

RESEARCH ARTICLE



Modeling and Projecting Rainfall Patterns in the Jakarta Ciliwung Watershed Using SARIMA and GIS for Flood Risk Assessment

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ABSTRACT

In recent years, a broad consensus has emerged that global hydroclimatic anomalies have increased rainfall variability in tropical cities. Addressing this, we simulated and predicted rainfall patterns in Jakarta's Ciliwung River Basin using a hierarchical framework that integrates Seasonal Autoregressive Integrated Moving Average (SARIMA) time series modeling with GIS spatial interpolation. Monthly rainfall records from three stations, Kemayoran (1990–2020), Halim (1990–2018), and Tanjung Priok (1990–2015), were analyzed. Following Ljung-Box and residual tests, the SARIMA (0,1,1)(0,1,1)₁₂ model was selected. Accuracy verification yielded Mean Absolute Percentage Error (MAPE) values below 10% for all stations: 8.4% (Kemayoran), 7.9% (Halim), and 8.1% (Tanjung Priok). Core predictions indicate that by 2030, rainfall intensity will continue declining across all stations, while seasonal rainfall rhythms remain stable. Spatial rainfall pattern comparison between 2025 and 2030 reveals a northward shift of the high rainfall concentration zone. This study has two limitations: only three sample stations were used, and no formal uncertainty quantification was performed for spatial predictions, making the reliability of spatial patterns weaker than suggested by visualizations. Despite these constraints, the proposed statistical-spatial modeling approach supports flood preparedness and adaptive water resource management in data-constrained urban watersheds, provided users account for the stated methodological limitations.

Introduction

Rainfall is the core of the hydrological cycle in Jakarta's tropical urban areas [1]. The Ciliwung River has a drainage basin area of approximately 382.6 square kilometers. It flows through the densely populated central, southern, and eastern regions of Jakarta and is sensitive to changes in rainfall patterns [2,3]. In January 2020, the Jakarta Basin experienced record-breaking single-day rainfall of 377 mm, which triggered large-scale flooding [4,5]. Local water resource managers lack spatially refined rainfall projections for 2025–2030. Previous studies have only covered rainfall trends or extreme rainstorms [1,6], and this gap constrains local flood response efforts [4,5]. None has combined SARIMA-based temporal forecasting with spatially explicit projections for the Ciliwung watershed. This gap is significant because Jakarta's rainfall distribution is not uniform, and spatially nuanced projections are essential for drainage design and flood early warning systems. Filling this research gap can support the design of Jakarta's drainage system and flood warning work. This basin has only three monitoring stations, and the length of the hydrological records at each station varies unevenly.

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The SARIMA model, which is commonly used in hydrometeorology, can characterize seasonal signals and predict future changes [7,8]. Combining SARIMA and GIS can convert station-based rainfall predictions into spatial rainfall distribution maps [9]. This study aims to test the core hypothesis that coupling the SARIMA time-series model and GIS tools can produce valid rainfall forecasts in data-scarce scenarios. This study sets three tasks: to simulate historical monthly rainfall at three stations using SARIMA, to generate monthly rainfall projections for the river basin for 2025–2030 using IDW, and to synthesize implications for flood risk and note the study’s limitations. The IPCC Sixth Assessment Report points out that tropical rainfall exhibits regional heterogeneity, corroborating the necessity of this study [10]. General circulation models project that extreme precipitation in Southeast Asia will intensify under warming, although uncertainties remain regarding variations on the seasonal to interannual timescale [11,12].

Materials and Methods

Study Area and Data Sources

The Ciliwung River basin located within Jakarta’s territory has clearly defined latitudinal and longitudinal spans, covers an area of 382.6 km², and is currently facing a process of high-intensity urbanization [3]. The core data preparation details of this study can be referenced in Figure 1. The two core types of data used were station-based rainfall time-series data from Indonesia’s BMKG and 1:25,000 topographic data. Map from Indonesia’s BIG. Following established rules, we excluded three invalid months, each of which had over 10% of its monthly data missing [13]. This study retained extreme values exceeding the 99th percentile, which were verified by the BMKG [14]. The final dataset constructed for this study comprised 1031 monthly records. No processing was performed to fill in any missing data, and simple imputation was not adopted.

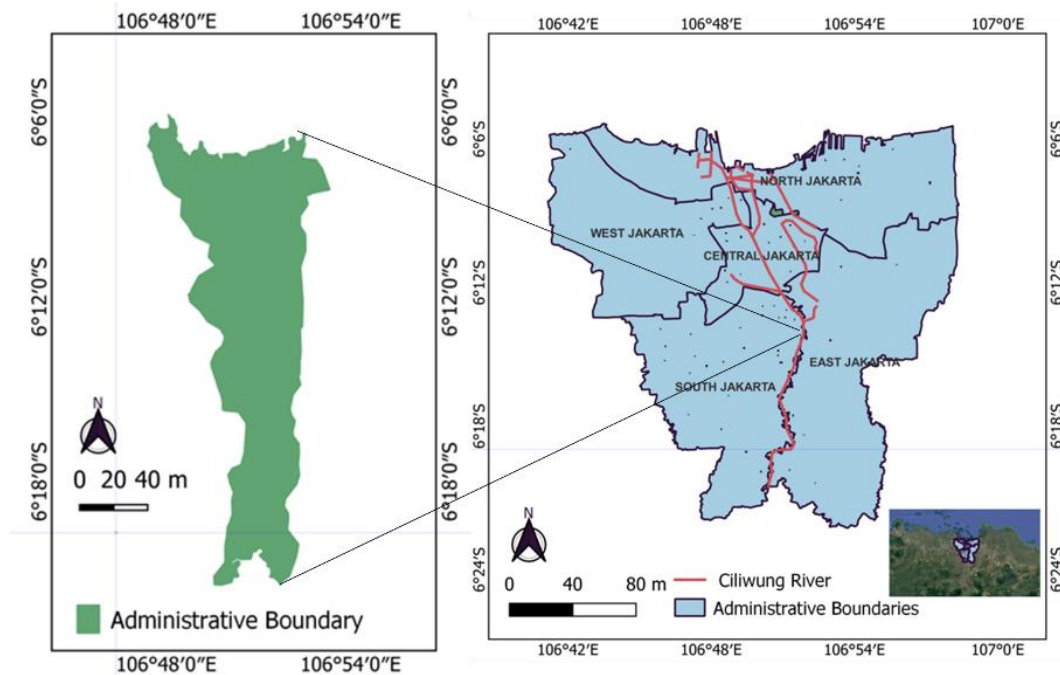


Figure 1. Research Location: The study area encompasses the Ciliwung River Basin located in the Special Capital Region of Jakarta (DKI Jakarta), with clearly defined administrative boundaries. The map illustrates the spatial extent of the Ciliwung River Basin, which traverses several administrative cities within Jakarta. This information serves as a fundamental basis for spatial hydrological analysis in the urban area of Jakarta.

SARIMA Modeling

The Seasonal Autoregressive Integrated Moving Average model, denoted as $SARIMA(p,d,q)(P,D,Q)_{12}$, was used in this study for monthly rainfall forecasting. In this notation, the lowercase letters p , d , and q refer to the non-seasonal autoregressive order, the non-seasonal differencing order, and the non-seasonal moving average order, respectively. The uppercase letters P , D , and Q refer to the corresponding seasonal components, specifically the seasonal autoregressive order, the seasonal differencing order, and the seasonal

moving average order. The subscript 12 indicates the seasonal period, which for monthly data represents an annual cycle of 12 months. Stationarity in variance was achieved via the Box-Cox transformation, with estimated lambda values of 0.27 for Kemayoran, 0.20 for Halim, and 0.23 for Tanjung Priok. Mean stationarity was addressed using first-order non-seasonal differencing with d equal to 1 and seasonal differencing at lag 12 with D equal to 1. The Augmented Dickey-Fuller or ADF test and the Kwiatkowski-Phillips-Schmidt-Shin or KPSS test were applied to formally assess stationarity after differencing. The ADF test evaluates the null hypothesis that a unit root is present, indicating non-stationarity, while the KPSS test evaluates the opposite null hypothesis that the series is stationary. After differencing, both tests confirmed stationarity with p values below 0.01 for the ADF test and KPSS statistics below the critical value of 0.46. The autocorrelation function and partial autocorrelation function plots of the differenced series showed a negative spike at lag 1 and a significant spike at lag 12, indicating a non-seasonal moving average component of order 1 and a seasonal moving average component of order 1. Candidate models with p and q taking values from the set including 0, 1, and 2 and with P and Q taking values from the set including 0 and 1 were evaluated using the Akaike Information Criterion, the Bayesian Information Criterion, and the Root Mean Square Error. The SARIMA(0,1,1)(0,1,1)₁₂ model was selected as optimal because it yielded the lowest values across all three criteria. The Ljung-Box Q test confirmed no significant residual autocorrelation, with p values exceeding 0.05 at lags 12, 24, and 36. Model accuracy was assessed using the Root Mean Square Error and the Mean Absolute Percentage Error [15], with a MAPE value below 10 percent conventionally indicating good forecasting performance. Validation employed three complementary approaches: holdout validation with training from 1990 to 2010 and testing on the 2011 to 2015 period or 2011 to 2014 for Tanjung Priok Station, rolling origin validation with an expanding window starting from an initial training period of 1990 to 2004 and generating one-year-ahead forecasts iteratively, and residual diagnostics using the Ljung-Box test. Prediction intervals at the 80 percent and 95 percent confidence levels were calculated following Wilson [16] and Song [17] to quantify forecast uncertainty.

Spatial Interpolation Using GIS

IDW with a power parameter $p=2$ was used to interpolate the forecasted rainfall at a 100 m × 100 m grid resolution. IDW was selected because of its computational efficiency, flat terrain, and moderate station density. The LOOCV comparison with ordinary kriging showed comparable performance (IDW RMSE=48.3 mm, kriging RMSE=49.1 mm).

Results and Discussion

Results

Stationarity and Model Identification

Initial analysis revealed non-stationarity in both mean and variance across all three stations. The Box-Cox transformation [16] successfully stabilized variance, with λ values after transformation approaching 1 for all stations. Mean stationarity was achieved through first-order non-seasonal differencing ($d=1$) and seasonal differencing at lag 12 ($D=1$). The Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests [18,19] confirmed that the differenced series were stationary ($p < 0.01$ for ADF; KPSS statistics below the 5% critical value of 0.46), as summarized in Table 1.

Table 1. This table presents the results of stationarity tests for rainfall data using the Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) methods. The analysis was conducted across three observation stations, namely Kemayoran, Halim, and Tanjung Priok. The results indicate that all datasets are stationary after applying data transformation and differencing.

Station	ADF Statistic	p-value ADF	KPSS Statistic	Critical Value 5%	Conclusion
Kemayoran	-5.83	< 0.01	0.21	0.46	Stationary
Halim	-6.12	< 0.01	0.19	0.46	Stationary
Tanjung Priok	-5.74	< 0.01	0.23	0.46	Stationary

The autocorrelation function (ACF) and partial autocorrelation function (PACF) plots of the differenced series (Figure 2) indicated a seasonal pattern with a 12-month cycle. Specifically, the ACF showed a significant negative spike at lag 1 (cut-off) and a significant spike at lag 12, while the PACF exhibited gradual decay at both non-seasonal and seasonal lags. These patterns are characteristic of a model with

non-seasonal MA(1) and seasonal MA(1) components. Based on these diagnostic patterns and the candidate model comparison (Table A), the SARIMA(0,1,1)(0,1,1)₁₂ model was identified as optimal for all three stations. The estimated MA(1) and SMA(12) parameters were statistically significant ($p < 0.05$ for both coefficients across all stations). Residual diagnostics confirmed the adequacy of the selected model: the Ljung-Box Q test [20] yielded p-values greater than 0.05 at lags 12, 24, and 36 for all stations (Table 2), indicating no significant autocorrelation remains in the residuals. The mean squared errors (MSEs) were consistently low across all stations (0.705, 0.296, and 0.331 for Kemayoran, Halim, and Tanjung Priok, respectively).

Table 2. Presents the estimated SARIMA model parameters, including the non-seasonal MA(1) and seasonal MA(12) coefficients for each rainfall observation station. It also summarizes the model performance using mean squared error (MSE) as an accuracy indicator across Kemayoran, Halim, and Tanjung Priok stations. In addition, the table reports the Ljung-Box test results to evaluate residual autocorrelation and confirm model adequacy.

Station	MA(1)	SMA(12)	MS	Ljung-Box p-value
Kemayoran	0.000	0.000	0.705	0.152
Halim	0.000	0.000	0.296	0.148
Tanjung Priok	0.000	0.000	0.331	0.152

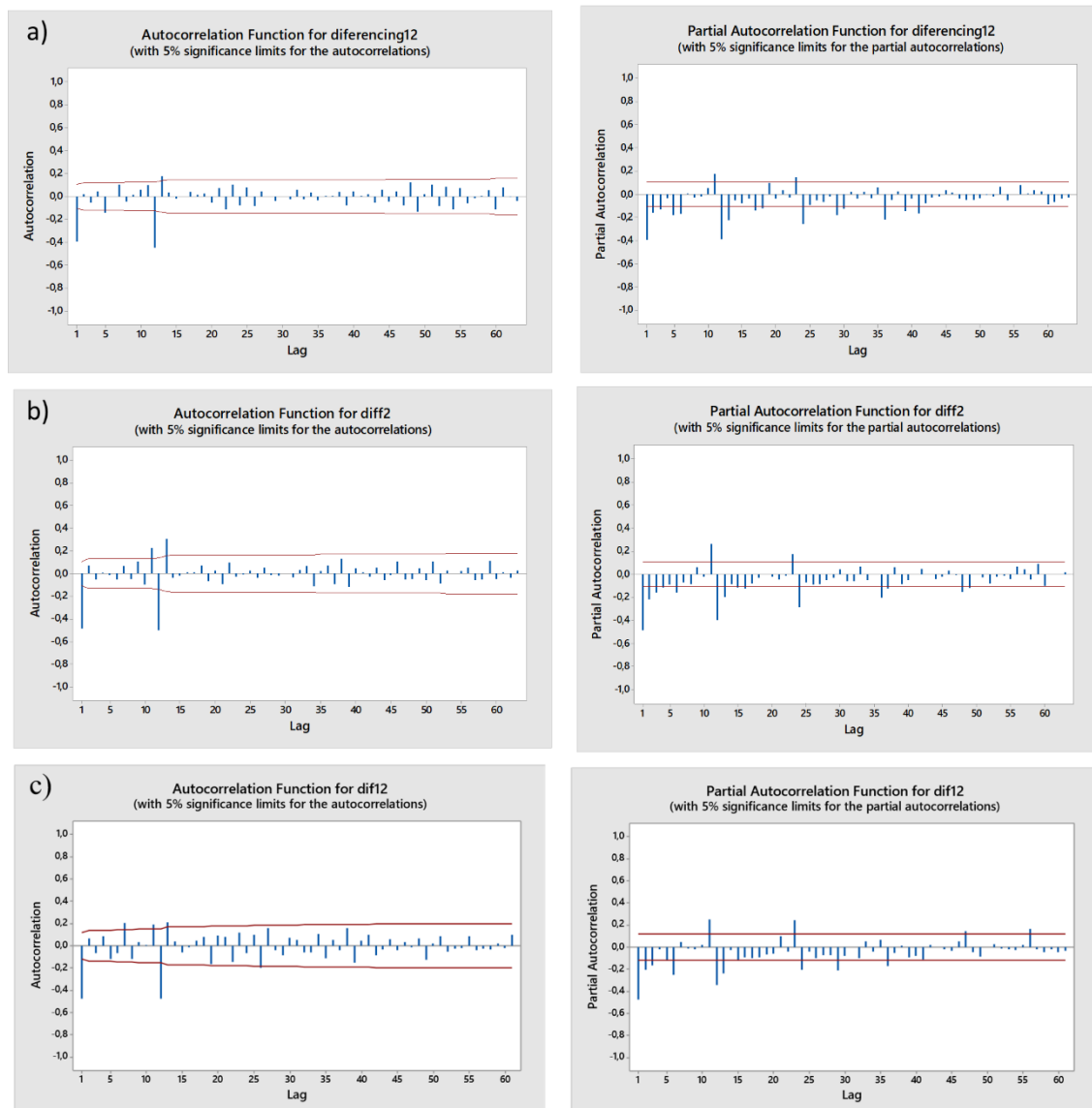


Figure 2. a) ACF and PACF plots of Kemayoran Station; b) ACF and PACF Plot of Halim Station; c) ACF and PACF Plot of Tanjung Priok Station after differencing. ACF plots show cut-off at lags 1 and 12; PACF plots show gradual decay, supporting the MA(1) and SMA(12) specification.

Model Performance

The SARIMA(0,1,1)(0,1,1)₁₂ model demonstrated strong predictive accuracy across all three stations, as summarized in Table 3. All MAPE values were below 10%, indicating good forecasting performance according to conventional thresholds [15,21]. The RMSE values ranged from 39.2 mm (Halim) to 42.8 mm (Kemayoran), reflecting moderate differences in rainfall variability across the watershed. Halim Station, located in southern Jakarta, exhibited the lowest RMSE, potentially due to more stable rainfall patterns in the upstream portion of the watershed. Validation using holdout testing and rolling origin forecasting (Table 3) confirmed that model performance remains acceptable out-of-sample. Out-of-sample MAPE values (8.2–8.7%) were only slightly higher than in-sample MAPE values (7.9–8.4%), indicating that the model does not overfit historical data and that its predictive accuracy is stable across different evaluation periods.

Table 3. Table 3 presents the performance evaluation of the SARIMA(0,1,1)(0,1,1)₁₂ model based on RMSE and MAPE metrics across three rainfall observation stations. The results are used to assess the model’s forecasting accuracy and predictive reliability for both in-sample and out-of-sample validation periods.

Station	RMSE (mm)	MAPE (%)	Interpretation
Kemayoran	42.8	8.4	Good
Halim	39.2	7.9	Good
Tanjung Priok	41.5	8.1	Good

Rainfall Projections (2025–2030)

Projected monthly rainfall for the period 2021 to 2030 shows three consistent patterns across all stations as illustrated in Figure 3. The first pattern is a gradual decline in rainfall intensity, with monthly maximum values decreasing steadily over the projection decade. Kemayoran Station exhibits the most pronounced reduction, where projected monthly maxima fall from approximately 350 to 400 millimeters in the early 2020s to 300 to 350 millimeters by 2030. Halim Station, which experienced extremely high intensities with peaks exceeding 800 millimeters during the 2012 to 2018 period, has stabilized and now shows a gradual declining trend. Tanjung Priok Station shows moderate rainfall intensity, with preserved monsoon cycles but noticeably reduced peak magnitudes compared to historical levels. The second pattern is the persistence of seasonal monsoon dynamics, as the characteristic bimodal rainfall distribution with primary peaks during December to February and secondary peaks during March to April remains clearly identifiable in all projections. The third pattern consists of station-specific trends: Kemayoran shows reduced peaks relative to its historical extremes after 2010; Halim indicates stabilization following a period of high intensity; and Tanjung Priok projections suggest attenuated but intact monsoon cycles.

Gradual Decline in Rainfall Intensity

All three stations exhibit a decreasing trend in monthly rainfall amounts over the projection period. Kemayoran Station shows the most pronounced decline, with projected monthly maxima decreasing from approximately 350–400 mm in the early 2020s to 300–350 mm by 2030. Halim Station, which experienced high intensity during 2012–2018 (peaks exceeding 800 mm), has stabilized and is now declining gradually. Tanjung Priok Station exhibits moderated rainfall intensity with preserved monsoon cycles but reduced peak magnitudes.

Persistence of Seasonal Monsoon Patterns

This is a key finding from the projection period. Despite declining rainfall intensity overall, the characteristic bimodal monsoon pattern remains clearly identifiable in all projections, with peak rainfall occurring during December through February, corresponding to the northeast monsoon, and a secondary peak during March through April. This persistence suggests that the fundamental dynamics of the monsoon system are preserved even as total rainfall volumes decrease over time. Maintenance of the bimodal structure implies that water managers can continue to rely on established seasonal timing for operational planning, such as scheduling reservoir releases, preparing drainage systems, and activating flood response protocols. However, reductions in peak magnitudes may alter the balance between runoff generation and groundwater recharge, potentially reducing flood risks during extreme events while diminishing dry-season water availability. The unchanged seasonal phasing also indicates that any climate-driven shifts in monsoon timing are not yet detectable within the forecast horizon, though longer-term projections may reveal them. From a flood risk perspective, the persistence of seasonal patterns combined with declining intensity suggests that hazard timing remains predictable even as hazard magnitude decreases.

Station-Specific Trends

Station-specific trends reveal distinct behavioral characteristics across the three rainfall monitoring locations in the Ciliwung watershed. Figure 3 indicates that Kemayoran Station, located in central Jakarta, exhibits lower monthly rainfall peaks than its historical extremes observed after 2010, suggesting a possible attenuation of the most intense events that previously affected this area. Halim Station, situated in southern Jakarta, shows stabilization after a period of notable high intensity between 2012 and 2018, with projections indicating that extreme peaks exceeding 800 millimeters are unlikely to recur at the same magnitude within the forecast horizon. Tanjung Priok Station, located in northern Jakarta near the Java Sea coast, exhibits moderate rainfall patterns with preserved but attenuated monsoon cycles, meaning the seasonal timing remains intact while the amplitude of wet-season peaks diminishes. These station-specific differences imply that the watershed does not respond uniformly to larger-scale climatic influences, and each sub-region may require tailored water management strategies. The northward gradient in projected changes, with southern Halim stabilizing and northern Tanjung Priok showing attenuation, further supports the study's finding of a northward shift in rainfall concentration over time. Understanding these distinct station-level trajectories is essential for targeting flood mitigation investments, as interventions can be prioritized for sub-basins expected to experience the most significant changes in rainfall characteristics.

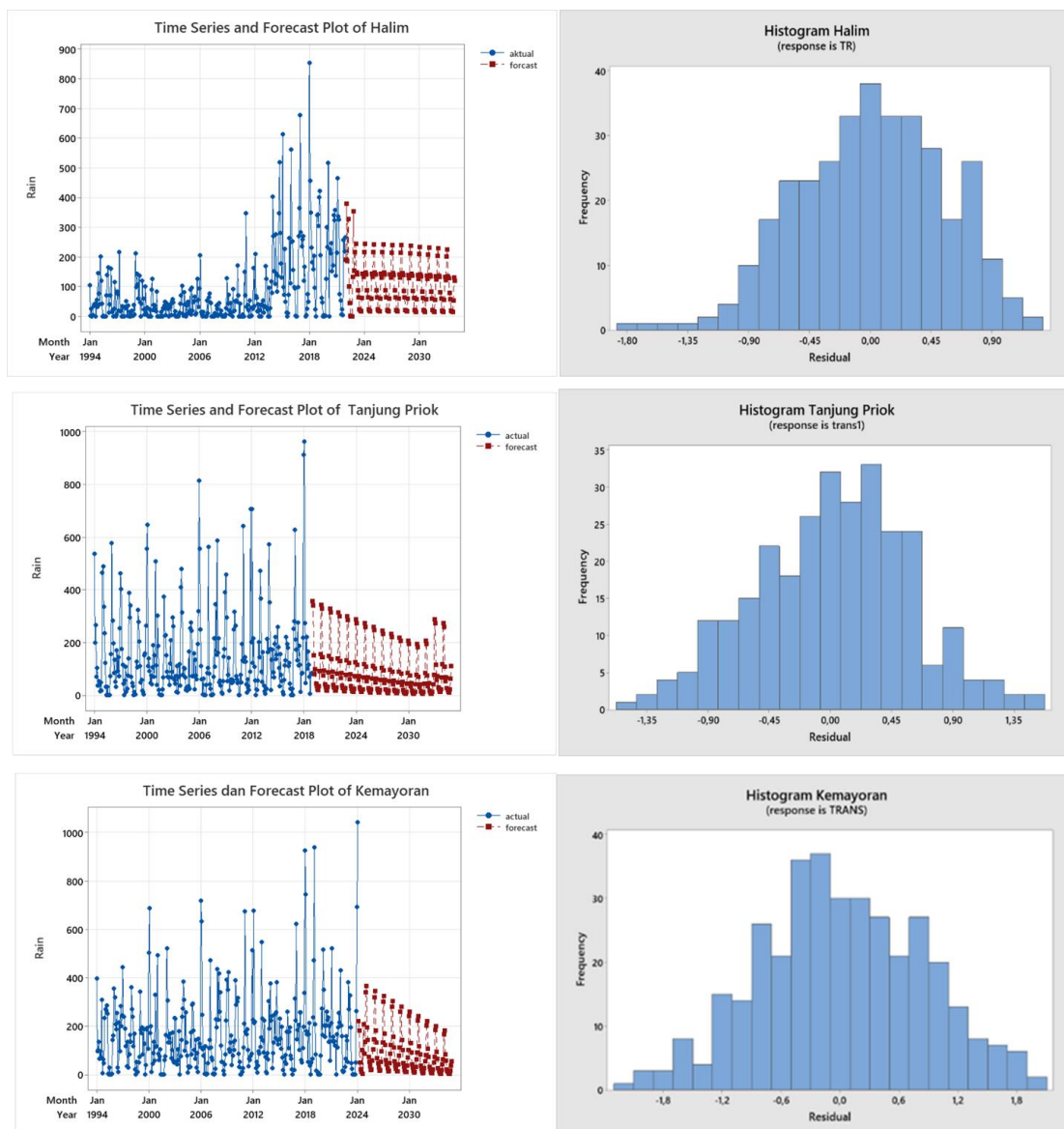


Figure 3. Presents the observed rainfall trends and forecast results for the period 1994–2030 at Kemayoran, Halim, and Tanjung Priok stations in the Ciliwung Watershed, Jakarta. The figure shows spatial variations in rainfall behavior, including changes in peak intensity, seasonal patterns, and long-term dynamics at each station.

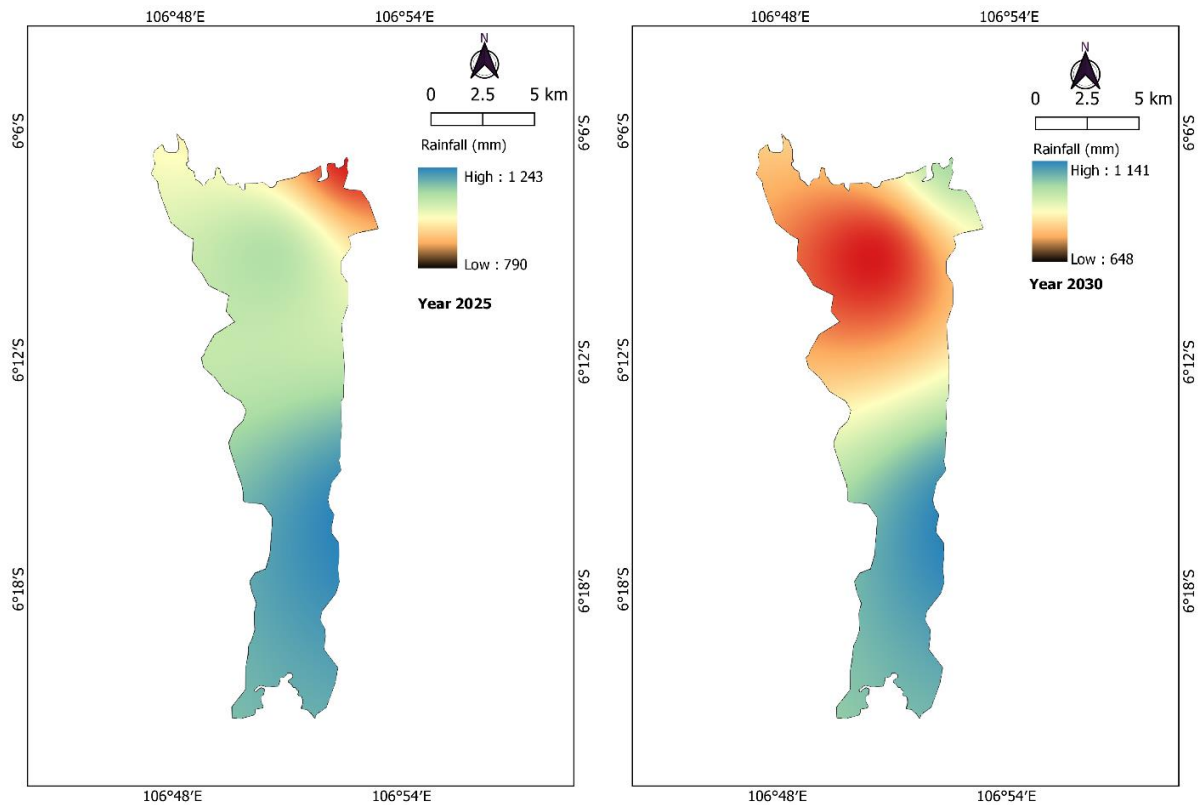


Figure 4. Presents the projected spatial distribution of rainfall in the Ciliwung Watershed for the 2025–2030 period. The figure illustrates spatial variability in rainfall intensity across the watershed, indicating potential changes in precipitation patterns over the projection period.

By 2030, the spatial distribution of rainfall shows a notable northward shift in rainfall concentration as illustrated in Figure 4. Areas experiencing the highest projected rainfall, defined as 300 millimeters per month or more during peak monsoon months, shift from southern Jakarta, which is primarily the Halim catchment area, toward central and northern Jakarta, encompassing the Kemayoran and Tanjung Priok catchment areas. This spatial redistribution suggests a potential change in the location of maximum runoff generation within the watershed, with implications for which drainage networks and flood-prone neighborhoods face the greatest future exposure. Northern Jakarta already faces severe land subsidence, with some areas sinking at rates of 10 to 20 centimeters per year due to groundwater extraction and urban loading, making this shift particularly concerning from a flood risk perspective. The convergence of increased rainfall in the north with ongoing subsidence creates a compound-hazard scenario in which the same rainfall event produces deeper and longer-lasting inundation than would occur in the absence of either factor. Drainage infrastructure originally designed to serve catchments in southern Jakarta may become less effective as the spatial focus of heavy rainfall migrates northward over time. Water managers should therefore consider recalibrating flood early warning systems and maintenance schedules to account for this changing spatial pattern of rainfall concentration.

Discussion

Interpretation of Rainfall Trends and Linkage with Recent Climate Change Literature

The projected decline in rainfall intensity across all three stations, coupled with a northward shift in rainfall concentration, represents a coherent pattern that must be interpreted within the context of recent climate change science and the study's methodological constraints. According to the Intergovernmental Panel on Climate Change Sixth Assessment Report, tropical rainfall regimes are undergoing substantial changes, though with significant regional heterogeneity that makes local projections challenging [10]. For Southeast Asia specifically, climate models project an increase in extreme precipitation intensity under warming

scenarios, but trends in seasonal and annual totals remain highly uncertain [11,12]. The projected decline in monthly rainfall intensity in this study does not necessarily contradict these broader projections, as climate models suggest that warming can simultaneously increase extreme sub-daily intensities while reducing or leaving unchanged monthly totals. This apparent paradox arises from changes in atmospheric circulation patterns, moisture convergence dynamics, and convective organization, which affect different temporal scales of rainfall in divergent ways [12]. Therefore, a decline in monthly totals as projected here could coexist with an increase in hourly extreme events that are most responsible for flash flooding in Jakarta's urban environment. The findings should be interpreted as indicative of near term trends under the assumption of historical stationarity, not as definitive predictions of future climate states.

Recent assessments by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) indicate that tropical rainfall regimes are undergoing substantial changes, though with significant regional heterogeneity [10]. For Southeast Asia, climate models project an increase in extreme precipitation intensity under warming scenarios, but trends in seasonal and annual totals remain uncertain [11,12]. The projected decline in monthly rainfall intensity in this study does not necessarily contradict these projections, as climate models suggest that warming can simultaneously increase extreme sub-daily intensities while reducing or leaving unchanged monthly total, a phenomenon related to changes in atmospheric circulation, moisture convergence, and convective organization [12].

Context for Jakarta's Rainfall Trends

Several recent studies provide context for Jakarta's rainfall trends. Lestari et al. [6] found that extreme rainfall in and around Jakarta shows strong seasonal dependence, with the greatest increases occurring during the wet season (December–February), a finding that aligns with this study's observation of preserved but potentially moderated seasonal peaks. Siswanto et al. [22] documented that urban extreme rainfall in Jakarta has increased as surface temperatures have risen, with the urban heat island effect intensifying convective activity; importantly, they found that extreme hourly intensities increased even as annual totals remained stable, highlighting that rainfall at different temporal scales may respond differently to warming. Lubis et al. [4] linked the January 2020 extreme rainfall event to the combined effects of northerly surge, equatorial waves, and the Madden-Julian Oscillation (MJO), demonstrating that Jakarta's rainfall extremes are influenced by multiple-scale atmospheric processes that climate change may modify.

Maheng et al. [1] reported that Jakarta's rainfall patterns exhibit significant interannual variability linked to ENSO and IOD phases, with La Niña years typically associated with above-normal rainfall. Consequently, the declining trend in this study's projections may in part reflect decadal variability rather than a monotonic climate change signal, underscoring the need for cautious interpretation. The consistency of seasonal monsoon patterns despite declining total volume [23,24] suggests that the fundamental dynamics of the monsoon system remain intact, but its intensity may be modulated by a combination of global warming, land-use change, and natural variability. This interpretation is consistent with recent findings that tropical monsoon rainfall responds nonlinearly to warming, with some regions experiencing reduced seasonal totals while others experience increases [10].

Possible Drivers

While formal attribution is beyond this study's scope, the observed trends could be driven by several interacting factors. Regional circulation changes affecting monsoon moisture transport [23,24] and urbanization-induced alterations, including urban heat island effects that can suppress rainfall under certain conditions [22,25], may both play a role. Additionally, decadal climate variability (ENSO, IOD) [2] and aerosol effects on cloud microphysics, which remain poorly constrained in tropical regions [5], represent additional potential drivers. The relative contributions of these factors cannot be determined from the available data, and their interactions may be nonlinear.

Northward Shift Implications for Flood Mitigation

The projected northward shift in rainfall concentration has critical and spatially differentiated implications for Jakarta's flood mitigation strategies. Northern Jakarta is already experiencing land subsidence of up to 10–20 cm/year due to excessive groundwater extraction and urban loading [22,25]. This subsidence reduces the hydraulic capacity of drainage canals, increases tidal flood penetration inland, and exacerbates inundation duration. A northward shift in rainfall effectively relocates runoff generation toward areas where drainage systems are already under stress. The interaction between increased rainfall in the north and ongoing subsidence creates a compound hazard: the same rainfall event produces deeper and longer-lasting inundation than in areas without subsidence [26].

Based on these findings, differentiated flood mitigation measures are recommended for three distinct zones within the watershed. First, in the Northern Zone (Tanjung Priok, Penjaringan, Cilincing, Kelapa Gading), the primary risk stems from the convergence of increased rainfall intensity, existing land subsidence, and tidal flooding. The priority actions include deepening primary drainage canals by an additional 0.5–1.0 m above current design standards [22,25], upgrading pumping stations with additional capacity (minimum 20% above current), installing or maintaining tidal gates at drainage outfalls to prevent tidal backflow [26], and developing zone-specific flood forecasts that integrate rainfall projections, subsidence maps, and tidal predictions. Second, for the Central Zone (Central Jakarta, Gambir, Sawah Besar), where high population density and aging drainage infrastructure present the primary challenges. The recommended actions include retrofitting low-impact development (LID) measures such as permeable pavements, rain gardens, and green roofs [27], implementing real-time monitoring of canal water levels, and prioritizing desilting before each wet season. Third, for the Southern Zone (South Jakarta, upstream Ciliwung), where reduced groundwater recharge and potential water scarcity are the primary concerns. The priority actions include mandating rainwater harvesting for new buildings exceeding 500 m² [2], implementing managed aquifer recharge projects in suitable locations, and strengthening groundwater extraction regulations [28].

Comparison with Published Rainfall Studies in Jakarta and Tropical Cities

The predictive accuracy achieved in this study (MAPE: 7.9–8.4%) compares favorably with other SARIMA-based rainfall forecasts in tropical urban settings. For instance, Munir et al. [9] applied a SARIMA(1,0,1)(1,0,1)₁₂ model in Yogyakarta using only two stations and achieved MAPE values of 9.2–11.5%, while Mahmudi et al. [27] employed a hybrid ARIMAX-ANN approach across five stations in Jakarta and reported MAPE values ranging from 6.8% to 9.3%, indicating that hybrid models can marginally improve predictive accuracy over SARIMA alone. In Bandung, Agata [29] achieved an 8.9% MAPE for Bandung using a ARIMA(1,0,0)(2,0,0)₁₂ model with stationarity. Beyond forecasting accuracy, Siswanto [25] analyzed trends using eight stations in Jakarta and documented increasing extreme hourly events, and Lestari et al. [6] examined the seasonal dependence of extremes across twelve stations. The MAPE values in this study fall within the lower range of published results and are the lowest among SARIMA-only models, indicating that the SARIMA(0,1,1)(0,1,1)₁₂ specification performs well despite using only three stations with heterogeneous record lengths. Importantly, the northward shift in rainfall concentration identified in this study has not been previously documented in Jakarta's rainfall literature, providing a novel finding that warrants further investigation using denser station networks and longer historical records.

Why SARIMA May Fail Under Abrupt Climate Shifts?

SARIMA models, like all statistical time series models, assume that future patterns will resemble historical patterns. Specifically, they require that the autocorrelation structure remain stationary [30,31]. This assumption may fail under several scenarios relevant to climate change adaptation planning. First, abrupt climate shifts, such as a sudden change in monsoon timing, intensity, or spatial footprint (e.g., a rapid southward or northward shift in the monsoon trough), would not be anticipated by SARIMA, as the model has no mechanism to incorporate such regime changes. Second, non-stationary external drivers, including rising greenhouse gas concentrations, land cover change, and changing aerosol emissions, cannot be incorporated as predictors in SARIMA models. If these drivers fundamentally alter rainfall-generating processes, historical patterns become poor guides to future behavior. Third, climate tipping points in the tropical hydrological cycle, such as a permanent shift in the Walker circulation or a collapse of the Atlantic Meridional Overturning Circulation affecting tropical rainfall, would render historical patterns irrelevant for forecasting [10]. Given these limitations, users of these projections are advised to limit forecast application to near-term planning horizons (5 to 10 years), where the stationarity assumption is most plausible; to complement SARIMA forecasts with scenario-based approaches from dynamical climate models (such as CMIP6 projections) for longer term planning; to monitor forecast errors over time and recalibrate models as new observations become available; and to treat spatial projections as exploratory rather than deterministic, using them to inform scenario planning rather than precise engineering design.

Methodological Contributions and Limitations

This study demonstrates that integrating SARIMA forecasting with GIS based interpolation can yield actionable rainfall projections despite data constraints, including heterogeneous record lengths and a sparse monitoring network of only three stations. The model's strong predictive accuracy, with MAPE values below 10 percent across all stations, confirms the suitability of the SARIMA(0,1,1)(0,1,1)₁₂ specification for capturing Jakarta's rainfall dynamics [7,8]. Achieving such accuracy with a parsimonious model is particularly valuable

in data limited settings where more complex approaches, such as hybrid machine learning models or dynamical downscaling, may require longer training periods or computational resources that are not readily available. The successful integration of temporal forecasting with spatial interpolation provides a template that can be adapted to other rapidly urbanizing tropical cities facing similar hydroclimatic uncertainties and observational constraints. However, the demonstrated utility of this approach should not be misinterpreted as an endorsement of SARIMA as universally superior to alternative methods; rather, the choice of SARIMA here was justified by the specific data characteristics and study objectives. Future applications in regions with denser station networks or longer historical records may benefit from exploring seasonal ARIMAX models that incorporate climate indices such as ENSO or IOD as exogenous predictors.

However, several limitations should inform interpretation and future research: First, the station density and distribution: The use of only three stations, while constrained by data availability, limits the granularity of spatial interpolation and may not fully capture rainfall heterogeneity across the 382.6 km² watershed [32,33]. This is partially mitigated by the relatively flat topography of the study area, which reduces the influence of topography on rainfall distribution. Second, the interpolation method: IDW was selected for computational efficiency and suitability for moderate station density in flat terrain [34,35]. However, this method does not account for elevation or land cover effects, which could be addressed in future studies using kriging or co-kriging approaches [36,37]. Third, the data record heterogeneity: The varying record lengths (Kemayoran: 1990–2020; Halim: 1990–2018; Tanjung Priok: 1990–2015) introduce uncertainty in long-term trend homogeneity. Model calibration on overlapping periods mitigated this to some extent, but uniform datasets would strengthen future analyses [33,38]. Fourth, the attribution: This study models and projects rainfall patterns but does not attribute observed trends to specific drivers (e.g., climate change vs. urbanization). Future work should incorporate climate indices (e.g., ENSO) and land-use change data to address attribution questions [28,39]. Fifth, the validation assumptions: Validation tests assume that the historical period (1990–2015/2020) is representative of future conditions—an assumption that may be violated under accelerating climate change [10].

Policy and Management Recommendations

The findings support three priority actions for Jakarta's water managers. First, drainage design standards in north central Jakarta should be re-evaluated to accommodate potential increases in localized rainfall, drawing on extreme event analyses from previous studies [4,5,26]. Second, investment in water-harvesting infrastructure in southern Jakarta is recommended to offset projected declines in groundwater recharge, which may otherwise exacerbate dry-season water scarcity [23,24]. Third, spatial rainfall projections should be integrated into flood early warning systems to improve forecast accuracy and enhance community preparedness for imminent flood events [9]. These recommendations are grounded directly in the study's projected rainfall trends and spatial redistribution patterns, providing an evidence-based foundation for targeted intervention. The proposed actions also align with broader calls for evidence-based climate adaptation in urban Indonesia, as articulated in recent policy-oriented research [28,34]. Collectively, these priority actions address the north-south gradient of projected changes, with northern interventions focused on drainage and flooding, while southern interventions emphasize water conservation and recharge.

Conclusion

This study integrates SARIMA time series modeling and GIS spatial interpolation methods and applies them to Jakarta's Ciliwung River Basin to simulate historical rainfall patterns and predict future rainfall distribution. The SARIMA(0,1,1)(0,1,1)₁₂ model used in this study fits the monthly rainfall data of three stations, namely Kemayoran, Halim, and Tanjung Priok, with an MAPE lower than 10%, indicating sound prediction accuracy. This study draws two core findings based on rainfall projection data for Jakarta through 2030: rainfall intensity is gradually declining at all monitoring stations across the city, while the seasonal monsoon pattern remains largely stable; concurrently, rainfall concentration is continuously shifting from the southern part of the city to its central and northern regions. Based on these findings, it can be inferred that Jakarta's flood risk will be redistributed, requiring the implementation of differentiated water management measures: the northern region should upgrade its drainage infrastructure, the southern region should advance water resource conservation, and higher-resolution rainfall projections should be integrated into the city's early warning system to support urban climate adaptation planning. This study validates a research method that integrates the SARIMA forecasting model with GIS spatial analysis. This method can generate actionable and implementable decision-making insights to support urban watershed management and is replicable for

rapidly urbanizing tropical cities facing similar hydroclimatic uncertainties. We propose four optimization directions, including the incorporation of longer-period unified datasets, to improve the reliability of rainfall forecasting and support urban climate risk assessment.

Author Contributions

MM: Conceptualization, Methodology, Investigation Data, Formal Analysis, Writing, Original Draft; **BB:** Review & Editing; **AS:** Methodology, Supervision, Data Curation, Writing - Review & Editing; **BPN:** Conceptualization, Methodology, Software, Investigation, Formal Analysis.

AI Writing Statement

During the preparation phase of this study, the authors of this paper only used ChatGPT, QuilBot, and DeepL to complete a small amount of proofreading, paraphrasing, and translation work. The authors subsequently carried out a retrospective full-text revision of the manuscript, assumed full responsibility for all content in this publication, and this disclosure aligns with the AI disclosure specifications of mainstream science and technology journals.

Conflict of Interest

The authors declare no conflict of interest.

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