Indonesian Journal of Interdisciplinary Research in Science and Technology (MARCOPOLO)
Vol. 4, No. 2, 2026 : 105 - 118

Community Adaptation Models to Changes in Raw Water Distribution Patterns due to Climate Change in Coastal Areas of South Flores

Valentinus Tan
Fakultas Teknik, Universitas Flores, Indonesia
Corresponding Author: Valentinus Tan tanvalentinus49@gmail.com

A R T I C L E I N F O

Keywords: Climate Change, Raw Water, Community-Based Adaptation, Coastal Areas, Seawater Intrusion

Received : 20 December 2025
Revised : 23 January 2026
Accepted: 24 February 2026

A B S T R A C T

Climate change is affecting the availability and distribution of raw water in the coastal region of South Flores, East Nusa Tenggara, which depends on seasonal rainfall and shallow coastal aquifers. The increase in the dry season and seawater intrusion reduces the quantity and quality of raw water. This study aims to analyze the model of community adaptation to changes in raw water distribution patterns due to climate change. The study used a mixed methods approach in four coastal villages with a survey of 120 households, rainfall data from 2013–2023, as well as groundwater surface and salinity measurements. The results showed a decrease in the availability of raw water in the dry season by 28.9% and an increase in salinity of up to 1,430 mg/L. Adaptation strategies in the form of rainwater harvesting and management of communal water distribution were able to reduce water shortage days by 24.6% ($p < 0.05$). This study concludes that community-based adaptation is effective in increasing the resilience of raw water distribution in the coastal areas of South Flores and needs to be integrated in the management of water resources that are adaptive to climate change.

DOI: https://doi.org/10.55927/marcopolo.v4i2.12
E-ISSN : 2986-8009
https://journalmarcopolo.my.id/index.php/marcopolo

INTRODUCTION

Climate change increases the pressure on the availability of raw water in coastal areas and small islands through changes in rainfall patterns, increased drought events, and sea level rise that increases the risk of salinization and seawater intrusion into coastal aquifers. The IPCC report confirms that coastal risks—including flooding, erosion, and salinization—tend to increase with sea level rise and are exacerbated by limited local adaptation capacity (IPCC, 2024). In the context of water resources, seawater intrusion is one of the main threats to freshwater supply security because it degrades groundwater quality and narrows freshwater zones that can be used for domestic needs and public services (Xiao et al., 2022; Salvati et al., 2023).

The coastal area of South Flores in East Nusa Tenggara Province (NTT) is an example of a vulnerable area because it is highly dependent on seasonal rainfall and shallow aquifers, while surface water sources are limited and fluctuating. NTT climate information published periodically by BMKG shows the importance of monitoring regional climate variability (BMKG NTT Climatology Station, 2025). In addition, the availability of rainfall data by district/city published by the Central Statistics Agency (BPS) shows the dynamics of monthly rainfall which is an important basis for assessing seasonal-based water security in NTT (BPS NTT Province, 2025). On the hydrogeological side, the characteristics of the groundwater system in NTT also show technical challenges in raw water management, especially related to the limitations of productive aquifers and the vulnerability of water quality in certain areas (ITATS Journal, 2024).

Operationally, changes in the distribution pattern of raw water on the coast are not only determined by a decrease in discharge or seasonal availability, but also by changes in quality due to seawater intrusion that can increase salinity levels in shallow wells and reduce the feasibility of water for consumption. The international literature emphasizes that climate change can amplify the intensity of intrusion through a combination of sea level rise, recharge changes, and groundwater uptake pressures, thus demanding adaptive responses based on local conditions (Xiao et al., 2022; Salvati et al., 2023). Thus, the issue of raw water distribution on the coast of South Flores needs to be understood as an integrated problem of quantity-quality-governance, not solely an infrastructure problem.

On the other hand, the adaptation practices of coastal communities often develop independently through a combination of technical strategies (e.g., rainwater harvesting and distribution arrangements) and social-institutional strategies (e.g., rotation agreements, communal management, and utilization rules). Evidence from coastal adaptation studies shows that the effectiveness of adaptation is strongly influenced by governance support, inter-stakeholder coordination, as well as local institutional capacity to collectively manage climate risks (Adelekan et al., 2024). However, adaptation studies often emphasize aspects of coastal risk in general, while analyses that specifically link changes in raw water distribution patterns to community-based adaptation models in dry island regions are relatively limited.

These research gaps are important because water resources management policies require an evidence base to design contextually appropriate interventions—from planning to implementation of sustainable raw water management. Indonesia's water resources sector planning document also places the sustainability of groundwater and raw water management as a strategic issue in the development framework (Ministry of PUPR, 2020–2024). Therefore, research is needed that not only maps the impact of climate on availability and quality, but also examines how community adaptation strategies work, how effective, and what factors determine their success.

Based on this background, this study aims to analyze the model of community adaptation to changes in raw water distribution patterns due to climate change in the coastal area of South Flores. This study combines seasonal water balance analysis and quality indicators (salinity) with socio-institutional studies to identify adaptation strategies, assess their effectiveness, and formulate implications for climate change-adaptive water resource management planning in coastal areas and small islands.

LITERATURE REVIEW

Climate Change and Raw Water Availability Dynamics in Coastal Areas

Climate change has triggered significant shifts in the global hydrological cycle, particularly in coastal areas and small archipelagos that have a high dependence on rainfall and shallow groundwater systems. Recent studies show that increased climate variability contributes to the uncertainty of raw water supply through changes in precipitation patterns, increased evapotranspiration, as well as pressure on coastal aquifer systems (Taylor et al., 2021). This condition leads to a decrease in groundwater recharge capacity and increases susceptibility to seawater intrusion, especially in areas with uncontrolled groundwater exploitation (Werner et al., 2022).

Regional research in the Southeast Asian region confirms that tropical coastal regions are experiencing double pressures, namely a decrease in freshwater quantity and quality degradation due to salinization (Hussain et al., 2021). This impact not only affects domestic water availability, but also increases the risk of water insecurity in coastal communities that have limited infrastructure and adaptation capacity (Mukherjee et al., 2023).

Seawater Intrusion and Degradation of Coastal Groundwater Quality

Seawater intrusion is one of the main indicators of degradation of raw water sources in coastal areas. Recent hydrogeological research shows that sea level rise and groundwater subsidence due to prolonged droughts accelerate the movement of saltwater into coastal aquifers, which is characterized by an increase in the total value of dissolved solids (TDS) and chlorides (Post & Werner, 2021). This phenomenon is exacerbated in areas with shallow aquifers and high porous lithology, which are commonly found in the eastern part of Indonesia's archipelago.

Empirical studies in Indonesia show that the salinity value of groundwater in coastal areas can exceed the threshold of suitable water for consumption during the long dry season, thereby reducing the reliability of groundwater as a

source of raw water (Sutrisno et al., 2022). Therefore, raw water management in coastal areas requires an adaptive approach that considers seasonal water quality dynamics, not just quantity aspects.

Community Adaptation to Changes in Raw Water Availability

Community adaptation is a key component in improving water resilience in climate-sensitive areas. Recent literature emphasizes that community-based adaptation tends to be more responsive to local conditions because it leverages local knowledge, practices, and social networks (Armitage et al., 2020). In the context of raw water management, common adaptation strategies include rainwater harvesting, water source diversification, communal water management, and collective distribution arrangements (Shah et al., 2021).

Studies in coastal regions of Africa and Asia show that households that implement a combination of technical and institutional adaptation strategies have higher levels of water resilience than households that rely on a single water source (Venkatesh et al., 2022). Such adaptations not only reduce the frequency of water scarcity, but also increase the capacity of communities to deal with long-term climate uncertainty.

Community-Based Raw Water Management in the Indonesian Context

In the Indonesian context, community-based wastewater management has long been an adaptive practice, especially in rural and archipelagic areas. National research shows that non-governmental water management systems are relatively effective in ensuring the sustainability of water supply during the dry season, although they still face limitations in terms of technical capacity and policy support (Pranoto & Nugroho, 2021).

Another study emphasizes that the success of adaptation is strongly influenced by local institutional factors, such as village leadership, clarity of water use rules, and community participation in decision-making (Yuliana et al., 2023). However, most national research still focuses on aspects of water access and services, while studies that link community adaptation to changes in raw water distribution patterns due to climate change are still quantitatively limited.

Research Synthesis and Gaps

Based on a literature review, it can be concluded that climate change has a significant impact on the quantity and quality of raw water in coastal areas through the mechanism of rainfall variability and seawater intrusion. Community-based adaptation has proven to play an important role in improving water resilience, but its effectiveness depends heavily on suitability to local hydrological conditions and institutional support. However, there is still a research gap related to the integration of quantitative hydrological analysis with the social study of community adaptation, especially in coastal areas and small islands in Indonesia. Therefore, this study seeks to fill this gap by analyzing the model of community adaptation to changes in raw water distribution patterns due to climate change in a measurable and contextual manner.

METHODOLOGY

This study uses a mixed methods approach with a cross-sectional design to analyze changes in raw water distribution patterns due to climate change and community adaptation models in the coastal area of South Flores, East Nusa Tenggara Province. This approach was chosen because it is able to integrate quantitative analysis of hydrology with the socio-institutional understanding of the community, thus providing a comprehensive picture of the dynamics of water resources in climate-sensitive coastal areas (Creswell & Creswell, 2021; Armitage et al., 2020).

The study locations included four coastal villages that were purposively selected based on the characteristics of dependence on shallow coastal aquifers, limited surface water sources, and exposure to seawater intrusion. The study population was all households in the village, with a sample of 120 households determined using purposive sampling techniques. The selection criteria for respondents included households that use groundwater or communal water distribution systems as the main source of raw water, and have lived for at least five years to ensure adaptation experience to local climate variability (Etikan et al., 2020).

Quantitative data was collected through daily rainfall analysis for the 2013–2023 period, groundwater level and shallow well salinity measurements at a depth of 5–15 meters, and recording household raw water distribution during the dry season. The analysis was carried out using seasonal water balance calculations to assess changes in raw water availability, as well as groundwater quality evaluation based on salinity parameters as indicators of seawater intrusion (Taylor et al., 2021; Post & Werner, 2021). Social data was collected through structured surveys and in-depth interviews with household heads, village water managers, and community leaders to identify the adaptation strategies implemented, water distribution mechanisms, as well as institutional factors that affect the effectiveness of adaptation.

Data analysis was carried out descriptively and inferentially. Descriptive analysis was used to describe the pattern of raw water availability, salinity levels, and forms of community adaptation. To assess the effectiveness of adaptation, a comparative analysis was carried out on the number of days of water scarcity between households that implemented one adaptation strategy and those that implemented integrated adaptation, with a significance level of $p < 0.05$. Qualitative data were analyzed thematically to strengthen quantitative interpretations and explain the socio-institutional context of raw water adaptation at the community level (Braun & Clarke, 2021).

The entire research process is carried out by paying attention to the ethical principles of social and environmental research, including respondent consent (informed consent), anonymity, and data confidentiality. The data is collected and used solely for academic purposes and the formulation of recommendations for water resource management that are adaptive to climate change (Israel & Hay, 2020).

RESEARCH RESULTS

The results of the hydrological analysis show that the coastal area of South Flores has experienced significant changes in the pattern of raw water availability in the last decade. Analysis of seasonal water balance based on rainfall data for the 2013–2023 period shows a tendency to decrease water surplus in the rainy season and increase in water deficit in the dry season. The average availability of raw water in the dry season decreased by 28.9% compared to normal conditions before the recurrent climate anomaly, especially in years with moderate to strong El Niño events. This decline has a direct impact on the reduced continuity of household raw water distribution, which previously could be met throughout the year to be intermittent in the dry months. Details of changes in raw water availability based on seasonal water balance analysis are presented in Table 1.

Table 1. Changes in Seasonal Raw Water Availability Based on Water Balance Analysis (2013–2023)

Parameters	Baseline Conditions[1]	Conditions Affected by Climate	Absolute Change	Relative Change (%)
Availability of dry season raw water (m^3/month)	2.000	1.422	−578	**−28.9**

In terms of water quality, the results of facial measurements and groundwater salinity of shallow wells show indications of seawater intrusion that is increasingly widespread in coastal zones. The average salinity value of groundwater at a distance of less than 500 meters from the coastline increased from the range of 700–900 mg/L to 1.200–1.430 mg/L during the peak of the dry season, exceeding the threshold for water suitable for consumption. This increase in salinity correlates with faster groundwater level decline during long dry periods, which indicates reduced freshwater pressure against seawater intrusion. Household wells with a depth of less than 10 meters show the highest level of vulnerability to water quality degradation. Changes in groundwater salinity in coastal zones are shown in Table 2.

Table 2. Changes in Groundwater Salinity of Shallow Wells in Coastal Zones (< 500 m from Coastline)[2]

Water Quality Parameters	Normal Condition (mg/L)	Peak of the Dry Season (mg/L)	Difference (mg/L)
Average salinity of groundwater	820	1.430	+610

[1] Baseline conditions represent the average availability of raw water in normal climatic periods before recurrent climatic anomalies

[2] The salinity value of >1,000 mg/L indicates a strong indication of seawater intrusion and a decrease in the feasibility of water for domestic consumption

A social-quantitative analysis of 120 households showed that the impact of changes in the distribution of raw water was not felt uniformly. Households that rely on a single water source, particularly individual wells, experience an average of 18–25 days of water shortages per month during the peak of the dry season. In contrast, households that have access to more than one water source—for example, a combination of collective wells and rainwater harvesting—show lower levels of vulnerability. This difference confirms that the diversification of water sources is a key factor in increasing household water security in coastal areas.

Table 3. Average Household Water Shortage Days at the Peak of the Dry Season

Household Groups	n	Mean (day/month)	Standard Deviation
No unified adaptation (0–1 strategy)	60	20.3	4.9
Integrated adaptation (≥2 strategies)	60	15.3	4.6

The results of the community adaptation analysis show that there are a variety of strategies that develop locally, both technical and institutional. The most commonly applied technical strategy is household-scale rainwater harvesting with a holding capacity of between 3–5 m^3, which is used as a backup water source for 1–2 months of the early dry season. In addition, the community also utilizes collective wells built in a zone that is relatively safe from seawater intrusion, although it requires a mutually agreed distribution management system. Institutional strategies include regulating water distribution on a rotating basis, setting a water collection schedule, and contributing to the maintenance of communal water storage infrastructure. The variety of adaptation strategies implemented by the community and their adoption rates are presented in Table 4.

Table 4. Proportion of Adoption of Raw Water Adaptation Strategies by Households

Adaptation Strategy	Number of Households (n)	Percentage (%)
Rainwater harvesting (3–5 m^3 reservoir)	72	60.0
Deal-based rotating water distribution	78	65.0
Collective well utilization	54	45.0
Communal water reservoirs	48	40.0
Integrated adaptation (≥2 strategies)	60	50.0

Comparative analysis showed that households that implemented an integrated adaptation strategy—that is, combined at least two adaptation strategies—experienced an average decrease in the number of days without water deficiency by an average of 24.6% compared to households without adaptation or with a single strategy. This difference is statistically significant (p

< 0.05), which indicates that adaptation based on a combination of strategies is more effective in reducing the impact of raw water deficits due to climate change. In addition, households with a high level of participation in communal water management show better water supply stability than individualistic households.

The qualitative findings of the in-depth interviews reinforce the quantitative results by showing that the success of adaptation is determined not only by the availability of infrastructure, but also by local institutional strength and social trust. Villages with active local leadership and clear water distribution rules are able to reduce water use conflicts and increase compliance with the rotating distribution system. In contrast, in villages with weak institutional coordination, technical adaptation is often unsustainable and triggers tensions between residents at the height of the dry season.

Table 5. In-Depth Interview Findings on Community-Based Adaptation in Raw Water Distribution Management in the South Flores Coast

Informant Code	Interview Date	The Role of the Informant	Village	Narrative Summary of Findings
W-01	June 12, 2024	Village Head	Village A	Explained that the rotating water distribution rules are quite effective in suppressing conflicts, but their implementation is often disrupted by residents who take water outside the schedule during long droughts
W-02	June 13, 2024	Village Water Manager	Village A	It revealed that the maintenance of water reservoirs is often constrained by non-routine residents' contributions, so that the infrastructure does not always function optimally
W-03	June 14, 2024	Community Leaders	Village B	Stating that deliberation based water distribution agreements exist, but compliance decreases when water availability is severely limited
W-04	June 15, 2024	Hamlet Head	Village B	Highlighting the weak coordination between hamlet areas and the lack of clear sanctions for violations of water distribution rules

W-05	June 17, 2024	Village Head	Village C	Acknowledging that technical adaptations such as rainwater harvesting help, but not enough to cover water needs during extreme dry seasons
W-06	18 June 2024	Collective Well Managers	Village C	He said that there are often disputes between residents regarding the turn to fetch water, especially at certain hours
W-07	June 20, 2024	Female Characters	Village D	Illustrates that women often bear the additional burden of finding water, and that water distribution has not fully taken into account household needs
W-08	June 21, 2024	Water Group Leader	Village D	Explained that the group-based distribution system is running relatively well, although there are still residents who are less actively participating
W-09	June 22, 2024	Youth Figures	Village D	Stating the low involvement of the younger generation at first, but increased after being involved in water distribution supervision
W-10	June 24, 2024	Village Apparatus	Village B	Assessing that without assistance from the local government, the capacity of villages in managing water conflicts is still limited

Overall, the results of this study show that climate change has affected the distribution of raw water on the coast of South Flores through the mechanism of reducing seasonal availability and degrading groundwater quality. However, these impacts can be significantly mitigated through community-based adaptation models that are integrated with local hydrological conditions and supported by strong institutions. These findings confirm that raw water resilience in coastal areas depends not only on natural factors, but also on social adaptive capacity and local governance.

DISCUSSION

The results of this study show that climate change has had a significant impact on the pattern of raw water availability and distribution in the coastal area of South Flores through the mechanism of seasonal water availability reduction and degradation of groundwater quality due to seawater intrusion.

The decrease in dry season raw water availability by 28.9% reflects an increasing water balance deficit in areas that are heavily dependent on rainfall and shallow coastal aquifers. These findings are in line with recent hydrological studies that show that increased climate variability and the occurrence of long droughts directly increase the risk of raw water scarcity in coastal areas and small islands (Taylor et al., 2021; Mukherjee et al., 2023).

In terms of water quality, the increase in groundwater salinity to reach 1.430 mg/L in the near-shore zone indicates that seawater intrusion has become a serious pressure on the sustainability of raw water sources. The coastal hydrogeological literature explains that groundwater subsidence during the dry season, combined with sea level rise, accelerates the movement of saltwater into coastal aquifers and decreases the suitability of groundwater for domestic consumption (Post & Werner, 2021; Werner et al., 2022). Thus, the findings of this study strengthen the argument that raw water management in coastal areas must consider the close relationship between water quantity and quality simultaneously.

Socio-quantitative analysis shows that the impact of changes in raw water distribution is not homogeneous between households. Households that rely on a single water source, particularly individual shallow wells, experience a higher number of water-scarce days during the peak of the dry season than households that have access to diversified water sources. These findings are consistent with the water resilience approach that emphasizes the importance of diversifying water sources as a key adaptation strategy in the face of climate uncertainty (Venkatesh et al., 2022). Diversification not only increases supply flexibility, but also reduces dependence on water sources that are most vulnerable to climate change.

The results of the study also show that community adaptation in South Flores develops in the form of a combination of technical and institutional strategies. Household-scale rainwater harvesting is the most widely adopted technical strategy because it is relatively cheap and in accordance with local conditions. The water adaptation literature shows that rainwater harvesting is one of the effective adaptation strategies in areas with high rainfall variability, especially as a backup water source at the beginning of the dry season (Shah et al., 2021). However, the effectiveness of these technical strategies increases significantly when supported by institutional mechanisms, such as collective well management and social agreement-based water distribution arrangements.

The empirical finding that integrated adaptation is able to significantly reduce household water scarcity by 24.6% indicates that raw water adaptation is synergistic. Partially implemented adaptation strategies tend to be less effective than integrated approaches that combine several solutions at once. This is in line with the community-based adaptation framework that places successful adaptation as the result of an interaction between technical, social, and institutional factors (Armitage et al., 2020; Adelekan et al., 2024). In other words, effective adaptation is not just about "what" the strategy is implemented, but "how" the strategy is organized and managed collectively.

The role of local institutions is emerging as a key factor in the sustainability of adaptation. Villages with active local leadership, clear water distribution rules, and high levels of social trust are able to minimize water use conflicts and increase compliance with the rotating distribution system. These findings support an adaptive governance approach that emphasizes the importance of institutional capacity, community participation, and social learning in dealing with climate change risks (Folke et al., 2021). Conversely, weak institutional coordination leads to unsustainable technical adaptation and has the potential to exacerbate social tensions in periods of drought.

Conceptually, this study expands the literature on water resource management by showing that the resilience of raw water distribution in coastal areas is not solely determined by hydrological conditions, but also by social adaptive capacity and local governance. The policy implications of these findings are the need to shift the approach to raw water management from one oriented solely on infrastructure development to one that integrates water balance analysis, seawater intrusion mitigation, and community-based institutional strengthening. This kind of approach is considered more adaptive and sustainable in dealing with climate uncertainty in coastal areas such as South Flores.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that climate change has significantly affected the pattern of raw water availability and distribution in the coastal area of South Flores through a decrease in seasonal water availability and degradation of groundwater quality due to seawater intrusion. Water balance analysis showed a decrease in the availability of raw water in the dry season by 28.9%, while an increase in groundwater salinity of up to 1,430 mg/L indicates a decrease in the feasibility of groundwater as the main source of raw water for coastal households. This condition underscores the vulnerability of raw water supply systems that depend on rainfall and shallow aquifers to climate variability.

The results of the study also show that the impact of changes in the distribution of raw water is not felt evenly between households. Households that depend on a single water source have a higher level of vulnerability than households that implement water source diversification. Community-based adaptation that combines technical and institutional strategies has proven effective in improving water security, as shown by a 24.6% reduction in household water scarcity days at the peak of the dry season. These findings confirm that integrated adaptation is more effective than the implementation of a single strategy.

Overall, this study confirms that the resilience of raw water distribution in coastal areas is determined not only by hydrological factors, but also by social adaptive capacity and local institutional strength. Therefore, the management of raw water resources in the coast of South Flores needs to integrate hydrological analysis, seawater intrusion mitigation, and strengthening community-based governance in a policy framework that is adaptive to climate change, in order to ensure the sustainability of raw water supply in the future.

ADVANCED RESEARCH

Follow-up research needs to develop a longitudinal approach to assess the sustainability of community adaptation to changes in raw water distribution in coastal areas and small islands. The integration of hydrogeological modeling, climate projections, and socio-institutional analysis is needed to map the risk of seawater intrusion and the effectiveness of community-based adaptation more precisely. In addition, comparative studies between coastal areas in Eastern Indonesia are important to test the generalization of findings and support the formulation of adaptive and sustainable water resources management policies.

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