Enhanced Representation of Java Sea Tidal Propagation through Sensitivity Analysis

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***Abstract-* Java Sea is a very complex tidal region due to its associated intrinsic geometrical characteristics which include coastline geometry, small islands and sharply varying bottom topography. Several numerical modelling studies have been conducted to evaluate the tidal characteristics of Java Sea. The present modelling study is an attempt to enhance the representation of tidal propagation of Java Sea by performing sensitivity analysis using Delft3D. Several simulations were done with Manning (0.015, 0.018 0.02, 0.03, 0.032 and 0.035) and Chezy (50, 55, 60, 65 and 70) bottom roughness coefficients in order to enhance the model performance. In general Java Sea is shallow in nature however based on sensitivity analysis with different bottom roughness coefficients, bottom roughness coefficients map was created and applied in combination with varying spatial wind to understand its effect on tidal propagation. The model performance has been verified by comparing with observed amplitudes and phases of M2, S2, K1, O1 tidal constituents at several locations on southern and northern coast of Java Sea. The root mean square error (RMSE) between observed and modelled amplitudes were 0.05, 0.04, 0.06, 0.04 calculated for M2, S2, K1 and O1 tidal constituents respectively at northern coast. Similarly, the maximum RMS error between observed and modelled phase of 34.07 was calculated for S2 tidal constituent. Most importantly, model results clearly indicated bottom roughness coefficients of 0.02, 0.03, 0.032 and 0.035 largely influencing the semi-diurnal tidal harmonic constituents compared to diurnal tidal constituents. However, the spatial varying wind had minimal effect on amplitude and phase. The present study clearly indicates that the assessment of tidal propagation in such a shallow water environment could be enhanced through detailed sensitivity analysis.**

Keywords- Java Sea; Numerical Model; Sensitivity Analysis; Tidal Propagation; Bottom Roughness; Spatial Wind

I. INTRODUCTION

Java Sea is a shallow water basin with depths varying from 20 m off the coast of south-east Sumatra to about 60 m on the eastern part in a region of Indonesia/Southeast Asia [1]. It is surrounded by three main islands in the Indonesian archipelago viz., Kalimantan, Java and Sumatra as shown in Fig. 1. It is the most southern part of the Sunda Shelf, which connects western part of Indonesia with the Asia mainland. Java Sea is nearly a rectangular shallow water basin with long axis of approximately 890 Km parallel to Java and a short axis of 390 Km [2]. In the northern open boundary, the Java Sea is linked with three straits: Karimata, Gaspar and Bangka. The eastern and western open boundaries are connected with the Flores Sea and Sunda Strait, respectively.

Tidal hydrodynamics in the Java Sea are complex, due to its rugged shallow bottom topography, complicated coastline, and the interference of tidal waves propagating from the Pacific Ocean, Indian Ocean, and South China Sea. Several studies related to tides and tidal currents in the Indonesian seas have been published with emphasis on Java Sea Region. Wyrtki reported that the predominantly diurnal tide in the Java Sea is related to the behaviour of tidal propagation from the adjacent seas [3]. The semi-diurnal tidal wave entering the Java Sea is weak due to the effect of deflection of a northward tidal wave from the Indian Ocean in the Flores Sea. On the other hand, the stronger diurnal tidal wave from the Pacific Ocean is able to penetrate into the Flores Sea to meet with waves from the Indian Ocean through the Lesser Sunda Islands and Timor Sea. Although the results are impressively reasonable in the Indonesian seas, mapping of the Indonesian tides is still incomplete owing to lack of observations. During the past decades, remarkable progress by investigations about tidal phenomena has benefited by use of satellite altimeter measurements and high-resolution numerical simulation, and with no exception in the Indonesian seas. Based on tide gauge observations and TOPEX/Poseidon (T/P) satellite altimeter data, Mazzega and Berge [4] produced the co-tidal charts of M2 and K1 in the Indonesian seas using an inversion method. Using a barotropic tide model; Hatayama et al. [5] investigated the characteristics of M2 and K1 tides and tidal currents in the Indonesian seas, which showed that the tidal currents in the Java Sea and in the vicinities of narrow straits, i.e., the Lombok and Malacca straits, are relatively strong. Also, indicated through Simpson's parameter [6] that the tidal front generally forms in southwestern part of the Makassar Straight and Java Sea. Ray et al. [7] investigated the behavior of K1 and M2 tidal currents in Indonesian seas using data assimilation technique [8].

Alan and Motoyoshi [1] had investigated the effects of the barotropic tides for four tidal harmonic constituents on tidal circulation and tidal mixing using three-dimensional hydrodynamic model combined with observation data and had suggested that the M2 tide dominates over the entire Java Sea. They also observed that; K1 had lowest mode resonance in Java Sea and contributed as a major source of tidal energy which dissipated westwards. In a very recent study, Mustaid Yusuf and Tetsuoyanagi [9] performed numerical experiments to study the characteristic of tide and tidal current in the Java Sea using the

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COHERENS V2.0 model. This study revealed that the tidal energy fluxes propagate westward in Java Sea and clearly indicated the bifurcation of M2 in the Makassar Strait. Though, energy dissipation was observed while entering the Java Sea due to steep bottom topography at the inlets. Hatayama et al. [5] have also investigated the characteristics of tides and tidal currents in the Indonesian Seas, with particular emphasis on the predominant tidal constituents. The root mean square errors (RMSE) were estimated as 11.2 and 8.5 cm, respectively between tide gauge observations and calculated M2 and K1 tidal constituents over the entire Indonesian Seas. It was observed that the tidal currents play essential role in the transport and mixing process in the Indonesian seas. However, it was noticed none of the studies performed the sensitivity analysis and evaluated the combined effect of bottom roughness coefficients and spatially varying wind on tidal propagation.

In this study we concentrated to enhance the model performance compared to observed data. The effect of bottom roughness coefficients and spatial wind on the overall tidal propagation in the Java Sea has been assessed. It has also been noticed in previous studies due to unreliability of detailed bathymetry data and grid resolution the model accuracy was compromised. Therefore, high resolution bathymetry data and high resolution grid was used in this study. In addition model boundary has been fixed in a way to get the full overview of Java Sea to capture the influence of inflows from South China Sea, Malacca Strait, Sunda Strait, Flores Sea and Makassar Strait respectively.

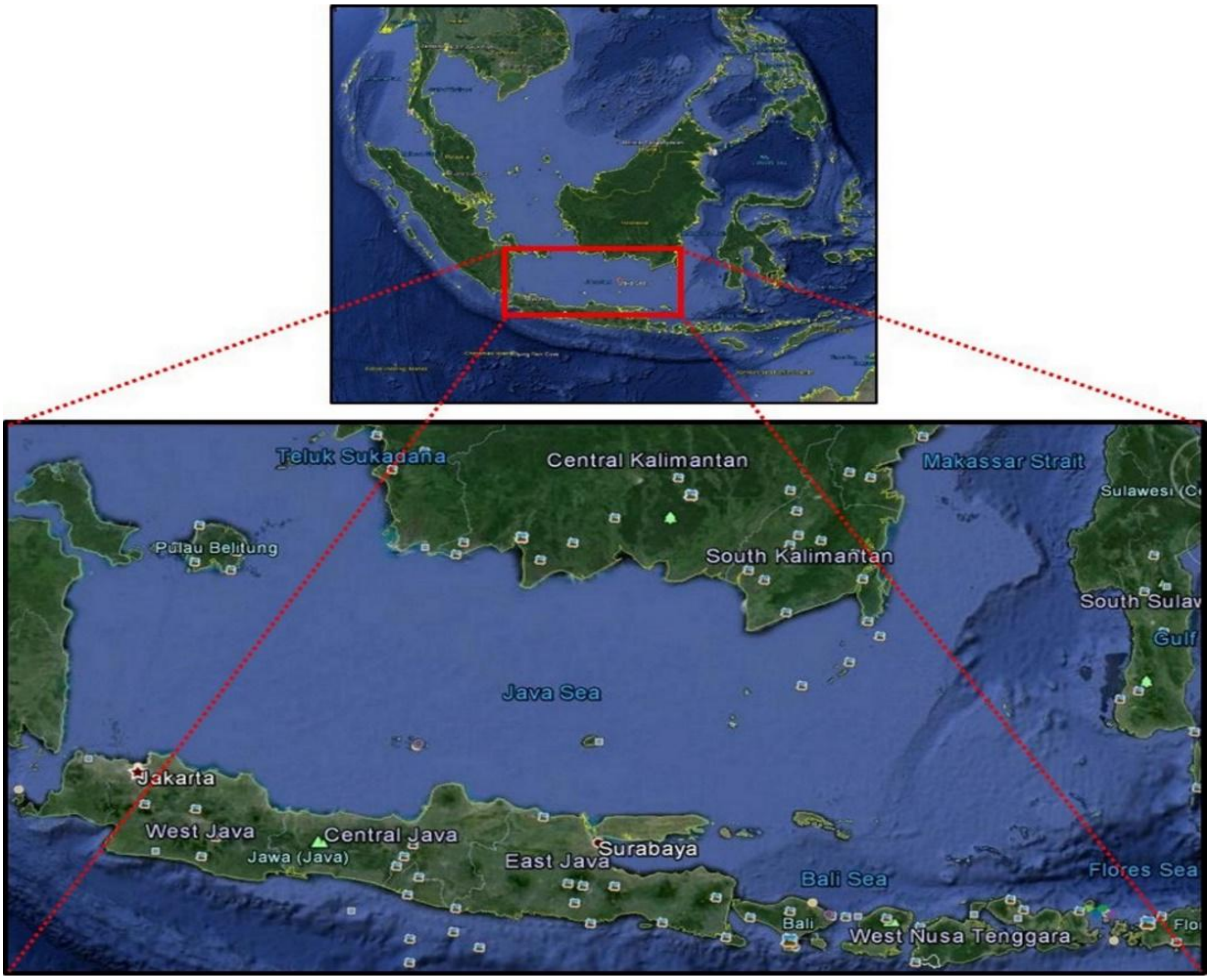

Fig. 1 Map showing the location of Java Sea – Source: Google Earth

II. MODEL SETUP

We investigated the effect of bottom roughness coefficient and spatially varying wind on tidal propagation using Delft3D-Flow module which solves the shallow water equations for conservative constituents with an ADI finite difference scheme. It is a multi-dimensional hydrodynamic and transport simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear grid. Recently a similar study has been performed in Singapore Regional Waters (SRW) and detailed sensitivity analysis done to enhance the accuracy of tidal predictions using OpenDA in combination with long track satellite altimeter data [10]. It has clearly been indicated in this study that sub regions of SRW are very sensitive to forcing boundaries, depth and bottom friction and it is understood that uncertainties in physical parameters could be the source of error in such kind of numerical modelling studies. Therefore, through sensitivity analysis model performance can be improved further.

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The present Java Sea model ranges from approximately 105° E to 114° E Longitude and from 2° S to 8° S Latitude. A curvilinear spherical grid was generated for this study which consists of 50,200 grid cells (Fig. 2). Curvilinear boundary fitted grid allows to overcome the uncertainties of model results compared to rectilinear grids [10]. In this study varying grid resolution was considered with decreasing element sizes (i.e. with increasing level of accuracy) [11]. To study the tidal currents and tidal circulation in Java Sea, 5' by 5' grid resolution has been used in two and three dimensional models respectively [1, 9]. Study shows some discrepancies in terms of over prediction of amplitude compared to observed data. In general to overcome such discrepancies detailed sensitivity analysis needs to be performed to evaluate the model sensitivity in such type of shallow environment [12]. Computational grid was prepared in a way to minimize the error caused by bathymetry data interpolation. Bathymetry interpolation was done using the data digitized from Admiralty charts (Fig. 3). Previously, Kantha and Clayson [13] reported minor discrepancies in interpolated bathymetry data in the central part of Java Sea. Therefore, in this study accuracy of interpolated bathymetry was cross checked especially in central part of the Java Sea by comparing with other open sources bathymetry data sets. Initially, several simulations were performed with constant Chezy coefficient of 50, 55, 60, 65, 70 and Manning coefficient values of 0.015, 0.018, 0.02, 0.03, 0.032, 0.035, respectively over the entire model domain to check the sensitivity of the coefficients on tidal propagation. Based on sensitivity check with bottom roughness coefficients a detailed Manning map was created and model was simulated further with varying Manning map. In addition, model was also simulated with varying Manning map in combination with spatial wind field to evaluate combined effect of both on tidal propagation. Six-hourly NCEP/NCAR real-time wind data was downloaded for entire model domain from National Centers for Environmental Prediction (NCEP). Spatially varying wind speed (m/s) and direction (degree) at particular time step are shown in Fig. 4. Maximum wind speed observed was around 11m/s in central part of the Java Sea and dominant wind direction was from East to West over the entire domain.

The model was forced with eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf, Mm) and one non-linear (M4) tidal constituents. Tidal constituents were extracted from TPXO Version 7.1 (Global Model of Ocean Tides). In general, the TOPEX/POSEIDON altimetry data more accurate for deep oceans [14] compared to shallow region like Java Sea. Hence, the boundary corrections were applied locally at few locations. Initial water level applied a value as zero at the start of the simulation and the horizontal eddy viscosity chosen was 1 m^2/s. Time step of 2 min was chosen to maintain the numerical stability and accuracy of the results.

Fig. 2 Map showing the model extent and high resolution curvilinear computational model grid used in this study

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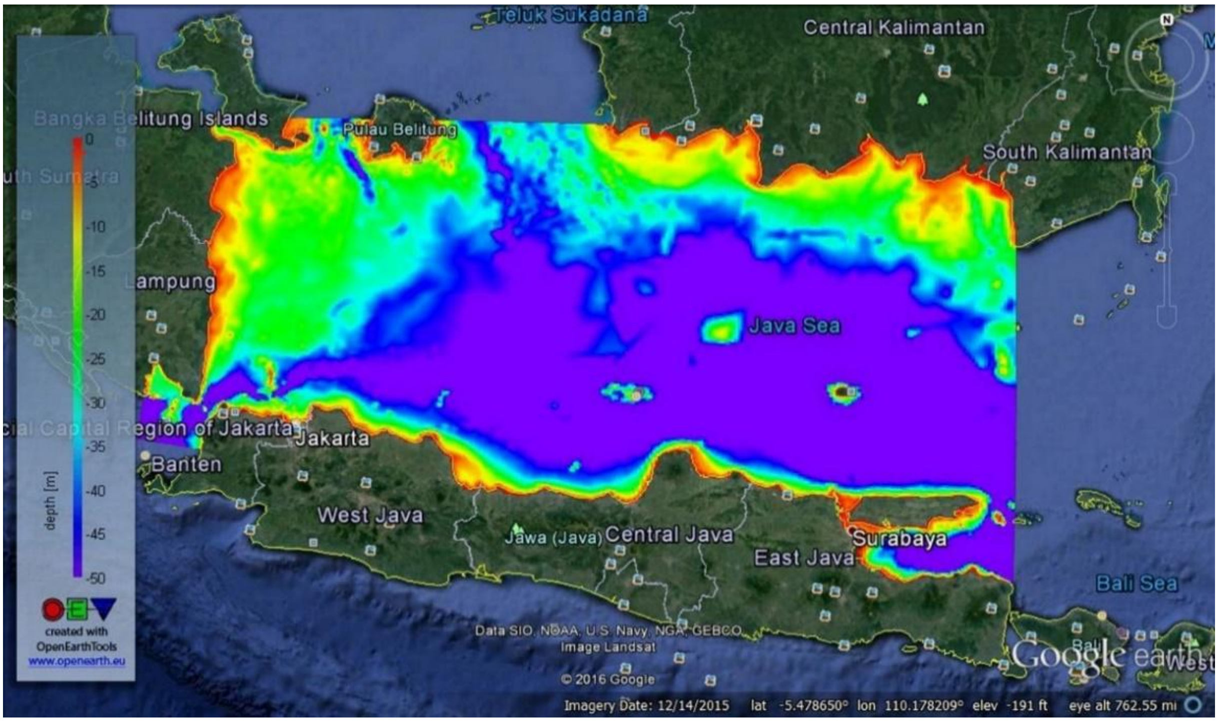

Fig. 3 Map shows the detailed bathymetry of Java Sea. Color bar (left) showing the variation in bathymetry gradient

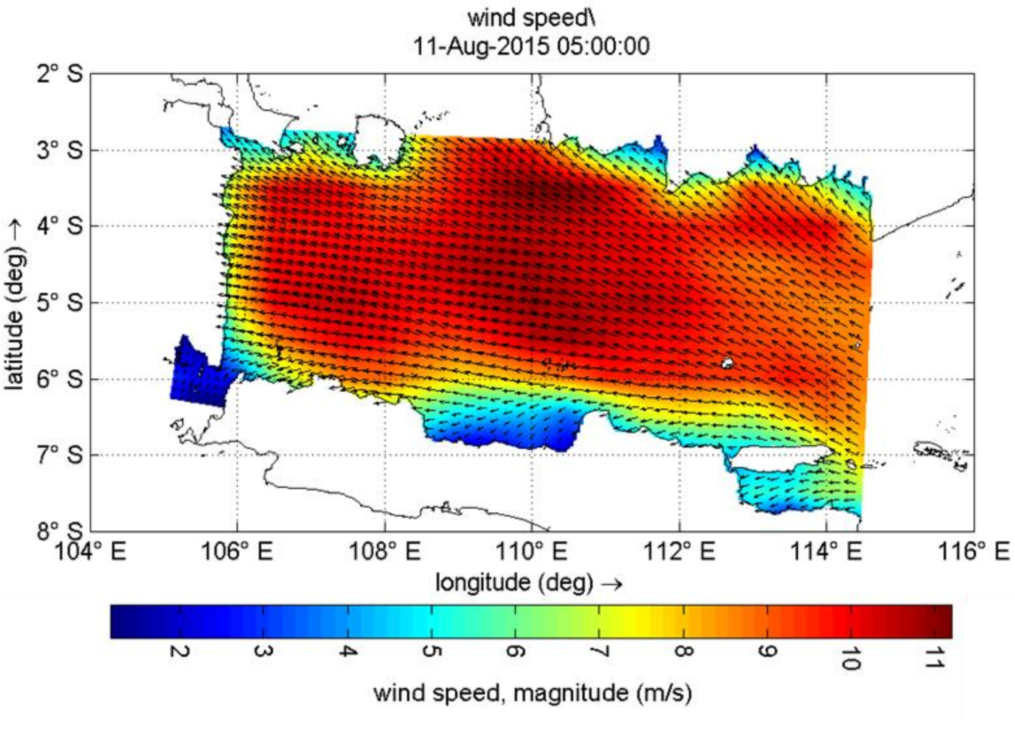

Fig. 4 Map shows the spatial wind over entire Java Sea domain on 11th Aug 2015 around 5 am. Black arrows showing the dominant wind direction (deg) and color bar indicates the varying wind speed (m/s). The maximum wind speed observed around 11 m/s in central part of Java Sea

III. RESULTS AND DISCUSSION

To evaluate the model accuracy and its response against various physical parameter settings, sensitivity analysis has been done. Several simulations were performed with default parameter settings to evaluate the model performance. Sensitivity of the bottom roughness on the tidal propagation in the Java Sea was carried out with different Chezy and Manning bottom roughness coefficients. Several simulations were performed with constant Chezy coefficient of 50, 55, 60, 65, 70 and Manning coefficient

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of 0.015, 0.018, 0.02, 0.03, 0.032, 0.035, respectively over the entire model domain. Model performance was assessed based on the results with different bottom roughness coefficient parameters and accuracy of the tidal propagation in the Java Sea was obtained with varying Manning coefficient map as shown in Fig. 5. Co-tidal maps (Figs. 6-9) were prepared which represent the amplitude and phases of M2, S2, K1 and O1 tidal constituents for model simulation with varying Manning coefficient map. It is clear from the co-tidal maps the tidal fluxes propagates westward in Java Sea as shown in earlier studies [9]. Amplitudes are comparatively higher for K1 and O1 tidal constituents compared to M2 and S2 constituents. In addition, the model performance was tested by applying the corrections to the astronomical boundary conditions derived from TPXO 7.2. The influence of spatially varying wind on the tidal propagation in the Java Sea was verified by applying wind over the entire model domain downloaded from National Centers for Environmental Prediction (NCEP). Comparison of the Admiralty Tide Table (ATT) reported amplitude and phases of tidal constituents viz., M2, S2, K1 and O1 with model predicted values for the coastal station within the model domain are indicated in Tables 1-4. Amplitude and phase reported in Admirality Tide Table (ATT) extracted at 28 coastal stations from NP05 Admirality Tide Table Volume 5, 2015.

The calculated root mean square error (RMSE) of amplitudes of M2, S2, K1, O1 are 0.05, 0.04, 0.06 and 0.04, respectively, for varying Manning coefficient on the northern coast of the Java Sea where the average depth is about 30 m. Similarly, root mean square error (RMSE) of amplitudes of M2, S2, K1, O1 are 13.78, 34.07, 6.74 and 10.55, respectively. The root mean square error (RMSE) of amplitudes of M2, S2, K1 and O1 tidal harmonic constituents on southern Java Sea coast for varying Manning bottom roughness is almost same as that on the northern coast. Whereas, the root mean square error of phases of M2, S2, K1 and O1 on the southern coast of Java Sea were significantly different than that observed on the northern coast. The differences in root mean error of phases could be attributed to the variation of bathymetry between the northern and southern coasts of Java Sea. Other explanation could be that the model grid resolution could not resolve the steep bathymetry variation on the southern part of Java Sea. The root mean square error of amplitudes and phases of M2, S2, K1 and O1 for various Manning bottom roughness coefficients and with wind are presented in the Table 5. The model results show that very marginal differences were observed with amplitudes and phases of tidal constituents due to wind. This is imperative to indicate minimum effect of spatially varying wind on the overall tidal propagation in the Java Sea.

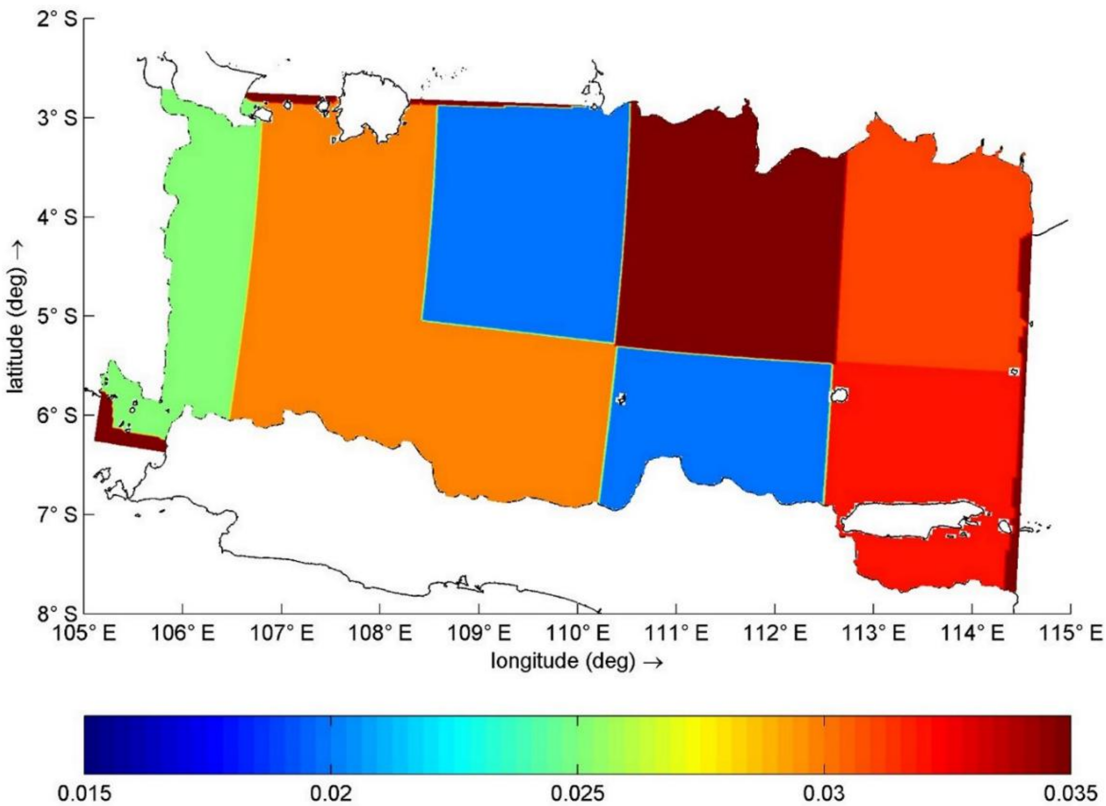

Fig. 5 Map shows the optimized varying Manning bottom roughness coefficient map applied over the entire model domain. Bottom roughness map is based on sensitivity analysis with individual Manning roughness coefficients

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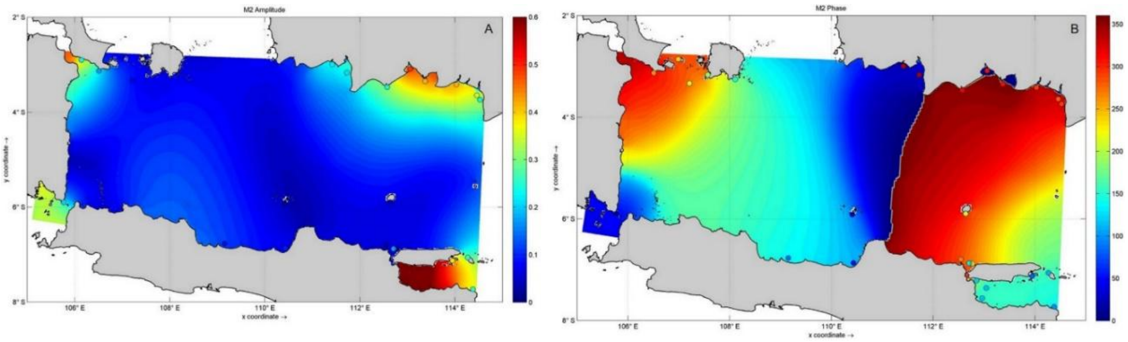

Fig. 6 Co-tidal map of Amplitude (a) and Phase (b) for M2 tidal harmonic constituent

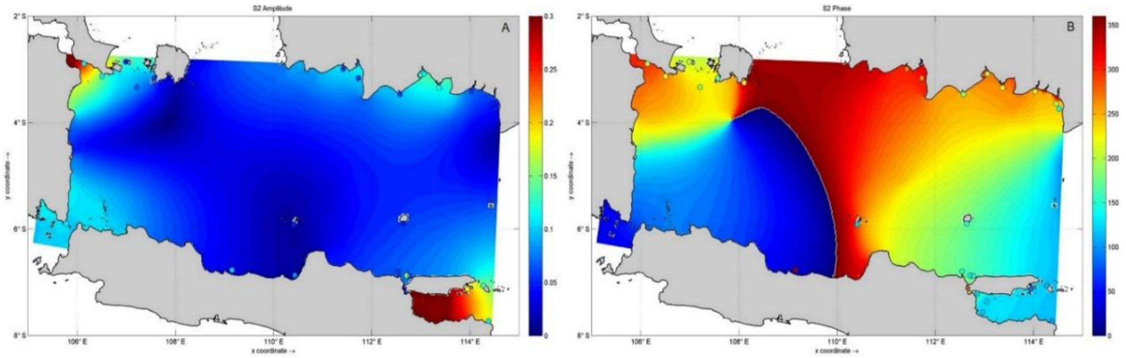

Fig. 7 Co-tidal map of Amplitude (a) and Phase (b) for S2 tidal harmonic constituent

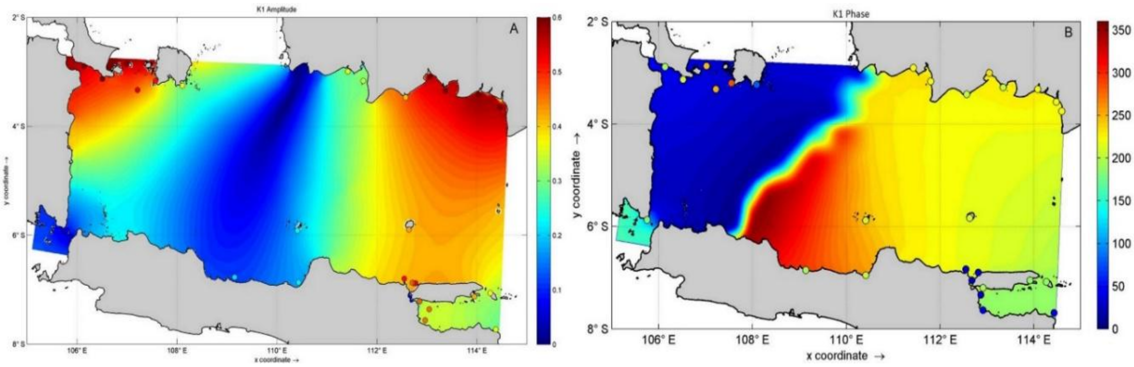

Fig. 8 Co-tidal map of Amplitude (a) and Phase (b) for K1 tidal harmonic constituent

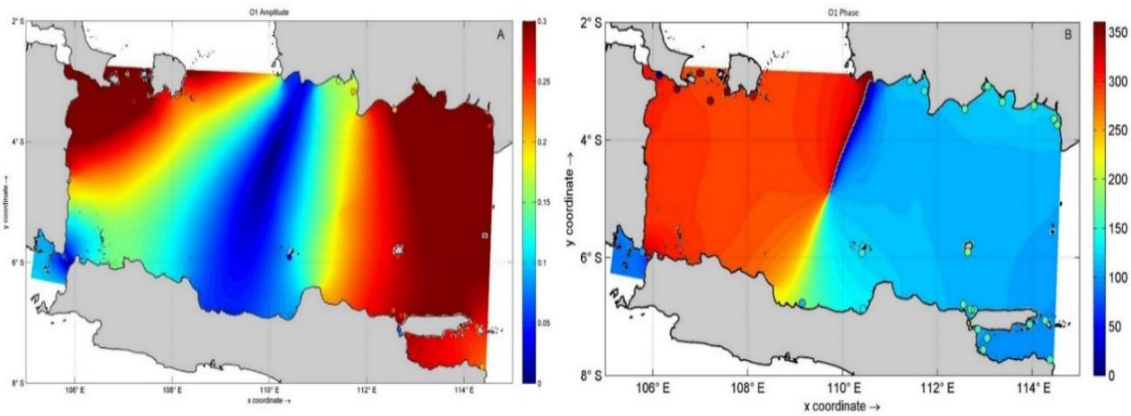

Fig. 9 Co-tidal map of Amplitude (a) and Phase (b) for O1 tidal harmonic constituent

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TABLE 1 COMPARISON OF AMPLITUDE AND PHASES FOR "M2" TIDAL CONSTITUENT BETWEEN ATT (ADMIRALTY TIDE TABLE) AND MODEL PREDICTED RESULTS FOR DIFFERENT SCENARIOS (1) MANNING 0.02, (2) MANNING 0.025, (3) MANNING 0.03, (4) VARYING MANNING COEFFICIENTS AND (5) VARYING MANNING COEFFICIENTS INCLUDING WIND)

Station Name	**Latitude**	**Longitude**	**M2 Tidal Constituent**											
			ATT		Manning 0.02		Manning 0.025		Manning 0.030		Varying Manning		Varying Manning+Wind	
			Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Kuala Sapu	-2.9000	111.4330	0.22	335.11	0.26	327.48	0.24	332.53	0.23	335.89	0.22	335.15	0.22	334.89
Sungai Aru Tobal	-3.1670	111.8000	0.21	342.11	0.28	328.47	0.26	334.34	0.24	338.47	0.24	338.45	0.23	338.19
Kuala Pembuang	-3.4170	112.5670	0.24	314.11	0.43	293.17	0.36	296.28	0.31	299.00	0.32	301.33	0.30	300.58
Teluk Smpit	-3.0000	113.0500	0.49	306.11	0.70	299.82	0.58	304.86	0.49	309.80	0.49	313.15	0.47	312.46
Pegatan	-3.2830	113.3500	0.42	304.11	0.62	295.81	0.52	299.99	0.44	304.19	0.44	307.38	0.42	306.87
Tanjung Damaran	-3.3170	114.0830	0.42	289.13	0.56	283.27	0.48	285.15	0.43	287.63	0.42	290.34	0.41	289.38
Sungai Barito	-3.5670	114.4830	0.34	280.13	0.46	275.20	0.40	275.23	0.36	275.87	0.35	277.92	0.34	277.07
Sungai Tabanio	-3.7500	114.6000	0.23	289.13	0.44	274.39	0.38	274.21	0.34	274.66	0.34	276.64	0.33	275.79
Pulau Besar	-7.6830	114.4330	0.23	315.11	0.63	292.73	0.44	290.75	0.32	288.71	0.39	281.51	0.39	277.77
Dapur	-7.6330	112.9170	0.17	261.11	0.37	272.87	0.26	265.95	0.20	258.76	0.24	257.87	0.23	254.60
Celaka	-7.3330	112.8670	0.07	239.11	0.09	231.19	0.09	226.73	0.09	223.66	0.09	224.82	0.09	222.80
Simedang	-6.8330	112.5500	0.08	212.11	0.12	236.21	0.11	225.31	0.10	216.86	0.10	219.62	0.10	217.80
Seliu	-6.9000	112.8170	0.09	186.11	0.10	230.30	0.09	220.87	0.09	214.21	0.09	216.72	0.09	214.93
Tanjung Batunitam	-7.0500	112.6830	0.09	143.11	0.08	137.60	0.08	139.34	0.08	139.96	0.08	139.27	0.08	138.46
Gosong Karangmas	-7.2000	112.9170	0.25	98.11	0.39	89.86	0.39	89.90	0.39	89.94	0.39	89.95	0.39	89.94
Pasuruan	-7.0500	113.9170	0.60	115.11	0.72	101.09	0.72	102.27	0.71	103.51	0.71	103.94	0.71	103.95
Karang Kleta	-7.0830	114.2670	0.59	116.11	0.71	101.46	0.71	102.59	0.70	103.80	0.70	104.21	0.70	104.22
Ujung Pangkah	-5.8330	112.6330	0.03	268.11	0.06	257.85	0.05	243.61	0.05	232.43	0.05	233.73	0.05	231.06
Tanjung Modung	-5.8830	110.4170	0.02	239.11	0.05	241.18	0.05	224.83	0.05	214.07	0.05	216.39	0.06	213.47
Sembilagan	-6.9500	110.4170	0.18	131.11	0.05	245.57	0.05	229.65	0.05	218.69	0.05	220.85	0.05	217.92
Gading	-6.8500	109.1330	0.59	119.11	0.76	120.22	0.72	126.74	0.68	133.33	0.66	136.22	0.66	136.08
Kalianget	-5.8670	105.7500	0.39	82.11	0.47	100.94	0.47	101.48	0.47	102.06	0.47	102.25	0.47	102.24
Sapudi	-2.8830	106.1330	0.26	109.11	0.32	105.89	0.32	105.94	0.32	106.01	0.32	106.07	0.32	106.01
Sangkapura Bay	-3.1330	106.5170	0.04	207.11	0.06	268.35	0.05	257.80	0.05	247.61	0.05	248.44	0.05	245.58
Marimun Jawa Road	-2.8670	107.0170	0.02	26.11	0.11	76.10	0.07	69.83	0.05	61.12	0.05	60.88	0.04	48.48
Semerang	-3.3170	107.2170	0.10	55.11	0.16	80.83	0.11	77.15	0.08	72.40	0.08	71.37	0.07	61.78
Tegal	-3.2000	107.5500	0.09	88.11	0.23	95.18	0.16	94.48	0.12	93.64	0.12	92.81	0.11	87.07
Bakauhuni	-3.2330	108.0830	0.20	19.11	0.26	359.63	0.27	0.58	0.28	1.56	0.28	1.95	0.29	2.94

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TABLE 2 COMPARISON OF AMPLITUDE AND PHASES FOR "S2" TIDAL CONSTITUENT BETWEEN ATT (ADMIRALTY TIDE TABLE) AND MODEL PREDICTED RESULTS FOR DIFFERENT SCENARIOS (1) MANNING 0.02, (2) MANNING 0.025, (3) MANNING 0.03, (4) VARYING MANNING COEFFICIENTS AND (5) VARYING MANNING COEFFICIENTS INCLUDING WIND

Station Name	Latitude	Longitude	S2 Tidal Constituent											
			ATT		Manning 0.02		Manning 0.025		Manning 0.030		Varying Manning		Varying Manning+Wind	
			Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Kuala Sapu	-2.9000	111.4330	-2.9000	111.4330	0.06	266.00	0.11	297.70	0.11	303.95	0.10	309.68	0.09	314.31
Sungai Aru Tobal	-3.1670	111.8000	-3.1670	111.8000	0.06	263.00	0.12	300.15	0.11	307.20	0.10	313.75	0.09	319.73
Kuala Pembuang	-3.4170	112.5670	-3.4170	112.5670	0.06	188.00	0.11	264.52	0.09	261.94	0.08	260.37	0.08	275.66
Teluk Smpit	-3.0000	113.0500	-3.0000	113.0500	0.11	203.00	0.16	279.08	0.13	279.39	0.11	280.93	0.11	298.66
Pegatan	-3.2830	113.3500	-3.2830	113.3500	0.12	216.00	0.14	276.12	0.11	275.44	0.09	276.13	0.10	294.01
Tanjung Damaran	-3.3170	114.0830	-3.3170	114.0830	0.06	209.00	0.09	283.74	0.07	283.10	0.06	285.35	0.07	303.72
Sungai Barito	-3.5670	114.4830	-3.5670	114.4830	0.05	201.00	0.06	285.52	0.05	284.19	0.04	285.51	0.05	301.69
Sungai Tabanio	-3.7500	114.6000	-3.7500	114.6000	0.05	146.00	0.06	286.04	0.04	284.57	0.03	285.72	0.05	301.63
Pulau Besar	-7.6830	114.4330	-7.6830	114.4330	0.11	199.00	0.31	297.10	0.25	301.36	0.21	306.80	0.24	304.54
Dapur	-7.6330	112.9170	-7.6330	112.9170	0.11	228.00	0.18	271.48	0.15	271.27	0.13	272.01	0.14	276.29
Celaka	-7.3330	112.8670	-7.3330	112.8670	0.05	197.00	0.12	205.23	0.12	204.27	0.12	203.53	0.12	207.74
Simedang	-6.8330	112.5500	-6.8330	112.5500	0.07	187.00	0.09	230.65	0.08	227.97	0.08	226.20	0.08	232.04
Seliu	-6.9000	112.8170	-6.9000	112.8170	0.06	171.00	0.09	226.11	0.09	224.29	0.09	223.24	0.08	228.48
Tanjung Batunitam	-7.0500	112.6830	-7.0500	112.6830	0.01	226.00	0.01	291.61	0.01	293.00	0.01	294.48	0.02	292.20
Gosong Karangmas	-7.2000	112.9170	-7.2000	112.9170	0.11	106.00	0.20	120.23	0.20	120.29	0.20	120.35	0.19	122.27
Pasuruan	-7.0500	113.9170	-7.0500	113.9170	0.30	117.00	0.39	128.01	0.38	129.48	0.38	131.03	0.37	134.08
Karang Kleta	-7.0830	114.2670	-7.0830	114.2670	0.29	120.00	0.38	128.37	0.38	129.80	0.37	131.30	0.36	134.31
Ujung Pangkah	-5.8330	112.6330	-5.8330	112.6330	0.06	147.00	0.05	172.53	0.06	169.43	0.06	167.81	0.05	171.57
Tanjung Modung	-5.8830	110.4170	-5.8830	110.4170	0.06	150.00	0.06	165.99	0.06	163.20	0.06	161.77	0.06	165.72
Sembilagan	-6.9500	110.4170	-6.9500	110.4170	0.16	139.00	0.06	167.69	0.06	164.83	0.06	163.38	0.06	167.34
Gading	-6.8500	109.1330	-6.8500	109.1330	0.30	120.00	0.40	150.98	0.38	158.93	0.35	166.86	0.33	173.03
Kalianget	-5.8670	105.7500	-5.8670	105.7500	0.19	88.00	0.24	126.43	0.24	127.14	0.24	127.91	0.23	130.49
Sapudi	-2.8830	106.1330	-2.8830	106.1330	0.13	107.00	0.16	125.00	0.16	125.05	0.16	125.12	0.16	127.72
Sangkapura Bay	-3.1330	106.5170	-3.1330	106.5170	0.05	151.00	0.04	177.10	0.05	172.57	0.05	170.14	0.04	174.34
Marimun Jawa Road	-2.8670	107.0170	-2.8670	107.0170	0.05	123.00	0.01	64.43	0.00	334.28	0.01	289.29	0.00	197.56
Semerang	-3.3170	107.2170	-3.3170	107.2170	0.08	307.00	0.02	62.16	0.01	32.31	0.01	341.51	0.01	110.77
Tegal	-3.2000	107.5500	-3.2000	107.5500	0.10	345.00	0.05	66.68	0.03	52.82	0.02	35.40	0.02	76.84
Bakauhuni	-3.2330	108.0830	-3.2330	108.0830	0.11	64.00	0.12	64.78	0.13	64.62	0.13	64.58	0.12	61.92

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TABLE 3 AMPLITUDE AND PHASES FOR "K1" TIDAL CONSTITUENT BETWEEN ATT (ADMIRALTY TIDE TABLE) AND MODEL PREDICTED RESULTS FOR DIFFERENT SCENARIOS (1) MANNING 0.02, (2) MANNING 0.025, (3) MANNING 0.03, (4) VARYING MANNING COEFFICIENTS AND (5) VARYING MANNING COEFFICIENTS INCLUDING WIND

Station Name	**Latitude**	**Longitude**	**K1 Tidal Constituent**											
			ATT		Manning 0.02		Manning 0.025		Manning 0.030		Varying Manning		Varying Manning+Wind	
			Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Kuala Sapu	-2.9000	111.4330	0.36	219.71	0.34	228.57	0.34	230.82	0.33	234.72	0.34	226.75	0.34	228.81
Sungai Aru Tobal	-3.1670	111.8000	0.33	222.71	0.36	228.41	0.36	230.91	0.35	235.06	0.36	227.88	0.36	229.88
Kuala Pembuang	-3.4170	112.5670	0.41	204.71	0.56	219.30	0.55	220.89	0.54	223.44	0.56	221.13	0.55	222.19
Teluk Smpit	-3.0000	113.0500	0.60	230.71	0.67	223.36	0.66	226.05	0.64	229.57	0.66	228.59	0.64	229.83
Pegatan	-3.2830	113.3500	0.62	207.71	0.65	221.44	0.64	223.69	0.63	226.77	0.64	225.68	0.63	226.89
Tanjung Damaran	-3.3170	114.0830	0.67	219.67	0.70	221.32	0.69	223.74	0.68	226.61	0.68	226.87	0.67	228.53
Sungai Barito	-3.5670	114.4830	0.64	219.67	0.67	218.82	0.67	220.40	0.66	222.34	0.66	222.61	0.65	223.95
Sungai Tabanio	-3.7500	114.6000	0.55	221.67	0.67	218.66	0.66	220.15	0.66	221.99	0.65	222.23	0.65	223.51
Pulau Besar	-7.6830	114.4330	0.73	47.71	0.69	40.62	0.68	47.31	0.66	53.77	0.63	49.08	0.62	47.48
Dapur	-7.6330	112.9170	0.61	42.71	0.63	32.81	0.62	38.16	0.61	43.30	0.58	40.70	0.57	39.89
Celaka	-7.3330	112.8670	0.67	36.71	0.64	32.40	0.64	33.32	0.64	34.09	0.65	33.77	0.65	34.09
Simedang	-6.8330	112.5500	0.53	38.71	0.55	29.35	0.55	32.73	0.55	35.78	0.52	35.16	0.51	35.05
Seliu	-6.9000	112.8170	0.51	36.71	0.56	31.07	0.56	33.85	0.56	36.39	0.54	36.03	0.53	36.01
Tanjung Batunitam	-7.0500	112.6830	0.38	31.71	0.37	22.56	0.37	25.78	0.36	28.52	0.34	28.30	0.33	26.61
Gosong Karangmas	-7.2000	112.9170	0.37	191.71	0.33	185.41	0.33	185.39	0.33	185.38	0.32	185.59	0.32	185.62
Pasuruan	-7.0500	113.9170	0.45	190.71	0.41	187.77	0.41	188.02	0.41	188.34	0.39	188.97	0.38	189.17
Karang Kleta	-7.0830	114.2670	0.45	190.71	0.41	188.01	0.41	188.25	0.41	188.54	0.39	189.10	0.38	189.11
Ujung Pangkah	-5.8330	112.6330	0.51	212.71	0.50	216.77	0.49	217.32	0.48	218.62	0.48	215.80	0.48	216.86
Tanjung Modung	-5.8830	110.4170	0.52	212.71	0.50	214.96	0.50	215.49	0.49	216.71	0.49	214.30	0.48	215.38
Sembilagan	-6.9500	110.4170	0.46	205.71	0.50	215.42	0.50	215.96	0.49	217.21	0.49	214.72	0.48	215.82
Gading	-6.8500	109.1330	0.46	194.71	0.39	198.86	0.38	202.35	0.37	205.95	0.34	208.13	0.34	207.54
Kalianget	-5.8670	105.7500	0.42	178.71	0.38	188.18	0.38	188.18	0.38	188.21	0.36	188.39	0.36	188.35
Sapudi	-2.8830	106.1330	0.37	191.71	0.39	192.86	0.39	192.84	0.39	192.87	0.37	192.99	0.37	193.01
Sangkapura Bay	-3.1330	106.5170	0.43	212.71	0.48	216.28	0.47	216.80	0.47	218.10	0.47	214.83	0.47	215.81
Marimun Jawa Road	-2.8670	107.0170	0.23	245.71	0.23	247.76	0.22	247.59	0.21	249.66	0.22	237.82	0.21	239.10
Semerang	-3.3170	107.2170	0.22	247.71	0.24	258.75	0.22	259.14	0.21	261.68	0.21	249.88	0.20	252.90
Tegal	-3.2000	107.5500	0.21	284.71	0.19	292.04	0.17	295.08	0.16	299.78	0.14	282.88	0.14	287.48
Bakauhuni	-3.2330	108.0830	0.08	83.71	0.03	92.65	0.04	99.24	0.05	104.85	0.05	101.68	0.03	110.16

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TABLE 4 AMPLITUDE AND PHASES FOR "O1" TIDAL CONSTITUENT BETWEEN ATT (ADMIRALTY TIDE TABLE) AND MODEL PREDICTED RESULTS FOR DIFFERENT SCENARIOS (1) MANNING 0.02, (2) MANNING 0.025, (3) MANNING 0.03, (4) VARYING MANNING COEFFICIENTS AND (5) VARYING MANNING COEFFICIENTS INCLUDING WIND

Station Name	Latitude	Longitude	O1 Tidal Constituent											
			ATT		Manning 0.02		Manning 0.025		Manning 0.030		Varying Manning		Varying Manning+Wind	
			Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Kuala Sapu	-2.9000	111.4330	0.16	131.40	0.16	155.62	0.15	163.61	0.14	173.39	0.15	167.03	0.14	171.64
Sungai Aru Tobal	-3.1670	111.8000	0.21	151.40	0.18	156.82	0.16	164.66	0.14	174.30	0.16	169.01	0.15	173.68
Kuala Pembuang	-3.4170	112.5670	0.21	163.40	0.29	161.97	0.27	166.03	0.26	170.90	0.27	169.78	0.26	172.23
Teluk Smpit	-3.0000	113.0500	0.31	166.40	0.35	167.82	0.33	172.42	0.32	177.76	0.33	177.13	0.32	179.32
Pegatan	-3.2830	113.3500	0.34	168.40	0.34	166.51	0.33	170.42	0.31	175.08	0.33	174.43	0.32	176.68
Tanjung Damaran	-3.3170	114.0830	0.37	170.46	0.37	170.06	0.36	173.39	0.36	176.94	0.36	176.75	0.36	178.76
Sungai Barito	-3.5670	114.4830	0.33	169.46	0.36	168.30	0.36	170.53	0.35	172.97	0.35	172.80	0.35	174.48
Sungai Tabanio	-3.7500	114.6000	0.26	172.46	0.36	168.17	0.35	170.29	0.35	172.62	0.35	172.46	0.35	174.13
Pulau Besar	-7.6830	114.4330	0.42	1.40	0.35	1.95	0.38	5.76	0.39	9.74	0.37	3.62	0.37	2.31
Dapur	-7.6330	112.9170	0.32	357.40	0.32	353.58	0.33	356.44	0.34	359.36	0.33	355.29	0.33	354.00
Celaka	-7.3330	112.8670	0.38	341.40	0.38	341.69	0.38	342.08	0.38	342.45	0.38	341.98	0.39	342.09
Simedang	-6.8330	112.5500	0.28	352.40	0.30	347.53	0.31	348.99	0.31	350.34	0.30	348.40	0.31	347.20
Seliu	-6.9000	112.8170	0.34	354.40	0.31	347.86	0.32	348.85	0.32	349.87	0.31	348.27	0.32	347.18
Tanjung Batunitam	-7.0500	112.6830	0.23	330.40	0.20	349.60	0.21	349.72	0.21	349.88	0.20	347.86	0.21	345.00
Gosong Karangmas	-7.2000	112.9170	0.21	157.40	0.21	160.36	0.21	160.37	0.21	160.38	0.21	160.37	0.21	160.37
Pasuruan	-7.0500	113.9170	0.26	163.40	0.25	160.77	0.25	161.13	0.25	161.52	0.25	161.68	0.25	161.77
Karang Kleta	-7.0830	114.2670	0.27	162.40	0.25	161.01	0.25	161.36	0.25	161.73	0.25	161.89	0.25	161.99
Ujung Pangkah	-5.8330	112.6330	0.24	166.40	0.26	163.36	0.25	166.56	0.25	169.96	0.25	167.42	0.25	170.19
Tanjung Modung	-5.8830	110.4170	0.24	149.40	0.27	162.93	0.26	165.83	0.25	168.90	0.26	166.69	0.26	169.22
Sembilagan	-6.9500	110.4170	0.25	164.40	0.26	163.05	0.26	166.03	0.25	169.19	0.26	166.90	0.25	169.49
Gading	-6.8500	109.1330	0.26	156.40	0.27	173.31	0.27	177.43	0.27	181.55	0.26	183.21	0.26	183.11
Kalianget	-5.8670	105.7500	0.24	152.40	0.23	160.69	0.23	160.89	0.23	161.10	0.23	161.16	0.23	161.26
Sapudi	-2.8830	106.1330	0.23	161.40	0.24	161.75	0.24	161.94	0.24	162.08	0.24	162.04	0.24	162.09
Sangkapura Bay	-3.1330	106.5170	0.25	187.40	0.26	162.04	0.25	165.03	0.24	168.36	0.25	166.06	0.24	168.64
Marimun Jawa Road	-2.8670	107.0170	0.04	151.40	0.10	159.10	0.08	168.11	0.07	180.45	0.08	173.08	0.08	186.01
Semerang	-3.3170	107.2170	0.08	134.40	0.08	165.30	0.07	178.39	0.06	195.04	0.07	184.46	0.07	200.83
Tegal	-3.2000	107.5500	0.05	116.40	0.02	164.16	0.01	249.67	0.03	282.39	0.02	238.45	0.04	260.16
Bakauhuni	-3.2330	108.0830	0.07	103.40	0.02	167.24	0.02	176.54	0.02	176.37	0.02	178.90	0.03	204.93

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TABLE 5 COMPUTED ROOT MEAN SQUARE ERROR (RMSE) OF AMPLITUDE AND PHASES OF TIDAL CONSTITUENT M2, S2, K1 AND O1 FOR DIFFERENT SCENARIOS (1) MANNING 0.02, (2) MANNING 0.025, (3) MANNING 0.03, (4) VARYING MANNING COEFFICIENTS AND (5) VARYING MANNING COEFFICIENTS INCLUDING WIND

Root Mean Square Error (RMSE) - Northern part of Java Sea										
Tidal Constituents	Manning 0.02		Manning 0.025		Manning 0.030		Varying Manning		Varying Manning+Wind	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
M2	0.11	17.38	0.06	13.86	0.04	12.18	0.05	13.78	0.05	14.16
S2	0.05	31.16	0.04	20.64	0.03	31.07	0.04	34.07	0.04	32.2
K1	0.05	8.19	0.05	7.6	0.05	7.77	0.06	6.74	0.06	7.42
O1	0.04	8.63	0.04	9.77	0.04	11.76	0.04	10.55	0.04	11.95
Root Mean Square Error (RMSE) - Southern part of Java Sea										
Tidal Constituents	Manning 0.02		Manning 0.025		Manning 0.030		Varying Manning		Varying Manning+Wind	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
M2	0.07	36.02	0.07	32.78	0.06	30.73	0.06	30.87	0.06	29.84
S2	0.06	98.91	0.06	122.39	0.06	96.35	0.06	93.6	0.06	90.34
K1	0.03	5.08	0.03	6.03	0.03	7.37	0.04	7.01	0.04	8.18
O1	0.03	22.02	0.02	38.27	0.02	45.51	0.02	36.32	0.02	44.01

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The final calibrated model was also validated with hourly gauge water level data downloaded at three locations Surabaya, Pari and Jakarta from the University of Hawaii Sea Level Centre (UHSLC). However, validation of the model through comparison of predicted and observed data will provide a benchmark and qualitative approach in the assessment of tidal propagation through mathematical models [15]. A spring–neap tidal cycle of predicted and computed water levels at Surabaya, Pari and Jakarta (locations denoted in Fig. 3) were compared. The tidal range at Surabaya is approximately 1.2 m during neap tide and increases up to 3.2 m during spring tide (Fig. 10). Whereas the tidal ranges at Jakarta and Pari is approximately 0.6 m during neap tide and increases up to 0.9 m during spring tide (Figs. 11 and 12). The water surface fluctuations obtained from the Java Sea model were in good agreement with the predicted tide though some minor discrepancies exist such as the observed low waters were slightly lower than the predicted low waters, and there was a minor phase shift.

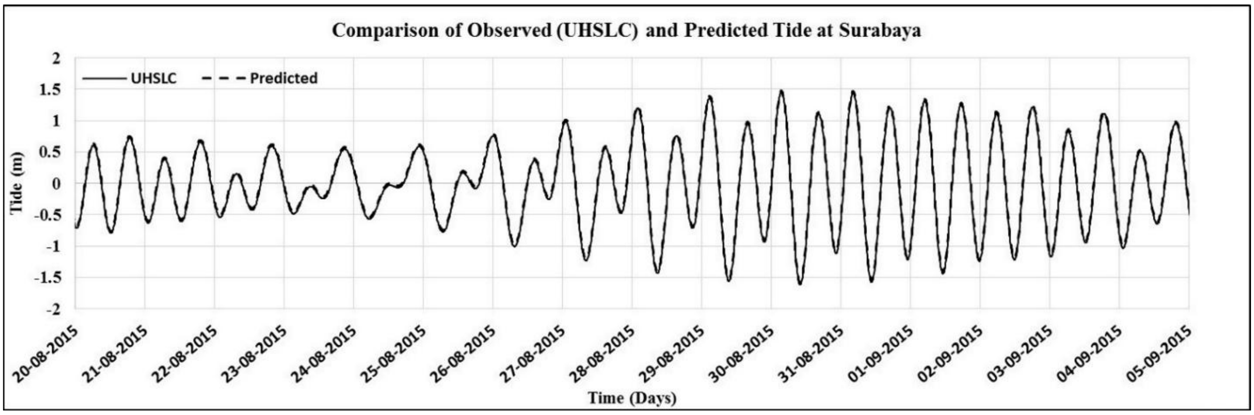

Fig. 10 Comparison of simulated and predicted tide from Aug. 20 – Sep. 5, 2015 at Surabaya. Predicted tide based on UHSLC observations

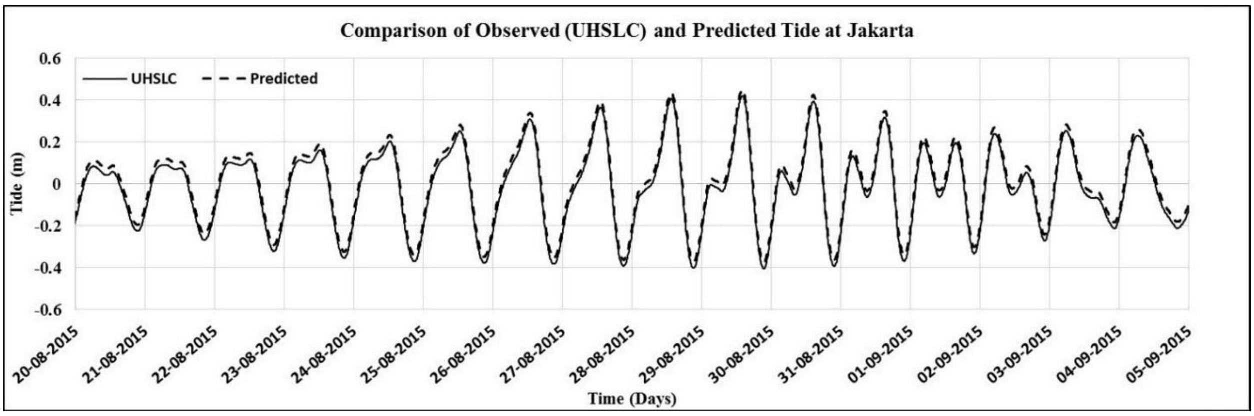

Fig. 11 Comparison of simulated and predicted tide from Aug. 20 – Sep. 5, 2015 at Jakarta. Predicted tide based on UHSLC observations

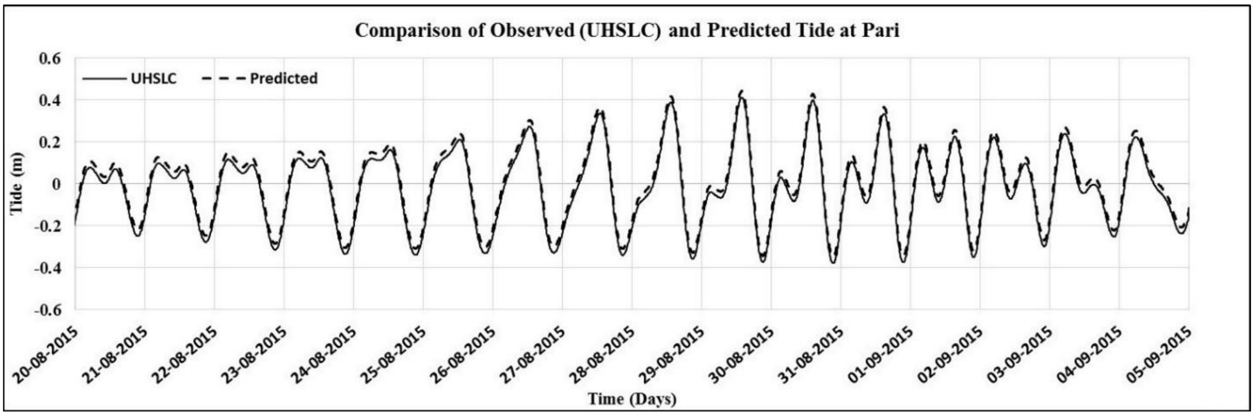

Fig. 12 Comparison of simulated and predicted tide from Aug. 20 – Sep. 5, 2015 at Pari. Predicted tide based on UHSLC observations

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IV. CONCLUSION

Java sea regional model was developed to assess the effect of bottom roughness and influence of atmospheric forcing on the tidal propagation in this shallow water basin. Model simulations were conducted by varying the Chezy and Manning bottom roughness coefficients in combination with spatially varying wind field. The study indicates that the assessment of tidal propagation of such shallow water bodies could be enhanced through detailed sensitivity analysis. In addition to validate the calibrated model performance it was compared with the UHSLC research quality observations at three coastal stations viz. Surabaya, Jakarta and Pari. Our results indicate the study to be in good agreement with predicted tide based on the UHSLC observations. In summary, the study concluded that model simulated overall tidal propagation in Java Sea signified the importance of bottom roughness in the shallow water basin. It can also be observed that the influence of spatially varying wind has minimum effect on overall tidal propagation of Java Sea. However, this conclusion does not mean that the model chosen in the current study is free from biases or other technical limitations. Hence, the robustness of the study can further improve the model performance with detailed bathymetry of the nearshore region and sensitivity of other physical parameters. Notably, the discrepancy between the modelled and observed data could mainly be due to relatively shallow bathymetry of the Java Sea compared to the adjacent seas.

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REFERENCES

[1] Alan, F. Koropitan and Motoyoshi Ikeda., "Three-dimensional modeling of tidal circulation and mixing over the Java Sea," *J. Ocean*, vol. 64, pp. 61-80, 2008.

[2] D. Pauly, P. Martosubroto and J. Saeger, "The mutiara 4 surveys in the Java and Southern South China Sea", November 1974 to July 1976. pp. 47-54. In: D. Pauly and P. Martosubroto (eds.) *Baseline Studies in Biodiversity: The fish Resources of Western Indonesia*. ICLARM Studies and Reviews 23, 1996.

[3] K. Wyrtki, *Physical Oceanography of the Southeast Asian Waters*. NAGA Rep. 2, Scripps Inst. of Oceanogr. Univ. of Calif., La Jolla, California, p. 195, 1961.

[4] P. Mazzega, and M. Bergé, "Ocean tides in the Asian semienclosed seas from TOPEX/POSEIDON," *J. Geoph. Res.*, 99(24), pp. 867-24,881, 1994.

[5] T. Hatayama, T. Awaji, and K. Akitomo, "Tidal currents in the Indonesian Seas and their effect on transport and mixing," *J. Geophys. Res.*, 101(12), pp. 353, 12-373, 1996.

[6] J. H. Simpson, C. M. Allen, and N. C. G. Morris, "Fronts on the continental shelf," *J. Geophys. Res.*, vol. 83, pp. 4607-4614, 1978.

[7] R. D. Ray, G. D. Egbert, and S. Y. Erofeeva, "A brief overview of tides in the Indonesian Seas," *Oceanography*, 18(4), pp. 74-79, 2005.

[8] G. D. Egbert and S. Y. Erofeeva., "Efficient inverse modeling of Barotropic Ocean tides," *J. Atmos. Oceanic Technol.*, vol. 19, pp. 183-204, 2002.

[9] M. Yusuf and T. Yanagi, "Numerical modeling of tidal dynamics in the Java Sea," *J. Coast. Mar. Scie.*, 36(1), pp. 1-12., 2013.

[10] A. Kurniawan, S. K. Ooi, S. Hummel, and H. Gerritsen, 2011. "Sensitivity analysis of the tidal representation in Singapore regional waters in a data assimilation environment," *Ocean Dynamics*, 61(8), pp.1121-1136, 2011.

[11] H. Sibtey, "Changes in Flow Hydro-Dynamics during Moderate, Typical and Extreme Historical Discharge Events at the Gautami Godavari River Entrance, India-A Case Study," *Jr. of Wat. Res. and Hydr. Eng.*, 5(4), pp. 160-171, 2016.

[12] M. Su, M. J. F. Stive, C. K. Zhang, P. Yao, Y. P. Chen, and Z. B. Wang, "The Tidal Wave System in the Chinese Marginal Seas," *Coastal Dyn.*, vol. 160, pp.1559-1570, 2013.

[13] Kantha, L. H. and C. A. Clayson., *Numerical Models of Oceans and Oceanic Processes. International Geophysics Series.* Academic Press, San Diego, vol. 66, p. 940, 2000.

[14] C. K. Shum., P. L. Woodworth, O. B. Anderson, G. D. Egbert, O. Francis, C. King, S. M. Klosko, C. Le. Provost, X. Li, J-M Molines, M. E. Parke, R. D. Ray, M. G. Sehlax, D. Stammer, C. C. Tiemey, P. Vincent, and C. I. Wunsch, "Accuracy assessment of recent ocean tide models," *Jour. of Geo. Res.*, C11(102), pp. 25, 173-25, 194, 1997.

[15] C. Le Provost, A. F. Bennett., and D. E. Cartwright., "Ocean tides for and from TOPEX/POSEIDON," *Science*, vol. 267, pp. 639-642, 1995.

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