

Research article

Assessing the Association between ENSO, IOD, and Streamflow Variability in the Lower Batanghari River Basin, Sumatra, Indonesia

Linda Handayani^{1,2}, Munajat Nursaputra^{1,3}, Rustan^{2,4}, Nanang T. Puspito⁵, Rusmawan Suwarman^{6,*}

¹ Doctoral Program in Earth Science, Faculty of Earth Science and Technology, Institut Teknologi Bandung, Jalan Ganesa No. 10, Bandung, 40132, West Java, Indonesia; ² Physics Study Program, Faculty of Science and Technology, University of Jambi, Jalan Jambi - Ma Bulian KM. 15 Muaro Jambi, 36361, Provinsi Jambi, Indonesia; ³ Laboratory of Forestry Planning and Information System, Faculty of Forestry, Hasanuddin University, Jl. Perintis Kemerdekaan Km. 10, Tamalanrea, Makassar, 90245, South Sulawesi, Indonesia; ⁴ Doctoral Program in Physics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesa No. 10, Bandung, 40132, West Java, Indonesia; ⁵ Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa No. 10, Bandung, 40132, West Java, Indonesia; ⁶ Atmospheric Sciences Research Group, Faculty of Earth Science and Technology, Institut Teknologi Bandung, Jalan Ganesa No. 10, Bandung, 40132, West Java, Indonesia.

*Correspondence: rusmawan@itb.ac.id

Citation:

Handayani, L., Nursaputra, M., Rustan, R., Puspito, N.T., Suwarman, R. (2026). Assessing the Association of ENSO, IOD, and Streamflow Variability in the Lower Batanghari River Basin, Sumatra, Indonesia. *Forum Geografi*. 41(1), 145-167.

Article history:

Received: 16 April 2026
Revised: 27 September 2026
Accepted: 27 September 2026
Published: 29 September 2026

Abstract

This study examines the relationship between the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and seasonal streamflow variability. Streamflow was simulated using the Soil and Water Assessment Tool Plus (SWAT+) during two specific land-use periods (2000 and 2023), integrating topographic, soil, land-use and climate data, and evaluated at three lower stations: Muara Kilis, Sungai Duren and Simpang Berbak. Pearson and partial correlation analyses were used to assess antecedent June–July–August (JJA) and concurrent September–October–November (SON) climate conditions against September–November (SON) streamflow. Both ENSO and IOD showed consistently negative relationships with SON streamflow. The results reveal distinct seasonal patterns: JJA conditions showed clearer ENSO–streamflow relationships, whereas during SON, the IOD–streamflow relationships became more pronounced, with correlation reaching -0.64 at Muara Kilis. Partial correlation showed that the associations remained significant after accounting for the other climate index, although their magnitudes varied in the JJA–SON and SON–SON relationships. These findings demonstrate seasonal and spatial variability in climate–streamflow relationships across the lower Batanghari River Basin.

Keywords: Batanghari; ENSO; IOD; streamflow

1. Introduction

Global climate variability is one of the primary factors controlling water availability patterns and hydrological dynamics worldwide, particularly in tropical regions that are highly sensitive to changes in atmospheric and oceanic circulation (Caretta *et al.*, 2023). Climate variability refers to the natural fluctuations of the climate system over time, driven by large scale processes such as the El Niño Southern Oscillation (ENSO) and IOD (Norel *et al.*, 2021). Within the hydrological system, streamflow represents a key component that reflects the integrated response of atmospheric processes, surface characteristics, and the biophysical conditions of a river (Chen *et al.*, 2019; Depetris, 2021). Variations in streamflow are associated with both large-scale climate variability and anthropogenic activities, ultimately affecting water availability and even triggering hydrometeorological hazards (J. Gao *et al.*, 2025; H. Wang *et al.*, 2024).

Over the past decades, numerous studies have demonstrated that global climate phenomena such as ENSO are closely associated with hydrological variability through their relationship with atmospheric circulation and precipitation patterns. ENSO consists of two primary phases: El Niño, which is associated with anomalous warming of the sea surface temperature (SST) in the eastern Pacific and is typically linked to drier conditions in Indonesia; and La Niña, which is associated with enhanced rainfall (Iskandar *et al.*, 2019; Kurniadi *et al.*, 2021; Suwarman *et al.*, 2017). At the global scale, ENSO has been shown to generate distinct runoff anomalies across major river basins worldwide (You *et al.*, 2021). At the basin scale, streamflow variability has also been closely associated with seasonal rainfall dynamics and monsoonal systems (Shelton & Lin, 2019).

On the other hand, the Indian Ocean Dipole (IOD) develops over the Indian Ocean and represents the sea surface temperature gradient between its western and eastern regions. The positive phase of IOD is often associated with drier conditions in western Indonesia, whereas the negative phase is linked to increased rainfall (Permatasari *et al.*, 2022; Putri Maulida *et al.*, 2025). The interaction between ENSO and IOD (climate mode coupling) can amplify or dampen climate anomalies; for instance, the co-occurrence of El Niño and a positive IOD can lead to more severe hydrological drought conditions (Mulsandi *et al.*, 2024; Xiao *et al.*, 2022). Recent studies indicate that the



Copyright: © 2027 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

combined occurrence of ENSO and IOD may produce more complex hydrological responses compared to the influence of each phenomenon individually (Jia *et al.*, 2023).

Despite extensive research on the relationships between ENSO, IOD and precipitation, understanding of the association between these two climate modes and streamflow variability remains incomplete, particularly in tropical regions. Most previous studies have focused primarily on precipitation or have analyzed ENSO-related relationships independently, resulting in limited exploration of the integrated hydrological response represented by streamflow (Jia *et al.*, 2023; Sinaga *et al.*, 2022; You *et al.*, 2021).

Given that Indonesia is located between the Pacific and Indian Oceans, rainfall patterns and geohydrodynamic conditions across the region are closely linked to ENSO and IOD variability (Hanifa & Wiratmo, 2024; Kurniadi *et al.*, 2021; Mulsandi *et al.*, 2024). This mechanism operates through changes in the Walker circulation, which modulates convection over the Indonesian maritime continent. In the Indonesian context, the Batanghari River Basin represents one of the largest and most important river systems in Sumatra. The river serves as a primary source of water for domestic use, agricultural irrigation, hydropower generation, transportation and the sustainability of wetland and peat-swamp ecosystems. The basin's complex characteristics, including variations in topography, geology and land use, strongly influence hydrological processes such as runoff generation and infiltration (Aswandi *et al.*, 2023).

Numerous studies of the Batanghari River Basin have shown that the system is highly vulnerable to changes in land use and climate. Land cover changes characterized by deforestation and agricultural expansion have been associated with higher surface runoff and sediment loads, with potential implications for floods and droughts (Ridwansyah *et al.*, 2023). In addition, hydrological modelling studies have demonstrated that climate change may increase the frequency and extent of flooding, particularly in the downstream areas of the basin (Yamamoto *et al.*, 2021). Other studies have also indicated an increasing trend in extreme rainfall events, which is strongly correlated with rising flood occurrences in the region (Handoko *et al.*, 2023; Nursaputra *et al.*, 2026).

Nevertheless, most previous studies have primarily focused on the relationships between land use change and climate change in general, with ones explicitly linking large scale climate variability such as ENSO and IOD to hydrological responses in terms of streamflow variability in the Batanghari River Basin remaining very limited. Furthermore, most studies have not considered the downstream region as an integrator of overall watershed processes, which in fact represent the accumulated response to climate variability and environmental changes.

Therefore, this study analyzes and evaluates the relationship between ENSO, IOD and monthly streamflow variability in the lower Batanghari River Basin during the period 1993–2023. To achieve this objective, a semi-distributed hydrological modelling approach using the Soil and Water Assessment Tool (SWAT+) was employed, as this is able to represent the complex interactions between topography, land use, soil properties and climatic factors. By integrating multi-decadal geospatial and climatological datasets, the study aims to accurately simulate monthly streamflow dynamics and examine the relationship between climate variability, represented by ENSO and IOD indices, and streamflow variability at the river outlet (Marhaento *et al.*, 2018; Semlali *et al.*, 2017; Shabir *et al.*, 2025). The results are expected to provide scientific contributions toward understanding the link between global climate teleconnections and hydrological responses in tropical regions, as well as supporting water resource management and hydrometeorological disaster risk mitigation in Jambi Province.

2. Methods

2.1. Study Area and Analytical Design

The study area was the Batanghari River Basin in Jambi Province, Indonesia, as shown in Figure 1. The basin is located between S 01°15'00" to S 02°02'00" and E 102°30'00" to E 104°30'00". Its topography ranges from flat and gently sloping lowlands to undulating, hilly and mountainous terrain. The topographic characteristics were derived from a digital elevation model (DEM). Based on this, elevations below 200 m above sea level occupy approximately 65.39% of the basin area, whereas slopes of 0–8% account for approximately 77.33%. The upper Batanghari catchment functions as a headwater area, with predominantly steep and very steep terrain, whereas the downstream region is characterised by a narrower sub-basin and predominantly flat topography.

These heterogeneous geological formations give rise to a diverse set of soils within the basin. Geologically, it is underlain by young alluvial deposits and the Palembang Formation (lower–middle–upper members). The dominant soil type is Dystrypepts (42%), followed by Tropudults (25%) and Tropaquepts (5.5%), with generally fine to moderately fine textures that are highly

susceptible to erosion. The Schmidt–Ferguson climate classification designates the basin as an Am (wet) climatic type, characterized by an average annual precipitation of approximately 2,500 mm and a mean temperature of 26 °C. The precipitation pattern adheres to an equatorial monsoon model, characterized by a primary rainy season in November and December and a comparatively arid interval from June to August (Aswandi *et al.*, 2023).

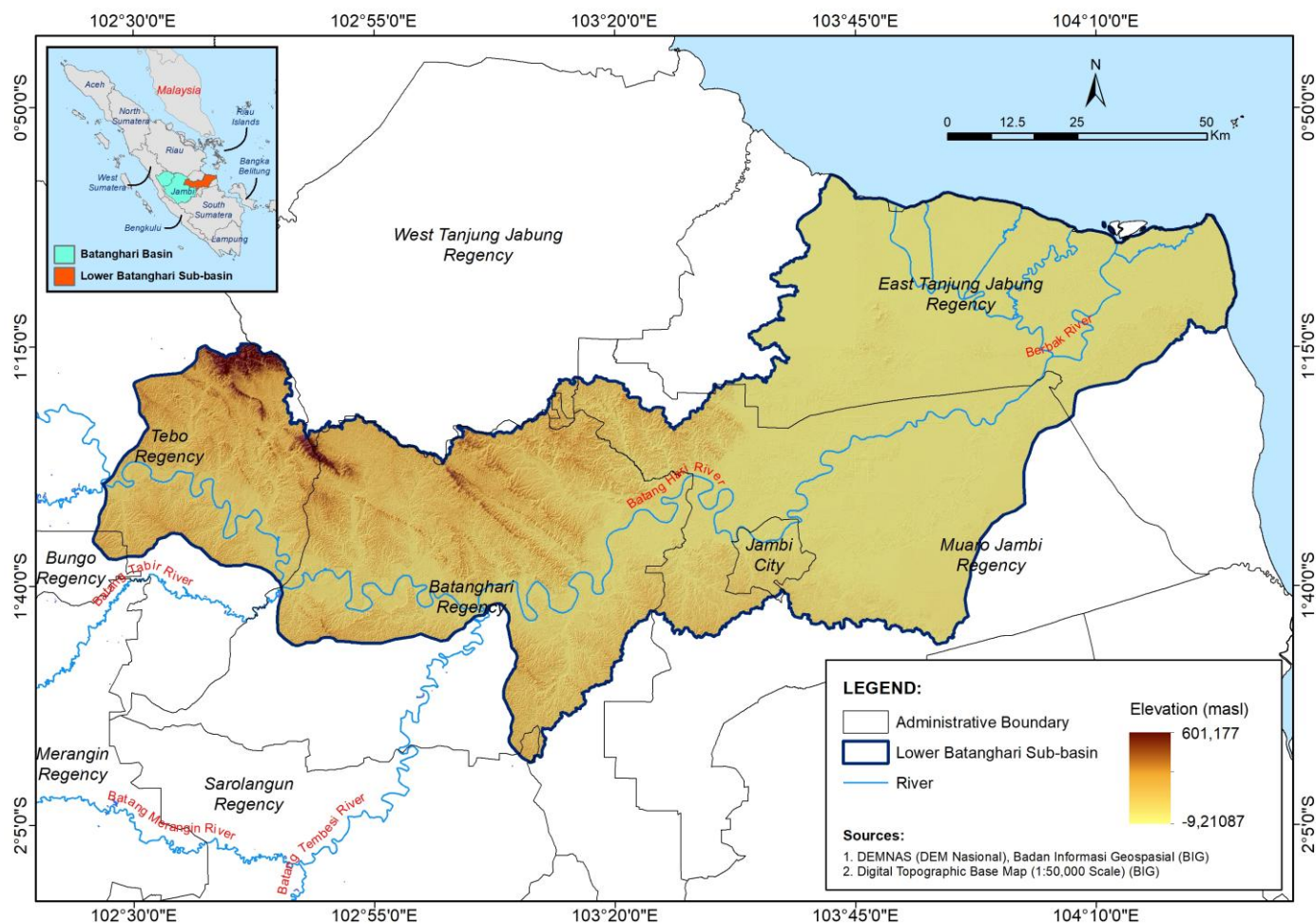


Figure 1. Study area: Batanghari River Basin, Sumatra Island, Indonesia (Source: BPDAS Batanghari Jambi, 2024)

The Batanghari River Basin, covering approximately 4.44 million hectares, consists of five major sub-basins: (1) Upper Batanghari, (2) Batang Tebo, (3) Batang Merangin–Tembesi, (4) Batang Tabir, and (5) Lower Batanghari. Batang Tebo, Batang Merangin–Tembesi and Batang Tabir are sometimes collectively represented as the Middle Batanghari sub-basin (KemenPUPR, 2021). Each sub-basin exhibits distinct physiographic characteristics and land-use conditions, which may contribute to differences in hydrological responses associated with climate variability. To examine streamflow variability at different locations within the lower part of the basin, river streamflow analysis was conducted at three gauging stations: Muara Kilis, Sungai Duren and Simpang Berbak. These stations were selected based on their locations along the lower Batanghari River, which encompass different lower settings. Muara Kilis is located in the lower zone, but near to the transition from the middle basin, whereas Sungai Duren functions as a transitional area towards the coastal region. Simpang Berbak represents the lowest downstream point approaching the coast. Differences in soil types between these sites provide a scientific basis for assessing how land surface characteristics association the hydrological responses.

The hydrological analysis was designed to characterize streamflow variability across the Batanghari River Basin over the 1993–2023 period. Two specific LULC datasets were incorporated into the SWAT+ modelling framework to generate streamflow simulations for the corresponding periods. After model calibration, the simulations were used to construct a continuous streamflow series for the period. The resulting streamflow series was then analyzed in relation to rainfall variability, extreme events, seasonal characteristics, and climate variability.

The overall sequence of data preparation, watershed delineation, HRU definition, SWAT+ simulation, calibration and subsequent streamflow analysis is presented in Figure 2.

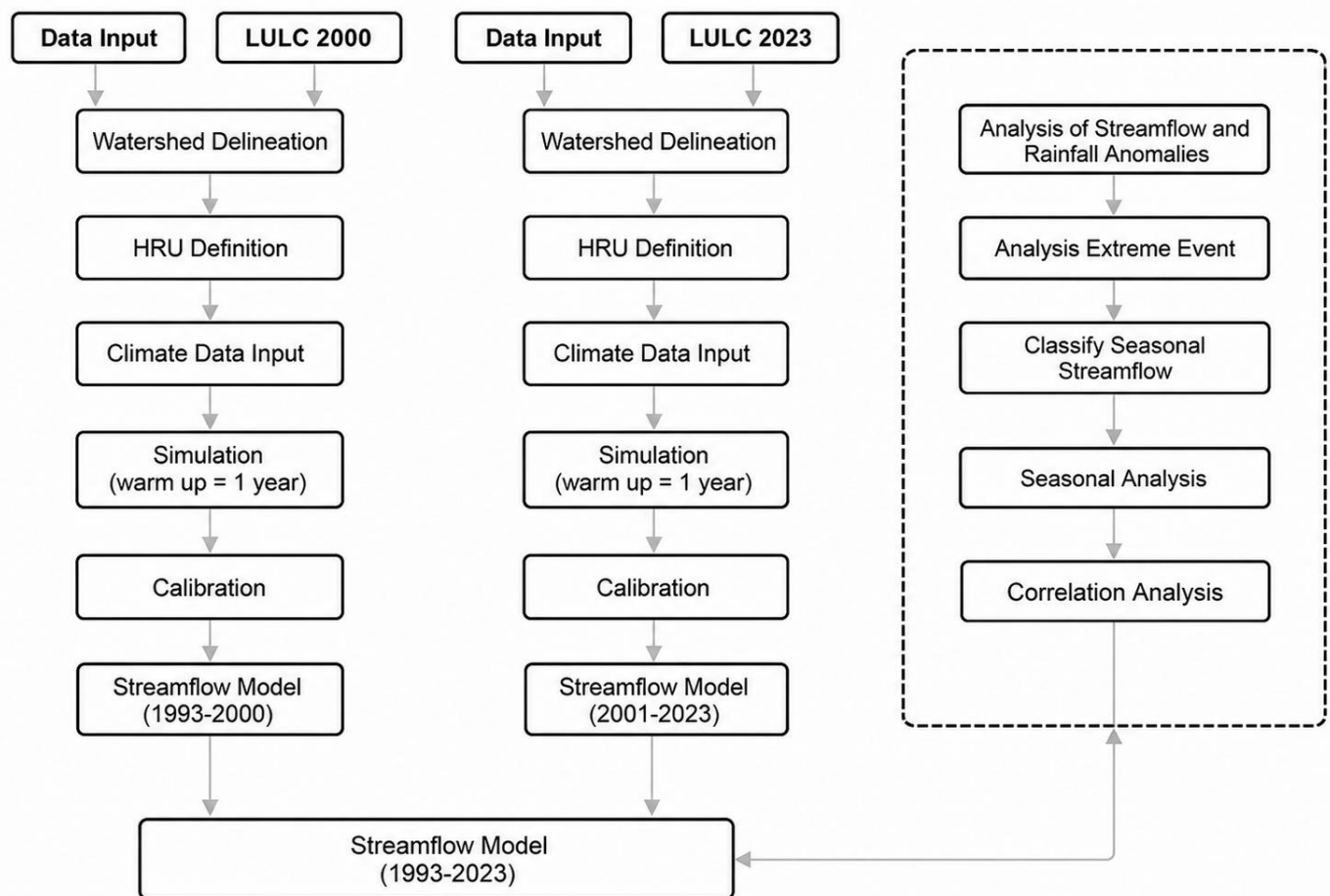


Figure 2. Analytical workflow of SWAT+ modelling and streamflow analysis in the Batanghari River Basin.

2.2. Data

The research integrates various geospatial and hydroclimatic datasets to support hydrological modeling of the Batanghari River Basin, as summarized in Table 1. Digital elevation model (DEM) data were sourced from DEMNAS, which offers a nationwide elevation product with an 8 m resolution (Iswari & Anggraini, 2018). DEM-derived layers were utilized to outline the watershed, extract slopes and flow directions, and characterize basin topography from alpine headwaters to lowland swamp regions (Aswandi *et al.*, 2023).

Land use and land cover (LULC) data were obtained from the nationally produced Landsat-based land-cover maps (30 m) (2023) and LULC 2000. The LULC map was officially issued by the Ministry of Environment and Forestry (KLHK). Figures 3 and 4 show two land use and land cover (LULC) snapshots (2000 and 2023) that were utilized as static inputs for SWAT+ to represent the periods 1993–2000 (LULC-2000) and 2001–2023 (LULC-2023). The temporal evolution of LULC composition from 2000 to 2023 (Figure 5) shows a significant decline in forest cover, accompanied by increases in secondary forest, oil palm plantation, orchard, rice field, rangeland, and urban areas, while agricultural land and wetland areas decreased. These changes indicate a progressive transformation of the river basin. Although the use of the 2023 LULC map as a static representation for the 2001–2023 simulation period may introduce uncertainty, an additional simulation using the intermediate land use representation (LULC 2011) was conducted to examine the robustness of simulated streamflow to the land-use assumption. The simulation using LULC 2011 produced streamflow results that were broadly comparable to those obtained using LULC 2023. This indicates that the simulated streamflow was relatively insensitive to the tested LULC representation, providing support for the use of the 2023 LULC map as a reasonable static representation for the long-term simulation.

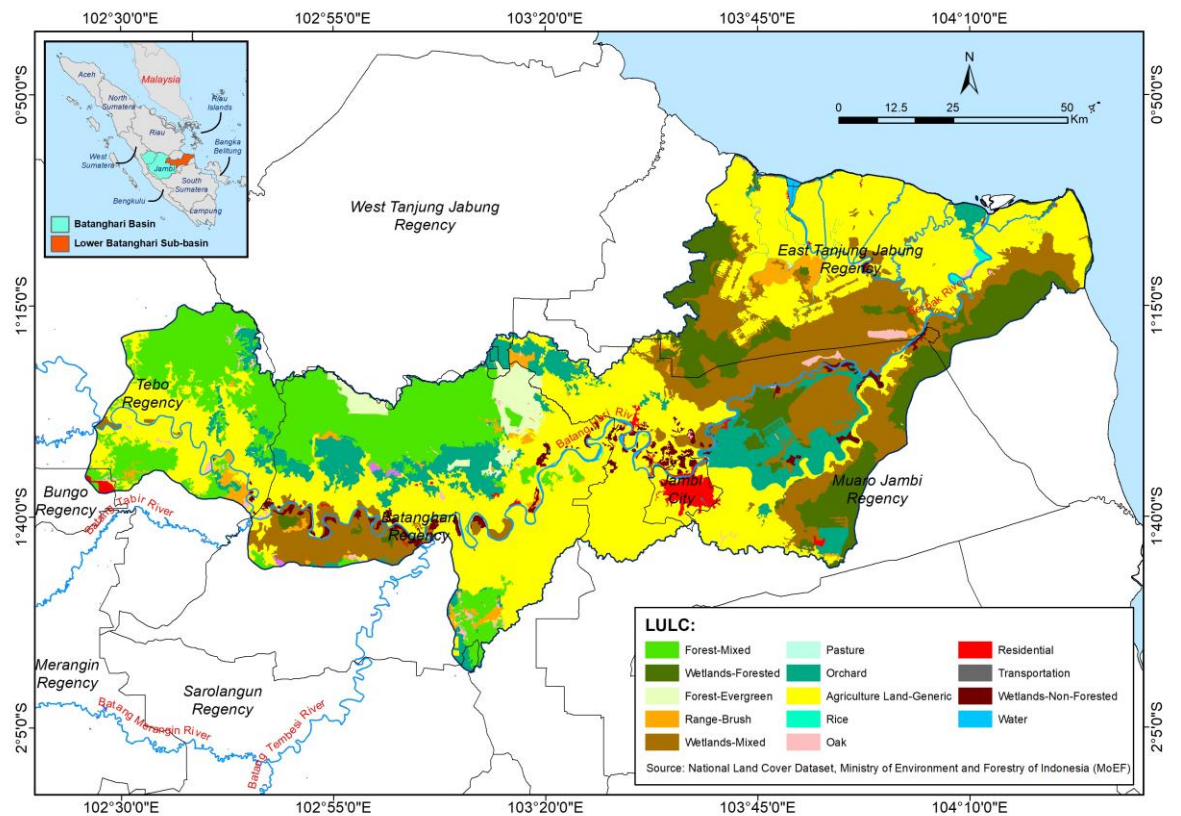


Figure 3. Landuse and Landcover (LULC) of the Batanghari River Basin 2000 (Source: Ministry of Environment and Forestry, 2000)

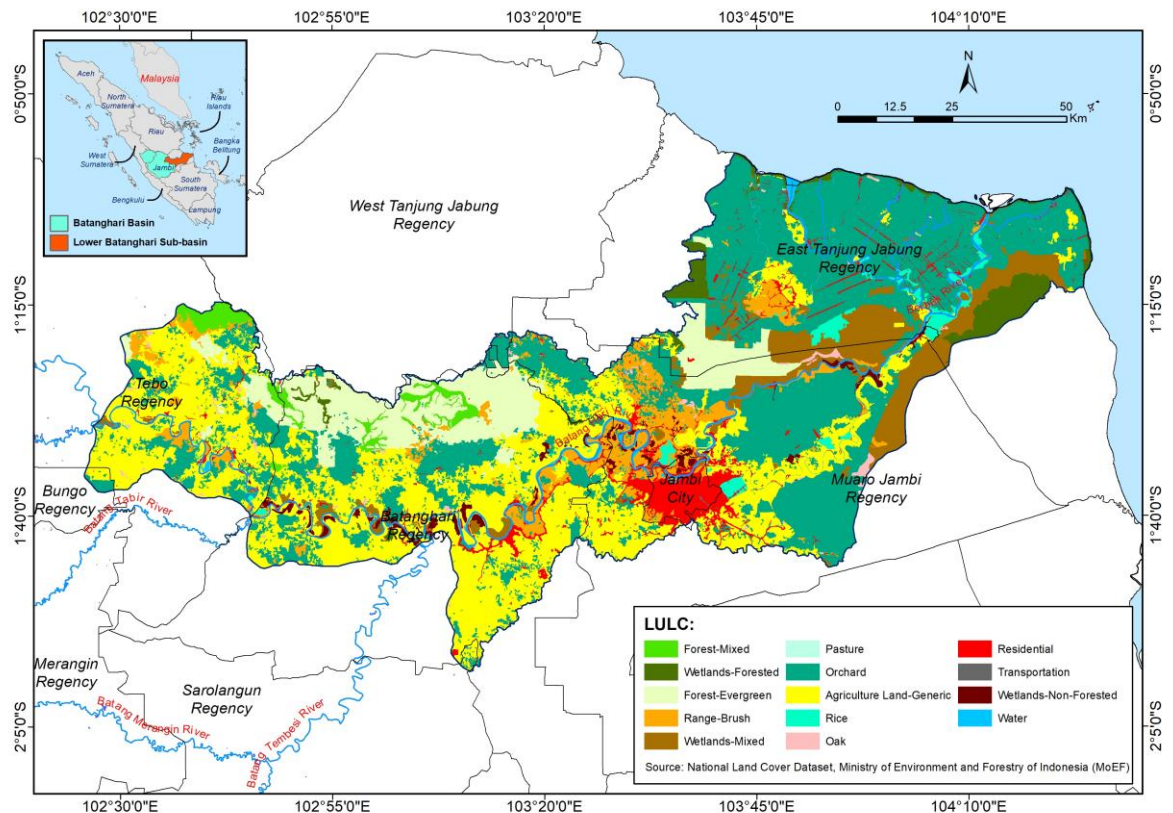


Figure 4. Landuse and Landcover (LULC) of the Batanghari River Basin 2023 (Source: Landsat Image Interpretation)

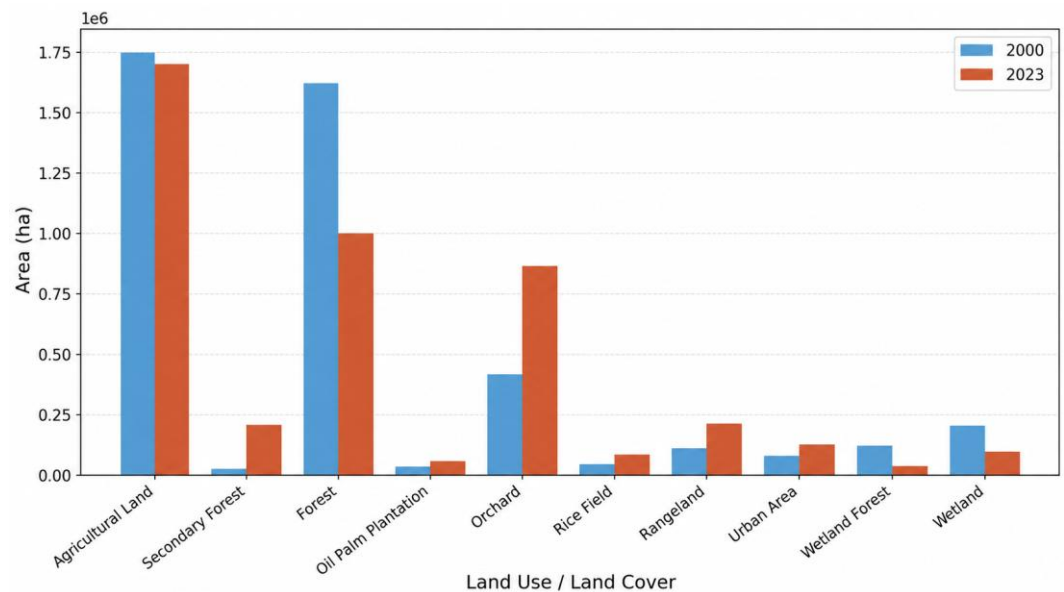


Figure 5. Temporal LULC dynamics: forest decline and land use intensification (Processed from SWAT+ simulation results)

Soil data were obtained from the FAO/UNESCO Digital Soil Map of the World (DSMW), which delineates a mosaic of Acrisols, Ferralsols, Andosols, Histosols, Gleysols and Vertisols within the basin (Schad, 2023), as shown in Figure 6. Soil type data are crucial in SWAT+ because they affect infiltration, percolation, erosion, soil moisture and the reliability of streamflow and water quality predictions (Busico *et al.*, 2020; Lei *et al.*, 2024; Oruç *et al.*, 2023). Climate forcing was sourced from NASA POWER, while daily precipitation data were obtained from CHIRPS, with subsequent bias corrected using a random forest methodology to enhance the depiction of spatial rainfall patterns and extremes. This process was performed by adjusting satellite-based precipitation estimates using observations from the nearest rainfall stations, thereby reducing systematic bias and improving model reliability.

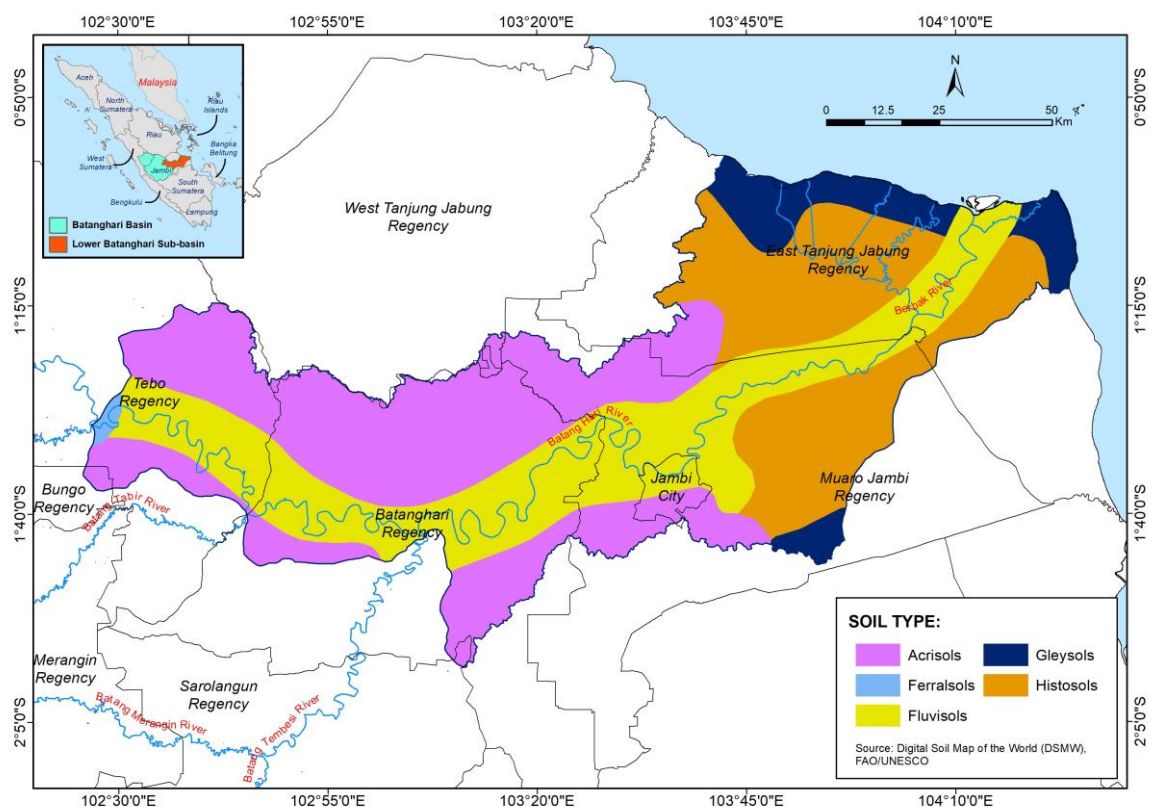


Figure 6. Soil types in the Batanghari River basin (Source: FAO Digital Soil Map of the World, 1976)

Table 1. Datasets, spatial temporal resolutions and data providers employed in the study

No	Parameter	Product	Resolution	Source
1	Basemap	Rupa Bumi Indonesia (RBI)	1:50000	Indonesian Geospatial Information Agency (BIG)
2	Elevation	DEMNAS	8 m (resampled 30 × 30 m)	Indonesian Geospatial Information Agency (BIG)
3	Landuse	Landsat Imagery	30 m	The Ministry of Environment and Forestry
4	Soil Type	Digital Soil Map of the World (DSMW)	1:5000000 (2.5 km/px)	FAO
5	Climate Data	NASA POWER	0.5°/px	NASA
6	Streamflow Data	Automatic Water Level Recorder (AWLR)	Daily	Ministry of Public Works and Housing, Indonesia
7	Rainfall Data	CHIRPS	Daily	UCSB/CHG
8	ENSO Index	El Niño 3.4 SST Anomaly	Monthly	NOAA USA (ERSSTv5)
9	IOD Index	Dipole Mode Index (DMI)	Monthly	NOAA USA (ERSSTv5)

2.3. Data Analysis

The hydrological response of the Batanghari River Basin was evaluated through a structured modeling analysis framework consisting of four main stages: (1) preprocessing and model set-up; (2) hydrological simulation using SWAT+; (3) sensitivity analysis, parameterization and calibration against observed streamflow using SWAT+ Toolbox; and (4) vValidation was using the calibrated parameter set exported from SWAT+ Toolbox to the SWAT+ model and rerunning of the simulations. This workflow followed a standard SWAT+ modelling procedure to represent watershed processes under varying land-surface and climate conditions.

2.3.1. Preprocessing and model set-up

Watershed delineation was conducted in QGIS using the SWAT+ plug-in to define basin boundaries, sub-basin divisions, river networks and hydrologic response units (HRUs). HRUs were defined as unique combinations of LULC, soil type and slope. Climate data were compiled and formatted in the SWAT+ Editor to serve as input for streamflow simulation. A warm-up period of one year was applied prior to each simulation period to minimize the influence of initial model conditions. Accordingly, the first year of each simulation (1993 for the 1993–2000 simulation and 2001 for the 2001–2023 simulation) was used exclusively for model initialization and was excluded from the anomaly analysis. Consequently, the apparent discontinuities observed in Figure 9 and 10 correspond to these warm-up periods rather than to missing streamflow or precipitation data.

2.3.2. Sensitivity analysis

Sensitivity analysis was performed using the Latin Hypercube One Factor at a Time (LH-OAT) approach, with 1,700 samples. The Nash Sutcliffe efficiency (NSE) was used as the objective function at the downstream outlet, which represents the integrated hydrological response of the basin. For the period 1993–2000, the most influential parameters were perco (0.5363), k (0.2215), cn2 (0.0609), cn3_swf (0.0540), esco (0.0415), bd (0.0363), revap_co (0.0265) and flo_min (0.0224). For the period 2001–2023, the dominant parameter ranking shifted, with bd (0.3771) and perco (0.3279) becoming the most influential, followed by esco (0.1027), revap_co (0.0650), flo_min (0.0453), k (0.0369), cn3_swf (0.0249), and cn2 (0.0110). These results indicate that model sensitivity varied between the simulation periods, which may reflect changes in land surface conditions, and highlight the importance of prioritizing key parameters during calibration, as presented in Table 2.

Table 2. Comparison of parameter sensitivity and change types between simulation periods (1993–2000 and 2001–2023)

No	Period 1993–2000				Period 2001–2023			
	Parameter	Sensitivity	Group	Change Type	Parameter	Sensitivity	Group	Change Type
1	perco	0.5363	hru	Replace	bd	0.3771	sol	Replace
3	k	0.2215	sol	Replace	perco	0.3279	hru	Replace
4	cn2	0.0609	hru	Percent	esco	0.1027	hru	Replace
5	cn3_swf	0.0540	hru	Percent	revap_co	0.0650	aqu	Replace
6	esco	0.0415	hru	Replace	flo_min	0.0453	aqu	Replace

No	Period 1993-2000				Period 2001-2023			
	Parameter	Sensitivity	Group	Change Type	Parameter	Sensitivity	Group	Change Type
7	bd	0.0363	sol	Percent	k	0.0369	sol	Replace
8	revap_co	0.0265	aqu	Replace	cn3_swf	0.0249	hru	Percent
9	flo_min	0.0224	aqu	Replace	cn2	0.0110	hru	Replace

2.3.3. Calibration and verification

Calibration was performed automatically using the Calibration module in the SWAT+ Toolbox based on the CALSI algorithm, following the sensitivity analysis stage. The objective of this process was to optimize model parameters so that the simulated streamflow closely matched the observed streamflow (Figure 7). Although streamflow was analyzed at multiple downstream stations, calibration was performed at a single basin outlet. The calibrated parameter dataset obtained from SWAT+ Toolbox was subsequently exported and applied to the entire model domain, and the simulation was rerun in SWAT+. This approach allowed model performance to be evaluated at multiple stations.

Due to the inconsistent availability of observed discharge data, which varied significantly across stations and periods, calibration and verification were conducted using stations and periods with sufficiently available observation. Among the three gauging stations in the lower basin in this research, Muara Kilis was selected for calibration and verification because it provided relatively longer periods of observed discharge records for model evaluation. In contrast, observed discharge data were unavailable at Simpang Berbak, while the Sungai Duren records exhibited periods of discontinuous availability.

For the first simulation (1993-2000), observed data from Muara Kilis station were used, with calibration conducted for 1994-1996 and verification for 1997-1998. For the second simulation period (2000-2023), the Muara Kilis station was also used, with a one-year warm up period. Calibration was conducted for 2008-2009, followed by verification for 2012-2013, corresponding to the periods with available observed discharge records. For the first simulation period, calibration during 1994-1996 resulted in $NSE = 0.473$, $R^2 = 0.486$, $KGE = 0.498$ and $PBIAS = -3.85\%$, indicating satisfactory model performance. The R^2 value was close to 0.50, indicating moderate agreement between simulated and observed discharge, while the low absolute PBIAS indicated good agreement in terms of water-balance bias. During verification for 1997-1998, the model achieved $NSE = 0.521$, $R^2 = 0.565$, $KGE = 0.726$ and $PBIAS = 6.76\%$, indicating satisfactory to good performance across the evaluation metrics. The model response was also assessed during selected ENSO-IOD periods. These results indicate that the model generally captured the observed streamflow response under ENSO-IOD conditions, including reduced streamflow during El Niño-IOD+ periods and increased streamflow during La Niña-IOD- periods, although some differences in timing and magnitude remained.

For the second simulation period, calibration during 2008-2009 yielded $NSE = 0.444$, $R^2 = 0.582$, $KGE = 0.718$ and $PBIAS = 15.12\%$, indicating satisfactory to good model performance. During verification for 2012-2013, the model achieved $NSE = 0.515$, $R^2 = 0.530$, $KGE = 0.519$ and $PBIAS = -0.30\%$, demonstrating satisfactory performance with very low bias. The model response was further examined during periods of ENSO and IOD. The results indicate that the model generally captured the observed streamflow response under varying ENSO-IOD conditions, although some differences in timing and magnitude remained. Overall, the model demonstrated consistent performance across the calibration and verification periods. Given that the model achieved satisfactory performance during verification, it was considered suitable for subsequent simulations under different land-use representations (Marek *et al.*, 2016). The detailed interpretation of model performance refers to the criteria developed by Almeida *et al.* (2018), as summarized in Table 3. In addition, the Kling-Gupta Efficiency (KGE) was calculated as a complementary performance metric. Following Ahmed *et al.* (2023), KGE values were classified as unacceptable/poor (≤ 0.30), acceptable/satisfactory ($>0.30-0.53$), good ($>0.53-0.77$), and excellent (≥ 0.77).

Table 3. Classification Criteria for Interpreting Model Performance

No	NSE	PBIAS	R ²	Classification
1	$0.75 < NSE \leq 1.00$	$PBIAS \leq \pm 10$	$0.75 < R^2 \leq 1.00$	Very good
2	$0.60 < NSE \leq 0.75$	$\pm 10 < PBIAS \leq \pm 15$	$0.60 < R^2 \leq 0.75$	Good
3	$0.36 < NSE \leq 0.60$	$\pm 15 < PBIAS \leq \pm 25$	$0.50 < R^2 \leq 0.60$	Satisfactory
4	$0.00 < NSE \leq 0.36$	$\pm 25 < PBIAS \leq \pm 50$	$0.25 < R^2 \leq 0.50$	Poor
5	$NSE \leq 0.00$	$\pm 50 \leq PBIAS$	$R^2 \leq 0.25$	Inappropriate

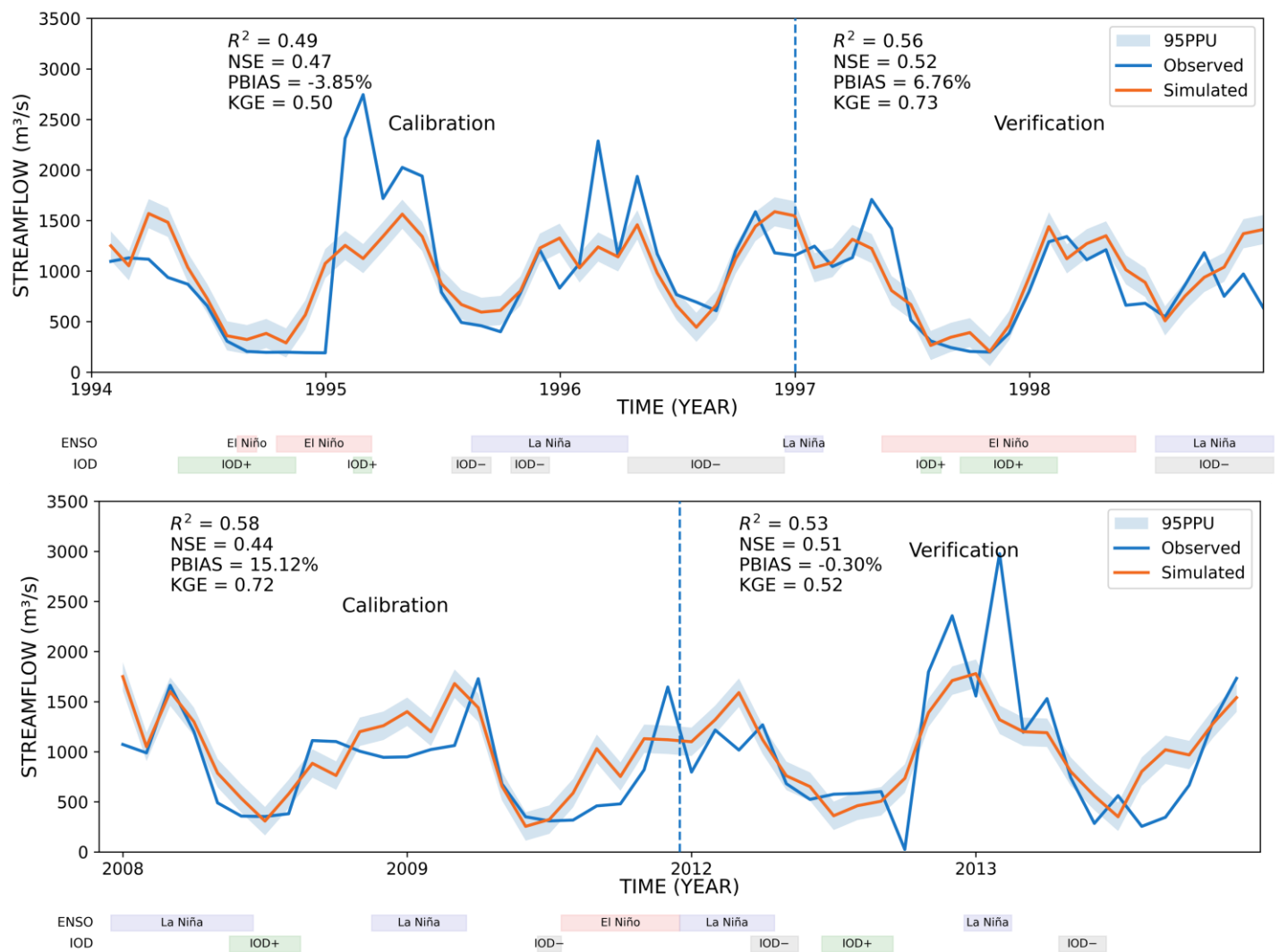


Figure 7. Calibration and verification of streamflow at Muara Kilis station period 1993-2000 (top), Muara Kilis station period 2008-2029 (calibration) and 2012-2013 (verification) (bottom) (Observation data source: BHLK Ministry of Public Works, 2025).

2.3.4. Correlation analysis

Given the discontinuous availability of observed streamflow records throughout the 1993-2023 study period, SWAT+ simulated streamflow was used as the primary streamflow dataset for the long-term climate-streamflow analysis. The available observed records, although limited to specific periods, were used for model calibration and verification. The calibrated and validated SWAT+ model was then used to generate a continuous simulated streamflow series throughout the study period, enabling consistent assessment of climate-streamflow relationships across the basin and different land-use periods. The calibrated and validated SWAT+ simulations provided a consistent basis for long-term analysis despite limited observed discharge records. Nevertheless, model-generated streamflow remains an important methodological limitation.

Our aim was not to conduct a comprehensive lagged analysis across all possible monthly or seasonal combinations. Instead, the focus is on two targeted relationships: antecedent JJA climate conditions and concurrent SON climate conditions in relation to SON streamflow. The SON period coincides with the peak development of the IOD and the strengthening of ENSO-related climate signals, making large-scale climate signals more pronounced. Moreover, streamflow during this season begins to respond to increasing rainfall, allowing climate-related variability to be more clearly detected in hydrological responses (Sahu *et al.*, 2012). The selected seasons represent key stages of climate variability over Indonesia. Boreal summer (JJA) corresponds to the development phase of ENSO and IOD, whereas boreal fall (SON) represents their mature phase and the transition from the dry to the wet season, during which streamflow begins to increase and climate signals become more evident in hydrological responses (Sahu *et al.*, 2012). To account for this, the relationship between climate indices and streamflow was evaluated not only for the concurrent

period (climate indices from September to November and streamflow from September to November), but also by considering antecedent climate conditions from the previous season (climate indices from June to August and streamflow from September to November). This approach allowed for the identification of time-lagged statistical relationships between ocean–atmosphere variability and streamflow response, providing insight into how large-scale climate drivers are associated with hydrological responses and extreme flow events in the Batanghari River Basin.

To assess the relationship between climate variability and river streamflow, Pearson and partial correlation analyses were conducted between the climate indices and SWAT+ simulated streamflow. Pearson correlation was used to evaluate the strength and direction of the linear relationship, whereas partial correlation was applied to assess the relationship between each climate index and streamflow, while controlling for the association with the other climate index. These correlation approaches are commonly used to examine relationships and variability patterns between climate indices and hydroclimatic variables (Caroletti *et al.*, 2021; dos Santos *et al.*, 2023). Following the framework of Sahu *et al.* (2012), streamflow and rainfall anomalies were calculated based on long-term climatological means to identify deviations from normal conditions. In the original framework, extreme high-flow and low-flow conditions were identified using thresholds of $+1.5\sigma$ and -1σ , respectively. In this study, the threshold was modified to a symmetric criterion, with values greater than $+1.5\sigma$ classified as extreme high-flow conditions and values lower than -1.5σ classified as extreme low-flow conditions. This modification was made to ensure that extreme high and low flow conditions were defined using a consistent standardized deviation from climatological mean. For the correlation analysis, although partial correlation accounted for the contribution of the other climate index, the analysis did not quantitatively assess interactions or coupling between ENSO and IOD. The discussion on coupling is presented in a conceptual context rather than a quantitatively assessed interaction.

The Pearson (r) and partial ($r_{XY.Z}$) correlation coefficients were calculated using equations (1) and (2):

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (1)$$

$$r_{XY.Z} = \frac{r_{XY} - r_{XZ} r_{YZ}}{\sqrt{(1 - r_{XZ}^2)(1 - r_{YZ}^2)}} \quad (2)$$

where X_i and Y_i represent the climate indices and streamflow variables; $\bar{X}$ and $\bar{Y}$ are their respective means, and n is the number of observations. The partial correlation is expressed as shown in Equation (2), where r_{XY} , r_{XZ} and r_{YZ} represent the Pearson correlation between the respective pairs of variables. In this study, X and Y represent the climate index and streamflow respectively, while Z represents the other climate index. The strength of the correlation coefficient was interpreted based on the classification (Handoko *et al.*, 2023), shown in Table 4.

Table 4. Interpretation Criteria for Pearson Correlation Coefficient

No	Correlation coefficient (r)	Interpretation
1	0.00 – 0.19	Very weak
2	0.20 – 0.39	Weak
3	0.40 – 0.59	Moderate
4	0.60 – 0.79	Strong
5	0.80 – 1.00	Very strong

3. Results and Discussion

3.1. ENSO and IOD Events 1993–2023

ENSO and IOD events exhibited significant fluctuation from 1993 to 2023. The temporal variation is shown in Figure 8. During the period 1993–2000, the strongest positive IOD (pIOD) events occurred from mid- to late 1994 and in 1997, while a strong El Niño event developed in the period 1997–1998. These climate anomalies were associated with a weakened westerly monsoon flow; enhanced lower-tropospheric stability, and reinforced dry, stable atmospheric conditions, thereby contributing to reduced precipitation across many regions through large-scale atmospheric teleconnections (Kasera & Minocha, 2025). Such teleconnections refer to physically meaningful links between climate anomalies over large distances, driven by energy transport and wave propagation within the atmosphere–ocean system (Alizadeh, 2024). From a hydrological perspective, these are

often associated with lower soil moisture and reduced river streamflow, particularly within catchment areas such as river basins.

The period 2000–2023 is characterized by highly active ENSO and IOD dynamics, with several notable events over the past two decades. The period exhibits pronounced climate variability, in which ENSO and IOD are closely associated with local and regional climate patterns (Ummenhofer *et al.*, 2013). In the early 2000s, several moderate El Niño events occurred (2002–2003 and 2006–2007), followed by a transition to La Niña in 2007–2008. Another relatively weak El Niño episode was observed from 2009 to mid-2010.

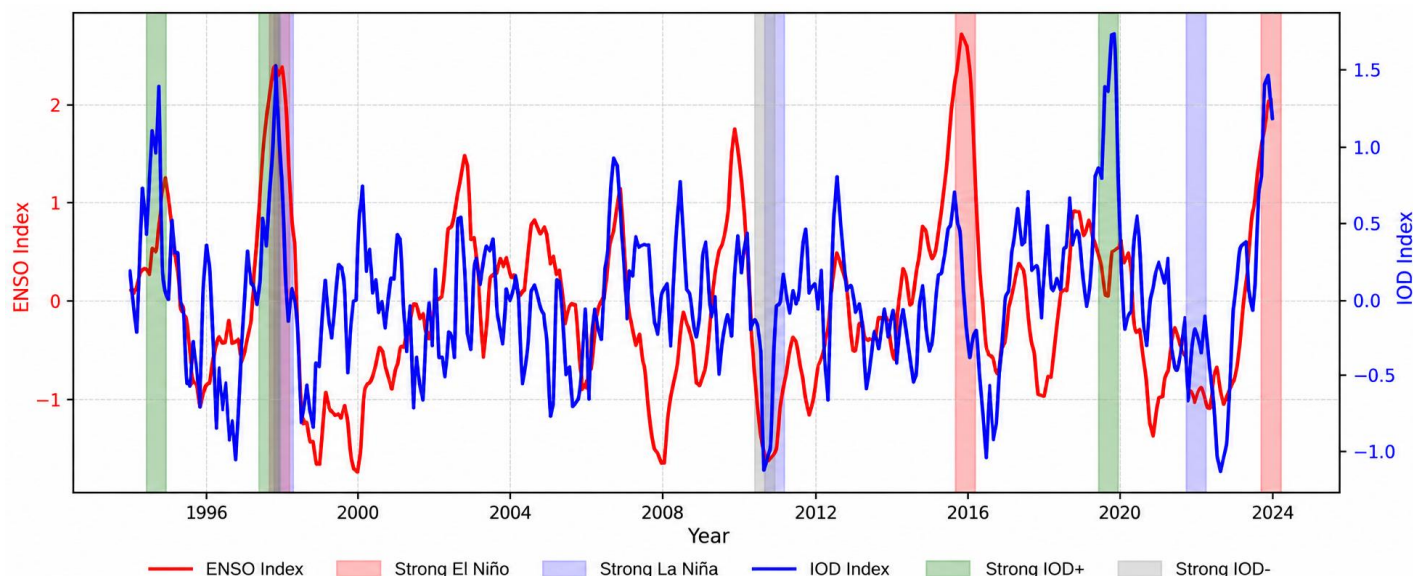


Figure 8. ENSO and IOD events during the period 1993–2023 with of strong events highlighted

During this period, a strong El Niño developed in 2015–2016, comparable in intensity to the 1997–1998 event. Extensive sea surface warming in the Pacific induced large-scale circulation anomalies, including a weakening of the Walker circulation, anomalous ascent over the central–eastern Pacific, and subsidence over the western Pacific, thereby altering wind and rainfall patterns worldwide (C. Wang, 2002; Zhang *et al.*, 2017). These years represent key milestones in modern climatology. Subsequently, La Niña conditions recurred in 2010–2011, 2016–2018 and 2020–2022, indicating sustained cooling in the central and eastern Pacific for more than two consecutive years. Such cooling is linked to complex interactions between subsurface temperature anomalies, ocean currents and strengthened trade winds, which intensify the Walker circulation and promote further cooling (C. Gao *et al.*, 2022; Song *et al.*, 2022).

A significant positive IOD (pIOD) event occurred in 2019, distinguished as one of the most notable events since the 1960s. This pIOD evolved primarily independently of El Niño and was initiated by Rossby waves in the southern Indian Ocean, which caused a sea-level rise, with warming in the west and cooling in the east, further intensified by ocean-atmosphere feedback mechanisms (Du *et al.*, 2020; Lu & Ren, 2020). In addition, strong negative IOD (nIOD) events occurred, particularly in 2010 and 2016. These events were marked by extreme warming in the eastern Indian Ocean and very high sea surface temperature anomalies, while anomalies in the western basin remained relatively weak, producing a monopolar pattern distinct from the classical dipole structure. The 2016 event was further driven by both surface and subsurface conditions in the Indian Ocean and reinforced by long-term warming in the region.

3.2. Streamflow Anomalies

Monthly anomalies of streamflow and precipitation at the three gauging stations in the lower Batanghari River Basin are presented in Figure 9, namely those of (a) Muara Kilis, (b) Sungai Duren, and (c) Simpang Berbak. The orange line represents streamflow anomalies, while the blue indicates precipitation anomalies. Red and green markers denote extreme high-flow and low-flow anomalies respectively.

The three downstream stations exhibit broadly balanced distributions of positive and negative streamflow anomalies, but differ in the occurrence of extreme-flow events. Muara Kilis, located in the upper part of the lower basin and adjacent to the middle sub-basin, shows a relatively balanced distribution of positive and negative anomalies, with extreme low-flow events more

frequent than extreme high-flow ones. In contrast, Sungai Duren is characterized by a similar overall balance between positive and negative anomalies, while extreme high-flow events are somewhat more frequent than extreme low-flow one. Finally, Simpang Berbak, situated near the river mouth, also shows a closely balanced distribution of positive and negative anomalies, with a slightly higher occurrence of extreme high-flow events than extreme low-flow ones. Across all the stations, extreme high-flow events occur at relatively similar frequencies, whereas the occurrence of extreme low-flow ones is comparatively higher at Muara Kilis. Periods of relatively high and low streamflow generally coincide with positive and negative precipitation anomalies respectively, suggesting a possible association between rainfall variability and streamflow dynamics in the lower Batanghari River Basin. This pattern indicates a link between atmospheric forcing and hydrological response, whereby variations in precipitation are associated with changes in river flow conditions in this humid tropical system.

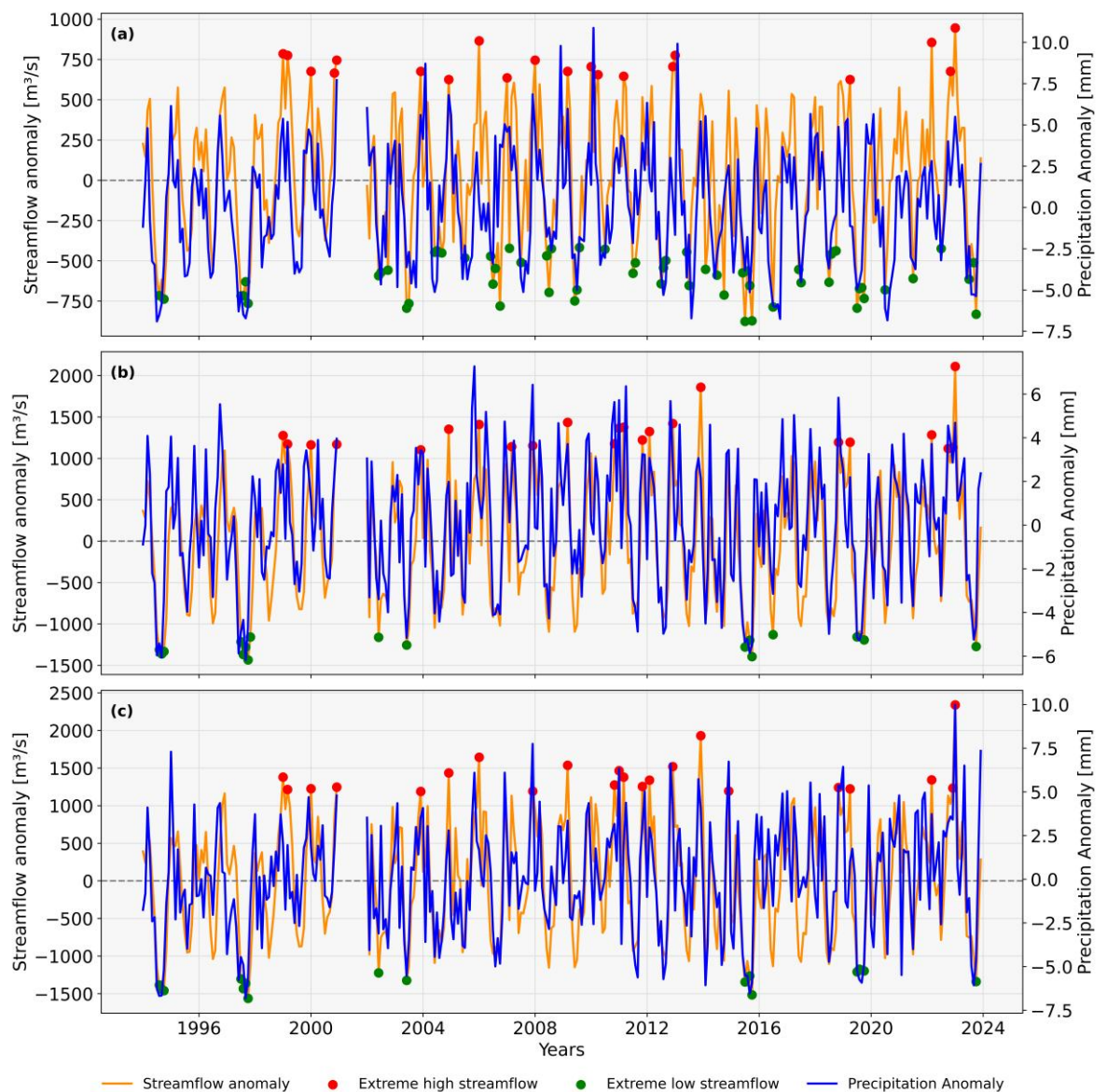


Figure 9. Streamflow and precipitation anomalies for the three hydrological stations along the Lower Batanghari River Basin. Panels correspond to the following stations: (a) Muara Kilis (b) Sungai Duren (c) Simpang Berbak. The apparent discontinuities in the time series correspond to the one-year SWAT+ warm-up periods (1993 and 2001), which were excluded from the anomaly analysis.

Further analysis during the September–November season, as shown in Figure 10, reveals a generally consistent pattern of extreme flow conditions among the three stations. At Muara Kilis, extreme high-flow conditions are relatively infrequent and occurred only in specific years, notably in 2000 and 2022. In contrast, extreme low flow conditions occur more frequently, particularly during several episodes in the analysis period. This indicates that low flow extremes were more prevalent than high-flow ones at this station during SON.

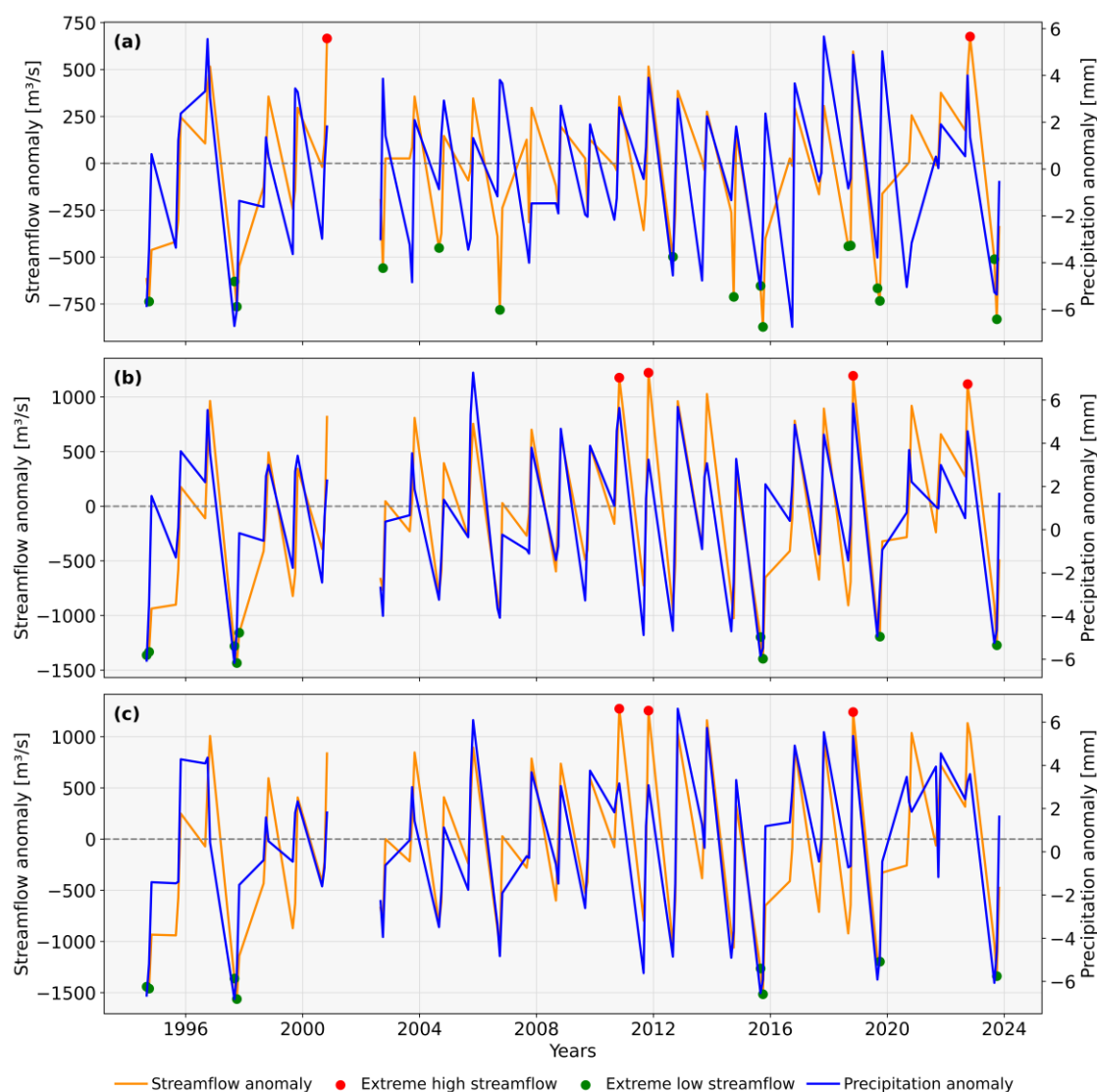


Figure 10. September-November streamflow and precipitation anomalies at the three stations in the lower Batanghari River Basin: (a) Muara Kilis, (b) Sungai Duren, and (c) Simpang Berbak. Note that the apparent discontinuities correspond to the one-year SWAT+ warm-up period and do not represent missing data.

At the Sungai Duren station, both extreme high and low flow conditions are observed, with low flow extremes occurring more frequently than high-flow ones. Extreme high-flow anomalies are observed in 2010, 2011, 2018 and 2022, while extreme low-flow events occur across several years, particularly during the earlier and later parts of the analysis period. At the Simpang Berbak station, extreme high-flow events are relatively infrequent, whereas extreme low flow ones occur more frequently. The timing of several extreme events is broadly consistent with those identified at Sungai Duren, particularly during the 2010-2011 and 2015-2019 periods. The occurrence of extreme events during similar periods at the two stations suggests a degree of temporal coherence in downstream flow variability.

Overall, the three stations exhibit a relatively similar frequency of extreme events during SON, with the total number of events ranging from 11 to 13. Extreme low-flow events consistently outnumber extreme high-flow ones at all three stations. Rather than indicating a systematic increase in the frequency of streamflow intensity anomalies from upper to lower, the results suggest a relatively consistent seasonal pattern of extreme streamflow conditions across the lower Batanghari River Basin.

3.3 Correlation between Climate Indices and Streamflow

The correlation analysis between two large-scale climate indices and seasonal streamflow anomalies in the Batanghari River at the three downstream stations (Table 5) reveals a consistent pattern of association between climate variability and hydrological response. It should be noted that this analysis is based on overall streamflow anomalies across the full dataset, rather than being limited

to extreme high or low events. These events were examined separately in the previous section to illustrate the range and variability of streamflow responses.

Table 5. Pearson Correlation Analysis Between Climate Indices and Streamflow September–November

No.	Station	JJA → Q SON				SON → Q SON			
		IOD		ENSO		IOD		ENSO	
		<i>r</i>	<i>p</i> -value	<i>r</i>	<i>p</i> -value	<i>r</i>	<i>p</i> -value	<i>r</i>	<i>p</i> -value
1	Muara Kilis	−0.39	2.15×10^{-4}	−0.58	1.00×10^{-6}	−0.64	1.00×10^{-6}	−0.59	1.00×10^{-6}
2	Sungai Duren	−0.33	1.85×10^{-3}	−0.51	1.00×10^{-7}	−0.56	1.00×10^{-7}	−0.54	1.10×10^{-6}
3	Simpang Berbak	−0.33	1.67×10^{-3}	−0.52	0	−0.58	0	−0.54	1.50×10^{-5}

Across all stations and index configurations, the Pearson correlation coefficients are uniformly negative. This suggests that El Niño conditions and positive IOD phases are generally associated with reduced streamflow during the September–November period, whereas La Niña conditions and negative IOD phases tend to correspond to increased streamflow. All correlations are statistically significant ($p < 0.001$). In terms of magnitude, the correlation coefficients range from weak–moderate to moderate–strong. For the June–August (JJA) indices correlated with September–November (SON) streamflow, IOD correlations range from −0.33 to −0.39, whereas ENSO correlations are stronger, ranging from −0.51 to −0.58 across the three stations. When SON indices are correlated with SON streamflow, IOD correlations increase to −0.56 to −0.64, while ENSO correlations range from −0.54 to −0.59. Among the three stations, Muara Kilis exhibits the strongest correlations, with the IOD–SON and ENSO–SON streamflow period correlations reaching −0.64 and −0.59, respectively. Sungai Duren and Simpang Berbak show relatively similar correlation magnitudes, with SON IOD–SON streamflow correlations of −0.56 and −0.58, and SON ENSO–SON streamflow correlations of −0.54 for both stations (Figure 11).

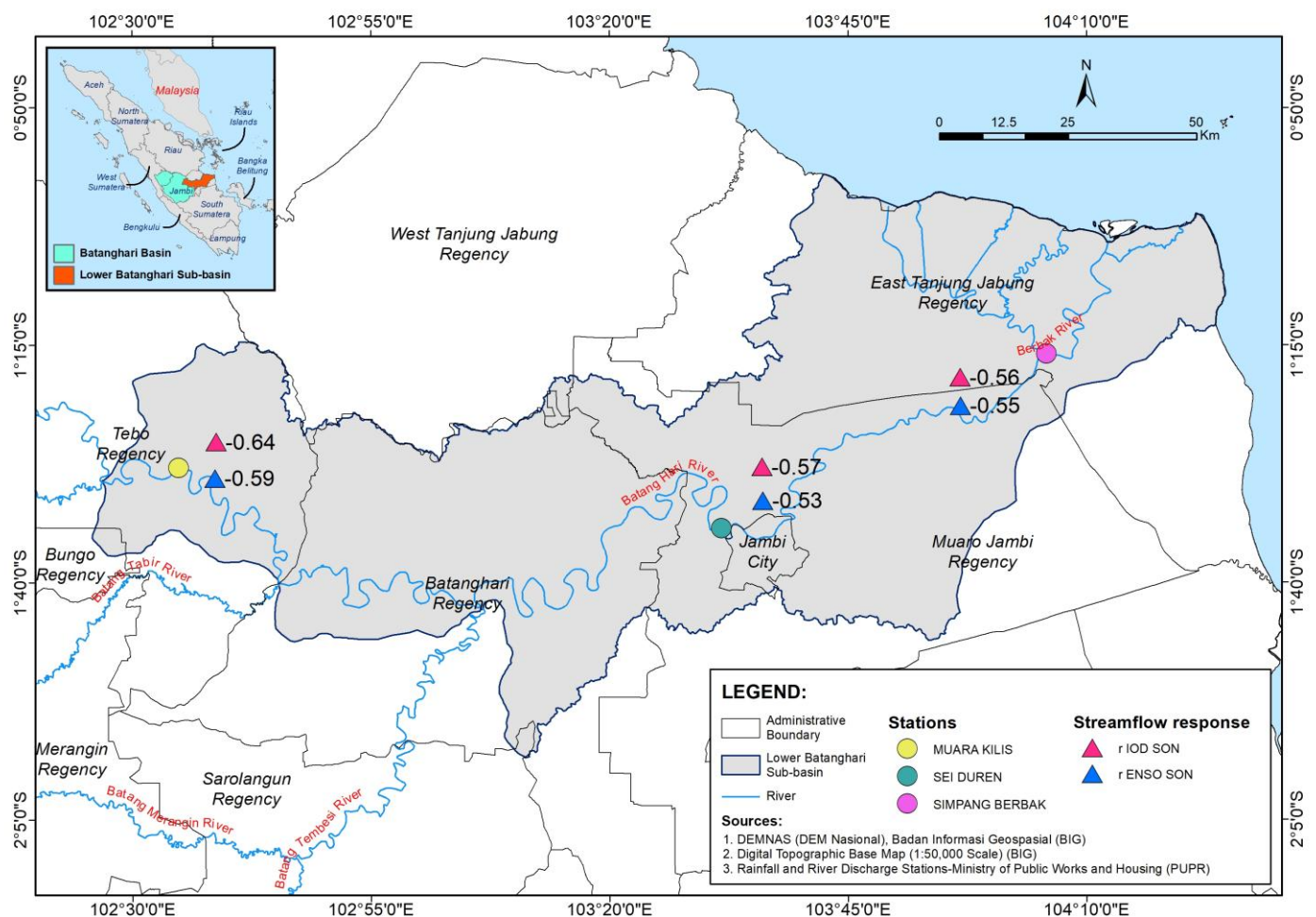


Figure 11. Spatial variability of streamflow response to ENSO and IOD during the SON season in the lower Batanghari River Basin

Nevertheless, differences in the relative association of ENSO and IOD are apparent depending on the seasonal timing of the climate indices relative to the streamflow period. For JJA indices and SON streamflow, ENSO exhibits stronger correlations than IOD at all three stations. In contrast, for SON indices and SON streamflow, IOD shows slightly stronger correlations than ENSO at the three stations. The stronger correlations obtained when climate indices and streamflow are considered within the same SON season also indicate a closer statistical association between climate variability and seasonal streamflow anomalies within the same season than between preceding JJA climate conditions and subsequent SON streamflow. Overall, the results suggest that the associations of ENSO and IOD with streamflow variability in the lower Batanghari River basin exhibit clear seasonal and spatial variability. The relationship between climate indices and streamflow is consistently stronger for the SON season, with IOD showing a slightly stronger association than ENSO across all three stations (Figure 11). Spatially, the strongest correlations were observed at Muara Kilis, whereas Sungai Duren and Simpang Berbak exhibited relatively similar correlation magnitudes. These findings highlight the importance of considering both the seasonal timing of climate indices and spatial variability among lower stations when characterizing climate–streamflow relationships in tropical river systems.

To further illustrate the linear relationships identified by the Pearson correlation analysis, scatter plots with fitted regression lines were used to visualize the relationship between the climate indices and SON streamflow. The regression lines provide a visual representation of the direction and relative strength of the linear associations identified by the correlations analysis across the three lower stations. At Muara Kilis, the scatter plots and fitted regression lines show a consistently negative linear relationship between the climate indices and SON streamflow (Figure 12). The relationship is relatively weak for IOD JJA, whereas ENSO JJA exhibits a stronger negative linear association with SON streamflow. For the SON indices, both IOD and ENSO demonstrate stronger negative relationships, with IOD SON exhibiting the strongest association among the four relationships. These patterns are consistent with the Pearson correlation results (Table 5), with the regression lines providing a visual representation of the direction and relative strength of the climate–streamflow relationships.

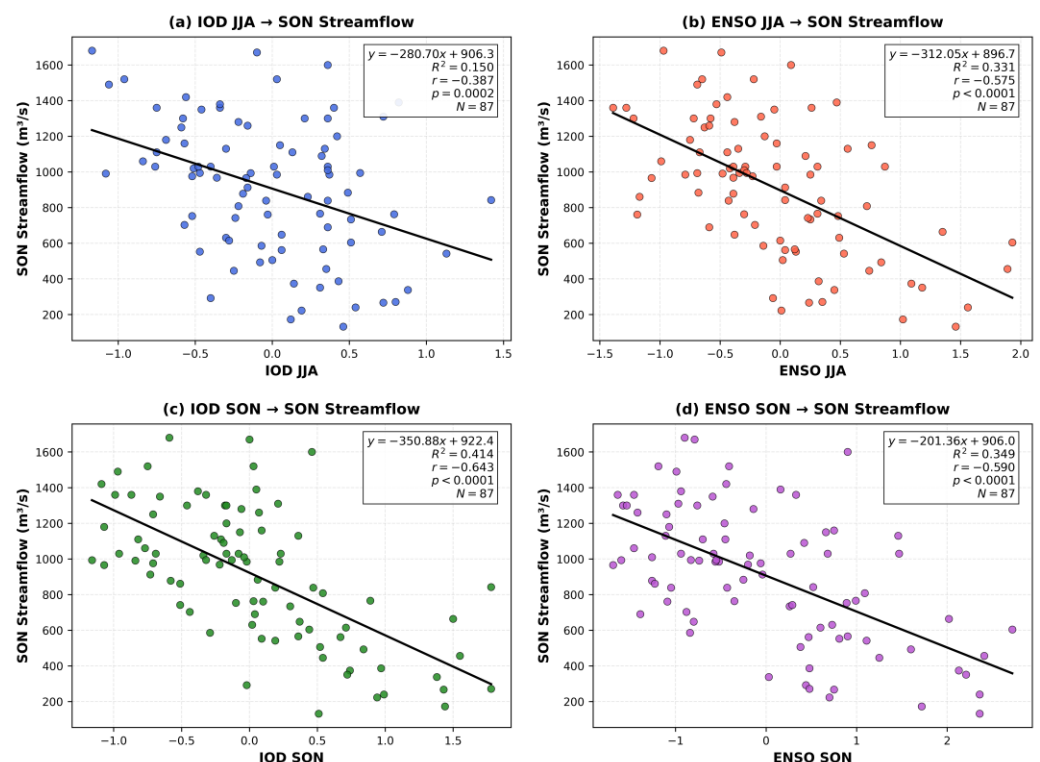


Figure 12. Scatter plots and fitted regression lines between climate indices and SON streamflow at Muara Kilis: (a) IOD JJA, (b) ENSO JJA, (c) IOD SON, and (d) ENSO SON.

The scatter plots for Sungai Duren similarly show consistently negative linear relationships between the climate indices and SON streamflow (Figure 13). The relationship is weaker for IOD JJA, whereas ENSO JJA exhibits a stronger negative association with SON streamflow. For the SON indices, IOD shows a stronger negative relationship than ENSO, with the IOD SON

relationship exhibiting the highest coefficient of determination among the four relationships. Overall, these regression patterns are consistent with the Pearson correlation result.

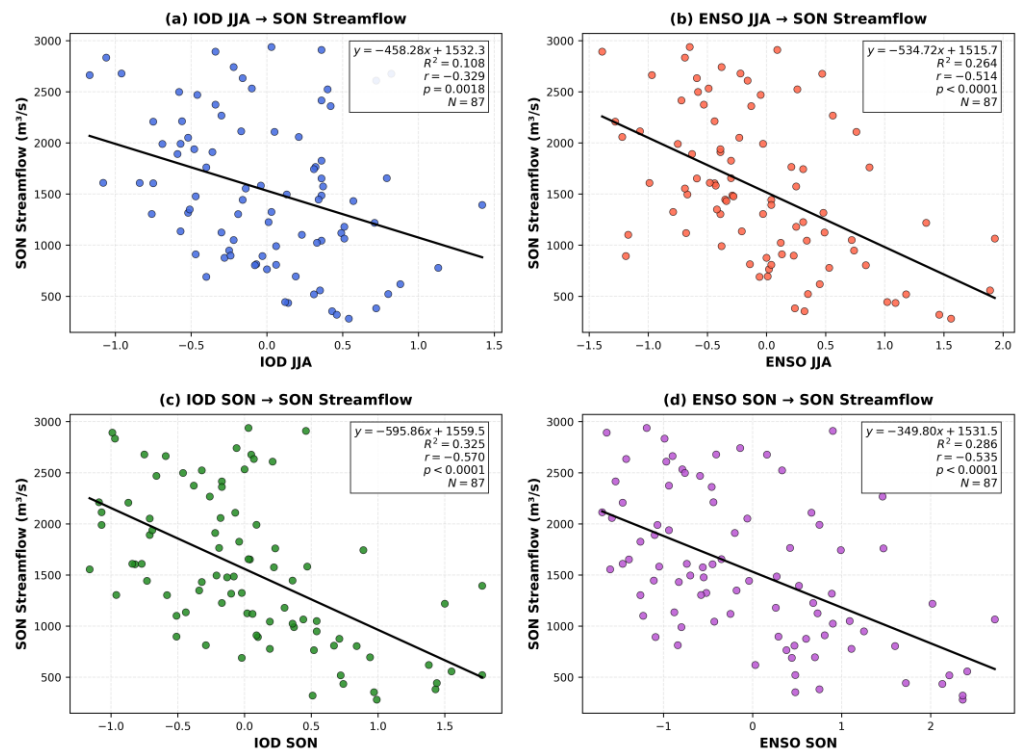


Figure 13. Scatter plots and fitted regression lines between climate indices and SON streamflow at Sungai Duren: (a) IOD JJA, (b) ENSO JJA, (c) IOD SON, and (d) ENSO SON.

A similar pattern was observed for Simpang Berbak, where all four relationships of climate index-SON streamflow show negative regression slopes (Figure 14). ENSO JJA exhibits a stronger negative association with SON streamflow than IOD JJA, while for the SON indices, IOD shows a slightly stronger relationship than ENSO. The IOD SON relationship also shows a higher coefficient of determination than the ENSO SON relationship, consistent with the stronger Pearson correlation observed for IOD.

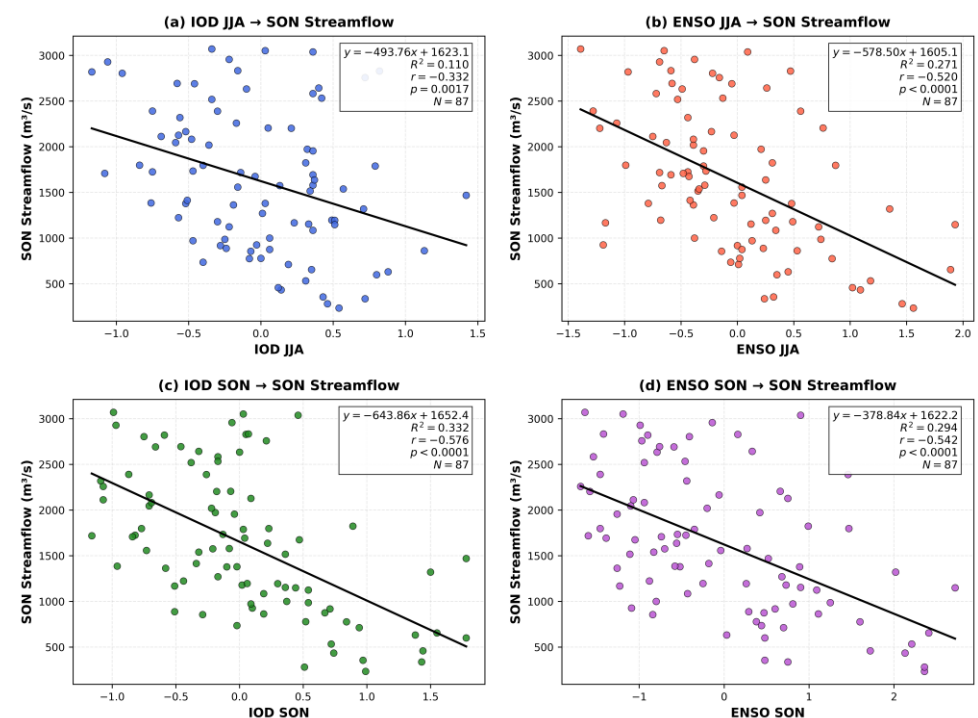


Figure 14. Scatter plots and fitted regression lines between climate indices and SON streamflow at Simpang Berbak: (a) IOD JJA, (b) ENSO JJA, (c) IOD SON, and (d) ENSO SON.

However, because ENSO and IOD may occur concurrently, Pearson correlations cannot distinguish the individual association of each climate index with streamflow while accounting for the other climate index. Therefore, a partial correlation analysis was conducted to evaluate the association of each climate index with SON streamflow, while statistically controlling for the other climate index. The partial correlation results show a clearer distinction between the associations of ENSO and IOD with SON streamflow (Table 6). For the relationship between JJA climate indices and SON streamflow, ENSO remains significantly and negatively correlated with SON streamflow at all three stations, with partial correlation coefficients ranging from -0.44 to -0.50 ($p < 0.001$). In contrast, the partial correlations between IOD and SON streamflow become much weaker, ranging from -0.17 to -0.22, and are not statistically significant at Sungai Duren or Berbak ($p = 0.12$ and 0.12 , respectively). At Muara Kilis, the IOD association remains statistically significant but is weak ($r = -0.22$, $p = 0.04$). This indicates that the association between JJA climate indices and SON streamflow is more consistently represented by ENSO than IOD after accounting for the variability of the other climate index.

Table 6. Partial Correlation Analysis Between the Climate Indices and Streamflow

Station	Relationship	Partial (r)	p -value
Muara Kilis	IOD JJA $\rightarrow$ Q SON (ENSO JJA)	-0.22	4.00×10^{-2}
	ENSO JJA $\rightarrow$ Q SON (IOD JJA)	-0.50	7.81×10^{-7}
	IOD SON $\rightarrow$ Q SON (ENSO SON)	-0.43	3.75×10^{-5}
	ENSO SON $\rightarrow$ Q SON (IOD SON)	-0.30	1.00×10^{-2}
Sungai Duren	IOD JJA $\rightarrow$ Q SON (ENSO JJA)	-0.17	1.20×10^{-1}
	ENSO JJA $\rightarrow$ Q SON (IOD JJA)	-0.44	1.00×10^{-6}
	IOD SON $\rightarrow$ Q SON (ENSO SON)	-0.35	1.60×10^{-4}
	ENSO SON $\rightarrow$ Q SON (IOD SON)	-0.27	1.00×10^{-2}
Berbak	IOD JJA $\rightarrow$ Q SON (ENSO JJA)	-0.17	1.20×10^{-1}
	ENSO JJA $\rightarrow$ Q SON (IOD JJA)	-0.45	1.00×10^{-5}
	IOD SON $\rightarrow$ Q SON (ENSO SON)	-0.35	1.00×10^{-3}
	ENSO SON $\rightarrow$ Q SON (IOD SON)	-0.27	1.00×10^{-3}

In contrast, regarding the relationship between the SON climate indices and SON streamflow, both indices remain significantly associated with streamflow after accounting for the other index. However, IOD consistently exhibits stronger negative partial correlations than ENSO at all three stations. The partial correlations for IOD range from -0.35 to -0.43, whereas those for ENSO range from -0.27 to -0.30. The strongest IOD association was observed at Muara Kilis ($r = -0.43$), followed by Simpang Berbak ($r = -0.354$) and Sungai Duren ($r = -0.349$), while the corresponding ENSO correlations were -0.30, -0.27, and -0.27, respectively. All of these relationships are statistically significant ($p \leq 0.012$). Overall, the partial correlation results indicate that the associations of ENSO and IOD with SON streamflow depend on the seasonal timing of the climate indices. ENSO JJA shows a more consistent association with SON streamflow, whereas for the concurrent SON period, IOD exhibits a stronger association with the streamflow than ENSO. These findings further demonstrate that the two climate indices show distinct patterns of association with seasonal streamflow variability. To quantify the relative strength of these associations, while accounting for the simultaneous presence of the other climate index, multivariate regression analysis was performed (Figure 15).

In relation to the resulting regression coefficients (β) and their 95% confidence intervals (Figure 15a), ENSO generally exhibits more negative regression coefficients than IOD across all three stations, indicating a stronger association with SON streamflow when the preceding JJA climate conditions are considered simultaneously. In contrast, for the same-season relationships between the SON climate indices and SON streamflow (Figure 15b), IOD consistently shows more negative coefficients than ENSO at all three stations, indicating a stronger association of IOD with SON streamflow for the same season. The error bars represent the 95% confidence intervals of the regression coefficients and indicate differences in the precision of the estimated associations among stations and climate indices. Overall, these results are consistent with the patterns identified by the Pearson and partial correlation analysis.

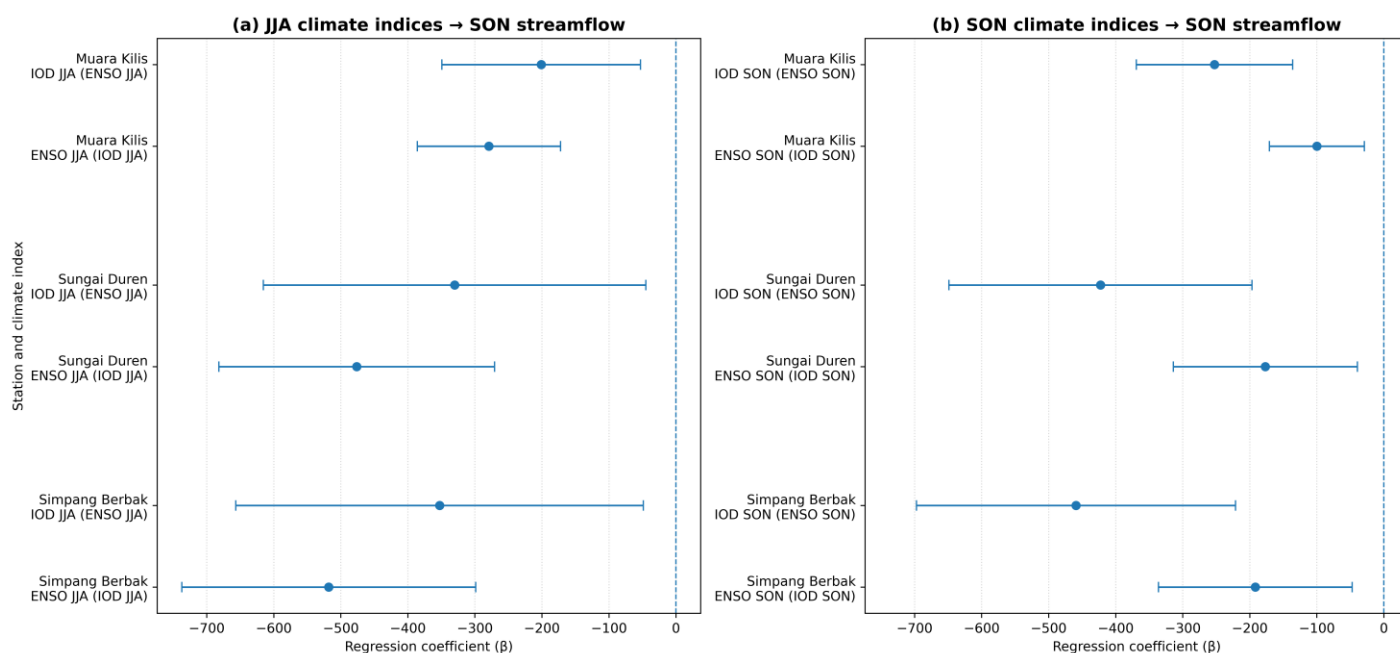


Figure 15. Multivariate regression coefficients (β) and 95% confidence intervals for the climate indices and SON streamflow. (a) JJA Climate Indices-SON Streamflow; (b) SON Climate Indices-SON streamflow.

3.4 Discussion

The analysis shows that streamflow variability in the lower Batanghari River Basin is characterized by significant temporal fluctuations, with both extreme high-flow and extreme low-flow occurring at different periods across the three stations. In general, the frequency of extreme events is relatively similar among the stations, although differences are observed in the timing and type of extremes. During SON, extreme low-flow extremes occurred more frequently than high-flow extremes at all three stations. This pattern indicates that the frequency of extreme events does not exhibit a systematic change from Muara Kilis to Simpang Berbak. Several extreme events also occurred during relatively similar periods across the stations, indicating a degree of temporal coherence in streamflow variability during SON. Similar spatiotemporal variability in extreme streamflow has been reported in other large river basins, where the timing and magnitude of extreme flows vary across seasons and locations and can be influenced by large-scale climate variability (Huang *et al.*, 2024). At the global basin scale, ENSO has been linked to variations in flood frequency and duration, including simultaneous and lagged responses (Yan *et al.*, 2020), while IOD has also been identified as an important climate mode influencing streamflow variability (Bates & Dowdy, 2024). This hydrological pattern provides a context for understanding the relationship between streamflow variability and large-scale climate signals, particularly ENSO and IOD.

The observed streamflow variability shows a consistent relationship with ENSO and IOD. The negative correlations observed at all stations indicate that El Niño and positive IOD conditions tend to be associated with lower streamflow, whereas La Niña and negative IOD conditions tend to be linked to higher streamflow. Similar relationship between ENSO-IOD phases and streamflow variability have been reported in the Jinsha River Basin, China, where both climate modes influenced annual and seasonal streamflow, with their effects varying between developing and decaying phases (Jia *et al.*, 2023). Similar climate-streamflow linkages have also been reported for the Lancang-Mekong River, where ENSO and IOD were identified as important drivers of interannual streamflow variability and extreme hydrological conditions (S. Wang *et al.*, 2024). From a hydroclimatic perspective, this pattern may be related to changes in atmospheric circulation and rainfall conditions in Indonesia during different ENSO and IOD phases. As-syakur *et al.* (2014), on the basis of TRMM rainfall data, showed that rainfall responses to ENSO and IOD were relatively strong during JJA and SON, with pronounced patterns over southeastern Sumatra and Java. These findings provide a relevant hydroclimatic context for the lower Batanghari River Basin, as changes in rainfall conditions associated with Indo-Pacific climate variability may be reflected in changes in streamflow across contributing catchments. The negative relationships identified in this study are also consistent with the findings of Sahu *et al.* (2012) for the Citarum River, which showed associations between El Niño and positive IOD

conditions with lower flow conditions, and between La Niña and negative IOD conditions with higher flows.

However, the ENSO and IOD associations exhibit different patterns depending on the timing of the climate signal relative to the streamflow period. When JJA indices were related to SON streamflow, ENSO showed stronger relationships than IOD at all stations. More importantly, after statistically controlling for IOD through partial correlation, the relationship between JJA ENSO and SON streamflow remained significant, with coefficients ranging from -0.44 to -0.50 , whereas the relationship between JJA IOD and SON streamflow weakened from -0.17 to -0.22 and became non-significant at Sungai Duren and Simpang Berbak. In contrast, for the SON–SON relationship, IOD showed stronger partial associations than ENSO at all stations. This difference indicates that the relative associations between the two climate modes and streamflow vary according to the timing of the climate signal and the period of hydrological response. This seasonal and lagged dependence is consistent with recent studies showing that ENSO and IOD influence hydrological variability differently across seasons and climate mode combinations, while ENSO can also modify seasonal river discharge variability (Zhu *et al.*, 2025).

The stronger relationship between JJA ENSO and SON streamflow may be linked to the development of ENSO-related hydroclimatic signals that are already evident during JJA, as well as the broader spatial extent of ENSO-related hydroclimatic variability across Indonesia. Kurniadi *et al.* (2021), who also examined this relationship in the tropics, showed that ENSO was independently associated with extreme rainfall across a broader area of Indonesia. Similarly, As-syakur *et al.* (2014) showed that rainfall responses to ENSO and IOD were evident during both JJA and SON. Therefore, the hydroclimatic signal associated with ENSO during JJA may provide a clearer antecedent condition when entering the SON period. This is consistent with our results, in which the relationship between JJA ENSO and SON streamflow remains significant after controlling for IOD, whereas the relationship with JJA IOD is weakened. This interpretation is also consistent with Nugroho *et al.* (2021), who reported a significant relationship between ENSO and the streamflow regime of the Code River, Indonesia. Conversely, the stronger association of IOD in the SON–SON relationship may be related to its development from JJA toward SON, bringing the climate signal closer in time to the streamflow response. The IOD begins to develop during boreal summer and strengthens toward boreal fall. Zhang *et al.* (2017) showed that IOD development is associated with strengthening southeasterly wind anomalies around Sumatra and Java, which promote cooling in the eastern equatorial Indian Ocean through interactions between wind, evaporation, SST and Bjerknes feedback. These processes subsequently strengthen the SST gradient characteristic of IOD development, leading to its mature phase during SON. Therefore, IOD conditions that begin to develop during JJA may provide an early hydroclimatic signal, while the subsequent strengthening of IOD toward its mature phase in SON may enhance its association with hydroclimatic conditions during the same season.

The findings of this study are generally consistent with previous research on the relationship between IOD and hydrological variability in Indonesia. Sahu *et al.* (2012), based on observed daily discharge from the Citarum River, identified a relationship between antecedent IOD conditions and SON discharge. This finding supports our result that JJA IOD remains associated with SON streamflow. Weller and Cai (2014) showed that some IOD events develop during JJA and reach their mature phase during SON, supporting the cross-seasonal IOD relationship observed in our research. Zhang *et al.* (2017) also showed that IOD development can extend from JJA to SON, consistent with the temporal pattern of IOD considered in this study. At the regional scale, As-syakur *et al.* (2014) found that during SON, the relationship between IOD and rainfall was stronger than that of ENSO over southeastern Sumatra and Java. This pattern is consistent with our findings, in which IOD showed a stronger association with SON streamflow than ENSO in the SON–SON relationship. Overall, the results of this study are consistent with these regional characteristics: ENSO is more clearly expressed as an antecedent signal during JJA, whereas IOD shows a stronger concurrent association when both the climate index and streamflow are considered during SON.

The differences between the JJA–SON and SON–SON relationships also highlight the importance of hydrological response timescales. River discharge integrates rainfall variability from the contributing catchment, meaning that the statistical relationship between climate indices and streamflow may depend on the timing of the climate signal relative to the river response period (Canchala *et al.*, 2024; Moges *et al.*, 2022). Therefore, the relationship between JJA ENSO and SON streamflow should not necessarily be interpreted as a direct response occurring at the same time as the index, but rather as an association between antecedent climate conditions and streamflow conditions in the subsequent season. Conversely, the stronger IOD SON–SON relationship indicates closer temporal alignment between the climate signal and hydroclimatic

Acknowledgements

The authors would like to thank the Indonesian Education Scholarship (BPI), the Centre for Higher Education Funding and Assessment (PPAPT), and the Indonesian Endowment Fund for Education (LPDP) for supporting this research (Grant Number: 00476/BPPT/BPI.06/9/2023).

Author Contributions

Conceptualization: Linda Handayani, Nanang T. Puspito, Rusmawan Suwarman; **methodology:** Linda Handayani, Rusmawan Suwarman; **investigation:** Linda Handayani, Munajat Nuraputra; **writing—original draft preparation:** Linda Handayani, Rusmawan Suwarman; **writing—review and editing:** Linda Handayani, Rustan, Nanang T. Puspito, Rusmawan Suwarman; **visualization:** Linda Handayani, Rustan, Munajat Nursaputra. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Generative AI Declaration

During the preparation of this work the author(s) used AI in order to support the writing process, including language refinement, editing, and improving of manuscript clarity. All outputs generated by the AI were reviewed and validated by the author(s).

Data availability

The data are available from the corresponding author upon reasonable request.

Funding

This research was funded by the Beasiswa Pendidikan Indonesia (BPI) through the Indonesia Endowment Fund for Education (LPDP) with grant number 00476/BPPT/BPI.06/9/2023.

response during the same season. In addition to temporal alignment, spatial contributions should also be considered. Rice and Emanuel (2017) showed that watersheds can act as spatiotemporal filters that modify how hydroclimatic signals are translated into streamflow responses, together with other geohydrological factors. This concept may also help explain the spatial variability observed in the lower Batanghari River Basin.

Although all three stations are located in the lower part of the basin, Muara Kilis exhibits the strongest associations, whereas Sungai Duren and Simpang Berbak show relatively similar magnitudes. Previous studies have also shown that the relationship between large-scale climate variability and streamflow can vary spatially among river basins because of differences in catchment characteristics and hydrological response (Pérez-Ciria *et al.*, 2022; Worako *et al.*, 2021). Muara Kilis is located relatively farther upstream than the other two stations and is adjacent to the transition between the middle and lower basin. Its position means that streamflow at the station is augmented by upstream and middle-basin catchments before the flow continues toward the downstream stations. This transition is also accompanied by a change in river morphology and topographic setting, from relatively steeper upstream and middle-basin reaches, towards a gentler and more alluvial downstream environment. The convergence of flows from upstream and middle basin contributing areas at this transition may allow the regional hydroclimatic signal to remain relatively pronounced at Muara Kilis. Further downstream, the river channel becomes increasingly meandering, as observed along the reaches toward Sungai Duren and Simpang Berbak. The greater channel sinuosity may increase the flow path and contribute to the attenuation and temporal smoothing of upstream streamflow signals during downstream propagation (Barneveld *et al.*, 2024; Paiva & Lima, 2024). In addition, increasing contributions from groundwater and baseflow in the alluvial lower reaches may further modify the streamflow signal. These processes may partly explain why the associations with ENSO and IOD are relatively stronger at Muara Kilis. However, this difference does not indicate a simple upstream-to-downstream gradient (Wohl *et al.*, 2025), as Sungai Duren and Simpang Berbak exhibit relatively similar associations.

From an applied hydrological perspective, these findings may be useful for understanding seasonal streamflow conditions in the lower Batanghari River Basin by considering the phase of climate signals rather than simply the ENSO or IOD phase. The stronger JJA ENSO–SON streamflow association indicates that ENSO conditions during JJA are more strongly linked to subsequent SON streamflow conditions, whereas SON IOD shows a closer association with streamflow variability during the same season. This finding highlights the potential relevance of antecedent climate conditions for understanding seasonal streamflow variability, consistent with previous studies examining the role of climate information in hydrological assessment (Beckers *et al.*, 2016; Petry *et al.*, 2023; Slater & Villarini, 2018). However, the findings do not constitute an evaluation of operational forecasting skill; the development of a forecasting system would require explicit assessment of lead time, hindcasts, prediction uncertainty and predictive performance.

Nevertheless, a more comprehensive understanding of the basin's hydrological system requires further investigation, particularly through spatial analysis of hydrological responses from upstream to downstream. Such an approach is essential for capturing variations in hydrological processes along the river continuum. In addition, incorporating more dynamic land use/land cover (LULC) representations with multiple time periods is necessary to better capture surface changes within the basin. This would allow for a more robust assessment of the relationship between land use change and streamflow variability. Furthermore, recent studies based on observed discharge have also highlighted the importance of considering temporal scales and hydrological persistence in climate–streamflow relationships (Mendoza *et al.*, 2026). A broader lag analysis across multiple monthly and seasonal windows is also needed in future studies to further evaluate the predictive value of ENSO and IOD for streamflow variability in the lower Batanghari River Basin.

4. Conclusion

The results show that ENSO and IOD are consistently associated with SON streamflow variability across the lower Batanghari River Basin, with negative relationships observed at all stations studied. ENSO JJA showed a stronger association with SON streamflow, whereas during the concurrent SON period, IOD showed a stronger association than ENSO. The strength of these climate–streamflow associations varied spatially and was not directly related to absolute streamflow magnitude. Muara Kilis showed the strongest statistical associations, whereas Simpang Berbak had the highest absolute streamflow, but showed correlation magnitudes comparable to those at Sungai Duren. These findings indicate that the timing of climate signals and the spatial

differences among contributing catchments are important considerations when interpreting climate-streamflow relationships in the lower Batanghari River Basin. Overall, the study provides evidence that the relative association of ENSO and IOD with streamflow varies across seasons and locations, rather than indicating a consistently stronger association of one climate mode across seasons and locations. Further research should consider a broader range of monthly and seasonal lag periods to better assess the potential predictive value.

References

- Ahmed, M. I., Stadnyk, T., Pietroniro, A., Awoye, H., Bajracharya, A., Mai, J., Tolson, B. A., Shen, H., Craig, J. R., Gervais, M., Sagan, K., Wruth, S., Koenig, K., Lilhare, R., D ry, S. J., Pokorny, S., Venema, H., Muhammad, A., & Taheri, M. (2023). Learning from hydrological models' challenges: A case study from the Nelson basin model intercomparison project. *Journal of Hydrology*, 623, 129820. <https://doi.org/10.1016/j.jhydrol.2023.129820>
- Alizadeh, O. (2024). A review of ENSO teleconnections at present and under future global warming. *Wiley Interdisciplinary Reviews: Climate Change*, 15(1), e861. <https://doi.org/10.1002/wcc.861>
- Almeida, R. A., Pereira, S. B., & Pinto, D. B. F. (2018). Calibration and Validation of the SWAT Hydrological Model for the Air Dingin Watershed. *IOP Conference Series: Earth and Environmental Science*, 515(1), 55–63. <https://doi.org/10.1088/1755-1315/515/1/012043>
- As-syakur, A. R., Adnyana, I. W. S., Mahendra, M. S., Arthana, I. W., Merit, I. N., Kasa, I. W., Ekayanti, N. W., Nuarsa, I. W., & Sunarta, I. N. (2014). Observation of spatial patterns on the rainfall response to ENSO and IOD over Indonesia using TRMM Multisatellite Precipitation Analysis (TMPA). *International Journal of Climatology*, 34(15), 3825–3839. <https://doi.org/10.1002/joc.3939>
- Aswandi, A., Arbain, A., & Mahdi, M. (2023). *Perlindungan dan Pengelolaan DAS Batanghari Berkelanjutan Melalui Kerjasama Antar Daerah*. Universitas Jambi.
- Barneveld, H. J., Mosselman, E., Chavarrias, V., & Hoitink, A. J. F. (2024). Accuracy Assessment of Numerical Morphological Models Based on Reduced Saint-Venant Equations. *Water Resources Research*, 60(1), e2023WR035052. <https://doi.org/10.1029/2023WR035052>
- Bates, B. C., & Dowdy, A. J. (2024). Discerning the influence of climate variability modes, regional weather features and time series persistence on streamflow using Bayesian networks and multiple linear regression. *International Journal of Climatology*, 44(4), 997–1013. <https://doi.org/10.1002/joc.8368>
- Beckers, J. V. L., Weerts, A. H., Tiedeman, E., & Welles, E. (2016). ENSO-conditioned weather resampling method for seasonal ensemble streamflow prediction. *Hydrology and Earth System Sciences*, 20(8), 3277–3287. <https://doi.org/10.5194/hess-20-3277-2016>
- Busico, G., Colombani, N., Fronzi, D., Pellegrini, M., Tazioli, A., & Mastrocicco, M. (2020). Evaluating SWAT model performance, considering different soils data input, to quantify actual and future runoff susceptibility in a highly urbanized basin. *Journal of Environmental Management*, 266, 110625. <https://doi.org/10.1016/j.jenvman.2020.110625>
- Canchala, T., Carvajal-Escobar, Y., Alfonso-Morales, W., Torres, W. A., S nchez-Torres, L. D., & Cer n, W. L. (2024). Seasonal influence of tropical Pacific and Atlantic sea surface temperature on streamflow variability in the patia river basin. *Theoretical and Applied Climatology*, 155(6), 5417–5431. <https://doi.org/10.1007/s00704-024-04934-6>
- Caretta, M. A., Mukherji, A., Arfanuzzaman, M., Betts, R. A., Gelfan, A., Hirabayashi, Y., Lissner, T. K., Liu, J., Lopez Gunn, E., Morgan, R., Mwanga, S., & Supratid, S. (2023). Water. In *Climate Change 2022: Impacts, Adaptation and Vulnerability* (pp. 551–712). Cambridge University Press. <https://doi.org/10.1017/9781009325844.006>
- Caroletti, G. N., Coscarelli, R., & Caloiero, T. (2021). A sub-regional approach to the influence analysis of teleconnection patterns on precipitation in Calabria (southern Italy). *International Journal of Climatology*, 41(9), 4574–4586. <https://doi.org/10.1002/joc.7087>
- Chen, X., Leung, L. R., Wigmosta, M., & Richmond, M. (2019). Impact of Atmospheric Rivers on Surface Hydrological Processes in Western U.S. Watersheds. *Journal of Geophysical Research: Atmospheres*, 124(16), 8896–8916. <https://doi.org/10.1029/2019JD030468>
- Depetris, P. J. (2021). The Importance of Monitoring River Water Discharge. *Frontiers in Water*, 3, 745912. <https://doi.org/10.3389/frwa.2021.745912>
- dos Santos, D. C., Santos, C. A. G., Brasil Neto, R. M., da Silva, R. M., & dos Santos, C. A. C. (2023). Precipitation variability using GPCC data and its relationship with atmospheric teleconnections in Northeast Brazil. *Climate Dynamics*, 61(11–12), 5035–5048. <https://doi.org/10.1007/s00382-023-06838-z>
- Du, Y., Zhang, Y., Zhang, L. Y., Tozuka, T., Ng, B., & Cai, W. (2020). Thermocline Warming Induced Extreme Indian Ocean Dipole in 2019. *Geophysical Research Letters*, 47(18), e2020GL090079. <https://doi.org/10.1029/2020GL090079>
- Gao, C., Chen, M., Zhou, L., Feng, L., & Zhang, R. H. (2022). The 2020–2021 prolonged La Ni a evolution in the tropical Pacific. *Science China Earth Sciences*, 65(12), 2248–2266. <https://doi.org/10.1007/s11430-022-9985-4>
- Gao, J., Li, C., Zhou, X., Yi, Y., Wang, X., & Liu, Q. (2025). Climate change and human activities amplify runoff variability risks in lower reaches of large rivers. *Communications Earth and Environment*, 6(1), 794. <https://doi.org/10.1038/s43247-025-02759-3>
- Handoko, E. Y., Syariz, M. A., & Wenda, P. J. (2023). Estimation of Sea Surface Topography Using Jason-3 Satellite Altimetry Across the Eastern Indonesian Seas in a period of 2016 to 2021. *IOP Conference Series: Earth and Environmental Science*, 1276(1), 12010. <https://doi.org/10.1088/1755-1315/1276/1/012010>
- Hanifa, R., & Wiratmo, J. (2024). ENSO and IOD Influence on Extreme Rainfall in Indonesia: Historical and Future Analysis. *Agromet*, 38(2), 78–87. <https://doi.org/10.29244/j.agromet.38.2.78-87>
- Huang, A., Gao, G., Yao, L., Yin, S., Li, D., Xuan Do, H., & Fu, B. (2024). Spatiotemporal variations of inter- and intra-annual extreme streamflow in the Yangtze River Basin. *Journal of Hydrology*, 629, 130634. <https://doi.org/10.1016/j.jhydrol.2024.130634>
- Iskandar, I., Lestrai, D. O., & Nur, M. (2019). Impact of El Ni o and El Ni o Modoki Events on Indonesian Rainfall. *Makara Journal of Science*, 23(4), 217–222. <https://doi.org/10.7454/mss.v23i4.11517>
- Iswari, M. Y., & Anggraini, K. (2018). Demnas: Model Digital Ketinggian Nasional Untuk Aplikasi Kepesisiran. *Oseana*, 43(4). <https://doi.org/10.14203/oseana.2018.vol.43no.4.2>
- Jia, W., Wu, Y., Wang, S., Chen, M., & Liu, X. (2023). Combined Impacts of ENSO and IOD on Streamflow: A Case Study of the Jinsha River Basin, China. *Water (Switzerland)*, 15(1), 45. <https://doi.org/10.3390/w15010045>

- Kasera, R., & Minocha, V. K. (2025). Impact of El Niño onset timing on Indian Monsoon Rainfall patterns. *Global and Planetary Change*, 245, 104689. <https://doi.org/10.1016/j.gloplacha.2024.104689>
- Kurniadi, A., Weller, E., Min, S. K., & Seong, M. G. (2021). Independent ENSO and IOD impacts on rainfall extremes over Indonesia. *International Journal of Climatology*, 41(6), 3640–3656. <https://doi.org/10.1002/joc.7040>
- Lei, Q., Zhang, T., An, M., Luo, J., Qin, L., Zhu, A. X., Qiu, W., Du, X., & Liu, H. (2024). Sensitivity analysis of SWAT streamflow and water quality to the uncertainty in soil properties generated by the SoLIM model. *Journal of Hydrology*, 642, 131879. <https://doi.org/10.1016/j.jhydrol.2024.131879>
- Lu, B., & Ren, H. (2020). What caused the extreme Indian Ocean Dipole event in 2019? *Geophysical Research Letters*, 47(11), e2020GL087768.
- Marek, G. W., Gowda, P. H., Evett, S. R., Baumhardt, R. L., Brauer, D. K., Howell, T. A., Marek, T. H., & Srinivasan, R. (2016). Calibration and validation of the SWAT model for predicting daily ET over irrigated crops in the Texas High Plains using lysimetric data. *Transactions of the ASABE*, 59(2), 611–622. <https://doi.org/10.13031/trans.59.10926>
- Marhaento, H., Booi, M. J., & Hoekstra, A. Y. (2018). Hydrological response to future land-use change and climate change in a tropical catchment. *Hydrological Sciences Journal*, 63(9), 1368–1385. <https://doi.org/10.1080/02626667.2018.1511054>
- Mendoza, L. A. F., Lima, A. G. G., de Mello, H. D., Maceira, M. E. P., Melo, A. C. G., & Pacheco, M. A. C. (2026). Data-Driven Detection of Climate–Streamflow Dependencies and Multi-Year Hydrological Persistence in Brazilian Reservoir Systems. *Water (Switzerland)*, 18(12), 1499. <https://doi.org/10.3390/w18121499>
- Moges, E., Ruddell, B. L., Zhang, L., Driscoll, J. M., & Larsen, L. G. (2022). Strength and Memory of Precipitation's Control Over Streamflow Across the Conterminous United States. *Water Resources Research*, 58(3), e2021WR030186. <https://doi.org/10.1029/2021WR030186>
- Mulsandi, A., Koesmaryono, Y., Hidayat, R., Faqih, A., & Sopaheluwakan, A. (2024). On The Interannual Variability of Indonesian Monsoon Rainfall (IMR): A Literature Review of The Role of its External Forcing. *Jurnal Meteorologi Dan Geofisika*, 24(2), 115–127. <https://doi.org/10.31172/jmg.v24i2.1049>
- Norel, M., Kalczyński, M., Pińskwar, I., Krawiec, K., & Kundzewicz, Z. W. (2021). Climate variability indices—a guided tour. *Geosciences (Switzerland)*, 11(3), 1–27. <https://doi.org/10.3390/geosciences11030128>
- Nugroho, A. R., Tamagawa, I., & Harada, M. (2021). The relationship between river flow regimes and climate indices of ENSO and IOD on code river, southern Indonesia. *Water (Switzerland)*, 13(10), 1375. <https://doi.org/10.3390/w13101375>
- Nursaputra, M., Suwarman, R., & Riawan, E. (2026). Spatiotemporal classification of flood-triggering rainfall in urban watersheds of Mamminasata, Indonesia. *Natural Hazards*, 122(17), 599. <https://doi.org/10.1007/s11069-026-08365-6>
- Oruç, H. N., Çelen, M., Gülgen, F., Öncel, M. S., Vural, S., & Kılıç, B. (2023). Evaluating the effects of soil data quality on the SWAT runoff prediction Performance; A case study of Saz-Cayirova catchment, Turkey. *Urban Water Journal*, 20(10), 1592–1607. <https://doi.org/10.1080/1573062X.2022.2056060>
- Paiva, R. C. D., & Lima, S. G. (2024). A Simple Model of Flood Peak Attenuation. *Water Resources Research*, 60(2), e2023WR034692. <https://doi.org/10.1029/2023WR034692>
- Pérez-Ciria, T., Labat, D., & Chiogna, G. (2022). Heterogeneous spatiotemporal streamflow response to large-scale climate indexes in the Eastern Alps. *Journal of Hydrology*, 615, 128698. <https://doi.org/10.1016/j.jhydrol.2022.128698>
- Permatasari, R., Ilhamsyah, Y., Purnawan, S., Setiawan, I., Ramadhaniaty, M., Sutarni, S., & Pristiwantoro, E. C. (2022). The influences of the Indian Ocean Dipole (IOD) on rainfall in South Aceh. *Depik*, 11(3), 306–312. <https://doi.org/10.13170/depik.11.3.25984>
- Petry, I., Fan, F. M., Siqueira, V. A., Collishonn, W., de Paiva, R. C. D., Quedi, E., de Araújo Gama, C. H., Silveira, R., Freitas, C., & Paranhos, C. S. A. (2023). Seasonal streamflow forecasting in South America's largest rivers. *Journal of Hydrology: Regional Studies*, 49, 101487. <https://doi.org/10.1016/j.ejrh.2023.101487>
- Putri Maulida, N., Ariska, M., Suhadi, S., & Akhsan, H. (2025). Rainfall Characteristics in Kalimantan Island During ENSO and IOD Phases: Insights from Composite Analysis. *Jurnal Ilmu Fisika | Universitas Andalas*, 17(1), 88–100. <https://doi.org/10.25077/jif.17.1.88-100.2025>
- Rice, J. S., & Emanuel, R. E. (2017). How are streamflow responses to the El Niño Southern Oscillation affected by watershed characteristics? *Water Resources Research*, 53(5), 4393–4406. <https://doi.org/10.1002/2016WR020097>
- Ridwansyah, I., Apip, A., Wibowo, H., Rahmadya, A., Susiwiidyaliza, S., Handoko, U., Setiawan, F., & Utami, N. (2023). The Impact of Land-Use and Climate Change on Water and Sediment Yields in Batanghari Watershed, Sumatra, Indonesia. *Sains Malaysiana*, 52(3), 705–721. <https://doi.org/10.17576/jsm-2023-5203-03>
- Sahu, N., Behera, S. K., Yamashiki, Y., Takara, K., & Yamagata, T. (2012). IOD and ENSO impacts on the extreme stream-flows of Citarum river in Indonesia. *Climate Dynamics*, 39(7–8), 1673–1680. <https://doi.org/10.1007/s00382-011-1158-2>
- Schad, P. (2023). World Reference Base for Soil Resources—Its fourth edition and its history. *Journal of Plant Nutrition and Soil Science*, 186(2), 151–163. <https://doi.org/10.1002/jpln.202200417>
- Semlali, I., Ouadif, L., Baba, K., Akhssas, A., & Bahi, L. (2017). Using GIS and SWAT model for hydrological modelling of Oued Laou Watershed (Morocco). *ARPJ Journal of Engineering and Applied Sciences*, 12(23), 6933–6943.
- Shabir, M. H., Shakoor, A., & Hafeez, I. (2025). Hydrological modeling with SWAT: A case study of Shahpur catchment. *Meteorology Hydrology and Water Management*, 13(1), 20–39. <https://doi.org/10.26491/mhwm/208181>
- Shelton, S., & Lin, Z. (2019). Streamflow variability over the Period of 1990-2014 in Mahaweli River basin, Sri Lanka and its possible mechanisms. *Water (Switzerland)*, 11(12), 2485. <https://doi.org/10.3390/w11122485>
- Sinaga, E. R., Suwarman, R., Riawan, E., Simanjuntak, Y. S. M., & Djamil, Y. S. (2022). Analysis of the Variation of the Upper Citarum Discharge and Its Relationship with La Niña. *Springer Proceedings in Physics*, 275, 605–612. https://doi.org/10.1007/978-981-19-0308-3_48
- Slater, L. J., & Villarini, G. (2018). Enhancing the Predictability of Seasonal Streamflow With a Statistical-Dynamical Approach. *Geophysical Research Letters*, 45(13), 6504–6513. <https://doi.org/10.1029/2018GL077945>
- Song, C., Zhang, X., Zheng, F., Chen, X., & Jiang, H. (2022). The Roles of Off-Equatorial Subsurface Cold-Water Incursions in Triggering the Second-Year Cooling of the La Niña Event in 2021. *Journal of Marine Science and Engineering*, 10(11), 1667. <https://doi.org/10.3390/jmse10111667>
- Suwarman, R., Ichianagi, K., Tanoue, M., Yoshimura, K., Mori, S., Yamanaka, M. D., Syamsudin, F., & Belgaman, H. A. (2017). El niño southern oscillation signature in atmospheric: Water isotopes over maritime continent during wet season. *Journal of the Meteorological Society of Japan*, 95(1), 49–66. <https://doi.org/10.2151/jmsj.2017-003>

- Ummenhofer, C. C., D'Arrigo, R. D., Anchukaitis, K. J., Buckley, B. M., & Cook, E. R. (2013). Links between Indo-Pacific climate variability and drought in the Monsoon Asia Drought Atlas. *Climate Dynamics*, 40(5–6), 1319–1334. <https://doi.org/10.1007/s00382-012-1458-1>
- Wang, C. (2002). Atmospheric circulation cells associated with the El Niño-Southern Oscillation. *Journal of Climate*, 15(4), 399–419. [https://doi.org/10.1175/1520-0442\(2002\)015<0399:ACCAWT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<0399:ACCAWT>2.0.CO;2)
- Wang, H., Liu, J., Klaar, M., Chen, A., Gudmundsson, L., & Holden, J. (2024). Anthropogenic climate change has influenced global river flow seasonality. *Science*, 383(6686), 1009–1014. <https://doi.org/10.1126/science.adi9501>
- Wang, S., Chen, F., Hu, M., Chen, Y., Cao, H., Yue, W., & Zhao, X. (2024). Past, present and future changes in the annual streamflow of the Lancang-Mekong River and their driving mechanisms. *Science of the Total Environment*, 947, 174707. <https://doi.org/10.1016/j.scitotenv.2024.174707>
- Weller, E., & Cai, W. (2014). Meridional variability of atmospheric convection associated with the Indian Ocean Dipole Mode. *Scientific Reports*, 4(1), 3590. <https://doi.org/10.1038/srep03590>
- Wohl, E., Clark, M., Li, L., Soulsby, C., & Tetzlaff, D. (2025). Knots in the Strings: Do Small-Scale River Features Shape Catchment-Scale Fluxes? *Wiley Interdisciplinary Reviews: Water*, 12(5), e70036. <https://doi.org/10.1002/wat2.70036>
- Worako, A. W., Haile, A. T., & Taye, M. T. (2021). Streamflow variability and its linkage to ENSO events in the Ethiopian Rift Valley Lakes Basin. *Journal of Hydrology: Regional Studies*, 35, 100817. <https://doi.org/10.1016/j.ejrh.2021.100817>
- Xiao, H. M., Lo, M. H., & Yu, J. Y. (2022). The increased frequency of combined El Niño and positive IOD events since 1965s and its impacts on maritime continent hydroclimates. *Scientific Reports*, 12(1), 7532. <https://doi.org/10.1038/s41598-022-11663-1>
- Yamamoto, K., Sayama, T., & Apip. (2021). Impact of climate change on flood inundation in a tropical river basin in Indonesia. *Progress in Earth and Planetary Science*, 8(1), 5. <https://doi.org/10.1186/s40645-020-00386-4>
- Yan, Y., Wu, H., Gu, G., Ward, P. J., Luo, L., Li, X., Huang, Z., & Tao, J. (2020). Exploring the ENSO Impact on Basin-Scale Floods Using Hydrological Simulations and TRMM Precipitation. *Geophysical Research Letters*, 47(22), e2020GL089476. <https://doi.org/10.1029/2020GL089476>
- You, Y., Liu, J., Zhang, Y., Beck, H. E., Gu, X., & Kong, D. (2021). Impacts of El Niño–southern oscillation on global runoff: Characteristic signatures and potential mechanisms. *Hydrological Processes*, 35(10), e14367. <https://doi.org/10.1002/hyp.14367>
- Zhang, R. H., Min, Q. Y., & Su, J. Z. (2017). Impact of El Niño on atmospheric circulations over East Asia and rainfall in China: Role of the anomalous western North Pacific anticyclone. *Science China Earth Sciences*, 60(6), 1124–1132. <https://doi.org/10.1007/s11430-016-9026-x>
- Zhu, M., Yu, D., Yu, Y., Zheng, Y., Li, S., Cai, X., & Chen, N. (2025). ENSO Enhances Seasonal River Discharge Instability and Water Resource Allocation Pressure. *Water Resources Research*, 61(1), e2023WR036965. <https://doi.org/10.1029/2023WR036965>