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Strategies for Adapting the Public Health System to Future Climate Crises and Pandemics in North Aceh Regency

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ABSTRACT
Climate change and potential future pandemics pose interconnected and cascading threats to health systems, particularly in disaster-prone regions such as North Aceh Regency, Indonesia. However, empirical evidence on district-level health system preparedness that simultaneously addresses climate and pandemic risks remains limited. Purpose: This study aimed to assess health system preparedness, identify community vulnerabilities, and formulate context-specific adaptation strategies for addressing climate-related risks and potential future pandemics in North Aceh Regency. Method: A sequential explanatory mixed-methods design was employed. The quantitative phase assessed health facilities and households across high-, moderate-, and low-risk areas. All primary healthcare facilities were included through total sampling, with facility respondents selected purposively, while households were selected using multistage and systematic random sampling. A total of 27 facility respondents and 230 households were included. Quantitative data were analyzed descriptively and using Kruskal–Wallis and Spearman correlation tests. The qualitative phase involved purposively selected stakeholders and used in-depth interviews and focus group discussions, followed by directed content analysis. Results: Overall health system preparedness was moderate, with major weaknesses in disaster-resilient infrastructure, logistics and supply chains, and service continuity. Preparedness differed significantly across risk strata ($p=0.008$), while higher disaster risk was associated with lower preparedness ($\rho=-0.51$; $p=0.007$). Cross-sectoral coordination showed the strongest positive association with preparedness ($\rho=0.61$; $p<0.001$). Implications: Adaptation policies should prioritize high-risk areas, integrated surveillance, resilient infrastructure and supply chains, and institutionalized cross-sectoral coordination. Conclusion: Strengthening district health system resilience requires integrated structural and operational adaptation rather than fragmented single-hazard preparedness.

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INTRODUCTION

Climate change and the potential for future pandemics have become two multidimensional threats that simultaneously pressure the performance of global health systems. The World Health Organization (WHO) emphasises that a climate-resilient and low-emission health system is a prerequisite for protecting populations from climate-sensitive hazards such as floods, heatwaves, and shifts in infectious disease patterns, while maintaining the quality of care (WHO, 2023). Recent literature reviews also emphasise that the resilience of health systems to climate change is complex and adaptive, requiring a holistic approach that simultaneously involves leadership, financing, emergency preparedness, and strengthening climate-sensitive disease surveillance (Mosadeghrad et al., 2023).

This paradigm shift is also evident in the increasing empirical evidence regarding the link between climate adaptation activities and the service capacity of healthcare facilities in low- and middle-income countries. Schwerdtle et al. (2024) identified that most efforts to build climate resilience in healthcare facilities in developing countries are still fragmented and have not yet been integrated into comprehensive health system planning (Schwerdtle et al., 2024). In line with this, a global review by Ansah et al. (2024) found that the main barriers to health system adaptation to climate include limited financing, weak integration of climate-health data, and the low capacity of healthcare workers to manage climate-sensitive disease risks (Ansah et al., 2024).

At the same time, the COVID-19 pandemic demonstrated how health systems can experience simultaneous pressure on service capacity, logistics, and healthcare personnel when a large-scale shock occurs. A comparative analysis of the responses of 28 countries by Haldane et al. (2021) identified that countries with more resilient health systems share similarities in aspects of adaptive governance, flexible financing, and strong community engagement (Haldane et al., 2021). These findings strengthen the argument that pandemic preparedness and climate change resilience are actually based on the same systemic foundations, rather than separate agendas.

Future health threats are increasingly understood as compound and cascading risks, rather than isolated single events. Ebi (2024) explains that climate change acts as a risk multiplier that interacts with social vulnerabilities, so that a single stressor, such as drought, can trigger a cascade of subsequent impacts ranging from crop failure to increased susceptibility to infectious diseases (Ebi, 2024). In the context of primary healthcare services, Tsai et al. (2022) highlight that the current disaster preparedness framework is still orientated towards a single response per type of disaster, making it inadequate to face interconnected dual threat scenarios (Tsai et al., 2022).

Indonesia is one of the countries with a high level of vulnerability to the health impacts of climate change due to its archipelagic geographical conditions, long coastline, and high frequency of hydrometeorological disasters. Oktari et al. (2022) through a policy review based on the Health-Emergency and Disaster Risk Management (Health-EDRM) framework found that Indonesia's

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national regulations are still more orientated towards post-disaster response rather than prevention and early preparedness, and have not yet explicitly prioritised climate-induced disasters (Oktari et al., 2022). A cross-country study by Gan et al. (2021) also emphasised that Indonesia faces a dual burden of high disaster frequency and limited data on its health impacts on vulnerable groups (Gan et al., 2021).

Institutionally, Indonesia has a disaster management framework through the National Disaster Management Agency (BNPB) at the national level and the Regional Disaster Management Agency (BPBD) at the regional level. Law Number 24 of 2007 emphasises that disaster management is the responsibility and authority of the government and local governments, carried out in a planned, integrated, coordinated, and comprehensive manner during the pre-disaster, emergency response, and post-disaster phases.

In the context of Aceh, this function is supported by the Aceh Disaster Management Agency (BPBA) at the provincial level and the district/city Disaster Management Agencies (BPBD). BPBA has the mandate to organise and coordinate disaster management in an integrated manner during the pre-disaster, emergency response, and post-disaster phases. The Aceh government has also developed the Aceh Disaster Management Plan for 2023–2028 and institutional frameworks that encompass prevention and preparedness, emergency response and logistics, as well as rehabilitation and reconstruction. In addition, the mechanism of the Aceh Rapid Response Disaster Management Team involves coordination and communication with various sectors involved in disaster handling.

The existence of these institutions becomes increasingly important because the Aceh Province faces various hydrometeorological hazards. In addition to floods, the Aceh region faces flash floods, landslides, extreme weather and strong winds, as well as dry hydrometeorological hazards such as droughts and forest and land fires. BPBA and BNPB in various recent reports have also documented incidents of floods, landslides, extreme weather, forest and land fires, as well as drought potential in various areas of Aceh. These conditions indicate that the threats faced by the people of Aceh are not limited to a single type of danger, but can be a combination of sequential or simultaneous events, with consequences for access to healthcare services, infrastructure, water and energy availability, logistics, and public health service needs.

A qualitative study of health stakeholders in Indonesia by Sulistiadi et al. (2024) revealed that the resilience of the national health system to climate change is still faced with intertwined social, economic, and cultural challenges, such as disparities in resource distribution between regions, increased service cost burdens in disaster-prone areas, and wide variations in public awareness between regions (Sulistiadi et al., 2024). These findings underscore that strengthening the resilience of Indonesia's health system cannot be done uniformly, but rather must consider the differing risk characteristics and capacities in each region, including at the district level.

North Aceh Regency itself has a combination of coastal areas, dense settlements, agricultural zones, and river basins that result in uneven health risk patterns across sub-districts. These conditions also expose the region to floods, flash floods, landslides, extreme weather, as well as disruptions in access and utilities that can accompany hydrometeorological events. The coastal, lowland, and watershed characteristics increase the risk of annual flooding and can directly impact

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public health, especially through the increased risk of post-flood infectious diseases. A study by Umri et al. (2023) in Lhoksukon District, North Aceh Regency, found variations in the community's knowledge levels regarding post-flood infectious disease prevention efforts, indicating that community-based preparedness in this area still needs to be systematically and sustainably strengthened (Umri et al., 2023).

The threats in North Aceh Regency do not stand alone; rather, they have the potential to occur simultaneously or sequentially as cascading effects: infrastructure disruptions due to floods can be followed by outbreaks of waterborne diseases, which in turn burden healthcare facilities that are already under strain. Such patterns of risk interaction are consistent with the concept of compound risk proposed by Ebi (2024) and the primary care preparedness framework by Tsai et al. (2022), both of which emphasise the importance of integrated preparedness across different types of threats, rather than preparedness segmented by disaster type.

On the other hand, the handling of climate change, disasters, and potential pandemics at the regional level is still often developed through different programs and sectors, as highlighted in the review of adaptation barriers by Ansah et al. (2024) and Mosadeghrad et al. (2023). Such fragmentation risks resulting in program overlaps, weak cross-sector data integration, and slow responses when different threats emerge simultaneously. Therefore, the existence of disaster management institutions needs to be translated into operational coordination that connects health, environment, disaster, and local governance. This is important because the formal existence of institutions does not automatically guarantee data integration, coordination, logistics, and service sustainability at the facility level.

Health system resilience can be used as a conceptual framework to analyse the ability of North Aceh Regency to face future crises, encompassing dimensions of risk anticipation, prevention capacity, preparedness, response capacity, ability to maintain essential services, and the ability to adapt and transform post-crisis. This framework is relevant to be applied in the district context because it allows for the identification of health system components that most need specific and contextual strengthening, rather than merely adopting generic recommendations from the national or global level.

Although the literature on the resilience of health systems to climate change in Indonesia continues to develop, empirical evidence specifically mapping the preparedness of health systems at the district level, particularly integrating climate risks and pandemic potential within a single analytical framework, remains limited (Sulistiadi et al., 2024). National policy studies also indicate that the direction of policy towards a climate-resilient health system has not yet been fully translated into contextual strategies and operational indicators at the regional level (Oktari et al., 2022). This gap underlies the need for an in-depth study on the adaptation strategies of the health system in North Aceh Regency. Based on this description, this research is directed to analyse the adaptation strategies of the public health system in North Aceh Regency in facing the risks of climate change and the possibility of future pandemics. The focus of the analysis includes the identification of climate and pandemic risks to public health, mapping the vulnerability of the population and health facilities, assessing the available health system capacity, and formulating adaptation strategies based

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on risk priorities and local capacity. This research is expected to provide empirical contributions as well as contextual policy recommendations for strengthening the resilience of the health system in North Aceh Regency in facing future multifaceted health crises.

METHODS

This research uses a sequential explanatory mixed methods design, conducted in order through quantitative and qualitative stages. The quantitative stage is carried out first to measure the preparedness capacity of healthcare facilities and to map community vulnerabilities in a structured manner, while the qualitative stage is used to explain and deepen the quantitative findings, identify contextual barriers, and formulate adaptation strategies together with stakeholders. This design was chosen because the research requires a combination of quantitative measurements of capacity and vulnerability with contextual understanding of risk perception, coordination barriers, resource needs, and alternative adaptation strategies in facing future climate crises and pandemics.

The research was conducted in North Aceh Regency, Aceh Province, taking into account the diversity of regional characteristics, including coastal areas, lowlands, river basins, and densely populated settlements that have the potential to produce variations in health risk levels between sub-districts. The selection of areas was conducted purposively based on the characteristics of hydrometeorological disaster risks, particularly flood events, taking into account historical data from the Aceh Utara District Disaster Management Agency (BPBD) and the Indonesian Disaster Risk Index (IRBI). Sub-districts are then categorised into high, medium, and low-risk categories to ensure representation of the variation in regional risk characteristics.

The research population includes health service facilities, health workers, policymakers, and the community. The facility population consists of all Puskesmas and their networks in North Aceh Regency, while the health worker population includes those involved in environmental health programs, epidemiological surveillance, and health crisis preparedness. The policymaker population includes program managers at the Health Office and BPBD, as well as relevant cross-sectoral elements, while the community population consists of heads of households or household representatives residing in villages in areas at risk of hydrometeorological disasters.

In the quantitative stage, all Puskesmas in North Aceh Regency were used through total sampling. Facility respondents were purposively selected, namely the head of the Puskesmas or the manager of environmental health programs, surveillance, and/or disaster preparedness, who were deemed to have the best understanding of the facility's capacity and preparedness conditions, with 1–2 respondents from each Puskesmas. The measurement of community vulnerability was conducted using multistage sampling, with stratification of sub-districts based on high, medium, and low-risk levels. From each stratum, 1–2 villages were purposively selected considering the characteristics of the area, and then households in the selected villages were chosen using systematic random sampling based on the household head list. The sample size of households was determined using the Lemeshow formula with a 95% confidence level and a precision level that was established before the study. The inclusion criteria for community respondents included heads of households or household representatives aged at least 17 years, residing in the selected village for at least one

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year, and willing to participate in the study. Respondents who cannot be found after three visits or have conditions that hinder the completion of the instrument are excluded from the study. In the qualitative stage, informants were selected using purposive sampling with a maximum variation approach to obtain a variety of perspectives from different sectors and levels of regional risk. Informants come from the Health Office, BPBD, heads of Puskesmas or program managers from high, medium, and low-risk areas, health workers or cadres, community leaders/village officials, as well as cross-sectoral elements relevant to the quantitative results. Qualitative data collection is conducted through in-depth interviews and focus group discussions to deepen the findings and formulate adaptation strategies participatively until data saturation is reached.

The quantitative instrument consists of a structured questionnaire and a checklist of healthcare facility capacity adapted from the WHO Operational Framework for Climate-Resilient and Low Carbon Health Systems, as well as primary healthcare service readiness indicators. The instruments are used to assess governance, surveillance and information, emergency preparedness, human resources, infrastructure and utilities, logistics and supply chain, risk communication, and service sustainability. The qualitative instruments include semi-structured interview guidelines and focus group discussion guides that cover risk perception, preparedness capacity, cross-sector coordination barriers, resource availability, service sustainability, and adaptation strategy needs. Before use, the quantitative instruments undergo content validity through expert judgement and reliability testing through trials at healthcare facilities outside the research location.

Quantitative data were analysed using descriptive and inferential statistics. Descriptive analysis is used to describe the characteristics of respondents, the distribution of community vulnerability levels, as well as preparedness capacity scores in each domain and risk stratum. The results are presented in the form of frequency, percentage, mean value, standard deviation, median, range, and 95% confidence interval according to the characteristics of the variables.

The differences in preparedness capacity scores between regions based on three disaster risk strata were analysed using the Kruskal-Wallis test because the data were compared across more than two independent groups and the analysis used a non-parametric approach. The relationship between disaster risk levels, access to health facilities, availability of health resources, surveillance systems, cross-sector coordination, and preparedness scores was analysed using Spearman correlation. The value of the correlation coefficient (ϱ), the direction of the relationship, and the p-value are used to interpret the strength and direction of the relationship. The level of statistical significance is set at α=0.05.

Qualitative data from in-depth interviews and focus group discussions were analysed using directed content analysis. The analysis process was conducted through data transcription, repeated reading, coding based on initial categories derived from the health system resilience framework and quantitative results, identification of categories and subthemes, and theme development that explains the mechanisms behind the quantitative findings. The emerging themes were then compared across informant groups and regional risk levels. Qualitative research reporting follows the principles of the Consolidated Criteria for Reporting Qualitative Research (COREQ).

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Data integration is carried out at the interpretation stage (mixing at interpretation stage). Quantitative findings are used to identify patterns, the magnitude of gaps, and preparedness components that are related to risk characteristics, while qualitative findings are used to explain the mechanisms, context, and institutional factors underlying those patterns. Thus, qualitative data is not intended to replace quantitative results, but to provide contextual explanations and enrich the interpretation of statistical outcomes. The integration of both data sources is subsequently used as the basis for formulating adaptation strategies for the health system in North Aceh Regency.

This research obtained ethical clearance from the Research Ethics Committee of Abulyatama University with the number No. 259/UA-EC/2026, issued in 2026. Before data collection, all respondents and informants received an explanation regarding the purpose, procedures, benefits, potential risks, data confidentiality, and participation rights in the research. Participation was voluntary after respondents provided informed consent. The identities of respondents and informants were kept confidential, data was used solely for research purposes, and each participant had the right to stop or withdraw from the research at any time without consequence.

RESULTS

1. Characteristics of Regions and Respondents

The quantitative phase involved health care facilities and households from areas with varying levels of hydrometeorological risk. Regional stratification based on high, medium, and low risk was used to capture variations in health system capacity and community vulnerability. Respondent characteristics demonstrate the representation of actors with direct knowledge of facility preparedness and household vulnerability.

Table 1. Characteristics of Respondents and Unit of Analysis

Characteristics	n	%
Regional groups		
High risk	10	37.0
Moderate risk	9	33.3
Low risk	8	29.7
Health facility respondents		
Head of the Community Health Center	14	51.9
Surveillance/preparedness manager	13	48.1
Gender of facility respondents		
Male	12	44.4
Female	15	55.6
Respondent educational level		
Diploma	7	25.9
Bachelor	15	55.6
Postgraduate	5	18.5

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The composition of the analysis units demonstrated relatively balanced representation across risk strata, ensuring that capacity mapping did not only reflect high-risk areas. The involvement of community health center heads and program managers provided a relevant information base, as both groups possess operational knowledge of preparedness, surveillance, and the sustainability of health services.

2. Health Facility Readiness Capacity

Facility capacity is assessed based on several domains adapted from the WHO framework on climate-resilient and low-carbon health systems and primary health care preparedness indicators. The assessment covers governance, surveillance and information, emergency preparedness, human resources, infrastructure, logistics, risk communication, and continuity of care.

Table 2. Distribution of Community Health Center Preparedness Capacity Based on Domain

Capacity domain	Mean ± SD	Median	Range	Dominant category
Governance and leadership	72.4 ± 10.8	73.0	50–90	Good
Surveillance and information	68.7 ± 12.4	70.0	45–88	Currently
Emergency preparedness	64.2 ± 13.1	65.0	40–87	Currently
Health workers	70.1 ± 11.6	71.0	48–91	Good
Infrastructure and utilities	59.8 ± 14.7	60.0	35–85	Currently
Logistics and supply chain	61.5 ± 13.9	62.0	38–86	Currently
Risk communication	66.3 ± 12.0	67.0	43–89	Currently
Continuity of service	62.7 ± 14.2	64.0	36–88	Currently
Overall capacity score	**65.7 ± 10.9**	**66.2**	**43–86**	**Currently**

The findings indicate that the health system's capacity has generally not reached optimal levels. Relative strengths are evident in governance and human resources, while infrastructure, logistics, and service continuity mechanisms are the components most in need of strengthening. This pattern indicates that institutional readiness has not been fully matched by material and operational readiness to maintain services during simultaneous disruptions.

3. Preparedness Capacity Based on Regional Risk Level

Table 3. Comparison of Preparedness Capacity Based on Risk Strata

Risk level	n	Mean ± SD	95% CI	Median	p
High	10	59.8 ± 8.7	53.6–66.0	60.1	
Currently	9	65.4 ± 8.9	58.6–72.2	65.8	**0.008**
Low	8	73.4 ± 7.5	67.1–79.7	74.0	

Kruskal–Wallis test.

There are differences in preparedness capacity according to regional risk levels. Facilities in high-risk areas show relatively lower capacity than in low-risk areas. This finding indicates an imbalance between risk exposure and health system capacity, suggesting that areas with the greatest threat require priority for strengthening resources, infrastructure, and operational preparedness.

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4. Level of Community Vulnerability

Community vulnerability was analyzed based on risk exposure characteristics, household sensitivity, and adaptive capacity. A multistage sampling approach was used to ensure representativeness of households from areas with varying levels of risk.

Table 4. Distribution of Household Vulnerability Levels

Vulnerability level	High risk n (%)	Moderate risk n (%)	Low risk n (%)	Total n (%)
Low	14 (18.2)	22 (28.9)	31 (40.3)	67 (29.8)
Currently	30 (39.0)	38 (50.0)	35 (45.5)	103 (45.8)
High	33 (42.8)	16 (21.1)	11 (14.2)	60 (26.7)
Total	**77 (100)**	**76 (100)**	**77 (100)**	**230 (100)**

Community vulnerability shows a pattern of increasing risk levels in the region. Households in high-risk areas are more likely to be in the high-vulnerability category, indicating that disaster exposure is determined not only by geographic conditions but also by households' ability to anticipate and respond to health hazards. This finding reinforces the need for an adaptation approach that differentiates intervention priorities based on regional characteristics.

5. Relationship between Regional Characteristics and Health System Preparedness

Table 5. Analysis of the Relationship between Regional Characteristics and Preparedness Scores

Variables	Correlation coefficient (r/ϱ)	p-value
Disaster risk level	-0.51	0.007
Access to health facilities	0.43	0.019
Availability of health resources	0.58	0.002
Availability of surveillance systems	0.49	0.009
Cross-sector coordination	0.61	<0.001

Spearman test.

Health system preparedness is primarily related to resource capacity and cross-sectoral coordination. A negative relationship with risk level indicates that areas with higher risk exposure tend to have lower preparedness. Conversely, cross-sectoral coordination emerged as one of the most consistent components related to preparedness capacity, demonstrating the importance of integration between the health, disaster, environment, and local government sectors.

6. Prioritize Health System Weaknesses

Table 6. Mapping of Priorities for Strengthening the Health System

Component	Capacity score	Level of inequality	Priority
Disaster-resistant infrastructure	59.8	High	I
Supply chain and logistics	61.5	High	I
Continuity of service	62.7	High	I
Emergency preparedness	64.2	Medium–high	II

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Risk communication	66.3	Currently	II
Surveillance and information	68.7	Currently	II
Health workers	70.1	Low–medium	III
Governance	72.4	Low	III

The mapping results indicate that adaptation priorities lie not primarily on administrative aspects, but rather on the operational capacity of facilities to remain operational during disruptions. Infrastructure, logistics, and service continuity are top priorities because these three components have the potential to become bottlenecks when climate disasters occur, coupled with increased service demand due to extraordinary events or pandemics.

7. Qualitative Findings

Directed content analysis of in-depth interviews and focus groups yielded several key themes that explain the quantitative patterns. Qualitative findings primarily point to limitations in data integration, cross-sector coordination, logistical continuity, human resource capacity, and community preparedness.

Table 7. Main Themes of Qualitative Analysis Results

Theme	Main subthemes	Meaning of findings
Information integration	Health, climate and disaster data are not yet integrated	The warning and decision-making system is not yet fully based on integrated risk information.
Cross-sector coordination	Coordination mechanisms are not yet consistent	Responses have the potential to be sectoral when a compound crisis occurs.
Infrastructure	Vulnerability of facilities and utilities	Disruptions to electricity, water, access and buildings can hinder continuity of service.
Logistics	Stock availability and distribution	Crisis can extend the time to meet medical needs
HR	Capacity and workload limitations	Simultaneous crises increase pressure on healthcare workers
Public	Variations in preparedness	The adaptive capacity of communities varies between regions.
Adaptation strategy	Integrated system requirements	Stakeholders emphasize integration of climate, disaster and pandemic preparedness

Qualitative findings make clear that the primary issue is not simply absolute resource limitations, but also the fragmentation of health system functions. Lack of integrated information and coordination means that available capacity cannot be fully converted into a rapid and coordinated response. Stakeholder perspectives also indicate that adaptation strategies need to focus on mechanisms that can be used collectively across multiple crisis scenarios, rather than building separate systems for each type of threat.

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8. Integration of Quantitative and Qualitative Findings

Table 8. Integration of Mixed Methods Findings and Strategic Implications

Quantitative findings	Qualitative explanation	Strategy implications
Lower capacity in high-risk areas	Limited infrastructure and access magnify the impact of disruptions.	Priority for strengthening facilities in high-risk areas
Infrastructure is the weakest component	Facilities face potential utility and access disruptions	Development of disaster-resilient health facilities
Logistics has a high gap	Distribution and stock are not yet fully adaptive to the crisis	Strengthening resilient health supply chains
Coordination related to preparedness	The program is still running cross-sectorally partially	Establishment of an integrated coordination mechanism
Community vulnerability is higher in high-risk areas	The adaptive capacity of communities varies between regions.	Strengthening risk communication and community empowerment
Surveillance is not optimal	Health, environmental and disaster data are not yet fully integrated	Development of risk-based integrated surveillance

The integration of the two approaches demonstrates that the quantitative and qualitative findings provide complementary perspectives on health system adaptation capacity in North Aceh Regency. The quantitative analysis identified the level and distribution of adaptation capacity across locations and key components, highlighting the weakest areas that require priority attention. In contrast, the qualitative findings provided contextual explanations for these quantitative patterns by identifying the underlying mechanisms, institutional constraints, resource limitations, coordination challenges, and implementation barriers that contribute to the observed weaknesses. Thus, the quantitative findings indicate where and in which components adaptation capacity is weakest, while the qualitative findings explain why these weaknesses occur and how they affect the implementation of adaptation strategies. The convergence of these findings indicates that adaptation strategies should focus not only on improving individual preparedness but also on addressing structural and institutional constraints within the health system. Therefore, adaptation priorities in North Aceh Regency should include strengthening disaster-resilient health facilities, integrating surveillance systems, improving supply chain resilience, developing health worker capacity, strengthening cross-sectoral coordination, and enhancing community adaptive capacity.

DISCUSSION

The findings of this study indicate that the overall preparedness capacity of primary health facilities in Kabupaten Aceh Utara remains at a moderate level. Relative strengths were observed in governance and leadership and in human resources, whereas infrastructure and utilities, logistics and supply chains, and continuity of essential services represented the most constrained domains. This pattern indicates that institutional arrangements and personnel competencies have developed

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more rapidly than the material and operational foundations required to maintain service delivery under simultaneous climate-related and health shocks. The inverse relationship between disaster-risk strata and facility preparedness further indicates a structural disparity, whereby areas with higher exposure tend to have lower readiness. Household vulnerability showed a comparable gradient, with greater adaptive deficits concentrated in high-risk areas. The quantitative findings identified resource availability and cross-sectoral coordination as important correlates of preparedness, while the qualitative findings provided explanations for these patterns through fragmentation of information systems, inter-agency coordination, logistics, and community adaptive capacity.

These findings are consistent with the health-system resilience framework articulated by the World Health Organization, which emphasizes the capacity of health systems to anticipate risks, absorb shocks, adapt service delivery, and transform following crises. In this study, the moderate overall preparedness score and weaknesses in specific domains indicate that absorptive and adaptive capacities remain incomplete, particularly in physical infrastructure and supply-chain robustness. The stronger performance of governance compared with operational domains is also consistent with evidence from low- and middle-income settings, where formal planning structures may develop faster than the physical strengthening of facilities and establishment of redundant logistical pathways (Morris et al., 2025). Thus, the presence of policies, plans, and institutional structures does not necessarily translate into operational resilience when supporting infrastructure, logistics, and service-continuity mechanisms remain limited.

The significant difference in preparedness capacity across risk strata ($p=0.008$) further demonstrates that health-system capacity is unevenly distributed geographically. Facilities located in high-risk areas had lower preparedness capacity than those in medium- and low-risk areas, indicating that exposure to hazards is not necessarily accompanied by proportional adaptive capacity. This pattern is consistent with Sulistiadi et al. (2024), who identified unequal distribution of resources across Indonesian regions as an important barrier to building climate-resilient health systems. WHO (2026) similarly reported that nearly 97% of Indonesia's population lives in disaster-prone areas and that, in 2024, 142 health facilities were damaged by climate-related disasters, particularly floods, flash floods, and landslides. These conditions reinforce the importance of prioritizing health facilities located in high-risk areas within climate and disaster adaptation planning (World Health Organization, 2026).

The lowest preparedness scores in infrastructure and utilities (59.8), logistics and supply chains (61.5), and continuity of essential services (62.7) indicate that the principal weaknesses are operational rather than merely administrative. In this context, physical hardening refers to structural and infrastructural measures designed to reduce the vulnerability of health facilities and maintain essential functions during hazards. Such measures include improving the physical resilience of buildings against flooding and other hazards, protecting electrical systems and critical equipment from water damage, ensuring backup electricity and water supplies, strengthening drainage and access routes, safeguarding medical equipment and pharmaceutical storage, and providing redundant utility systems where feasible. These measures are particularly relevant in areas exposed

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to recurrent hydrometeorological hazards because physical disruption can rapidly translate into interruption of health services. Schwerdtle et al. (2024) similarly found that climate-resilient health facilities in low- and middle-income countries require adaptation measures that extend beyond emergency planning to include resilient infrastructure and facility-level operational capacity.

Evidence from Indonesia also supports the importance of strengthening facility infrastructure and environmental health systems. UNICEF Indonesia (2024), through a pilot study involving 26 Puskesmas in five provinces, reported that integration of PERIKSA-WASHFIT increased the climate-resilience index from 71% to 81% within six months (UNICEF, 2025). This finding suggests that structured interventions addressing water, sanitation, hygiene, infrastructure, and facility preparedness can generate measurable improvements in climate resilience, although their sustainability depends on continuous institutional commitment and financing. Therefore, the infrastructure deficit identified in Kabupaten Aceh Utara should not be interpreted solely as a need for physical construction, but as a broader requirement to ensure that facilities, utilities, environmental health systems, and essential services remain functional during and after disruptive events.

The quantitative and qualitative findings complement each other in explaining these operational weaknesses. Quantitative analysis identified the magnitude and distribution of preparedness deficits and demonstrated statistically significant relationships between preparedness and disaster risk, access to health facilities, health resources, surveillance, and cross-sectoral coordination. Qualitative findings subsequently explained the mechanisms underlying these relationships, particularly fragmented information flows, inconsistent inter-agency coordination, logistical constraints, and limitations in community preparedness. Thus, quantitative data answer where and in which components preparedness is weak, whereas qualitative data explain why those weaknesses occur and how they affect system functioning. The mixed-methods design therefore provides a more comprehensive interpretation than either dataset would provide independently.

Cross-sectoral coordination emerged as one of the strongest correlates of preparedness. This finding is consistent with the characteristics of climate-sensitive and pandemic risks, which are inherently multi-hazard, interconnected, and capable of producing cascading consequences. For example, flood-related damage to infrastructure may be followed by disruption of water and sanitation systems and subsequently by increased transmission of waterborne diseases. Such scenarios require integrated surveillance, joint contingency planning, coordinated emergency response, and shared logistical mechanisms rather than isolated sector-specific interventions. Sari et al. (2024) similarly identified weak cross-sectoral collaboration as an important obstacle to health-facility resilience in Indonesia, including difficulties in securing medical oxygen during the COVID-19 pandemic because its management involved authorities outside the health sector. This illustrates how fragmented institutional authority can affect continuity of health services during emergencies.

The qualitative findings further indicate that coordination mechanisms need to move beyond formal arrangements toward operational integration. Gooding et al. (2026) reported that formal multisectoral platforms may exist but operate inconsistently at subnational levels, resulting in fragmented data flows and delayed responses. Conversely, coordination supported by clear role

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delineation, shared early-warning systems, and dedicated climate-and-health mechanisms can strengthen facility-level readiness. In Kabupaten Aceh Utara, therefore, the challenge is not simply the absence of institutions but the need to connect existing health, disaster-management, environmental, and local-government mechanisms through routine information exchange, joint risk assessment, contingency planning, and coordinated resource mobilization.

The findings also reinforce the concept of compound and cascading risks. Ebi (2024) explains that climate change can act as a risk multiplier in which individual hazards interact with social and environmental vulnerabilities to generate cascading impacts. Tsai et al. (2022) similarly emphasizes the limitations of preparedness frameworks that remain organized around single-hazard scenarios. In Kabupaten Aceh Utara, the possibility of flooding, infrastructure disruption, disease outbreaks, population displacement, and pressure on health services occurring sequentially or simultaneously requires a preparedness framework that integrates climate, disaster, and pandemic risks. This also explains why surveillance, logistics, infrastructure, workforce, and coordination should be strengthened as an interconnected system rather than through isolated programs.

The present findings are further consistent with broader evidence concerning climate-resilient health systems. Mosadeghrad et al. (2023) emphasize that climate resilience requires simultaneous attention to leadership, financing, emergency preparedness, surveillance, and health-system capacity. Ansah et al. (2024) identify inadequate financing, weak climate-health data integration, and limited workforce capacity as persistent barriers to health-system adaptation. Haldane et al. (2021), based on comparative evidence from 28 countries during the COVID-19 pandemic, similarly highlights adaptive governance, flexible financing, and community engagement as common features of resilient health systems. These findings indicate that climate adaptation and pandemic preparedness should not be treated as separate agendas because both depend on the same underlying capacities for anticipation, coordination, resource mobilization, and continuity of essential services.

The Indonesian context further demonstrates the importance of a differentiated, locally responsive strategy. Oktari et al. (2022) found that disaster and climate-health policy in Indonesia has historically placed substantial emphasis on post-disaster response, while preventive and preparedness dimensions require further strengthening. Gan et al. (2021) also identified the combined burden of frequent climate-related disasters and limited evidence regarding their health impacts on vulnerable populations. In addition, Sulistiadi et al. (2024) showed that social, economic, and cultural factors influence the capacity of Indonesian health systems to adapt to climate change. Consequently, the strategy for Kabupaten Aceh Utara should be based on local risk profiles rather than applying a uniform intervention across all facilities and communities.

The qualitative findings concerning community capacity are also important because facility resilience cannot be separated from population-level adaptive capacity. The vulnerability gradient identified in this study suggests that communities living in higher-risk areas may simultaneously experience greater exposure and more limited access to resources, information, and health services. This finding is relevant to evidence from Aceh Utara showing the need to strengthen community knowledge for preventing communicable diseases after floods (Umri et al., 2023). Community-based

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risk communication, early warning, environmental health management, and preparedness education should therefore be integrated with facility-level interventions so that adaptation operates on both the supply and demand sides of the health system.

Taken together, the quantitative and qualitative evidence indicates that strengthening resilience requires simultaneous action across several interdependent domains: physical hardening of health facilities, resilient logistics and supply chains, integrated health-climate-disaster surveillance, sustained workforce capacity, continuity planning, community adaptive capacity, and institutionalized cross-sectoral coordination. Improvements in one domain are unlikely to generate durable resilience if other critical domains remain weak. The findings therefore provide a contextual empirical basis for translating existing governance capacity into stronger operational readiness. This approach is consistent with the broader evidence that health-system resilience depends not only on the existence of plans and institutions but also on the capacity to mobilize resources, maintain infrastructure and services, share information, and coordinate action during compound and cascading crises (Mosadeghrad et al., 2023; Morris et al., 2025; Gooding et al., 2026).

From a policy perspective, the findings support prioritizing high-risk health facilities for infrastructure and utility strengthening, establishing resilient logistics and supply-chain mechanisms, integrating health-climate-disaster surveillance, developing reserve workforce and surge capacity, and institutionalizing routine cross-sectoral coordination. Implementation requires adequate financing, trained human resources, reliable information and communication systems, resilient utilities, emergency logistics, medical supplies, transportation, and mechanisms for joint planning and monitoring. These resources should be allocated according to local risk and capacity profiles so that areas with greater exposure and lower preparedness are not left with disproportionate adaptive deficits. Such an approach would allow the existing governance strengths in Kabupaten Aceh Utara to be translated into operational continuity under simultaneous climate-related hazards and future pandemic threats.

CONCLUSIONS

This study shows that the preparedness capacity of the public health system in North Aceh Regency to cope with climate change and potential pandemics remains at a moderate level, with key weaknesses in infrastructure and utilities, logistics and supply chains, and service continuity. Conversely, governance and human resources are relatively stronger components. Preparedness also reveals disparities between regions, with high-risk areas tending to have lower capacity and higher community vulnerability.

The mixed-methods findings indicate that limitations in preparedness are not only related to the availability of resources, but also to the fragmentation of information, cross-sectoral coordination, logistics, surveillance, and the community's adaptive capacity. Cross-sectoral coordination, health resources, surveillance and access to health facilities are key components of preparedness. Therefore, adaptation strategies need to focus on strengthening disaster-resilient facilities and utilities, enhancing the resilience of logistics and supply chains, integrating health–

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climate–disaster surveillance, building the capacity of health workers and communities, and institutionalising cross-sectoral coordination.

Within the institutional framework, these strengthening measures need to be integrated with existing disaster management mechanisms at national and regional levels so that the functions of preparedness, response, recovery and service continuity can operate in a coordinated manner. Implementation requires support in the form of funding, human resources, resilient infrastructure and utilities, integrated information and surveillance systems, logistics and service reserves, transport and communication facilities, and cross-sectoral planning and monitoring mechanisms. This approach is necessary to transform existing governance strengths into operational capacity capable of sustaining health services in the face of simultaneous and cascading climate and pandemic risks.

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