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Exploring future inundation risk due to sea level rise using CMIP6 models in Indonesia

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Abstract

Sea level rise (SLR) is one of the most significant impacts of climate change which threatening coastal areas, particularly in archipelagic countries like Indonesia. This study projects the extent of inundation, the number of at-risk populations, and estimates of damage cost due to SLR through 2100. The analysis was conducted by combining the projections of sea level (zos and zostoga) from five CMIP6 models: MIROC6, ACCESS-ESM1-5, CanESM5, NorESM2-MM and MRI-ESM2-0, elevation data from ETOPO2022, tides from TPXO10, and population data from NCAR and IIASA. The estimated damage cost was calculated using a regression model based on historical disaster data from EM-DAT. The findings of the analysis indicate that, without mitigation and adaptation measures, Indonesia could experience permanent inundation of 18,700 to over 39,500 km² with an affected population of around 10 million in 2100. National damage cost due to SLR is projected to reach USD 7 billion in 2050 and increase to USD 10 billion in 2100 in high emission scenario. The provinces with the highest physical impact are South Kalimantan and South Sumatra, highest social impact and damage cost occur in East Java and South Kalimantan. These findings emphasize that climate change mitigation and adaptation policies in Indonesia must be planned equitably and supported by robust projections.

Introduction

Climate change occurs and poses significant impacts on lives, security and well being in many sectors (EPA, 2025). Coastal areas are particularly vulnerable sector and increasingly facing threats from impacts of climate change. Such impacts include rises in sea level, salt water intrusion (Oppenheimer et al., 2019), severe storms and storm surges (IPCC, 2021a), warming ocean temperature, and ocean acidification (Talukder et al., 2022). Among these, sea level rise (SLR) is one of the most obvious and global consequences of climate change (Clark et al., 2016; Titus et al., 1991). Sea level rise causes permanent and irreversible inundation, which is triggering widespread long–term losses such as damage to coastal ecosystems (Talukder et al., 2022), population displacement, and the loss of local cultures that depend on coastal lands (Das & Swain, 2024; Buchori et al., 2021). During 1971–2018, SLR was driven by thermal expansion (resulting from warming of the ocean) which contributed 50%, while melting glaciers contributed 22%, ice sheets 20%, and changes in land–water storage explained the remaining 8% (IPCC, 2021b). According to Sixth Assessment Report (AR6) of IPCC (Intergovermental Panel on Climate Change),

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global mean sea level for SSPs (Shared Socioeconomic Pathways) scenarios projected to be increase to 0,38–0.77 m relative to 1995–2014 baseline in 2100 (Fox-Kemper et al., 2021).

Indonesia is the largest archipelagic country (FAO, 2025) which has third longest coastline in the world (CIA, 2025) and has numerous inhabited islands. Given this condition and fact that many Indonesia's major and provincial cities (such as Jakarta, Surabaya, Semarang, and Makassar) are located on the coast, is indeed a compelling reason for Indonesia to be more vigilant about the adverse impacts of climate change.

An early study that made an important contribution to understanding the SLR risks in coastal Indonesia prior to the SSPs and RCPs scenarios, identified the potential for inundation using the A2 and B1 scenarios of the IPCC AR4. The study show that the highest relative SLR in 2100 is predicted to occur in Jakarta at 0.6 meters (A2 scenario) and in Jambi at 0.5 meters (B1 scenario) (Grashoff et al., 2009). World Bank report on 2021 estimated that the average number of Indonesians affected by permanent inundation due to coastal flooding without adaptation efforts between 2070 and 2100 would reach more than 1.3 million people under the RCP 4.5 scenario, increasing to 4.2 million under the RCP 8.5 scenario (World Bank Group, 2025).

Some regional studies have been conducted to gain detailed understanding of the severity of climate change impacts in Indonesia. The Indonesia government even planned to relocate the capital city from Jakarta to Nusantara, with one of the main reasons is SLR in 2050 which threatens Jakarta (Kementerian PPN/Bappenas, 2021). Additionally, the national strategic project NCICD (National Capital Integrated Coastal Development) has been launched as an integrated solution to address water–related challenges in Jakarta, ranging from flooding, sanitation, to water supply (Pemerintah Provinsi DKI Jakarta, 2023). By 2050, coastal flooding is expected to inundate north part of Jakarta (Takagi et al., 2016) and will experience significant economic losses due to combined flooding caused by SLR, extreme precipitation, and land subsidence (Karondia, et al., 2019). Other threatened areas are along the northern coast of Java, including key cities such as Semarang (Marfai & King, 2008; Purwanto, 2011; Karondia, et al., 2019; Putri, et al., 2021), Surabaya (Imaduddina et al., 2014; Sulma, et al., 2012; Agustina, et al., 2023) and Banten (Agustina, et al., 2023). Considering future land–use changes from mangrove forests, fish ponds, and agricultural land to industrial and residential areas in northern coast of Java, it is estimated that the area affected by coastal flooding due to global SLR will reach thousands of hectares, with the potential for significant economic losses (Suroso & Firman, 2018). Not only areas on the Java island, other areas such as Medan in Sumatra island (Lumban-Gaol et al., 2024), Makassar in Sulawesi island (Tejakusuma, 2011; Hidayat, 2012), and south part of Kalimantan island (Saidy & Azis, 2009) also face similar threats which potentially cause significant losses.

Previous studies indicate that research on the impacts of SLR in Indonesia has been conducted more at a regional or local scale than national analysis. Nor has any study mapped and compared the potential greatest impacts across provinces based on extent of inundation inundation area, number of affected population, and estimated economic losses due to permanent inundation. To date, there has been no comprehensive study analyzing the future impacts of SLR across Indonesia using Global Climate Models (GCMs) derived from the latest CMIP6 (Coupled Model Intercomparison Project Phase 6) datasets. Therefore, this study aims to fill the gap in the assessment of SLR risks in Indonesia by conducting analysis of the potential impacts of SLR across Indonesia until 2100. The analysis in this study was conducted without considering adaptation efforts, allowing for the identification of the most fundamental potential impacts if no intervention is implemented. The results of this study are expected to enrich the scientific basis for formulating more equitable climate change mitigation and adaptation measures and policies in Indonesia's coastal areas.

Data and Method

CMIP6 Model

This study uses three GCMs, namely MIROC6 (Model for Interdisciplinary Research on Climate), ACCESS–ESM1–5 (Australian Community Climate and Earth System Simulator– Earth System Model), and CanESM5 (Canadian Earth System Model), which are part of the CMIP6 climate projection scenarios (Table 1). The three Shared Socioeconomic Pathways (SSP) scenarios used include SSP1–2.6 (low emissions), SSP2–4.5 (moderate emissions), and SSP5–8.5 (high emissions).

The main variables of the models used in the analysis include *zos* and *zostoga*. Variable z*os* describes as sea surface height relative to the geoid mat a specific location and time. This is spatial and temporal variable, and reflects local dynamics such as ocean currents, atmospheric pressure, and water mass redistribution. Meanwhile, *zostoga* is a variable representing the average global change in sea level caused by ocean thermal expansion. This variable is non spatial, has a single value for each point in time, and reflects the global trend of steric sea level.

Sea level is calculated based on a combination of zos and $zostoga$ variables using the formula:

$$SL_{i,t} = zos_{i,t} - \overline{zos}_t + zostoga_t \qquad (1)$$

where $SL_{i,t}$ indicates corrected sea level to represent local and global change, $zos_{i,t}$ is zos value at i grid and t time, $\overline{zos}_t$ is global average of zos in t time, and $zostoga_t$ is global mean sea level change due to thermal expansion in *t* time.

From the combination of *zos* and *zostoga*, it is projected that SLR rate in Jakarta Bay due to thermal expansion between 2015 and 2100, ranges from 1.5 to 4.6 mm/yr depending on the models and scenarios (Figure 1). Thus, the total SLR due to thermal expansion during that period is estimated to be in the range of 12.7 to 39.1 cm. This number is lower than the estimate as one of the reasons for relocating the capital city from Jakarta, namely the threat of a SLR of 25–50 cm by 2050 (Kementerian PPN/Bappenas, 2021). However, it should be noted that this is likely due to differences in methodological approaches, the scope of variables, or the data sources used in each study.

Table 1. CMIP6 models used in this study

No.	Model	Institute	Horizontal resolutions (lon x lat)
1.	MIROC6	National Institute for Environmental Studies (NIES), Atmosphere and Ocean Research Institute, University of Tokyo, and Japan Agency for Marine–Earth Science and Technology (JAMSTEC)	1º x 0.70º
2.	ACCESS–ESM1–5	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Australian Bureau of Meteorology (BoM)	1º x 0.60º
3.	CanESM5	Canadian Centre for Climate Modelling and Analysis (CCCma)	1º x 0.62º
4.	NorESM2–MM	NorESM (Norwegian Earth System Model) Climate modeling Consortium	1º x 0.47º
5.	MRI–ESM2	Meteorological Research Institute (MRI) Japan	1º x 0.50º

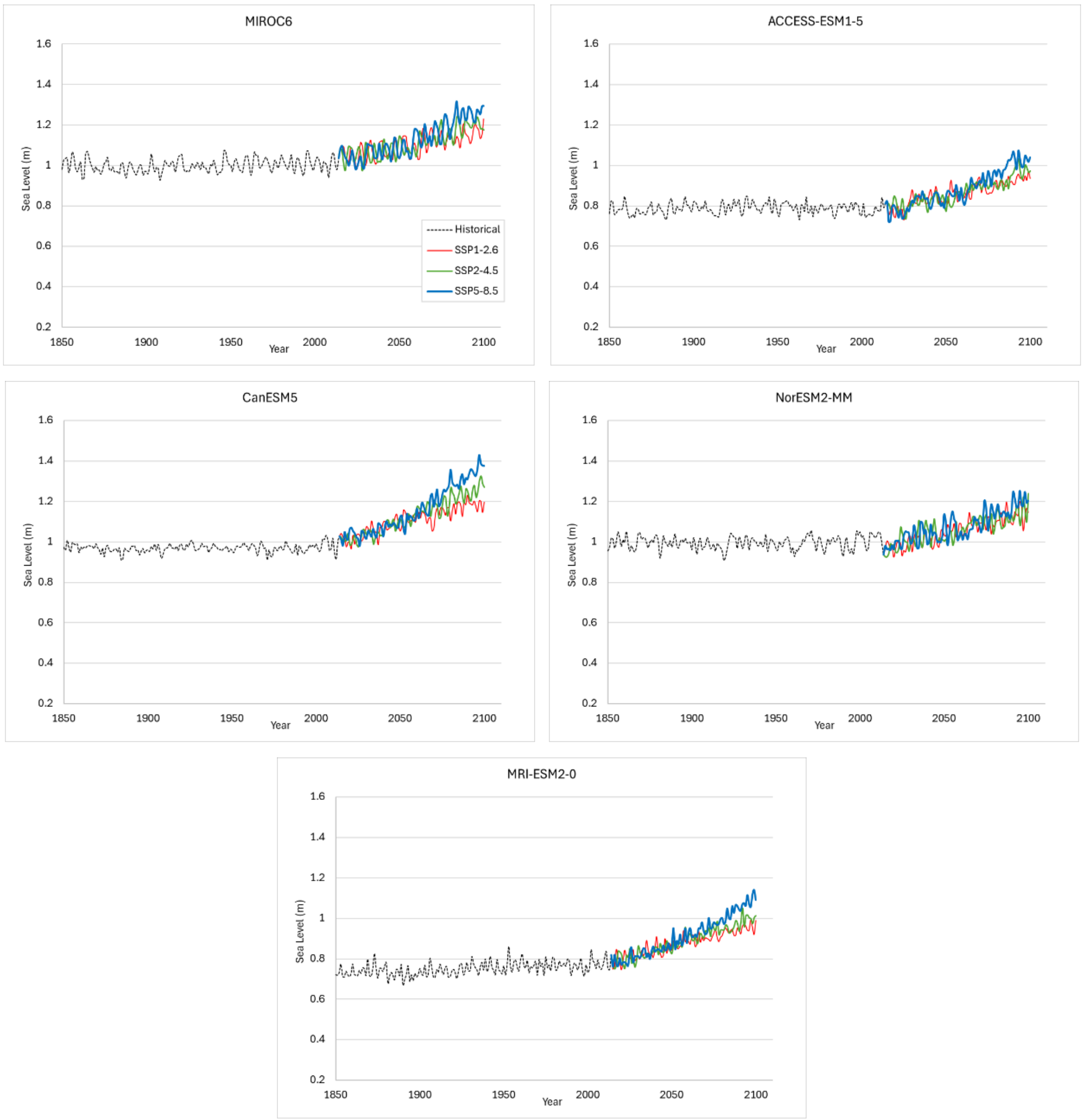


Figure 1. Historical and Projection of Sea Level in Jakarta Bay based on models

Impact Analysis

In the impact analysis, the two main indicators analyzed were the inundated area and the number of people affected. The depth of inundation was calculated based on the difference between the high–water level (HWL) from sea level and tide, and the elevation of the land. The calculation of the inundated area is performed spatially, considering the curvature of the earth to ensure the accuracy of the estimate, especially in high latitude and tropical regions.

The HWL was calculated by adding tide with projected sea level, which is a combination of *zos* and *zostoga*. The land elevation and bathymetry data used in this study were obtained from the ETOPO2022 dataset (NCEI, 2025), while tidal data was taken from the TPXO10 model (Egbert & Erofeeva, 2002), which includes the main tidal components, namely M_2, S_2, O_1, and K_1.

These tidal constituents consist of semidiurnal and diurnal components, each influenced by the gravitational pull of the moon and the sun, respectively. M_2 is the main semidiurnal constituent driven by the gravitational pull of the moon and is generally the largest component in the global tidal system. S_2 derived from the gravitational influence of the

Sun, the combination of the two produces the cycle of spring tides and neap tides. Meanwhile, O_1 is the main diurnal component derived from the gravitational pull of the Moon and the tilt of the Earth's rotation axis, producing one high tide and one low tide per day. The other diurnal component is K_1, a lunisolar constituent influenced simultaneously by the Moon and the Sun, and is often the most dominant diurnal component, especially in tropical regions. Together, these four constituents form the basic pattern of daily tidal variations at various coastal locations.

The TPXO10 model includes global, regional, and local models of barotropic tides. The amplitude of each tidal component is according to the following Equation 2:

$$Tide = h_{M_2} + h_{S_2} + h_{O_1} + h_{K_1} \qquad (2)$$

where h denotes the amplitude of the tidal components.

In this analysis, a spatial resolution of 0.5 arc minutes was applied to ensure adequate detail in identifying areas affected by SLR.

The inundation map is then combined with population density data from the National Center for Atmospheric Research (NCAR) and future population data from the International Institute for Applied Systems Analysis (IIASA) to identify the population affected in the impacted areas (Figure 2). Thus, estimation of impacts is obtained for various projection years and scenarios.

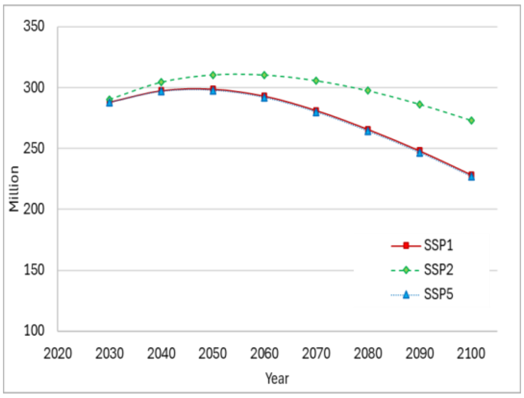


Figure 2. Population Projection in each SSPs scenario by IIASA (IIASA, 2024)

Indonesia's population projections are categorized as low–fertility countries because the Total Fertility Rate (TFR) for the 2005–2010 period was recorded at less than 2.9 (KC & Lutz, 2017). Population projections in the SSP are determined by a combination of demographic indicators regarding fertility, mortality, migration, and education. In SSP1, Indonesia's population growth follows the pattern of low fertility, low mortality, medium migration, and high education. These characteristics are similar to SSP5, where Indonesia is projected to experience low fertility, low mortality, high education, and high migration. Therefore, both scenarios produce similar population growth patterns that increase until around 2050, then gradually decline until 2100. Meanwhile, SSP2 depicts a middle–of–the–road scenario, where Indonesia is projected to have all demographic indicators at a medium level. Thus, the population decline in SSP2 is not as sharp as that projected in SSP1 and SSP5.

Damage Cost Analysis

Damage costs due to inundation were estimated using a statistical approach based on a regression model using historical disaster data from EM–DAT (Emergency Events Database), same approach as applied by Tsuchida et al. (2018) and Tamura (2019). However, adjustments were made to the gross domestic product variable from the national level (pGDP – gross domestic product per capita) to the regional level (pGRDP – gross regional domestic product per capita). This was necessary, because economic variables must reflect regional conditions to enable comparison of damage costs between regions. The formula for calculating damage cost is, Equation 3:

$$\log(DC) = y + \alpha \log(pGRDP) + \beta \log(POPrisk) \qquad (3)$$

where DC is the total damage cost, $pGRDP$ is the gross regional domestic product per capita, and $POPrisk$ is the number of affected populations by SLR.

This regression model was built based on hydrogeological and geophysical disasters related to the impacts of climate change in Indonesia recorded in the EM–DAT database. The data from EM–DAT includes the location, time, and duration of disaster, number of affected populations, and reported damage cost. Although there were 65 disaster data of Indonesia since 1966 in EM–DAT, only 40 data during the period 2000–2022 can be used due to the completeness and consistency of the damage cost information. The damage cost values in the EMDAT are adjusted using the Consumer Price Index (CPI), all values are expressed in constant recent year (*r.year*) prices.

Initially, this research planned to use disaster data from the National Disaster Management Agency (BNPB) due to its high national relevance. However, BNPB data on disaster events, affected populations, and damage cost were quite inconsistent. This study does not use data from BNPB because the official BNPB website (dibi.bnpb.go.id) shows inconsistencies in linking disaster impacts to monetary loss figures. Although some events include complete information, such as the type of disaster, number of victims, and detailed economic losses, many events in a given year do not provide loss data in rupiah. In several cases, the database instead reports rehabilitation and reconstruction budget requirements rather than actual recorded losses.

This adjustment is needed to ensure consistency in damage cost comparison and eliminate inflation's distortions. This process uses the following Equation 4:

$$X_{adj,r.year} = CPI_{r.year} \, x \, \frac{X}{CPI_y} \qquad (4)$$

where $CPI_{r.year}$= 100.

Future GRDP projections are calculated based on GDP projections from IIASA and the OECD (Organisation for Economic Cooperation and Development) that have been adjusted to socioeconomic scenarios (Figure 3).

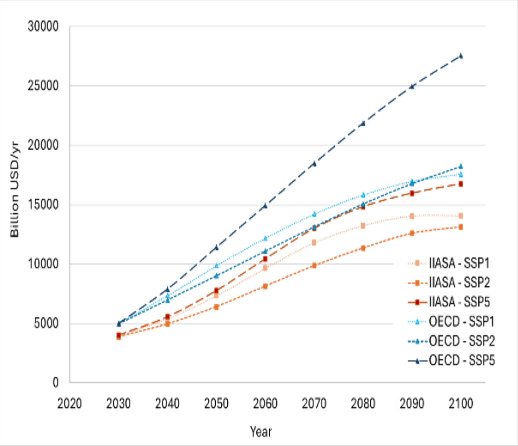


Figure 3. GDP Projections in each SSPs scenario by OECD and IIASA (IIASA, 2024)

The OECD framework is based on the income convergence assumption, which states that lower–income countries will gradually catch up with developed countries, while the IIASA model emphasizes the role of labor quality through education, innovation capacity, and technology adoption as fundamental factors shaping economic growth trajectories.

By focusing on the convergence process, the OECD model tends to produce higher future GDP projections than the IIASA model. GRDP projections are obtained by distributing national GDP projections (from OECD and IIASA) based on the average percentage of historical GRDP distribution in Indonesia, obtained from 2016–2024 data from the Indonesia's Central Statistics Agency (BPS). In the same way, population projections per province are obtained by distributing national population projections (from IIASA) based on historical population percentages in Indonesia from 2010–2024 (Table 2). Jakarta has the highest GRDP distribution, while West Java has the highest population percentage. GRDP per capita is calculated by dividing the total GRDP of each province by its population

Table 2. Average distribution of GRDP and population in Indonesia's provinces (BPS, 2025)

No.	Province	GRDP (%)	Population (%)
1.	Aceh	1.1	2.0
2.	North Sumatera	5.0	5.5
3.	West Sumatera	1.5	2.0
4.	Riau	5.0	2.4
5.	Jambi	1.4	1.3
6.	South Sumatera	2.9	3.1
7.	Bengkulu	0.5	0.7
8.	Lampung	2.2	3.2
9.	Bangka Belitung Island	0.5	0.5
10.	Riau Islands	1.6	0.8
11.	Jakarta	17.1	3.9
12.	West Java	13.0	18.1
13.	Central Java	8.4	13.3
14.	Yogyakarta	0.9	1.4
15.	East Java	14.5	15.0
16.	Banten	4.0	4.6
17.	Bali	1.4	1.6
18.	West Nusa Tenggara	0.8	1.9
19.	East Nusa Tenggara	0.6	2.0
20.	West Kalimantan	1.3	1.9
21.	Central Kalimantan	1.0	1.0
22.	South Kalimantan	1.2	1.5
23.	East Kalimantan	4.2	1.4
24.	North Kalimantan	0.6	0.3
25.	North Sulawesi	0.8	1.0
26.	Central Sulawesi	1.3	1.1
27.	South Sulawesi	3.1	3.3
28.	Southeast Sulawesi	0.8	1.0
29.	Gorontalo	0.3	0.4
30.	West Sulawesi	0.3	0.5
31.	Maluku	0.3	0.7
32.	North Maluku	0.3	0.5
33.	West Papua	0.3	0.2
34.	Papua	0.4	0.4
35.	Southwest Papua	0.2	0.2
36.	South Papua	0.1	0.2
37.	Central Papua	0.7	0.5
38.	Highland Papua	0.1	0.5

Results and discussion

Inundated Area and Affected Population

This study uses decadal snapshots to mitigate the influence of interannual climate variability and to align with the decadal reporting convention commonly used in climate impact assessments, such as those in the CMIP and IPCC. This approach, which focuses on 10-year time slices, simplifies the identification of sea-level rise impact patterns and facilitates clearer comparisons of impacts across models and scenarios.

Based on the analysis results, without adaptation or mitigation measures against SLR, the total area of Indonesia that is potentially inundated permanently in the future ranges from 18,700 km² to 39,500 km² depending on the climate model and emission scenario used from 2030 to 2100. Meanwhile, the range of the average inundation depth is estimated to reach 1.10 m in 2030 and is likely to increase up to 1.23 m in 2100. Spatial analysis indicates that all provinces in Indonesia are projected to experience inundation in 2030, with the exception of Yogyakarta and Papua Pegunungan, which remain unaffected by sea-level rise. In the Figure 4, it can be seen that the most vulnerable areas to inundation are generally located around the mouths of large rivers, such as the Musi rivermouth in Sumatera, the Kapuas and Barito rivermouth in Kalimantan, and the Bengawan Solo rivermouth in Java. South Kalimantan is consistently recorded as the region with the largest extent of inundation across all models and scenarios, confirming its vulnerability to the impacts of SLR.

Model projections (Figure 5) show significant variation between scenarios and between models, with CanESM5 consistently producing the largest potential inundation areas and affected population, while ACCESS–ESM1–5 produces the smallest. By 2050, the total inundated area in Indonesia is estimated to be at least 18,700 km² (ACCESS–ESM1–5, SSP2–4.5) and could reach as high as 28,700 km² (NorESM2–MM, SSP2–4.5). By 2100, this projection increases to 22,400 km² in the minimum scenario (ACCESS–ESM1–5, SSP1–2.6) and could reach 39,500 km² in the maximum scenario (CanESM5, SSP5–8.5).

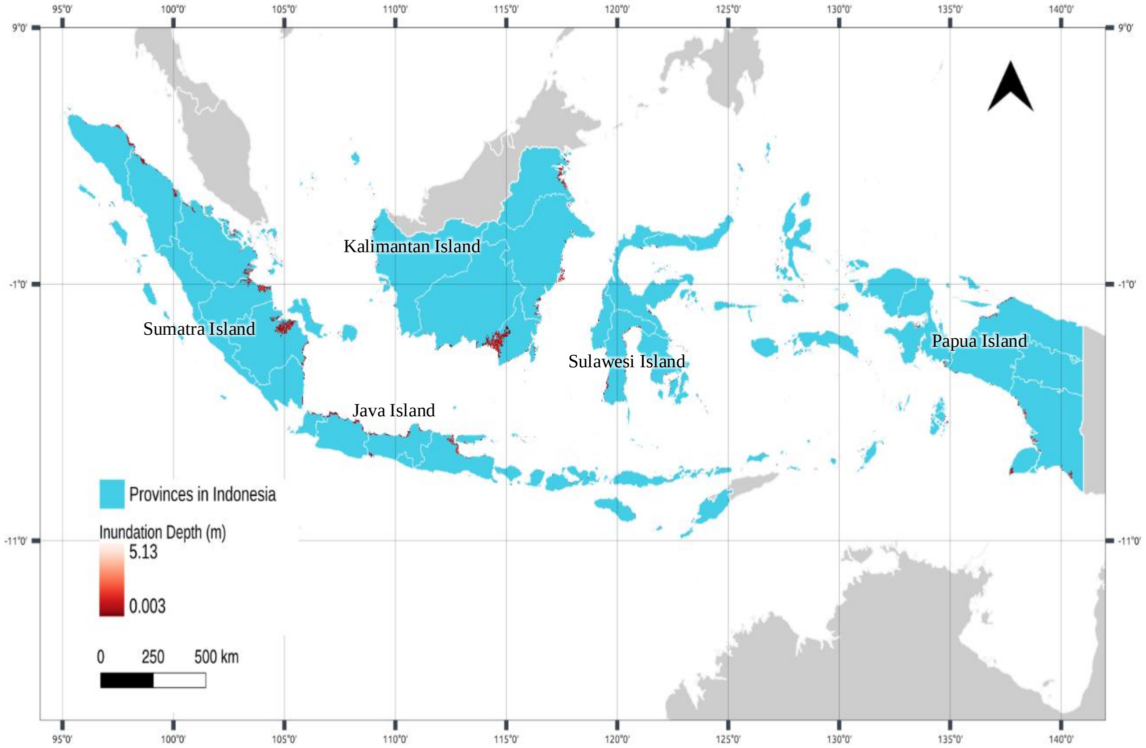


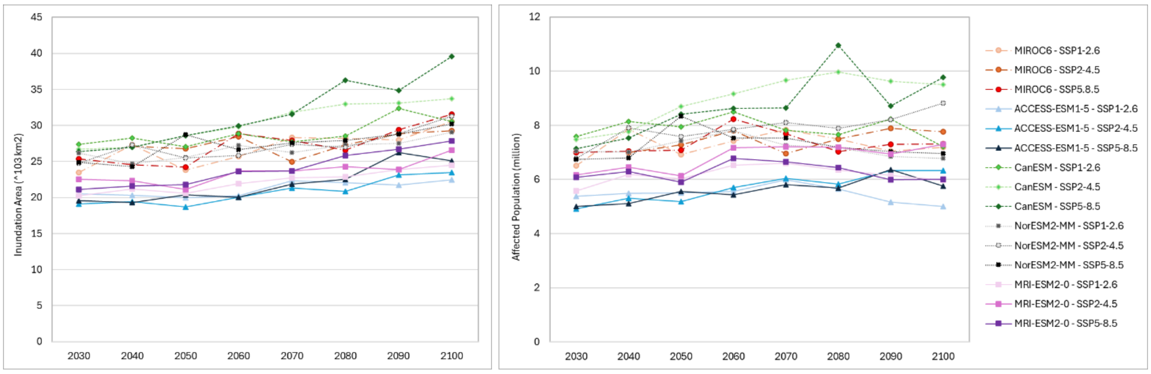
Figure 4. Potential permanent inundation map in Indonesia due to SLR without adaptation by 2100 based on MIROC6 – SSP5–8.5 model

By 2050, permanent inundation is estimated to threaten at least 5.2 million people, and this number could potentially increase to 9.8 million by 2100 depending on the models and scenarios used. The analysis confirms that the projected affected population by permanent inundation due to SLR is much higher than the 2021 World Bank report (World Bank Group, 2025). The report estimated that around 4.2 million people would be affected by 2100 under the RCP8.5, while this study produced a range of 5.7–9.8 million people in the same year under the SSP5-8.5 scenario. This difference is also seen in 2070, where the study's projections show an affected population of 6.0–9.7 million people under the SSP2-4.5 scenario, far above the World Bank's estimate of only around 1.3 million people under the RCP4.5 scenario.

Population projections based on the IIASA in Figure 2 indicate an increasing trend, peaking around 2050 and then declining, however the affected population in Figure 5 shows a different dynamic pattern. Most projections show the population at risk peaking later, around 2060, this because the affected population is determined by the extent of inundation area.

This finding has important implications for adaptation and mitigation strategies, as the peak population at risk should ideally be prevented from being occured. The measures should ideally be designed to be effective before the peak period, thereby significantly minimizing the long–term impacts of SLR.

As shown in Figure 5, CanESM5 SSP5–8.5 projections stand out particularly around 2080. By 2080, the inundation area and the number of potentially affected populations increased significantly. This increase not only reflects the long-term trend of sea level rise but is also influenced by the decadal oscillation that governs sea level variability.



(a) (b)

Figure 5. Trends of total inundation area (a) and total affected population (b) due to SL

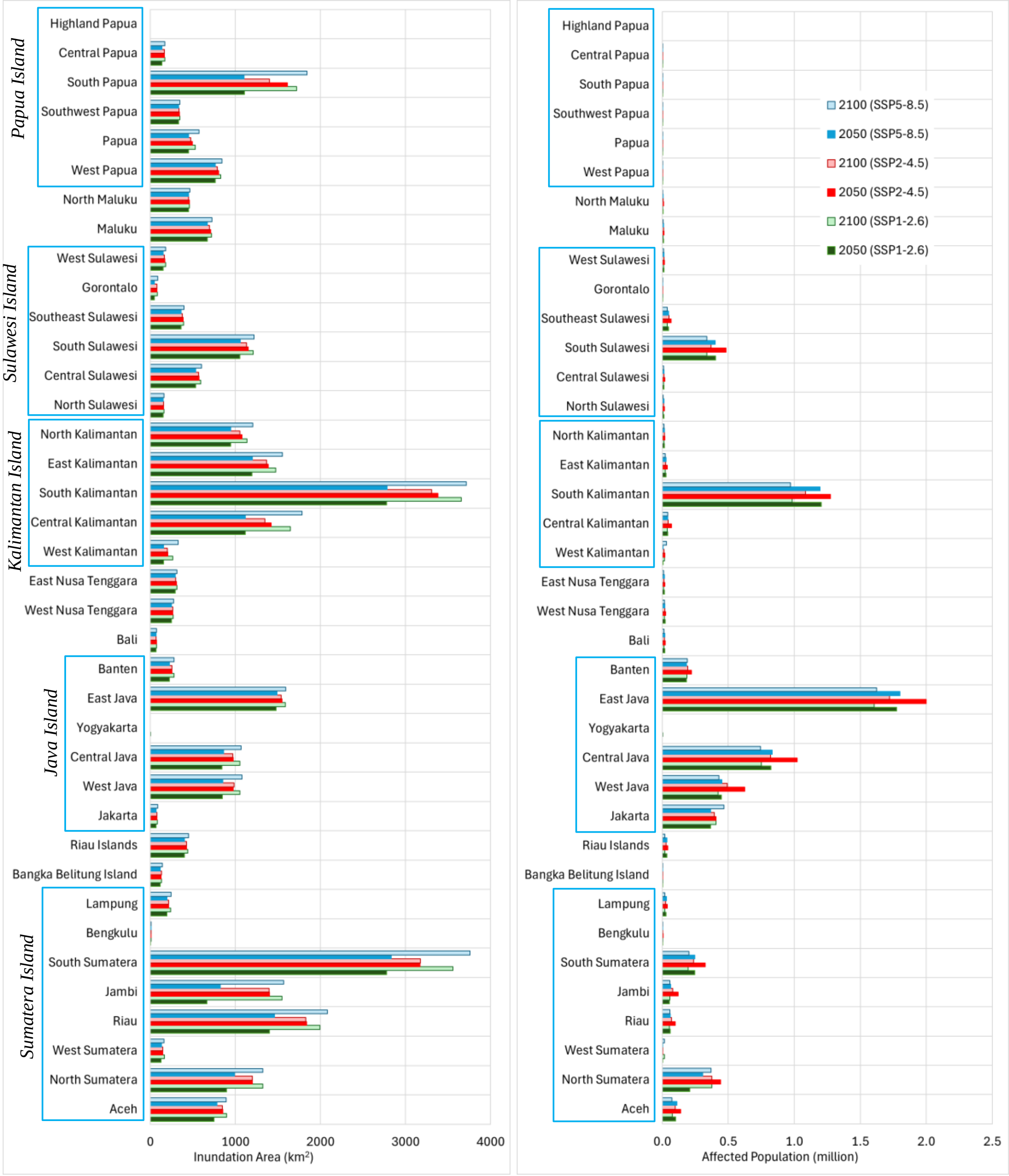
During this period, sea level was in a positive phase of internal variability, resulting in higher elevation anomalies compared to other years within the analysis range. Considering that all models capture the influence of regional climate variability, including El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), the combination of the long-term SLR trend and the positive phase of this climate oscillation amplified sea level elevation. The interaction of these two factors increased inundation depth and directly increased the number of populations categorized as at risk, as clearly seen in the CanESM5 projections for 2080.

Since the 5 models produce a quite wide range in the analysis results, then in the comparative analysis of the impact of SLR between provinces are focused on projections from the MIROC6 model, which provides relatively moderate and representative results. Based on estimates of the extent of inundation and the population at risk, it appears that inundation is not always proportional to the number of affected populations (Figure 6). In many provinces outside Java island, the inundated area is relatively large but the number of affected populations is relatively small.

On the other hand, despite the smaller inundation area, the potential for the population to be affected by SLR could be very high in Java. This is due to the high population concentration, particularly dense population in coastal areas, which increases vulnerability to the impacts of SLR.

According to MIROC6 across all scenarios for 2050 and 2100, there are two provinces with the largest projection of potential permanent inundation, namely South Kalimantan and South Sumatra, with both have inundation area ranging from 2,700 km² to 3,700 km². Followed by Riau which is projected to experience of 1,400 km² to 2,000 km² of inundation area. Interestingly, although Jakarta is often become the primary focus of SLR issues in Indonesia, the projected inundation area in this province is relatively small compared to other provinces, at around 66 km² to 86 km² for 2050 and 2100 depending on the models and scenarios.

The province with the highest at–risk population is East Java, with the population at risk reaching 2.0 million in 2050 (SSP2–4.5) and decreasing to 1.7 million in 2100. In the low–carbon scenario (SSP1–2.6), the impacted population in East Java is estimated at around 1.7 million in 2050 and decreasing to 1.6 million in 2100. South Kalimantan ranks second among the provinces with the largest impacted population, followed by Central Java. Jakarta ranks fifth after West Java, with a relatively comparable values to South Sulawesi. In 2050, the population affected by SLR in Jakarta is projected to reach 365,000 people (SSP5–8.5) and is estimated to increase to 467,000 people in 2100 under the same scenario.



(a) (b)

Figure 6. Potential inundation area (a) and population at risk (b) in each province derived from MIROC6 in 2050 and 2100

The distribution pattern of the affected population does not always align with the extent of the inundation area. The analysis of the affected population density in 2100 based on SSP 5–8.5 reveals a sharp contrast between regions. Jakarta recorded an extreme density of around 5,400 people/km² of inundated area, far exceeding other area in Java such as East Java (~1,000 people/km²) and Central Java (~690 people/km²). On other islands that expected to have large inundation areas, population density is not directly comparable given the vastly different magnitudes from Java island’s provinces, particularly Jakarta.

The population at risk density in South Kalimantan is only about 260 people/km², in South Sumatra around 54 people/km², and in Riau around 27 people/km², all of which are significantly lower than Jakarta. Taken together, these results suggest that there are variations in risk characteristics between regions: regions with patterns such as East Java, Central Java, and Jakarta have high social vulnerability due to the dense concentration of coastal populations, while regions such as South Kalimantan, South Sumatera, and Riau show more dominant physical vulnerability due to the large area of inundation. These findings indicate that the high concentration of population in coastal areas plays a significant role in determining the level of risk due to SLR.

Damage Cost

Estimation of damage cost due to disasters is carried out using a logarithmic regression approach using two main variables, namely GRDP per capita (*pGRDP*) and the number of affected populations (*POPrisk*).

The regression obtained from historical EM_DAT data is:

$$\log(DC) = 2.829 + 0.1716 \log(pGRDP) + 0.8817 \log(POPrisk) \tag{4}$$

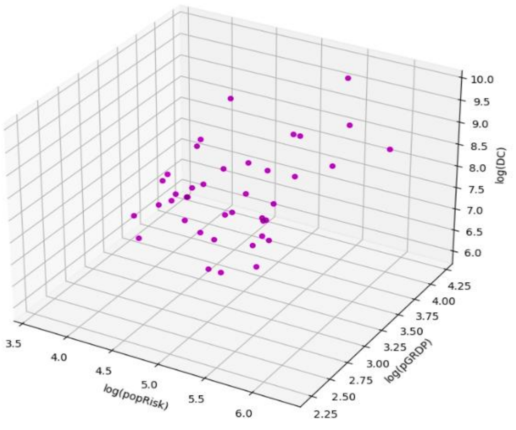
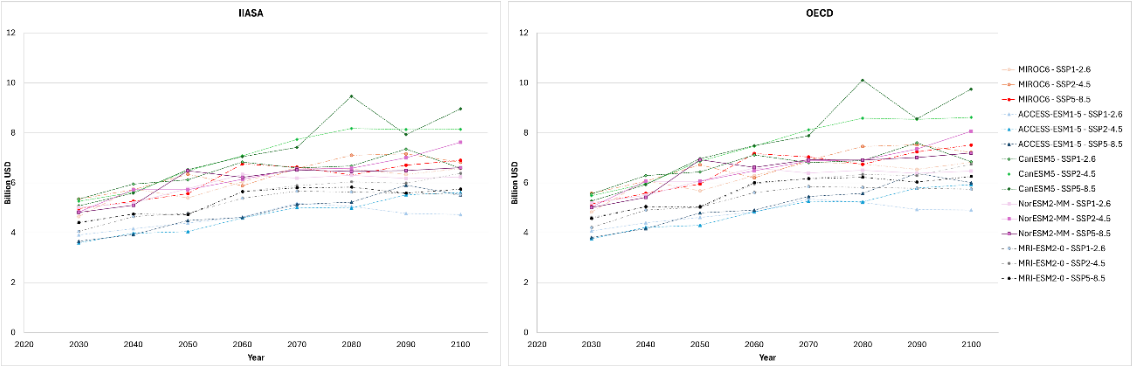


Figure 7. Log-Scaled relationship between Damage Cost (DC), GRDP per capita (*pGRDP*) and the number of affected populations (*POPrisk*)

The results show that the affected population variable (*POPrisk*) is the most significant factor, with a coefficient of β = 0.8817, a *t–value* of 3.738, and a *p–value* of 0.001. Meanwhile, the *pGRDP* variable has a coefficient of α = 0.1716 but is not statistically significant (p = 0.651), and the constant value γ = 2.829 is also insignificant (p = 0.122). The adjusted R^2 value is 0.235 which indicates that the model is able to explain 23.5% of the variation in the damage cost data.

The damage cost pattern resembles the affected population pattern, which can be explained by the fact that mathematically the population at risk is the most significant variable (Figure 8). The results of damage cost analysis shows that potential total damage costs due to inundation in 2050 are estimated at USD 4.0–6.5 billion based on IIASA and USD 4.3–7.0 billion based on OECD. By 2100, these values increase to USD 4.7–9 billion (IIASA) and USD 4.9–10 billion (OECD), in line with SLR and economic growth in the affected areas.

Damage cost projections based on OECD data are generally higher than those using IIASA data. This difference is primarily due to differences in values between projections reflecting the higher economic growth assumptions in the OECD compared to the IIASA. Examining the distribution pattern of damage costs in Indonesia based on the Figure 9, it is shown that East Java consistently recorded the highest estimated damage costs reaching nearly USD 1.8 billion in the OECD projection and USD 1.6 billion in the IIASA projection by 2100. This confirms East Java's position as a region with a combination of high population exposure and significant inundation. Other provinces such as South Kalimantan, Central Java, West Java, and Jakarta also rank high.



(a) (b)

Figure 8. Total damage cost in Indonesia based on IIASA (a) and OECD (b) projections

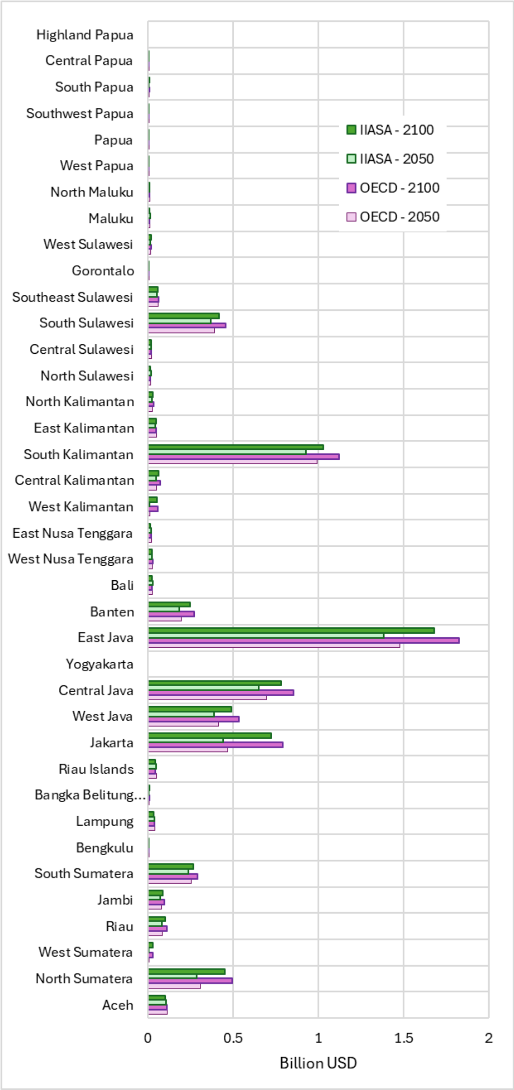


Figure 9. Damage cost projections based on MIROC6 – SSP5–8.5

Based on previous research, Jakarta is projected to experience flooding of 110 km² in 2050 (Takagi et al., 2016), with economic losses reaching USD 380 million in 2030 and USD 517 million in 2050 due to flooding due to a combination of SLR, extreme rainfall, and land subsidence (Budiyono et al, 2016). The results based on the model used in this study show a smaller inundation estimate, namely in the range of 66–79 km² in 2050. However, the estimated damage costs are higher, namely reaching USD 401 million in 2030, USD 582 million in 2050, and USD 941 million in 2100. Despite the smaller inundation, Jakarta's damage cost indicating that the impact is not only determined by the inundated area, but also by the population and economic value of the affected area.

Conclusion

The results of this study shows that Indonesia faces significant threat from SLR. Sea level rise is projected to continue increasing until the end of the 21st century if no adaptation and mitigation implemented to address climate change. The estimated permanent inundation area due to SLR is estimated to reach more than 39,500 km², while the population at risk is estimated to reach more than 10 million in the end of 21st century based on the worst-case scenario. Provinces such as South Kalimantan, South Sumatra, and Riau have large spatial inundation areas. Meanwhile, provinces on the island of Java, such as East Java, Central Java, West Java, and Jakarta, show a highly vulnerable combination of moderate inundation areas and high numbers of affected populations due to the dense population in coastal areas. Economically, damage cost estimates show a consistent upward trend until 2100, with a total value exceeding USD 10 billion in a high-emission scenario and high economic projections from OECD.

Overall, this study provides a clear picture of the impact of SLR in each province of Indonesia. The analysis confirms that damage cost from SLR reflect not only physical dimensions such as inundation area, but also the complexity of spatial economic structures, population distribution, and asset values. Therefore, adaptation policies need to be designed equitably and supported by robust projection data. Provinces at high risk, whether due to large inundation areas, affected populations, or significant damage cost, should be prioritized in future national climate change mitigation and adaptation strategies.

Limitations

This analysis does not incorporate land subsidence, storm impacts, or other short-term extreme events, as the focus is limited to long-term SLR. Although in this study the regression model can be used to estimate economic losses, the availability of more extensive and high–quality data in the future is crucial to improve the accuracy and balance of the model. With more comprehensive disaster data availability, the regression model can be refined to produce more precise and representative projections. With it, regression model will likely have better *p–values, t–statistics*, and adjusted R^2, thus better representing the relationship between *pGRDP* and *POPrisk* in calculating damage costs.

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Declaration Statement

The authors declare that ChatGPT (OpenAI) was used solely for language proofreading, grammar correction, and improvement of writing clarity during the preparation of this manuscript. All scientific content, including the study design, methodology, data analysis, interpretation of findings, and conclusions, were developed and verified exclusively by the authors. The authors take full responsibility for the accuracy, originality, integrity, and validity of the manuscript's content.

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