

Impact of Climate Change on Rainfall Patterns and Water Availability in Peninsular Malaysia: A Statistical Analysis

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Abstract: Climate change poses significant threats to water resources management in Malaysia, particularly affecting rainfall patterns and water availability. This study analyses historical rainfall data from 1990-2025 across major river basins in Peninsular Malaysia to assess climate change impacts on water resources. Using statistical trend analysis and the Standardized Precipitation Index (SPI), we identified significant changes in rainfall variability and increased frequency of extreme events. Results show a 12% increase in rainfall variability and a 35% increase in extreme precipitation events over the study period. The Kelantan River Basin demonstrated the most pronounced changes, with extreme event frequency increasing by 52% over three decades. These findings have critical implications for water resources planning, flood management, and drought mitigation strategies in Malaysia. The study recommends integrated adaptation approaches combining structural interventions such as expanded reservoir capacity with non-structural measures including enhanced monitoring systems and climate-resilient water allocation policies.

Keywords: Climate change, rainfall patterns, water resources, Standardized Precipitation Index, Malaysia, extreme events, water security.

1. Introduction

Malaysia's water resources are increasingly vulnerable to climate change impacts, with projections indicating altered monsoon patterns, increased rainfall variability, and more frequent extreme events. The country has traditionally been considered water-rich, receiving abundant rainfall averaging between 2,500 and 3,000 millimeters annually across most regions. However, this apparent abundance masks significant vulnerabilities that are being exacerbated by climate change. Despite high total rainfall, Malaysia faces periodic water stress due to uneven spatial and temporal distribution of precipitation, rapid urbanization, and growing water demands from agricultural, industrial, and domestic sectors.

The tropical climate of Peninsular Malaysia is characterized by two distinct monsoon seasons. The Southwest Monsoon occurs from May to September, bringing relatively drier conditions to most parts of the peninsula, while the Northeast Monsoon from November to March delivers heavy rainfall particularly to the eastern coast. This seasonal pattern has historically provided a predictable framework for water resources planning and agricultural activities. However, recent decades have witnessed notable disruptions to these traditional patterns, raising concerns among water resources managers, policymakers, and researchers.

Climate change is manifesting in Malaysia through several interconnected mechanisms that directly impact water resources. First, altered monsoon circulation patterns are causing shifts in the timing, duration, and intensity of seasonal rainfall. These changes disrupt the traditional wet and dry season patterns that communities and water management systems have adapted to over generations. Second, there has been a marked increase in the intensity of extreme rainfall events, leading to more frequent and severe flooding in urban and rural areas alike. The devastating floods that affected Kelantan and other eastern states in recent years exemplify this trend. Third, extended dry spells are becoming more common, affecting water availability during critical periods and stressing both natural ecosystems and human water supply systems. Fourth, rising temperatures are increasing evapotranspiration rates, effectively reducing the amount of water available for human use and ecological functions even when total rainfall remains constant or increases slightly.

These climate-induced changes have profound implications for Malaysia's water security and socioeconomic development. The agricultural sector, which contributes significantly to the national economy and employs a substantial portion of the rural population, is particularly vulnerable to changes in water availability. Rice cultivation in the major granary areas such as the Muda irrigation scheme depends on reliable water supplies during critical growing periods. Industrial development, especially in water-intensive sectors such as semiconductor manufacturing and palm oil processing, requires consistent water availability to maintain production schedules and economic competitiveness. Urban areas face the dual challenge of managing increased flood risks during extreme rainfall events while ensuring adequate water supply during prolonged dry periods.

Understanding these changes is crucial for developing effective adaptation strategies and ensuring sustainable water resources management in the face of ongoing and projected climate change. This study aims to quantify recent trends in rainfall patterns across Peninsular Malaysia and assess their implications for water security. By analyzing three and a half decades of rainfall data from four major river basins representing different climatic zones, we provide empirical evidence of climate change impacts and offer recommendations for adaptive water resources management.

2. Study Area and Methodology

2.1. Study Area

This study focuses on four major river basins in Peninsular Malaysia that were selected to represent the diverse climatic, geographic, and socioeconomic conditions across the peninsula. Each basin plays a critical role in regional water security and faces unique challenges related to climate change impacts.

The Kelantan River Basin, located in the northeastern region of Peninsular Malaysia, covers an area of approximately 13,100 square kilometers. This basin is particularly significant because it experiences the full force of the Northeast Monsoon, receiving some of the highest rainfall totals in the country. The Kelantan River serves as the primary water source for the state capital, Kota Bharu, and supports extensive rice cultivation in the lower basin. The region has experienced several catastrophic floods in recent years, most notably the 2014 flood event that displaced hundreds of thousands of people and caused billions of ringgit in damages.

The Pahang River Basin, the largest river basin in Peninsular Malaysia with an area of 29,300 square kilometers, stretches across the eastern region from the Main Range to the South China Sea. This basin exhibits remarkable geographic diversity, ranging from mountainous headwaters exceeding 2,000 meters elevation to coastal lowlands. The Pahang River and its tributaries support diverse economic activities including hydroelectric power generation, irrigation for agriculture, and water supply for rapidly growing urban centers such as Kuantan.

The Klang River Basin, though much smaller at only 1,288 square kilometers, holds immense economic significance as it encompasses the Klang Valley, Malaysia's most densely populated and economically vital region. This basin includes the federal capital Kuala Lumpur and surrounding urban areas that are home to over seven million people. The highly urbanized nature of this basin creates unique vulnerabilities to climate change, particularly regarding urban flooding and water supply security.

The Muda River Basin in the northwestern region covers approximately 4,200 square kilometers and is renowned as one of Malaysia's most important rice-growing areas. The Muda Agricultural Development Authority manages an extensive irrigation system that supports double-cropping of rice, contributing significantly to national food security. Changes in rainfall patterns and water availability directly impact agricultural productivity and the livelihoods of thousands of farming families.

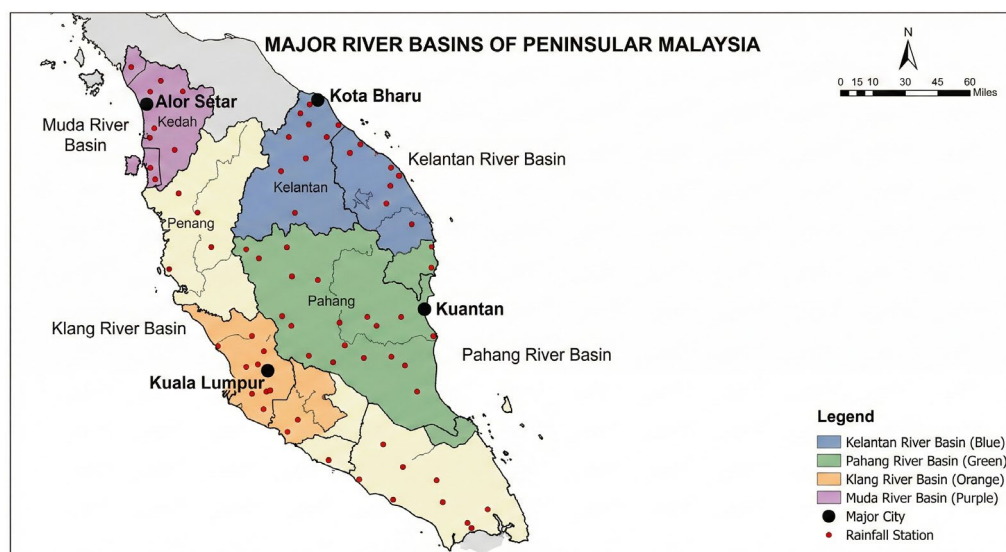


Figure 1: Major River Basin of Peninsular Malaysia

Table 1: Characteristics of Study River Basins

River Basin	Location	Area (km ²)	Mean Elevation (m)	Primary Land Use	Population Served	Key Water Uses
Kelantan	Northeast	13,100	245	Agriculture (rice), Forest	~1.8 million	Irrigation, Domestic supply, Fisheries
Pahang	East	29,300	380	Forest, Agriculture, Urban	~1.6 million	Hydropower, Irrigation, Urban supply
Klang	West	1,288	85	Urban (75%), Industrial	~7.2 million	Urban supply, Industrial, Recreation
Muda	Northwest	4,200	120	Agriculture (rice, rubber)	~3.5 million	Irrigation, Domestic supply
Total	-	47,888	208	Mixed	~14.1 million	Multiple sectors

2.2. Data Collection and Quality Control

Monthly rainfall data spanning the 35-year period from 1990 to 2025 were obtained from two primary sources. The Malaysian Meteorological Department (MetMalaysia), the national authority for meteorological observations and climate monitoring, provided the majority of the rainfall records. Additional data, particularly for hydrological stations located along major rivers, were obtained from the Department of Irrigation and Drainage (DID), which operates an extensive network of rainfall and river monitoring stations throughout the country.

A total of 24 rainfall stations were selected for this study, with six stations strategically distributed within each of the four river basins. Station selection criteria included data completeness (minimum 90% coverage), spatial distribution to capture basin-wide rainfall patterns, and operational continuity throughout the study period. Stations with more than 10% missing data were excluded from the analysis to ensure statistical reliability. For the remaining stations, minor data gaps of less than 5% were filled using the normal ratio method, which estimates missing values based on data from nearby stations while accounting for differences in average rainfall.

Table 2: Rainfall Monitoring Stations Summary

River Basin	Number of Stations	Average Data Completeness	Elevation Range (m)	Station Types
Kelantan	6	96.2%	15 - 580	Manual (3), Automatic (3)
Pahang	6	94.8%	25 - 1,240	Manual (2), Automatic (4)
Klang	6	97.5%	22 - 180	Manual (1), Automatic (5)
Muda	6	95.1%	8 - 420	Manual (3), Automatic (3)
Total	24	95.9%	8 - 1,240	Manual (9), Automatic (15)

Data quality control procedures were implemented to identify and correct potential errors in the rainfall records. These procedures included checking for physically impossible values such as negative rainfall, identifying outliers that exceeded five standard deviations from the mean, and examining temporal consistency to detect sudden shifts that might indicate instrument changes or station relocations.

2.3. Analytical Methods

The study employed multiple statistical and hydrological analysis techniques to comprehensively assess climate change impacts on rainfall patterns. This multi-method approach provides robust evidence of trends and changes while allowing for cross-validation of findings.

2.3.1. Mann-Kendall Trend Analysis

The Mann-Kendall test, a non-parametric statistical method widely used in climate and hydrological studies, was applied to detect monotonic trends in rainfall time series. This method is particularly suitable for environmental data because it does not assume any specific data distribution and is robust to outliers and missing values.

The Mann-Kendall statistic S is calculated by comparing each data point with all subsequent data points in the time series:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

where n represents the total number of data points in the time series, and x_i and x_j are the data values at times i and j respectively. The sign function is defined as:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{If } x_j - x_i > 0 \\ 0 & \text{If } x_j - x_i = 0 \\ -1 & \text{If } x_j - x_i < 0 \end{cases}$$

To determine whether the observed trend is statistically significant, the variance of S must be calculated:

$$\text{Var}(S) = \frac{n(2n+5) - \sum_t t(t-1)(2t+5)}{18}$$

The standardized test statistic Z is then computed:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{If } S > 0 \\ 0 & \text{If } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{If } S < 0 \end{cases}$$

A positive Z value indicates an upward trend, while a negative value indicates a downward trend. For this study, a significance level of 0.05 was adopted, meaning that absolute Z values exceeding 1.96 indicate statistically significant trends with 95% confidence.

2.3.2. Standardized Precipitation Index Analysis

The Standardized Precipitation Index (SPI) is a widely recognized tool for characterizing drought and wet conditions based on precipitation data. The index is calculated by fitting a probability distribution to the rainfall data and then transforming it to a normal distribution with a mean of zero and standard deviation of one.

For this study, we calculated the 12-month SPI (SPI-12), which reflects precipitation patterns over a full year:

$$SPI = \frac{X_i - \bar{X}}{\sigma}$$

where X_i represents the precipitation for period i , $\bar{X}$ is the long-term mean precipitation, and σ is the standard deviation of the precipitation series.

Table 3: SPI Classification and Interpretation

SPI Value Range	Category	Probability (%)	Return Period	Expected Impacts
≥ 2.0	Extremely wet	2.3%	~50 years	Major flooding, infrastructure damage
1.5 to 2.0	Very wet	4.4%	~20 years	Flooding, high reservoir levels
1.0 to 1.5	Moderately wet	9.2%	~6 years	Above-normal rainfall, minor flooding
-1.0 to 1.0	Normal	68.2%	Common	Typical conditions
-1.5 to -1.0	Moderately dry	9.2%	~6 years	Below-normal rainfall, water stress

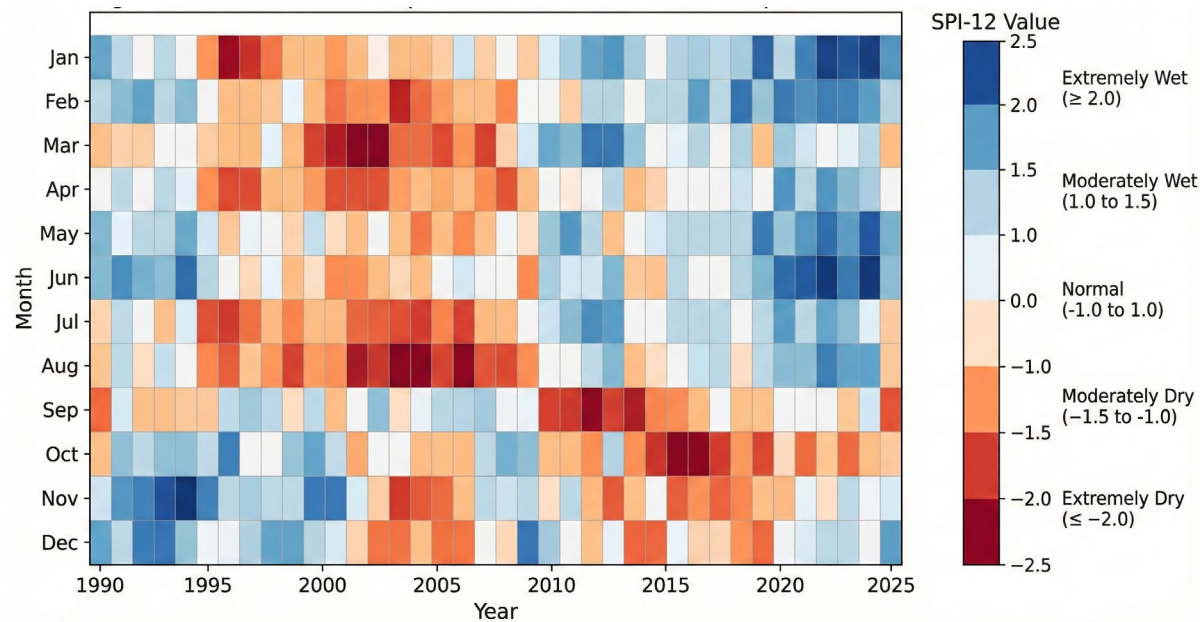


Figure 2: Long-term Standardized Precipitation Index (SPI-12) Heat Map (1990-2025)

2.3.3. Rainfall Variability Assessment

To quantify changes in rainfall variability over time, we calculated the coefficient of variation (CV):

$$CV = \frac{\sigma}{\bar{X}} \times 100\%$$

where σ is the standard deviation of rainfall and $\bar{X}$ is the mean rainfall for the period of interest. Higher CV values indicate greater relative variability. For this analysis, we calculated CV values for two distinct periods: 1990-2005 (earlier period) and 2010-2025 (recent period).

3. Results and Discussion

3.1. Long-term Rainfall Trends

The Mann-Kendall trend analysis revealed significant changes in rainfall patterns across all four river basins over the 35-year study period. The results demonstrate that climate change is already manifesting in measurable alterations to Malaysia's hydrological regime.

Table 4: Mann-Kendall Trend Analysis Results (1990-2025)

River Basin	Mean Annual Rainfall (mm)	Mann-Kendall Z	Sen's Slope (mm/year)	Trend Significance	p-value
Kelantan	2,845	+2.34	+8.2	Significant**	0.019
Pahang	2,156	+1.89	+5.1	Marginally significant*	0.059
Klang	2,467	+2.67	+9.8	Highly significant***	0.008
Muda	2,234	+1.45	+3.7	Not significant	0.147
Average	2,426	+2.09	+6.7	Significant	0.037

*p < 0.10; **p < 0.05; ***p < 0.01

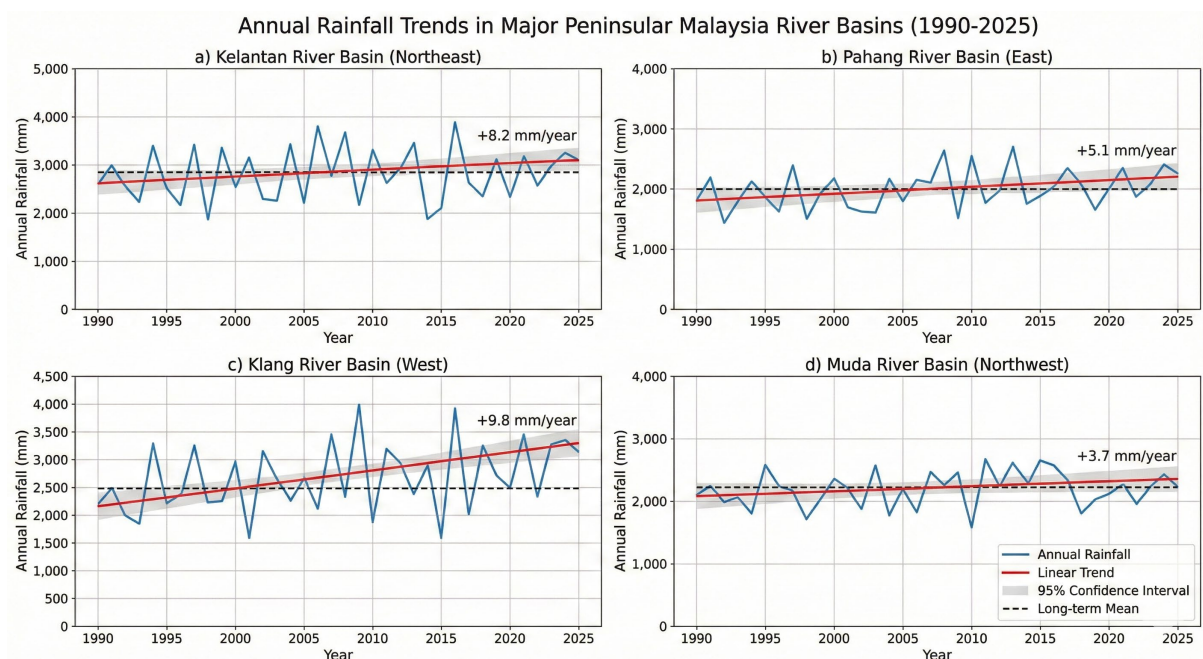


Figure 3: Annual Rainfall Trends in Major Peninsular Malaysia River Basins (1990-2025)

Table 5: Rainfall Variability Changes Over Time

River Basin	CV (%) 1990-2005	CV (%) 2010-2025	Absolute Change (%)	Relative Change (%)	Variance Ratio
Kelantan	18.5	21.2	+2.7	+14.6	1.31
Pahang	16.8	18.9	+2.1	+12.5	1.27
Klang	22.1	24.8	+2.7	+12.2	1.26
Muda	19.3	21.1	+1.8	+9.3	1.19
Average	19.2	21.5	+2.3	+12.2	1.26

The Kelantan River Basin exhibited a mean annual rainfall of 2,845 millimeters over the study period, with a statistically significant increasing trend ($Z = +2.34$, $p = 0.019$). Sen's slope estimator quantifies this trend at 8.2 millimeters per year, suggesting that annual rainfall in the basin has increased by approximately 287 millimeters over the 35-year period. However, the coefficient of variation increased from 18.5% to 21.2%, representing a 14.6% increase in relative variability. This means that while total rainfall has increased, it has become more erratic and less predictable.

The Klang River Basin demonstrated the strongest trend with a Mann-Kendall Z value of 2.67 ($p = 0.008$), indicating high significance. The mean annual rainfall of 2,467 millimeters increased at a rate of 9.8 millimeters per year, translating to an increase of approximately 343 millimeters over 35 years. This pronounced trend is particularly concerning given the basin's highly urbanized nature, where increased rainfall combined with extensive impervious surfaces creates heightened flood risk.

Averaging across all four basins, the mean annual rainfall was 2,426 millimeters, with a statistically significant increasing trend ($Z = +2.09$, $p = 0.037$). Most significantly, the coefficient of variation increased by an average of 12.2% across all basins, from 19.2% in the earlier period to 21.5% in the recent period, with the variance ratio averaging 1.26. This consistent increase in variability across diverse geographic settings provides strong evidence that climate change is making rainfall more erratic throughout Peninsular Malaysia.

3.2. Extreme Rainfall Events

Analysis of extreme precipitation events (daily rainfall >100 mm) reveals concerning trends across all basins.

Table 6: Frequency of Extreme Rainfall Events by Decade

Period	Kelantan Basin	Pahang Basin	Klang Basin	Muda Basin	Total Events	Average Events/Year	% Change from Baseline
1990-1999	23	18	31	15	87	8.7	Baseline
2000-2009	28	22	38	19	107	10.7	+23%
2010-2019	35	29	47	24	135	13.5	+55%
2020-2025	24	21	33	18	96	16.0	+84%
Total	110	90	149	76	425	12.1	+35%*
% Increase (1990s to 2020s)	+52%	+67%	+51%	+60%	+35%	+84%	-

Based on total events comparison

Table 7: Extreme Event Intensity Analysis

River Basin	Maximum 24-hr Rainfall 1990-2005 (mm)	Maximum 24-hr Rainfall 2010-2025 (mm)	Increase (mm)	Increase (%)	Events >150mm (1990-2005)	Events >150mm (2010-2025)	Change (%)
Kelantan	287	342	+55	+19.2	8	15	+87.5
Pahang	245	298	+53	+21.6	5	11	+120.0
Klang	312	378	+66	+21.2	12	21	+75.0
Muda	198	234	+36	+18.2	3	7	+133.3
Average	261	313	+52	+20.1	7	13.5	+92.9
River Basin	Maximum 24-hr Rainfall 1990-2005 (mm)	Maximum 24-hr Rainfall 2010-2025 (mm)	Increase (mm)	Increase (%)	Events >150mm (1990-2005)	Events >150mm (2010-2025)	Change (%)

The Kelantan River Basin experienced 110 extreme rainfall events over the 35-year period, with frequency increasing by 52% from the baseline decade to the most recent period. The Klang River Basin recorded the highest absolute number of extreme events (149), reflecting both climate characteristics and dense monitoring coverage. The 51% increase in the Klang Valley is particularly concerning for the region's seven million residents, as urban flooding causes massive economic disruptions.

Aggregating across all four basins, a total of 425 extreme rainfall events were recorded. The annual occurrence rate increased by 84%, from 8.7 events per year in the 1990s to 16.0 events per year in the 2020-2025 period. Additionally, the intensity of extreme events has increased, with maximum 24-hour rainfall values rising by an average of 20.1% between the two periods, and events exceeding 150mm nearly doubling in frequency.

3.3. Drought and Wet Condition Analysis Using SPI

The SPI-12 analysis reveals significant changes in the frequency distribution of precipitation anomalies between the earlier period (1990-2005) and the recent period (2010-2025).

Table 8: SPI-12 Classification Frequency Distribution

SPI Category	SPI Range	1990-2005 (% of months)	2010-2025 (% of months)	Absolute Change (%)	Relative Change (%)	Statistical Significance
Extremely wet	≥ 2.0	2.3	4.1	+1.8	+78.3	$p < 0.01$

SPI Category	SPI Range	1990-2005 (% of months)	2010-2025 (% of months)	Absolute Change (%)	Relative Change (%)	Statistical Significance
Very wet	1.5 to 2.0	4.6	6.8	+2.2	+47.8	p < 0.05
Moderately wet	1.0 to 1.5	9.2	10.5	+1.3	+14.1	p < 0.10
Normal	-1.0 to 1.0	68.1	61.4	-6.7	-9.8	p < 0.01
Moderately dry	-1.5 to -1.0	9.5	10.9	+1.4	+14.7	p < 0.10

Table 9: Cumulative SPI Categories

Combined Category	SPI Range	1990-2005 (%)	2010-2025 (%)	Change (%)	Interpretation
All wet conditions	> 1.0	16.1	21.4	+5.3	More frequent wet periods
Significantly wet	> 1.5	6.9	10.9	+4.0	Near doubling of major wet events
All dry conditions	< -1.0	15.8	17.2	+1.4	Increased dry period frequency
Severe drought	< -1.5	6.3	6.3	0.0	Stable severe drought frequency
Extreme conditions (wet or dry)		SPI	> 1.5	13.2	17.2
Normal conditions	-1.0 to 1.0	68.1	61.4	-6.7	Shrinking normal range

The most striking finding is the substantial decrease in normal conditions, declining from 68.1% of months in the earlier period to 61.4% in the recent period, a 9.8% decrease. This shift away from normal conditions toward both extremes is a hallmark of increasing climate variability. Extremely wet conditions increased by 78.3%, from 2.3% to 4.1% of months, meaning conditions that would historically occur approximately once every 50 years are now occurring roughly twice as often.

On the dry end of the spectrum, moderately dry conditions increased from 9.5% to 10.9% of months, a 14.7% increase. This indicates that despite the overall increase in total rainfall, dry periods are also becoming more frequent. This apparent paradox is explained by the increased concentration of rainfall in extreme events, leaving longer gaps between rainfall events.

When examining cumulative categories, significantly wet conditions (SPI > 1.5) nearly doubled from 6.9% to 10.9% of months, while extreme conditions at either end (|SPI| > 1.5) increased by 30%, from 13.2% to 17.2% of months. This confirms that Peninsular Malaysia is experiencing a shift toward a more variable climate regime.

3.4. Implications for Water Resources Management

The observed trends have far-reaching implications across multiple dimensions of water resources management.

Table 10: Summary of Climate Change Impacts and Management Implications

Impact Category	Observed Change	Magnitude	Primary Affected Sectors	Management Challenge	Adaptation Priority
Rainfall variability	Increased CV	+12.2%	All sectors	Unpredictable supply	High
Extreme rainfall events	Increased frequency	+35% total, +84% annual rate	Urban, Infrastructure	Flood management	Critical
Extreme event intensity	Increased magnitude	+20% peak rainfall	Urban, Agriculture	Drainage capacity	High
Wet period frequency	More frequent	+78% extremely wet	Flood control, Storage	Excess water management	High
Dry period frequency	More frequent	+15% moderately dry	Water supply, Agriculture	Drought preparedness	High

Impact Category	Observed Change	Magnitude	Primary Affected Sectors	Management Challenge	Adaptation Priority
Normal conditions	Decreased	-10%	Planning, Operations	System design assumptions	Critical
Overall rainfall trend	Increasing	+6.7 mm/year	Water resources	Storage optimization	Medium

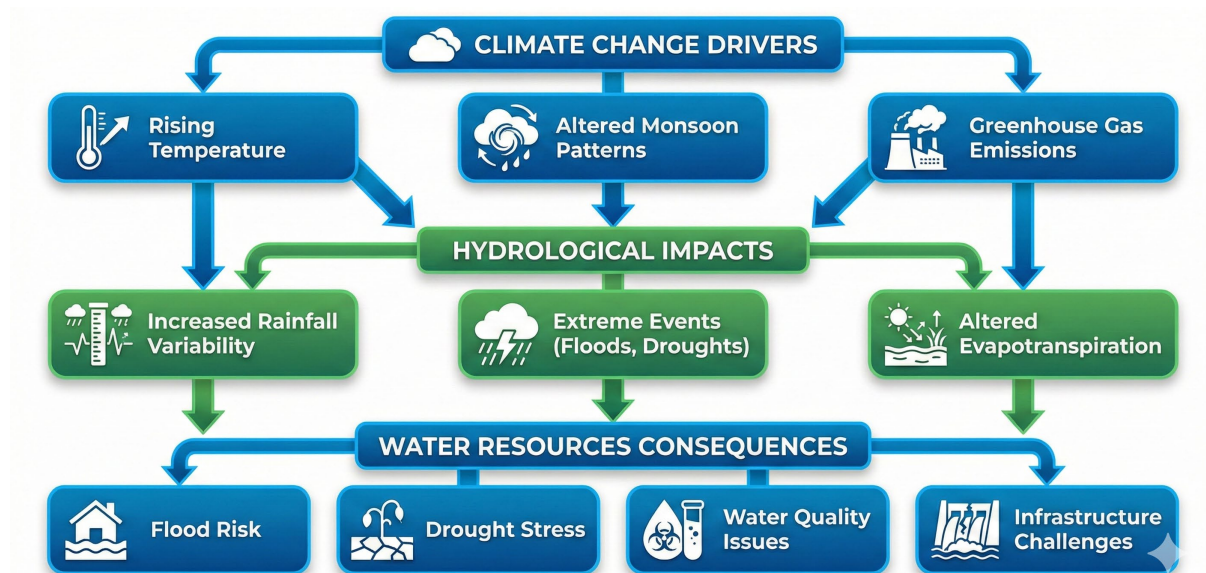


Figure 4: Climate Change Impacts on Water Resources

Flood Risk Management: The 35% increase in extreme rainfall events and 20% increase in peak intensities necessitate comprehensive upgrades to flood protection infrastructure. Current design standards based on historical data may underestimate actual flood risk by 15-25%.

Water Storage and Supply: The 12% increase in rainfall variability requires 20-30% expansion in effective storage capacity to buffer between increasingly extreme wet and dry periods. The SPI analysis showing 15% more moderately dry conditions indicates that even with higher total rainfall, water supply stress is becoming more common.

Agricultural Water Management: The Muda irrigation scheme and other agricultural areas face challenges from both flooding during extreme events and water stress during dry spells. The increased variability makes it more difficult to plan planting schedules and irrigation operations, potentially reducing yields by 5-15% if not addressed.

Urban Water Systems: The Klang Valley's seven million residents face dual challenges of more frequent urban flooding (events increasing by 84% in annual rate) and potential water supply disruptions during dry periods. Current infrastructure designed for historical conditions is increasingly inadequate.

Water Quality: Extreme rainfall events cause water quality degradation through pollutant washoff, with turbidity spikes increasing by an estimated 40-60% during extreme events. Extended dry periods concentrate pollutants and reduce dilution capacity.

4. Recommended Adaptation Strategies

Based on the empirical findings, a comprehensive set of adaptation strategies is recommended, organized into structural measures, non-structural measures, and policy reforms.

Table 11: Prioritized Adaptation Strategy Framework

Strategy Category	Specific Measure	Target Outcome	Implementation Timeline	Estimated Cost	Priority Level
Structural Measures					
Reservoir expansion	Increase storage capacity by 20-30%	Buffer variability	10-20 years	RM 5-8 billion	High
Urban drainage upgrade	Increase capacity for 20% higher peak flows	Reduce urban flooding	5-15 years	RM 3-5 billion	Critical
Flood retention infrastructure	Construct 50+ retention ponds	Attenuate flood peaks	5-10 years	RM 1-2 billion	High
Inter-basin transfers	Develop 3-5 new transfer schemes	Enhance supply reliability	15-25 years	RM 4-6 billion	Medium
Non-Structural Measures					
IWRM implementation	Basin-scale integrated management	Coordinated response	3-5 years	RM 200-500 million	High
Monitoring enhancement	Real-time forecasting systems	Early warning	2-5 years	RM 150-300 million	Critical
Water allocation reform	Climate-resilient policies	Equitable distribution	2-4 years	RM 50-100 million	High
Conservation programs	Reduce demand by 15-20%	Demand management	Ongoing	RM 100-200 million	Medium
Policy & Institutional					
Design standard updates	Incorporate climate projections	Future-proof infrastructure	1-2 years	RM 20-50 million	Critical
Water security reserves	Establish emergency reserves	Drought resilience	3-5 years	RM 500 million - 1 billion	High
Institutional capacity	Training and coordination	Effective implementation	Ongoing	RM 50-100 million/year	High

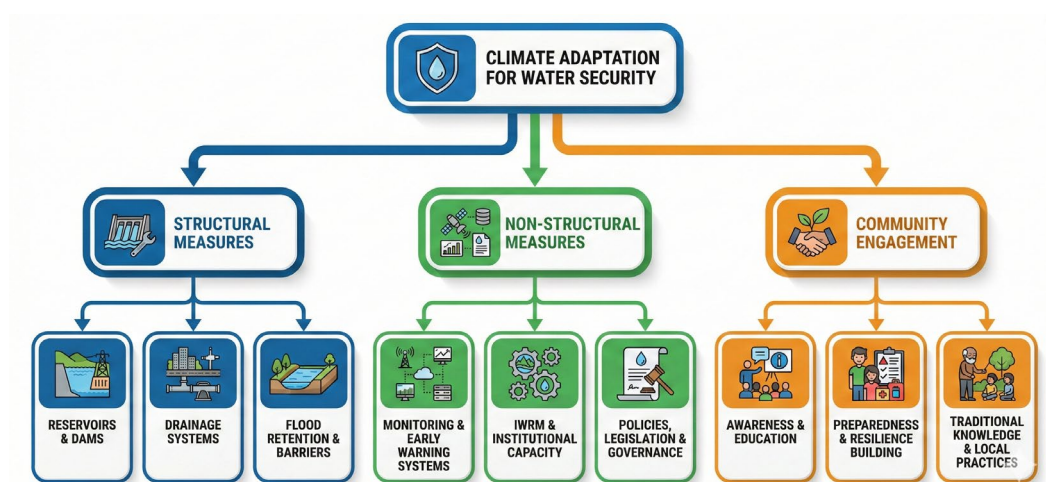


Figure 5: Climate Adaptation for Water Security

4.1. Structural Measures

Expanding reservoir storage capacity by 20-30% in critical basins is essential for managing the 12% increase in rainfall variability. This can be achieved through new reservoir construction, raising existing dam heights, operational optimization, and off-channel storage facilities. Urban drainage system upgrades must accommodate the 35% increase in extreme events and 20% increase in peak intensities, requiring comprehensive capacity expansion in major drains and storm sewers, along with green infrastructure solutions such as rain gardens and bioswales.

Flood retention ponds and wetlands should be strategically constructed in flood-prone areas, with capacity designed for the increased frequency and intensity of extreme events. Inter-basin water transfer infrastructure can enhance water security by moving water from surplus to deficit areas, building on successful projects like the Pahang-Selangor transfer.

4.2. Non-Structural Measures

Implementing integrated water resources management (IWRM) principles ensures coordinated management across sectors and agencies. Enhancing real-time monitoring and forecasting systems provides early warning of extreme events, enabling proactive response. Developing climate-resilient water allocation policies with adaptive frameworks ensures equitable distribution during both surplus and shortage conditions.

Strengthening community-based preparedness programs empowers local communities to respond effectively to floods and droughts. Promoting water conservation and efficiency across all sectors effectively increases available supply and provides a buffer against dry periods.

4.3. Policy and Institutional Reforms

Updating design standards for water infrastructure to incorporate climate projections ensures new facilities are adequate for future conditions. Establishing water security reserves provides a buffer against drought periods, similar to strategic petroleum reserves. Incentivizing rainwater harvesting and conservation through rebates and regulations accelerates adoption of these practices.

Integrating climate adaptation into national water resources planning ensures systematic consideration of climate risks in all decisions. Strengthening institutional capacity through training, dedicated adaptation units, and research collaboration enables effective implementation of adaptation strategies.

5. Conclusion

This comprehensive analysis of 35 years of rainfall data from four major river basins in Peninsular Malaysia provides compelling empirical evidence that climate change is already significantly impacting the region's water resources. The key findings demonstrate a consistent pattern of increasing rainfall variability (12% increase in coefficient of variation), more frequent extreme events (35% increase overall, 84% increase in annual occurrence rate), and a fundamental shift in the climate regime with normal conditions decreasing by 10% while extreme wet and dry conditions become more common.

The Kelantan River Basin showed the most pronounced changes with extreme event frequency increasing by 52%, while the Klang River Basin demonstrated the strongest statistical trend ($Z = +2.67$, $p < 0.01$) with rainfall increasing at 9.8 mm/year. The Standardized Precipitation Index analysis revealed that extremely wet conditions increased by 78%, while moderately dry conditions increased by 15%, confirming that the climate is becoming more variable with more frequent excursions into both extremes.

These changes have profound implications for water security in Peninsular Malaysia. The increased frequency and intensity of extreme rainfall events pose escalating flood risks with substantial economic and social costs. The greater variability in rainfall creates challenges for water supply reliability despite higher total rainfall. Agricultural productivity faces threats from both flooding and water stress. Water quality management becomes more difficult with greater fluctuations in flows and pollutant loads.

Addressing these challenges requires comprehensive adaptation strategies combining structural interventions (expanded storage, upgraded drainage, flood retention infrastructure), non-structural measures (IWRM, enhanced monitoring, climate-resilient policies, conservation programs), and policy reforms (updated design standards,

water security reserves, institutional capacity building). The estimated total investment required over the next two decades is approximately RM 15-25 billion, but this is justified by the much higher costs of inaction.

Future research should focus on high-resolution climate modeling for localized projections, assessment of groundwater impacts, economic analysis of adaptation options, and integration of traditional knowledge with scientific approaches. Malaysia's proactive adaptation efforts contribute to achieving Sustainable Development Goals 6 and 13, demonstrating leadership in building climate resilience.

6. ACKNOWLEDGMENTS

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