Makara Journal of Technology

Volume 19 | Issue 3 Article 3

12-3-2015

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Recommended Citation

Sutikno, Sigit; Murakami, Keisuke; Handoyo, Dwi Puspo; and Fauzi, Manyuk (2015) "Calibration of Numerical Model for Shoreline Change Prediction Using Satellite Imagery Data," *Makara Journal of Technology*: Vol. 19: Iss. 3, Article 3.
DOI: 10.7454/mst.v19i3.3042
Available at: https://scholarhub.ui.ac.id/mjt/vol19/iss3/3

Makara J. Technol. 19/3 (2015), 113-119
doi: 10.7454/mst.v19i3.3042

Calibration of Numerical Model for Shoreline Change Prediction Using Satellite Imagery Data

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Abstract

This paper presents a method for calibration of numerical model for shoreline change prediction using satellite imagery data in muddy beach. Tanjung Motong beach, a muddy beach that is suffered high abrasion in Rangsang Island, Riau province, Indonesia was picked as study area. The primary numerical modeling tool used in this research was GENESIS (GENEralized Model for Simulating Shoreline change), which has been successfully applied in many case studies of shoreline change phenomena on a sandy beach.The model was calibrated using two extracted coastlines satellite imagery data, such as Landsat-5 TM and Landsat-8 OLI/TIRS. The extracted coastline data were analyzed by using DSAS (Digital Shoreline Analysis System) tool to get the rate of shoreline change from 1990 to 2014. The main purpose of the calibration process was to find out the appropriate value for K_1 and K_2 coefficients so that the predicted shoreline change had an acceptable correlation with the output of the satellite data processing. The result of this research showed that the shoreline change prediction had a good correlation with the historical evidence data in Tanjung Motong coast. It means that the GENESIS tool is not only applicable for shoreline prediction in sandy beach but also in muddy beach.

Abstrak

Kalibrasi Model Numerik untuk Prediksi Perubahan Garis Pantai menggunakan Data Citra Satelit. Artikel ini menyajikan metode kalibrasi model numerik untuk memprediksi perubahan garis pantai menggunakan data citra satelit pada pantai berlumpur. Lokasi penelitian ini dipilih Pantai Tanjung Motong, yang merupakan pantai berlumpur yang telah mengalami tingkat abrasi yang tinggi, di Pulau Rangsang, Provinsi Riau, Indonesia. Perangkat lunak utama yang digunakan dalam penelitian ini adalah GENESIS (*GENEralized Model for Simulating Shoreline Change*) yang telah banyak digunakan di banyak studi kasus perubahan garis pantai berpasir. Model ini kemudian dikalibrasi dengan dua data garis pantai yang telah diekstraksi dari citra satelit, seperti Landsat-5 TM dan Landsat-8 OLI/TIRS. Data tersebut kemudian dianalisis menggunakan DSAS (*Digital Shoreline Analysis System*) untuk mendapatkan tingkat perubahan garis pantai dari tahun 1990 sampai tahun 2014. Tujuan utama dari proses kalibrasi ini adalah untuk mendapatkan nilai yang optimum untuk koefisien K_1 dan K_2 sehingga perubahan garis pantai yang telah diprediksi memiliki korelasi yang sesuai dengan hasil proses data satelit. Hasil penelitian ini menunjukkan bahwa prediksi perubahan garis pantai memiliki korelasi yang baik dengan data historis di pantai Tanjung Motong. Hal ini menunjukkan bahwa program GENESIS tidak hanya dapat digunakan untuk memprediksi garis pantai berpasir tetapi juga pantai berlumpur.

Keywords: DSAS, numerical model, shoreline change

1. Introduction

Study about shoreline change phenomena in the coast is very important in order to countermeasure coastal erosion and sedimentation to maintain environmental sustainability. Because of the long time occurrence of shoreline change phenomena, the most effective method for this study is numerical simulation model. Numerical simulation models provide a powerful and unique capability for engineering studies of complex shoreline change occurring under realistic field conditions. Two numerical model which are well known for studies of shoreline change phenomena are GENESIS (GENEralized Model for Simulating Shoreline change) and LTC (Long-Term Configuration) [1]. The GENESIS model was developed to simulate long-term shoreline change on an open coast, produced by spatial and temporal differences in longshore sand transport [2], and it has been used since the late 1980's. The LTC model was firstly presented by Caelho *et al* [3].The GENESIS model has been successfully applied in many case studies of shoreline change phenomena especially for sandy beach [4-6]. Applicability of the model for muddy beach is further discussed in this research.

In order to make the model capable to predict the most realistic results, it has to be calibrated for establishment the calibration coefficients and parameters associated with variables representing the reality of the system. Calibration process is an iterative procedure to match model output as close as possible to the measured shoreline change or rate of shoreline change. The most common problem usually in calibration process is the lack of the measured historical shoreline position. However, with the rapid development of remote sensing technology, the historical shoreline position could be analyzed for calibration process.

This paper presents a method for calibration of numerical model for shoreline change prediction using satellite imagery data in muddy beach. Tanjung Motong coast in Rangsang Island, Riau province, Indonesia, which suffers from high abrasion,was picked as study area in this research. Two extracted coastlines satellite imagery data, such as Landsat-5 TM and Landsat-8 OLI/TIRS were used for model calibration. The extracted coastline data were analyzed by using DSAS (Digital Shoreline Analysis System) tool [7] to get the rate of shoreline change from June 1990 to February 2014.

This study was located in Tanjung Motong coast, a coast that suffers from high erosion in Rangsang Island, Riau province, Indonesia. Tanjung Motong coast is located in Rangsang Barat subdistrict which is situated directly to Malacca strait, as shown in Figure 1. The coast, especially its north region, is very vulnerable to coastal erosion because the coast is located directly to the open ocean with relatively high wave. It is very important to maintain the shoreline position of Rangsang island because it is directly bordered with another country. The island is also an important island in Riau province because it has many natural resources.

2. Methods

Data. Some data are needed for numerical modeling, such as topography and bathymetry, wave, tide, wind, soil properties, and satellite imagery data. Wave data were obtained from the results of the analysis and forecasting of wind data recorded at station BMKG (Meteorology and Geophysics Agency) Tanjung Balai Karimun, Riau Islands as shown in Figure 2.

This study used two imagery satellite data, such as Landsat TM (Thematic Mapper) 1999 and Landsat 8 OLI/TIRS 2014. Landsat TM has 30 meters spatial resolution, and Landsat 8 OLI/TIRS has 8 bands with 30 meters spatial resolution that can be sharpened with 1 band (band 8) to 15 meters spatial resolution. The specification of satellite data used in this study can be seen in Table1.

Shoreline model overview. The primary numerical modeling tool for shoreline change prediction in this study was GENESIS (GENEralized model for SImulating Shoreline changes). GENESIS is a linear shoreline evolution model developed by ERDC that uses a mass-balance routine to predict future shoreline positions. GENESIS is a USACE certified numerical model and was operated within the CEDAS (Coastal Engineering Design & Analysis System) software platform. Input required for running the model includes shoreline positions at several points in time, sequential wave data that spans these intervals, sediment characteristics, and positions and dimensions of any stabilizing structures.

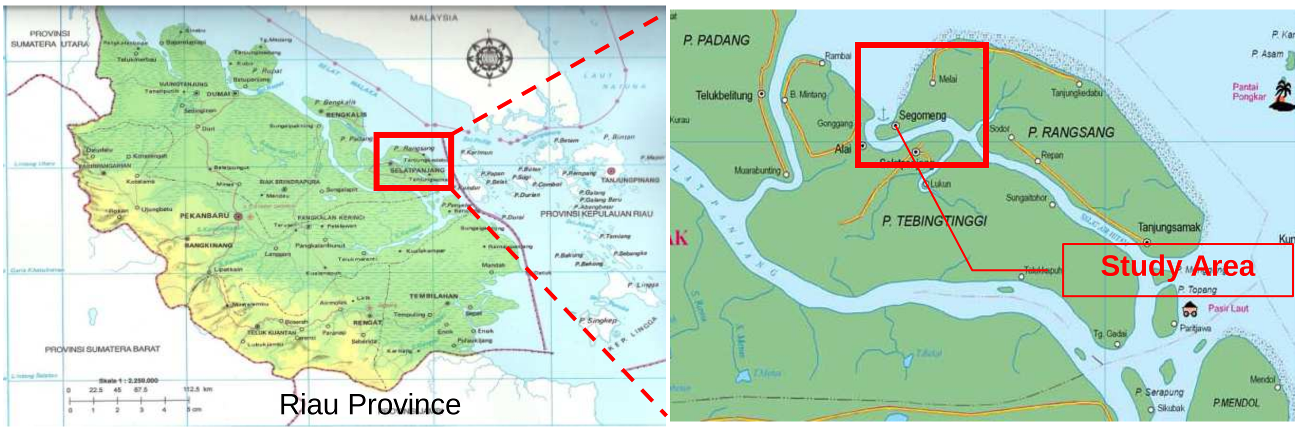

Figure 1. Study Area of This Research

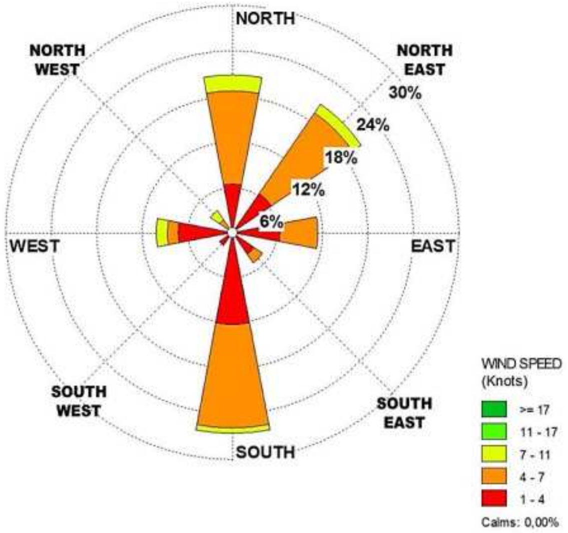

Figure 2. Wind Rose Data of Tanjung Motong Coast

Table 1. Satellite Imagery Data used for This Study

Date of acuisition	Satellite	Sensor type	Band	Resolution
06/06/1990	Landsat 5	TM	5 (SWIR-1) 4 (Near-IR) 2 (Green)	30 m 30 m 30 m
13/02/2014	Landsat 8	OLI	6 (SWIR-1) 5 (Near-IR) 3 (Red) 8 (Pan)	30 m 15 m

The changes in the shoreline were calculated in GENESIS using equations which were obtained from the conservationof the sediment volume Eq.(1).

$$\frac{\partial y}{\partial t}+\frac{1}{(D_B+D_c)}\left(\frac{\partial Q}{\partial x}-q\right)=0 \qquad (1)$$

where Q is the alongshore sand transport rate calculated as a function of the breaking wave height, the approach angle of breaking waves and other wave characteristics [8,2,5]; D_B is the berm height and D_C is the depth of closure. The x-axis is directed alongshore from the left to the right (for the observer looking to the offshore) and the y-axis is directed offshore. The model state variable is the position of the coastline $y(x,t)$, interpreted as a function of time t and coordinate x. The alongshore sediment transport is calculated using the following expression, which consists of a sediment transport term and a diffraction term recommended by Coastal Engineering Research Centre [9].

$$Q=\left(H^2C_g\right)_b\left(a_1\sin 2\theta_{bs}-a_2\cos 2\theta_{bs}\frac{\partial H}{\partial x}\right)_b \qquad (2)$$

where,

$$a_1=\frac{K_1}{16\left(\left(\frac{\rho_s}{\rho_w}-1\right)(1-p)(1.416)^{5/2}\right)} \qquad (3)$$

$$a_2=\frac{K_2}{8\left(\frac{\rho_s}{\rho_w}-1\right)(1-p)\tan\beta\,(1.416)^{7/2}} \qquad (4)$$

where H is the wave height; C_g is the wave group speed given by the linear wave theory; b is a subscript denoting wave breaking condition; θ_{bs} is the approach angle of breaking waves with respect to the local shoreline; K_1, K_2 are empirical coefficients, treated as a calibration parameters (K_1 characterizes the magnitude of alongshore sand transport; K_2 is controlling distribution of sand within calculation area); ρ_s is the density of sand ($2.65.10^3$kg/m^3); ρ_w is the density of water ($1.03.10^3$*kg/m*^{3}); p is the porosity of sand on the bed (0.4); tan β is the average bottom slope from the shoreline to the depth of closure.

Wave model. Due to the lack of wave data in study area, this study used wind data for generating the wave. Wind data from 2001 to 2012 in Tanjung Balai Station were used for this analysis. To analyse wave periods and wave height, this research used empirical formula based on parametric of JONSWAP wave spectrum.The first step in performing the shoreline modeling for this study was to set up the wave transformation model. The STWAVE (STeady-state spectral WAVE) model was used for this purpose. Both STWAVE and GENESIS were run within the CEDAS (Coastal Engineering Design & Analysis System) framework developed by the U.S. Army Corps of Engineers' Engineering Research and Development Center [8]. The wave model needed some input data such as bathymetry, wave, permutation file, spatial domain, specgen, data station, and wind data. The output of the wave model werestation file and field file. The simulation output of STWAVE couldbe visualized using WMV model to show the result of wave transformation.

The bathymetry data were used to construct the STWAVE grid which was prepared in ASCII format. Then, the datawereimported to grid generator as shown in Figure 3. The initial shoreline extracted from landsat data 2014 was then overlaid with bathymetry data as shown in Figure 3. The length of the shoreline was ±4.000 m which was divided into grid size dx = 50 dan dy = 50 and a total of 6400 grid cells comprise the bathymetric grid. The wave transformation as simulation result of STWAVE model from this research can be seen in Figure 4. The wave direction can be seen clearly from the figure. This phenomenon had a correlation with occurrence of erosion and shoreline in Tanjung Motong coast.

GENESIS model set up. The GENESIS grid extended along the full length of Tanjung Motong coast, as shown in Figure 3. Information required to construct the model

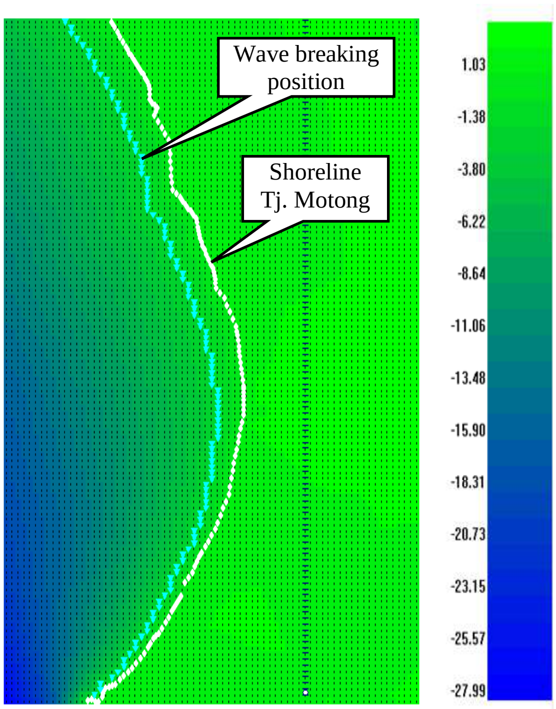

Figure 3. Shoreline and Bathymetry Grid of Tanjung Motong coast

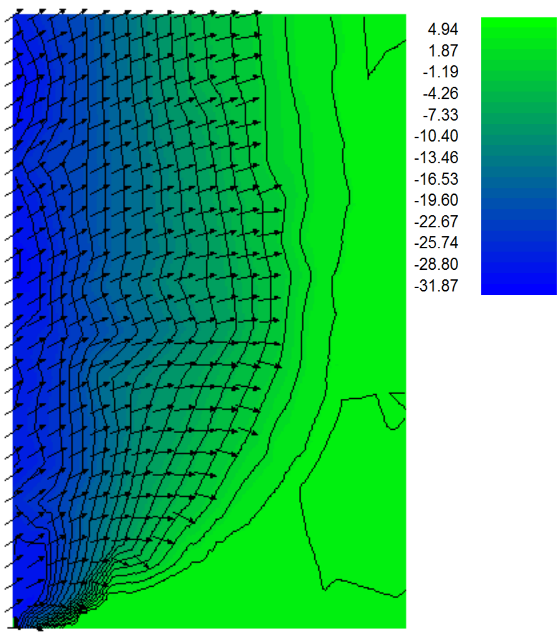

Figure 4. Wave Transformation in Tanjung Motong Coast

domain included the grid location, orientation, number and positioning of calculation cells, and positions of several shorelines that were needed to conduct calibration, verification, as well as production runs. Information was also required on the boundary conditions at both ends of the model grid. Shoreline positions and elevations through the surf zone and subaerial beach were obtained from field survey. Other GENESIS modeling inputs include physical parameters such as median sediment grain size, berm elevation, and depth of closure; these values were also obtained from field survey. Some assumptions were taken into account in this simulation, such as constant parameters and wave data, which were not changed significantly during simulation: coastal slope was 50 m and the grain size was 0.05 mm.

GENESIS calibration. The first step in preparing the GENESIS model for performing production runs was to calibrate the model to the study area. This was done by selecting shoreline positions at two points in time, and running the GENESIS model to calculate the change that occurs to the initial shoreline, using wave data from that time period. The two GENESIS calibration coefficients K_1 and K_2 were adjusted between each model run in an iterative procedure, to match model output as close as possible to the measured shoreline changes or rate of shoreline change during the calibration period. The model became calibrated when the calculatedshoreline changes closely approximate the final measuredshoreline changes. The points of comparison were not only the shoreline positions, but also include transport rates, volumetric changes, and a minimization of the ‘calibration/ verification error’ provided in the model output.

This study used comparison of rate of shoreline change between output of GENESIS model and DSAS (Digital Shoreline Analisis System) analysis result for extraction of shoreline data from satellite for calibration process. DSAS is a digital shoreline analysis tool that can be used to compute rate-of-change statistics for a time series of shoreline vector data [7]. This study used End Point Rate (EPR) method, one of statistical method that can be used in DSAS. The End Point Rate method was calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline (Figure 5). The major advantages of the EPR are the ease of computation and minimal requirement of only two shoreline dates with acceptable accuracy [10].

3. Results and Discussions

Shoreline change analysis using satellite data. After image processing of 1990 and 2014 landsat data, the shoreline position of each year could be digitized clearly. The extracted digital shorelines then were overlaid each other to identify the shoreline change during 24 years. From this process, the erosion and sedimentation area were identified, as shown in Figure 6.

To analyse the rate of shoreline change statistically using DSAS, the coast was divided into 72 stations with 100 meters interval. The rate of shoreline change of Tanjung Motong coast from 1990 to 2014 as a result of digital shoreline analysis using DSAS is shown in Figure 6. The

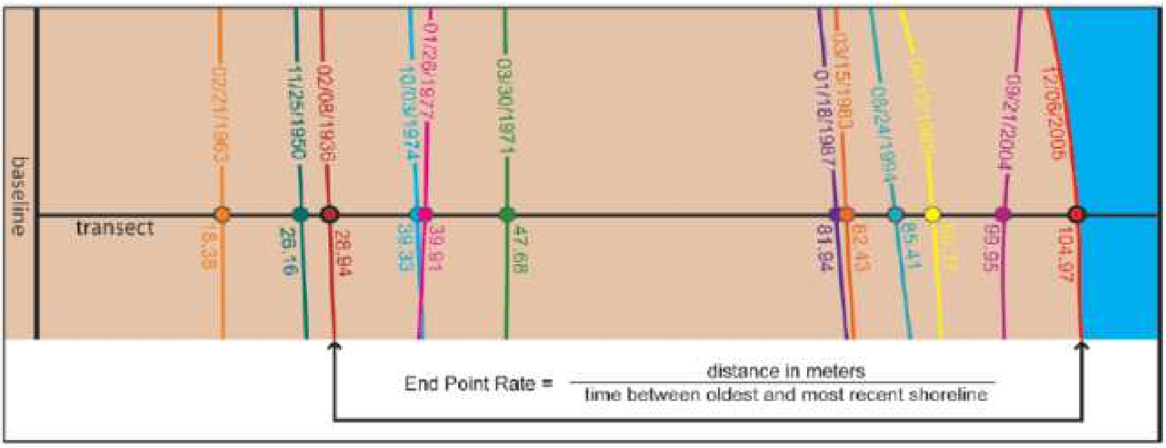

Figure 5. Computation Method for Calculating Rate of Shoreline Chane using End Point Rate (EPR) Method

figure shows the rate of shoreline changed in each station. Minus sign (-) signifies erosion at those locations. The analysis result shows that erosion occured in the south part of Tanjung Motong coast, on the other hand sedimentation occured in the north part. The maximum rate of erosion in south coast was about 9.63 meters/year and the maximum rate of sedimentation in north coast was about 5.32 meters/year. The rate of shoreline change in each station then might be used for calibration process in numerical model.

Model calibration. In model calibration process, two calibration coefficients K_1 and K_2 were adjusted between each model run in an iterative procedure, to match the rate of shoreline from model output as close as possible to the rate of shoreline change from DSAS output. For adjustment of calibration coefficients, Hanson [2] recommended for sandy beach that the values are typically in the ranges of $0.1 < K_1 < 1.0$ and $0.5\ K_1 < K_2 < 1.5\ K_1$. This research tried some couples value of K_1 and K_2 for this calibration as shown in Table 2. First trial was 0.1 and 0.05 for coefficient value K_1 and K_2 respectively. The comparison of shoreline change rate for this coefficient value between model output and DSAS output did not has a good correlation, as shown in Figure7a. The average error of this trial was 89.299% as shown in Table 2. By using coefficient value 0.5 and 0.25 for $K_1$and K_2 on second trial, the average error decreased to 72.979%. The rate of shoreline change from model get closer with DSAS one on third trial as shown in Figure7b by using coefficient value 0.75 and 0.375 for K_1 and K_2 respectively, and the average error was 54.773%. Trial Number 4, Number 5, and Number 6 showed better correlation with the average error 53.15%, 50.94%, and 39.96% respectively.

The rate of shoreline change from model got closer with DSAS one on the seventh trial, as shown in Figure7c, by using coefficient value 1.00 and 1.25 for $K_1$and K_2 respectively, and the average error was 36.655%. This

Table 2. Simulation of K_1 and K_2 for Model Calibration

Trial Number	Coeficient		Average Error
	K_1	K_2	
1	0.1	0.05	89.299 %
2	0.5	0.25	72.979 %
3	0.75	0.375	54.773 %
4	1	0.5	53.15 %
5	1	0.75	50.942 %
6	1	1	39.861 %
7	1	1.25	36.655 %
8	1.5	2	28.423 %
9	1.5	2.25	24.265 %
10	1.5	2.10	15.016 %

trial was the maximum effort to get the best correlation as recommended by Hanson [2] on using calibration coefficient range. However, this research tried to simulate other coefficient values outside Hanson recommendation range as shown in trial Number 8, Number 9, and Number 10, and the result showed better correlation. The best correlation was on the 10^{th} trial, where the coefficient values were 1.50 and 2.10 for K_1 and K_2 respectively, and the average error was 15.016% as shown in Figure 7d. This means that such coefficient values are the most appropriate one for numerical modeling of shoreline change in Tanjung Motong coast, Riau Province, Indonesia.

Model simulation. The model can be used to predict shoreline change in Tanjung Motong coast after the calibration process was satisfied. In this case, the model could beused to predict shoreline change for 10 years. Figure 8 shows the shoreline change prediction in Tanjung Motong coast in 2024 as result from numerical simulation model. As shown in the figures the erosion phenomena in the south area and the sedimentation in the north area of Tanjung Motong beach will continue. Based on field survey in 2013, the coastal areas had heavy damage because of erosion especially in point area Number 1 and Number 2. However, only a few damage occured in point area Number 3. This means that the numerical model simulations have a good correlation with the historical evidence data in shoreline change.

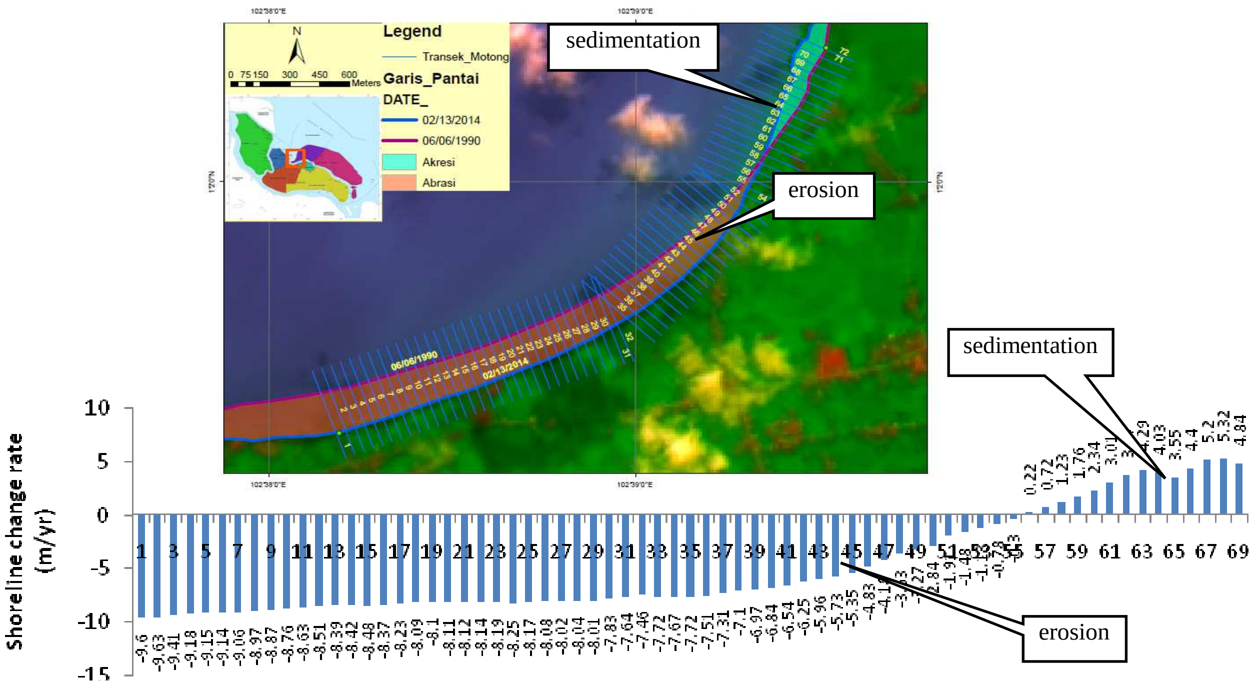

Figure 6. Rate of Shoreline Change of Tanjung Motong Coast

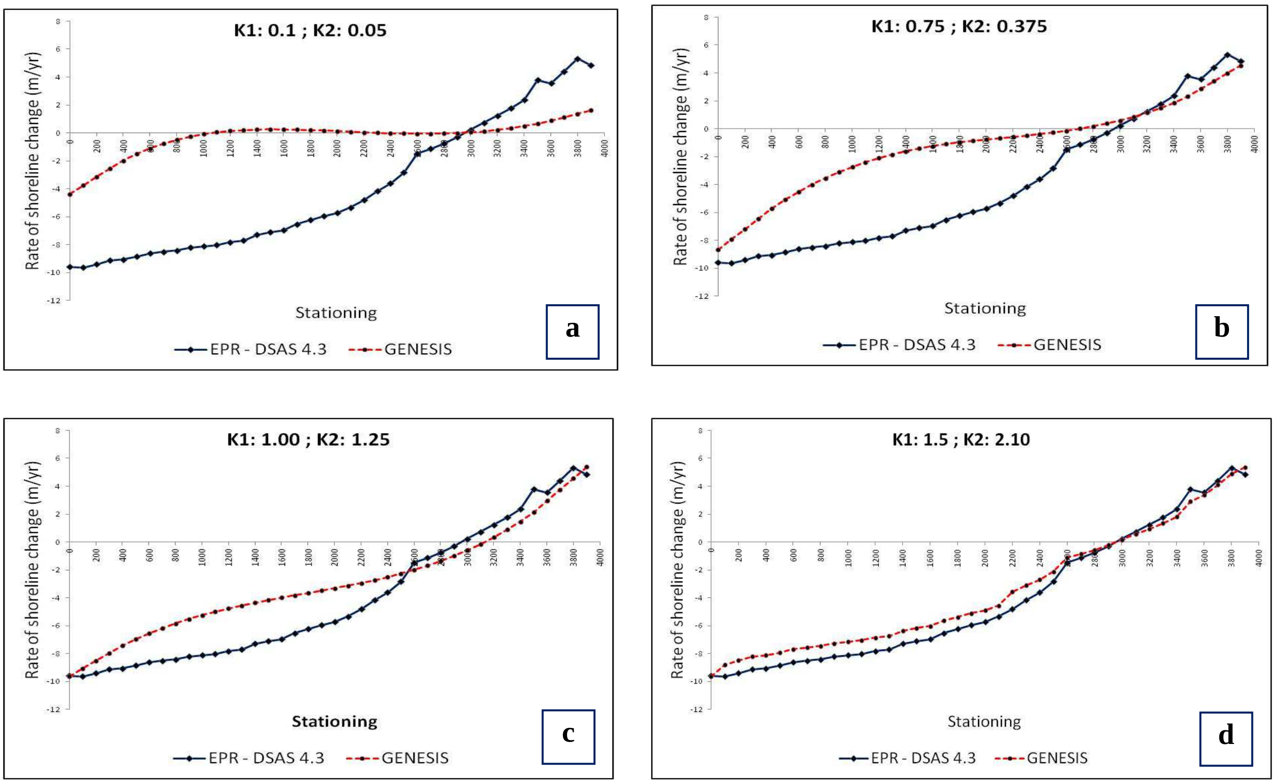

Figure 7. Comparison of Shoreline Change Rate between Model Simulation Output and DSAS Analysis in Tanjung Motong Coast

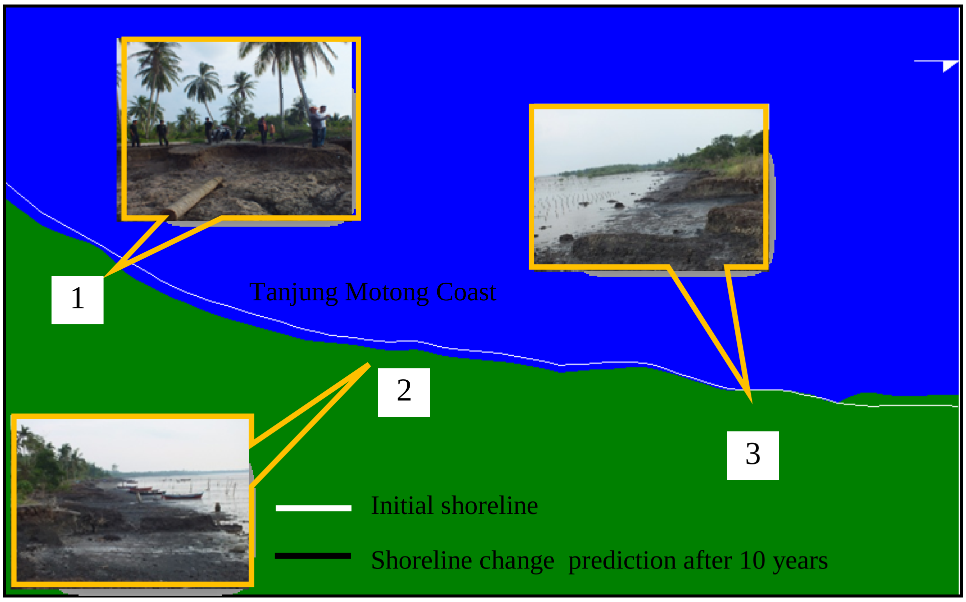

Figure 8. Shoreline Change Prediction in Tanjung Motong Coast in 2024

4. Conclusions

This research conducted a numerical modeling for shoreline change prediction using GENESIS tool at muddy beach. The model was calibrated using two extracted coastlines satellite imagery data which was analyzed using DSAS. The main purpose of the calibration process was to find out the appropriate value for K_1 and K_2 so that the predicted shoreline change had an acceptable correlation with the output of the satellite data processing. The result of this research showed that the best correspond value for K_1 and K_2 for the characteristics of muddy beach in Tanjung Motong were 1.5 and 2.1 respectively. The simulation of numerical model showed that the shoreline change prediction had a good correlation with the historical evidence data in Tanjung Motong coast. It means that the GENESIS tool is not only applicable for shoreline prediction in sandy beachbut also in muddy beach.

Acknowledgements

The author would like to thank the Directorate General of Higher Education (DIKTI) - Ministry of Research, Technology and Higher Education for its 2014Post Graduate research grants program (PPS).

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