JPPT
Journal of Public Policy Transformation

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Development of a Climate Risk Mathematical Model as a Basis for Public Policy Transformation in Sharia Financial Institutions

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Article Info

Article history:
Received: March 10, 2026
Revised: 09 April 2026
Accepted: 20 June 2026

Keywords:

Climate risk index,
Islamic financial institutions,
mathematical climate risk model,
public policy transformation.

ABSTRACT

Climate-related hazards are increasingly recognized as a source of systemic financial vulnerability, yet public-policy instruments for climate-responsive Islamic finance remain largely qualitative and reactive. This study develops an original Mathematical Climate Risk Model (MCRM) that integrates seasonal rainfall forecasting, climate variability, extreme-event frequency, financial exposure, and institutional sensitivity into a single Climate Risk Index (CRI), together with mathematically derived multi-level risk classification and decision rules. Using a SARIMA(1,1,1)(1,1,1)12 rainfall-forecasting sub-model and an illustrative panel of ten Islamic financial institutions (Islamic commercial banks, Islamic rural banks/BPRS, and Islamic microfinance cooperatives/BMT), the model is shown to correctly flag compounding, multi-component climate risk and to remain robust at the extremes of the risk distribution under sensitivity analysis of its weighting and thresholding choices. The CRI is embedded in an eight-stage Public Policy Transformation Framework that links climate observation to mathematical modelling, risk classification, financing adjustment, regulatory intervention, and monitoring/evaluation. The article positions mathematical modelling as the principal scientific contribution and public-policy transformation in Islamic finance as its applied context, and derives concrete policy recommendations for OJK, Bank Indonesia, the Ministry of Finance, and Islamic financial institutions, including risk-tiered financing ceilings and climate-adjusted profit-sharing buffers.

: https://doi.org/10.30598/jpptv1i1pp38-46

1. INTRODUCTION

Climate change has moved from a long-horizon environmental concern to a near-term macro-financial risk. Both the frequency and severity of hydrometeorological extremes have increased measurably in tropical and archipelagic economies such as Indonesia, and these physical hazards translate into financial risk through direct damage to productive assets, disruption of agricultural and marine-based livelihoods, and reduced borrower repayment capacity [2]. For Islamic financial institutions, this exposure is structurally distinctive: because murabahah, musyarakah, and mudharabah contracts embed asset-backed and profit-and-loss sharing features, climate shocks propagate into financing performance differently than under conventional debt contracts and cannot simply be repriced through interest-rate mechanisms [2]. Cross-country evidence shows Islamic-banking asset share is associated with measurable improvement in climate-adaptability indices, operating mainly through climate readiness rather than reduced vulnerability [1], while Indonesian BMT case studies identify financing, liquidity, and Shariah-compliance risk as the three risk categories most exposed to external shocks, including climatic ones [3].

Indonesian financial regulation has moved rapidly toward climate-risk integration. The Financial Sector Omnibus Law (P2SK Law) established the legal basis for sustainable-finance taxonomy; OJK Regulation No. 17/2023 obliges commercial banks to embed climate risk in governance, strategy, and risk management; and the OJK Climate Risk Management and Scenario Analysis (CRMS) guideline formalizes climate-risk stress testing, with a phased rollout that currently covers only large commercial banks [5]-[6]. Indonesia's Taxonomy for Sustainable Finance (TKBI) and the 2024 Climate Risk Stress Testing pilot covering 18 banks [6]-[7] demonstrate clear regulatory intent, yet the analytical instruments used to operationalize "climate risk" for supervisory purposes remain fragmented, largely descriptive, and borrowed from conventional-bank templates that do not reflect the asset-backed, profit-sharing structure of Islamic contracts, nor the balance-sheet realities of the BPRS and BMT institutions that dominate rural and agricultural financing.

This creates a genuine research gap. Existing studies either apply time-series forecasting methods such as SARIMA to rainfall data without connecting the forecast to a financial-risk metric [8]-[14], or construct composite climate-vulnerability indices for macro-level policy use without linkage to a specific financial-sector decision rule [15]-[19]. Separately, the public-health modelling literature has shown that mathematical models become genuine policy instruments only when built explicitly around the decision problem they are meant to inform, rather than repurposed after the fact [20]-[21]. No comparable policy-facing mathematical framework yet integrates rainfall forecasting, climate variability, extreme-event frequency, financial exposure, and institutional sensitivity into a single index calibrated to the specific decision problem faced by Islamic-finance regulators: whether, and by how much, to adjust financing ceilings, provisioning, and profit-sharing terms in the face of climate risk.

The novelty of this study is therefore positioned at the level of mathematical construction rather than forecasting technique. Five original contributions are made: (1) a new composite Mathematical Climate Risk Model (MCRM) integrating five sub-models into one normalized mathematical object; (2) a scalar Climate Risk Index (CRI) constructed through explicit normalization and entropy-weighting rather than an ad hoc score; (3) a multi-level risk classification derived mathematically from the empirical CRI distribution; (4) explicit mathematical decision rules-a Financing Adjustment Factor and a Policy Priority Score-that map the CRI onto concrete regulatory and institutional actions; and (5) an eight-stage Public Policy Transformation Framework tracing the full pipeline from climate observation to monitoring and evaluation.

This study aims to (a) formally represent climate uncertainty in a form suitable for financial decision-making, (b) quantify multiple heterogeneous climate and financial signals into a single interpretable risk index, (c) transform that index into public-policy instruments through explicit mathematical decision rules, and (d) demonstrate how Islamic financial institutions of different types and scales-banks, BPRS, and BMT-can operationalize the resulting index in financing and risk-management decisions. The theoretical contribution is a mathematically transparent, auditable climate-risk instrument for Islamic finance; the practical contribution is a reproducible basis for OJK, Bank Indonesia, and the Ministry of Finance to extend climate-risk supervision to institutions-particularly BPRS and BMT-that remain outside the current CRMS/CRST pilot scope.

2. METHOD

Mathematical modelling has an established record as a decision-support tool for public policy, most visibly in the public-health literature, where policy-facing models built jointly with decision-makers around a specific decision problem generate more actionable evidence than models developed independently and only later applied to policy questions [20]-[21]. A parallel methodological literature on composite climate-risk and climate-vulnerability indices shows that indicator normalization and weighting choices, more than data quality alone, are typically the dominant source of index instability [15]-[17]-[19], and that classification-threshold choice is likewise a material, and under-reported, source of ranking instability [16]. SARIMA models remain the workhorse method for monthly rainfall forecasting in Indonesia because of their capacity to capture the strong twelve-month seasonal cycle characteristic of monsoon-influenced rainfall [8]-[14]; in every study reviewed, however, the rainfall forecast is the end product of the analysis rather than one input among several into a broader financial-risk decision framework. This is precisely the gap the Mathematical Climate Risk Model (MCRM) developed below is designed to close.

This study follows a mathematical-modelling and simulation design. The research proceeds in four stages: (i) formal specification of the MCRM and its five component sub-models; (ii) estimation of the rainfall-forecasting sub-model using SARIMA; (iii) construction, normalization, and classification of the Climate Risk Index; and (iv) sensitivity and robustness analysis of the resulting classification. The climate layer uses monthly rainfall totals; in an operational deployment these would be sourced from Indonesia's Meteorology, Climatology, and Geophysics Agency (BMKG). Because the purpose of this study is to establish and validate the mathematical structure of the MCRM, the empirical illustration below uses a simulated monthly rainfall series (2013-2024, n = 144) constructed to reproduce the stylized statistical properties documented for Indonesian rainfall stations in [8]-[14]: a strong twelve-month seasonal cycle, a modest multi-decadal trend, an approximately 3.5-year ENSO-linked quasi-periodic component, and a small number of injected extreme-rainfall months. All reported descriptive statistics, forecasts, and CRI values are illustrative outputs of the mathematical model applied to simulated data, presented to demonstrate the model's mechanics and sensitivity behaviour; migration to an operational BMKG or institution-level dataset requires no change to the mathematical model itself, only substitution of the input series.

The financial layer uses an illustrative panel of ten Islamic financial institutions spanning three tiers-Islamic commercial banks, Islamic rural banks (BPRS), and Islamic microfinance cooperatives (BMT)-located in ten climate-exposed Indonesian regions. For each institution, four indicators are simulated within empirically plausible ranges reported in the Islamic-microfinance risk literature [3]-[4]: the non-performing financing ratio (NPF), the share of financing extended to climate-sensitive sectors, a collateral climate-sensitivity score, and an elasticity coefficient linking historical financing performance to rainfall anomalies. Validation uses three checks: in-sample SARIMA residual diagnostics and information-criterion comparison; a one-at-a-time (OAT) sensitivity analysis of the CRI with respect to each of the five MCRM weights (varied by ±50% with proportional renormalization); and a classification-boundary robustness check comparing risk-tier assignments under a fixed-quartile threshold rule versus a variance-minimizing (Otsu-type) threshold rule.

3. RESULTS AND DISCUSSION

3.1. Model Estimation and Climate Risk Index Results

All results below are generated from the simulated illustrative dataset described in Method and are intended to demonstrate the mathematical mechanics, internal consistency, and sensitivity behaviour of the MCRM, not to report empirical findings about any specific real-world station or institution.

Table 1. Illustrative Climate Risk Index (CRI) Results by Institution (fixed weights, quartile thresholds)

Institution	Financial Exposure (FE)	Sensitivity (S)	CRI	Risk Class
BSI - Jawa Barat	0.35	0.60	0.11	Low
BSI - Jawa Tengah	0.45	0.30	0.47	Moderate
BSI - Jawa Timur	0.51	0.01	0.01	Low
BPRS - Aceh	0.19	0.23	0.00	Low
BPRS - Sumatra Selatan	0.25	0.83	0.27	Moderate
BPRS - Nusa Tenggara	0.67	0.24	0.21	Low
BMT - Lampung	0.47	0.44	0.11	Low
BMT - Kalimantan Selatan	0.87	0.00	0.15	Low
BMT - Sulawesi Selatan	0.70	1.00	1.00	Severe
BMT - Maluku	0.69	0.18	0.42	Moderate

The simulated monthly rainfall series ($n = 144$, January 2013-December 2024) has a mean of 218.2 mm, standard deviation of 125.4 mm, minimum of 5.0 mm, and maximum of 612.8 mm, consistent with the strongly seasonal, right-skewed distribution typical of tropical monthly rainfall. The Augmented Dickey-Fuller test on the level series does not reject the unit-root null (ADF = −1.72, $p = 0.491$); after first-order differencing, the null is strongly rejected ($p < 0.001$), confirming that $d = 1$ is sufficient to induce stationarity. The ACF and PACF of the differenced series show a clear spike at seasonal lag 12 alongside rapid short-lag decay, consistent with a seasonal autoregressive/moving-average structure; a SARIMA(1,1,1)(1,1,1)12 specification is therefore selected and estimated by maximum likelihood via the state-space (Kalman-filter) representation, and used to generate a twelve-month-ahead forecast with a widening 90% forecast interval at longer horizons, as expected for an integrated seasonal process.

Applying Algorithm 1 to the simulated climate layer and the ten-institution financial-exposure panel, using the fixed benchmark weights α = (0.20, 0.15, 0.15, 0.30, 0.20) and quartile thresholds τ = (0.25, 0.50, 0.75), yields the CRI results summarized in Table 1. Three institutions are classified Moderate, one Severe, and six Low. The single Severe-classified institution (BMT - Sulawesi Selatan) is jointly driven by high climate variability, high extreme-event frequency, and the maximum observed sensitivity coefficient in the panel-illustrating that the composite structure of the MCRM correctly identifies compounding risk (multiple simultaneously elevated components) rather than flagging institutions on the basis of any single indicator.

Applying the entropy-weighting procedure to the same component matrix yields α_entropy = (0.14, 0.21, 0.27, 0.07, 0.31) for (hazard-forecast, variability, extreme-frequency, exposure, sensitivity)-placing markedly more weight on climate variability, extreme-event frequency, and institutional sensitivity than the fixed regulatory benchmark. The resulting ranking has a Spearman rank correlation of ϱ = 0.61 with the fixed-weight ranking: the two schemes agree closely at the extremes (the same institution is identified as highest-risk under both) but diverge for institutions in the middle of the distribution, consistent with the composite-indicator literature's general finding that weighting choice is the dominant source of mid-distribution ranking instability [15]-[17]. A one-at-a-time sensitivity analysis, varying each of the five weights by ±50% with proportional renormalization of the remainder, shows the CRI is most responsive to perturbation of the financial-exposure and sensitivity weights and least responsive to the hazard-forecast weight; critically, no single-weight perturbation of ±50% changes the identity of the highest-risk institution, indicating that the classification of the most climate-vulnerable institution is robust to reasonable disagreement over the exact weighting scheme. Re-deriving thresholds via the variance-minimizing rule yields τ = (0.15, 0.30, 0.50) instead of the fixed quartiles, changing the classification of four of the ten institutions (60% agreement rate)-an important finding in its own right, showing that threshold choice, not only weighting choice, materially affects which institutions are flagged for regulatory attention.

Relative to SARIMA-only rainfall-forecasting studies [8]-[14], the MCRM retains the same forecasting rigor but treats the forecast as one of five inputs rather than the final output. Relative to composite climate-vulnerability indices built for macro or sub-national policy use [15]-[19], the MCRM is deliberately narrower in scope-calibrated specifically to the financing-decision problem of Islamic financial institutions-trading generality for direct actionability. Relative to the Islamic-finance climate literature, which is dominated by ex-post panel-regression evidence linking Islamic-banking characteristics to adaptation outcomes [1]-[22], the MCRM is prospective and instrument-oriented: it is designed to inform a financing decision before losses materialize rather than to explain outcomes after the fact. For individual institutions, the MCRM offers a low-cost, mathematically transparent self-assessment tool that does not require the data infrastructure used in large-bank climate-stress-testing exercises-directly relevant to BPRS and BMT institutions that the current CRST pilot excludes [3]-[4], [6]-[7]. For OJK, Bank Indonesia, and the Ministry of Finance, the model offers a common, reproducible analytical basis that could plausibly be extended from large commercial banks to BPRS and BMT institutions using the same mathematical structure with tier-appropriate data requirements. The finding that weighting scheme materially changes mid-distribution classification while leaving the highest-risk institution's classification unchanged also has a direct supervisory implication: composite risk indices of this kind are most reliable at their extremes and warrant more caution-possibly supplementary qualitative review-for institutions near a classification boundary.

These results are embedded in an eight-stage Public Policy Transformation Framework: (1) Climate Observation-collection of BMKG rainfall records; (2) Mathematical Model (MCRM)-estimation of the five component sub-models; (3) Climate Risk Index-aggregation into a scalar CRI_i per institution; (4) Risk Classification-assignment to Low/Moderate/High/Severe tiers; (5) Policy Priority-ranking via the Policy Priority Score for supervisory attention; (6) Financing Adjustment-application of the Financing Adjustment Factor to financing ceilings or profit-sharing buffers; (7) Government/OJK/Bank Indonesia Intervention-macroprudential and fiscal response informed by aggregated CRI distributions; and (8) Monitoring and Evaluation-comparison of realized climate and financing outcomes against forecasts, closing the feedback loop into the next period's Climate Observation stage. Concrete, measurable policy actions follow directly from this framework: OJK could extend CRMS/CRST reporting to BPRS institutions using a simplified MCRM variant and require that any CRI-based classification publish its weighting and threshold-derivation method in advance [5]-[7]-[26]; Bank Indonesia could incorporate sector-aggregated CRI distributions into macroprudential monitoring of climate-sensitive-sector concentration; the Ministry of Finance could link eligibility for blended climate-adaptation financing to institutions demonstrating Low/Moderate CRI classification with expanding climate-resilient portfolios; and Islamic banks, BPRS, and BMT could adopt the Financing Adjustment Factor as an internal risk-based pricing input for musyarakah and mudharabah profit-sharing ratios in climate-sensitive sectors [2]-[4]-, [27]-[28].

4. CONCLUSION

This study developed the Mathematical Climate Risk Model (MCRM), an original composite mathematical framework integrating seasonal rainfall forecasting, climate variability, extreme-event frequency, financial exposure, and institutional sensitivity into a single Climate Risk Index, together with mathematically derived, sensitivity-tested classification thresholds and decision rules-the Financing Adjustment Factor and Policy Priority Score-that convert the index into operational policy instruments. Embedded in an eight-stage Public Policy Transformation Framework, the MCRM offers Indonesian financial regulators and Islamic financial institutions, including the BPRS and BMT tiers currently outside formal climate-risk-stress-testing scope, a transparent, reproducible, and auditable basis for climate-risk-adjusted supervision and financing decisions. The illustrative results show the model correctly flags compounding, multi-component risk rather than single-indicator outliers, remains reasonably robust at the extremes of the risk distribution, and is appropriately sensitive to weighting and thresholding choices in ways that are now explicit and testable. The central claim of this study is that the mathematical structure-not the SARIMA forecasting technique it partly relies on-constitutes the scientific contribution, with public-policy transformation in Islamic finance as its immediate field of application. Future research should validate the MCRM on real BMKG rainfall data matched to disclosed institutional financial data, extend the model to a spatial or spatio-temporal formulation incorporating multiple climate-hazard types, and pilot the eight-stage framework with a small group of BPRS or BMT institutions to evaluate its operational feasibility before wider rollout.

Acknowledgments
Not applicable. The authors did not receive personal assistance beyond their own contributions.

Funding Information (mandatory)
Authors state no funding involved.

Author Contributions Statement
- Mutia Pamikatsih: Conceptualization, methodology, formal analysis, software, writing - original draft.
- [Co-Author Name]: Conceptualization, investigation, resources, writing - review and editing, supervision. All authors discussed the results and contributed to the final manuscript.

Conflict of Interest Statement
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

Informed Consent
Not applicable. This study did not involve human participants or the collection of personal or identifiable information from individual research subjects; the illustrative dataset used in the Results and Discussion section is entirely simulated for methodological demonstration.

Ethical Approval
This study did not involve human participants, human data, or animal subjects, and did not collect or disclose confidential institutional financial data. Ethical approval was therefore not required.

Data Availability
The simulation code used to generate the illustrative rainfall series, SARIMA estimates, institutional panel, Climate Risk Index values, and figures in this article is available from the corresponding author upon reasonable request, to allow full reproducibility of Algorithm 1. No confidential or proprietary institutional data are included.

Declaration of Generative AI and AI-assisted Technologies
During the preparation of this manuscript, the authors used an AI-based language and coding assistant to assist with drafting text, structuring the mathematical exposition, and generating the illustrative simulation code. All mathematical formulations, interpretations, and conclusions were reviewed and are the responsibility of the authors, who will substitute the illustrative dataset with real climate and institutional data and verify all citations prior to submission.

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