability Index	34th
2021	Notre Dame Global Adaptation Index	13th

4. CHALLENGES IN WASH CONDITIONS DURING DISASTER

Access to WASH is recognised as a fundamental human entitlement. WASH is fundamental for saving lives in both emergency and everyday contexts and remains a top priority in emergency response (Pacheco *et al.* 2021). The absence of safe drinking water and the destruction of sanitation facilities pose significant risks to survivors in the aftermath of a disaster (Alam & Rahman 2014). Disasters can cause severe damage to WASH infrastructure and services (MacDonald *et al.* 2017). In addition to causing a decline in water availability and quality, as evident in the case of Bungtang village, where the lack of water and sanitation facilities following relocation due to an earthquake-triggered landslide created a serious problem, as demonstrated by a study from the National Planning Commission (2015). In developing countries such as Nepal, the WASH system is already facing numerous challenges, and disasters serve to exacerbate these issues (Aihara *et al.* 2015). However, this can also be seen as an opportunity to plan and effect change in WASH behaviour (Krishnan 2019). Accessibility to clean water is a critical challenge following a disaster, as water sources may become contaminated, damaged, or inaccessible. The following section discusses the specific impacts of disasters on water accessibility and infrastructure.

4.1. Accessibility to clean water

Disasters can significantly reduce or break water yield at sources by physically damaging water systems and altering natural water flows (Nepal 2015). The aftermath of disasters often limits access to clean water, significantly impacting sanitation and hygiene practices, which in turn heightens health risks and complicates emergency responses. For instance, floods frequently introduce pollutants like sediments, sewage, and industrial waste into water sources. Following the 2021 Melamchi flood, turbidity levels in the river spiked to 43.25 NTU due to debris flow and landslides, rendering the water unsafe for consumption (ADB 2023). Similarly, earthquakes and floods cause severe physical damage to water infrastructure, including pipelines, reservoirs, and boreholes. After the Gorkha earthquake, numerous water sources dried up, forcing residents to travel up to 1.5 h for water (Brown *et al.* 2012). A report by Nepal's National Planning Commission (2015) revealed that, among

11,288 assessed water supply systems, 1,570 sustained severe damage across the 14 most-affected districts, with restoration costs estimated at NPR 11.4 billion (approximately USD 114 million). Moreover, disasters further degrade the quality of both ground and surface water, exacerbating the challenges in providing safe and reliable water access.

4.2. Sanitation and hygiene

Limited access to and availability of water significantly impairs sanitation and hygiene activities in disaster-stricken areas (Brown *et al.* 2012). Insufficient water leads to reduced adherence to hygiene practices, such as handwashing. Overcrowding in shelters makes maintaining hygiene difficult, and disruptions to sanitation services, such as waste collection, exacerbate the situation. Damage to sanitation infrastructure also leads to a decline in hygiene practices (Shrestha *et al.* 2022). Toilets became unusable due to structural collapse, water contamination, and sedimentation.

Following the 2015 Gorkha earthquake, the National Planning Commission (2015) reported that over 22,000 toilets were completely damaged and 168,000 partially damaged, accounting for an estimated damage of NPR 4.52 billion (approximately USD 45 million). Partially damaged toilets often exhibit issues such as cracked walls, unstable foundations, or damaged roofs and doors, rendering them unsafe or less functional but not entirely unusable. However, this partial damage often meant limited use, leading many to open defaecation. Additionally, only 40% of camps had adequate sanitation facilities. The compromised sanitation and hygiene in disaster-affected areas create an environment where infectious diseases can quickly spread, increasing the risk of outbreaks among vulnerable populations.

4.3. Disease outbreak

The destruction of water and sanitation infrastructure, along with poor sanitary conditions triggered by disasters, can lead to disease outbreaks (Kouadio *et al.* 2012). Disasters can contaminate water and lead to waste accumulation (Gao *et al.* 2016), while population displacement results in overcrowding and inadequate shelters, making hygiene maintenance challenging (Kouadio *et al.* 2012). The Haitian experience following the 2010 earthquake shows a well-documented case study of these dynamics, where the factors like delayed response in some areas (with initial case fatality rates being higher in newly affected departments), challenges in water purification (despite distribution of millions of purification tablets), and difficulties in implementing sustained sanitation measures contributed to rapid spread of cholera (Orata *et al.* 2014; CDC 2011). By November 2010, the disease had affected all 10 administrative departments and capital Port-au-Prince, offering crucial insights for other nations facing similar risks (Tappero & Tauxe 2011). Similar patterns were seen after the Gorkha earthquake in 2015, when a health post in Barpak, Nepal, reported approximately 120 daily cases of diarrhoea and dysentery (Wanner 2022). Disasters increase the risk of various diseases, including diarrhoea, respiratory infections, malaria, leptospirosis, measles, dengue, hepatitis, typhoid, meningitis, tetanus, and fungal infections such as mucormycosis (Kouadio *et al.* 2012). A significant rise in diseases linked to WASH systems was observed following the 2009 earthquake and floods in Karonga District Hospital (Wanda & Manda 2017). In disaster settings, vulnerable groups, including women, children, and marginalised communities, face increased challenges, making it harder for them to access critical WASH services and protect themselves from disease.

4.4. Vulnerable populations

Women, children, the elderly, individuals with disabilities, pregnant or nursing women, and economically disadvantaged groups face higher risks during disasters. These individuals often face challenges accessing water due to its distance and scarcity, worsening their difficulties (Brown *et al.* 2012). Women, who typically collect water for their households, experience increased burdens during disasters. Specific needs for sanitation and hygiene, such as menstrual hygiene management, are often overlooked during relief efforts, as was evident after the 2015 Gorkha earthquake (Uprety *et al.* 2017). This oversight compels women to wake up at odd hours to fetch water and walk long distances to access toilets or makeshift facilities. Additionally, female students often face challenges in their studies due to the time spent fetching water, while many schools lack adequate WASH facilities to support their needs (Pacheco *et al.* 2021).

Vulnerable groups may also have limited access to information from local officials and can be excluded from community activities (Wisner *et al.* 2004). In countries like Nepal, where the caste system is prevalent, local caste and Dalit groups face additional challenges and disadvantages, such as limited access to clean water and sanitation, exclusion from relief efforts, social stigma, economic barriers, etc. Political instability and frequent

changes in government further complicate the implementation of effective disaster risk reduction policies, potentially exacerbating the vulnerabilities of these marginalised communities (Wanner 2022).

5. IMPACT OF NATURAL DISASTERS ON WASH INFRASTRUCTURE IN NEPAL: CASE STUDIES AND ANALYSIS

Throughout history, Nepal has been affected by numerous disasters, resulting in the loss of thousands of lives. Figures 3–5 illustrate the impact of earthquakes, landslides, and floods on the country's population. Nearly

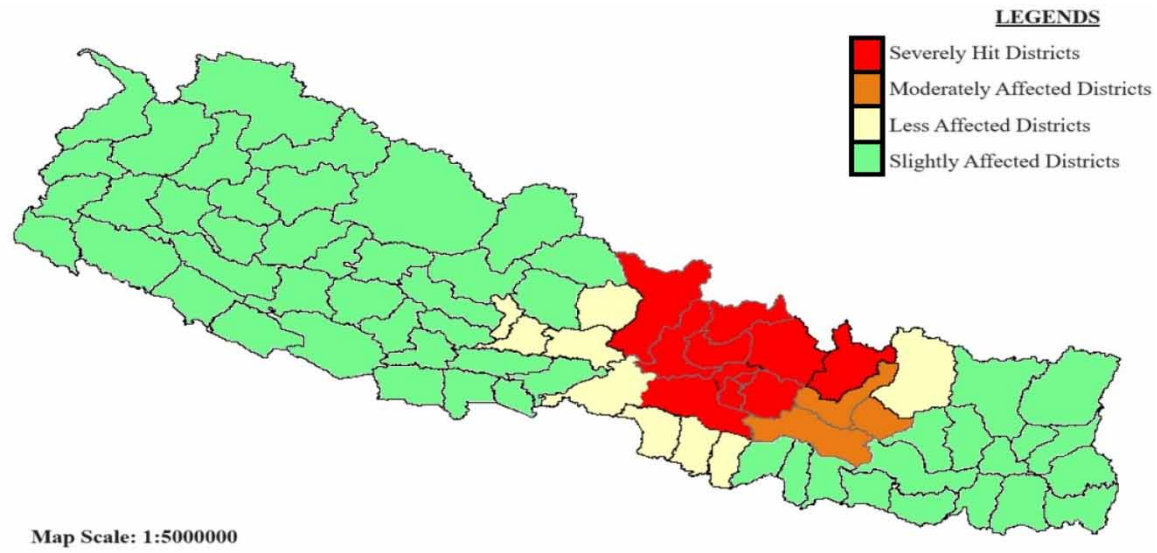


Figure 3 | Impact of 2015 Gorkha earthquake on Nepal's districts (HRRP 2018).

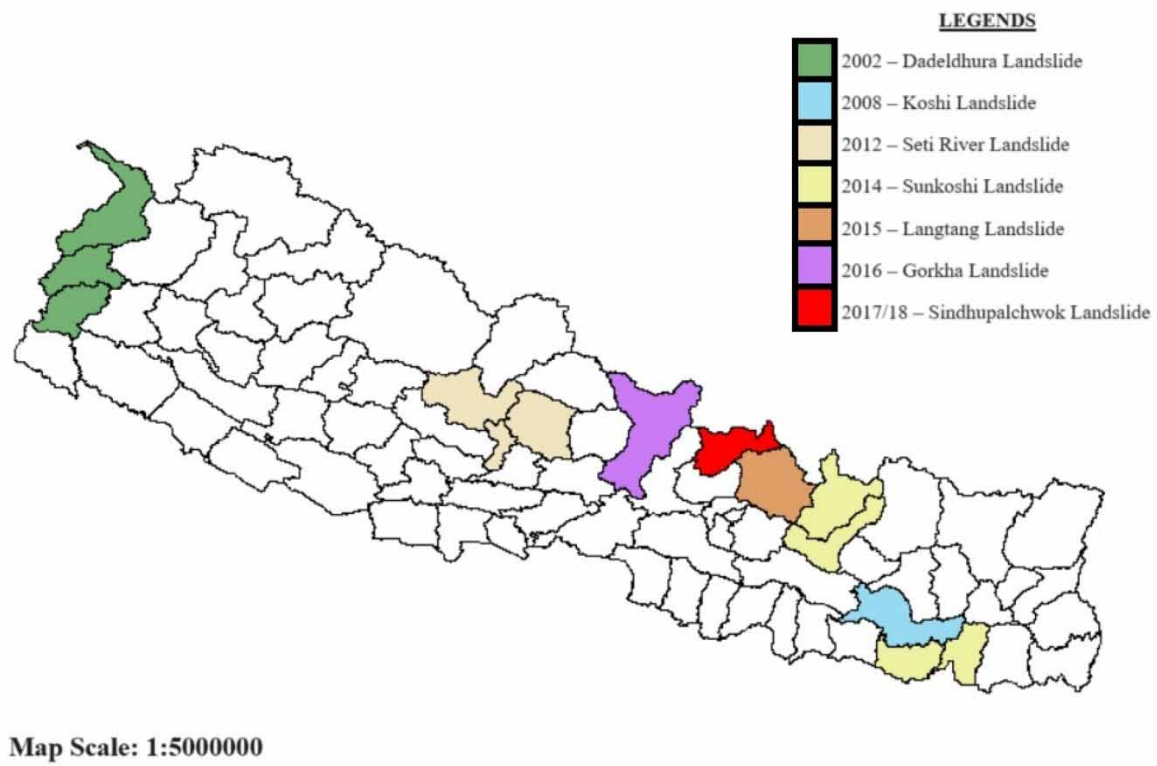


Figure 4 | Major landslides of Nepal (data source: Guo *et al.* 2022).

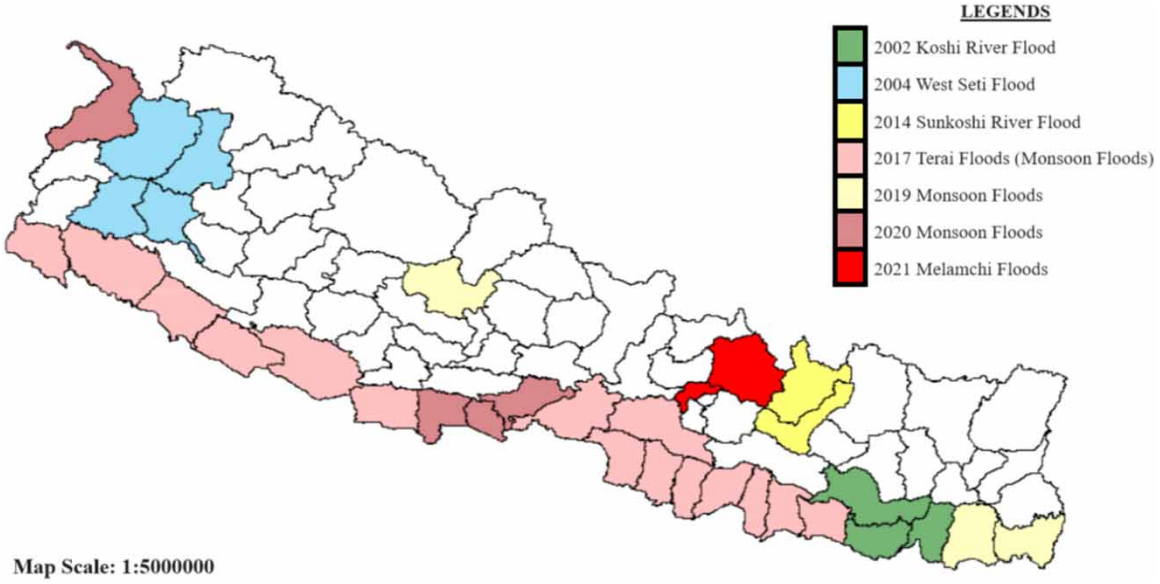


Figure 5 | Major floods of Nepal (data source: Uprety *et al.* 2017).

8,800 people were killed due to the devastating earthquake of 2015, which had its epicentre in the Gorkha district of Nepal (Uprety *et al*. 2017). It damaged infrastructure and properties, highlighting the need for stronger infrastructure and emergency preparedness. Table 2 illustrates the impact of the earthquake on various WASH infrastructures and compares the WASH impact and response strategies implemented within Nepal during different earthquakes with those worldwide.

Additionally, as shown in Figure 4, landslides have also been a recurring natural hazard in Nepal, resulting in destructive consequences. Notable events include the 2000 Syangja landslide that killed over 60 people, the 2002 Khotang landslide with 21 fatalities, and the 2009 Darchula landslide that caused 23 deaths. Studies have shown that landslide occurrences have increased since 2018, with the landslide density rising from 0.85 events per 1,000 km^2 in 2011 to 3.34 events per 1,000 km^2 in 2020 (Uprety 2017). One such landslide with destructive consequences was the Jure Landslide in 2014, which swept the mountainside, resulting in the deaths of 156 lives as per the Ministry of Home Affairs (Acharya *et al.* 2016).

Similarly, with the growing global temperature, the risk of flooding in countries like Nepal has also increased, especially in mountain basins, as floods have become more frequent than in the past. Although Nepal receives approximately 55 inches of rainfall annually, more than 80% of this occurs over just 4 months (June–September), which can lead to disasters such as floods (Bagale *et al.* 2023). Figure 5 illustrates the impact of floods in various districts of Nepal since 2000. One such incident is the 2021 flood in Melamchi Bazaar, which resulted in five fatalities, six injuries, and 20 missing persons, leaving behind debris over 10-m high (Adhikari *et al.* 2023). It also caused severe damage to the Melamchi water supply project and disrupted road access to villages. The Asian Development Bank (2023) reported that public infrastructures, including 13 suspension bridges, 7 motorable bridges, and multiple road stretches in areas above Melamchi Bazaar, were destroyed. This impacted the Melamchi Drinking Water Project, a national initiative aimed at supplying 170 million litres of water daily to the capital.

5.1. Impact of disasters on hygiene

One of the most vulnerable groups of population during disasters related to hygiene is women. Disasters can severely impact the female menstrual hygiene practices. According to Nepal News, only 10% of adolescent girls in Nepal practice adequate menstrual hygiene. Moreover, menstrual health management (MHM) is often overlooked during disaster response efforts, leaving women and girls particularly vulnerable during their menstrual cycles in post-disaster contexts (Krishnan & Twigg 2016). The disasters significantly impact women and girls by preventing them from accessing menstrual hygiene products and safe spaces to manage their periods as most of the emergency shelters are reportedly not women friendly, thus the prevalence of good menstrual

Table 2 | Comparative analysis of WASH impact and response strategies in earthquake-affected regions

Earthquake	Location	Date	Magnitude	WASH impact	Response strategies	Analysis of successes, limitations, and improvements	Source
Gorkha	Nepal (Gorkha, Dhading, Kathmandu)	25-Apr-2015	7.8	- 80% of water sources unusable (contaminated but potentially repairable) - 1,570 water systems destroyed (beyond repair) - Widespread contamination	- Community-based recovery - Emergency supplies - Temporary shelters - WASH repairs	**Successes**: Community-based recovery empowered locals, providing long-term resilience. **Limitations**: Initial resources were limited, resulting in a delayed response. **Potential Improvements**: Establish pre-earthquake WASH protocols and stock emergency supplies regionally.	(Uprety *et al.* 2017)
Jajarkot	Nepal (Jajarkot, West Rukum, Salyan)	3-Nov-2023	5.7	- Damage to water infrastructure - Increased risk of waterborne diseases	- Mobile water treatment units - Distribution of hygiene kits	**Successes**: Mobile units provided immediate clean water access, reducing disease risk. **Limitations**: Limited reach in remote areas. **Potential Improvements**: Integrate local water sources and expand mobile unit coverage for greater impact in remote regions.	(Baniya *et al.* 2024)
Udayapur	Nepal (Eastern Region, Udayapur)	20-Aug-1988	6.6	- Water pipelines damaged - Limited access to clean drinking water	- Immediate water trucking - Establishment of temporary water points	**Successes: Quick deployment of water trucking addressed immediate needs.** **Limitations: Delays in repairing pipelines caused extended water shortages.** **Potential Improvements: Enhance coordination for faster pipeline repairs and set up backup water storage facilities**	(Uprety *et al.* 2017)
Lamjung	Nepal (Lamjung, Kaski, Gorkha)	19-May-2021	5.8	- Minor damage to water infrastructure - Contaminated water sources reported	- Local repair teams mobilised - Hygiene promotion activities	**Successes: Rapid response by local teams ensured minimal disruption.** **Limitations: Limited training in hygiene promotion led to gaps in awareness.** **Potential Improvements: Implementing regular training programmes for local teams and providing sustained hygiene education.**	(Shrestha *et al.* 2022)
Bajhang	Nepal (Bajhang, Far-Western Region)	31-Aug-2022	6.1	- Springs dried up or shifted - Loss of access to key water sources	- Installation of alternative water supply systems - Community awareness on water conservation	**Successes: Alternative water sources provided short-term relief.** **Limitation: Implementing permanent solutions took time.** **Potential Improvements: Conduct geological studies to anticipate spring behaviour and plan alternate sources pre-emptively.**	(Baniya *et al.* 2024)

hygiene ranges anywhere between 11 and 85% with a pooled prevalence of 54% in low- and middle-income countries (Sumpter & Torondel 2013). Following the earthquake-induced landslides in the Gorkha district in 2015, which destroyed 180,000 individual toilets thus many women reportedly faced difficulties with menstrual hygiene due to a lack of private spaces and access to sanitary products (Thapa 2018; Amatya *et al.* 2018). Similarly, the Melamchi flood had washed away 50% of the hygiene supplies, including soap, sanitary pads, and other essentials, forcing many people to adopt unsafe practices such as using contaminated water for handwashing and using unsanitary latrines (Baniya *et al.* 2024). Similarly, the disasters caused substantial issues for people with disabilities to follow safe hygiene practice, notably including people with autism spectrum disorder (ASD), who found it particularly difficult to adapt to normal hygiene practices (Azadeh & Shahrokh 2015). Thus, it severely affects hygiene practices.

5.2. The impact of disasters on waste management

Disasters have a devastating impact on waste management systems. For example, the Waste processing centre, located in the heart of Melamchi Bazar, offered regular waste collection services and had a very engaged community. Established in 2019, the waste processing centre was designed to handle approximately 10 tons of waste per day and served as the primary facility for managing waste. The 2021 flood caused severe damage to the waste management infrastructure, as the waste processing treatment plant was destroyed and approximately 50% of waste collection vehicles were damaged or destroyed, making it difficult to collect waste from households and businesses. The waste storage facilities were also flooded and damaged, resulting in contamination and leakage of waste (Baniya *et al.* 2024). The report by ICIMOD (International Centre for Integrated Mountain Development) estimated that up to 80% of waste was being disposed of improperly after the flood. The disposal methods included dumping waste in open areas, burning it, and discarding it in water bodies, which further polluted drinking water sources. They increased the risk of waterborne, water-washed, and other water-related diseases. Disruptions in sanitation practices, such as increased open defaecation and improper waste disposal, led to a significant surge in diarrheal diseases, with the prevalence increasing from 10.5% before the flood to 25.3% after the flood (Baniya *et al*. 2024). Similarly, the 2015 landslide, triggered by the Gorkha earthquake, significantly impacted waste management systems, generating approximately 3.23 million tons of debris, of which only 1.07 million tons were effectively managed within a 2-year post-disaster period (Baniya *et al.* 2024). Field observations and governmental reports indicated a substantial portion of the debris was disposed through environmentally precarious methods, predominantly through open dumping along riverbanks and undesignated spaces, highlighting the critical need for developing disaster-resilient waste management infrastructure and implementing comprehensive emergency waste management protocols that integrate environmental sustainability, public health considerations, and community resilience strategies (Khanal *et al.* 2021).

5.3. The impact of disasters on water facilities and public health

The disasters also have a significant impact on water facilities, as they may contaminate water supplies, destroy pipelines, and obstruct access to safe drinking water (Galetzka *et al.* 2015; Ge *et al.* 2015). Water scarcity and contamination contribute to the spread of waterborne diseases, thereby worsening public health. The 2015 Gorkha earthquake, for example, significantly impacted water facilities, destroying 1,570 water systems and damaging 3,663, rendering almost 80% of the water sources unusable (Ge *et al.* 2015). Following the earthquake, 76 confirmed cholera cases were also reported in Kathmandu alone, most likely due to a lack of clean water and inadequate sanitation (Ge *et al.* 2015). The 2012 landslides in Kaski District affected 60,000 people, with 25% of the households reporting waterborne diseases (Karki *et al.* 2022). The 2018 Myagdi landslides destroyed major water supply systems serving an estimated 15,000 people, forcing women and girls to spend an average of 3 added hours per day collecting water from distant sources (Shrestha *et al.* 2022). The Nepal Water Supply Corporation reported that landslides account for 40% of annual maintenance costs for rural water supply systems (NWSC 2020). Similarly, the Melamchi Drinking water project which the government selected as the best technical option to provide drinking water to the Kathmandu valley in 1988 had its water quality severely contaminated by sediments and debris due to the Melamchi flood on 2021 which also had damaged the project in several places, further delaying the scheduled plan to complete the project by mid-February, 2022 (Baniya *et al.* 2024). A study done by Barbetta *et al.*, presented in Table 3 found the following changes in the water quality before and after the flood in a different river (Barbetta *et al.* 2022). The finding thus proved the change in the water quality of the river due to the flood.

Table 3 | The change in water quality before and after a flood (Source: Barbetta *et al.* 2022)

Parameter	Pre-flood	Post-flood	Percentage change
Turbidity (NTU)	20	350	1,650.00%
Total organic carbon (mg/L)	2	5	150.00%
Total dissolved solids (mg/L)	100	150	50.00%
Total coliform (CFU/100 mL)	10	1,000	9,900.00%
Fecal coliform (CFU/100 mL)	1	100	9,900.00%

However, a 2021 study conducted by the Asian Development Bank found that the initial turbidity of the Melamchi River was 6 NTU. After the flood, however, a quantitative study on sediment erosion and deposition along river channels indicated that approximately 10.1 $\pm$ 8.11 million m^3 of sediment might have raised the turbidity levels to around 10,000 NPT, which is far beyond the WHO's maximum allowable turbidity limit of 5 NTU (Barbetta *et al.* 2022). The turbidity, however, also decreased with time. Figure 6 illustrates the impacts of earthquakes on Nepal's WASH systems, highlighting issues such as unusable water sources and destroyed water systems (Ge *et al.* 2015). It also presents the impact of floods on water quality (Barbetta *et al.* 2022). These figures highlight the substantial challenges that natural disasters pose to Nepal's WASH infrastructure and environmental health.

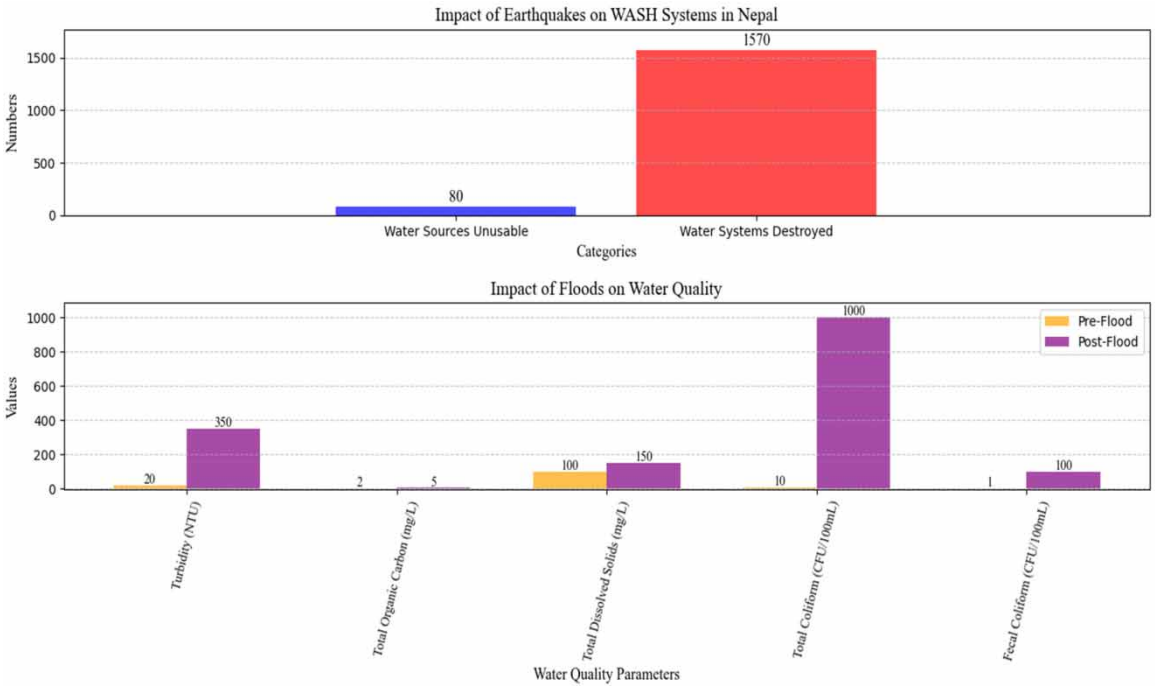


Figure 6 | Impact of various disasters on water facilities and water quality (data sources: Barbetta *et al.* 2022; Ge *et al.* 2015).

6. DISASTER PREPAREDNESS AND RESPONSE

Nepal's vulnerability to disasters, such as floods, landslides, and earthquakes, severely impacts its WASH infrastructure. The 2015 earthquake alone disrupted access to clean water for approximately 1.7 million people across 14 districts and damaged 80% of sanitation facilities in the most affected regions (GoN 2018). Despite efforts to mitigate these challenges, the fragility of WASH systems continues to affect public health risks during disasters. Proactive disaster preparedness and response strategies are crucial for minimising these impacts. The following are the various strategies adopted in Nepal for disaster preparedness and response.

6.1. National Disaster Management Framework

The National Disaster Management Framework (NDMF) provides guidelines to coordinate disaster response efforts effectively. However, evidence suggests room for improvement in integrating WASH priorities. During the 2015 earthquake, less than half of the affected households received WASH assistance within the first month of the disaster (NDRF 2019). The framework focuses on preparedness and immediate response. For example, in 2017, when monsoon floods affected over 1.7 million people in Nepal, emergency water distribution programmes provided safe drinking water to 800,000 individuals (Kafle 2017). However, a lack of pre-disaster planning led to uneven resource allocation, resulting in rural areas being disproportionately affected. Internationally, frameworks for post-disaster needs assessment, such as the comprehensive Handbook for Disaster Assessment developed by the Economic Commission for Latin America and the Caribbean (ECLAC 2014), also emphasise a multi-sectoral approach that integrates WASH considerations into broader recovery and risk reduction planning, offering models for enhancing national preparedness protocols by providing methodologies to evaluate damages, losses, and human development impacts across various sectors including water and sanitation. Drawing from these international best practices the NDMF must prioritise comprehensive WASH strategies, including disaster-resilient infrastructure, real-time data integration, and prepositioned supplies, to ensure equitable and effective response during emergencies (GoN 2018).

6.2. Early warning systems

Early warning systems (EWSs) play a critical role in disaster mitigation, particularly for WASH infrastructure. Nepal's Community-Based Flood Early Warning System (CBFEWS), implemented in 2010, utilises telemetry systems to monitor water levels and issue warnings. These systems have proven effective, as seen during the 2012 West Rapti River floods. With water levels peaking at 7.24 m, timely warnings enabled communities to relocate and protect their WASH facilities, thereby preventing water contamination and disease outbreaks (Shrestha *et al.* 2022). However, EWS alone cannot safeguard immovable WASH infrastructure, such as water treatment plants. Measures such as building elevated treatment facilities and using adaptable designs are necessary to mitigate the direct impacts of disasters. For instance, during the 2015 earthquake, untreated water contamination resulted in a 60% increase in diarrhoea cases in affected districts (Paul *et al.* 2022). In addition to flood warnings, EWSs for landslides, such as the one established in Dolakha in 2018, demonstrate the adaptability of such systems. It successfully relocated 495 individuals from 117 households and safeguarded water storage units, which are critical for maintaining hygiene (Thapa & Adhikari 2019).

6.3. Role of government agencies

Government agencies play a key role in disaster preparedness and response. The Ministry of Water Supply and the Department of Water Supply and Sewerage Management play key roles in maintaining WASH services during crises. For instance, during the 2015 earthquake, the Nepal Army deployed over 3,000 portable sanitation units and established temporary water supply systems benefiting more than 500,000 displaced individuals (GoN 2018). However, coordination between the Ministry of Home Affairs and sectoral agencies was lacking, resulting in delayed responses in remote areas. Rural districts saw a 40% higher prevalence of waterborne diseases than urban centres due to uneven resource distribution (NDRF 2019). Future strategies must integrate WASH-specific policies, such as the construction of disaster-resilient water and sanitation facilities and expand the scope of the Ministry of Water Supply in disaster response planning (Cook *et al.* 2018).

6.4. Roles of NGOs and INGOs

Both NGOs and international non-governmental organisations (INGOs) play crucial roles in enhancing WASH services in disaster-affected areas. These organisations not only fill gaps in disaster response but also foster resilience by addressing immediate needs, promoting sustainable practices, and enhancing community capacities. During the 2015 earthquake, local NGOs, such as the Nepal Red Cross Society, were instrumental in providing emergency WASH support. They constructed over 3,000 temporary latrines, distributed hygiene kits to 250,000 people, and launched hygiene awareness campaigns that significantly reduced post-disaster health risks (Cook *et al.* 2018). INGOs have made significant contributions to Nepal's disaster preparedness and response, particularly in large-scale emergencies. Organisations such as Oxfam, UNICEF, and WaterAid have played pivotal roles in addressing WASH needs during disasters. During the 2015 earthquake, Oxfam supported water trucking operations and distributed water purification kits, benefiting over 300,000 individuals. The organisation also installed

handwashing stations in shelters, promoting hygiene and preventing disease outbreaks (Cook *et al.* 2018). Following the 2017 floods, UNICEF rehabilitated 450 damaged water points, ensuring access to clean water for 150,000 children (NDRF 2019). WaterAid focused on improving disaster-resilient WASH infrastructure, including elevated water tanks and flood-resistant latrines, in flood-prone areas of southern Nepal. Figure 7 shows the WASH contributions by major organisations in Nepal.

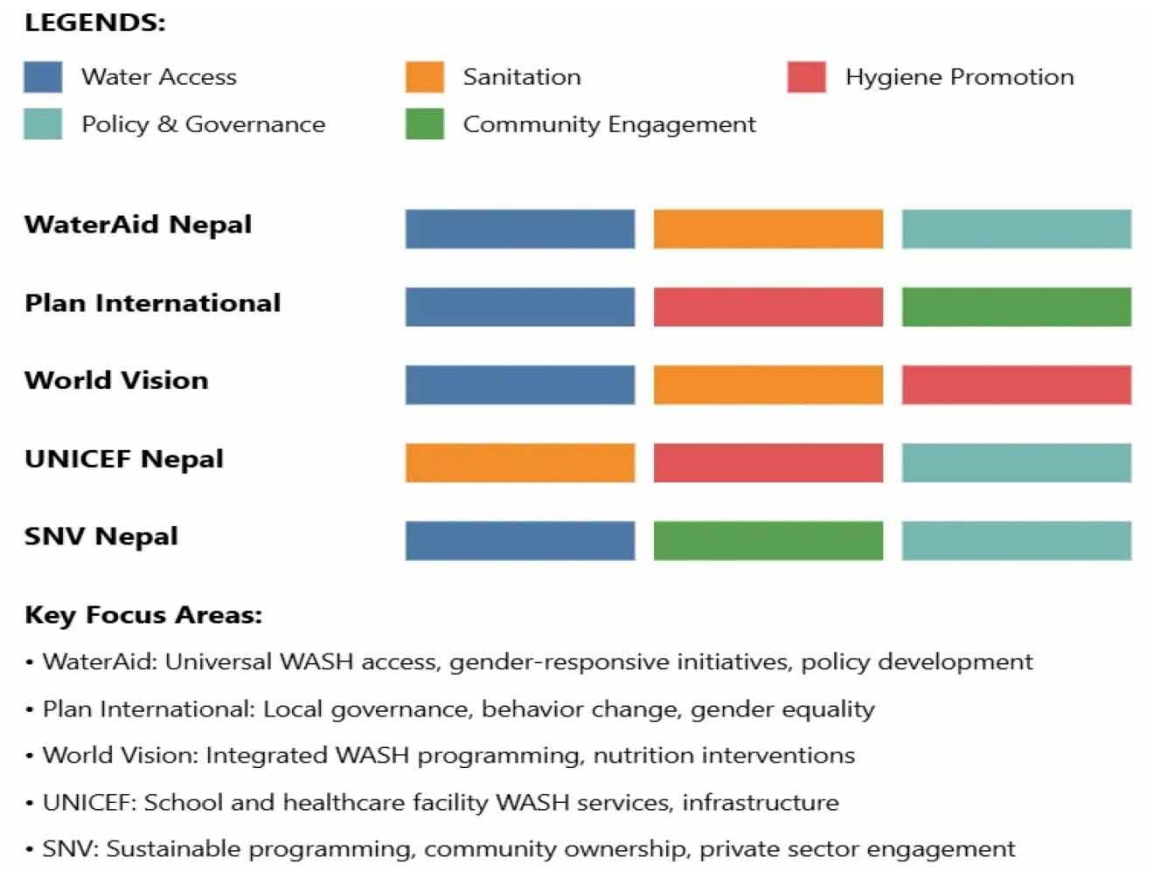


Figure 7 | WASH contributions by major organizations in Nepal.

6.5. Coordination and capacity building

Effective disaster response can be effective in coordination and capacity building. However, Nepal's disaster response has often faced challenges in these areas. The lack of clear communication channels between government agencies and NGOs during the 2017 floods resulted in resource duplication in some regions and shortages in others (Kafle 2017). Capacity building should focus on resilience. Training local communities to construct elevated water storage tanks and disaster-resistant sanitation units can significantly reduce vulnerabilities. For instance, post-disaster reconstruction programmes that incorporated resilient design principles saw a 30% reduction in WASH service disruptions during subsequent floods (Cook *et al.* 2018).

7. RECOMMENDATIONS

The disasters had a devastating impact on WASH conditions in affected communities, severely disrupting access to clean water, sanitation systems, and hygiene practices. The immediate aftermath of the disaster was characterised by a scarcity of safe water, inadequate sanitation, and suboptimal hygiene measures, which led to a heightened risk of waterborne illnesses and other health concerns. To effectively address these WASH challenges and promote long-term WASH resilience, a comprehensive recovery plan is essential. This plan should prioritise the following key areas, which are summarised in Figure 8:

Figure 8 | Comprehensive WASH strategies for disaster-affected communities.

- WASH assessment and monitoring: Conduct comprehensive assessments of WASH conditions in affected communities, including water quality testing, evaluation of sanitation infrastructure, and surveys of hygiene behaviour. Regularly check WASH indicators to track progress and address emerging challenges.
- WASH infrastructure restoration and rehabilitation: Prioritise the restoration and rehabilitation of damaged WASH infrastructure, employing resilient construction techniques and materials to withstand future disasters.
- WASH coordination and collaboration: strengthen coordination and collaboration among WASH stakeholders at national and local levels, setting up clear roles, responsibilities, and communication channels for an effective response.
- Hygiene promotion and education: implement tailored hygiene promotion and education campaigns, emphasising handwashing practices, safe water storage, and proper sanitation techniques.
- Community empowerment and engagement: involve affected communities in decision-making processes and empower them to manage WASH practices. Establish community-based WASH committees to oversee activities and promote sustainability.
- Disaster preparedness and risk reduction: integrate WASH considerations into disaster preparedness strategies, develop contingency plans, conduct training for response teams, and incorporate vulnerability assessments into land-use planning.

The outlined recommendations include proactive measures aimed at enhancing disaster preparedness and reactive strategies designed to ensure effective interventions both during and after disasters. These strategies focus on improving infrastructure resilience, promoting community engagement, and integrating disaster risk reduction into policy frameworks.

Figure 9 outlines a comprehensive and integrated approach required to address the vulnerabilities present in the WASH sector, especially during periods of natural disasters. Natural disasters pose significant challenges to WASH infrastructure, leading to an increased risk of waterborne diseases. Thus, these health issues are one of the critical outcomes of infrastructure failures that are further compounded by insufficient preparedness and response mechanisms. This inadequacy is highlighted by systemic issues, including a lack of seismic-resilient systems, limited emergency planning, and insufficient integration of disaster mitigation into land-use policies. Therefore, the multimodal strategy is required, which serves as the major component of the proposed framework that emphasises a multifaceted approach to enhance WASH resilience and includes four major components:

1. Strengthen resilience through seismic-resistant systems: as Nepal is highly vulnerable to seismic activities, the development and adaptation of WASH infrastructure that can withstand earthquakes must be designed and incorporated into water supply systems, sanitation, and waste management units. Innovative materials and construction techniques, as well as retrofitting existing systems, should be prioritised to enhance resilience.
2. Emergency planning and localised capacity building: effective disaster preparedness relies on well-structured emergency plans tailored to local contexts. These plans should also involve capacity building at the community level so that local stakeholders are adequately trained to respond efficiently. Training programmes on disaster response and recovery can further foster the culture of resilience.
3. Land-use policies for integrated disaster mitigation: integrating disaster mitigation measures into land-use planning can prevent the construction of WASH infrastructures in high-risk areas. Therefore, the policy framework should aim at mandating risk assessments during infrastructure development.

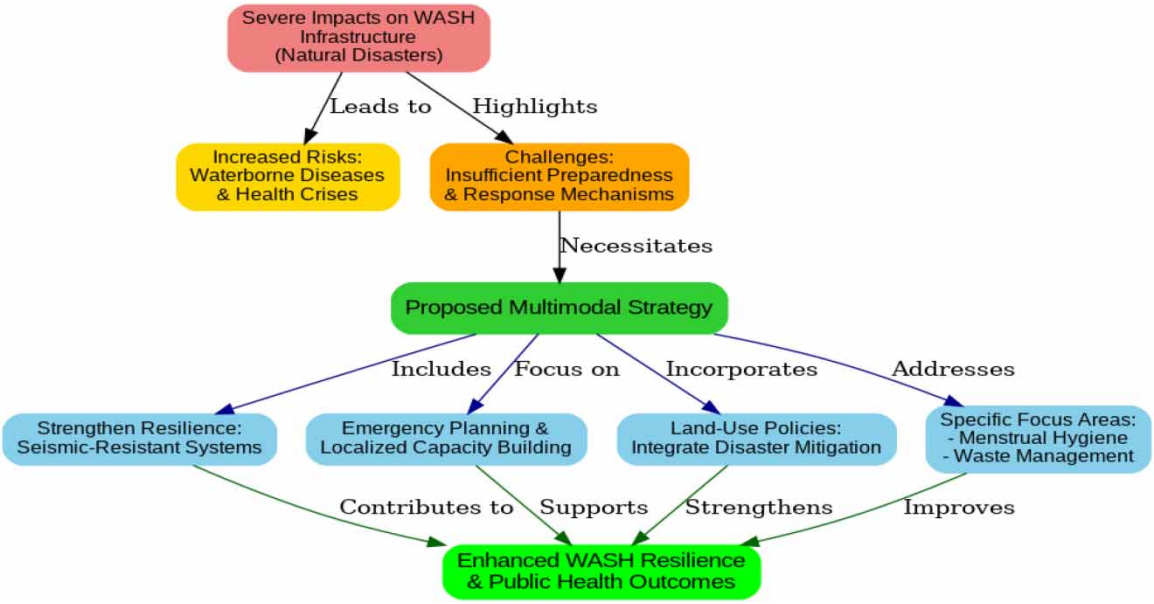


Figure 9 | Flow diagram of proposed strategies for enhancing WASH resilience in Nepal.

4. Specific focus area: menstrual hygiene and waste management: as menstrual hygiene is often overlooked during disaster response; it amplifies the vulnerabilities of women and girls. Therefore, incorporating menstrual hygiene into emergency WASH planning can address these gender-specific needs.

8. CONCLUSION

Natural disasters have a severe impact on Nepal's WASH infrastructure, which requires immediate attention and effective mitigation measures. This current study has shown the intricate relationship between WASH infrastructure and natural disasters, emphasising the critical necessity for proactive disaster planning and resilience measures. The outcomes demonstrate that the widespread damage to WASH facilities, coupled with insufficient disaster preparedness and response mechanisms, significantly elevates the risks of waterborne diseases and related health crises. To minimise this, we recommend practical and affordable solutions, such as constructing new WASH facilities with seismic and flood-resistant features like elevated tanks and sturdy pipelines. This study emphasises the importance of multi-sectoral collaboration, effective resource allocation, and the continued adoption of data-driven best practices to ensure the long-term sustainability of WASH systems. By incorporating WASH concerns into disaster preparedness plans and disaster mitigation into land-use regulations, various losses due to natural catastrophes can be minimised. We recommend establishing a national fund to enhance WASH systems in high-risk areas, expand EWSs – particularly for WASH protection – build on successful community flood alerts, and train communities to maintain these systems and promote hygiene practices. Every dollar invested yields returns – $2.5 from disaster preparedness (Shrestha *et al.* 2022) and $4 in avoided losses through resilience (Hallegatte *et al.* 2019). These smart investments protect health, secure infrastructure, and drive sustainable progress in Nepal. These actions will help safeguard infrastructure, protect health, and drive sustainable progress in Nepal. By adopting a holistic and multidisciplinary approach to WASH resilience, Nepal can establish a more sustainable and resilient WASH system, thereby preserving the health and well-being of its residents in the event of a natural disaster.

AUTHOR CONTRIBUTIONS

A.D., A.M., and A.A. equally contributed to writing the original draft, editing, and reviewing; S.B.G. contributed to reviewing, editing, and supervision; B.K.K. contributed to conceptualization, writing original draft, reviewing, editing, and supervision.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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