

Spatial Analysis of Flood Risk Projections in Aceh Province Using Coupled Model Intercomparison Project Phase 6 (CMIP6) Climate Models and GIS

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ABSTRACT

This study projects the potential for flooding using the Coupled Model Intercomparison Project Phase 6 (CMIP6) scenario through a two-scenario approach, namely SSP2-4.5 (emission stabilization) and SSP5-8.5 (high emissions). This study compares the baseline period of 1991-2010 to the near-future projection of 2031-2050 using the NEX-GDDP-CMIP6 climate projection dataset of the TaiESM1 model, geospatial information consisting of Indonesian topographic data, land cover, soil type, the National digital elevation model (DEMNAS), and historical data of flood events for the period 2008-2024. The research method involves spatial analysis with Geographic Information Systems (GIS), weighting scores, interpolation, and validation against historical floods. The results of the study show that in 2031-2050, the area affected by flooding based on the climate change model scenario SSP2-4.5 (emission stabilization) for the vulnerable category was 13,759,858 km² and the very vulnerable category was 2,549,715 km².

INTRODUCTION

Global climate change is one of the biggest challenges faced by countries throughout the world, including Indonesia (Pasqui & Di Giuseppe, 2019). The most significant and frequently felt impact of climate change is changes in rainfall patterns and an increase in the frequency of extreme rainfall which can result in an increase in the intensity of flood disasters (Fowler et al., 2021). Climate change due to global warming will affect the hydrological cycle and rainfall patterns, this has the potential to worsen these conditions in the future (Tabari, 2020). Using climate change model scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6), this study focuses on projecting potential flood disasters in Aceh Province by comparing the baseline period of 1991-2010 with near-future projections of 2031-2050. The CMIP6 rainfall projection data output is used by researchers to project the potential for flood disasters as global warming increases (Hirabayashi et al., 2021). Projections up to 2050 are not only aimed at understanding the short-term impacts of climate change, but also to support regional resilience, especially in Aceh Province, in facing the challenges of natural disasters such as flooding (Putera et al., 2022). CMIP6 uses a climate projection model scenario called Shared Socioeconomic Pathways (SSP), this scenario combines socio-economic scenarios and technological developments that can affect future greenhouse gas emission levels (Gidden et al., 2019; Su et al., 2021). The analysis of flood disaster potential projections in this study will be conducted based on two climate change model scenarios, namely SSP2-4.5 (stabilization scenario) and SSP5-8.5 (high emission scenario). SSP2-4.5 (stabilization scenario) or known as the middle of the road is a scenario that describes the trend of global development continuing with the implementation of low-carbon technology and climate change adaptation, but this is considered still insufficient to avoid climate change, while SSP5-8.5 (high emission scenario) or known as fossil-fueled development or business as usual is a scenario that describes rapid global development while still relying on fossil fuels and little effort to reduce greenhouse gas (GHG) emissions (Meinshausen et al., 2020).

LITERATURE REVIEW

Geographic Information Systems (GIS)

Through the use of GIS, geospatial data derived from satellite imagery, topographic maps, and meteorological data can be analyzed in-depth to identify risk zones and determine disaster mitigation priorities. GIS can be used to map flood-prone areas based on rainfall patterns and topography. Integration with climate projection models can predict areas at high risk of future flooding (Janizadeh et al., 2021; Steinschneider et al., 2015). The use of GIS to map disaster-prone areas is crucial for disaster risk mitigation. GIS plays a crucial role in increasing preparedness and reducing the impact of disasters on humans and the environment (Sulaiman et al., 2022). Regarding the use of remote sensing technology, satellite data allows monitoring of areas that are difficult for humans to reach or field measurements (Avisse et al., 2017). Satellite-based remote sensing relies on electromagnetic signals reflected or emitted from the Earth's surface to obtain various information, namely land cover, soil type, elevation, slope gradient, and river network (Franci et al., 2016). Satellite data is used in

climate models to predict the impacts of future climate change and produce more robust climate projections (Kaps et al., 2023). In this study, the data used include TaiESM1 rainfall data downloaded from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) with a spatial resolution of 25 x 25 km, land cover maps and soil type maps from the BMKG Aceh Climatology Station, then the Indonesian Topographic Map (RBI) and the Digital Elevation Model (DEM) Map from the Geospatial Information Agency (BIG).

Coupled Model Intercomparison Project Phase 6 (CMIP6) and Global Coupled Model (GCM)

CMIP (Coupled Model Intercomparison Project) is an international collaborative effort aimed at understanding and projecting climate change by developing and comparing global climate models (GCMs) (Almazroui et al., 2021). CMIP6 adopted a new set of scenarios called Shared Socioeconomic Pathways (SSP), which are more complex and integrated. SSP not only considers greenhouse gas emissions but also socioeconomic changes that can affect the climate, with several scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (Tong et al., 2020). CMIP6 offers a greater level of detail and complexity with additional components such as a more sophisticated carbon cycle, biogeochemical models, and more detailed human interactions with climate. This allows for a more realistic representation of the relationship between the climate system and human activities (Hurtt et al., 2020). SSP is used in the Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate modeling to evaluate how global economic and societal development will shape climate change patterns through the 21st century (Tebaldi et al., 2021). The following table will explain the summary of the SSP (Shared Socioeconomic Pathways) scenario.

Table 1. Summary of Shared Socioeconomic Pathways (SSP) Scenarios

SSP	Short Description	Global warming (°C)	Main Features
SSP1-1.9 / SSP1-2.6 (Sustainability - Green Growth)	The world is turning to sustainable development with renewable energy and strong climate policies.	<2°C	Emissions dropped drastically, social inequality reduced, mitigation maximized
SSP2-4.5 (Middle of the Road)	Moderate economic and social growth, limited mitigation, no major changes in climate policy	2.7-3°C	Emissions stable, climate policies partial, climate change risks remain high
SSP4-6.0 (Inequality -)	Developed countries are turning to clean energy, but developing countries	~3°C	High inequality, mitigation is only carried out by

Divided World)	remain dependent on fossil fuels.		developed countries
SSP3-7.0 (Regional Rivalry - Fragmented World)	Countries focus on domestic interests, global cooperation is weak, social inequality is increasing	3.5–4°C	Minimal mitigation, high geopolitical conflict, increasing disaster risk
SSP5-8.5 (Fossil-Fueled Development)	The world remains dependent on fossil fuels, resource exploitation is high, mitigation is neglected.	>4°C	Highest emissions, extreme temperature increases, highest disaster impacts compared to other scenarios

Source: Table processed by researchers from the website <https://climate-scenarios.canada.ca/?page=cmip6-overview-notes>

The selection of global climate models (GCM - Global Coupled Model) researchers conducted based on journal references (Bhanage et al., 2024) with the title "Identification of optimal CMIP6 GCMs for future typical meteorological year in major cities of Indonesia using multi-criteria decision analysis" and (Endiartia, 2021) with the title "City-Wise Assessment of Suitable CMIP6 GCM in Simulating Different Urban Meteorological Variables over Major Cities in Indonesia". The journal examined various global climate models (GCM - Global Coupled Model) that are suitable for several locations in Indonesia. Based on several GCM models from CMIP6 that were evaluated in the period 1980 - 2014, the results obtained were the global climate model (GCM - Global Coupled Model) that is suitable for Aceh is TaiESM. The following table describes the various CMIP6 global climate models (GCMs) available from various institutions around the world.

Table 2. Characteristics of Global Coupled Model (GCM)

CMIP6 GCM	Institution	Variant/run	Atmosphere lat/lon grid (°)
ACCESS-CM2	CSIRO	r1i1p1f1	1.2 × 1.8
ACCESS-ESM1.5	CSIRO	r1i1p1f1	1.2 × 1.8
AWI-CM-1-1-MR	Alfred Wegener Institute	r1i1p1f1	0.9 × 0.9
AWI-ESM-1-1-LR	Alfred Wegener Institute	r1i1p1f1	0.9 × 0.9

BCC-CSM2-MR	Beijing Climate Center	r1i1p1f1	1.1 × 1.1
BCC-ESM1	Beijing Climate Center	r1i1p1f1	2.8 × 2.8
CanESM5	Canadian Center for Climate Modeling and Analysis	r1i1p1f1	2.8 × 2.8
CanESM5-CanOE	Canadian Center for Climate Modeling and Analysis	r1i1p2f1	2.8 × 2.8
CIESM	Department of Earth System Science, Tsinghua University	r1i1p1f1	1.0 × 1.0
CAS-ESM2-0	Institute of Atmospheric Physics, Chinese Academy of Sciences	r1i1p1f1	1.4 × 1.4
CMCC-CM2-SR5	Euro-Mediterranean Center	r1i1p1f1	~ 0.9
CNRM-CM6-1-HR	National Center of Meteorological Research (NCMR), France	r1i1p1f2	~ 0.5
CNRM-CM6-1	National Center of Meteorological Research (NCMR), France	r1i1p1f2	1.4 × 1.4
CNRM-ESM2-1	National Center of Meteorological Research (NCMR), France	r1i1p1f2	1.4 × 1.4
EC-Earth3-Veg-LR	EC-EARTH consortium, The Netherlands/Ireland	r1i1p1f1	0.7 × 0.7
EC-Earth3-Veg	EC-EARTH consortium, The Netherlands/Ireland	r1i1p1f1	0.7 × 0.7
EC-Earth3	EC-EARTH consortium, The Netherlands/Ireland	r1i1p1f1	0.7 × 0.7
FGOALS-f3-L	Chinese Academy of Sciences, China	r1i1p1f1	2.3 × 2.0
FGOALS-g3	Chinese Academy of Sciences, China	r1i1p1f1	2.3 × 2.0
FIO-ESM-2-0	First Institute of Oceanography, State Oceanic Administration, China	r1i1p1f1	1.25 × 0.9
GFDL-CM4	NOAA Geophysical Fluid Dynamics Laboratory	r1i1p1f1	1.0 × 1.3
GFDL-ESM4	NOAA Geophysical Fluid Dynamics Laboratory	r1i1p1f1	1.0 × 1.3
GISS-E2-1-G	NASA Goddard Institute for Space Studies, New York, USA	r1i1p1f1	2.0 × 2.5
GISS-E2-1-G-CC	NASA Goddard Institute for Space Studies, New York, USA	r1i1p1f1	2.0 × 2.5
GISS-E2-1-H	NASA Goddard Institute for Space Studies, New York, USA	r1i1p1f1	2.0 × 2.5
HadGEM3-GC31-LL	UK Met Office Hadley Center	r1i1p1f3	2.2 × 2.2
HadGEM3-GC31-MM	UK Met Office Hadley Center	r1i1p1f3	0.9 × 0.9

INM-CM4-8	Institute for Numerical Mathematics (INM), Russia	r1i1p1f 1	1.5 × 2.0
INM-CM5-0	Institute for Numerical Mathematics (INM), Russia	r1i1p1f 1	1.5 × 2.0
IPSL-CM6A-LR	Institute Pierre Simon Laplace, France	r1i1p1f 1	1.3 × 2.5
KACE-1-0-G	Nat. Inst. of Meteorological Sciences/Korea Meteorological Admin.	r1i1p1f 1	2.2 × 2.2
KIOST-ESM	Korean Institute of Ocean Science and technology	r1i1p1f 1	2.2 × 2.2
MIROC-ES2L	National Institute for Environmental Studies, Japan	r1i1p1f 2	4.5 × 4.5
MIROC6	National Institute for Environmental Studies, Japan	r1i1p1f 1	1.4 × 1.4
MPI-ESM-1-2-HAM	Max Planck Institute for Meteorology (MPI), Germany	r1i1p1f 1	2.2 × 2.2
MPI-ESM1-2-HR	Max Planck Institute for Meteorology (MPI), Germany	r1i1p1f 1	~0.9
MPI-ESM1-2-LR	Max Planck Institute for Meteorology (MPI), Germany	r1i1p1f 1	~2.0
MRI-ESM2-0	Meteorological Research Institute, Japan	r1i1p1f 1	1.1 × 1.1
NESM3	Nanjing University of Information Science and Technology, Nanjing	r1i1p1f 1	1.9 × 1.9
NorCPM1	Norwegian Climate Center, Norway	r1i1p1f 1	1.9 × 2.5
NorESM2-LM	Norwegian Climate Center, Norway	r1i1p1f 1	1.9 × 2.5
NorESM2-MM	Norwegian Climate Center, Norway	r1i1p1f 1	0.9 × 0.9
SAM0-UNICON	Seoul National University	r1i1p1f 1	0.9 × 1.3
TaiESM1	Taiwan Earth System Model	r1i1p1f 1	0.9 × 0.9
UKESM1-0-LL	UK Met Office and NERC research centers	r1i1p1f 2	1.3 × 1.9

Source: Table Processed by Researchers from the Journal (di Virgilio Et Al., 2022)
 "Selecting CMIP6 Gcms for CORDEX Dynamical Downscaling: Model Performance, Independence, And Climate Change Signals

Based on the GCM selected by the researcher, the next step is to download the data in the form of a NetCDF file and convert it to CSV format using a Python script. The data that has been converted into CSV format, the researcher obtained from the Climate Change Analysis and Projection Sub-Division of the BMKG Deputy. Rainfall data from TaiESM1 was downloaded from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) with a resolution of 25 x 25 km, which has been bias-corrected using the Bias-Correction Spatial Disaggregation (BCSD) method.

The analysis of flood disaster potential projections in this study will be carried out based on two climate change model scenarios, namely SSP2-4.5 (stabilization scenario) and SSP5-8.5 (high emission scenario). SSP2-4.5 (stabilization scenario) or called middle of the road is a scenario based on the application of low-carbon technology in global development and the application of climate change adaptation, but this is considered insufficient to avoid climate change, while SSP5-8.5 (high emission scenario) or known as fossil-fueled development or business as usual is a scenario with rapid global development while still relying on fossil fuels, resulting in very high CO₂ concentrations, and little effort to reduce greenhouse gas (GHG) emissions (Meinshausen et al., 2020). The socio-economic assumptions in SSP2-4.5 include investment in low-carbon technologies with balanced economic and demographic development, while the socio-economic assumptions in SSP5-8.5 describe a world that relies heavily on fossil fuels for economic growth accompanied by rapid urbanization and industrialization (Bauer et al., 2016). The SSP2-4.5 scenario presents efforts to stabilize greenhouse gas emissions with a projected global average CO₂ level reaching 600 ppm by 2100, while the SSP5-8.5 scenario presents a high increase in emissions and is projected to have CO₂ concentrations reaching 1100 ppm by 2100 (Meinshausen et al., 2020).

Based on the SSP2-4.5 scenario, the impact of climate change is that the world experiences significant climate change but is still within limits that can be managed by implementing effective mitigation and adaptation strategies, while based on the SSP5-8.5 scenario, it is projected that the world will experience the impact of extreme climate change with broad and difficult to control impacts, thus having a serious impact on ecosystems and society (Kwiatkowski et al., 2020; Supharatid et al., 2022).

Geographic Information System (GIS)-Based Flood Risk Mapping

Geographic Information Systems (GIS) are a highly effective technology for mapping flood risk because they integrate various environmental factors into spatial analysis. With the increasing incidence of flooding due to climate change, the use of GIS is becoming increasingly important for understanding flood patterns and areas vulnerable to flooding. GIS allows for the processing and analysis of variables such as rainfall, topography, soil type, land cover, slope, and elevation to determine flood-prone areas (Ali et al., 2019). Through a combination of digital satellite data, historical flood event data, and climate change prediction models such as CMIP6, GIS can provide a more accurate picture of areas at high potential flood risk in the future. In the flood risk mapping process, the initial

stage is collecting geospatial data from various sources. Rainfall data is taken from global climate models such as CMIP6 to predict future rainfall patterns, while Digital Elevation Model (DEM) data is used to analyze topography and land elevation, which influence water flow. In addition, land use data derived from satellite imagery is used to understand surface types that influence water infiltration and runoff (Bhat et al., 2019).

Once the data is collected, the next step is to conduct spatial analysis using an overlay method that combines various layers of information including rainfall, topography, slope, soil type, and land cover. The main advantage of using GIS in flood risk mapping is its ability to perform multidimensional analysis that simultaneously integrates various factors causing flooding (Radwan et al., 2019). By using GIS, flood risk mapping can be done more efficiently and accurately, so that it can become the basis for spatial planning, disaster mitigation, and the development of a more effective early warning system.

METHODOLOGY

The research began with a literature review and data collection, consisting of land cover data, soil type data, and DEMNAS data (elevation and slope). These data were then processed and analyzed through statistical analysis, reclassification, and spatial analysis. The data processing and analysis produced static data in the form of land cover maps, soil type maps, slope maps, and elevation maps. The NEX-GDDP-CMIP6 rainfall data of the TaiESM model consists of historical data from the baseline period 1991-2010 and the near future period 2031-2050 which have been bias corrected using the Bias-Correction Spatial Disaggregation (BCSD) technique, then these data are converted from NetCDF files into CSV xlsx files containing near future rainfall data for 2031-2050 SSP2-4.5 and SSP5-8.5 scenarios using a python script. The next process is the creation of a near future rainfall database for 2031-2050 SSP2-4.5 and SSP5-8.5 scenarios so that the data can be processed in a Geographic Information System (GIS) application consisting of statistical analysis, interpolation, reclassification, and spatial analysis. The data processing process produces dynamic data in the form of a near future rainfall map for 2031-2050 SSP2-4.5 and SSP5-8.5 scenarios. Based on static and dynamic data, geoprocessing, overlay, statistical weighting, reclassification, and spatial analysis were then performed. This final process resulted in a near-future flood hazard projection map for 2031-2050 using the SSP2-4.5 and SSP5-8.5 scenarios, validated against historical flood data.

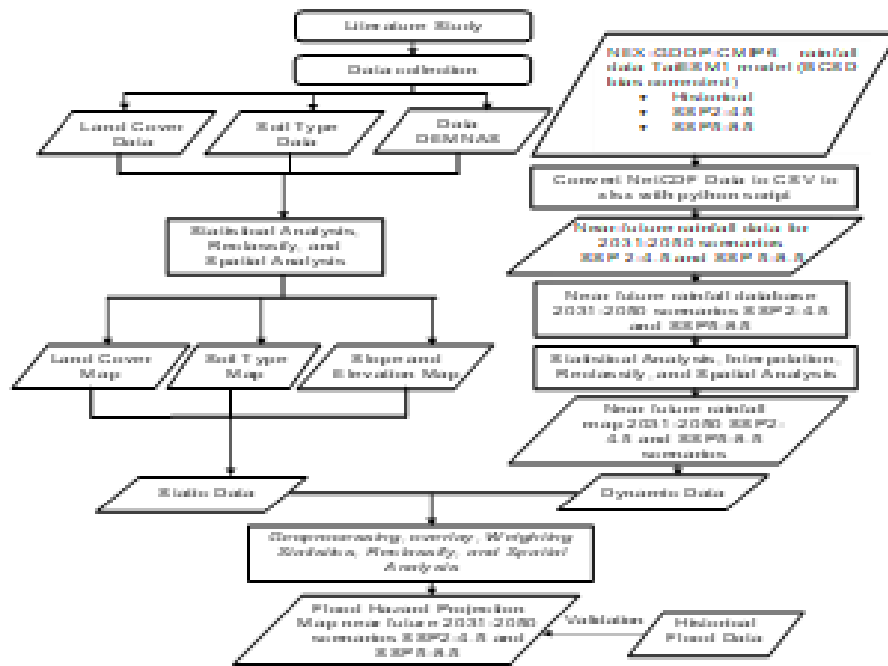


Figure 1. Research Flowchart
 Source: Processed by Researchers

RESEARCH RESULT AND DISCUSSION

The data processing process for the projection of near-future flood potential for the 2031-2050 period based on the SSP2-4.5 (emission stabilization) and SSP5-8.5 (high emissions) climate change scenarios is carried out through a series of spatial analysis stages. The first stage is the creation of a rainfall database by processing data from the NEX-GDDP-CMIP6 TaiESM1 model that has been converted to Excel format. This rainfall data is then analyzed statistically to see the trend pattern of future rainfall changes, and converted into a format suitable for interpolation and spatial analysis purposes. Next, statistical analysis, IDW interpolation, reclassification, and spatial analysis are carried out to map the distribution of rainfall in the near-future period based on the SSP2-4.5 and SSP5-8.5 scenarios. Interpolation is carried out to smooth the spatial data distribution, while reclassification is used to group rainfall intensity based on the level of flood risk. Spatial analysis is then applied to identify areas with significant increases in rainfall, which have the potential to increase flood risk.

In addition to rainfall analysis, this study also conducted geoprocessing and overlay of various environmental parameters that contribute to flood risk, such as land cover maps, soil type maps, slope maps, and area elevation maps. The overlay process was carried out by combining various layers of spatial information to obtain an overview of areas that are potentially prone to flooding. The following table explains the weighting and reclassification statistics applied to assign risk values to each parameter, which were then combined to produce the final flood risk projection map. The final result of this study produced a flood risk projection map for the period 2031-2050 for the SSP2-4.5 and SSP5-8.5 scenarios, which depict areas with different levels of flood risk based on climate change scenarios. This map was then validated using historical flood event data for the period 2008-2024 to ensure the accuracy of the projection model. The

validation results show that areas that experience repeated flood events in the historical data tend to have a high flood risk level in the projection map.

Table 3. Reference Score and Weighting of Rainfall Parameters

Rainfall Scoring Reference	Score	Weight	Final Score
< 1500 mm/year	1	0.2	0.2
1500 - 2000 mm/year	2		0.4
2000 - 2500 mm/year	3		0.6
2500 - 3000 mm/year	4		0.8
> 3000 mm/year	5		1

Source: Indonesian National Standard (SNI) 8197:2015 on Flood Hazard Maps

Table 4. Reference Score and Weighting of Land Cover Parameters

Rainfall Scoring Reference	Score	Weight	Final Score
Highland Forest	1	0.2	0.2
Plantation forests, Lowland Forests, Shrubs	2		0.4
Mixed dryland farming, Open land, Dryland farming, Plantation	3		0.6
Secondary mangrove forest, ponds, swamps, rice fields, swamp scrub, secondary swamp forest, primary swamp forest, primary mangrove forest	4		0.8
Pemukiman, Bandara / Pelabuhan	5		1

Source: Indonesian National Standard (SNI) 8197:2015 on Flood Hazard Maps

Table 5. Reference Score and Weighting of Soil Type Parameters

Soil Type Scoring Reference	Score	Weight	Final Score
Regosol, Rensing Complex and Litosol, Brown Podsol Complex, Podsol and Litosol, Organosol and Gle Humus, Red Yellow Podsol Complex and Litosol	1	0.2	0.2
Andosol	2		0.4
Red Yellow Podsollic, Red Yellow Podsollic	3		0.6
Latosol	4		0.8
Alluvial, Grey Hydromorph	5		1

Source: Indonesian National Standard (SNI) 8197:2015 on Flood Hazard Maps

Table 6. Reference Score and Weighting of Slope Parameters

Slope Scoring Reference	Score	Weight	Final Score
Very Steep (>40%)	1	0.2	0.2
Steep (25 - 40%)	2		0.4
A bit steep (15 - 25%)	3		0.6
Sloping (8 - 15%)	4		0.8
Flat (0 - 8%)	5		1

Source: Indonesian National Standard (SNI) 8197:2015 on Flood Hazard Maps

Table 7. Reference Score and Weighting of Altitude Parameters

Height Reference	Scoring	Score	Weight	Final Score
> 200 m		1	0.2	0.2
100 - 200 m		2		0.4
50 - 100 m		3		0.6
10 - 50 m		4		0.8
0 - 10 m		5		1

Source: Indonesian National Standard (SNI) 8197:2015 on Flood Hazard Maps



Figure 2. Rainfall Classification Map SSP2-4.5 of Aceh Province
Source: Processed by Researchers

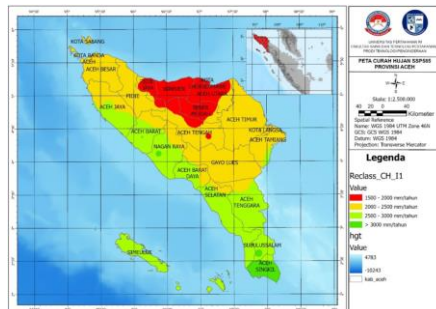


Figure 3. Rainfall Classification Map SSP5-8.5 of Aceh Province
Source: Processed by Researchers

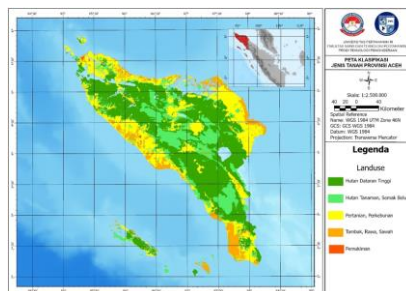


Figure 4. Land Cover Classification Map of Aceh Province
Source: Processed by Researchers

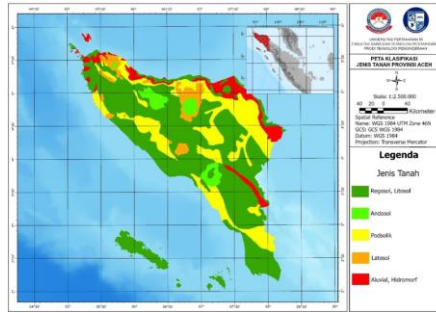


Figure 5. Land Type Classification Map of Aceh Province
 Source: Processed by Researchers

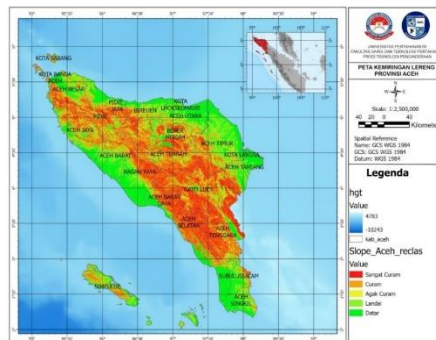


Figure 6. Slope Classification Map of Aceh Province
 Source: Processed by Researchers

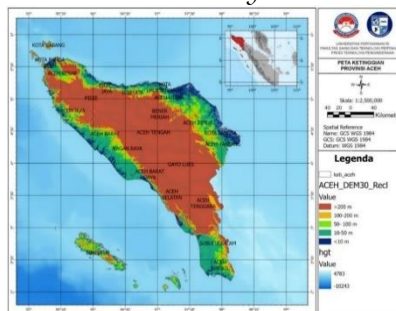


Figure 7. Aceh Province Height Classification Map
 Source: Processed by Researchers

Next, the five types of map parameters that have been classified are assessed using a raster calculator according to the scoring and weighting references. Based on the calculation results, an interval range is obtained which is then used to determine the level of potential flood risk. In this study, the level of potential flood risk is divided into 4 (four) classifications: not vulnerable, moderately vulnerable, vulnerable, and very vulnerable. The way to determine the distance between intervals is by using the Sturges formula, namely by subtracting the highest and lowest values presented in the following equation:

$$Ci = \frac{Xt - Xr}{k}$$

Information : Ci = Class interval

Table 8. Flood Hazard Classification SSP2-4.5

Potential Flood Risk SSP2-4.5	Interval
Not Vulnerable	2.1
A little bit vulnerable	3
Vulnerable	3.9
Very Vulnerable	4.8

Source: Processed by Researchers

Table 9. Flood Hazard Classification SSP5-8.5

Potential Flood Risk SSP5-8.5	Interval
Not Vulnerable	2.05
A little bit vulnerable	2.9
Vulnerable	3.75
Very Vulnerable	4.6

Source: Processed by Researchers

Analysis of Flood Hazard Projection Map for Near Future 2031-2050 SSP2-4.5 and SSP5-8.5 Scenarios

The analysis of the flood hazard projection map for the 2031-2050 period based on the SSP2-4.5 and SSP5-8.5 scenarios was carried out by converting raster data to polygon format using the raster to polygon process in a Geographic Information System (GIS). This conversion is necessary to calculate the potential flood-prone area in square kilometers (km²) according to predetermined risk level criteria. Raster data containing spatial information about the flood risk level based on rainfall intensity, topographic conditions, and environmental characteristics are converted into polygon form for further analysis in vector data form. The raster to polygon process allows for more accurate identification of the spatial distribution of flood-prone areas, as well as assisting in statistical calculations of the affected area in each risk category.

Based on table 10 regarding the potential area affected by flooding in the SSP2-4.5 scenario and figure 7 regarding the SSP2-4.5 flood hazard potential map, areas with potential hazards include the north and west of Sabang City, Banda Aceh City, the north coast of Aceh Besar, the north coast of Pidie, the coast of Pidie Jaya, part of the coast of Bireuen, Lhokseumawe City, the coast of North Aceh, the coast and the northern and eastern parts of East Aceh, Langsa City, the coast and the southern part of Aceh Tamiang, the coast of Aceh Jaya, the coast of West Aceh, the coast of Nagan Raya, the coast of Southwest Aceh, the coast of South Aceh, the coast of Simeulue, the southern and eastern parts of Subulussalam City, the southwestern part of Aceh Singkil, and the eastern part of Southeast Aceh. The areas that are highly prone to flooding are the western part of Aceh Besar, the northern and eastern parts of Pidie, the coast of Pidie Jaya, a small part of the coast of Bireuen, Lhokseumawe City, the coast of North Aceh, the coast of East Aceh, Langsa City, the coast and northern part of Aceh Tamiang, part of the coast of Aceh Jaya, a small part of West Aceh, a small part of Nagan

Raya, the coast and eastern part of South Aceh, part of Subulussalam City, a small part of the coast of Aceh Singkil, and the eastern part of Southeast Aceh.

Table 10. Potential Area Affected by Floods in SSP2-4.5 Scenario

No	Category	Area affected (km ²)
1	Not Vulnerable	23,241.256
2	A little bit vulnerable	12,091.262
3	Vulnerable	13,759.858
4	Very Vulnerable	2,549.715

Source: Processed By Researchers

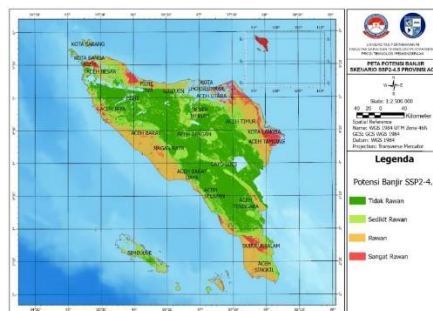


Figure 8. Flood Hazard Potential Map SSP2-4.5 of Aceh Province

Source: Processed by Researchers

Based on table 11 regarding the potential area affected by flooding in the SSP5-8.5 scenario and figure 8 regarding the SSP5-8.5 flood hazard potential map, areas with potential hazards include the north and west of Sabang City, Banda Aceh City, the north coast of Aceh Besar, the north coast of Pidie, the coast of Pidie Jaya, part of the coast of Bireuen, Lhokseumawe City, the coast of North Aceh, the coast and the northern and eastern parts of East Aceh, Langsa City, the coast and the southern part of Aceh Tamiang, the coast of Aceh Jaya, the coast of West Aceh, the coast of Nagan Raya, the coast of Southwest Aceh, the coast of South Aceh, the coast of Simeulue, the southern and eastern parts of Subulussalam City, the southwestern part of Aceh Singkil, and the eastern part of Southeast Aceh. Meanwhile, the potential for very high flood risk extends to the western part of Aceh Besar, the northern and eastern parts of Pidie, the coast of Pidie Jaya, a small part of the coast of Bireuen, Lhokseumawe City, the coast of North Aceh, the coast of East Aceh, Langsa City, the coast and northern part of Aceh Tamiang, part of the coast of Aceh Jaya, a small part of West Aceh, a small part of Nagan Raya, the coast and eastern part of South Aceh, part of Subulussalam City, a small part of the coast of Aceh Singkil, and the eastern part of Southeast Aceh.

Table 11. Potential Area Affected by Floods in SSP5-8.5 Scenario

No	Category	Area affected (km ²)
1	Not Vulnerable	23,943.878
2	A little bit vulnerable	11,464.329
3	Vulnerable	12,064.778
4	Very Vulnerable	4,169.005

Source: Processed by Researchers

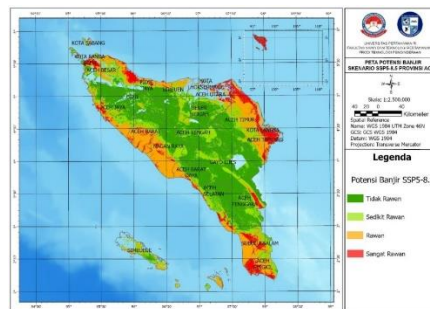


Figure 9. Flood Hazard Potential Map SSP5-8.5 of Aceh Province

Source: Processed by Researchers

CONCLUSIONS AND RECOMMENDATIONS

Based on a series of data analyses and discussions, it can be concluded that research on flood risk projections in Aceh Province shows that climate change has a significant impact on regional vulnerability. Using the CMIP6 model, flood risk mapping for the period 2031-2050 shows varying results depending on the emission scenario. In the emission stabilization scenario (SSP2-4.5), the flood-prone area is projected to reach 13,759,858 km², while the highly vulnerable area is 2,549,715 km². Meanwhile, in the high emission scenario (SSP5-8.5), the vulnerable area decreases to 12,064,778 km², but the highly vulnerable area actually increases drastically by 63.51% to 4,169,005 km². This increased risk is mainly concentrated in coastal areas.

Based on the research results, there are several things that can be implemented by related institutions to support regional resilience, especially in Aceh Province, namely:

- a. The Ministry of Defense can use the results of this research to design regional resilience strategies in facing the impacts of climate change
- b. The National Disaster Management Agency (BNPB) can use the flood risk projections from this study to develop mitigation and adaptation strategies for flood disasters, as well as to allocate resources optimally
- c. The Ministry of Public Works and Public Housing (PUPR) and the Aceh Irrigation Agency can use the results of this research for adaptive infrastructure planning against flooding, including river management and optimization of urban drainage systems and rice field drainage systems.

ADVANCED RESEARCH

Future research on spatial analysis of flood risk projections in Aceh Province using Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models and Geographic Information Systems (GIS) should be directed toward the integration of advanced climate modeling with geospatial technologies to enhance accuracy and policy relevance. In-depth studies may focus on downscaling CMIP6 projections to regional and local levels, enabling more precise flood risk mapping that reflects Aceh's hydrological and topographical characteristics. The application of machine learning and big data analytics could be explored to improve predictive capabilities and capture dynamic interactions between climate variability, land use change, and flood hazards. Additionally, the integration of GIS-based multi-criteria decision analysis (MCDA) and participatory mapping approaches would strengthen community-based risk assessment and adaptive planning. The development of scenario-based simulations that combine climate projections with socio-economic variables can also support disaster risk reduction strategies and long-term resilience building. Future studies should consider establishing collaborative frameworks involving local governments, research institutions, and international organizations to ensure the applicability of scientific findings in policymaking. Evaluation of early warning systems, spatial data infrastructure, and adaptive governance mechanisms is equally essential to ensure sustainable disaster risk management in Aceh Province. The outcomes of such research are expected to provide a comprehensive model for flood risk analysis that is scientifically robust, socially inclusive, and capable of supporting climate resilience at both local and regional levels.

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