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A Daily Transition Analysis of Disaster Events in Riau Islands using Markov Chains: Dominant Disaster Identification and Risk Assessment

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ABSTRACT

Objectives: This study employs a Markov Chain approach to analyze daily disaster transition patterns in the Riau Islands, with the primary objectives of identifying dominant hazards, quantifying long-term disaster risks, and providing evidence-based recommendations for disaster management. Methods: The research utilized daily disaster records from Indonesia's National Disaster Management Agency (BNPB) for 2024. A dominant state classification approach was applied to handle days with multiple disaster occurrences, followed by the construction of a transition probability matrix and steady-state analysis to determine long-term disaster distribution. Results: The analysis reveals that no disaster conditions represent the most prevalent state in the region. Among actual disasters, wildfires demonstrate the highest persistence, followed by extreme weather events, floods, and landslides. The transition patterns indicate that most disasters occur as isolated events rather than consecutive sequences, though wildfires show a tendency for temporal clustering. Conclusion: The study provides two key contributions. Methodologically, it demonstrates an effective approach for simplifying complex multi disaster daily data. Practically, it offers scientific evidence for prioritizing wildfire management in the Riau Islands while maintaining preparedness for other episodic disasters. These findings support the development of targeted early warning systems and resource allocation strategies for local disaster management agencies.

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A. INTRODUCTION

Natural disasters have become increasingly prevalent worldwide, with climate change exacerbating their frequency and intensity (Hernández-Delgado, 2024; Mehta et al., 2017; Setiawati et al., 2023; Situ et al., 2025). According to the United Nations Office for Disaster Risk Reduction (2025), global economic losses from disasters have increased by 150% over the past decade. Coastal regions are particularly vulnerable, facing compound risks from both terrestrial and marine hazards (Ahmad et al., 2021; Amores et al., 2021; Griffen & Robinson, 2023; Harahap et al., 2025; Rubinato et al., 2020). This trend necessitates advanced predictive modelling to enhance disaster preparedness and risk reduction strategies globally.

Indonesia, as an archipelagic nation, experiences disproportionate impacts from natural disasters. National Disaster Management Agency (BNPB) reported over 3,000 disasters events annually, with coastal regions accounting for 65% of these incidents (Badan Nasional

Penanggulangan Bencana, 2025; Low Carbon Development Indonesia, 2022). The combination of geographical location, climate patterns, and anthropogenic factors creates a complex risk landscape. Studies by Nurhidayah et al. (2022) highlight that sea-level rise and land subsidence further amplify vulnerability in low-lying coastal areas.

The Riau Islands represent a critical economic zone with heightened disaster susceptibility. Wulandari et al. documented the region's exposure to floods, landslides, and wildfires, exacerbated by rapid urbanization and limited infrastructure (Wulandari et al., 2023). Regional Disaster Management Agency data indicates increasing disaster frequency, particularly during seasonal transitions (Atje, 2021). This unique combination of economic significance and environmental vulnerability necessitates specialized risk assessment approaches.

Mathematical models, particularly stochastic processes, have emerged as powerful tools for disaster prediction. Markov Chain have been successfully applied in various contexts, as demonstrated by Bagwan (2025); Kamaruzzaman et al. (2018) for drought assessment, Bai et al. (2025); Sun et al. (2023); Liu et al. (2022) for flood modelling. These applications show the method's versatility in capturing temporal patterns and transition probabilities between different disaster states. The strength of Markov models lies in their ability to handle sequential dependencies while maintaining computational efficiency, making them suitable for regional-scale analysis.

Despite these advancements in mathematical modelling, significant gaps remain in daily-scale disaster transition analysis. Previous studies by Hidayati et al. (2021) in Semarang and Novianti & Utari (2021) in Klaten demonstrated Markov Chain applications but were limited to monthly or annual scales, lacking the granularity required for effective early warning systems. Furthermore, research by Dalimunthe et al. (2023) in Bangka Belitung, while valuable, focused primarily on single-hazard contexts without addressing concurrent disaster events. This temporal and methodological limitation is particularly critical for archipelagic regions like Riau Islands where rapid-onset disasters require daily-scale monitoring.

This study addresses these gaps by developing a daily-scale Markov Chain model with dominant-state classification for Riau Islands. Our research aims to quantify daily transition probabilities between disaster states using 2024 BNPB data, identify dominant disaster patterns and their long-term equilibrium probabilities, and provide evidence-based recommendations for early warning systems and risk mitigation strategies. Methodologically, we contribute a novel dominant-state approach for handling multi-disaster scenarios, while practically supporting local disaster management agencies in resource allocation and preparedness planning.

B. METHODS

1. Research Design

This study employs a quantitative analytical approach utilizing a finite state Markov Chain model to examine daily transition dynamics between disaster states in Riau Islands. The framework incorporates discrete state classification and memoryless property assumptions to analyze disaster progression patterns (Hayati et al., 2023; Seabrook & Wiskott, 2023).

a. State Space Configuration

The system comprises five mutually exclusive states: S_0 (no disaster occurrence), S_1 (flood), S_2 (landslide), S_3 (extreme weather), and S_4 (wildfire). Each day is classified into one dominant state to maintain analytical clarity.

b. Markovian Properties

The model adheres to fundamental Markov assumptions of state discreteness, time homogeneity, and memoryless transitions between daily states.

2. Data Collection and Processing

The study utilized daily disaster occurrence records from National Disaster Management Agency (BNPB) for the Riau Islands throughout 2024 (366 days). The dataset documented all reported natural disasters, including floods, landslides, extreme weather, and wildfires (Badan Nasional Penanggulangan Bencana, 2025). To ensure consistency in state transitions, the following rules were applied:

a. Single Type Disaster Days

If multiple incidents of the same disaster type occurred on a single day (e.g., three flood events), it was recorded as one occurrence of that disaster.

b. Multi Type Disaster Days

If different disaster types occurred on the same day (e.g., flood and extreme weather), the dominant disaster was selected based on frequency (the disaster type with highest number of incidents that day) and temporal dominance (if frequencies were equal, the disaster occurring closest to the reporting date was prioritized).

This approach streamlined the Markov Chain analysis by converting complex multi-disaster days into a single dominant state, ensuring clarity in transition probability calculations.

3. Analytical Procedure

The analytical framework adopted a structured three stage methodology to derive meaningful insights from disaster transition patterns. This approach combined empirical observation with theoretical validation to ensure relevance to Riau Islands' specific disaster context:

a. Transition Probability Matrix Construction

Daily state transitions were quantified through frequency analysis. The transition probability matrix P was constructed using maximum likelihood estimation, where each probability element p_{ij} represents transition likelihood from disaster state i to state j.

b. Steady-state Analysis

Long-term disaster probabilities were derived through equilibrium equations solving $\pi = \pi P$, where π represents the stationary distribution vector (Hayati et al., 2025; Odhiambo et al., 2020). This solution provides crucial insights into the relative frequency of different disaster types over extended periods, serving as valuable tool for regional disaster preparedness planning.

c. Validation Framework
Model consistency was verified through row stochasticity checks and probability non-negativity validation, ensuring adherence to Markov Chain fundamentals.

C. RESULT AND DISCUSSION

1. Daily Transition Results

The transition probability matrix below quantifies the daily shifts between disaster states in Riau Islands during the observation period. The values represent absolute frequencies of transitions from one state to another, providing empirical evidence of disaster progression patterns. This matrix serves as the foundation for understanding both short term disaster sequences and long-term risk tendencies in the region, as shown in Table 1.

Table 1. Disaster Transition Patterns

From \ To	No disaster occurrence	Flood	Landslide	Extreme weather	Wildfire	Total Outflows
No disaster occurrence	268	4	1	11	24	308
Flood	4	0	0	0	0	4
Landslide	1	0	0	0	0	1
Extreme weather	11	0	0	0	0	11
Wildfire	24	0	0	0	17	41
Total Inflows	308	4	1	11	41	365

Based on Table 1, the transition patterns reveal several key insights. First, the no-disaster (s_0) shows strong persistence (268 transitions to itself), indicating most days were disaster-free. Second, transitions from no-disaster to wildfires (24) were more frequent than to floods (4) or extreme weather (11), suggesting wildfires are the most common initial disaster following calm periods. Similar counts were collected for all other disasters. The transition probability matrix (Table 1) was derived by normalizing observed frequencies, revealing several key patterns:

$$P = \begin{bmatrix} 0.870 & 0.013 & 0.003 & 0.036 & 0.078 \\ 1.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 1.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 1.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.585 & 0.000 & 0.000 & 0.000 & 0.415 \end{bmatrix}.$$

to better visualize the disaster transition dynamics, Figure 1 presents a flow diagram of inter-disaster transitions with arrows indicating the probability percentages. This graphical representation highlights the most probable disaster pathways and their relative likelihoods, complementing the numerical analysis discussed earlier.

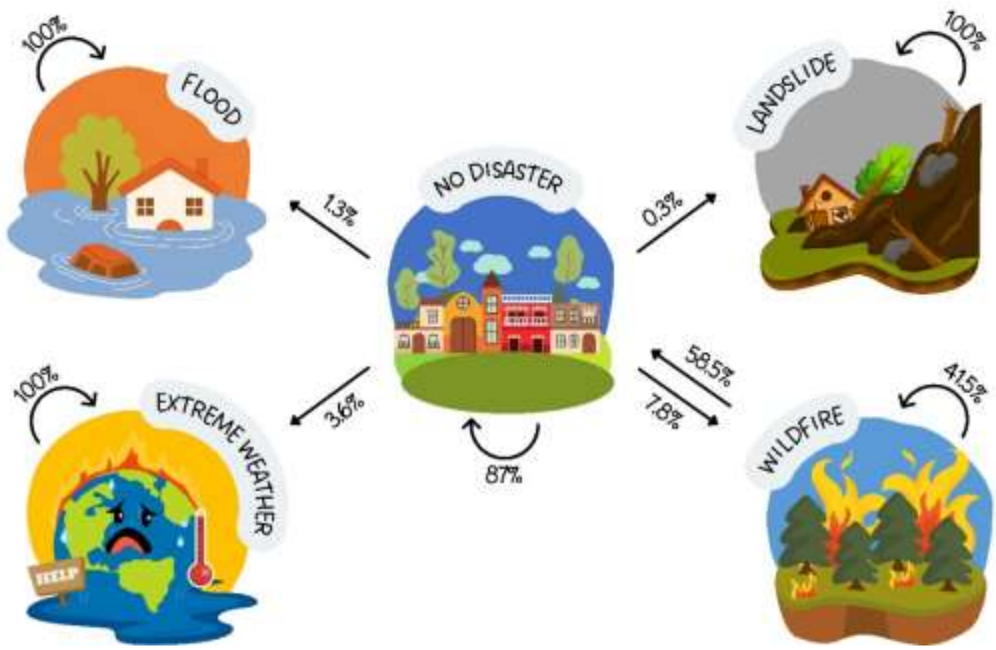

Figure 1. Disaster Transition Probability Flow Diagram in Riau Islands

Based on Figure 1, the transition probability matrix P reveals distinct patterns in disaster state transitions across Riau Islands. The no-disaster state demonstrates strong persistence with an 87% probability of remaining unchanged, while showing higher transition probabilities to wildfires (7.8%) compared to floods (1.3%) or extreme weather (3.6%). Notably, all active disaster states (floods, landslides, and extreme weather) exhibit absolute absorption properties. Once they occur, they inevitably transition back to the no-disaster state (100% probability) rather than persisting or evolving into other disaster types. Wildfires present a unique case, showing moderate persistence (41.5% probability of recurrence) while otherwise transitioning back to normal conditions (58.5%). These patterns suggest that the most disasters in the region are episodic rather than consecutive, wildfires display greater temporal clustering than other hazards, and disaster sequences rarely occur without returning to the baseline no-disaster state first. The matrix's dominant diagonal element confirms that disaster-free conditions are the most stable state in this ecosystem.

2. Long Term Disaster Prevalence

The steady state probabilities were computed through numerical solution of the Markov Chain equilibrium equations. The system was formulated by setting $\pi = \pi P$, where P represents the derived transition probability matrix. The solution was obtained through Gaussian elimination, a robust numerical method for solving linear systems. This computational approach determined the equilibrium probabilities $\boldsymbol{\pi}$ that remain unchanged under repeated application of the transition matrix, representing the asymptotic distribution of disaster states.

$$\boldsymbol{\pi} = [\ \underset{\text{No disaster occurrence}}{0.844}\quad \underset{\text{Flood}}{0.011}\quad \underset{\text{Landslide}}{0.003}\quad \underset{\text{Extreme weather}}{0.030}\quad \underset{\text{Wildfire}}{0.112}\ ].$$

To better visualize the long-term disaster prevalence in Riau Islands, Figure 2 presents the steady state probabilities in a pie chart format. This graphical representation highlights the relative dominance of each disaster state.

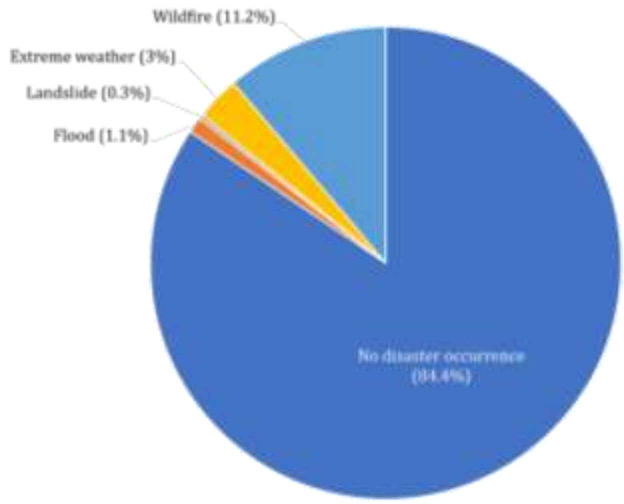

Figure 2. Steady State Probability Distribution of Disaster Occurrences in Riau Islands

Based on Figure 2, the steady state analysis reveals the long-term equilibrium distribution of disaster states in Riau Islands, with no disaster conditions (84.4%) emerging as the dominant state. This indicates that the region remains disaster-free for approximately 84.4% of the time in the long run. Among disaster states, wildfires (11.2%) show significantly higher prevalence compared to floods (1.1%), extreme weather (3%), and landslide (0.3%). This pattern suggest wildfires are the most persistent hazard, occurring nearly 10 times more frequently than floods and 3.7 times more often than extreme weather events at equilibrium. The extremely low probability of landslides (0.3%) aligns with their typically localized and episodic nature in the archipelago. The high probability of no disaster states reflects the region's general resilience, with disasters acting as intermittent disturbances rather than persistent conditions.

3. Comparative Regional Analysis

Comparative analysis with other Indonesian regions reveals striking contrasts in disaster patterns between Riau Islands and other areas where Markov Chains have been applied. The long-term flood probability of 1.1% in Riau Islands is dramatically lower than the 34. 21% reported by Novianti & Utari (2021) in Klaten and the 31.46% found by Dalimunthe et al. (2023) in Bangka Belitung. This substantial discrepancy suggests fundamentally different hydrological regimes, where Riau's archipelagic characteristics and better drainage systems may prevent flood accumulation compared to the inland flood-prone regions of Klaten and Bangka Belitung. Similarly, the wildfire prevalence of 11.2% in Riau Islands, while dominant locally, is considerably lower than the forest and land fire probability of 43.81% reported in Bangka Belitung by Dalimunthe et al. (2023). This contrast indicates varying levels of fire risk and management effectiveness between these two island provinces, with Bangka Belitung facing more severe fire challenges despite their geographical similarities.

Most notably, the complete absence of disaster chains in Riau Islands, where all active disasters transition directly back to normal conditions, contrasts sharply with the disaster mixing observed in Semarang by Hidayati et al. (2021), who reported multiple concurrent disaster probabilities including floods (22%), landslides (22%), and fires (33%) occurring in complex combinations. This suggests that Riau Islands experience cleaner disaster separations, possibly due to different meteorological triggers or geographical isolation between disaster-prone areas.

The 73.53% hurricane probability in Klaten (Novianti & Utari, 2021) further highlights regional specialization in dominant hazards, with Riau Islands 3% extreme weather probability representing a much lower severe wind risk profile. These comparative findings underscore that disaster transition patterns are highly region-specific, influenced by local topography, climate, and environmental factors that create distinct hazard portfolios for each area. This comparative perspective yields an important methodological insight, while Markov models provide universal analytical frameworks, their state definitions and transition probabilities must be calibrated to regional characteristics. The assumption of disaster independence that holds in Riau Islands may not apply in regions like Semarang with more complex disaster interactions, necessitating context-driven model specification for accurate risk assessment.

4. Risk Assessment and Early Warning Implication

Building on these integrated findings, disaster risk management in Riau Islands requires strategically tailored approaches that address both immediate response needs and long-term resilience building. For wildfire management, the dominant persistent threat, a combined approach of satellite monitoring (for early detection), community fire brigades (for rapid response), and regulated agricultural burning (for prevention) should be prioritized, particularly during the southeast monsoon period from June to September. The observed 41.5% self-transition probability indicates that fire recurrence is a significant concern, necessitating sustained vigilance even after initial containment.

For flood and extreme weather response, the patterns suggest optimizing rapid response systems during the northwest monsoon (December-March), when transition probability peak. The episodic nature of these events, with quick return to normal condition, allows for efficient resource allocation without long-term deployment. Mobile alert systems tailored to high-risk districts should emphasize immediate protective actions rather than prolonged preparedness. The predominance of no-disaster conditions (84.4%) of time presents a strategic opportunity for proactive resilience building. Rather than indicating low risk, this high probability of normalcy allows systematic investment in infrastructure maintenance, community training, and resource stockpiling during calm periods. Disaster management agencies should develop temporal resource allocation models that optimize preparedness activities during these predictable calm intervals.

These evidence-based strategies align with both Indonesia's Disaster Management Law (No.27/2007) and the Sendai Framework's emphasis on context-specific, proactive risk reduction (UNDANG-UNDANG REPUBLIK INDONESIA NOMOR 27 TAHUN 2007, 2007; United Nations Office for Disaster Risk Reduction, 2025). The Markov model's quantification of transition probabilities provides scientific foundation for prioritizing wildfire management while maintaining capacity for other hazards, enabling efficient use of limited resources in this strategically important economic region.

D. CONCLUSION AND SUGGESTIONS

This study provides a novel application of Markov Chain modelling to analyze daily disaster transitions in the Riau Islands, offering unique insights into disaster risk patterns through a temporal resolution approach previously unexplored in archipelagic contexts. The analysis reveals three fundamental characteristics of the region's disaster ecology. First, the overwhelming dominance of no disaster conditions (84.4% steady state probability) underscores the region's inherent resilience. Second, wildfires emerge as the most persistent threat (11.2%) with notable self-persistence (41.5% recurrence probability). Third, the consistent return to normalcy after disaster events indicates an episodic rather than cascading disaster pattern. These findings collectively demonstrate that disaster transitions in this archipelagic region follow distinct temporal dynamics that differentiate it from continental disaster progression models.

The practical implications of these findings are substantial for disaster management policy. For immediate application, we recommend prioritizing wildfire management through AI enhanced detection systems and regulated land use in fire prone zones, particularly given wildfire's dominant role in the disaster profile. Concurrently, early warning systems should be optimized for rapid response to floods and extreme weather during seasonal transitions, leveraging the predictable return to normal conditions for efficient resource allocation. These evidence based strategies directly support Sendai Framework priorities by enabling targeted risk reduction and enhancing community preparedness through temporally aware planning.

For advancing the research frontier, this study identifies several promising directions. Future work should integrate climate variables to assess transition probability shifts under climate change scenarios, potentially revealing new disaster correlations. Testing higher order Markov models could capture multi-day disaster dependencies that may be obscured in daily transitions. Furthermore, expanding the spatial resolution to district level analysis would enable targeted mitigation strategies that account for local variations in disaster susceptibility. The methodological approach demonstrated here, combining daily scale analysis with dominant state classification, provides a replicable framework for disaster transition modelling in similar archipelagic regions, representing a significant contribution to the evolving literature on probabilistic disaster risk assessment.

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