Recommendations on Flood Management at Cengkareng Drain Estuary in Enhancing Estuary Resilience to Compound Hazard

Athena Hastomo  
*Universitas Indonesia*, athena.hastomo@ui.ac.id

Evi Anggraheni  
*Universitas Indonesia*, evi.anggraheni@yahoo.com

Adi Prasetyo  
*Directorate General of Water Resources*, adi.prasetyo246@yahoo.com

Dwita Sutjiningsih  
*Universitas Indonesia*, dwita@eng.ui.ac.id

Follow this and additional works at: https://scholarhub.ui.ac.id/jid

Part of the Civil Engineering Commons, Environmental Engineering Commons, Hydraulic Engineering Commons, and the Risk Analysis Commons

Recommended Citation

This Article is brought to you for free and open access by the Faculty of Engineering at UI Scholars Hub. It has been accepted for inclusion in CSID Journal of Infrastructure Development by an authorized editor of UI Scholars Hub.
Recommendations on Flood Management at Cengkareng Drain Estuary in Enhancing Estuary Resilience to Compound Hazard

Cover Page Footnote
The authors would like to extend their gratitude to Universitas Indonesia for their assistance in this research, SNVT PTPIN and all parties that provided data for this study.

This article is available in CSID Journal of Infrastructure Development: https://scholarhub.ui.ac.id/jid/vol6/iss2/2
RECOMMENDATION ON FLOOD MANAGEMENT AT CENGKARENG DRAIN ESTUARY IN ENHANCING ESTUARY RESILIENCE TO COMPOUND HAZARD

Athena Hastomo¹, *, Evi Anggraheni¹, Adi Prasetyo², Dwita Sutjiningsih¹

¹Department of Civil Engineering, Universitas Indonesia, 16424, Indonesia
²Coastal Engineering Agency, Directorate General of Water Resources, 81155, Indonesia

(Received: August 2023 / Revised: October 2023 / Accepted: December 2023)

ABSTRACT
Jakarta's coastal region, characterized by dense settlements and industrial zones, faces significant flood risks due to land subsidence and rising sea levels, exacerbated by human activities and climate change. This study evaluates the effectiveness of the National Capital Integrated Coastal Development (NCICD) project, which proposes embankments along Jakarta's coast for enhanced flood resilience. Focusing on the Cengkareng Drain estuary, two-dimensional HEC-RAS simulations were employed. This study incorporates various factors such as precipitation, tides, waves, rising sea levels, and land subsidence to model extreme flood scenarios. The analysis reveals key strategies to improve flood management. Firstly, introducing new pumping stations and augmenting existing ones can reduce inundation by 43.16% under present conditions and significantly up to 53.16% by 2050. Secondly, regular dredging to sustain channel capacity is crucial. Additionally, mitigating local land subsidence through stringent law enforcement and heightened public awareness is vital for long-term flood control. These findings offer actionable insights into advancing Jakarta's flood management strategies in the face of evolving environmental challenges.

Keywords: Coastal protection; HEC-RAS 2D; Hydrodynamic; Land subsidence; Sea level rise

1. INTRODUCTION

Jakarta, Indonesia's bustling capital, is uniquely positioned adjacent to Jakarta Bay, rendering it vulnerable to three primary types of flooding: pluvial, fluvial, and coastal. These flood risks are often exacerbated by simultaneous high precipitation, tidal activities, and waves, a phenomenon known as a compound hazard (Lewis et al., 2011). Covering an area of 664.01 km² and home to over 10,562,088 people (as of 2020), Jakarta's northern coastal region is densely consisted of residential areas and industrial zones (Purnama et al., 2015). This concentration of development contributes to the city's economic vitality while also amplifies the potential for significant property and infrastructure damage during flood events.

In response to these challenges, the Indonesian government has initiated the National Capital Integrated Coastal Development (NCICD) master plan to enhance coastal resilience. A key component of this plan involves constructing and reinforcing embankments spanning 36 km along Jakarta's coast and 100 km along its rivers (Kementerian Koordinator Bidang Perekonomian Republik Indonesia, 2014). These embankments are designed to be a structural shield for the coast, integrated seamlessly with the existing urban infrastructure.

*Corresponding author’s email: athena.hastomo@ui.ac.id, Tel. +62-812-8414-9640
DOI: 10.7454/jid.v6.i2.1116
A crucial site within this plan is the Cengkareng Drain Estuary, a significant floodway in Jakarta. The proposed embankments here necessitate thorough evaluation to ascertain their effectiveness and potential areas for improvement. While factors like tidal activities, waves, and precipitation are accounted for in the planning, emerging challenges such as sea-level rise (SLR) and land subsidence (LS) due to climate change and urbanization, respectively, pose additional risks (Pasquier et al., 2019; Prasetyo et al., 2019). These evolving factors could diminish the efficacy of structural solutions like embankments, underscoring the need for a comprehensive approach to coastal flood management incorporating SLR and LS considerations.

This study aims to enhance coastal resilience by refining the existing NCICD plan. We will focus on developing recommendations using the two-dimensional Hydrologic Engineering Center-River Analysis System (HEC-RAS) model to evaluate and optimize flood management strategies at the Cengkareng Drain Estuary.

2. LITERATURE STUDY

2.1. Design Rainfall

The analysis of hydrological processes, characterized by temporal variability, is a dynamic approach to represent changing environmental conditions accurately. This approach often called the stochastic method, is particularly relevant in rainfall data analysis (Soewarno, 1995). Selecting an appropriate distribution model is crucial as it must accurately reflect the specific conditions of the location under study. Harto (2000) emphasizes that errors in choosing the right distribution can lead to significant overestimations or underestimations of design rainfall values. Commonly used rainfall distribution models and their respective formulas are as follows (Soewarno, 1995):

Normal Distribution:

\[ x_t = \bar{x} + K_t S_x \]  

(1)

Log-Normal Distribution:

\[ \log x_t = \log \bar{x} + K_t S_x \]  

(2)

Gumbel Distribution:

\[ x_t = \bar{x} + \frac{(Y_t - Y_n)}{S_n} S_x \]  

(3)

Log Pearson Type III Distribution:

\[ \log x_t = \log \bar{x} + K_t S_{\log x} \]  

(4)

Where \( x_t \) is design rainfall with \( t \) years return period (mm), \( \bar{x} \) is average rainfall (mm), \( K_t \) is standard variable for \( t \) years return period, \( S_x \) is standard deviation (mm), \( Y_t \) is a reduced variable, \( Y_n \) is average reduced variable, and \( S_n \) is reduced standard deviation.

2.2. Admiralty Method

Tidal movements, a key natural phenomenon in marine environments, involve the vertical motion of seawater from the surface down to the seabed. These movements are primarily driven by gravitational forces and centrifugal effects (Surinati, 2007). Several methods can be employed to calculate tidal harmonic components, each suited to different data length requirements. While the Least Square Method is preferable for longer datasets, the Admiralty Method is effective for shorter data lengths, such as 15 or 29 days.
The Admiralty Method, a well-established harmonic approach, calculates tidal components’ amplitude and phase differences (Ichsari et al., 2020). It analyzes major tidal components, including M2, S2, N2, K1, O1, P1, M4, MS4, and K2. These components are essential in predicting various sea level elevations, which are crucial for maritime and coastal planning, as shown in Table 1.

Table 1 Important Sea Level Elevations (Supriyadi et al., 2018)

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Symbol</th>
<th>Tidal Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest High Water Level</td>
<td>HHWL</td>
<td>( Z_0 + (M_2 + S_2 + K_2 + K_1 + O_1 + P_1) )</td>
</tr>
<tr>
<td>Mean High Water Level</td>
<td>MHWL</td>
<td>( Z_0 + (M_2 + K_1 + O_1) )</td>
</tr>
<tr>
<td>Mean Low Water Level</td>
<td>MLWL</td>
<td>( Z_0 - (M_2 + K_1 + O_1) )</td>
</tr>
<tr>
<td>Lowest Low Water Level</td>
<td>LLWL</td>
<td>( Z_0 - (M_2 + S_2 + K_2 + K_1 + O_1 + P_1) )</td>
</tr>
<tr>
<td>Lowest Astronomical Tide</td>
<td>LAT</td>
<td>( Z_0 - (M_2 + S_2 + K_2 + K_1 + O_1 + P_1 + N_2 + Q_1) )</td>
</tr>
</tbody>
</table>

2.3. Design Wave

Accurately determining the design wave value is critical in coastal and ocean engineering. Two commonly used methods are the Fisher-Tippet Type I/Gumbel Method and the Weibull Method (CERC, 2006). The mathematical formulations for these methods are as follows:

\[
H_m = \hat{A} y_m + \hat{B} \tag{5}
\]

\[
H_{sr} = \hat{A} y_r + \hat{B} \tag{6}
\]

for the Fisher-Tippet Type I/Gumbel Method:

\[
P(H_s \leq H_{sm}) = 1 - \frac{m^{-0.44}}{N_T + 0.12} \tag{7}
\]

\[
y_m = -\ln[-\ln P(H_s \leq H_{sm})] \tag{8}
\]

\[
y_r = -\ln\left[-\ln\left(1 - \frac{1}{L T_r}\right)\right] \tag{9}
\]

for the Weibull Method:

\[
P(H_s \leq H_{sm}) = 1 - \frac{m^{-0.2-0.27}}{N_T + 0.2 + \frac{0.27}{\sqrt{\kappa}}} \tag{10}
\]

\[
y_m = -\ln\left[1 - P(H_s \leq H_{sm})\right]^{\frac{1}{\kappa}} \tag{11}
\]

\[
y_r = \left[\ln(L T_r)\right]^{1/\kappa} \tag{12}
\]

Where \( H_{sm} \) is the \( m^{th} \) wave height \((m)\), \( N_T \) is the total of wave events, \( \kappa \) is the form parameter, \( H_m \) is wave height, \( \hat{A} \) is the linear coefficient, \( \hat{B} \) is the linear constant, \( y_m \) is the wave height variable, \( H_{sr} \) is significant to design wave height \((m)\), \( T_r \) is return period, \( \kappa \) is data length, \( L \) is average event per year \((N_T / K)\).

2.4. Sea Level Rise

Sea level rise, a notable impact of global climate change, is characterized by an increase in a region’s mean sea level (MSL). This phenomenon exhibits a complex pattern, evidence were shown by several years of observational data. In Indonesia, an analysis of sea level trends from
1990 to 2019 indicates notable fluctuations, but overall, the data reveal an ascending trendline (Triana & Wahyudi, 2020). This upward trend underscores the need for continuous monitoring and projection of sea levels to accurately assess the severity and potential impacts of sea level rise in the region.

Regarding observational data, Indonesia's sea level changes have been documented through various sources, including the National Oceanic and Atmospheric Administration (NOAA). Measurements by NOAA have primarily relied on altimetry readings from the TOPEX/POSEIDON and Jason 1–3 satellite data. These sophisticated satellite-based observations have been instrumental in providing accurate and reliable data. According to the latest reports by NOAA (2022), the rate of sea level rise in Indonesia has been quantified at 4.6 ± 0.4 mm/year.

The significance of these findings is profound, particularly in the context of coastal planning and management. Understanding the rate and pattern of rising sea levels is crucial for developing effective strategies to mitigate its impacts, especially in coastal regions like Indonesia, where such changes can have far-reaching consequences.

2.5. Land Subsidence

Land subsidence (LS) is the gradual sinking of land, typically due to the consolidation of underlying sediment, which results in increased effective stress and subsurface soil movement. While LS can occur naturally, it is often exacerbated by human activities, notably groundwater extraction. Jakarta's densely populated coastal areas are particularly susceptible to this phenomenon. Comparative research across major Asian cities has identified Jakarta as one of the most affected by high land subsidence rates.

Several studies have been conducted to understand LS in Jakarta. For instance, research covering 1997-2005 utilized GPS observations to analyze LS characteristics. This study, led by Abidin et al. (2008), revealed that the rate of land subsidence in Jakarta varied significantly, ranging from 1-10 cm/year to as high as 15-20 cm/year. Further, geodetic GPS measurements conducted between 2014 and 2017 indicated areas where land subsidence reached an alarming rate of approximately 8 cm/year on some of the areas, amounting to a total subsidence of 24 cm over three years (Dinas Perindustrian dan Energi Pemerintah Provinsi DKI Jakarta, 2017).

The implications of land subsidence are particularly critical in coastal areas, where it is a major contributor to increased flood risk (Fiaschi & Wdowinski, 2020). Therefore, LS is a key factor in flood management and urban planning, especially in coastal regions like Jakarta, where its impact is significant and ongoing.

2.6. Hydrodynamic Model: HEC-RAS 2D

HEC-RAS, developed by the US Army Corps of Engineers, is a sophisticated modeling software used extensively in hydrodynamic studies. The two-dimensional (2D) HEC-RAS model employs terrain data to calculate inundation areas and depths numerically. At the core of this model are the Saint-Venant equations, which are fundamental for the conservation of mass and momentum in fluid dynamics. The equations are as follows:

\[
\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = q \tag{13}
\]
\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} - f_c v = -g \frac{\partial z_s}{\partial x} + \frac{1}{h} \frac{\partial}{\partial x} \left( v_{t,xx} h \frac{\partial u}{\partial x} \right) + \frac{1}{h} \frac{\partial}{\partial y} \left( v_{t,yy} h \frac{\partial u}{\partial y} \right) - \frac{\tau_{by}}{\rho R} + \frac{\tau_{sy}}{\rho h} \quad (14) \]

\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - f_c u = -g \frac{\partial z_s}{\partial y} + \frac{1}{h} \frac{\partial}{\partial x} \left( v_{t,xx} h \frac{\partial v}{\partial x} \right) + \frac{1}{h} \frac{\partial}{\partial y} \left( v_{t,yy} h \frac{\partial v}{\partial y} \right) - \frac{\tau_{bx}}{\rho R} + \frac{\tau_{sx}}{\rho h} \quad (15) \]

where \( h \) is water depth (m), \( t \) is time (s), \( u \) and \( v \) are specific flow in both \( x \) and \( y \) directions (m²s⁻¹), \( g \) is the gravitational acceleration (m/s²), \( z_s \) is water elevation (m), \( v_{t,xx} \) and \( v_{t,yy} \) are horizontal eddy viscosity coefficient of surface wind shear stress (Nm⁻²), \( \rho \) is density (kgm⁻³), \( R \) is a hydraulic radius (m), and \( f_c \) is Coriolis parameter (rads⁻¹).

3. METHODS
3.1. Study Area

The Cengkareng Drain Estuary, situated in the northern part of Jakarta and adjacent to Jakarta Bay, is a critical component of Jakarta's flood management system. This estuary, lying downstream of the Pesanggrahan River, was developed as part of the 'Masterplan for Drainage and Flood Control of Jakarta.' Its primary function is to serve as one of the connector channels designed to control floods by efficiently redirecting water toward Jakarta Bay, thereby mitigating flood risks in the surrounding areas.

Covering an area of 25.58 km², the Cengkareng Drain Watershed is a densely populated region, as depicted in Figure 1. The land use map (Figure 1a) illustrates the extent of urban development in the area, a direct consequence of population growth and subsequent land use changes. These changes have primarily accommodated residential, educational, and other infrastructural needs. However, this rapid urbanization has increased impervious surfaces, exacerbating rainfall-runoff issues (Anggraheni et al., 2019).

The watershed is characterized by its flat topography and low elevation, often below mean sea level, as shown in Figure 1b. This geographical feature necessitates specialized flood protection measures. Historically, these measures have included the construction of embankments and pump stations across the polders to manage water levels effectively. Additionally, the Cengkareng Drain Estuary is particularly vulnerable to LS and SLR, compounding the risk of severe flooding.

![Figure 1 Cengkareng Drain Watershed: (a) Land Use, (b) Elevation](image-url)
3.2. Data

The data in this study was used to gather the hydrodynamic simulation inputs. The required input included unsteady flow, terrain, and geometric data. The unsteady flow data includes design rainfall, tides, design waves, and sea level rise. For the design of rainfall, historical daily rainfall data was required. The data from 2003 to 2021 was obtained from the (SNVT-PTPIN 2021b). For the tide analysis, sea level data was required. This data was gathered from the (UNESCO, 2023) sensor monitoring and ranged for February 2020. For the design wave, ten years of wind data were required. The data was also obtained from the (SNVT-PTPIN, 2021a).

The terrain data includes a digital elevation model (DEM) and land subsidence. The digital elevation model was LIDAR from 2021, gathered from the Directorate General of Human Settlements. The terrain data needs to be altered to depict the effects of land subsidence on the area. Therefore, a land subsidence rate was also needed. The rate was gathered from both observation and study data. This study used two sources, one being the study from 2002-2005 (Abidin et al., 2008) and the other was the observation data from 2014-2017 (Dinas Perindustrian dan Energi Pemerintah Provinsi DKI Jakarta, 2017).

Lastly, the geometric data includes the watershed area and existing infrastructures. The location consists of polder systems. Therefore, every pump station was also modeled. The data was gathered from the Directorate General of Water Resources.

4. RESULTS AND DISCUSSION

4.1. Scenario and Parameter

To effectively evaluate flood management improvements in the Cengkareng Drain estuary, a series of scenarios, as detailed in Table 2, were developed and analyzed. These scenarios were categorized into three main groups: Scenario A Represents the baseline condition without embankment construction. Scenario B: Encompasses conditions post-embankment construction. Scenario C: Illustrates conditions with the implementation of recommended flood management measures. Additionally, each scenario was examined under varying conditions to assess the system's performance in response to projected changes and the effectiveness of the implemented recommendations. These conditions focused on whether SLR and LS were factored into the analysis.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Embankment</th>
<th>Downstream Boundary</th>
<th>Precipitation</th>
<th>SLR</th>
<th>LS</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>v</td>
<td></td>
<td></td>
<td>v</td>
<td>Minimum</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>v</td>
<td></td>
<td></td>
<td>v</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>v</td>
<td>100-year design</td>
<td>100-year</td>
<td>v</td>
<td>Minimum</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>v</td>
<td>wave and HHWL</td>
<td>rainfall</td>
<td></td>
<td>v</td>
<td>Maximum</td>
</tr>
<tr>
<td>B3</td>
<td>v</td>
<td></td>
<td></td>
<td>v</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
<td>v</td>
<td>Minimum</td>
</tr>
<tr>
<td>C2</td>
<td>v</td>
<td></td>
<td></td>
<td>v</td>
<td>v</td>
<td>Maximum</td>
</tr>
<tr>
<td>C3</td>
<td>v</td>
<td></td>
<td></td>
<td>v</td>
<td>v</td>
<td>Minimum</td>
</tr>
</tbody>
</table>

This structured approach to scenario analysis allows for a comprehensive understanding of the impacts of various flood management strategies under different environmental conditions. The results from these scenarios will offer insights into the effectiveness of current and proposed flood control measures in the context of evolving climatic and geophysical factors.
4.2. Design Rainfall Analysis

The analysis of design rainfall, a critical component in understanding flood risks, was conducted using several statistical distributions. The resultant values, as detailed in Table 3, were adjusted using the area reduction factor (ARF) to ensure accuracy in the context of the study area. To validate the appropriateness of each distribution, two statistical tests were employed: the Chi-Square and Smirnov-Kolmogorov Methods.

The results of these tests indicated that both the Log-Normal Distribution and Log Pearson Type III Distribution were acceptable. However, the Log Pearson Type III Distribution was selected as it is more commonly used in hydrological studies. This decision was also influenced by the need to align the design rainfall with the 100-year return period, corresponding to the evaluated structural design standards.

<table>
<thead>
<tr>
<th>Return Period</th>
<th>Design Rainfall (Reduced)</th>
<th>Log-Normal</th>
<th>Gumbel</th>
<th>Log Pearson Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Normal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>91.88</td>
<td>87.01</td>
<td>87.36</td>
<td>88.25</td>
</tr>
<tr>
<td>5</td>
<td>117.66</td>
<td>116.21</td>
<td>134.65</td>
<td>116.65</td>
</tr>
<tr>
<td>10</td>
<td>131.17</td>
<td>135.24</td>
<td>142.10</td>
<td>133.94</td>
</tr>
<tr>
<td>25</td>
<td>145.60</td>
<td>159.02</td>
<td>169.66</td>
<td>154.32</td>
</tr>
<tr>
<td>50</td>
<td>154.82</td>
<td>176.33</td>
<td>190.10</td>
<td>168.56</td>
</tr>
<tr>
<td>100</td>
<td>163.41</td>
<td>194.20</td>
<td>210.38</td>
<td>182.13</td>
</tr>
<tr>
<td>Chi-Square</td>
<td>Accepted</td>
<td>Accepted</td>
<td>Accepted</td>
<td>Accepted</td>
</tr>
<tr>
<td>Smirnov-Kolmogorov</td>
<td>Rejected</td>
<td>Accepted</td>
<td>Rejected</td>
<td>Accepted</td>
</tr>
</tbody>
</table>

4.3. Tidal Analysis

The tidal analysis for this study was conducted using the Admiralty Method, which involved analyzing hourly sea level data from February 2020. This method was instrumental in determining key sea level elevations, which are crucial for understanding and preparing for tidal impacts. The results of this analysis are summarized in Table 4.

One of the significant outcomes of this tidal analysis was the determination of the Highest High-Water Level (HHWL). HHWL is often used as a benchmark for setting design water levels for coastal structures. In our study, the HHWL elevation was adopted as the downstream boundary condition in the simulation to represent extreme tidal conditions accurately.

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Symbol</th>
<th>Chart Datum (m)</th>
<th>MSL</th>
<th>LLWL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest High-Water Level</td>
<td>HHWL</td>
<td>+0.80</td>
<td>+1.60</td>
<td></td>
</tr>
<tr>
<td>Mean High Water Level</td>
<td>MHWL</td>
<td>+0.58</td>
<td>+1.38</td>
<td></td>
</tr>
<tr>
<td>Mean Sea Level</td>
<td>MSL</td>
<td>+0.00</td>
<td>+0.80</td>
<td></td>
</tr>
<tr>
<td>Mean Low Water Level</td>
<td>MLWL</td>
<td>-0.58</td>
<td>+0.22</td>
<td></td>
</tr>
<tr>
<td>Lowest Low Water Level</td>
<td>LLWL</td>
<td>-0.80</td>
<td>+0.00</td>
<td></td>
</tr>
</tbody>
</table>

Incorporating these tidal levels into our hydrodynamic model required converting them into a time-series format, as the model operates under unsteady conditions. Thus, the derived sea level data was used to project tidal fluctuations over a 30-day period. The graphical representation of this tidal time series, including the HHWL value, is depicted in Figure 2.
4.4. Design Wave Analysis

The analysis of the design wave was conducted using a decade of wind data spanning from 2011 to 2020. This extensive dataset was crucial for calculating the significant wave height for each year, thereby providing a reliable foundation for our wave analysis. Since the embankment design is based on a 100-year return period, aligning the wave analysis with this temporal benchmark was essential.

The wave height calculations were performed using two established statistical methods: the Fisher Tippet Type I/Gumbel Method and the Weibull Method. The results from these analyses are graphically represented in Figure 3. These methods determined the design wave heights to be 2.510 meters and 2.547 meters, respectively. To ensure that our model accounts for extreme conditions, the higher value of 2.547 meters was selected as the design wave height for subsequent simulations and analyses.

This approach to design wave analysis aligns with the structural design standards and provides a comprehensive understanding of the potential wave impacts under extreme conditions. This information is pivotal for assessing the effectiveness and robustness of the proposed embankment designs against significant wave events.
4.5. Sea Level Rise Rate

Observational data on Mean Sea Level (MSL) in Indonesia has consistently indicated an upward trend, pointing to a gradual increase in sea levels over the years. The analysis of annual changes in MSL suggests a linear progression of sea level rise (SLR). As illustrated in Figure 4, the calculated SLR rate stands at 4.86 mm/year, accompanied by a coefficient of determination (R²) value of 0.80. The R² value, ranging from 0 to 1, measures the extent to which the independent variable (in this case, 'year') can predict the dependent variable (here, 'MSL increase'). This value indicates a robust correlation, providing a reliable basis for projecting future MSL changes. Based on the SLR rate, SLR was projected, as shown in Table 5.

![Figure 4 Sea Level Rise from 1993-2022 (NOAA, 2022)](image)

Table 5 Linear SLR Projection

<table>
<thead>
<tr>
<th>Year</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLR (mm)</td>
<td>0</td>
<td>145.80</td>
</tr>
</tbody>
</table>

Despite the apparent linearity in the model, it is important to acknowledge the potential for deviation from observed data. Such deviations could result in either overestimation or underestimation of MSL projections. Sea level prediction is inherently complex, influenced by factors such as global warming, extreme weather events, and even lunar cycles (Musbikhin et al., 2020). Alternative modeling approaches, including Support Vector Regression (SVR), Long Short-Term Memory (LSTM), and Autoregressive Integrated Moving Average (ARIMA), have been explored for SLR prediction (Balogun & Adebisi, 2021). Each method presents unique strengths and limitations, and further research is necessary to identify the most appropriate approach for Indonesia, considering the specific data availability and regional characteristics.

4.6. Land Subsidence Rate

In assessing the impact of LS on the Cengkareng Drain Estuary, projections were made based on the assumption of a consistent LS rate over time. This approach is visually depicted in Figure 5, which illustrates the observed LS rates for two distinct periods. The period from December 2002 to September 2005 (33 months) provides data for the maximum LS scenario, while the data from 2014 to 2017 (36 months) represents the minimum LS scenario. These periods were selected to capture the variability in LS rates affecting the area.
The terrain data was modified by overlaying the terrain with the projected LS rates to integrate LS into the hydrodynamic modeling. This modification process is illustrated in Figure 6, which demonstrates how the land elevation is altered under both minimum and maximum LS scenarios.

The visualizations, particularly in Figures 6b and 6c, starkly highlight the potential impact of LS on the topography of the Cengkareng Drain Estuary. Most notably, most of the estuary is projected to fall below the mean sea level elevation under both LS scenarios. This finding underscores the critical influence of LS on the area's vulnerability to flooding and the necessity of incorporating LS considerations into flood risk management and infrastructure planning.

4.7. Flood Mapping: HEC-RAS 2D

The flood mapping for the Cengkareng Drain Estuary was conducted using HEC-RAS 2D, incorporating the hydrodynamic model and boundary conditions detailed earlier. This analysis produced various inundation maps corresponding to each defined scenario, shown in Figure 7.

Scenario A1 depicted inundation for the base year 2020 under compound hazards without considering the planned embankments. Scenarios A2 and A3 projected conditions for the year 2050, factoring in SLR and LS. These scenarios revealed substantial changes in the inundation area, suggesting extensive submersion in the northern part of the estuary during extreme floods. With a minimum LS rate in the 2020 base year and 2050, the embankments will still reduce the
inundation area. However, that is not the case with the last scenario. A more detailed value can be seen in Figure 8.

![Inundation Maps](image)

Figure 7 Inundation Map for Scenario A and B: (a) Plan A1, (b) Plan A2, (c) Plan A3, (d) Plan B1, (e) Plan B2, (f) Plan B3

Based on the result, the embankment plan demonstrated a significant reduction in inundation area by 25.19% in 2020. However, this effectiveness will diminish to between 15.42% and 0.12% by 2050 due to rising SLR and LS. The analysis highlighted that while embankments can mitigate flooding, their efficacy is compromised by increasing sea levels and subsiding land. Figure 8 compares the inundation areas between Scenarios A and B.
Additional pump locations and capacity upgrades were proposed to enhance flood management, as depicted in Figure 9. These recommendations were tailored based on inundation depth and area analysis.

The locations were proposed by considering the inundation area and depth that needs to be managed. Depending on the depth and area, there may be an urgency for the flooding to be reduced in time or severity. Therefore, the details on the pump recommendations' locations and capacities are provided in Table 6.

<table>
<thead>
<tr>
<th>No.</th>
<th>Polder</th>
<th>Location</th>
<th>Existing Capacity (m$^3$s$^{-1}$)</th>
<th>New Capacity (m$^3$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PIK Utara Timur</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>PIK Selatan Timur</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Cengkareng</td>
<td>Perumnas Cengkareng Drain</td>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Cengkareng</td>
<td>Daan Mogot KM 13</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Cengkareng</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 10 shows the decreased inundation areas in the recommended scenarios under current and projected minimum LS conditions in 2050. However, the impact is less pronounced under maximum LS projections. Figure 11 further illustrates the comparison between Scenarios A, B, and C regarding inundation areas.

![Inundation Map Comparison](image)

**Figure 10 Inundation Map Comparison**

The analysis found that the recommendations could substantially reduce inundation in various scenarios, with up to 43.16% reduction in the current condition and up to 53.16% in the 2050 scenario with minimum LS. However, the reduction was limited to 10.13% under the maximum LS in 2050. While additional infrastructure helps, it alone may not enhance coastal resilience, especially under maximum LS conditions.

Controlling LS rates is critical. This can be achieved through LS monitoring, water usage control, land use planning, and public awareness campaigns. Regular dredging of the Cengkareng Drain channel is also suggested to maintain channel capacity and ensure efficient water flow to the sea.
5. CONCLUSION

The current plan for the embankment on the Cengkareng Drain Estuary has effectively reduced inundation areas under current conditions. However, the projected year 2050 shows that the effectiveness will be reduced from the previous 25.19% to just 15.42% - 0.12%. This value shows a need to implement further measures to increase coastal resilience.

Three recommendations are presented in this study. First, add new pump locations and increase existing pump capacity. By implementing this recommendation, the inundation area will be reduced by 43.16% under current conditions and 53.16% to 10.13% by the projected year 2050. Second, local land subsidence should be controlled by enforcing the law and raising people's awareness of the issue's urgency. Lastly, periodic dredging is recommended to maintain the current channel capacity.

6. ACKNOWLEDGEMENT

The Authors would like to thank Universitas Indonesia, Ministry of Public Works and Housing, SNVT PTPIN, and all parties that provided data for this study for their assistance in this research.

REFERENCES


Kementerian Koordinator Bidang Perekonomian Republik Indonesia. (2014). Master Plan NCICD.


