Hydrodynamic and Sediment Transport Modelling of Suralaya Coastal Area, Cilegon, Indonesia

A. H. Fattah[1a], Suntoyo[1], H. A. Damerianne[1] and Wahyudi[1]

[1]Ocean Engineering Department, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia (60111)

[a]Email: harisfattah@gmail.com

Abstract. The coastal zone of Suralaya is located in the district Pulomerak, Cilegon City, Province Banten. This region is a part of the Sunda Strait region that is very important area to support the ongoing activities such as, industries, power plant, ports, and tourism. However, those various activities will certainly give effect to the surrounding environment. To determine the environmental conditions of Suralaya Coast, it is necessary to study the hydrodynamics analysis and sediment transport modelling including the analysis of currents patterns. Tidal elevation observation was conducted for 15 days used to validate the water elevation simulation results, in which a good agreement between the observed data and the model result was obtained with the error value of 1.6%. The dominant current direction is from northeast in west season, while in the east season predominant current direction is from northwest with a speed average current 12,44 cm/s. The dominant wave direction is from the west. The average temperature is at 27^{o}C and the bottom sediment dominant form is fine sand.

Keywords: Suralaya Coast, Modelling, Hydrodynamic, Sediment Transport

1. Introduction

Coastal area of Suralaya is located in the Suralaya village, Pulomerak district, Cilegon, Banten Province. As part of the Sunda Strait area, it is very important as a support area for various activities of industry, power plant, ferry port, and tourism, which led to very strategic location as the gateway of the voyage between the island of Java and Sumatra.

However, the various activities will certainly have an impact on the coastal environment and surrounding areas. To know the condition of coastal area, hence needed a comprehensive understanding related to coast hydrodynamics process and sediment transport. Therefore, it is necessary to conduct a research study on hydrodynamic and sediment transport modeling analysis of coastal area of Suralaya. Thus, hydrodynamic and sediment transport modelling in coastal area has been done by some reserachers [1,2,3]. The bottom shear stress and sediment transport model induced by non-linear wave shown the difference characteristics that can increase the accuracy of the costal morphological change [4, 5]. Moreover, the wave over topping also could lead to sediment intrusion into Lagoon [6].

Hydrodynamic and sediment transport modelling lead us possible to know and estimate hydrodynamic behavior and quantify erosion, deposition and transport sediment for given period over large or tight area [7]. It has been developed rapidly in recent decades since 20th century until now, either the experimental or the model simulation, and commonly used to predict the hydrodynamic and the morphodynamic response of low crested structures [8]. The environmental data used in this modelling were obtained by direct measurement, namely bathymetriy, tidal, currents velocity and bottom sediment sample data, while for met-ocean data such as wind, wave and tidal data for long time was provided by BMKG and Dishidros. And then the obtained data are used to model validation.

In the present paper, aims to investigate the hydrodynamic behavior, the current velocity and sediment transport pattern and bed level change occurring in the Suralaya Coastal Area. Thus, the outcomes of the study can be used as the basis information to manage the Suralaya and surrounding coastal areas.

2. Study Area for Numerical Modelling

The study area of this research is located in coastal area of Suralaya, Cilegon, Banten Province with total area about 7.05 km^2 shown in Figure 1, it has a land boundary involved the coastal area of Suralaya Power Plant as well as three open sea boundaries. The Suralaya coastel water is a part of the waters of the Sunda Strait with a fairly steep coastal condition with a slope range of 0.5. The bottom sediment of the beach is fine sand.

Figure 1. Study Area of Suralaya Coastal Water

3. Numerical Modelling of Hydrodynamics and Sediment Transport

The most important to get the high accuracy of numerical model results is the set-up of modeling supported by the high quality of fields survey data. The better the data quality and set-up, then the results obtained will also be satisfactory [9]. The model setup requires some important data ie bathymetry data and field data obtained directly through the hydro-oceanography survey in December 2015. The data consist of bathymetry, tidal, current, water quality, and basic sediment data. The data is very important because it is used as input in the modeling setup. The data required in hydrodynamic and sediment transport modeling include bathymetry, tidal time series, wind data, bottom sediment sampling data. But for wind data use the wind data obtained from BMKG.

3.1. Model Description

The numerical model used in this study is Mike 21 which has been developed by DHI. Mike 21 is a numerical 2D modeling for modeling simulation of hydraulic and environment phenomena in lakes, bays, coastal waters and seas, estuaries, river where stratification can be neglected [9]. It consists of several models module that can be applied to 2D free surface flows modeling. Mike 21 can solve models with complex and multidisciplinary problems such as hydraulic, coastal engineering, and environmental science [9].

In this study, there are 3 modeling modules that will be used for the simulation, namely the Hydrodynamic (HD), the Nearshore Spectral Wind-Wave (SW), and the Non-Cohesive Sediment Transport (ST).

3.2. The Hydrodynamic Model

Hydrodynamic (HD) module is the basic module in the Mike 21 flow model [9]. It provide hydrodynamic basis modelling for computations performed. This module simulates water level variations and its flows to time in response to the force acting on it and the output results used as input in other modules.

The basic principle in this module solves continuity equation and vertically integral momentum conservation mass for 2HD (two horizontal dimension), so it can explain the interaction of fluid variation to depth by [10]. The equations used in this module are as follows:

Continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \tag{1}$$

Momentum of mass in the X-directon:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial t}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\,\frac{\partial \zeta}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{C^2.h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx}) + \frac{\partial}{\partial y}(h\tau_{xy})\right] - \Omega p - fVV_x + \frac{h}{\rho_w}\frac{\partial}{\partial_x}(p_a) = 0 \tag{2}$$

Momentum of mass in the Y-directon:

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\,\frac{\partial \zeta}{\partial y} + \frac{gq\sqrt{p^2+q^2}}{C^2.h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy}) + \frac{\partial}{\partial x}(h\tau_{xy})\right] - \Omega p - fVV_y + \frac{h}{\rho_w}\frac{\partial}{\partial_y}(p_a) = 0 \tag{3}$$

where,

h(x,y,t)	*: water depth (=ζ-d,m)*
d(x,y,t)	*: time varying water depth (m)*
ζ(x,y,t)	*: surface elevation (m)*
p,q(x,y,t)	*: flux densities in x- and y-directions (m^3/s/m)=(uh,vh); (u,v)=depth averaged velocities in x- and y-directions*
C(x,y)	*: Chezy resistance ($m^{1/2}$/s)*
g	*: acceleration due to gravity (m/s^2)*
$f(V)$	*: wind friction factor*
V, V_x, V_y(x,y,t)	*: wind speed and components in x- and y- direction (m/s)*
$\Omega(x,y)$	*: Coriolis parameter, latitude dependent (s^{-1})*
p_a(x,y,t)	*: atmospheric pressure (kg/m/s2)*
ρ_w	*: density of water (kg/m3)*
x,y	*: space coordinates (m)*
t	*: time (s)*
τ_{xx}, τ_{xx}, τ_{xx}	*: component of effective shear tress*

For effective shear stress calculation in x- and y-direction can be calculated using following calculations by [11]:

$$\tau_{bx} = \rho c_f U\sqrt{U^2+V^2}\left[1 + \left(\frac{\partial z_b}{\partial x}\right)^2 + \left(\frac{\partial z_b}{\partial y}\right)^2\right]^{1/2} \tag{4}$$

$$\tau_{by} = \rho c_f V\sqrt{U^2+V^2}\left[1 + \left(\frac{\partial z_b}{\partial x}\right)^2 + \left(\frac{\partial z_b}{\partial y}\right)^2\right]^{1/2} \tag{5}$$

where *cf* is friction coefficient.

For heat dispersion analysis, heat dispersion modeling with Advection/Dispersion equation was used. This equation as given by [12] is as follows:

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}+\frac{\partial wT}{\partial z}=F_T+\frac{\partial}{\partial z}\left(D_v\frac{\partial T}{\partial z}\right)+\hat{\mathrm{H}}+T_s \tag{6}$$

Where, D_V is vertical eddy viscosity coefficient, $\hat{\mathrm{H}}$ is atmospheric heat transfer, T_S is temperature of outfall and F_T is horizontal diffusion.

3.3. Nearshore Spectral Wind-Wave Model

This module used to simulate the propagation, growth, decay and transformation of wind-generated waves and swell both in offshore and coastal areas. Basic principle of this module is derived from the conservation equation of spectral wave action density and solved using the Eulerian finite difference technique [13]. And the output of this module are integral wave parameters and spectral output data such as significant wave height, mean wave period, mean wave direction, directional standard deviation, radiation stresses and wave energy dissipation.

Wave radiation stress is included in the momentum equation by the mean of motion equations over depth and time (wave period):

$$\text{x-momentum: } \frac{\partial S_{xx}}{\partial x}+\frac{\partial S_{xy}}{\partial y} \tag{7}$$

$$\text{y-momentum: } \frac{\partial S_{yy}}{\partial y}+\frac{\partial S_{xy}}{\partial x} \tag{8}$$

where S_{xx}, S_{xy}, and S_{yy} are components of radiation stress.

3.4. Sediment Transport Model

The basic principle of this module is for calculating of non-cohesive sediment transport capacity as a function of local wave, current, and sediment conditions. Continuity equation describing rates of bed level change and solved by finite difference method. Optimum input data such as tidal, wind, wave, and current will influence optimum precision in the simulation [11].

In this module, Bijker's transport model is used to calculate sediment transport [14]. The total load sediment transport calculated as the sum of bed load transport and suspended load transport as following equation:

$$q_t = q_b + q_s = q_{bt}(1+1.83Q) \tag{9}$$

Q in Equation (9) is a dimensionless factor defined as

$$Q=\left[I_1 ln\left(\frac{33h}{r}\right)+I_2\right] \tag{10}$$

where h is water depth, r is bed roughness, I_1 and I_2 are Einstein's integrals, which should be evaluated on the basis of dimensionless reference level, A = r/h, and z^*, defined as following equation:

$$z^*=\frac{w}{\kappa U_{f,wc}} \tag{11}$$

With w is settling velocity of the suspended sediment, κ is von Karman's constant and $U_{f,wc}$ is the shear velocity under combined waves and current. The influence of the waves on the suspended-load transport is therefore taken into account through the shear velocity. The roughness, r, can be related to Chezy number, C, by:

$$C=18log\left(\frac{12h}{r}\right) \tag{12}$$

The shear velocity in combined waves and current is found as:

$$U_{f,wc} = U_{f,c}\sqrt{1+\frac{1}{2}\left(\xi\frac{\hat{u}_b}{V}\right)} = \frac{\sqrt{gV}}{C}\sqrt{1+\frac{1}{2}\left(\xi\frac{\hat{u}_b}{V}\right)^2} \quad (13)$$

Where $U_{f,c}$ is current-related shear velocity, V is the depth-averaged current velocity, $\hat{u}_b$ is the amplitude of the wave-induced oscillatory velocity at the bottom, and ζ is a dimensionless factor that can be expressed in terms of wave friction factor f_w and chezy's number C.

$$\zeta = C\sqrt{\frac{f_w}{2g}} \quad (14)$$

The wave friction factor f_w is calculated as

$$f_w = exp\left[-5.977+5.213\left(\frac{a_b}{r}\right)^{-0.194}\right] \text{ If } 1.47 < \frac{a_b}{r} < 3000 \quad (14a)$$

$$f_w = 0.32 \text{ If } \frac{a_b}{r} \leq 1.47 \quad (14b)$$

Where a_b is the amplitude of the wave motion at the bottom.

$$a_b = \frac{\hat{u}_b T}{2\pi} \quad (15)$$

a_b and $\hat{u}_b$ are evaluated using linear wave theory. And the bed load and suspended load transport are calculated according to:

$$q_b = Bd_{50}U_{f,c}exp\left(-\frac{0.27\Delta d_{50}g}{\mu U_{f,wc}^2}\right) \quad (16)$$

B is a dimensionless bed total load transport coefficient, Δ is the relative density of sediments and μ is the ripple factor. Δ and μ are defined as:

$$\Delta = s-1 = \frac{\rho_s}{\rho}-1 \quad (17)$$

$$\left(\frac{C}{C'}\right)^{3/2} = 1/4 \quad (18)$$

ρ_s is density of the sediment, ρ is the density of water, and C' is the Chezy number related to the geometric characteristics of the bed material. It is calculated as:

$$C' = 18log\left(\frac{12h}{d_{90}}\right) \quad (19)$$

d_{90} is the sediment size for which 90% in weight of the bed material is finer. For uniform bed material d_{90} become identical to the specified value of d_{50}.

4. Results and Discussion

The result of the model simulation in Suralaya coastal area are presented. The first part of discussion is model validation. In the second part, results concerning the hydrodynamic simulation and in the third part, results concerning sediment transport rates are described.

4.1. Model Validation

To obtain accurate results, the validation is required by comparison of measured fields data and numerical model results. So the data validity for the next simulation is obtained. Model validation of field data can be performed on tidal, current, and temperature modeling results by Root Mean Square (RMSE) and percentage errors:

$$RMSE = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N}\left[\hat{X}_i - X_i\right]^2\right]} \quad (20)$$

$$Error = \frac{1}{N}\left[\sum_{i=1}^{N}\left|\frac{\hat{X}_i - X_i}{TP}\right|\right] * 100\ \% \quad (21)$$

Where, *RMSE* is root mean square from errors, $\hat{X}_i$ is model result, X_i is field data and N is amount of data, *TP* is range of tide observation data.

Figure 2 showed the comparison between the measured tidal data and the model results, it is found that the average error value is 1.6%. So it can be concluded that the result of tidal parameter modeling approaching actual condition in the field.

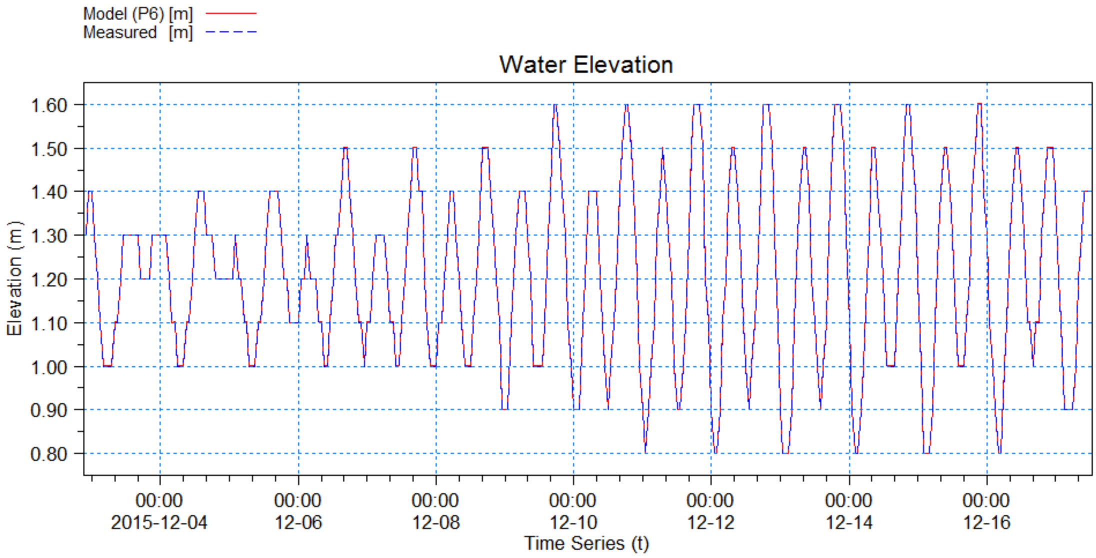

Figure 2. Comparison of measured and model water level at location 5, from 2th-17th December 2015. Measured data indicated with blue dash line and model data indicated with red line.

4.2. Hydrodynamic Simulation

The current velocity obtained by observing in the fields study area (for the five observation points) as given in Figure 1 is compared with the current velocity of simulation results shown in Table 1 and Figure 3. It can be seen that point 6 has the highest maximum current velocity about 0.224 m/s and 0.235 m/s for observed data and simulation results, respectively. And the comparison between the water level obtained from observing and that of obtained from simulation results showed a good agreement with the error is only 1.6%. The hydrodynamics model results simulated for West and East Season condition showed that the dominant current direction is from the Northeast and the Northwest for West Season and East Season, respectively within an average flow velocity of 12.44 cm/s as shown in Figure 3.

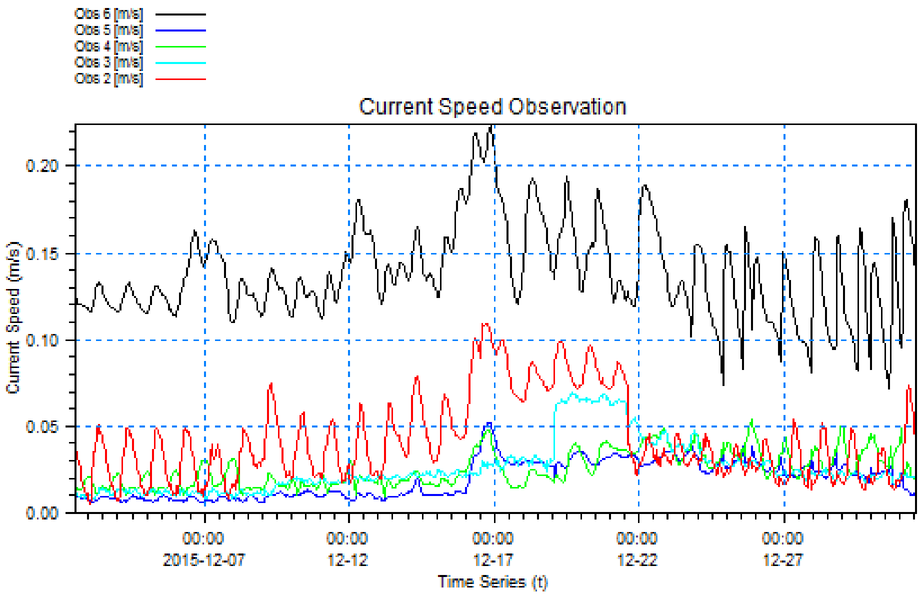

Figure 3. Current velocity on five different observation points

Table 1. Comparison current speed values between simulation data and field measured data

Observation point	**Model** (m/s)			**Measured** (m/s)		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
6	0.224	0.011	0.138	0.235	0.037	0.124
5	0.052	0.006	0.019	0.378	0.040	0.187
4	0.054	0.004	0.025	0.511	0,090	0.273
3	0.069	0.003	0.025	0.418	0.030	0.194
2	0.110	0.003	0.042	0.647	0.056	0.313

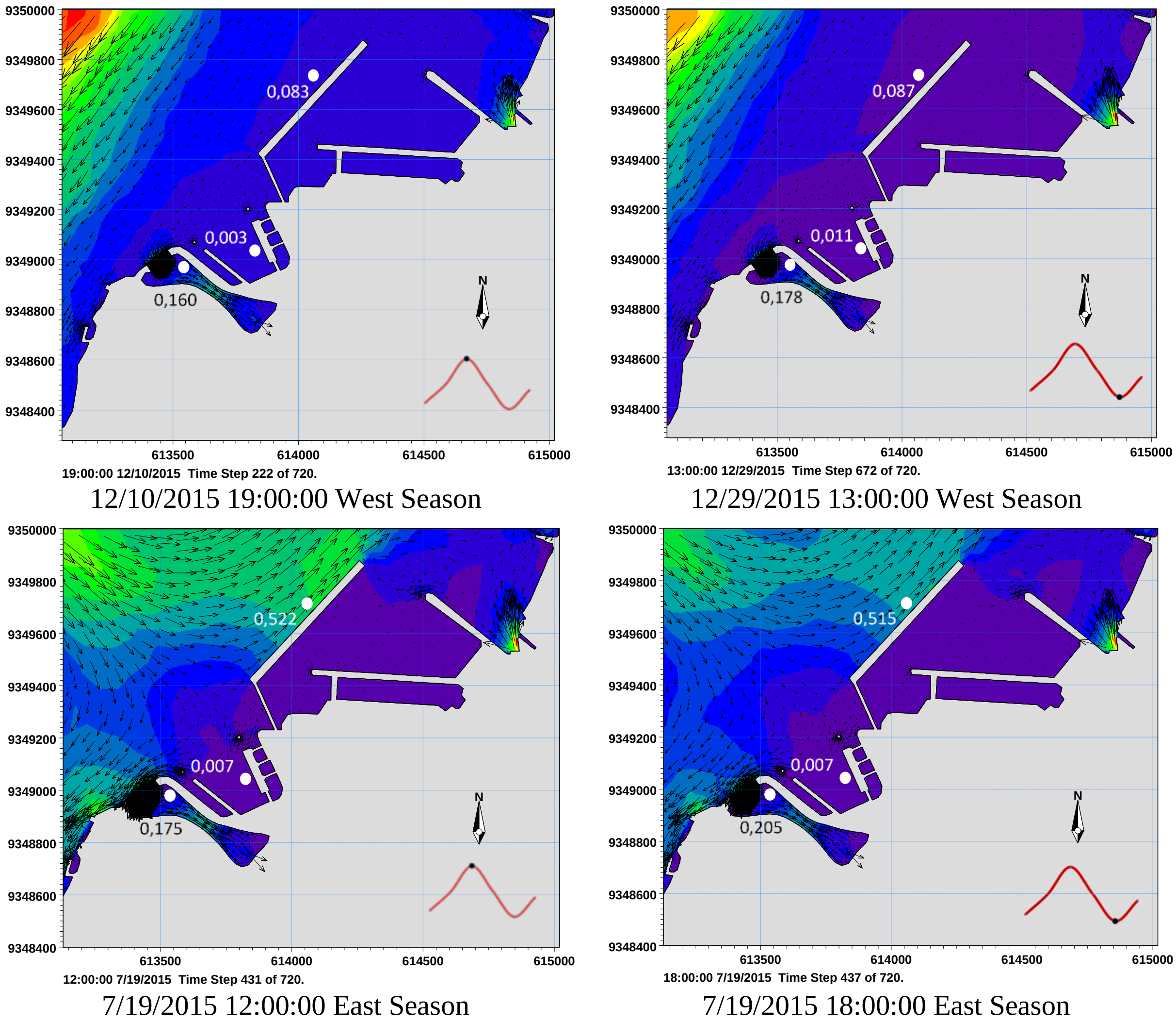

Figure 4. Current velocity pattern of Suralaya coastal area in two seasons (West and East Season) with two tidal condition (high and low tide)

The changing of seasons, followed by changing direction of wind movement. The season change give effect to the changes in the direction of waves and currents in the sea as shown in Figure 4. The current pattern change parallel to the shore in the West Season, while in the East Season, the flow pattern is perpendicular and then reach the land the current pattern becomes parallel to the coast.

4.3. Sediment Transport Simulation

Sediment transport modeling is an important step to know the pattern of sediment movement in a region to find out how many sediment transport rates and it also can be used to identify the area with tendency of erosion or sedimentation. Figure 5, shows that areas of light blue tend to erode, while dark blue areas tend to be deposition.

Based on numerical calculations on modeling, sediment transport rates in Suralaya coastal area in general in this study dominantly move to the southwest. This is congruence to the direction of simulated current movement in hydrodynamic modeling. The numerical model results show that the sediment transport rate is 51.4 m3 / day (in the point 5) and 32.32 m3 / day (in the point 6).

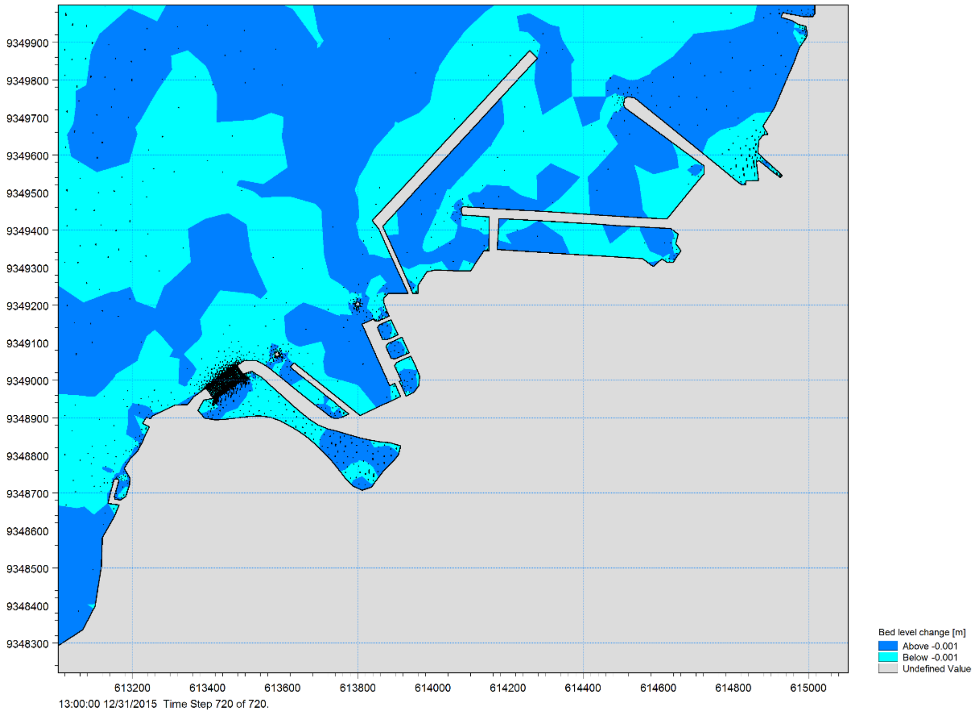

Figure 5. Bed Level Change in Last time step

5. Conclusions

Based on hydrodynamic and sediment transport modelling for Suralaya coastal area, it at can be concluded as follows:

- First, Hydrodynamic numerical model (Mike21 HD) gives simulation results of current velocity along with its movement pattern and water surface elevation which is very satisfying with existing conditions in the field. This has been proved by the validation between the water surface elevation models with the measurement with very satisfactory results.
- The simulation results of the current velocity have shown that point 6 has the highest current velocity between the other points. Maximum Speed Point 6 to be 0.224 ms^{-1} and minimum speed of 0.011 ms^{-1}. Second, water surface elevation has also got very good results, it can be seen from the error error is only 1.6%. The highest water level of simulation was 1,603 m and the lowest was 0.772 m.
- Third, the sediment transport module (MIKE21 ST) result shown that the direction of sediment transport movement in this study is dominant to the southwest. The numerical model calculations show that the sediment transport rate is 51.4 m3 / day (Point 5) and 32.32 m3 / day (Point 6).

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