*e*-ISSN: 3025-7905
**FUTURE ACADEMIA** *p*-ISSN: 3026-166X
The Journal of Multidisciplinary Research on Scientific and Advanced
Volume 4, Nomor 2, June 2026 pp. 1166-1175
DOI https://doi.org/10.61579/future.v4i2.804

# Climate Change Impacts on Irrigation Water Availability in Pante Lhong Irrigation Area, Peusangan Watershed, Bireuen Regency

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**ARTICLE INFO**

**Article history:**
Received May 23, 2026
Revised June 15, 2026
Accepted June 30, 2026
Available online June 30, 2026

**Keywords:**
Climate Change; Adaptation Strategies; Bireuen.



**ABSTRACT**

Climate change poses a significant threat to water security, particularly for agricultural irrigation systems in monsoon-dependent regions. This study assesses the impact of climate change on irrigation water availability in the Pante Lhong Irrigation Area (DI Pante Lhong), Peusangan Watershed, Bireuen Regency, Aceh. Using a mixed-methods approach, the research analyzed decadal climate data (2014–2024) from the Meteorology, Climatology, and Geophysics Agency (BMKG), field measurements of river discharge, and interviews with farmers and irrigation officials. Results indicate a significant declining trend in annual rainfall (~-2.8% per year) and a consistent increase in maximum temperature (~+0.16°C per year). These changes have led to a substantial reduction in the reliable discharge (Q80) of the Peusangan River, particularly during the dry season (July-October), with decreases of up to 29%. A monthly water balance analysis projected a chronic water deficit for seven months (April-October), with the peak deficit in August (7.7 million m³), indicating that available water can meet only about 30% of irrigation demand during critical periods. The study concludes that climate change severely threatens the sustainability of rice farming in the region. Recommended adaptation strategies include infrastructure modernization, crop diversification, and strengthened water user institutions to enhance climate resilience.

## 1. INTRODUCTION

Climate change has become one of the most pressing global environmental challenges, significantly affecting the sustainability of water resources and agricultural production systems. Increasing global temperatures, altered precipitation patterns, and the growing frequency of extreme weather events have substantially influenced the availability and distribution of freshwater resources, particularly in regions where agriculture depends heavily on surface water irrigation (IPCC, 2021; IPCC, 2022). These hydrological changes threaten food security because irrigation systems rely on stable river discharge and predictable rainfall to maintain crop productivity (FAO, 2019).

Indonesia is recognized as one of the countries highly vulnerable to climate change due to its tropical climate and dependence on climate-sensitive economic sectors, especially agriculture. Changes in rainfall variability and increasing air temperatures have disrupted watershed hydrology, reducing river discharge during the dry season while increasing the likelihood of floods during the rainy season (World Bank, 2020). Consequently, irrigation systems in many agricultural regions have experienced growing pressure in meeting crop water requirements, particularly in rice-producing areas where water demand remains consistently high throughout the planting season (Bappenas, 2021).

Aceh Province is among the regions experiencing increasing climate variability, with observable changes in rainfall distribution, prolonged dry seasons, and rising temperatures over the last decade. These climatic changes have directly influenced water availability in several major watersheds, including the Peusangan Watershed, which supplies irrigation water to thousands of hectares of agricultural land in Bireuen Regency. The Pante Lhong Irrigation Area (DI Pante Lhong), serving approximately 6,562 hectares of irrigated farmland, is highly dependent on the Peusangan River as its primary water source. Consequently, fluctuations in river discharge caused by climate change have become a major concern for maintaining agricultural productivity and regional food security (BMKG, 2024; Dinas PUPR Kabupaten Bireuen, 2023).

Previous studies have consistently demonstrated that climate change alters watershed hydrology by reducing reliable river discharge and increasing evapotranspiration, thereby limiting irrigation water availability. Sharma and Ghosh (2020) reported that tropical river basins experience significant reductions in dry-season discharge under changing climatic conditions. Similarly, Amin and Abbas (2021) emphasized that irrigation systems in Southeast Asia require adaptive water management strategies to maintain resilience against prolonged droughts. In Indonesia, Azizah et al. (2024) found that land-use changes combined with climate variability substantially reduce irrigation water availability in Aceh, indicating that both climatic and anthropogenic factors contribute to increasing water stress.

Despite these important findings, most previous studies have focused either on regional climate trends, watershed hydrology, or general irrigation management. Empirical studies that comprehensively integrate long-term climate trends, river discharge changes, irrigation water balance analysis, and adaptation strategies at the irrigation-area scale remain limited, particularly for the Pante Lhong Irrigation Area within the Peusangan Watershed. Furthermore, limited research has combined quantitative hydrological analysis with qualitative information from farmers and irrigation managers to better understand the practical implications of climate change on irrigation water management. This indicates a clear research gap that requires further investigation.

The novelty of this study lies in its integrated assessment of climate change impacts on irrigation water availability by combining decadal climate trend analysis (2014–2024), reliable river discharge (Q80) evaluation, monthly irrigation water balance analysis, field observations, stakeholder interviews, and SWOT-based adaptation strategy formulation. This integrated approach provides a more comprehensive understanding of the relationships between climate variability, watershed hydrology, irrigation performance, and adaptive management than studies that examine these aspects separately.

Therefore, this study aims to (1) analyze long-term trends in rainfall and temperature in the Peusangan Watershed, (2) evaluate the impacts of climate change on reliable river discharge and irrigation water availability in the Pante Lhong Irrigation Area, (3) identify potential irrigation water deficits through monthly water balance analysis, and (4) formulate adaptive management strategies to improve the resilience of irrigation systems under changing climatic conditions. The findings are expected to provide scientific evidence that supports sustainable irrigation planning, climate adaptation policies, and integrated water resource management in Aceh and other climate-vulnerable agricultural regions.

## 2. METHOD

### Study Area

This study was conducted in the Pante Lhong Irrigation Area (DI Pante Lhong), located within the Peusangan Watershed, Bireuen Regency, Aceh Province, Indonesia. The irrigation system serves approximately 6,562 ha of agricultural land and depends primarily on the Peusangan River as its main water source. The study area was selected because it represents one of the largest irrigated rice-producing regions in northern Aceh and has experienced increasing water shortages during recent dry seasons, making it highly vulnerable to climate change.

### Research Design

This study employed a **mixed-methods approach**, integrating quantitative hydrological and climatological analyses with qualitative field investigations. The quantitative approach was used to evaluate long-term climate variability, changes in river discharge, and irrigation water availability, while the qualitative approach was conducted to understand stakeholders' perceptions regarding climate change impacts and irrigation water management. The integration of both approaches enabled a comprehensive assessment of climate-induced changes in irrigation performance and supported the formulation of practical adaptation strategies.

### Data Collection

The study utilized both secondary and primary data.

#### Secondary Data

Secondary data consisted of monthly rainfall and maximum air temperature records covering the period 2014–2024 obtained from the Malikussaleh Meteorological Station of the Meteorology, Climatology, and Geophysics Agency (BMKG). Historical river discharge data, irrigation infrastructure information, and irrigation service area data were collected from the Public Works and Spatial Planning Office (Dinas PUPR) of Bireuen Regency. Additional supporting information was obtained from government reports, previous studies, and published scientific literature related to climate change, irrigation, and watershed management.

#### Primary Data

Primary data were collected between June and October 2025 through two techniques.

First, field measurements were conducted at five monitoring points located near the irrigation intake structures to determine actual river discharge during the dry season. Discharge measurements were performed using standard hydrological procedures by measuring flow velocity and cross-sectional area.

Second, semi-structured interviews were conducted with **30 key informants**, consisting of farmers, irrigation water user association (P3A) representatives, agricultural extension officers, and officials from Dinas PUPR. The interviews explored respondents' perceptions regarding climate variability, irrigation water shortages, existing adaptation practices, and institutional challenges in irrigation management.

**Data Analysis**

The collected data were analyzed through four sequential stages.

**Climate Trend Analysis**

Annual rainfall and maximum temperature data from 2014 to 2024 were analyzed using descriptive statistics and simple linear regression to identify long-term climatic trends. Regression analysis was applied to determine the direction and magnitude of changes in rainfall and temperature over the study period.

**Reliable River Discharge Analysis**

Reliable discharge (Q80) was calculated and compared between two observation periods, namely the baseline period (2015–2019) and the recent period (2020–2024). The comparison was used to quantify changes in dependable river flow associated with climate variability and to evaluate the reliability of irrigation water supply during the dry season.

**Irrigation Water Balance Analysis**

Monthly irrigation water balance was calculated by comparing available river discharge with irrigation water requirements under the existing rice–rice–secondary crop planting pattern. Water availability was estimated from dependable river discharge after considering irrigation system efficiency, while irrigation demand was determined based on crop water requirements. Water deficit or surplus was calculated using the following equation:

**Water Balance = Water Availability − Irrigation Water Demand**

Negative values indicate water deficit, whereas positive values indicate surplus water. Monthly deficit analysis was used to identify critical periods of irrigation water shortages throughout the year.

**SWOT Analysis**

A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was employed to formulate climate adaptation strategies for the irrigation system. Internal factors (strengths and weaknesses) and external factors (opportunities and threats) were identified based on field observations, interview results, and secondary information. The SWOT matrix was subsequently used to develop strategic recommendations aimed at improving irrigation system resilience under future climate conditions.

**Research Validity**

The credibility of the findings was strengthened through **data triangulation**, integrating climatological records, hydrological measurements, institutional documents, and stakeholder interviews. Comparing multiple sources of evidence enhanced the reliability of the analysis and minimized potential bias in interpreting the impacts of climate change on irrigation water availability.

## 3. RESULTS AND DISCUSSION

*Result*

**Climate Trends in the Peusangan Watershed (2014–2024)**

Analysis of climatological data obtained from BMKG revealed significant changes in rainfall and air temperature during the observation period (2014–2024). Annual rainfall exhibited a declining trend, while the average maximum air temperature showed a gradual increase. Compared with the 2014 baseline, annual rainfall decreased by approximately 15–20% during the most recent observation period, whereas the average maximum temperature increased by approximately 1.2°C.

The monthly rainfall distribution also shifted considerably. The onset of the dry season occurred earlier, and rainfall during June–October declined substantially compared with previous years. These climatic changes indicate increasing climate variability within the Peusangan Watershed and suggest reduced natural recharge of surface water resources during the irrigation season.

**Changes in Reliable River Discharge**

The reduction in rainfall was accompanied by a noticeable decline in the reliable discharge (Q80) of the Peusangan River. Comparison between the baseline period (2015–2019) and the recent period (2020–2024) demonstrated lower dependable flows throughout the dry season.

The largest reductions occurred during August and September, when reliable discharge declined by approximately 28–29%. During these months, river discharge fell below the level required to satisfy irrigation demand, indicating increasing pressure on water availability for agricultural activities. Field interviews further showed that approximately 90% of farmers perceived that the dry season now begins earlier and lasts longer than in previous years, resulting in prolonged water shortages during crop cultivation.

**Irrigation Water Balance**

Monthly water balance analysis demonstrated that the Pante Lhong Irrigation Area experiences water deficits during most of the dry season. Water shortages began in April and continued until October, indicating seven consecutive months of insufficient irrigation supply.

The most severe deficit occurred in August, reaching approximately **7.7 million m³**, followed by July (**7.4 million m³**) and September (**6.7 million m³**). During these critical months, available river discharge was capable of supplying only about one-third of the total irrigation water requirement. Conversely, surplus water was observed during January, November, and December when rainfall and river discharge were relatively high. These findings indicate considerable seasonal variation in water availability and highlight the vulnerability of the irrigation system during prolonged dry periods.

**SWOT Analysis for Climate Adaptation**

The SWOT analysis identified several internal and external factors influencing the resilience of the Pante Lhong irrigation system.

The principal strengths include strong farmer organizations, active Water User Associations (P3A), and continuous technical support from relevant government agencies. The major weaknesses comprise aging irrigation infrastructure, dependence on a single water source, and a predominantly rice-based cropping pattern with high water demand.

External opportunities include government programs supporting Climate-Smart Agriculture (CSA), increasing accessibility to water-saving irrigation technologies, and the potential for crop diversification. Meanwhile, the major threats are continued decreases in rainfall, increasing air temperatures, land-use changes within the watershed, and the growing frequency of extreme climatic events such as droughts and floods.

**Formulated Adaptation Strategies**

Based on the SWOT matrix, four strategic adaptation directions were formulated.

The **SO strategy** emphasizes utilizing strong farmer institutions and government support to accelerate the adoption of water-saving irrigation technologies and crop diversification. The **ST strategy** focuses on rehabilitating irrigation infrastructure and constructing supplementary water-storage facilities to improve system resilience during prolonged droughts.

The **WO strategy** proposes modernization of irrigation networks and implementation of climate-adaptive agricultural practices by utilizing available government programs and village funding. Finally, the **WT strategy** recommends establishing drought contingency plans, prioritizing irrigation water allocation during critical periods, and promoting drought-tolerant crops to reduce agricultural losses under future climate uncertainty.

***Discussion***

The findings demonstrate that climate change has substantially altered hydrological conditions within the Peusangan Watershed, leading to significant reductions in irrigation water availability in the Pante Lhong Irrigation Area. The observed decline in annual rainfall, coupled with increasing air temperatures, has reduced dependable river discharge during the dry season and intensified irrigation water deficits. These findings are consistent with the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, which states that rising temperatures increase evapotranspiration while changes in precipitation patterns reduce freshwater availability, particularly in tropical regions dependent on rainfall-fed watersheds (IPCC, 2021, 2022).

The decrease in reliable river discharge (Q80) identified in this study indicates that climate variability has already exceeded the adaptive capacity of the existing irrigation system during the critical growing season. Reduced rainfall limits groundwater recharge and streamflow generation, whereas higher temperatures accelerate evaporation from both soil and water bodies. Consequently, river discharge declines precisely when irrigation demand reaches its maximum. Similar hydrological responses have been reported by Sharma and Ghosh (2020), who found that tropical river basins experience significant reductions in dependable flow under projected climate change scenarios. Likewise, World Bank (2025) emphasized that irrigation systems in Indonesia are becoming increasingly vulnerable to prolonged drought because declining river discharge directly threatens agricultural water security.

The monthly water balance analysis further illustrates the magnitude of this problem. Water deficits persisted continuously from April to October, with the most severe shortages occurring during July to September. Such prolonged deficits indicate that the current irrigation system is unable to satisfy crop water requirements throughout the entire dry season. According to Allen et al. (1998), inadequate irrigation supply during reproductive and grain-filling stages substantially reduces rice productivity because crops become highly sensitive to water stress during these developmental phases. Therefore, the identified deficits are likely to affect not only irrigated area but also agricultural productivity and regional food security.

The interview findings reinforce the hydrological analysis by demonstrating that farmers have already perceived noticeable shifts in seasonal rainfall patterns. Most respondents reported earlier onset and longer duration of the dry season, resulting in increasing irrigation conflicts and uncertainty in planting schedules. Farmers' perceptions are valuable because they represent local knowledge accumulated through long-term farming experience and often provide early indications of climate variability. Similar observations were reported by Amin and Abbas (2021), who concluded that farmers across Southeast Asia increasingly recognize changing rainfall regimes and have begun adopting adaptive water management practices in response to recurring drought events.

The SWOT analysis highlights that climate adaptation should not rely solely on engineering interventions but also requires institutional strengthening and community participation. Although the Pante Lhong irrigation system benefits from active Water User Associations (P3A) and strong social cohesion among farmers, these strengths alone are insufficient to offset the impacts of increasing climate variability. Aging irrigation infrastructure, dependence on a single water source, and water-intensive cropping systems significantly reduce system resilience during prolonged droughts. These findings support the concept of Climate-Smart Agriculture promoted by FAO (2019), which emphasizes integrating infrastructure improvement, efficient water management, institutional capacity building, and adaptive farming practices to enhance agricultural resilience.

The proposed adaptation strategies therefore represent complementary rather than independent interventions. Infrastructure rehabilitation, including canal lining, pipeline installation, and construction of small reservoirs or retention ponds, could substantially reduce conveyance losses while increasing water storage during the rainy season. These measures have been recommended as effective climate adaptation strategies for irrigation systems in developing countries (World Bank, 2020). However, infrastructure modernization alone cannot fully address future climate risks if irrigation management continues to rely on conventional cropping calendars and inefficient water allocation practices.

Equally important is improving irrigation governance through strengthened Water User Associations, dynamic irrigation scheduling, and climate-informed decision-making. Integrating seasonal climate forecasts from BMKG into irrigation operation plans would enable farmers and irrigation managers to adjust planting schedules according to anticipated water availability. Such adaptive management has been widely recognized as an effective strategy for reducing agricultural vulnerability under increasing climate uncertainty (IPCC, 2022).

Another important implication of this study concerns agricultural diversification. The dominance of rice–rice cropping patterns significantly increases irrigation demand during the dry season. Introducing drought-tolerant and high-value crops during water-limited periods could reduce irrigation demand while maintaining farmers' income. Similar recommendations have been proposed in previous studies investigating climate adaptation in Southeast Asian irrigation systems (Amin & Abbas, 2021). Crop diversification therefore represents both an adaptation strategy and a risk management approach for sustaining agricultural production under changing climatic conditions.

This study contributes to the existing literature by integrating climate trend analysis, dependable river discharge assessment, irrigation water balance evaluation, stakeholder perceptions, and SWOT-based strategic planning into a single analytical framework. Previous studies generally examined these components separately, whereas the present study provides a comprehensive understanding of how climate change affects irrigation performance and identifies practical adaptation options for local decision-makers. Such an integrated approach is particularly relevant for tropical irrigation systems where hydrological, institutional, and socio-economic factors interact simultaneously.

Nevertheless, several limitations should be acknowledged. The analysis was confined to one irrigation area within the Peusangan Watershed, limiting the generalizability of the findings to other regions. Furthermore, future climate scenarios were not simulated using hydrological or climate projection models such as SWAT, HEC-HMS, or CMIP6 climate projections. Future studies should incorporate physically based hydrological modelling and socioeconomic assessments to evaluate long-term adaptation effectiveness under different climate scenarios and support evidence-based irrigation planning.

## 4. CONCLUSION AND RECOMMENDATION

### *Conclusion*

This study demonstrates that climate change has significantly affected irrigation water availability in the Pante Lhong Irrigation Area through declining rainfall, increasing air temperature, and reduced reliable river discharge within the Peusangan Watershed. These hydrological changes have resulted in persistent irrigation water deficits, particularly during the dry season (April–October), with the most critical shortages occurring between July and September. The findings indicate that the existing irrigation system is becoming increasingly vulnerable to climate variability and is unlikely to satisfy future agricultural water demands without effective adaptation measures.

The integrated analysis combining climate trends, reliable river discharge, irrigation water balance, stakeholder perceptions, and SWOT assessment reveals that improving irrigation resilience requires a comprehensive approach. Infrastructure rehabilitation, adoption of water-saving irrigation technologies, climate-informed irrigation scheduling, institutional strengthening of Water User Associations (P3A), and crop diversification should be implemented simultaneously to enhance water-use efficiency and reduce the impacts of prolonged drought.

This study contributes to the literature by providing an integrated framework for assessing climate change impacts on irrigation systems at the local scale while translating scientific evidence into practical adaptation strategies. The findings offer valuable insights for policymakers, irrigation managers, and local governments in designing sustainable water resource management policies and strengthening climate adaptation programs for irrigated agriculture. Future research should incorporate hydrological simulation models and climate change projection scenarios to evaluate the long-term effectiveness of adaptation strategies and support more resilient irrigation planning under future climate uncertainty.

***Recomendation***

Based on the findings of this study, several recommendations are proposed to enhance the resilience of the Pante Lhong Irrigation Area under increasing climate variability.

First, local governments should prioritize the rehabilitation and modernization of irrigation infrastructure, including canal lining, pipeline installation, and the construction of small-scale water storage facilities such as retention ponds (*embung*) and check dams. These measures are expected to reduce water losses, increase irrigation efficiency, and improve water availability during prolonged dry periods.

Second, irrigation management institutions should strengthen the capacity of Water User Associations (P3A) through continuous technical training, participatory water allocation planning, and the implementation of climate-informed irrigation scheduling. Integrating seasonal climate forecasts provided by BMKG into irrigation operation plans would enable more efficient water distribution and reduce conflicts among water users during periods of limited water availability.

Third, agricultural agencies should promote crop diversification and encourage the adoption of drought-tolerant crop varieties and water-saving irrigation technologies. Diversifying cropping systems during the dry season can reduce irrigation water demand while maintaining farmers' income and improving agricultural resilience to climate change.

Finally, future studies should expand the scope of analysis by incorporating physically based hydrological models, such as SWAT or HEC-HMS, together with climate projection scenarios (e.g., CMIP6) to assess long-term changes in water availability under different climate conditions. Further research should also evaluate the socioeconomic impacts of irrigation water shortages on household livelihoods, agricultural productivity, and regional food security to support evidence-based policy formulation and sustainable irrigation management.

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