Assessment of adaptive capacity to sea level rise using open-loop system, case study: Cirebon and Pangandaran

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Abstract. This research aims to assess the adaptive capacity of three adaptive strategies applied in Cirebon and Pangandaran by estimating community assets under threat of Sea-Level Rise (SLR) through open-loop system. Firstly, SLR in Cirebon and Pangandaran each month from 2006 to 2100 is simulated using ocean heat flux and ice melting model data by Representative Concentration Pathways (RCP) 8.5, Intergovernmental Panel of Climate Change Assessment Report (IPCC AR) 5. This simulation result is then added with ocean phenomena such as tide, Indian Ocean Dipole (IOD), Madden-Julian Oscillation (MJO), storm surge, and Kelvin wave along with their frequencies. By the year 2100, the sea level in Cirebon will reach 115.65 cm and 148.09 cm in Pangandaran. Secondly, the SLR and applied strategies are converted to be inundation maps of community assets. Overall, the result shows the best policy for both regencies is protect which has an adaptive capacity value of 96.30% and 76.65% respectively. But deeper, the adaptive strategy for each district in both regencies differs one to another.

1. Introduction
Coastal communities are increasingly facing major threats such as global climate change, hazardous storms, shoreline erosion, and dangerous effects of marine debris [1]. Those environmental-related problems are worsened by the fact that the poverty number of Indonesia reaches 26.58 million people with 61.36% of them are living in coastal areas [2]. Those issues encourage the climate researchers to not only focus on the climate aspect, but also the socio-economic aspect as well [3]. This multidiscipline interconnection could be mapped through the system dynamics in order to set the intervention of policies precisely to a system that might be beneficial for the communities [4].

West Java is one of the provinces that vulnerable to the sea-level rise (SLR) which has 3.54 million people living below the poverty line [2]. On the other hand, based on SRES a1b scenario on IPCC AR 4, the projection rate of SLR from 2006 to 2100 is 0.74 to 0.76 cm per year [5]. It indicates that the life of coastal communities in West Java is threatened by the upcoming SLR. Therefore, determining an on-target policy that has a good adaptive capacity to SLR is considerably needed to increase the resilience of coastal communities to this threat.
This study uses open-loop system to combine the two aspects of research, the physical system of sea-level rise and the social system which is defined as community assets. It is aimed to assess the most suitable adaptive capacity scenario (protect, accommodate, or retreat) to be implemented on the north and south coast of West Java, Cirebon and Pangandaran (Figure 1). The monthly SLR should be determined first to map the inundated community assets that are categorized into 3 types (public facilities, critical facilities, and houses). Then, each scenario will be assessed based on how many assets the scenario could protect.

2. Methodology
Figure 2 shows the flow chart of this research. Sea level rise added with the oceanographic events will cause ecological changes. Changes in ecology and social structure are simulated through open-loop system to determine adaptive scenarios.

Figure 1. Study area: Cirebon and Pangandaran

Table 1. Data sources

| Data                      | Year     | Resolution   | Source       |
|---------------------------|----------|--------------|--------------|
| Ocean heat flux           | 2006 – 2100 | 1° x 0.5°   | BOM-CSIRO   |
| Ice melting               | 2006 – 2100 | 2° x 1.5°   | IPSL         |
| Glacier melting           | 2006 – 2100 | 1.8° x 0.2° | MPI          |
| DTM (digital topographic model) | 2014     | 8 meters    | BIG          |
The simulation of SLR from 2006-2100 uses 3 global climate models (GCMs) which are ocean heat flux, ice melting, and glacier melting. Table 1 shows the data used for this research.

### Table 1

| Data                          | Year         | Resolution         | Source          |
|-------------------------------|--------------|--------------------|-----------------|
| 5 Reconstructed altimetry     | 1950 – 2009  | Monthly, 0.5°      | NASA, NOAA      |
| 6 Tidal                       | 2010 – 2014  | 1 minute           | BIG             |
| 7 IOD index                   | 1950 – 2018  | Monthly            | NOAA            |
| 8 MJO index                   | 1974 – 2019  | Daily              | NOAA            |
| 9 Outgoing longwave radiation | 1974 – 2018  | Daily, 2.5° x 2.5° | NOAA            |
| 10 Tropical cyclone           | 1972 – 2012  | Monthly            | BMKG            |
| 11 Social assets              | 2014         |                    | BIG             |

2.1. *Simulation of sea level rise*

Ocean heat flux in the form of heat radiation (W/m²) could be modified into Joule since time and grid space were known. It was assumed that the heat flux entering the sea reached a maximum depth of 200 meters or *photic zone*. So, the mass of seawater could be calculated by the multiplication product of the study case’s sea area covered by GCM and the depth. Then temperature changes could be obtained through the first law of thermodynamic,

\[
Q = m \cdot c \cdot \Delta T \tag{1}
\]

- \(Q\): Heat energy received by the sea / ocean heat flux (J)
- \(m\): mass of sea water (kg)
- \(c\): heat of sea water (J kg⁻¹K⁻¹)
- \(\Delta T\): temperature changes (K)

Sea level expansion or thermal expansion could be calculated through the ratio of global mean thermal expansion and global-mean temperature change of CSIRO-Mk3.6.0 on RCP 8.5 which is 6.82 cm/°C [6].

For ice melting, both polar and glacier ice data were obtained with the mass of melting ice (kg) per time. Thus,

\[
V = \frac{m}{\rho} \tag{2}
\]

- \(V\): volume of melting ice (m³)
- \(m\): mass of melting ice (kg)
- \(\rho\): density of ice (916.7 kg m⁻³)
The ice melting volume was then used to calculate SLR. A 1 mm of SLR needs $10^{-3}$ m$^3$ per m$^2$ of water [7]. It was assumed that there was no time delay for melting pole ice and glacier to arrive at the both of study cases.

2.2. Tidal analysis
Tidal data was used to calculate monthly Mean Sea-Level (MSL) which be added to the simulation of SLR. Secondly, Mean High Water Level (MHWL) or the average of high water was needed to be known as it happens every day. Moreover, tidal data was used to calculate the Highest Water Level (HWL) which was the requirement for the minimum height of seawall in protect scenario [8].

2.3. Indian ocean dipole and Madden-Julian oscillation
The Indian ocean dipole (IOD) and Madden-Julian Oscillation (MJO) could be identified through their monthly indexes. IOD (-) has a direct effect on additional Sea Surface Temperature (SST) [9]. An increase of SST could be measured by filtering the data of SST based on the period of IOD occurrence which is around 30 - 42 months [10]. Then the highest additional SST on IOD (-) was assumed to happen in such upcoming events and add the thermal expansion. Meanwhile, MJO has a considerable effect on outgoing longwave radiation [11]. This trapped radiation was firstly filtered based on the occurrence of MJO in West Java (phase 4 and phase 5), 30-50 days [12]. Finally, the highest radiation measured was assumed to occur again in the upcoming MJO.

2.4. Tropical cyclone and Kelvin wave
The number of tropical cyclones each month from 1972 to 2012 was divided into two regions, at the north latitude which generated storm surge in Cirebon and so did the south latitude in Pangandaran. By setting up the upper bound, the tropical cyclones in the north mostly occurred in July, August, and September. Whereas, tropical cyclones in the south mostly occurred in January, February, and March. This event was assumed to occur in the same months in the upcoming years.

Study literature was conducted to identify the additional sea level caused by tropical cyclone and Kelvin waves. Tropical cyclone generated storm surge which increases the sea level by 16.2 cm in Cirebon [13] and 19.0 cm in Pangandaran [14]. Meanwhile, Kelvin waves would mostly be generated in the phase transition between the west and east monsoon in the months of April to May and November to December [15]. A research by [16] suggested that Kelvin waves in the south of Java would likely increase the sea level by 17 cm.

2.5. Adaptive strategies
There are three intervention policies or adaptive strategies showed in Table 2. Open-loop system was used to measure the changes of the system. Furthermore, the three main data as exogenous variables were not influenced by the system. Figure A.1 illustrates the two systems conducted at this study. The protect scenario was applied by intervening the physical system of the sea level rise. Meanwhile, the accommodate and retreat scenarios were applied to the social system.

Mangrove forest in Indonesia in average could absorb 52.85 tons of CO$_2$/hectare/year [18]. By assuming that all the atmosphere was well mixed, 1 ppm CO$_2$ = 2.12 GtC [19]. On the other hand, the molar mass of atomic O is 16 and atomic C is 12. In conclusion, it is known that 1 GtCO$_2$ = 0.27 GtC and 1 GtCO$_2$ = 0.127 ppm CO$_2$. Equation (3) was used to obtain the reduction of radiative forcing [20],

$$ R = \frac{3.71}{\ln 2} \times \ln \frac{\text{CO}_2}{278} $$

The high of the seawall was adjusted to the Highest Water Level (HWL) on each coast of West Java. Accommodate and retreat scenarios were assessed and measured through GIS mapping. The
application of elevated buildings assumed that all assets in critical facilities and houses were not submerged. Meanwhile, the retreat scenario eliminated the assets within the coastal boundaries.

2.6. Adaptive capacity

The result of the simulated sea-level rise was visualized on the DTM using GIS. Each strategy was then assessed by counting the submerged assets. Each asset has a different contribution value to adaptive capacity showed in Table 3. The total number of assets was assumed to be constant from 2014 to 2100.

| Table 3. Value of each asset [21] |
|----------------------------------|
| **Asset** | **%** | **Component (unit)** |
| Critical facilities | 30 | Health services, education services, government offices (building units) |
| Public facilities | 30 | Road (km) |
| Houses | 40 | Residential services (building units) |

The concept of calculating vulnerability, resilience, and adaptive capacity is based on Table 4. The adaptive capacity of a scenario was assessed by comparing the number of community assets protected to the total number of inundated assets without adaptive strategy.

| Table 4 Asset-based calculation for vulnerability, resilience, and adaptive capacity [17] |
|------------------------------------------|
| **Indicator** | **Definition** | **Description** |
| Vulnerability | $V^j = TA^0 - TA^j$ | A difference between pre-climate change ($TA^0$) and post-climate change community assets under *No Adapt* ($TA^j$) |
| Resilience | $R^j(A_i) = TA^j(A_i) - TA^j$ | A reduced difference between pre-climate change ($TA^0$) and post-climate change community assets under an adaptation scenario of $TA^j(A_i)$ |
| Adaptive capacity | $AC^j(A_i) = \frac{R^j(A_i)}{V^j}$ | Total number of community assets which can be protected by applying a scenario $A_i$ compared to *No Adapt* ($TA^j$) |
| | | Ratio of a community resilience under a scenario $A_i$ and community vulnerability (*No Adapt*) |
3. Result

3.1. The sea level rise simulation
Figure 3 shows the simulation of SLR relative to 2006 based on the ocean heat flux and ice melting of RCP 8.5 IPCC AR 5. The SLR which is caused by heat flux fluctuates, depends on the apparent position of the sun.

![Figure 3](image)

**Figure 3.** The projection of sea level rise in 2006-2040 based on RCP 8.5 a) Cirebon and b)

This simulation result added with monthly MSL is verified to the altimetry in Pangandaran

Figure 4 is simulated SLR+MSL is verified to the altimetry in Pangandaran

![Figure 4](image)

**Figure 4.** Simulated SLR+MSL is verified to the altimetry in Pangandaran

This simulation result added with monthly MSL is verified to the reconstructed altimetry (data of sea level) in Pangandaran from 2006 to 2009. The correlation value which is depicted in Figure 4 is 0.74, while the root mean square error (RMSE) shows a value of 9.35 cm.

A brief comparison between this simulated SLR in West Java and global by IPCC AR 5 is displayed in Table 5. Overall, the SLR simulation in this research in both study cases are within the range of the global sea-level rise by IPCC AR 5 except for the result of SLR in Cirebon in 2046-2060.

| Any differences in the output value are caused by the input data of the simulation. This study merely covers heat flux and ice melting, while IPCC AR 5 has a more complex study which uses thermal expansion, glaciers, ice sheet of Greenland and Antarctic (including dynamics), land water storage, as well as ice-sheet rapid dynamics of Greenland and Antarctic [22]. Despite the diverge way of conducting the research, both studies show similar results for the SLR in this last century.|

| Table 5 | Comparison of SLR projections (cm) |
|---------|----------------------------------|
| **Projection** | **2046 - 2065** | **2081 - 2100** |
| | Average | Range | Average | Range |
| SLR Global (IPCC AR 5) | 30 | 22-38 | 63 | 45-82 |
| Cirebon | 37 | 29-44 | 64 | 56-72 |
| Pangandaran | 30 | 24-36 | 52 | 45-58 |
3.2. Oceanography events and their impacts
Oceanography events such as IOD (-), MJO, storm surge, and Kelvin waves have an impact on the sea level. An indirect increase of sea level caused by IOD(-) and MJO is already calculated by their index and the changing of pertinent parameters. This prior monthly index (1950-2018 for IOD and 1974-2019 for MJO) will always be repeated until 2100.

Meanwhile, tropical cyclone and Kelvin waves which have a direct impact on the sea level are projected to occur in the same months annually. Those changes in the sea level caused by the events above are concluded in Table 6.

Table 6 Changes caused by oceanography events

| Event          | Change          | Time                          |
|----------------|-----------------|-------------------------------|
| MJO<sup>a</sup> | Heat flux + 23.33 W/m² | Monthly index from 1974 – 2019 is repeated from 2020-2100 |
| IOD(-)<sup>b</sup> | Temp + 0.36 °C | Monthly index from 1950-2018 is repeated from 2020-2100 |
| SS<sup>c</sup>  | Sea level + 16.2 cm | South: Jan, Feb, Mar          |
| KW<sup>d</sup>  | Sea level + 17 cm | North: Jul, Aug, Sept         |
| MHWL<sup>e</sup> | Sea level + 77.35 cm | April, May, Nov, Dec          |

Figure 5. SLR + MHWL + oceanography events in a) Cirebon and b) Pangandaran

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<sup>a</sup> Madden-Julian Oscillation  
<sup>b</sup> Negative phase of Indian Ocean Dipole  
<sup>c</sup> Storm surge generated by tropical cyclone  
<sup>d</sup> Kelvin wave  
<sup>e</sup> Mean high water level
3.3. Inundated area

The simulation time is 960 months or 80 years (2020 to 2100) with one month of time step (dt). In some months, some oceanography events would appear simultaneously which reinforces the additional of SLR. MHWL is the only phenomenon that certainly appears every month. Figure 5 displays the simulated SLR which has been added with events in Table 6 relative to 2014. This is due to the DTM produces in that year. It shows the sea level every ten years.

The blue graph depicts the value of SLR which has been added with MHWL and oceanographic events. This graph picked the oceanography event which has the highest level of occurrence. In Cirebon, the sea level is highly influenced by storm surge while the sea level in Pangandaran is highly influenced by Kelvin waves. Thus, in 2100 as an instance, the sea level in Cirebon is likely would be 115.65 cm. Meanwhile, Pangandaran would be 148.09 cm of sea level.

Cirebon consist of 10 districts that have a direct border with the sea, while Pangandaran only has 4 less. Overall, the inundated area of Cirebon’s coast will be 8.94% of the total land in Cirebon regency which is 29,756.41 hectares. As for Pangandaran, there is only 1.94% inundated area of 66,212.43 hectares.

3.4. Adaptive capacity

The rise of sea level would impact several community assets. Table B.1 shows the increase in submerged assets. The lost assets are summed based on each portion in Table 3 to calculate the vulnerability of each strategy.

The community assets would still be 100% intact if there were no SLR. It is coloured orange in Figure 6 and 7. However, SLR occurs and the grey visualizes the decrease of assets value as there is no adaptive strategy applied. The different values between having SLR (no adapt) and not having one is defined as total community vulnerability (see Figure 6.a and 7.a). Overall, Cirebon has 5.45% of vulnerability which 2.2% higher than Pangandaran. It indicates that although Pangandaran suffers higher sea level (Figure 5), its assets are naturally on the higher ground compared to Cirebon.

In protect scenario, planting mangrove throughout 1000 hectare (100 km x 100 m) of coastline would only reduce $6.71 \times 10^{-6}$ ppm of CO$_2$ which is very small to be calculated in equation (3). Furthermore, the result would be negative or non-sense. Thus, building seawall is the main work in this strategy.

The HWL in Cirebon and Pangandaran is 49.49 cm and 113.05 cm respectively. The high of the seawall is set up to be 75 cm in Cirebon and 125 cm in Pangandaran relative to the coastline (0 meter). In both study cases (see Figure 6.b and 7.b), the value of the assets would start to decrease after the sea level exceeds the seawall. In Cirebon, the SLR would begin to inundate the land in 2050, 30 years earlier than in Pangandaran. The shade shows the resilience or the assets which could be protected by the protect scenario. Therefore, building seawall could decrease total community vulnerability by 4.18% and 3.13% or saving 76.65% and 96.30% of inundated assets in Cirebon and Pangandaran respectively. This analogy also works for other two adaptive strategies.

Accommodate or building an elevated building could not even decrease a half of total vulnerability, 2.49% in Cirebon and only 0.01% in Pangandaran (see Figure 6.c and 7.c).

Retreat or forbidding any assets to be built within 100 meters from HWL could only decrease total vulnerability by 3.79% in Cirebon and 1.45% in Pangandaran (Figure 6.d and 7.d).

Table 8 shows a brief report on applying three adaptive strategies. Both study cases will have a good resilient mechanism through implementing the protect scenario. But the resolution above is still in regency level. It will be certainly different if the research is carried out deep down to the district level.

Figure 8 shows the suggested adaptive strategy in each district. It is also calculated based on the method above. The community assets each district have different locations and altitudes which considerably affect the number of inundated community assets. Thus, the adaptive strategy of each district varies one to another, but the majority still follow the regency strategy.
Figure 6. The projection of asset’s value in Cirebon for a) No Adapt, b) Protect, c) Accommodate, and d) Retreat.

Figure 7. The projection of asset’s value in Pangandaran for a) No Adapt, b) Protect, c) Accommodate, and d) Retreat.
Table 7 The value of vulnerability, resilience, and adaptive capacity (average of 2020-2100)

| Adaptation Strategy | Total Asset Value | Vulnerability [Vj] | Resilience [Rj(Ai)] | Adaptive Capacity Rj(Ai)/Vj |
|---------------------|------------------|--------------------|---------------------|---------------------------|
|                     | TA0 - TAj        | TAj (Ai) - TAj     |                     |                           |
| Cirebon             |                  |                    |                     |                           |
| No SLR              | 100 %            | 0                  | 0                   | n/a                       |
| No adaptation       | 94.55 %          | 5.45 %             | 0                   | n/a                       |
| Protect             | 98.73 %          | 1.27 %             | 4.18 %              | 76.65 %                   |
| Accommodate         | 97.04 %          | 2.96 %             | 2.49 %              | 45.72 %                   |
| Retreat             | 98.34 %          | 1.66 %             | 3.79 %              | 69.50 %                   |
| Pangandaran         |                  |                    |                     |                           |
| No SLR              | 100 %            | 0                  | 0                   | n/a                       |
| No adaptation       | 96.75 %          | 3.25 %             | 0                   | n/a                       |
| Protect             | 99.88 %          | 0.12 %             | 3.13 %              | 96.30 %                   |
| Accommodate         | 97.03 %          | 2.97 %             | 0.01 %              | 0.31 %                    |
| Retreat             | 98.20 %          | 1.80 %             | 1.45 %              | 44.59                     |

Figure 8. Suggested adaptive strategy in every district of a) Cirebon and b) Pangandaran

4. Conclusion
The simulation of SLR has 0.74 of correlation value and 9.35 of error compared to altimetry in Pangandaran. Moreover, it also appropriates to the global sea-level rise by IPCC AR 5. In 2100, the sea level caused by SLR combined with MHWL and oceanography events is 115.65 cm and 148.09 cm in Cirebon and Pangandaran respectively. The suggested adaptive strategy for both study cases is protect, in which the values of adaptive capacity are 76.65% for Cirebon and 96.30% for Pangandaran.
Appendix A

Figure A.1 The adaptation strategies are such interventions to open loop systems of the physical aspect and social aspect through STELLA 9.0.2. The system above is generated by exogenous variable or input data from the IPCC AR5 (left box). Then they triggers physical oceanography changes such as sea temperature and sea level rise (middle box). Lastly, all the changes are visualized through GIS mapping to calculate the inundated community assets (right box). In order to decide a policy to decrease the community vulnerability, this research carries out adaptive capacity value from three adaptative strategies: protect, accommodate, and retreat. The colored arrows shows where each option rush a change into the system.
**Appendix B**

**Table B.1** The number of Inundated Assets each Adaptive Scenario

| Scenario     | Total Assets | Inundated Assets |
|--------------|--------------|------------------|
|              | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
| Cirebon       |      |      |      |      |      |      |      |      |      |
| No Adapt      | 342  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1    |
| Protect       | 342  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Accommodate   | 342  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Retreat       | 258  | 2    | 2    | 2    | 2    | 2    | 2    | 2    | 2    |
| Pangandaran   |      |      |      |      |      |      |      |      |      |
| No Adapt      | 258  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Protect       | 316.08| 27.90| 32.10| 33.71| 34.30| 34.30| 36.07| 36.19| 37.16| 38.81|
| Accommodate   | 316.08| 27.90| 32.10| 33.71| 34.30| 34.30| 36.07| 36.19| 37.16| 38.81|
| Retreat       | 282.72| 14.52| 16.43| 18.04| 18.04| 18.04| 19.81| 19.81| 20.78| 21.63|

| Critical Facilities; Public Facilities; Homes

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