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The Impact of Climate Change Projections on Flood Vulnerability of Electrical Infrastructure in the Kapuas River Basin, West Kalimantan

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ABSTRACT

Climate change has increased the frequency and intensity of extreme hydrometeorological events, particularly floods, which have the potential to disrupt the reliability of the electricity system in West Kalimantan. This study aims to examine historical rainfall conditions and projections until 2060, map flood risk in the Kapuas watershed, and assess its impact on the electricity system. Rainfall analysis was conducted using CMIP6 climate projection data based on the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios for the 2026–2060 period. Flood risk mapping was carried out spatially using the Weighted Linear Combination (WLC) approach, incorporating parameters such as rainfall, land slope, land cover, and soil texture. Furthermore, flood risk maps were overlaid with transmission infrastructure and substations in the Kapuas watershed to identify vulnerability levels. The results show that the Kapuas watershed will remain in the very wet climate category until 2060, with more than 300 rainy days per year and an increasing tendency for extreme rainfall intensity, especially under the SSP5-8.5 scenario. Flood risk mapping indicates that most areas of the Kapuas watershed consistently fall within the high to very high flood risk category, particularly in downstream and lowland regions. The overlay results reveal that more than 85% of transmission towers and nearly all substations are located within high flood risk zones.

Keywords: climate change, floods, Kapuas watershed, electricity

INTRODUCTION

West Kalimantan is highly vulnerable to disasters arising from climate change. Changing rainfall patterns and increasing extreme weather events, such as intense rainfall that triggers flooding, are becoming more frequent. Based on data from the National Disaster Management Agency (BNPB), between 2019 and 2023 there were 684 recorded flood incidents, with 609 of them occurring in the Kapuas watershed (Bencana, 2021).

Globally, the energy sector increasingly recognizes climate risk as a material threat to operations and asset management. A report by the International Energy Agency (IEA) highlights that extreme weather events—including floods, storms, and heatwaves—are already causing significant disruptions to global energy supplies, leading to economic losses measured in billions of dollars (IEA, 2022). For instance, major flood events in Thailand (2011) and Australia (2022) caused widespread and prolonged power outages, demonstrating the cascading failures that can occur when a few critical nodes in the network are damaged. These global precedents underscore the necessity for robust, forward-looking climate risk assessments to inform the planning and design of resilient energy infrastructure, particularly in regions projected to experience increased hydrological extremes.

Flooding events have a direct impact on extending the duration of power system outages. Flood incidents in West Kalimantan have caused power outages that brought economic, educational, governmental, and health service activities in several affected areas to a standstill (Novianti & Jiu, 2024). These incidents occurred because electricity infrastructure was submerged, forcing operators to shut down power distribution. The disruption of electricity access due to flood-related blackouts prevents people from using electricity for economic, social, and daily activities. Flooding in West Kalimantan Province is driven by high rainfall, water discharge exceeding river capacity, deforestation, and land-use changes.

The urgency of this research is paramount. Given the long lifespan of electricity infrastructure—often 50 years or more—assets built today must be resilient to future climate conditions. Decisions regarding the siting, design, and reinforcement of transmission towers and substations must rely on projected risks, not merely historical data. The increasing frequency of extreme flood events in West Kalimantan, as documented by BNPB (2021), coupled with the critical role of electricity in supporting modern society, makes this analysis not only academically important but also a practical necessity for disaster risk reduction and climate adaptation planning. Without such foresight, investments in energy infrastructure risk being undermined by avoidable climate impacts.

The novelty of this research lies in its integrated, forward-looking methodology. To the best of the authors' knowledge, it is the first study to systematically overlay high-resolution CMIP6 climate projections (SSP1-2.6, SSP2-4.5, and SSP5-8.5) for the period 2026–2060 with a detailed geospatial inventory of electricity transmission and substation infrastructure within the Kapuas River Basin. By employing a Weighted Linear Combination (WLC) approach within a GIS framework, this study moves beyond static hazard mapping to produce a dynamic assessment of future flood vulnerability for a specific and critical infrastructure system. This approach offers a more robust and realistic basis for adaptation planning.

The primary objective of this research is threefold: first, to analyze historical and projected rainfall patterns in the Kapuas watershed up to 2060 under different climate scenarios; second, to map the spatial distribution of flood risk based on these projections and physical parameters; and third, to assess the vulnerability of existing electricity transmission and substation infrastructure by overlaying flood risk maps with asset locations. The central aim is to quantify the proportion and location of infrastructure at high to very high risk of future flooding.

This research is expected to yield significant theoretical and practical contributions. Theoretically, it advances the growing body of literature on climate change impacts on critical infrastructure by presenting a replicable methodology for integrating climate projections with spatial vulnerability analysis. Practically, the findings will offer actionable insights for policymakers, planners, and utility companies. Identifying "flood-critical corridors" and "nodes" within the electricity network will enable targeted investments in adaptation measures such as structural hardening of existing assets, strategic relocation where feasible, and the inclusion of climate risk considerations in spatial planning for future grid expansions. Ultimately, this research aims to support the development of a more resilient and reliable electricity system for the people of West Kalimantan.

RESEARCH METHOD

This study examines the impact of flood events on the electricity system in the Kapuas watershed, West Kalimantan Province, to anticipate potential losses caused by future flooding. The study projects the frequency and extent of floods in upcoming periods using the CMIP6 Shared Socioeconomic Pathways (SSP) scenarios—namely SSP1-2.6, SSP2-4.5, and SSP5-8.5—based on rainfall or precipitation indicators.

Rainfall projection data for the 2026–2060 period in the Kapuas watershed for each scenario were obtained from the Power Data Access Viewer (DAV) through the NASA NEX-GDDP-CMIP6 dataset, with a spatial resolution of 0.25° × 0.25° (approximately 25 km × 25 km in the equatorial region). These data can be accessed via Google Earth Engine. The use of NEX-GDDP-CMIP6 data from GEE has been widely applied in scientific research, including analyses of extreme rainfall trends, variations in rainy seasons, and the increasing frequency of flood events. In many climate and impact studies, NEX-GDDP-CMIP6 is treated as a bias-corrected dataset and can be used directly without additional corrections, particularly for climatological analyses and regional-scale trend studies. Rainfall projection data for the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios in this study were used without bias correction because the focus was on relative changes and long-term trends. For regional-scale climate change analyses that emphasize anomalies and relative shifts compared with a baseline period, using raw model outputs without bias correction is considered more appropriate, as it maintains the dynamic and physical consistency of long-term change signals (Maraun et al., 2017).

The simulation results were then processed to model flood-affected areas using QGIS spatial data processing software. The output of this modeling served as the basis for identifying areas vulnerable to flooding by applying the Multi-Criteria Analysis (MCA) approach through the Weighted Linear Combination (WLC) method. Variables included projected rainfall (2026–2060) for each SSP scenario, land cover or land use, land slope, and soil texture, all of which were used to analyze the Flood Vulnerability Index (Indeks Kerentanan Banjir or IKB) of the Kapuas watershed. At this stage, each raster of the scoring criteria was multiplied by its corresponding variable weight, and all weighted rasters were summed to produce a composite index raster representing vulnerability or flood hazard/risk (Wang et al., 2018).
The value of the Flood Vulnerability Index (IKB) is calculated using the following weighted equation:

$$IKB = (0{,}30 \times H) + (0{,}30 \times L) + (0{,}20 \times S) + (0{,}20 \times T)$$

Description:
H = Annual Rainfall
L = Land Cover/Land Use
S = Slope
T = Infiltration and Soil Texture
With the weighting of each variable in Table 1.

Table 1 Weighting of the Flood Vulnerability Index

Yes	Data Type	Weight
1	Projected Rainfall SSP1-2.6, SSP2-4.5 and SSP5-8.5	0,30
2	Land Cover	0,30
3	Slope of the Land	0,20
4	Soil Texture	0.20

Source: Author Analysis, 2025

Each flood vulnerability parameter is classified into five to nine classes, with a scale of values indicating that the higher the score, the greater the level of flood vulnerability. The combination of weights reflects the dominance of hydrometeorological factors and land cover characteristics in influencing the level of flood risk, with rainfall being the most influential factor (Ariyani et al., 2024; Seprianto, 2024). The scale of values of each variable can be seen in Table 2 to Table 4.

Table 2. Rainfall Classification

Yes	Annual Rainfall (mm)	Remarks	Value	Weight
1	>3000	>Very wet	5	0,3
2	2501 – 3000	Wet	4	
3	2001 – 2500	Medium	3	
4	1501 – 2000	Dry	2	
5	<1500	Very Dry	1	

Source: (Yassar, 2020)

Table 3. Slope of the Kapuas Watershed

No	Slope	Remarks	Value	Weight	Area (km2)
1	0 – 8	Datar	5	0,2	68.500,33
2	8 – 15	Sloping	4		11.815,54
3	15 – 25	A bit steep	3		11.462,52
4	25 – 40	Curam	2		7.022,26
5	>40	Very Steep	1		1.260,67
		Quantity			100,061,32

Source: (Darmawan, 2017).

Table 4. Kapuas Watershed Land Use

No	Types of Land Cover	Land Cover Categories	Value	Weight	Wide (km2)
1	Primary Land Forest	Primary Dryland Forests	1	0,30	19337,691
2	Secondary Land Forests	Secondary Dryland Forest	1		714,941
3	Secondary Swamp Forest	Secondary Dryland Forest	1		7584,416
4	Plantation Forest	Plantation Forest	1		498,552
5	Primary Swamp Forest	Primary Dryland Forests	1		72.009
6	Secondary Dryland Forest	Secondary Dryland Forest	1		13686,318
7	Perkebunan	Perkebunan	3		9234,509
8	Bushes	Bushes	5		1917,151
9	Swamp Bushes	Bushes	5		2177,931
10	Settlements	Settlement	7		321,707
11	Mixed Dryland Farming	Mixed Dryland Agriculture	7		39462,558
12	Transmigration	Settlement	7		86,418
13	Dryland Agriculture	Dryland Agriculture	7		903,574
14	Airport/Port	Airport/Port	9		0,575

No	Types of Land Cover	Land Cover Categories	Value	Weight	Wide (km2)
15	Open Ground	Open Ground	9		1472,983
16	Tambak	Water bodies	9		23,541
17	Mining	Mining	9		405,070
18	Rice Fields	Rice Fields	9		339,421

Source: Yassar et al., 2020

Table 5. Types and Textures of Kapuas Watershed Soil

No	Soil Texture	Soil Texture Categories	Value	Weight	Wide (km2)
1	(Cl) *Clay*	Subtle - Insensitive	5	0,20	12090,223
2	(SiCl) *Silty Clay*	Subtle - Insensitive	5		0,788
3	(SaCl) *Sandy Clay*	Subtle - Insensitive	5		129,683
4	(ClLo) *Clay Loam*	Quite subtle - Insensitive	5		58786,508
5	(SiClLo) *Silty Clay Loam*	A bit subtle - a bit sensitive	4		1,973
6	(SaClLo) *Sandy Clay Loam*	Moderate subtlety - quite sensitive	4		9400,432
7	(Lo) *Loam*	Medium subtlety - medium sensitivity	3		18752,591
8	(SiLo) *Silty Loam*	Medium subtlety - medium sensitivity	3		0,054
9	(SaLo) *Sandy Loam*	It's A Bit Rough - Sensitive	2		84,245

Source: Darmawan and Suprayogi, 2017

RESULTS AND DISCUSSION

a. SSP Scenario Rainfall Projection

The predicted rainfall trend of the Kapuas watershed in 2026 – 2060 based on scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5 is involved in Figure 1 to Figure 4.

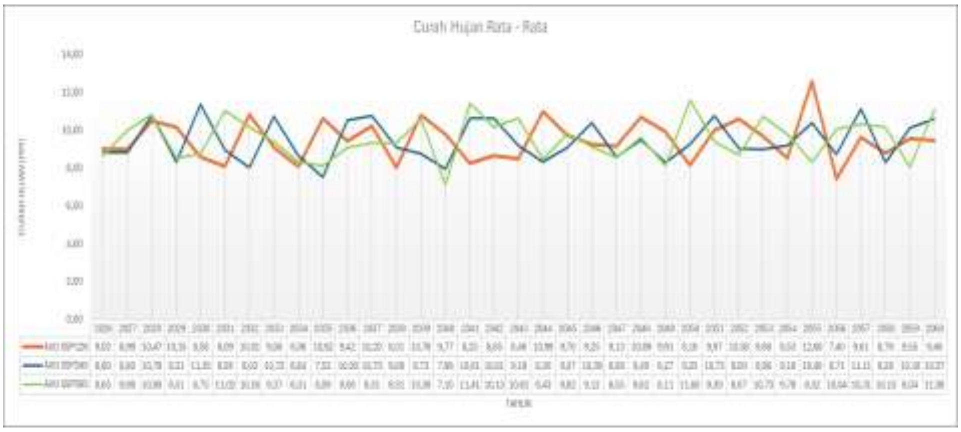

Figure 1. Average Rainfall for SSP Scenario in 2026 -2060

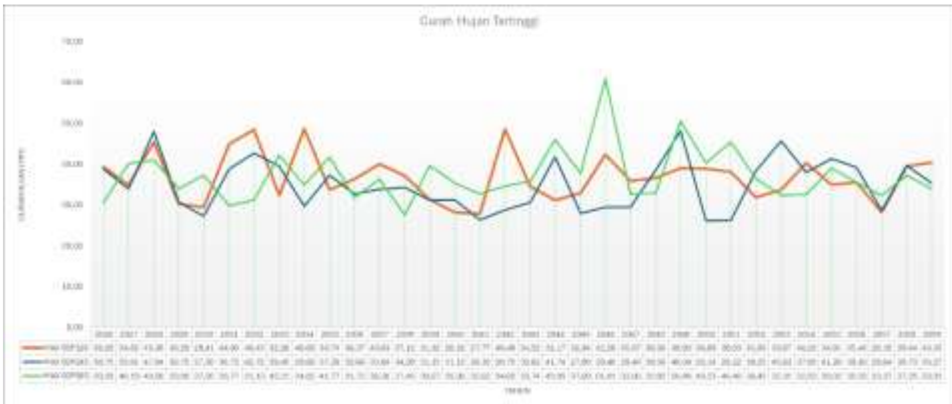

Figure 2. Highest Rainfall in the SSP Scenario in 2026 -2060

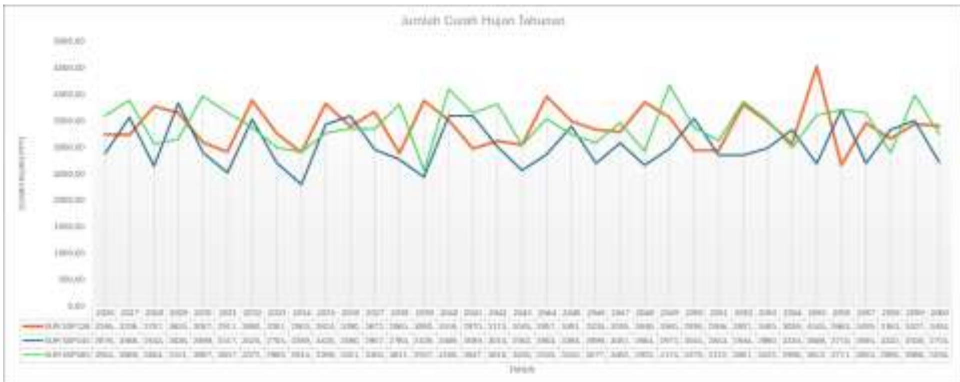

Figure 3. Total Rainfall for the SSP Scenario in 2026 -2060

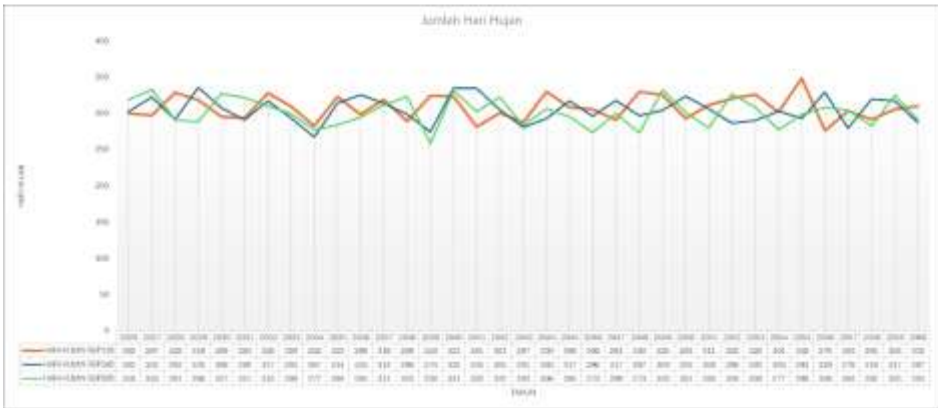

Figure 4. Number of Rainy Days in the SSP Scenario in 2026 -2060

In the SSP1-2.6 scenario, average rainfall tends to range between 8.0–10.5 mm/day, with certain years showing positive anomalies of up to about 12.6 mm/day. This pattern reflects climatic conditions under relatively high levels of emission mitigation, resulting in more moderate and stable changes in rainfall. The SSP2-4.5 scenario shows slightly higher averages, with rainfall values ranging from 7.5–11.3 mm/day. Meanwhile, the SSP5-8.5 scenario exhibits the highest variability among the three, with an average rainfall range of about 7.1–11.6 mm/day. This pattern reflects high-emission climate conditions, which tend to increase climate uncertainty and interannual fluctuations in rainfall, although the mean value is not always higher than in other scenarios (IPCC, 2021). The SSP5-8.5 scenario produces slightly higher and more volatile rainfall averages than SSP1-2.6 and SSP2-4.5, particularly during 2050–2060. This finding aligns with studies indicating that high-emission scenarios increase atmospheric water vapor content, thereby amplifying the potential for heavy rainfall, even when the average increase is not always statistically significant (Trenberth, 2011; Westra, 2014).

The annual maximum rainfall during 2026–2060 shows significant interannual variability across the SSP scenarios, with daily maximum values generally ranging between approximately 26–61 mm/day. This pattern is consistent with CMIP6 projections, which suggest that the intensity and frequency of extreme daily rainfall events are increasing and remain episodic, while changes in mean rainfall are smaller but can still raise flood risk (Almazroui, 2021). In the SSP1-2.6 scenario, maximum annual rainfall is typically around 29–49 mm/day, with the peak value recorded at approximately 49.21 mm/day. The SSP2-4.5 scenario exhibits a broader range of extremes, from around 28–60 mm/day, with the highest value reaching about 60.10 mm/day—one of the greatest maxima among all scenarios. This suggests that under medium-emission conditions, the potential for extreme rainfall events can increase sporadically and with greater intensity than under SSP1-2.6. Conversely, the SSP5-8.5 scenario shows the highest extreme variability and intensity, with annual maximum rainfall levels between approximately 29–61 mm/day. The highest peak value, around 61.01 mm/day, reflects a greater potential for extreme rainfall under high-emission conditions. Additionally, the frequency of occurrences exceeding 45–50 mm/day appears to be higher than in the other two scenarios. The main differences among the SSPs lie not only in the maximum averages but also in the magnitude of extreme peaks and interannual variability, with high-emission scenarios demonstrating the greatest extremes. This pattern is consistent with global and regional CMIP6 results, which indicate strong increases in extreme daily rainfall indices (Rx1day, R99p) and flood-related characteristics based on recurrence periods—especially under SSP5-8.5—thus heightening the risks of surface runoff, inundation, and drainage system failure (Scoccimarro & Gualdi, 2020).

Annual rainfall totals for 2026–2060 display considerable year-to-year fluctuations across all SSP scenarios, ranging generally between about 2,500–4,500 mm/year. This variability confirms that climate change affects not only daily rainfall intensity but also annual accumulation, which influences water balance and long-term flood potential (Alfieri, 2017; Chen, 2021; Hirabayashi, 2013; Kourgialas, 2016; Rentschler, 2022; Tabari, 2020; Zhang, 2019). Under the SSP1-2.6 scenario, annual rainfall ranges from approximately 2,585–4,492 mm/year, with most years between 3,000–3,700 mm/year. The SSP2-4.5 scenario presents a similar range of about 2,640–4,340 mm/year, although its annual accumulation tends to be more volatile than that in SSP1-2.6, with notable increases in certain years. Meanwhile, the SSP5-8.5 scenario exhibits the greatest annual variability and accumulation, ranging from around 2,900–4,360 mm/year. The highest value of approximately 4,360 mm/year and more frequent annual totals above 3,800 mm/year reflect the tendency of high-emission scenarios to amplify climate uncertainty and the potential for large yearly rainfall accumulations.

The number of annual rainy days during 2026–2060 indicates that the study area remains under very wet climatic conditions, with consistently high totals across all SSP scenarios. Generally, the number of rainy days ranges between about 270–345 days/year, suggesting that rainfall occurs throughout most of the year, though with varying intensity. Under SSP1-2.6, the annual count ranges from roughly 280–345 days/year, with most years recording over 300 rainy days—conditions that denote a high yet relatively stable rainfall frequency. The SSP2-4.5 scenario shows comparable conditions, with values between 275–335 days/year and a maximum reaching about 335 days/year. The SSP5-8.5 scenario similarly shows rainy days between approximately 270–335 days/year, with some years exceeding 330 days. Although this scenario is associated with more climate extremes, the results suggest that hydrometeorological risk arises more from rainfall intensity and annual accumulation than from an increase in the number of rainy days.

Based on the CMIP6 climate projections for SSP1-2.6, SSP2-4.5, and SSP5-8.5 during 2026–2060, rainfall characteristics in the study area indicate persistently wet conditions with high climatic variability. On average, daily rainfall ranges between approximately 8–12 mm/day across all SSP scenarios. These averages remain relatively stable across both scenarios and years, indicating no significant linear increase. However, stability in mean values does not fully capture hydrometeorological risk because it overlooks extreme event dynamics. This is evident from the maximum daily rainfall values, which vary widely between about 26–61 mm/day. The SSP5-8.5 scenario records the highest single-day maximum (about 61 mm/day), followed by SSP2-4.5 (about 60 mm/day) and SSP1-2.6 (around 49 mm/day). Daily extreme rainfall exceeding 50 mm/day contributes significantly to increased surface runoff and flood potential, even though such events do not occur every year.

Regarding accumulation, annual rainfall totals range from approximately 2,500–4,500 mm/year, with some years in all scenarios surpassing 4,000 mm/year. This high annual accumulation indicates that the Kapuas watershed consistently experiences hydrological surplus, leading to long-term soil saturation, especially during sequences of extreme rainfall events. Furthermore, the area records a very high number of rainy days (roughly 270–345 days/year), with most years exceeding 300 rainy days. This implies that rainfall occurs almost year-round, limiting soil and drainage system recovery time.

b. Kapuas Watershed Electricity Infrastructure Flood Vulnerability Index

The value of the Flood Vulnerability Index (IKB) is calculated using *the weighted linear combination* (WLC) approach, which is by adding up the results of the multiplication between the weight and score of each variable or parameter that makes up flood vulnerability. This approach is commonly used in flood hazard mapping based on Geographic Information Systems (GIS) because it is able to represent the relative contribution of each parameter to the level of vulnerability quantitatively (Tehrany et al., 2017). The Kapuas Watershed Flood Vulnerability Index (IKB) refers to the highest amount of rainfall from each SSP scenario. In the SSP1-2.6 scenario, the highest rainfall is projected in 2054 with a total rainfall of 4535.35 mm/year. The SSP2-4.5 scenario has the highest amount of rainfall in 2029 with the highest rainfall reaching 3836.96 mm/year. In the SSP5-8.5 scenario, rainfall projections in 2049 are used with a total rainfall of 4174.32 mm/year.

The results of the analysis of the Flood Vulnerability Index from the WLC approach were then overlaid with a map of the electricity system in the Kapua watershed so that the results of flood vulnerability in the electricity infrastructure were obtained which can be seen in Figure 5 to Figure 7 and Table 5.

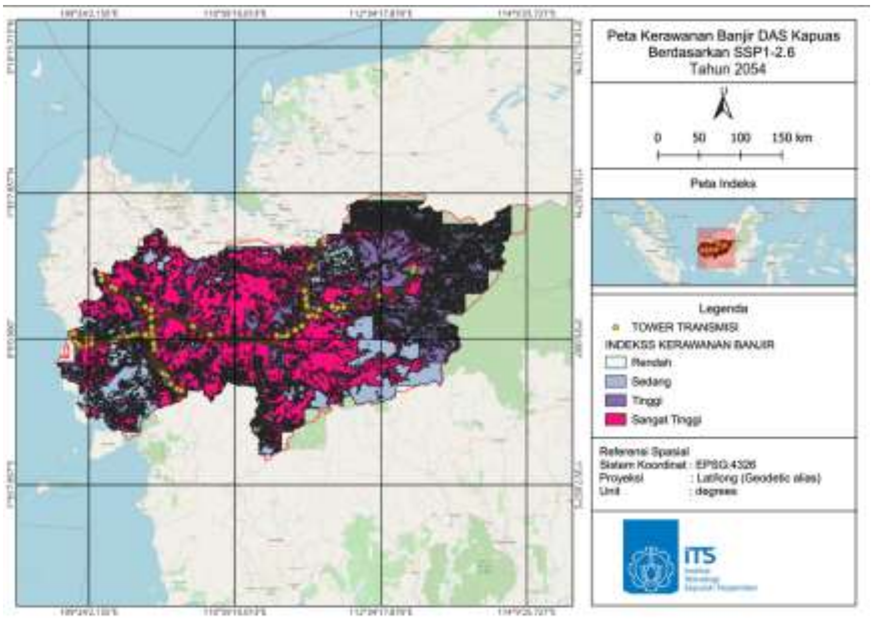

Figure 5. Flood Vulnerability Map of Electricity Transmission Lines in the Kapuas Watershed SSP1-26 Year 2054

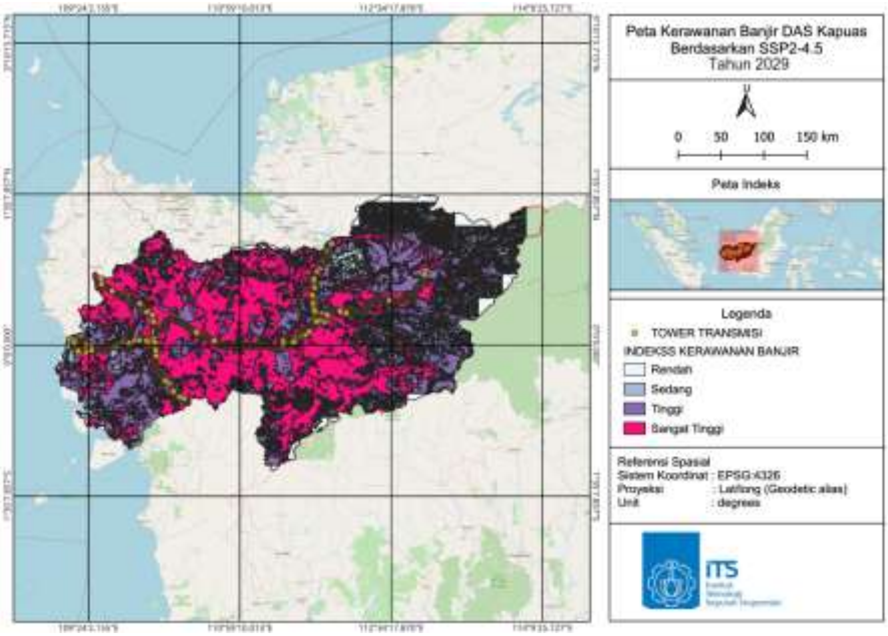

Figure 6. Flood Vulnerability Map of Electricity Transmission Lines in the Kapuas Watershed SSP1-26 Year 2054

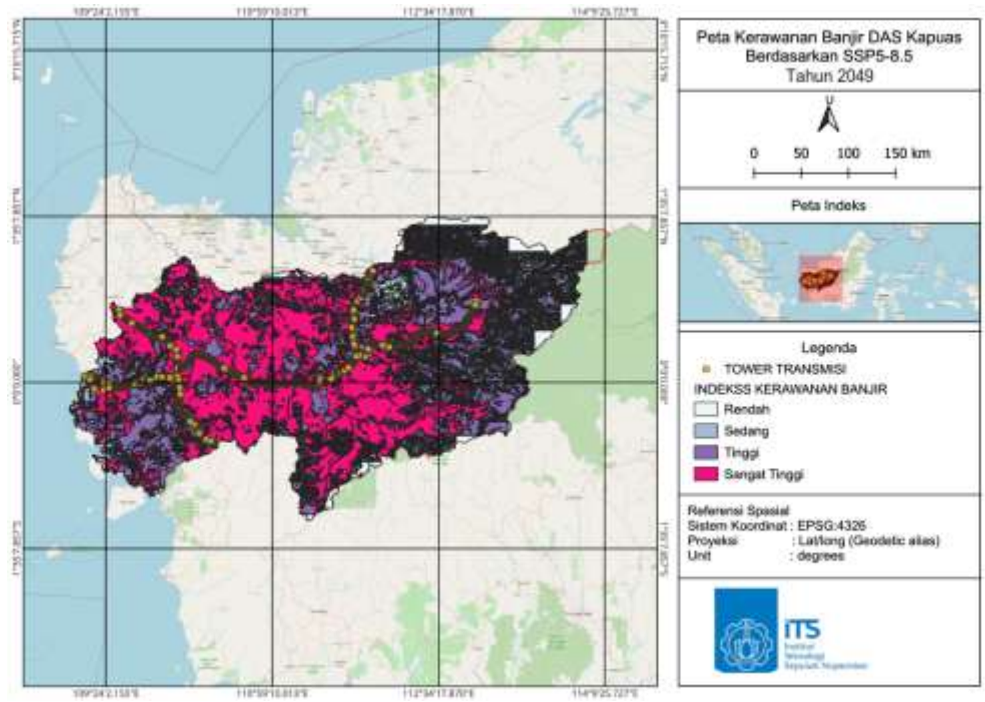

Figure 7. Flood Vulnerability Map of Electricity Transmission Lines in the Kapuas Watershed SSP5-8.5 Year 2049

Table 6. Flood Vulnerability on the Kapuas Watershed Electricity Transmission Line

Flood Vulnerability Level	SSP1-2.6 2054	SSP2-4.5 2029	SSP5-4.5 2049
Low	87	8	8
Medium	83	54	54
Height	428	480	475
Very High	1962	2018	2023

Flood Vulnerability Level	SSP1-2.6 2054	SSP2-4.5 2029	SSP5-4.5 2049
Number of Transmission Towers	2560	2560	2560

The results of the analysis of the Flood Vulnerability Index on the SUTT transmission infrastructure in the Kapuas watershed based on the climate change scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5 show a consistent trend of increasing flood vulnerability in line with the increase in emission levels and the intensity of climate change. Cross-scenario analysis shows that there are a number of transmission lines that consistently experience the dominance of high to very high flood vulnerability levels in all three SSP scenarios, so they can be categorized as *flood-critical corridors*. Pathways that always show very high vulnerability predominantly include:

SUTT Simpang Silat – Putussibau Route

More than 90% of SUTT towers are in the very high flood vulnerability class across all SSP scenarios

Tayan – Sanggau SUTT Line

Consistently having >200 SUTT towers in the very high flood vulnerability class in all SSP scenarios.

Sekadau – Sintang SUTT Line

The dominance of the SUTT level in the flood vulnerability class is very high which is stable from SSP1-2.6 to SSP5-8.5.

Siantan – Tayan SUTT Line and Bengkayang – Ngabang SUTT

Shows high exposure to flooding in all scenarios, especially in very high grades.

Parit Baru – Kota Baru SUTT Line and Sungai Raya – Siantan SUTT Line

It has a SUTT tower that is in the medium to very high flood vulnerability class.

Furthermore, an analysis of the Flood Vulnerability Index was carried out with the infrastructure of the Substation located in the Kapuas watershed. Based on the amount of rainfall in the year with the highest amount of rainfall in each SSP scenario, the number of Substations included in the flood-prone area is low to very high up to Figure 8 to Figure 10 and also Table 6.

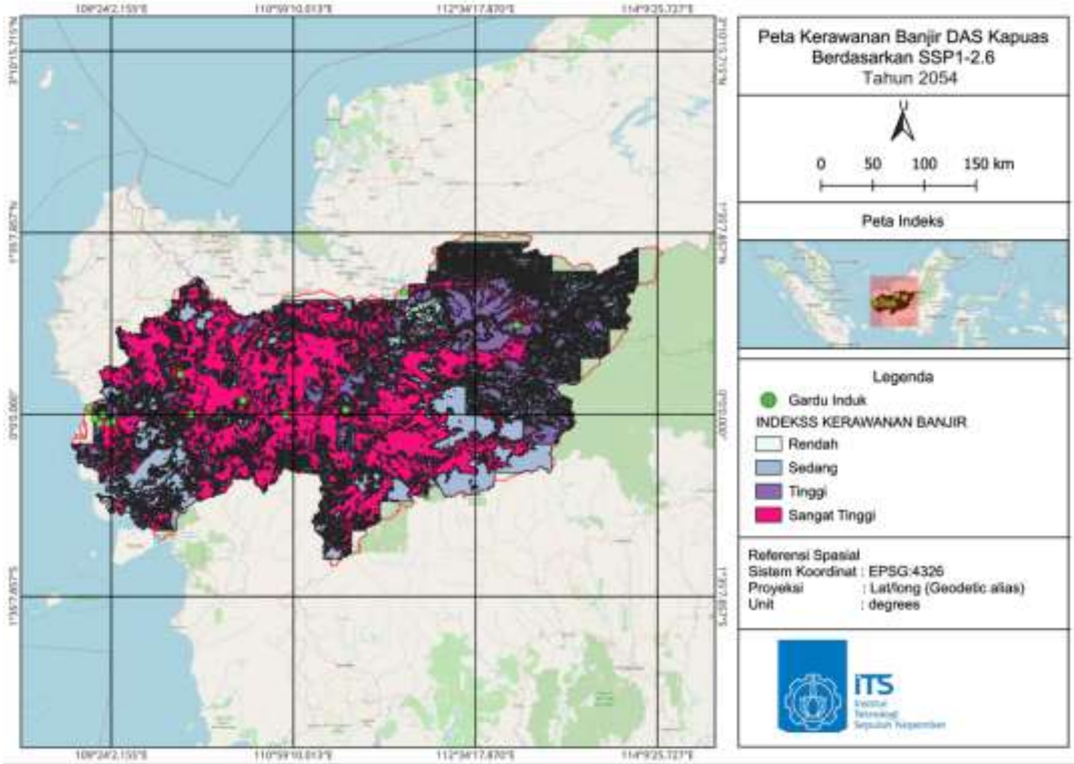

Figure 8. Substation Flood Vulnerability Map in the Kapuas Watershed SSP1-2.6 Year 2054

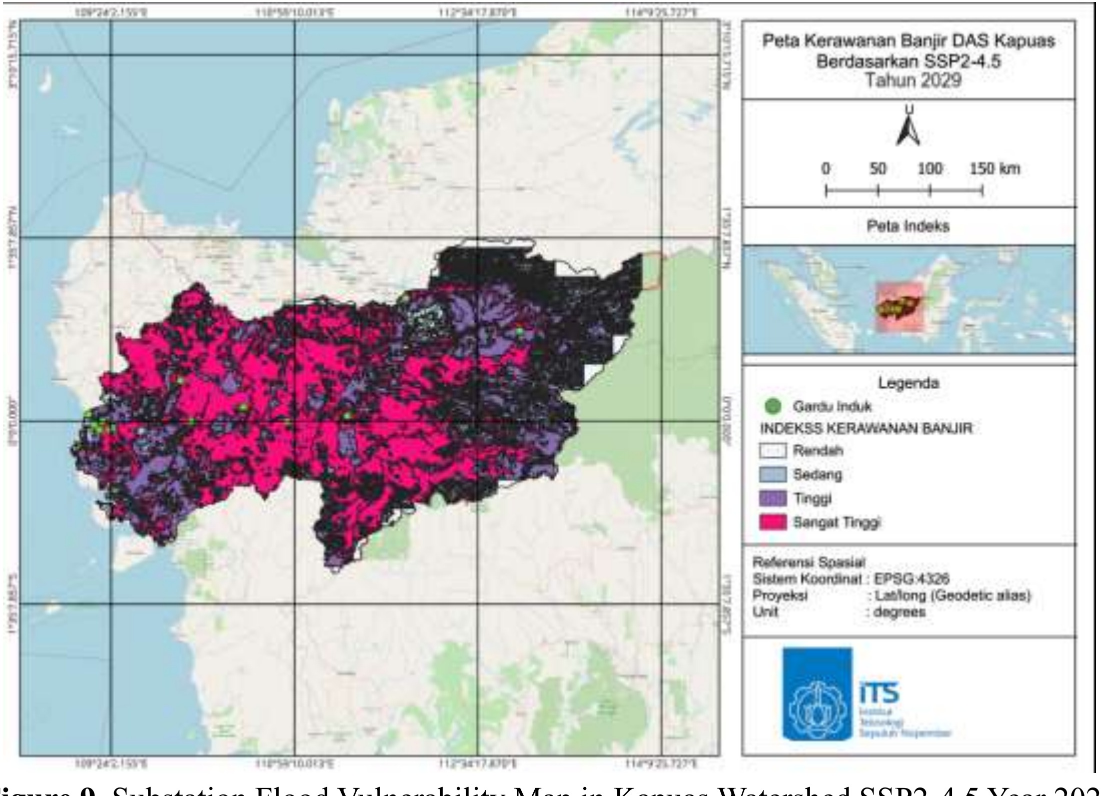

Figure 9. Substation Flood Vulnerability Map in Kapuas Watershed SSP2-4.5 Year 2029

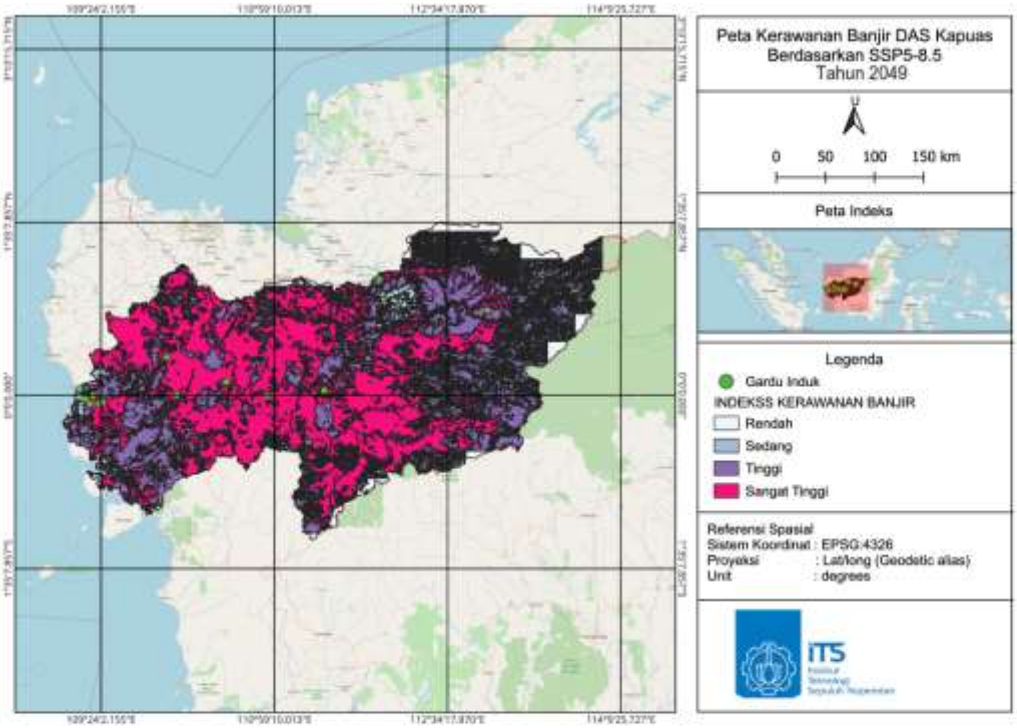

Figure 10. Substation Flood Vulnerability Map in the Kapuas Watershed SSP5-8.5 Year 2049

Table 7. Flood Vulnerability at the Kapuas Watershed Substation

Flood Vulnerability Level	**SSP1-2.6 2054**	**SSP2-4.5 2029**	**SSP5-4.5 2049**
New Trench Substation	Low	Height	Height
New City Substation	Very High	Very High	Very High
Siantan Substation	Very High	Very High	Very High
Sei Raya Substation	Very High	Very High	Very High
Ngabang Substation	Very High	Very High	Very High
Tayan Substation	Very High	Very High	Very High
Sanggau Substation	Very High	Very High	Very High
Sekadau Substation	Very High	Very High	Very High
Sintang Substation	Very High	Very High	Very High
Guard Induk Sendana	Height	Height	Height
Ambawang Substation	Very High	Very High	Very High
Putussibau Substation	Very High	Very High	Very High
Gardu Induk Badau	Low	Height	Height

Source: Author Analysis, 2025

Based on the results of the flood vulnerability assessment of 13 substations in the Kapuas watershed, the level of flood vulnerability is very high and consistent across most GIs, even under the most optimistic climate scenario. In SSP1-2.6 (2054), 10 out of 13 GIs (76.9%) fall into the very high category, 1 GI (7.7%) into the high category, and 2 GIs (15.4%) into the low category. This finding indicates that, despite strong mitigation efforts, the majority of GIs are situated in areas that are geomorphologically and hydrologically highly susceptible to flooding.

Under the SSP2-4.5 scenario (2029), a significant escalation in risk is observed, characterized by the disappearance of all low vulnerability categories. A total of 10 GIs (76.9%) remain in the very high category, while 3 GIs (23.1%) shift to the high category. This shift suggests that the increase in extreme rainfall and surface runoff accumulation under intermediate emission conditions has surpassed the natural adaptive threshold of the areas surrounding these substations—particularly those previously in the low category.

The most critical conditions persist under SSP5-8.5 (2049), where the vulnerability distribution not only fails to improve but instead reinforces a structural pattern of high risk. In this scenario, 10 GIs (76.9%) are in the very high category and 3 GIs (23.1%) in the high category, with no substation classified as low. This consistency demonstrates that substation exposure to flooding is both permanent and systemic, especially for GIs located in lowland, alluvial, and river-adjacent zones within the Kapuas watershed.

Most GIs—such as Kota Baru, Siantan, Sei Raya, Ngabang, Tayan, Sanggau, Sekadau, Sintang, Ambawang, and Putussibau—consistently fall within the very high vulnerability category across all three scenarios, identifying these sites as flood-critical nodes in the regional electricity system. Meanwhile, the Parit Baru GI and the Badau GI show an increase in vulnerability from low to high, while the Cendana GI remains consistently in the high category and never falls into the low category throughout the entire time horizon of climate change scenario analysis.

Analysis of flood vulnerability to substation infrastructure under the three climate change scenarios—SSP1-2.6, SSP2-4.5, and SSP5-8.5—confirms that more than 75% of substations in the Kapuas watershed fall under the very high flood vulnerability category in all cases. This finding indicates that the flood risk to electricity transmission and distribution systems is not only chronic but potentially systemic.

CONCLUSION

The results of the analysis show that rainfall in the Kapuas watershed significantly influences the potential and level of flood vulnerability in the region. Climate change affects flood potential primarily through increases in extreme rainfall intensity, rather than through changes in average rainfall or the number of rainy days. Across all three scenarios, the annual average rainfall remains relatively stable, ranging between approximately 8.5–11.8 mm/day, while the number of rainy days shows minimal variation (about 277–349 days/year). This indicates that the heightened flood risk is not primarily driven by more frequent rainfall events but by the increased intensity of extreme daily rainfall and higher annual rainfall accumulation.

Flood risk mapping in the Kapuas watershed reveals that the vulnerability of electricity infrastructure is dominated by high to very high categories across all climate scenarios. Of the 2,560 transmission towers, 1,962 locations fall into the very high category under SSP1-2.6 (2054), increasing to 2,018 locations under SSP2-4.5 (2029) and 2,023 locations under SSP5-8.5 (2049). The most consistently vulnerable transmission lines across the three scenarios include the Simpang Silat–Putussibau, Tayan–Sanggau, Sekadau–Sintang, and Siantan–Tayan SUTTs, most of which traverse lowland areas along the Kapuas River. Among the substations, Siantan, Sei Raya, Ngabang, Tayan, Sanggau, Sekadau, Sintang, Ambawang, and Putussibau are consistently at very high risk of flooding under all scenarios, while Parit Baru and Badau show relatively lower risks under SSP1-2.6 but higher vulnerability in the other scenarios.

Comparatively, SSP1-2.6 represents the lowest overall impact, SSP2-4.5 provides the most balanced and realistic basis for planning, and SSP5-8.5 reflects the maximum potential risk to the reliability of the electricity system.

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