Analysis of hydrodynamics and thermal dispersion by numerical modelling in Sele Strait, West Papua

Alvin Yesaya1, Anasya Arsita Laksmi 2, and Mikhael Mangopo3

1Undergraduate Program of Civil Engineering, Universitas Udayana, Jalan Raya Kampus Unud Jimbaran Bukit, Bali, Indonesia
2Department of Civil Engineering, Faculty of Science and Defense Engineering, Republic of Indonesia Defense University, Bogor, Indonesia
3PT Geovaruna Teknologi Indonesia, Jl. Dakota No.42e, Sukaraja, Cicendo, Bandung, Indonesia

Abstract. Indonesian standard for wastewater quality regulates 40°C for the maximum outfall temperature. Meanwhile, the seawater temperature below 30°C is utilized for the cooling facility which the intake area is close to the outfall source. This research examine the hydrodynamics and thermal dispersion condition in PT Kilang Pertamina Internasional Kasim process plant in Sele Strait, West Papua. This study uses a two-dimensional numerical model Mike21 for a one-year simulation. Considering the limited field data, the ERA5 reanalysis satellite was utilized for the model input boundary. It also finds the discharge from the river with a temperature assumption of 26.5°C also in the boundary. The model validated with tidal field data with an R-squared number is 0.86. The hydrodynamics model shows the current speed in the intake area varied between 0-0.5 m/s. Two-scenario thermal simulation model (outfall condition 37°C & 40°C) shows that the frequency of 27°C water temperature is 81.5% and 85.8% respectively. Both scenarios give less than 10% for the temperature above 30°C. It concludes that the intake and outfall design planned is proper in the Kasim process plant.

1 Introduction

The study of thermal dispersion in the ocean is one of the important aspects of the industry which use seawater as a cooling object. As regulated in the Indonesia effluent standard of Ministry of Environment regulation No 8, 2009, the maximum wastewater quality is 40°C for the outfall temperature [1]. On the other hand, the cooling facility needs a seawater temperature below 30°C. Therefore, the intake area cannot be far from the outfall source because it requires a long pipeline and space. Thermal dispersion analysis is commonly conducted as a binding document during Detail Engineering Design (DED) and Environment Impact Assessments (EIA). For instance, the study of thermal dispersion of water cooling for Gas and steam power plants at Cilegon [2], the study of the impact of coal fire power plant in Kotawaringin Timur, Central Kalimantan [3], and the thermal dispersion of power plant in Muara Karang, Jakarta bay [4].

This study aims to find the distribution of the seawater temperature based on the fixed location of the outfalls and intake seawater system. The method of the study is mainly focused on the numerical simulation for hydrodynamics and thermal dispersion condition in PT Kilang Pertamina Internasional Kasim process plant in Sele Strait, West Papua. This study uses a two-dimensional numerical model Mike21 software for a one-year simulation. Mostly the study uses the secondary data as the main input of the simulation while the primary data are used for model validation. The result of this study can benefit the stakeholders in finding the optimum area to design the intake channel.

2 Research data and method

2.1 Data collection

There are two types of data collection for this study, primary data and secondary data. Secondary data will utilize satellite and reanalysis data such as wind and rainfall. Therefore, due to the lack of the data in the study area, field observation is required to get important data such as bathymetry and tides. Some short data for current and wind were also collected to verify the numerical model.

2.1.1 Primary data

Field observation has been conducted on the target area. Wind speed, current speed, tidal data, and bathymetry data are collected for certain periods and some points. These data will be utilized for the validation of the numerical model. Fig. 1 shows the survey documentation in the Sele Strait, West Papua Province. Not only bathymetry and tide, wind and current data are collected as well for a short period as depicted in Fig.2. However, considering the data only took for a short time, it is quite difficult to use this data for long-

*Corresponding author: alvinyesaya@unud.ac.id
term analysis because the environment change time to time with yearly order. The data collection purpose is for validation and verification of numerical models.

Fig. 1. Survey of bathymetry and tide for observation data.

Fig. 2. Data collection for current and wind in Sele Strait.

2.1.2 Secondary data
Satellite data has been utilized to analyze long-term data such as wind and rainfall. European Centre for Medium-Range Weather Forecast (ECWMF) is one of the reanalysis data that can be used for long-term analysis. Reanalysis is a process in which model information and observations of various types are optimally combined to produce consistent, global best estimates of different atmospheric, wind, wave, rainfall intensity, and oceanographic parameters. Many studies gave a good performance of the ECWMF model for long-term analysis trends such as wave height in Western Australia [5], and Northern Indonesia [6], also rainfall data shows a good correlation for the observed rainfall gauge in Indonesia [7].

ERA5 provides hourly estimates many atmospheric, land and oceanic climate variables. The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km. ERA5 includes information about uncertainties for all variables at reduced spatial and temporal resolutions. Fig. 3 is shown the wind data received from ECWMF for 10 years. It can be seen the wind comes from the south with mainly 1.5 to 3 m/s for around 20%, 3-4.5 m/s for about 10% and 4.5-6 m/s for about 5%. Only 0.2 % for 10 years the wind speed reach 7.5 m/s.

Rainfall intensity data is extracted in Fig. 4 for a one-year period (Oct 2021 - Sep 2022). On average, rainfall intensity is between 1-3 mm/hour with the highest intensity in July 2022 at around 15 mm/hour.

Fig. 3. Windrose and wind histogram for 10 years.

Fig. 4. Rainfall intensity data extracted from ECWFM from October 2021 – September 2022.

The boundary of the numerical model will use Global Tide Model from satellite altimetry for sea level residual analysis Poseidon/TOPEX with a resolution of 0.125x0.125degree resolution for the major 10 constituents in tidal spectra [8]. The water level parameter was extracted with the length of the simulation. The time zone of extracted time series is given in GMT so the time need to adjust in the field which is located at GMT+9.
2.2 Numerical model analysis

2.2.1 Hydrodynamics and thermal dispersion equations

Thermal dispersion for numerical simulation in Mike21 software uses the continuity equation as depicted in Equation 1 and the two-dimensional momentum equation for x and y components in Equations 2-3 and for the thermal dispersion model for general transport-diffusion equation shown in Equations 4-5 and horizontal diffusion terms defined in Equation 6 [9].

\[
\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

\[
\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial u v}{\partial y} + \frac{\partial w}{\partial z} = f v - g \frac{\partial}{\partial x} \int_0^z \frac{\partial p}{\partial x} \, dz
\]

\[
F_v + \frac{\partial}{\partial x} \left( \frac{v_0}{\partial x} \right) + u S
\]

\[
F_v + \frac{\partial}{\partial x} \left( \frac{v_0}{\partial x} \right) + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = -f u - g \frac{\partial}{\partial y} \left( \frac{v_0}{\partial y} \right) - \frac{g}{\rho_0} \frac{\partial}{\partial x} \left( \frac{v_0}{\partial x} \right)
\]

\[
F_v + \frac{\partial}{\partial x} \left( \frac{v_0}{\partial x} \right) + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

where \( t \) = time; \( x,y,z \) = cartesian coordinates; \( u,v,w \) = flow velocity components; \( v_0 \) = temperature and salinity; \( D_v \) = vertical turbulent (eddy) diffusion coefficient; \( H \) = source term due to heat exchange with atmosphere; \( S \) = magnitude of discharge due to point sources; \( T_v \), \( s \) = temperature and salinity of source; \( F_v,F_s,F_u \) = horizontal diffusion terms; \( D_h \) = horizontal diffusion coefficient; \( h \) = depth [9].

2.2.2 Boundary Condition and model scenarios

The boundary condition and mesh of the numerical simulation can be seen in Fig.5. Boundary condition is divided into two sides North Boundary and South Boundary. These boundaries will use the Global Tide model from the altimetry satellite Poseidon/TOPEX provided in Mike 21 toolbox. Near the target area, there is one river flowing through the channel. This river will give a source for the hydrodynamic model, which is considered a river boundary of water discharge. In addition, the outfall from the pipe will count as a thermal source.

Fig. 5. Mesh and boundary condition for thermal dispersion numerical simulation.

The model scenarios for the simulation are divided into two categories. First is the outfall with the temperature of 37°C (Scenario 1) and the second is the temperature of 40°C (Scenario 2) with a constant outfall discharge of 6.67 m³/s. The detail of the simulation can be seen in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td>Software</td>
<td>DHI Mike 21</td>
</tr>
<tr>
<td>Module</td>
<td>Flow Model Couple</td>
</tr>
<tr>
<td>HD-ECO lab</td>
<td></td>
</tr>
<tr>
<td>Simulation Period</td>
<td>1 year: 1 October 2021 to 30 September 2022</td>
</tr>
<tr>
<td>Time step</td>
<td>3600 seconds (1 hour)</td>
</tr>
<tr>
<td>Solution technique</td>
<td>Time</td>
</tr>
<tr>
<td>Low-order, fast algorithm</td>
<td></td>
</tr>
<tr>
<td>(Shallow water equations)</td>
<td>Space</td>
</tr>
<tr>
<td>Low-order, fast algorithm</td>
<td></td>
</tr>
<tr>
<td>Minimum Time</td>
<td>0.01 second</td>
</tr>
<tr>
<td>Maximum Time</td>
<td>30 second</td>
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<td>Critical CFL</td>
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<td>Density</td>
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<tr>
<td>Eddy Viscosity</td>
<td>Formulation Smagorinsky with constant</td>
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<td></td>
</tr>
<tr>
<td>Bed resistance</td>
<td>Manning Contant 32</td>
</tr>
<tr>
<td>Wind forcing</td>
<td>Wind Data from ECO lab</td>
</tr>
<tr>
<td>Hydrodynamic</td>
<td></td>
</tr>
</tbody>
</table>
3 Results and discussions

3.1 Hindcasting and river discharge calculation

3.1.1 Wave hindcasting

Hindcasting was a method to calculate the wave height from the wind [10]. Hindcasting data is a good method for long-term analysis of at minimum 10 years of data. However, before conducting hindcasting calculation, fetch is needed to determine. Fetch is the area where wind can generate the wave. Fig 6. shows the fetching point. Fetch dominant is coming from the south and northwest.

Considering the study is located in the Sele channel, the hindcasting point is outside the channel. Fig 7. shows the wave-rose and wave histogram in the fetching point of the hindcasting calculation for 1 year. It offers more than 50% wave height between 0.1-0.5 m and only 1 % for more than 1 meter. Waves dominantly come from the south following the wind direction.

Fig. 6. Fetch of hindcasting calculation.

After doing the return period analysis by Log-Pearson III, the numerical simulation is required to get the distribution of the wave inside the channel. The result can be seen in Fig 8. Yellow pinned is the target area located in Pertamina Kasim. It is shown that the wave height that occurred in the Sele Strait throughout the year is really small at less than 0.1 m. The observation also confirmed that the wind-wave effect in the strait tended to be small. Based on the result above, the wave parameter can be excluded from the thermal simulation.

Fig. 7. Wave rose and wave histogram in the targeted area.

3.1.2 River discharge calculation

There is one river flow close to the study location, so the effect from this river should be considered as an input source in the numerical simulation. Considering the limitation of river discharge data, the measurement is calculated from the catchment area from Digital Elevation Model (DEM). The catchment area can be followed in Fig. 9. The catchment area is 3335 Ha. The method to calculate the river discharge when the data is limited can be used with the rational approach [11], as the calculation can be shown in Equation 7.

\[ Q_p = 0.00278.C.I.A \]  

where \( Q_p \) is the discharge (m\(^3\)/s), \( I \) is rainfall intensity (mm/hour), \( A \) is the water catchment area (Ha) and \( C \) is the coefficient runoff. Based on the table from the US Department of Agriculture [12] coefficient value of this study is chosen as 0.5 because it assumes the area resembles part of the irrigation area. River discharge is calculated for one-year long following the simulation time step.

Fig. 8. Mesh of the numerical model (top) and wave height data extraction in the Kasim area (bottom).

Fig. 9. Catchment area & river discharge yearly in Sele Strait.
3.2 Model validation

Considering the limitation of the observation data in the field, ERA-5 data analysis from ECMWF is utilized as an input for thermal dispersion analysis. Therefore, the model must be verified to ensure the simulation is reliable. The model is validated with wind, tide, and current field observation. The comparison of wind data between the observation and ECWMF data in the Kasim Area for 1 month is shown in Fig. 10.

![Wind data comparison between ECWMF and field observation](image1)

Fig. 10. Wind data comparison between ECWMF and field observation.

It shows that the magnitude of wind speed data for ECWMF data is bigger (around 2-3 m/s) than the observation (0.5-1 m/s). It is because the ECWMF data grid is bigger (0.25°x0.25°) for around 50 km which the data extracted in offshore. The observation in the field located on the land meaning the data of the domain is captured in a small area (region). On average, ECWMF wind speed magnitude is bigger than field data which concludes the model used the worst scenarios (high safety factor). It means the model simulated in the software has a good safety factor compared with the actual data. The calculation of extreme wave height is big to prepare for unexpected event (such as storms) in the location.

The simulation validated with the current and tide following the same location in the field observation as shown in Fig. 11.

Coefficient determination (R²) is a method to find the accuracy between model and observation data. The equation of R-squared can be seen in Equation 8.

\[
R^2 = \frac{\sum_i (X_0 - \overline{X_0})^2}{\sum_i (X_t - \overline{X_t})^2}
\]

where \(X_0\) is the height of the numerical model (water level); \(\overline{X_0}\); \(X_t\) is the tide observation; \(\overline{X_0}\) is mean of \(X_0\); and \(\overline{X_t}\) is the mean of \(X_t\). The amount of data (n) used is 525 hours. The result of R² is shown in Fig.12 which gives the value 0.8613. Considering the R-squared number is close to 1, the model has good performance and accuracy.

![Current and tide point observation location](image2)

Fig. 11. Current and tide point observation location.

![Numerical model vs observation data](image3)

Fig. 12. Numerical model vs observation data.

In addition to validating wind and tide data, the field data for ocean currents also verify the model. Tables 2-3 compare the ocean current between the model and observation data. The numerical model value is below the observation. It is because, in the model, the current speed is only defined from the interaction of tide and river discharge, while the real condition has a variety caused by the current. However, the phase and pattern are quite similar.

![Water Elevation Numerical Model vs Field Observation](image4)

![Model Vs Observation R-Squared Method](image5)
3.3 Hydrodynamic and thermal dispersion result

The result of the hydrodynamics simulation can be seen in Fig. 13. The figure shows the current speed extracted in the intake area (“A”) for one-year simulation with current rose and histogram. The current speed in average in intake area is varied between 0-0.5 m/s with a distribution below 0.5 m/s reaching 50%. The current rose shows the movement of the speed flow coming dominantly from the northeast and some from the southwest.

Table 2. Verification between observation and numerical model in point 1 for ocean current.

Table 3. Verification Between Observation and Numerical Model in Point 2 for Ocean Current.
The sea water temperature in both scenarios (1&2) mostly has a temperature between 26°-27°C for around 85.8% and 81.5% respectively. Scenario 2 has a wider range of temperatures; sometimes, the number goes 34°C. Considering the temperature frequency below 30°C is only less than 10%, it can be concluded that both scenarios are quite safe to keep the seawater temperature as a source for the intake. The intake area in point A can be used as cooling water, designed one kilometer from the outfall.

4 Conclusions

ECWMF ERA-5 data measurement for input simulation is bigger than the field observation. It means the simulation and calculation have a good safety factor. After simulating the wave height in the target area for 1-year simulation, the size is very small, which does not affect thermal dispersion — The reason because the outfall and intake area are located inside the channel. The numerical thermal diffusion model performed well with a good number of R-squared for water elevation validation. Current speed verification with the simulation gives the same pattern though speed is under observation data. The result of this study is the current speed mainly coming back and forth from northeast and southwest in the Sele Strait. The result of thermal dispersion shows the temperature distribution at the intake area majority below 30°C throughout the year for both scenarios. It is concluded that the intake and outfall location design is optimum and safe.

References

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8. MIKE, MIKE 21 toolbox global tide model – tidal prediction (DHI, 2013)
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