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Beyond Exposure: Vulnerability, Adaptive Capacity, and Climate-Resilient WASH in Rural Cambodia

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Abstract

This paper examines the impacts of climate-related hazards on water, sanitation, and hygiene (WASH) access and practices in rural Cambodia using a Vulnerability–Exposure–Adaptive Capacity (VEAC) framework. Drawing on survey data with 423 households and 96 local authorities across five climate-vulnerable provinces in rural Cambodia, the study integrates household experiences with perspectives from village, commune, and district authorities responsible for local WASH planning and service delivery. The analysis distinguishes exposure to floods and droughts from underlying socio-economic and environmental vulnerabilities in WASH access and use, and from the social, economic, and geographic determinants shaping adaptive capacity. The findings show that while exposure to climate hazards is geographically patterned, similar levels of exposure do not produce uniform WASH outcomes. Flood impacts on hygiene, sanitation, and health are mediated by village environmental conditions and household economic status, while drought impacts and responses reflect broader locational factors alongside income insecurity and social marginalisation, including disability, older age, and female-headed households. Although awareness of climate risks and adaptive WASH options is relatively high, uptake of adaptation measures remains uneven. Adaptive capacity is constrained less by knowledge deficits than by structural and economic barriers, resulting in short-term coping rather than sustained adaptation. Overall, the study demonstrates that climate-related WASH vulnerability is shaped more by socio-economic vulnerability and mismatches in adaptive capacity across household and authority scales than by hazard exposure alone.

Keywords: climate change; water, sanitation, and hygiene (WASH); adaptive capacity; vulnerability; floods and droughts; rural livelihoods; climate resilience; Cambodia



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1. Introduction

Cambodia is highly exposed to climate-related hazards, particularly floods and droughts, which pose persistent risks to rural livelihoods and WASH systems. These hazards increasingly undermine water quality, sanitation functionality, and hygiene practices in poor and marginalised communities. While physical exposure is widespread, evidence shows that climate impacts on WASH are uneven and shaped not only by hazard intensity but also by socio-economic conditions, infrastructure quality, and governance capacity. Despite expanding climate policy frameworks and investments in rural WASH, many households in rural Cambodia continue to experience climate-related service degradation and constrained adaptive responses, highlighting the need for analytical approaches that move beyond hazard-centric assessments to examine how vulnerability and adaptive capacity mediate WASH outcomes.

This paper applies a Vulnerability–Exposure–Adaptive Capacity (VEAC) framework to examine the impacts of climate-related hazards and adaptation pathways in rural Cambodia. Drawing on survey data with 423 households and 96 local authorities across five climate-vulnerable provinces in rural Cambodia, the study integrates household experiences with perspectives from village chiefs, and commune- and district-level authorities (referred to as local authorities in this paper) responsible for local WASH planning and service delivery. The analysis examines (i) exposure to floods and droughts, (ii) underlying vulnerabilities in WASH access and use, and (iii) the social, economic, and geographic determinants of adaptive capacity. By triangulating evidence across household and local authority scales, the paper provides new empirical insight into why similar levels of climate exposure produce different WASH outcomes, and why adaptation remains uneven despite relatively high awareness of climate risks.

The remainder of the paper is organised as follows. Sections 2 and 3 review the literature on climate change, WASH, and adaptation in Cambodia and introduce the Vulnerability–Exposure–Adaptive Capacity framework adopted in this study. Section 4 describes the study design, data collection, and analytical methods. Section 5 presents the results, structured around exposure to climate hazards, patterns of vulnerability, and determinants of adaptive capacity across households and local authorities. Section 6 discusses the findings in relation to the VEAC framework and existing literature, Section 7 concludes by summarising key contributions and highlighting implications for climate-resilient WASH policy and practice in climate-vulnerable rural Cambodia or similar contexts, emphasising the central role of adaptive capacity in shaping WASH outcomes beyond exposure alone.

2. Literature Review

2.1. *Climate Change and Its Impact on WASH Access and Use in Cambodia*

Cambodia remains highly vulnerable to climate change, particularly floods and droughts that directly affect water supply, sanitation, and hygiene (WASH) services. It is consistently ranked among the most climate-vulnerable countries globally, with the 2020 Global Climate Risk Index placing it among those at highest risk due to increasing frequencies of extreme weather events [1]. Flood exposure continues to disrupt lives and livelihoods, while intensifying drought conditions threaten water availability and agricultural productivity [2]. These hazards have profound implications for rural WASH systems, where flooding contaminates water sources and strains infrastructure, and droughts exacerbate water scarcity and hygiene constraints, particularly among poor and marginalised populations [2,3].

According to the Climate Risk Profile: Cambodia (2024), climate risks are escalating due to rising temperatures, increased hydrological variability, and greater exposure to extreme weather events [4]. Average temperatures are projected to rise by more than 3 °C by the end of the century under high-emissions scenarios, increasing risks to health and labour productivity. Flooding remains the most severe hazard, with Cambodia ranked among the most flood-exposed countries globally, while drought risk is projected to intensify, reducing water availability for domestic use, hygiene, and agriculture. Without effective adaptation, combined flood and drought impacts could reduce national GDP by close to 10% by mid-century, underscoring the urgency of strengthening climate-resilient systems and adaptive capacity [4].

Flooding mobilises faecal contaminants and pollutants into surface and groundwater sources, while droughts concentrate contaminants and increase reliance on unsafe or distant water sources, undermining hygiene practices and service reliability [5,6]. Flooding frequently contaminates sanitation facilities, leading to pit inundation, septic tank failure, and drinking water contamination, while intensified rainfall and river flooding increas-

ingly overwhelm drainage and sanitation systems [4,5,7,8]. Sanitation systems, including faecal sludge management (FSM), face particularly acute risks with direct public health consequences. While drier conditions may marginally reduce groundwater contamination risks for some onsite sanitation technologies, these benefits are frequently offset by increasingly intense flood events. Flooding can inundate pits, cause septic tank failure and backflow, restrict access for desludging services, damage transport infrastructure, disrupt treatment facilities—often located in flood-prone areas—and increase unsafe disposal practices, particularly in low-lying and high-groundwater areas [5,6,9,10]. Declining water availability further undermines water-dependent sewerage and septic systems by reducing flushing volumes and treatment efficiency, increasing the likelihood of system failure [11]. These impacts disproportionately affect poor and informal settlements with limited service alternatives [5,10].

Flood-related WASH failures are closely associated with disease outbreaks. Studies link flooding and rainfall variability in Cambodia and the wider Mekong region to increased incidence of diarrhoeal diseases, including infections caused by *Escherichia coli*, rotavirus, and *Shigella*, as well as periodic cholera outbreaks linked to temperature and hydrological changes [12–14]. Research in urban poor communities also reports elevated risks of skin infections, dengue, and other vector-borne diseases following floods, with disproportionate impacts on children, people with disabilities, and households reliant on climate-sensitive livelihoods [8].

Drought presents a parallel set of WASH challenges through reduced water availability, declining water quality, and constrained hygiene practices. Recurrent droughts reduce dry-season water availability, lower groundwater recharge, and increase reliance on marginal or unsafe water sources, particularly among rural households [4,5]. Water scarcity forces households to prioritise drinking and cooking over hygiene, increasing exposure to communicable and water-borne diseases during prolonged dry periods [13,14]. Rising temperatures and increased drought frequency are expected to intensify these pressures, with disproportionate impacts on poorer households and communities with limited adaptive capacity [5].

Climate impacts on WASH in Cambodia are unevenly distributed and strongly mediated by socio-economic conditions and access to resources. Poor households, residents of flood- and drought-prone areas, and those engaged in climate-sensitive livelihoods face heightened exposure alongside reduced capacity to cope [12]. Women are particularly vulnerable due to their disproportionate responsibility for water collection, sanitation management, caregiving, and household hygiene [7]. Recent assessments confirm that climate shocks magnify pre-existing inequalities in WASH access and service quality, increasing susceptibility to contamination, service disruption, and regression down the WASH service ladder during climate extremes [2,3]. National climate risk profiling further shows how high exposure to floods and droughts interacts with persistent poverty and limited adaptive capacity to produce differentiated WASH risks across regions and social groups [4]. In summary, the literature shows that climate-related WASH risks in Cambodia are driven not by exposure alone, but by the interaction between climate hazards and entrenched socio-economic inequalities that shape vulnerability and constrain adaptive capacity over time.

2.2. Climate Change Adaptation on WASH in Cambodia

Cambodia has progressively strengthened its climate governance framework over the past two decades, moving from early international commitments toward more integrated and multi-sectoral climate planning. The country became a Party to the UNFCCC in 1995, ratified the Kyoto Protocol in 2002, and subsequently established the National

Climate Change Committee in 2006 and the Department of Climate Change within the Ministry of Environment in 2009. Early adaptation planning was articulated through the National Adaptation Programme of Action, which identified priority interventions in climate-sensitive sectors including health, water, agriculture, and coastal zones [15].

More recent policy developments reflect a shift toward mainstreaming climate change into national development planning. The Cambodia Climate Change Strategic Plan 2014–2023 provides the first comprehensive framework for integrating climate considerations into economic and social development, with a strong emphasis on building adaptive capacity and resilience in sectors such as water and sanitation [4]. This approach is reinforced by Cambodia's Nationally Determined Contributions under the Paris Agreement, submitted in 2016 and updated in 2020, which outline national mitigation and adaptation priorities aligned with climate-smart development objectives [4]. Additional instruments, including the Second National Communication to the UNFCCC and the Strategic National Action Plan for Disaster Risk Reduction, further highlight climate risks to economic development and natural resources, particularly in agriculture, water, and health [4].

Despite this expanded policy architecture, implementation capacity remains uneven. Persistent constraints related to financing, technical expertise, data availability, and coordination across ministries and development partners—especially at sub-national levels—continue to limit the translation of national strategies into effective climate-resilient outcomes, with sectoral integration for WASH lagging behind policy ambition [3,4].

Empirical studies suggest that Cambodia's adaptation challenge lies less in the absence of policy frameworks than in weak institutional foundations. Research in the health and water sectors identifies financial resources, coordination, climate information, and institutional understanding of climate risks as key determinants of adaptive capacity, with insecure funding and weak inter-ministerial coordination emerging as critical constraints [16]. Subsequent analysis shows that adaptation policies in water and agriculture remain weakly informed by research due to chronic underfunding, fragmented climate data, weak research–policy communication, and political sensitivities, resulting in largely reactive responses and the systematic under-prioritisation of slower-onset risks such as drought [17].

Recent assessments confirm that these challenges persist despite an expanding policy landscape. While national adaptation efforts increasingly emphasise climate-resilient agriculture, water resource management, disaster risk reduction, and community- and ecosystem-based approaches, progress is constrained by weak coordination across scales, limited climate data and monitoring systems, and a substantial adaptation finance gap estimated at 90–95% of required resources under the National Adaptation Plan [18]. Vulnerability remains socially differentiated, with women, indigenous groups, and poor rural households facing higher exposure and fewer resources to adapt [18].

At the local level, decentralisation of rural WASH responsibilities to district and provincial authorities since 2020 has created opportunities for more context-responsive adaptation. However, sub-national adaptive capacity remains limited due to gaps in technical expertise, financing, data systems, and coordination, constraining local governments' ability to plan and implement climate-responsive WASH services [4,19]. As a result, climate and WASH investments risk reinforcing existing inequalities unless capacity building and institutional support are strengthened, particularly for marginalised and remote households [2].

Community-level preparedness for climate extremes also remains low. Although households commonly identify adaptation measures such as improving water storage, flood-proofing infrastructure, and rehabilitating drainage systems, financial constraints, limited technical support, and weak institutional follow-through prevent implementation

at scale [4]. Early warning and climate information systems remain uneven and weakly institutionalised, with many communities relying on informal communication rather than accessible and actionable forecasts, limiting anticipatory adaptation [2,4].

In this context, household-level adaptation to flooding is dominated by short-term and reactive coping strategies, including elevating houses, temporary relocation, stockpiling food, repairing damage, and relying on informal social networks. While these responses can reduce immediate harm, they are often costly and provide limited protection against future climate risks [7,8]. Some coping practices are erosive—such as using floodwater for daily needs, unsafe sanitation behaviours, and borrowing from moneylenders—exacerbating health risks and household indebtedness [8,20].

More transformative adaptation strategies, including improved drainage and sanitation systems, livelihood diversification, relocation from highly flood-exposed areas, and participation in preparedness programmes, are far less common and tend to emerge only where institutional support, social capital, or external assistance is stronger [20]. External support for flood adaptation remains largely short-term and emergency-focused, limiting its contribution to preventive or resilience-building pathways [7].

Drought adaptation follows similar patterns. Household responses are typically incremental and consumption-reducing, such as reduced bathing and hygiene practices which pose significant health risks [21]. Common strategies such as digging wells or relying on ponds for dry-season storage offer limited protection, while financial constraints consistently restrict access to more robust adaptation options.

Across the literature, climate change impacts on WASH in Cambodia reflect the interaction between exposure, vulnerability, and adaptive capacity. Recurrent floods and droughts disrupt water supply, sanitation infrastructure, and faecal sludge management systems, but unequal outcomes arise because these hazards intersect with poverty, gendered roles, climate-sensitive livelihoods, and uneven access to services. Adaptive capacity remains constrained across household, local, and institutional levels, resulting in a predominance of reactive coping rather than preventive or transformative adaptation. Consequently, adverse WASH outcomes are shaped not by climate hazards alone, but by how exposure interacts with entrenched vulnerability and limited adaptive capacity across scales.

3. Vulnerability–Exposure–Adaptive Capacity (VEAC) Framework

Building on the climate vulnerability literature, this paper adopts a Vulnerability–Exposure–Adaptive Capacity (VEAC) framework as its core analytical lens. The framework draws on the Intergovernmental Panel on Climate Change conceptualisation of vulnerability as a function of exposure and adaptive capacity [22–25], alongside social vulnerability scholarship emphasising the role of poverty, institutions, and governance in shaping adaptive responses [26]. In applied research contexts—particularly in WASH, livelihoods, and disaster risk—this framework provides a practical basis for analysing how climate hazards translate into uneven impacts and differentiated adaptation pathways.

In this paper, exposure refers to the nature, magnitude, and frequency of climate hazards—primarily floods and droughts—that affect WASH systems. Consistent with sustainability science perspectives, exposure is treated as an external stressor that disrupts water availability, sanitation functionality, and faecal sludge management systems, but does not alone determine outcomes [27]. Rather, exposure creates conditions of risk that interact with existing social, infrastructural, and institutional contexts.

Vulnerability is understood as the social and structural conditions that mediate how exposure translates into harm. Following Adger [26] and Brooks et al. [28], vulnerability is conceptualised as socially produced and unevenly distributed, reflecting factors such as poverty, livelihood dependence, gender roles, health status, settlement patterns, and

access to services. In the WASH context, vulnerability shapes who is most affected by system failures, contamination, and service interruptions during climate events, and whose wellbeing is most compromised.

Adaptive capacity refers to the ability of households, communities, institutions, and governance systems to anticipate, cope with, and adapt to climate-related WASH risks. The framework recognises adaptive capacity as multi-scalar. At the household level, it includes material assets, livelihood flexibility, social networks, and access to information. At the institutional level, it encompasses policy frameworks, financing mechanisms, technical standards, inter-sectoral coordination, and the capacity to deliver climate-responsive WASH services [9,28]. The framework also distinguishes between short-term coping responses, which may reduce immediate exposure but often erode long-term capacity, and transformative adaptation pathways that address underlying vulnerability and enhance system resilience [29].

The VEAC framework is applied in this paper as an organising and interpretive tool for the empirical analysis. It is used to structure the assessment of climate-related impacts on WASH by distinguishing climate hazards (exposure) from the social and structural conditions that shape risk (vulnerability) and the capacities that shape responses (adaptive capacity). The framework also supports interpretation of adaptation pathways by differentiating short-term, household-level coping strategies from institutionally supported and longer-term adaptations, and by examining how mismatches in adaptive capacity across household and authority scales can reinforce vulnerability and limit the effectiveness of WASH adaptation.

4. Methods

4.1. Study Design and Respondent Characteristics

This study was conducted within a donor-funded WASH service delivery program implemented across five provinces in Cambodia, broadly spanning central and eastern regions of the country, and selected to capture variation in climate-related hazards affecting rural livelihoods and WASH systems. The provinces include Kratie and Kampong Cham along the Mekong mainstream; Prey Veng and Kampong Speu in the downstream Mekong Basin; and Pursat in the Tonle Sap Basin (Figure 1). These provinces are among the most climate-vulnerable in Cambodia: Kampong Speu, Pursat, and Prey Veng rank among the ten most vulnerable nationally, followed by Kratie and Kampong Cham [30]. Approximately 85% of Cambodia's land area lies within the Lower Mekong Basin and is predominantly floodplain, resulting in recurrent exposure to storms, intense rainfall, and upstream runoff that drive seasonal flooding of the Mekong and Tonle Sap systems [31]. Low-lying provinces such as Prey Veng, Pursat, Kratie, and Kampong Cham are primarily affected by flooding during the rainy season (July–October), whereas Kampong Speu, characterised by higher elevation and hilly terrain, is more prone to drought [4].

A cross-sectional survey was conducted to assess climate-related impacts on WASH access and use, as well as household and institutional adaptive responses within the programme context. Household respondents were drawn from 32 rural communes across the five provinces and purposively sampled from the official lists of programme beneficiaries, ensuring the sample include households that had project-supported water, sanitation, and hygiene services. This approach enabled assessment of climate impacts and adaptive responses among households targeted by the programme rather than the general rural population. The final household sample comprised 423 households. Socio-economic status was classified using Cambodia's national IDPoor system, which identifies poor households based on multidimensional criteria including assets, housing, and livelihood conditions, rather than income alone. In this study, IDPoor status was combined with indicators of

social vulnerability to generate the four categories of socio-economic status presented in Table 1.

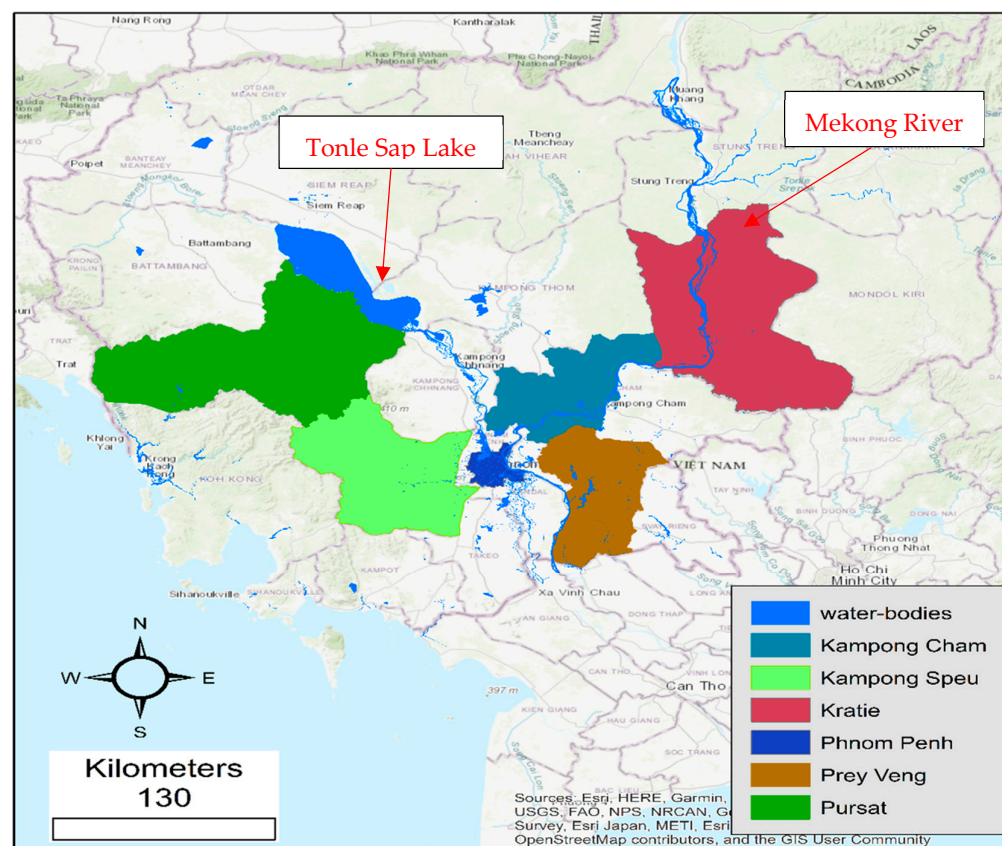


Figure 1. Overview of the study site.

Table 1. Household respondents' sociodemographic characteristics (n = 423).

Characteristic	Percentage (%)
Socio-economic status	
Poor	27.6
Non-poor	25.7
Poor and socially vulnerable	21.0
Non-poor and socially vulnerable	25.7
Total	100
Gender of respondent	
Female	71.4
Male	28.6
Total	100
Household size	
1–3 members	28.8
4–6 members	55.6
7–10 members	13.0

Table 1. *Cont.*

Characteristic	Percentage (%)
≥11 members	2.6
Total	100
Education (highest level attained)	
No formal schooling	20.0
Primary education	39.1
Secondary education	25.3
Upper secondary education	12.3
Vocational/university	3.3
Total	100
Monthly household income	
<USD 50	13.0
USD 50–100	31.0
USD 100–150	14.2
Irregular income	1.4
No income	40.4
Total	100

Note to the table: “Poor” refers to households classified as *IDPoor* under Cambodia’s national poverty identification system. “Socially vulnerable” refers to households with characteristics such as elderly members, persons with disabilities, or female-headed households.

In parallel, 96 local authorities were surveyed, comprising village chiefs and commune- and district-level authorities responsible for local WASH planning and service delivery. Female respondents accounted for 21.9% of the sample, male 78.1%, and all had resided in their villages for more than seven years.

4.2. Survey Instrument, Administration, and Analysis

The survey was developed by the author for both household and local authority surveys. It comprised six sections aligned with the Vulnerability–Exposure–Adaptive Capacity (VEAC) framework and informed by prior empirical research. The first section captured baseline vulnerability through questions on water, sanitation, and hygiene access, including water sources, availability, quality, sanitation facilities, and challenges related to latrine access and use, consistent with applied WASH vulnerability and service reliability studies in climate-stressed rural contexts [1,30]. The second section addressed exposure by asking about experiences of climate-related events and perceived climate variability, in line with climate risk and exposure assessment approaches [23,24]. The third and fourth sections examined perceived impacts of, and coping responses to, flooding and drought respectively, reflecting empirical methods used to analyse climate shock pathways and household- and community-level responses in flood- and drought-prone settings [27,29]. The fifth section assessed adaptive capacity through measures of community-level resources, institutional support, and awareness of climate change adaptation options, drawing on frameworks that conceptualise adaptation as shaped by material assets, knowledge, and social and institutional context [26,28]. The final section collected demographic information, including income sources, education level, socioeconomic status, gender, and age.

The local authority questionnaire followed the same overall structure as the household instrument but excluded items specific to individual household circumstances (e.g., income and education).

Face-to-face interviews were conducted to maximise response rates and minimise item non-response. Enumerators received training prior to data collection on questionnaire administration, ethical considerations, and consistency in probing and recording responses. Interviews with local authorities were also conducted face-to-face by two Cambodian consultants. All interviews were conducted in Khmer. The two consultants translated the survey responses into English, and entered into the Qualtrics platform for data management and analysis.

The study relies on self-reported data, which may introduce recall and social desirability bias. To mitigate this, structured questionnaires aligned with established frameworks were used, alongside trained enumerators and face-to-face interviews to ensure consistency and clarity. In addition, ethical procedures were followed throughout the study, including voluntary participation, informed consent, and assurances of confidentiality and anonymity.

The sample was drawn from programme-participating households rather than randomly selected from the general population, which limits the generalisability of findings beyond similar rural, programme-engaged contexts. However, this sampling approach was appropriate for the study's objective of examining climate impacts and adaptive responses among households targeted by WASH interventions. Multiple indicators and cross-variable checks were used to enhance internal validity and support the robustness of the findings within the study context.

Data analysis was conducted using SPSS (version 20) for both household and local authority datasets. First, descriptive statistics (frequency distributions) were used to examine response patterns across all variables. Chi-square goodness-of-fit tests were performed to assess whether observed response distributions differed significantly from expected distributions.

Second, chi-square tests of association were conducted to identify relationships between key variables, including access to water and sanitation, experiences and perceptions of climate variability, reported impacts and responses to floods and droughts, awareness of adaptation options, and household characteristics such as income source, income level, education, and socio-economic status. Statistical significance was assessed at conventional levels ($\alpha \leq 0.05$). Effect sizes were evaluated using Phi (for 2×2 tables) and Cramer's V (for larger contingency tables), where values above 0.15 indicate moderate to strong associations.

Third, multinomial logistic regression analysis was applied to variables that showed statistically significant associations in the chi-square tests. These models were used to examine the relationship between household characteristics—including economic capacity, individual attributes, and demographic factors—and outcomes related to climate impacts, coping responses, and adaptation awareness and intentions. Results are reported as Relative Risk Ratios (RRR), which represent the relative likelihood of an outcome occurring compared to a reference category, with 95% confidence intervals indicating the precision of the estimates.

5. Results

5.1. Exposure

5.1.1. Experience of Flooding and Reported Flood-Related Impacts

Households reported recurrent flooding over the past decade, with most experiencing floods annually or every 2–3 years. Exposure varied geographically, with provinces along the Mekong and Tonle Sap systems reporting more frequent and prolonged flooding than upland areas such as Kampong Speu.

Chi-square tests indicate that flood exposure is significantly associated with village geography and household income source ($p < 0.001$), with moderate to strong effect sizes (Phi and Cramer's $V > 0.15$).

Flood impacts were most evident in disruptions to mobility, livelihoods, health, and WASH conditions. Households commonly reported inability to travel for work or access services, alongside income loss, increased living costs, and crop damage. These impacts were strongly associated with coping strategies such as livelihood diversification, non-farm employment, and reliance on government support ($p < 0.001$; Phi and Cramer's $V > 0.15$), particularly among agriculture-dependent households.

Health and WASH impacts were also significant. Flooding was associated with deterioration in water quality and increased incidence of health issues such as flu, skin diseases, and insect bites. These effects were significantly associated with village geography and income source, indicating the interaction between environmental exposure and livelihood vulnerability. Sanitation systems were also disrupted, with reported toilet overflow, waste leakage, and temporary increases in open defecation.

Local authority responses closely mirrored household reports, confirming consistent patterns of flood-related impacts across mobility, livelihoods, health, and WASH systems.

5.1.2. Experience of Drought and Perceived Drought-Related Impacts

Households reported recurrent experiences of drought, with most indicating annual or biennial occurrence. Compared to flooding, drought was experienced as a more widespread and persistent stressor, though with some geographic variation. Perceived drought frequency and duration were significantly associated with village geographical characteristics ($p < 0.001$), indicating spatial patterning of exposure.

Drought impacts were primarily economic and livelihood-related, including income loss, increased living costs, reduced crop yields, diminished farming capacity, and loss of livestock. These impacts were strongly associated with village geography ($p < 0.001$), but even stronger and more consistent associations were observed for income-related characteristics, including income level and income source, particularly for loss of livestock, income, crop yield, and farming capacity. This indicates that while geography shapes exposure, economic capacity plays a more decisive role in shaping the severity of drought impacts.

Drought-related constraints on water access and use were also significantly associated with both village geography and household income level, highlighting the interaction between environmental exposure and economic capacity in shaping water insecurity.

Coping responses remained largely short-term and resource-constrained, including reliance on social networks, livelihood diversification, and temporary migration, with limited uptake of longer-term adaptation measures such as irrigation improvement or crop changes.

Local authority responses largely aligned with household-reported impacts, particularly in relation to economic and livelihood stress. A key divergence emerged in the assessment of health impacts: local authorities identified clearer geographic patterning of drought-related health risks, while household responses were more closely tied to immediate constraints on water access, reflecting differences in scale of perception.

5.2. Adaptation: Awareness, Uptake, and Differentiated Responses

This section examines adaptation responses to climate-related impacts, focusing on differences in awareness, uptake, and constraints across households and local authorities.

5.2.1. Households

Households demonstrated moderate awareness of climate change adaptation options, with the most commonly recognised measures including social and health services, raised

roads, rainwater harvesting, and community-managed water systems (Figure 2). As shown in Figure 2, awareness is concentrated around service- and infrastructure-based interventions, with relatively lower recognition of more technical or capital-intensive options such as climate-resilient latrines. Awareness was significantly associated with village geographical characteristics ($p < 0.05$; Phi and Cramer's $V > 0.15$), indicating that exposure to climate hazards shapes knowledge of adaptation options.

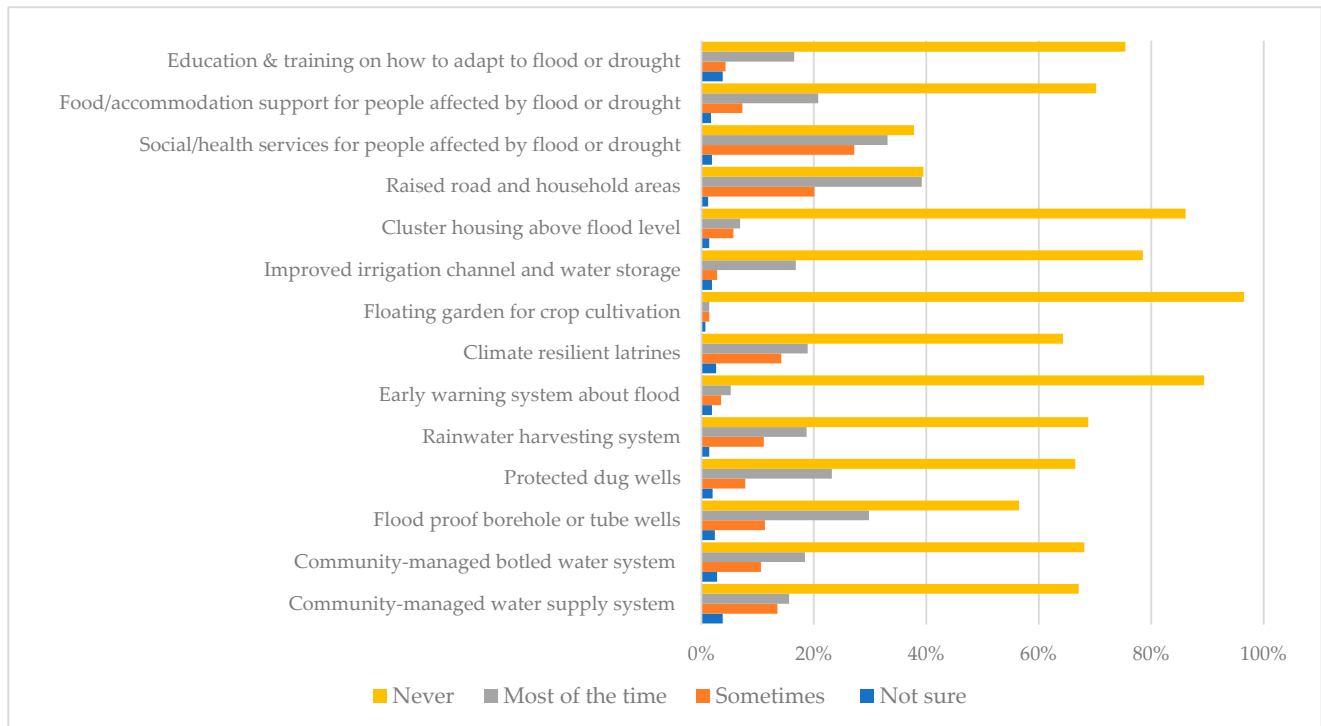


Figure 2. Household awareness of adaption options.

Despite this awareness, uptake of adaptation measures remained limited and uneven. As illustrated in Figure 3, household responses are concentrated in lower-cost, short-term strategies, particularly rainwater harvesting, elevation of ground levels, and increased food storage. More resource-intensive or long-term adaptations are notably less common. Uptake was significantly associated with both village geography and economic characteristics, including income level and income source ($p < 0.05$), indicating that adaptation responses are shaped by the interaction between local hazard exposure and household economic capacity.

Economic constraints emerged as a key limiting factor. Income level was significantly associated with both awareness of adaptation options and decisions to implement measures such as well construction or rainwater harvesting. However, many households reported no intention to invest in more capital-intensive adaptations, such as climate-resilient latrines or piped water systems, with financial limitations cited as the primary barrier.

Adaptive capacity was further constrained by limited access to information and training. While most households expressed willingness to participate in climate-related education, a majority had not previously engaged in such programmes. Participation in training was significantly associated with adaptation intentions ($p < 0.05$), suggesting that access to information plays a critical enabling role alongside financial resources.

Households consistently identified a need for external support, particularly government investment in infrastructure and basic services, including water supply, roads, irrigation, and sanitation.

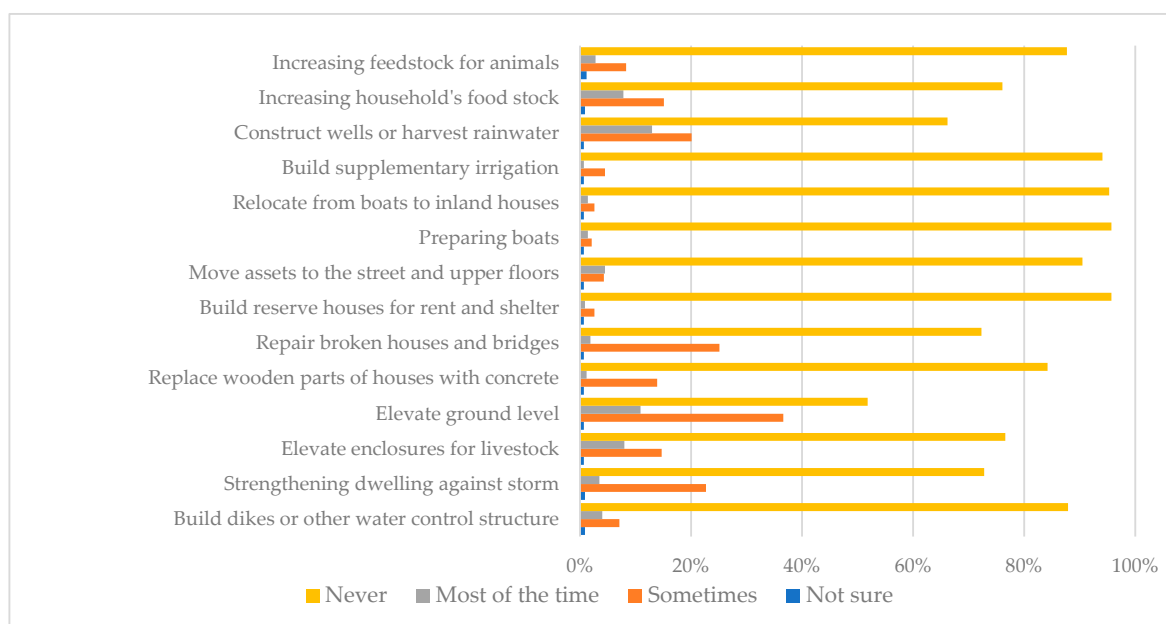


Figure 3. Adaptation option taken up by households.

5.2.2. Local Authorities

Local authority perceptions of adaptation broadly align with household-reported patterns but reflect a wider system-level perspective. Authorities identified a broader range of community- and infrastructure-based adaptation measures, including water supply systems, flood-proof infrastructure, irrigation improvements, and emergency support services.

Differences are more pronounced in reported uptake. While Figure 3 shows that household-level actions are concentrated in a limited set of low-cost responses, local authorities reported a wider range of adaptation activities occurring at the community level, including infrastructure improvements and structural measures. This suggests that authorities capture adaptation at a broader system level, while households report actions constrained by their own resources.

Despite these differences, both households and local authorities converged on key constraints and priorities. Financial limitations were consistently identified as the primary barrier to adopting resilient WASH infrastructure, and both groups emphasised the importance of government support for infrastructure development and improved access to clean water.

A notable gap exists in access to adaptation training. While most local authorities reported having received training and expressed interest in further capacity building, significantly fewer households had participated in such programmes, despite similar levels of interest. This disparity highlights uneven distribution of knowledge and capacity between institutional and household levels.

5.3. Vulnerability

5.3.1. Infrastructure Vulnerability in WASH Systems

Household survey results indicate that although access to basic WASH infrastructure is relatively widespread, vulnerability persists due to limited adaptive capacity, declining service quality during climate shocks, and weaknesses in sanitation management.

Water access is generally high, with most households relying on groundwater sources supplemented by rainwater, piped supply, and bottled water. However, limited variation in water source use across normal, flood, and drought conditions indicates low flexibility

under climate stress. While most households reported consistent availability, a substantial proportion experienced intermittent access.

Water quality represents a key vulnerability. Although most households reported acceptable water quality under normal conditions, perceived safety declined sharply during floods, accompanied by increased reports of contamination and health risks. Adaptive responses remained limited, with a notable proportion of households not treating drinking water, even during flood periods.

Sanitation coverage is relatively high, but important structural and safety gaps remain. While most households use improved latrines, a minority lack access or continue to practice open defecation. More critically, sanitation management practices constrain adaptive capacity. Very few households reported emptying pit latrines, and unsafe disposal of faecal sludge into open environments was common. In addition, some households reported lack of continuous access to toilets and safety concerns during use. These issues showed no significant association with socio-economic status or geographic location, suggesting that sanitation vulnerability reflects broader systemic and environmental constraints.

Local authority responses largely align with household findings. Authorities confirmed high reliance on groundwater, limited seasonal switching of water sources, and substantial deterioration in water quality during floods. Reported water treatment practices and sanitation coverage were broadly consistent across datasets.

However, triangulation highlights governance gaps in sanitation management. While some authorities reported awareness of pit emptying practices, a majority could not identify final disposal pathways for faecal sludge, indicating limited institutional oversight. This suggests that vulnerabilities in WASH systems are not only household-level constraints but also reflect systemic weaknesses in service provision and regulation.

5.3.2. Determinants of Adaptation: Social, Economic, and Geographic Factors

This section presents regression results showing that adaptive capacity is primarily driven by economic conditions, shaped by household characteristics, and influenced—but not determined—by geographic location.

Household economic characteristics emerged as the most influential determinants of adaptation-related outcomes. Economic status significantly predicted households' experienced climate impacts, including crop loss (RRR = 1.74, 95% CI: 1.22–2.49), income loss (RRR = 1.78, 95% CI: 1.21–2.60), insect bites (RRR = 1.64, 95% CI: 1.09–2.45), and transport disruption (RRR = 1.44, 95% CI: 1.01–2.04). Conversely, higher household income was associated with a lower likelihood of adverse impacts, including income loss (RRR = 0.87, 95% CI: 0.76–0.99) and insect bites (RRR = 0.77, 95% CI: 0.64–0.91).

Economic factors also shaped coping responses to water insecurity and livelihood stress, as well as awareness of locally practiced adaptation options such as rainwater harvesting, flood-proof boreholes, community-managed water supply systems, elevated roads, climate-resilient latrines, and social and health services. In addition, household economic capacity was associated with forward-looking adaptation intentions, including plans to build climate-resilient latrines and connect to resilient water supply systems. Across models, goodness-of-fit statistics indicated acceptable model performance, supporting the consistent role of economic capacity across multiple adaptation-related outcomes. Full regression results are provided in Supplementary Tables S1 and S2.

Individual characteristics also played a role in shaping adaptive decision-making, particularly in relation to drought coping strategies. Education level was significantly associated with selected coping responses, including combinations of irrigation improvement and other livelihood strategies (RRR = 7.85, 95% CI: 1.19–51.95), reliance on government support (RRR = 6.68, 95% CI: 1.08–41.45), and combined strategies involving income di-

versification (RRR = 8.20, 95% CI: 1.72–39.22). These findings indicate that education may enhance households' capacity to engage in more complex and proactive adaptation responses. Full regression results are provided in Supplementary Tables S3 and S4.

Village geographical characteristics were significant predictors of selected climate-related impacts and short-term responses. Geography was significantly associated with the likelihood of being unable to work during floods (RRR = 0.81, 95% CI: 0.69–0.96) and with increased food costs (RRR = 1.17, 95% CI: 1.03–1.33). In addition, village characteristics were associated with reported crop loss during flood periods (RRR = 1.15, 95% CI: 1.01–1.32). In contrast, village geography was not consistently associated with longer-term adaptation intentions. Across models, goodness-of-fit statistics indicated acceptable model performance. Full regression results are provided in Supplementary Tables S5 and S6.

6. Discussion

6.1. Vulnerability: Access as a Structural Precondition for Risk

The findings largely confirm the literature reviewed in Section 2, which shows that climate-related WASH risks in Cambodia are shaped less by exposure alone than by the fragility of baseline WASH access and underlying socio-economic conditions. Although most households reported physical access to water and sanitation infrastructure, this access remains fragile rather than resilient. Heavy reliance on fixed water sources, flood-related water quality deterioration, limited treatment practices, unsafe faecal sludge management, and gendered water collection responsibilities collectively heighten vulnerability during climate stress. These patterns echo Cambodian and regional evidence showing that nominal access does not equate to resilience when systems fail under climatic stress [5,6,32].

Sanitation vulnerability is particularly pronounced, reinforcing existing evidence that pit latrines and informal faecal sludge disposal represent key climate risk pathways, especially in flood-prone and high-groundwater areas [7,8,10,32]. These findings align with social vulnerability theory, which emphasises that infrastructure alone does not reduce climate-related vulnerability without a parallel investment in sanitation safety and system resilience.

Regression analyses confirm that vulnerability is socially differentiated. Socio-economic status—including income level and related indicators of household vulnerability—emerged as the most consistent predictor of households' capacity to manage climate risks and invest in safer WASH practices. This aligns with extensive evidence that poverty and inequality often outweigh physical exposure in shaping climate outcomes [2,3,12]. While geographical exposure was significantly associated with selected climate impacts, it did not consistently predict adaptive responses or longer-term investment intentions. This reinforces the VEAC insight that vulnerability and adaptive capacity mediate the relationship between climate hazards and WASH impacts.

6.2. Exposure: Floods as Acute Shocks and Drought as Chronic Stress

Consistent with the literature, exposure to climate hazards is widespread but operates through distinct temporal and spatial mechanisms. Floods act as acute, compound shocks that disrupt mobility, livelihoods, health, water quality, and sanitation systems simultaneously. Both households and local authorities reported transport disruption, income loss, increased living costs, water contamination, sanitation failure, and increased open defecation during flood periods, consistent with documented flood-related WASH pathways in Cambodia and the Mekong region [4,7,8].

Drought, by contrast, functions as a chronic and region-wide stressor, primarily affecting livelihoods and water availability rather than causing immediate infrastructure failure. Reported impacts on income, crop yields, farming capacity, and livestock mirror national

and regional assessments identifying water scarcity and reduced dry-season availability as central drought impacts [4,5]. Extending the literature, the survey findings suggest that drought impacts were less spatially differentiated than flood impacts, helping explain why economic capacity—rather than exposure alone—was more consistently associated with drought-related stress.

Differences between household and authority perceptions reflect a scale effect noted in climate governance literature. Household exposure was closely tied to village-level conditions, while local authorities tended to frame drought impacts at broader community or regional scales, with implications for how risks are prioritised in adaptation planning [24,27].

6.3. Adaptive Capacity: Determinants and Divergent Pathways

Consistent with the literature (e.g., [2,19]), adaptive capacity emerges as the most decisive dimension of the VEAC framework shaping WASH adaptation outcomes. Across regression analyses, economic capacity was the most consistent predictor of adaptation awareness, uptake, and future intentions, outweighing geographic and individual characteristics. Income level—rather than income source alone—was particularly important in predicting investment in resilient WASH options, reinforcing evidence that affordability and material resources remain the primary constraint on household-level adaptation in Cambodia and similar contexts [24,26,28].

Individual characteristics, particularly education, influenced aspects of risk perception and decision-making but remained secondary to economic constraints. This aligns with prior findings that social position and gendered roles shape exposure and coping, but do not compensate for limited financial capacity in enabling sustained adaptation [2,8,20]. Geography was associated with exposure and short-term coping responses, but did not consistently predict longer-term adaptation intentions, reinforcing a core insight from the VEAC and vulnerability literature: where households live shapes what they experience, but what they can do depends primarily on resources and institutional context [23,25].

Extending the literature, the findings reveal misaligned adaptation pathways between household- and local authority-level actors. At the household level, adaptation remains largely reactive and resource-constrained, dominated by short-term coping strategies such as alternative water sourcing, reduced hygiene practices, food storage, livelihood diversification, and temporary migration. Even where households expressed strong intentions to adopt more robust measures—such as climate-resilient latrines or flood-adaptive water systems—uptake remained limited, with financial constraints consistently cited as the primary barrier. These patterns closely reflect studies documenting erosion-prone coping and affordability constraints among poor households in flood- and drought-prone settings [7,8,20,21].

In contrast, local authorities' perceived adaptation pathways are more anticipatory and infrastructure-led, emphasising community-managed water systems, flood-proof boreholes, irrigation and storage improvements, clustered housing above flood levels, emergency support, and training initiatives. These priorities align with Cambodia's national and sub-national adaptation strategies, as well as sectoral assessments highlighting the central role of local governments in enabling climate-resilient WASH through planning, coordination, and infrastructure investment [2–4,19].

Despite convergence around the importance of infrastructure development and government support, the results reveal a persistent gap between system-level adaptation planning and household-level feasibility. While local authorities emphasise collective and infrastructure-based solutions, household adaptation remains shaped by affordability constraints and short-term coping. This misalignment confirms concerns in the adaptation literature that decentralisation without adequate financing, data, and implementation ca-

capacity risks reinforcing inequality and limiting the effectiveness of climate-resilient WASH interventions [2,9,19,20].

7. Conclusions

This study provides empirical evidence on climate change, WASH, and adaptation in rural Cambodia, showing that exposure to floods and droughts alone does not explain patterns of impact or response. Although climate hazards were widely experienced, similar levels of exposure did not result in similar WASH outcomes. Instead, outcomes were shaped by interactions between exposure, underlying vulnerability, and adaptive capacity, consistent with the Vulnerability–Exposure–Adaptive Capacity (VEAC) framework and recent IPCC assessments [22,24,25].

Survey findings indicate relatively high awareness of climate risks and adaptation options among both households and local authorities. However, adaptation uptake was uneven, revealing a persistent gap between awareness and action. This gap suggests that adaptation is constrained less by knowledge than by structural and capacity-related barriers, particularly economic limitations. Moreover, households' priorities for short-term coping underscore the role of vulnerability in shaping adaptation choices.

WASH-specific findings reveal a pattern of infrastructure adequacy but adaptive fragility. While many households have physical access to water and sanitation, climate-driven service degradation—especially flood-related water quality deterioration, unsafe sanitation management, limited hygiene adjustment, and gendered water collection responsibilities—substantially heightens vulnerability. Triangulation of household and local authorities data strengthens confidence in these findings, while differences in perspective point to potential institutional blind spots in monitoring service performance and managing climate-related WASH risks.

Regression analyses converge on a central insight: climate change adaptation is more consistently associated with economic capacity and socio-economic vulnerability than with hazard exposure alone. Geography shapes exposure to climate hazards and the lived experience of their impacts but does not consistently predict adaptation actions. Households' ability to translate awareness into adaptation is closely associated with income-related factors and broader socio-economic constraints. This reinforces Adger's [26] distinction between contextual vulnerability and vulnerability as an outcome and aligns with IPCC's [22–25] conclusions that vulnerability is socially differentiated and shaped by multiple stressors.

Several limitations should be acknowledged. Findings are context-specific and based on programme-engaged communities, limiting generalisability beyond similar settings. Results also reflect self-reported perceptions rather than independently verified measures. Despite this, consistent patterns across households and local authorities support the robustness of the core findings.

The key contribution of this paper is to empirically demonstrate that adaptive capacity mediates the relationship between exposure and vulnerability in the WASH context. Without sufficient economic and institutional support, households remain locked into reactive coping even where climate awareness is high. Climate-resilient WASH interventions in rural Cambodia must therefore move beyond hazard-focused or infrastructure-only solutions toward integrated strategies that strengthen baseline access, reduce exposure, and expand adaptive capacity—particularly for economically and socially marginalised households. Bridging household and institutional adaptation pathways is essential if adaptation is to address not only climate hazards, but the structural conditions that determine who can adapt, and how.

From a policy perspective, the findings highlight that reducing climate-related health risks in rural Cambodia requires addressing economic and social constraints on adaptation,

rather than focusing on exposure alone. At the national level, this implies prioritising targeted financial support mechanisms—such as subsidies, credit schemes, or social protection—for poor and socially vulnerable households to enable uptake of climate-resilient WASH infrastructure, including safe water systems and resilient sanitation facilities.

At the local level, interventions should move beyond top-down training approaches and ensure that adaptation knowledge and support reach households directly. This includes expanding community-based training and outreach, particularly for vulnerable groups, and strengthening links between local authorities and households to translate awareness into action. In addition, government and development partners should prioritise investment in adaptation measures that households are aware of but unable to adopt—such as resilient latrines, flood-proof water systems, and reliable water treatment and storage—alongside improved sanitation management, including safe faecal sludge handling. Integrating these investments with social and health services is critical to reduce the risk of waterborne and sanitation-related diseases in high-risk communities.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/world7040058/s1>, Table S1: Multinomial regression model fit statistics for the influence of household economic characteristics on climate impact experiences, coping responses, adaptation awareness, and adaptation intentions; Table S2: Multinomial logistic regression results (RRR and 95% CI) for significant predictors of climate-related impacts (household economic characteristics); Table S3: Multinomial regression model fit statistics for the influence of individual household characteristics on climate impact experiences, coping responses, adaptation awareness, and adaptation intentions; Table S4: Multinomial logistic regression results (RRR and 95% CI) for individual characteristics; Table S5: Multinomial regression model fit statistics for geography-related climate impact and adaptation outcomes; Table S6: Multinomial logistic regression results (RRR and 95% CI) for geographic predictors.

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Informed Consent Statement: Informed consent was obtained from all participants prior to data collection. Participation was voluntary, and respondents were informed of the purpose of the study, their right to withdraw at any time, and the confidentiality of their responses.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy reasons.

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