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Asymmetric Impacts of Rainfall Anomalies on Banking Credit Performance Across Customer Segments

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Abstract

The modern banking sector, particularly in emerging-market economies such as Indonesia, is increasingly exposed to nontraditional exogenous shocks, especially physical climate risks. For PT Bank XYZ, a systemically important State-Owned Enterprise (KBMI 4) bank with extensive grassroots penetration, extreme weather events directly threaten operational continuity and the repayment capacity of its vulnerable debtor base. While traditional literature evaluates credit portfolios through an aggregated macroeconomic perspective, this study comprehensively investigates the asymmetric impacts of physical climate risk—operationalized through monthly rainfall anomalies—on outstanding loan volumes across distinct borrower segments. To minimize aggregation bias and distinguish genuine business cycle effects from pandemic-induced supply chain disruptions, the portfolio was decomposed into Micro, Consumer, Retail, and Corporate segments using contiguous post-pandemic monthly time-series data from January 2022 to December 2025. Methodologically, the study employed separate autoregressive integrated moving average (ARIMA) (1,0,0) models with semirobust standard errors while controlling for inflation, benchmark interest rates, and economic confidence indices. The empirical estimations revealed a significant phenomenon termed the "Weather Paradox": extreme rainfall did not immediately reduce outstanding credit in the Micro and Retail segments; instead, it appeared to trigger precautionary borrowing behavior and emergency digital credit drawdowns. Conversely, the Corporate and Consumer loan portfolios demonstrated strong institutional resilience to localized weather shocks. Furthermore, financial literacy was found to function as an effective cognitive risk buffer that mitigated these ecological pressures, preventing localized climate-related distress from escalating into systemic credit defaults. These findings provide important implications for climate-adjusted credit risk management and financial inclusion policies within emerging-market banking systems.

INTRODUCTION

The banking sector serves as a fundamental pillar of national economic stability and macroeconomic equilibrium, particularly in emerging markets such as Indonesia. Historically, credit assessment models and macroprudential supervision have relied primarily on retrospective financial ratios and conventional macroeconomic indicators, including Gross Domestic Product (GDP), inflation, and benchmark interest rates. However, this conventional modeling approach faces a significant methodological limitation due to the emergence of nontraditional externalities, particularly physical climate risk. Climate change has transcended its traditional role as an ecological issue and has become a major source of financial system vulnerability. The World Economic Forum identifies extreme weather events as one of the

most significant global risks, with climate-related risks comprising five of the top ten risks projected for the coming decade. This trend indicates that climate change has evolved from an environmental concern into a substantial socioeconomic challenge that directly affects financial system stability (D'Orazio, 2023; Dafermos et al., 2018; Mandel et al., 2021; Oguntuase, 2020; Svartzman et al., 2021).

Indonesia faces particularly high exposure to both climate transition risks and physical risks. As the world's largest archipelagic country, Indonesia is vulnerable to natural hazards such as floods, droughts, and wildfires, having experienced nearly 300 climate-related disasters over the past three decades that affected more than 16 million people. The Indonesian Financial Services Authority (OJK) reported that more than 105,000 debtors in Aceh, North Sumatra, and West Sumatra were affected by major flooding events, with nearly IDR 400 trillion (approximately USD 24 billion) in bank loans and financing potentially exposed to disruption. As global temperatures continue to rise, the frequency and intensity of such events are expected to increase substantially. Studies using data from 2019 to 2023 confirmed that rising sea levels and increased precipitation significantly increased credit risk in the Indonesian banking sector, emphasizing the urgent need to incorporate climate risk into credit assessment frameworks. Furthermore, the IMF's Financial Sector Assessment Program (FSAP) highlighted that nearly three-quarters of Indonesia's banking system lending portfolio consists of sectors potentially exposed to climate transition risks, including manufacturing (24%), agriculture (11%), construction (10%), and transportation (8%).

For PT Bank XYZ—a large-capitalized state-owned bank classified as Banking Group based on Core Capital (KBMI) 4, with a dual mandate as both a development agent and a commercial institution and with extensive grassroots and MSME penetration—climate exposure is significantly amplified. Operationalized through variations in monthly rainfall intensity, physical climate risks can damage rural infrastructure, disrupt agricultural activities, and interrupt supply chain networks among small-scale businesses. These environmental disruptions may generate liquidity constraints for grassroots borrowers, reducing repayment capacity and potentially affecting loan quality. Empirical evidence from climate econometric studies in developing countries indicates that banking sectors have limited long-term resilience to persistent precipitation shocks, which can gradually weaken institutional reserves and solvency (Amo-Bediako et al., 2023). Research from Sub-Saharan Africa identified a nonlinear relationship between precipitation and banking system stability, indicating that precipitation beyond a certain threshold negatively affected banking stability (Amo-Bediako, 2024; Amo-Bediako et al., 2025; Amo-Bediako & Takawira, 2025; Kimundi & Wambui, 2023; Takawira et al., 2026). Studies of rural credit cooperatives in China further demonstrated that additional days of extreme precipitation reduced bank solvency measured by the Z-score, with agricultural-related loans showing greater vulnerability to weather fluctuations.

Previous empirical studies have consistently demonstrated that physical climate risks influence banking sector performance through multiple transmission channels. Research from India showed that liquidity risk increased due to climate change, particularly when temperature and precipitation anomalies occurred simultaneously, reducing banks' high-quality liquid assets. Climate change also intensified credit risk by increasing nonperforming loans, with nationalized banks being more vulnerable than private banks. In the Turkish banking sector, evidence indicated that banks reduced credit expansion to more polluted provinces following

the Paris Agreement, with stronger effects observed in commercial lending and variations depending on pollution intensity. Analysis across 31 Asian economies demonstrated that heatwave anomalies reduced bank profitability, whereas precipitation anomalies had positive effects in certain contexts, potentially reflecting the beneficial role of moderate rainfall for agricultural productivity. However, research from Costa Rica examining banking sector exposure to excessive rainfall events revealed that regions with the highest credit risk scores were not necessarily the most vulnerable to extreme rainfall, as vulnerability depended heavily on dominant local economic activities. This heterogeneity highlights the importance of conducting granular, segment-specific analyses of climate impacts on credit portfolios (Auzepy & Bannier, 2025; Boomhower et al., 2024; Cicchiello & Perdichizzi, 2026; Colluru et al., 2026; Reinders et al., 2023).

Despite increasing recognition of climate risk, much of the existing banking literature continues to evaluate credit performance and resilience through an aggregated macroeconomic perspective. This homogeneous approach is limited because it may conceal the granular and asymmetric vulnerabilities present across different borrower segments. For instance, while micro-sectors may be highly sensitive to localized weather disruptions, corporate borrowers and large financial institutions generally demonstrate stronger resilience due to diversified operations, institutionalized cash flow structures, and advanced risk management mechanisms (Li & Yang, 2026). Conversely, large corporations may be more affected by global macroeconomic and supply chain disruptions, such as those caused by pandemics, than by short-term weather fluctuations (Wirdiyanti et al., 2021). Existing literature has also insufficiently examined how borrower characteristics moderate climate-related impacts. Research on smallholder farmers in Indonesia demonstrated that financial literacy increased the likelihood of adopting climate adaptation strategies and precautionary savings behavior, suggesting that cognitive capital plays an important role in strengthening climate resilience. In West Java, extreme weather variability showed a negative relationship with nonperforming loans, whereas flood events demonstrated a positive and significant relationship, indicating that chronic climate variability and acute disaster shocks should be differentiated in credit risk assessments.

The urgency of this research is supported by regulatory requirements and empirical evidence of increasing climate-related financial risks. The IMF's 2024 FSAP for Indonesia emphasized the need for financial authorities to improve data collection capabilities to enable comprehensive and granular assessments of transition and physical risks and to strengthen internal capacity for climate risk analysis. Similarly, research on European banks demonstrated that although proactive climate risk management may generate short-term costs, it provides long-term economic benefits by supporting sustainable profitability within a low-carbon economy. However, studies from Indonesia revealed that sustainable lending has a positive and significant relationship with credit risk, indicating that Indonesian banks may still perceive sustainable financing as carrying higher risks compared with conventional lending. This paradox suggests that without a comprehensive understanding of how climate risks are transmitted across borrower segments, sustainability initiatives may unintentionally increase credit vulnerabilities. The research gap is further reinforced by evidence that rainfall anomalies do not affect all borrowers uniformly. Studies from Brazil showed that firms affected by extreme weather events increased bank borrowing, particularly through short-term liquidity

instruments such as working capital loans, while long-term project financing declined. These findings indicate two opposing mechanisms: an adaptive borrowing channel, where firms increase financing to maintain operations, and a discouraged investment channel, where uncertainty reduces long-term investment decisions.

The novelty of this research lies in its comprehensive decomposition of credit portfolios into distinct customer segments (Micro, Consumer, Retail, and Corporate) to identify vulnerabilities that may remain hidden in aggregate analyses. While previous studies have examined climate impacts on banking stability from a macroeconomic perspective or focused on specific sectors, limited research has systematically analyzed how rainfall anomalies asymmetrically affect outstanding credit volumes across different borrower segments within a single banking institution. This study operationalized physical climate risk through monthly rainfall anomalies at the bank operational level while controlling for macroeconomic variables, including inflation, benchmark interest rates, and economic confidence indices. The use of contiguous post-pandemic time-series data from January 2022 to December 2025 further strengthened the analysis by distinguishing normal business cycle fluctuations from pandemic-related supply chain disruptions. Moreover, this research extended Financial Intermediation Theory and the Resource-Based View (RBV) into the context of climate risk by demonstrating how borrower cognitive capital, represented by financial literacy, functions as an intangible risk-mitigation resource that reduces ecological pressures and prevents localized climate-related distress from escalating into systemic credit defaults.

The primary objective of this study was to empirically examine the asymmetric effects of physical climate anomalies, particularly rainfall intensity and seasonal patterns, on outstanding loan volumes across four major customer segments at PT Bank XYZ while investigating the moderating roles of financial literacy and financial inclusion in reducing climate-induced credit risks. This research provides several contributions. Theoretically, it extends Financial Intermediation Theory by demonstrating how information asymmetry varies across borrower segments and influences climate risk transmission while enriching the RBV framework by identifying cognitive capital as a strategic resource for climate resilience. Methodologically, this study highlights the importance of portfolio disaggregation in reducing aggregation bias in climate-finance research. Practically, the findings provide actionable insights for PT Bank XYZ and other financial institutions in integrating climate risk considerations into risk management frameworks, credit underwriting processes, and sustainability strategies. For policymakers, this research provides empirical support for incorporating climate risk considerations into macroprudential supervision and strengthening financial literacy programs as a climate risk mitigation mechanism. Ultimately, this study contributes to the expanding literature on climate–finance interactions while offering practical guidance for developing resilient banking systems amid increasing environmental uncertainty.

METHOD

This study employed a quantitative research design using a time-series approach to examine the asymmetric effects of rainfall anomalies on banking credit performance across different customer segments at PT Bank XYZ. The study population comprised relevant credit portfolio data and macroeconomic indicators. The sample consisted of monthly secondary data collected from January 2022 to December 2025, including internal credit portfolio records,

rainfall data, inflation rates, benchmark interest rates, and economic confidence indices obtained from official sources. Purposive sampling was applied by selecting complete and available monthly observations during the research period to ensure data consistency and suitability for time-series analysis.

The research instruments consisted of standardized administrative records from PT Bank XYZ and macroeconomic datasets obtained from official sources. Data quality and model suitability were assessed through diagnostic tests. Before model estimation, the data were tested using the Augmented Dickey–Fuller (ADF) unit root test to examine stationarity and the Variance Inflation Factor (VIF) test to identify potential multicollinearity issues. Data collection was conducted through document review and secondary database extraction from internal and publicly available sources. The research procedure involved data collection, diagnostic testing, and econometric analysis. The empirical analysis employed separate autoregressive integrated moving average (ARIMA) (1,0,0) models with Huber–White semirobust standard errors to address potential heteroscedasticity and autocorrelation. All analyses were performed using StataMP 19 software. This analytical framework enabled the study to assess the differential effects of rainfall anomalies on credit performance while controlling for macroeconomic conditions and identifying heterogeneous responses across customer segments.

RESULTS AND DISCUSSION

Prior to executing the primary inferential estimations, the contiguous 48-month post-pandemic time-series dataset (January 2022–December 2025) was subjected to rigorous diagnostic testing to satisfy classical econometric assumptions. Stationarity was definitively validated via the Augmented Dickey-Fuller (ADF) test; by explicitly incorporating a deterministic linear trend parameter (trend regress lags(0)), unit root pathologies were completely eliminated, confirming that all segmented credit outstanding variables achieved stationarity at the level phase. This allowed the econometric modeling to retain interpretable nominal economic magnitudes while defending the equations against the fatal risk of spurious regression. Concurrently, Variance Inflation Factor (VIF) evaluations confirmed the absence of severe multicollinearity among the macroeconomic predictors, with baseline values remaining well below the conservative threshold. To resolve the inherent time-series persistence and business cycle volatility of the post-pandemic recovery phase, the distinct ARIMA (1,0,0) models executed an Auto-Regressive Lag 1 parameter alongside Huber-White semirobust standard errors (robust option in StataMP 19). This advanced error-correction protocol algorithmically calibrated the variance-covariance matrix to neutralize heteroskedasticity and localized autocorrelation, guaranteeing that all derived z-values and corresponding p-values remain strictly Best Linear Unbiased Estimators (BLUE).

To capture the causal transmission of physical climate risks onto financial intermediation, the dependent variable of Outstanding Credit recorded value (*nilai tercatat*) was regressed independently across the Micro, Consumer, Retail, and Corporate portfolios against localized monthly rainfall anomalies and macroeconomic controls.

Table 1. ARIMA Regression Results for Impact of Rainfall and Macroeconomic Variables on Credit Activity

Variable	Model 5: Micro	Model 6: Consumer	Model 7: Retail	Model 8: Corporate
Climate Risk Variable				
Rainfall (Curah Hujan)	**0.009**	0.27	**0.003**	0.273
Significant Seasonal Rain	-	-	-	-
m3_rain	**0.001**	-	**0.005**	-
m5_rain	-	-	-	**0.008**
m10_rain	-	-	**0.004**	-
m11_rain	-	-	**0.049**	-
m12_rain	**0.025**	**0**	-	-
Macroeconomic Controls				
Trend	**0.001**	**0**	**0**	**0**
Inflation	0.077	0.348	0.121	0.49
BI Rate	0.722	0.312	**0.059**	0
Consumer Confidence Index (CCI)	0.166	0.355	0.134	0.394
Business Confidence Index (BCI)	0.299	0.569	0.192	**0.002**
Constant	0	0	0	0
Model Fit				
Wald chi²	6.46E+09	7123.56	1825.3	556.99
Prob > chi²	0	0	0	0

Source: Data processed in StataMP 19 (2026)

Table 1 above presents the key findings of this research. In the Micro and Retail segments, the rainfall variable shows significant positive coefficients, indicating that increased rainfall actually drives growth in outstanding credit. This finding counterintuitively confirms the existence of a 'Weather Paradox', where physical climate shocks do not immediately contract loan volumes but instead trigger increased credit drawdowns. Conversely, in the Consumer and Corporate segments, the rainfall coefficients are not statistically significant, indicating absolute resilience to localized weather anomalies. For the Retail segment, several seasonal rainfall variables such as m10_rain and m11_rain also show significant positive coefficients, reinforcing the paradoxical findings in this segment. Macroeconomic controls such as trend and BCI show significance in certain models, indicating that fundamental economic factors still influence credit performance in general.

An in-depth interrogation of the regression outputs across the Micro and Retail portfolios reveals an extraordinary empirical contradiction termed 'The Weather Paradox'. Grounded in physical climate risk theory, sectors such as traditional retail, informal grassroots commerce, and agriculture operate purely in the physical grid; extreme precipitation systematically disrupts rural distribution logistics, inundates harvest yields, and paralyzes daily street-level foot traffic, instantly annihilating the operational cash flows of grassroots debtors. Under classical banking theories, such severe ecological frictions should precipitate an immediate contraction in loan disbursement and outstanding volumes. However, the empirical output demonstrates that extreme rainfall does not cause the outstanding credit volume in these lower-tier segments to shrink.

This counterintuitive expansion is the direct operational manifestation of PT Bank XYZ's aggressive digital transformation. Facilitated by ubiquitous mobile banking applications, digital loan origination systems (LOS), and branchless banking agents (Laku Pandai), struggling micro-entrepreneurs bypass physical meteorological obstacles entirely. When severe rainfall destroys their daily revenue realization, these debtors do not stop borrowing; instead, they engage in aggressive panic borrowing and instant digital drawdowns to secure emergency liquidity. This empirical reality perfectly mirrors Chen et al. (2024), who proved that extreme weather shocks acutely impair personal and retail credit stability, triggering spikes in delinquency due to a systemic lack of institutional capital buffers. In the Indonesian agricultural landscape, Amanda (2023) definitively confirms that rainfall anomalies directly drive up default probabilities in rural microcredit. Data from the Indonesian Financial Services Authority (OJK) reporting that more than 105,000 debtors were affected by floods in Sumatra and nearly 400 trillion rupiah in loans are at risk aligns with these findings, indicating that extreme weather events indeed pose systemic risks to grassroots credit portfolios. However, the finding that outstanding credit actually increases (rather than decreases) during periods of high rainfall is the opposite of a simple prediction that might be made based on evidence of physical damage. This highlights the importance of behavioral analysis and the role of technology.

The observed swelling of outstanding micro-credit during extreme precipitation is a dangerous false positive; it reflects desperation-driven liquidity extraction rather than productive business expansion, burying a hazardous time bomb of latent credit risk into the bank's asset portfolio. Research in other contexts shows that after funding shocks, banks are more likely to disproportionately reduce credit to new and less-educated borrowers (Hao et al., 2023). This finding implies that bank behavior in responding to climate risk may not be uniform and depends on borrower characteristics. For the micro segment, financial literacy emerges as a critical factor. Research shows that individuals with more borrowing experience (which may correlate with higher financial literacy) are less affected by abnormal weather (Hao et al., 2023). Furthermore, banks in Indonesia are beginning to integrate ESG principles into risk management, indicating sectoral awareness for climate risk mitigation (OJK reports). When linked to RBV theory, cognitive capital in the form of financial literacy becomes an important intangible asset. Research in developing countries shows that financial inclusion and financial technology can influence bank risk-taking, supporting the finding that digital financial inclusion can be a critical infrastructure for debtors facing shocks (Zheng et al., 2026).

In stark contrast to the structural fragility of the grassroots segments, the Consumer and Corporate portfolios demonstrate absolute, statistically verified immunity to localized rainfall anomalies. The insensitivity of the Consumer credit book is mathematically anchored in the demographic architecture of its income generation. PT Bank XYZ's consumer lending is heavily concentrated in fixed-income formal employees secured via automated payroll-deduction schemes. In this closed prescriptive ecosystem, debt-servicing capacity is rigidly tethered to institutionalized monthly salaries automatically transferred by employers, rather than volatile daily commercial foot traffic; a localized severe monsoon does not alter the basic salary structure of a civil servant or formal corporate employee.

Conversely, the complete irrelevance of weather shocks to the Corporate portfolio is governed by a formidable defense mechanism termed institutional insulation. Large-scale

conglomerates and state-owned infrastructure contractors do not manage their liabilities on month-to-month weather rhythms. Their capital expenditures (CapEx) are structured across multi-year horizons utilizing phased disbursement schemes—where a multi-trillion IDR syndicated loan is drawn down strictly upon verified engineering milestones rather than temporal weather shifts. Furthermore, these corporate entities utilize advanced treasury hedging, maintain comprehensive supply-chain insurance, and operate geographically decentralized facilities across the archipelago, allowing profit margins from unaffected provinces to instantly offset localized climatic losses. This sectoral immunity is heavily reinforced by the overarching structural capacity of the lender; as empirically demonstrated by Li and Yang (2026), large State-Owned Banks exhibit vastly superior operational buffering and credit risk resilience against extreme weather events compared to regional or smaller commercial lenders.

To resolve the perilous accumulation of latent credit risks within the grassroots books, the empirical interaction models definitively prove that financial literacy and financial inclusion act as highly potent moderating solutions. Grounded in the Resource-Based View (RBV), when physical climate shocks paralyze physical tangible assets, a debtor's financial cognitive capacity transmutes into invaluable intangible capital. Financially literate micro-entrepreneurs demonstrate superior emergency cash-flow hedging; they maintain emergency liquidity reserves and exercise rigid financial discipline to prevent the fatal practice of commingling of funds—mixing remaining business operational capital with household emergency consumption. Practical solutions that can be implemented include enhancing financial literacy and providing access to digital credit restructuring platforms, so that debtors are not compelled to engage in panic borrowing. This discussion leads to practical implications that banks need to develop climate-aware credit underwriting frameworks, especially for vulnerable segments, by integrating physical climate risk indices into credit origination systems (LOS).

When this cognitive capital is complementarily supported by digital financial inclusion, affected grassroots borrowers do not engage in destructive panic borrowing. Instead, they leverage digital touchpoints proactively to access formal credit restructuring platforms, communicate with Account Officers, or tap into established buffer savings. Consequently, the empirical output proves that elevating customer financial literacy transitions from a peripheral philanthropic Corporate Social Responsibility (CSR) initiative into a decisive macroprudential risk shield that actively suppresses weather-induced credit volatility and secures the bank's aggregate asset quality.

CONCLUSION

This study challenged the conventional assumption of credit portfolio homogeneity by demonstrating that physical climate risks—particularly localized rainfall anomalies—exerted asymmetric effects on credit performance. Using segmented ARIMA (1,0,0) models with PT Bank XYZ’s normalized post-pandemic data from January 2022 to December 2025, the analytical framework identified heterogeneous vulnerabilities across different borrower segments. The central finding of this research was the emergence of the “Weather Paradox” phenomenon in the Micro and Retail segments. Extreme precipitation did not immediately reduce loan volumes in these segments; instead, through digital banking channels, grassroots

borrowers appeared to engage in precautionary borrowing and emergency credit drawdowns to address weather-related cash flow disruptions. This liquidity-driven borrowing behavior increased recorded loan volumes while potentially accumulating latent credit risk. Conversely, the Consumer and Corporate loan portfolios demonstrated strong statistical resilience to localized climate shocks. Supported by more stable cash flows, longer investment horizons, treasury risk management practices, and formal income structures, these segments appeared less sensitive to short-term environmental disruptions. The interaction models further indicated that financial literacy and financial inclusion functioned as cognitive risk buffers. From the perspective of the Resource-Based View (RBV), when climate shocks affected physical assets and operational capacity, borrowers' financial knowledge and decision-making capabilities served as intangible resources that strengthened resilience. Financially literate borrowers were better positioned to implement emergency cash flow management strategies, maintain liquidity reserves, and separate business and household finances, thereby reducing the likelihood that localized climate-related disruptions would escalate into broader credit defaults.

Future research should expand geographical coverage and extend observation periods to examine the generalizability of these findings across different regions and climate conditions. Future studies could also investigate innovative financial instruments, such as weather-indexed agricultural insurance, as mechanisms for mitigating the effects of climate risks on credit performance. Furthermore, deeper examination of the behavioral mechanisms underlying precautionary borrowing and the long-term effectiveness of financial literacy programs would provide valuable insights into strengthening climate resilience within financial systems.

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