Preliminary Estimation of Tidal Current Energy for Three Straits in the Vicinity of Bali and Lombok Islands

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Abstract – Indonesia is an archipelago country which has a great potential of ocean energy resources including tidal current and wave power. In this present work, tidal power in three different straits, namely Alas Strait, Bali Strait and Lombok Strait will be estimated. In order to achieve our goal, a two-dimensional, depth-integrated Advanced Circulation (ADCIRC-2DDI) model is employed. Eight tidal constituents were imposed along the ocean open boundaries. Two different sources of tidal constituents namely Le Provost and OTIS (OSU Tidal Inversion Software) were used. Tidal elevations have been validated and calibrated against tide gauge data in which at least six tide gauges are available in the study location. We found that, tidal constituents from high resolution database that is OTIS give better results. Open boundary conditions have been improved using Green's function approach. As a result, a significant reduction of the root-mean-square error (RMSE) has been obtained. This indicates that the method is powerful. Furthermore, tidal current energy was estimated. Since there is no tidal current observation available in the area, tidal velocities were compared with the tidal current obtained from finite element solutions 2014 (FES2014). We found that the tidal current obtained from the ADCIRC model has a very good agreement with FES2014. Moreover, tidal current speed in the vicinity of Bali and Lombok islands could reach up to 3.8 m/s. As a consequence, tidal current power in those locations could exceed 10.98 kW/m^2 with assuming that turbine efficiency is about 0.39.

Keywords: Tidal elevation, tidal current, Green function, Bali Strait.

1. Introduction

Energy supply is now becoming a crucial part of the human life. The increasing demand of energy can be due to some reasons such as the increasing human population and advanced technology [1]. As reported by Asif and Muneer [1], about 80% of the global energy demand is supplied by oil, gas and coal. Since these fossil fuels may have serious side effects on the environment and human health, other sources of energy are being sought. A solution might come from renewable energy resources such as solar, biofuel, geothermal, wind as well as ocean renewable energies which include ocean thermal, wave and tidal current and wave energy [2-7].

Indonesia is an archipelago country in which about 64.97% of the country is covered by ocean [8]. This means that Indonesia has a great potential of ocean renewable energies such as ocean thermal, waves, current and tides. As reported in *http://there4i.org/* (accessed on 04 December 2018) the theoretical resources of ocean thermal, ocean and tidal currents, and ocean waves are about 4,247 GW, 288 GW and 141 GW, respectively. However, the practical resources are only about 41 GW, 18 GW and 2 GW, respectively for above-mentioned ocean renewable energy. Based on these figures, we can argue that ocean renewable energy in Indonesia is very promising.

There have been some attempts to assess ocean renewable energy around Indonesia such as ocean wave energy [2, 9] and tidal current energy [10-13]. Other studies on Indonesia's tides activity can be found in [14] and [15]. Since Indonesia has many straits which are potentially good for tidal energy, some intensive research have been done around Buton Island in Southeast Sulawesi [10], Sunda, Lanrantuka, dan Bali and Lombok [11-13]. The last two are particularly interesting locations as both islands are very famous for tourism, but their electrification ratio is not yet a 100%. It is only 94.42% in Bali and 79.93% in West Nusa Tenggara (NTB) where Lombok Island is located (*http://there4i.org/,* accessed on 04 December 2018). A preliminary assessment of tidal energy around these locations have been carried out by some researchers using different ocean circulation models such as Estuarine and Coastal Ocean Model (ECOM) [16], finite volume coastal ocean model (FVCOM) [17] and Delft3D Modelling System [11]. Here, tidal current energy assessments will be carried out using another widely used ocean circulation model called Advanced Circulation (ADCIRC) model.

The ADCIRC model, particularly for two-dimensional depth integrated, has been widely used for tidal simulations in the last two decades [10, 18-22]. In order to study tidal elevation and tidal current, the main input of the model at the open boundary condition is the tidal constituents. In this work, two different sources of tidal constituents are used, namely Le Provost [23, 24] and OTIS (OSU (Oregon State University) Tidal Inversion Software) [25].

As known, the open boundary condition plays an important role in tidal simulation [26]. However, even with the high-resolution tidal database, the discrepancy between the model and the observation is still large. Hence, a method to improve the input of the open boundary condition has to be used. In order to address this issue, Green's function approach will be utilized [10, 27-30].

Furthermore, tidal current energy is estimated based on the tidal current velocities obtained from the model in which the open boundary conditions have been optimized. Since tidal current observations at the study area are not available and difficult to obtain, our tidal current velocities are compared with the tidal current velocities obtained from tidal database FES2014 which was developed by the French tidal group (FTG) and based on the finite element solutions. The data have been validated by observations [31].

This paper is organized as follows: a short description of the study location will be presented in Section 2 as well as the model setup. Validation of the tidal elevation data against in-situ measurement data are presented in Section 3. This is followed by Section 4 that will explain a method to resolve the discrepancy between the model and observation. In Section 5, tidal current velocities as well as their comparisons to FES2014 data will be shown and then the estimation of the tidal power is shown in Section 6. Finally, a summary and conclusion as well as future works related to this field of research will be drawn in Section 7.

2. Locations and Methods

2.1 Location of the study

The assessment of tidal current energy is taking place around Bali and Lombok islands. This location contains three different straits, namely Bali Strait, Lombok Strait and Alas Strait. The study area is elongated from 113.974°E to 117.273°E and from 9.606°S to 7.217°S. The total surface area of the location is about 52,707 km^2 and detail location is depicted in Fig. 1.

2.2 Hydrodynamic model

As aforementioned, in order to carry out the assessments of tidal energy around Bali and Lombok islands, a well-known hydrodynamic model called Advanced Circulation (ADCIRC) model will be employed. This is particularly for two-dimensional depth-integrated model (ADCIRC-2DDI). This model has been widely used to study modelling tides and wind driven ocean circulations, prediction of hurricane storm surge and flooding and dredging. The model is based on the generalized wave continuity equation (GWCE) in conjunction with the primitive momentum equation. The advantage of this model is that it is based on a finite element method (FEM) with triangle element mesh and unstructured grids. This enables us to treat model resolution around the coastline particularly for the case of the Indonesian islands. A complete formulation can be found in [32] and the references therein.

2.3 Model setup

In order to run a tidal simulation using ADCIRC model, at least two compulsory data need to be provided, namely coastline and bathymetry data. The bathymetry data used in this work were obtained from the General Bathymetric Chart of the Oceans (GEBCO, *https://www.bodc.ac.uk/data/hosted_data_systems/gebco_gridded_bathymetry_data/*) which is maintained by the British Oceanographic Data Centre. The resolution of this bathymetry is 30 arc-seconds which is about one kilometre measured around equator. This bathymetry has been interpolated across the finite element mesh of the study domain. The coastlines were created using *Surface-water Modeling System* (*SMS*) where the maps have been imported from Google. The bathymetry and mesh are shown in Fig. 2*a* and Fig. 2*b*, respectively. The number of elements and nodes of the mesh are, respectively, 145,949 and 76,381. Moreover, the minimum grid spacing is 167 *m* which is usually around the coastline. Similarly, the maximum grid spacing is 8,284 *m* which is around open ocean. As abovementioned, the area of domain is about 52,707 km^2.

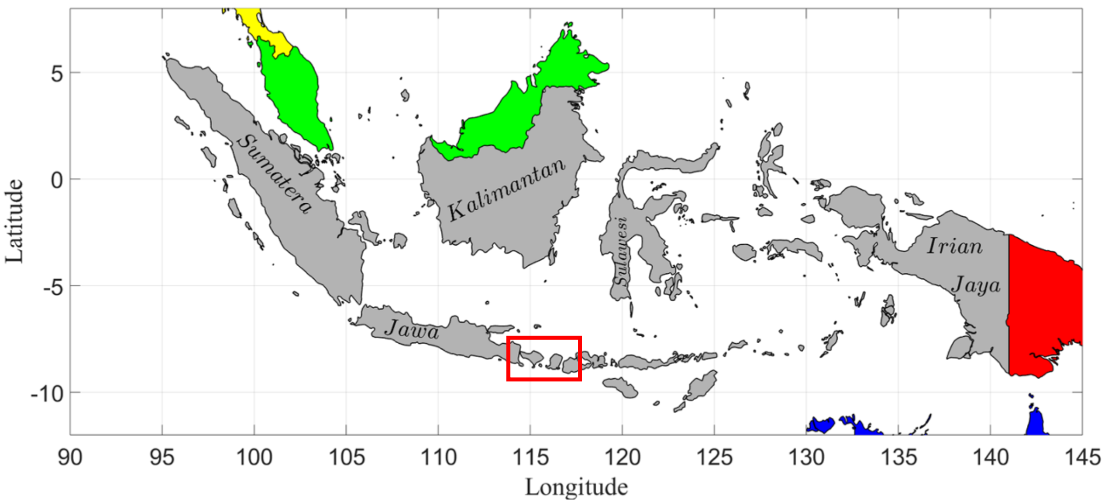
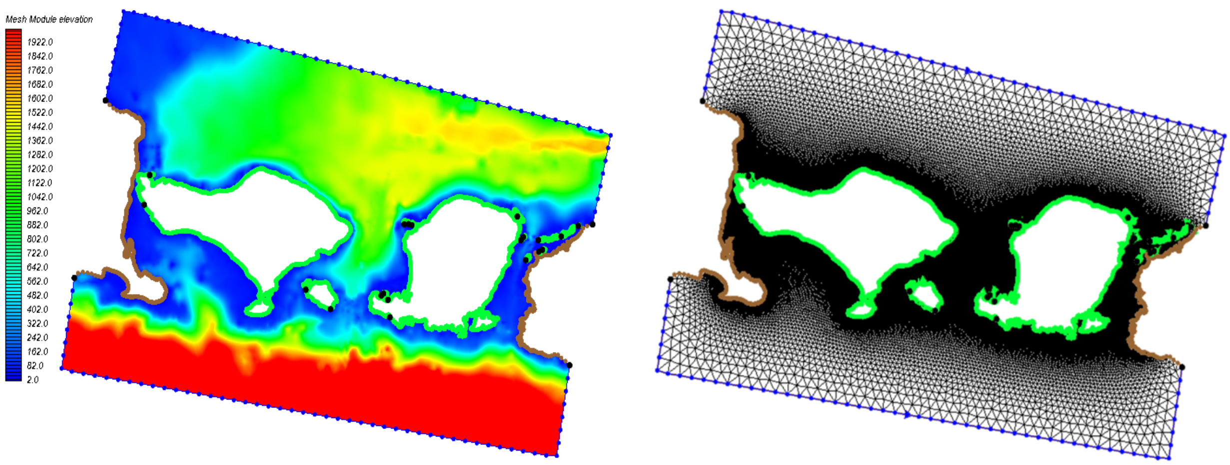


Fig. 1. Location of the study.

Eight major tidal constituents were imposed along open boundary conditions. These are K_1, O_1, P_1, Q_1, and K_2, M_2, N_2, S_2 which are diurnal and semi diurnal tidal constituents, respectively. Diurnal tide occurs about one cycle per day while semi-diurnal tide occurs about two cycles per day. The values of these tidal constituents used were sourced from two different tidal databases, namely, Le Provost which resolution is 1/2° and the Oregon State University (OSU) Tidal Inversion Software (OTIS) which resolution is 1/30°. The length of the simulation is 210 days with a ramp time of 25 days. Hence, the length of the simulations was 185 days which still enables us to use eight tidal constituents (see Emery and Thomson [33] for detail). The time step is very small which is one second. Finally, the simulations were started from 01 February 2016. However, it should be noted that the simulation can be started at any time.

3. Validation of tidal elevations

As aforementioned, two different sources of tidal constituents are imposed on the open boundary conditions. In order to validate the model output, the observation data from six different tide gauges will be used. As a matter of fact, seven tide gauges are available in the study area. However, only six of them can be used as one of them does not have data for a number of months. The locations of tide gauges are presented in Fig. 3 with the longitude and latitude are listed in Table 1. It should be mentioned that the observation data were purchased from the Geospatial Information Agency, which is the national surveying and mapping agency of Indonesia. In order to perform the comparisons between tidal elevation obtained from the model and tidal elevation obtained from tide gauges, a Matlab toolbox which is so-called *T_TIDE* has been used [34].



(a) *(b)*

Fig. 2. Domain of the study location. (a): Bathymetry and (b): Mesh.

Three different statistical parameters were used for the comparisons, namely, root-mean square error (*RMSE*), Pierson's correlation coefficient (ρ) and bias (B). These parameters were determined using the following equations in which M and O stand for model and observation, respectively.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2} \quad (1)$$

$$\rho = \frac{\mathrm{cov}(M,O)}{\sqrt{\mathrm{cov}(M)\,\mathrm{cov}(O)}} \quad (2)$$

$$B = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i) \quad (3)$$

The output model which is based on two different tidal databases were validated separately and the comparisons are summarised in Table 2. As can be seen from the table, the outputs of the model based on OTIS database gave better agreement compared to the results which based on Le Provost database. This conclusion was drawn based on the smaller RMSE and the higher correlation coefficient. Moreover, this conclusion is actually as expected as OTIS database has higher resolution (1/30°) than Le Provost database (1/2°). Since there are six figures for each case, for simplicity, only one figure will be shown for each case as presented in Fig. 4 and Fig. 5.

Table 1. Tidal gauges location in the vicinity of Bali and Lombok islands.

Islands	Tide gauge	Longitude	Latitude
Bali	Celukan Bawang	114.8328	-8.1891
	Benoa (13)	115.2167	-8.7666
	Jembrana (12)	114.5734	-8.3851
	Nusa Penida (7)	115.4867	-8.6766
Lombok	Carik (1)	116.4265	-8.2215
	Lembar (8)	116.0722	-8.7309
	Tanjung Luar (9)	116.5255	-8.7689

4. Resolving model – observation discrepancy

As seen from Table 2, root-mean square error for all cases are still very high even if we are using a high-resolution tidal database. Similarly, correlation coefficients are still low in terms of tidal elevations although they are still acceptable. In order to overcome such discrepancy, Green's function approaches were employed. The detail application of this method can be found in some references [27-29] and the recent application can be found in [10, 35] and [30] and the references therein. Here, we briefly explain the procedure. In order to apply the method, real observation data should be available in the study area. The optimum change for each parameter is calculated with the following formula:

$$\eta^a = \boldsymbol{P}\boldsymbol{G}^T\boldsymbol{R}^{-1}\boldsymbol{y}^d$$

where $\boldsymbol{P}$ is the uncertainty covariance matrix and is defined by $\boldsymbol{P} = \left(\boldsymbol{Q}^{-1} + \boldsymbol{G}^T\boldsymbol{R}^{-1}\boldsymbol{G}\right)^{-1}$. $\boldsymbol{y}^d$ is the difference between observation data and the model outputs. Superscript T is the transpose operator and $\boldsymbol{G}$ is a matrix whose columns are the Green's functions of G. $\boldsymbol{Q}$ is the uncertainty of the initial parameters and $\boldsymbol{R}$ is the uncertainty of the measurements. Following a similar procedure as given in [29] and [10], one will obtain the optimal change for all constituents used.

After applying this method, root-mean square error decreased significantly up to 75% on average if using OTIS tidal database and about 43% on average if using Le Provost tidal database. Detail reduction of RMSEs are summarised in Table 3 and the representative figures (Tanjung Luar station) are shown in Fig. 6 and Fig. 7 which are based on OTIS and Le Provost databases, respectively.

As shown in Table 3, the most significant reduction of RMSE based on Le Provost database occurred at Tanjung Luar tide gauge in which RMSE decreased about 54% from 0.1867 *m* to 0.0857 *m*. However, using OTIS tidal database, the most significant reduction of RMSE is located at Jembrana tide gauge in which RMSE decreased from 0.1732 *m* to 0.0224 *m* which is about 87% reduction. This, again, revealed that Green's function approach is a powerful tool to improve open boundary condition for the regional tidal model.

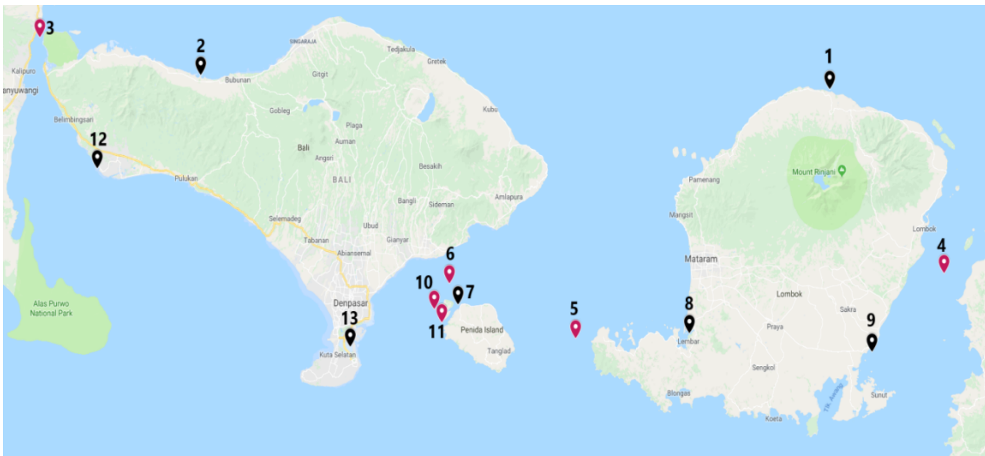


Fig. 3. Observation locations in the model. Black marks represent tide gauges while red marks are for tidal current recording.

Table 2. Statistical properties of the comparison between the observation and model based on Le Provost and OTIS tidal databases.

Station	Le Provost Database			OTIS Database		
	RMSE	ρ	Bias	RMSE	ρ	Bias
Benoa	0.2030	0.9340	-0.0000	0.1924	0.9414	-0.0001
Carik	0.1540	0.9272	-0.0001	0.1099	0.9598	-0.0003
Celukan Bawang	0.1224	0.9592	0.0001	0.0852	0.9733	-0.0002
Jembrana	0.1962	0.9441	-0.0001	0.1732	0.9567	-0.0001
Nusa Penida	0.1596	0.9359	0.0001	0.1490	0.9417	-0.0001
Tanjung Luar	0.1867	0.9507	0.0000	0.1567	0.9613	-0.0001
Average	**0.170317**	**0.94185**	**0.0000**	**0.1444**	**0.9557**	**-0.00015**

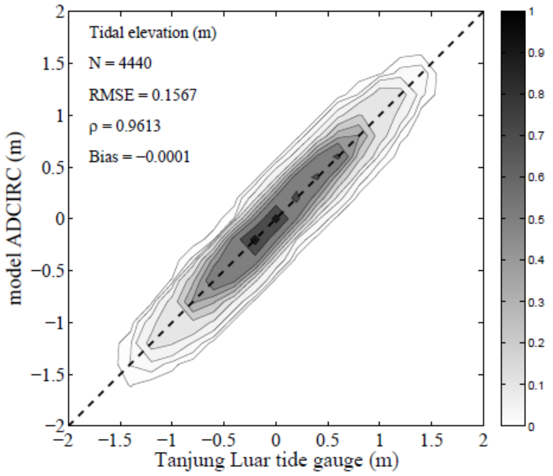


Fig. 4. Tidal elevation comparison based on OTIS tidal database.

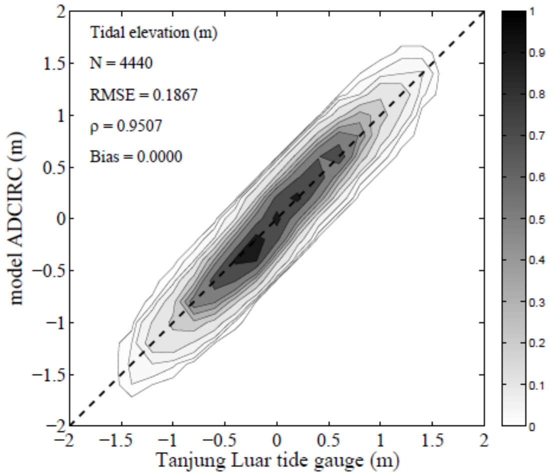


Fig. 5. Tidal elevation comparison based on Le Provost tidal database.

5. Tidal currents and their comparisons to FES2014

In this section, tidal current around Bali and Lombok islands will be presented. First of all, general tidal current in three different significant straits will be shown. After that, some locations as shown in Fig. 3 will also be observed. Furthermore, the comparison between tidal current obtained from ADCIRC model and FES2014 will be carried out.

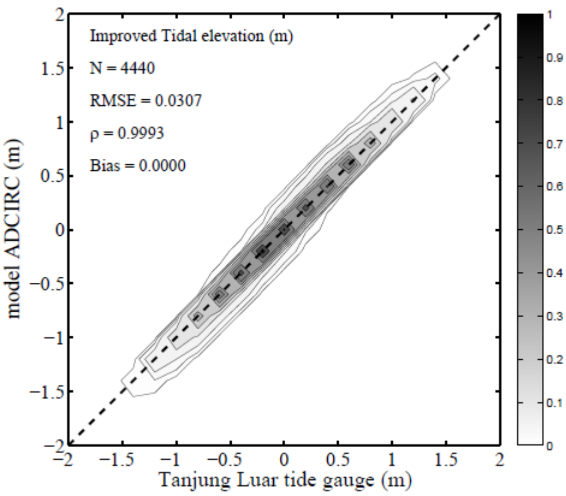


Fig. 6. Tidal elevation comparison after applying Green's function approaches based on OTIS tidal database.

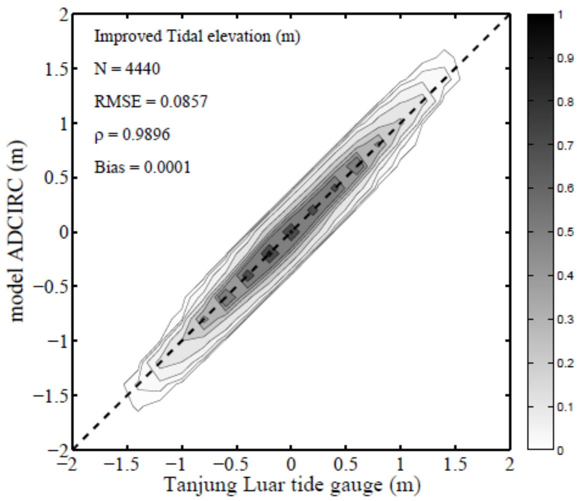


Fig. 7. Tidal elevation comparison after applying Green's function approaches based on Le Provost tidal database.

Table 3. Statistical properties of the comparison between the observation and model based on Le Provost and OTIS tidal databases after improving open boundary conditions.

Station	Le Provost Database			OTIS Database		
	RMSE		% Reduction	RMSE		% Reduction
	Before Green function	After Green function		Before Green function	After Green function	
Benoa	0.2030	0.1182	41.77	0.1924	0.0436	77.34
Carik	0.1540	0.0918	40.39	0.1099	0.035	68.15
Celukan Bawang	0.1224	0.0855	30.15	0.0852	0.0389	54.34
Jembrana	0.1962	0.1127	42.56	0.1732	0.0224	87.07
Nusa Penida	0.1596	0.0861	46.05	0.1490	0.0503	66.24
Tanjung Luar	0.1867	0.0857	54.10	0.1567	0.0307	80.41
Average	**0.1703**	**0.0967**	**43.24**	**0.1444**	**0.0368**	**74.50**

5.1 Tidal current in three different straits

Fig. 8 presents general overview of tidal stream around Bali and Lombok islands, particularly in three different straits, namely, Bali Strait, Lombok Strait and Alas Strait. As can be seen from the insets, tidal current is very strong in all three straits. In fact, tidal current in Lombok Strait reaches up to 3.8 *m/s*, while tidal current velocities in Bali Strait could exceed 3.3 *m/s*. Although tidal current velocity in Alas Strait is the lowest compared to the other two straits, they are still strong which could reach up to 2.7 *m/s*.

In order to observe the current velocity in more detail, six other stations have been added to the model (see Fig. 3). The presentation will be shown in three different cases, namely meridional velocity which is also called north-south velocity, zonal velocity in which the direction is from east to west and the absolute current velocities will also be shown in detail. However, only figures for station 10 will be presented for simplicity.

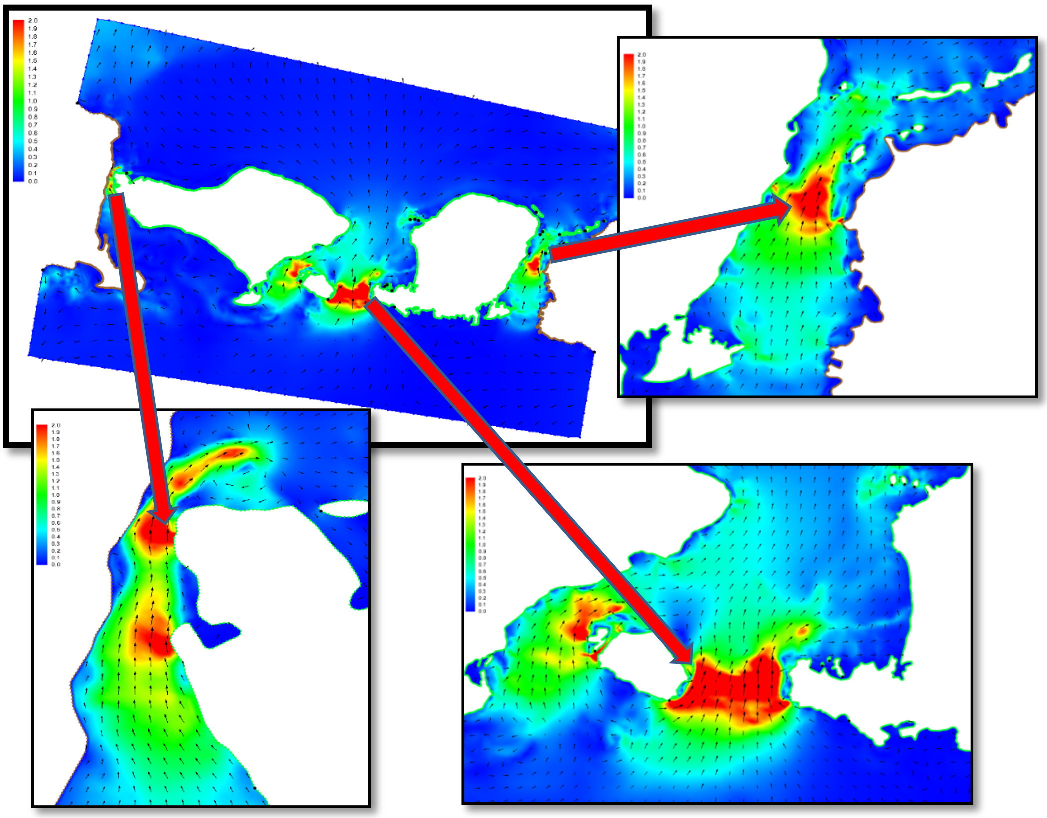


Fig. 8. Tidal current distribution in the vicinity of Bali and Lombok islands.

5.2 Meridional tidal current velocities

Meridional current velocity in which tidal stream from north to south or vice versa is presented in this section. As aforementioned, only figure for station 10 is shown for simplicity. However, the summary of meridional current velocities for all stations is presented in Table 4. As depicted in Fig. 9, meridional current velocity at station 10 which is located in Lombok Strait and is very close to Penida Island, reaches up to 3.7 *m/s*.

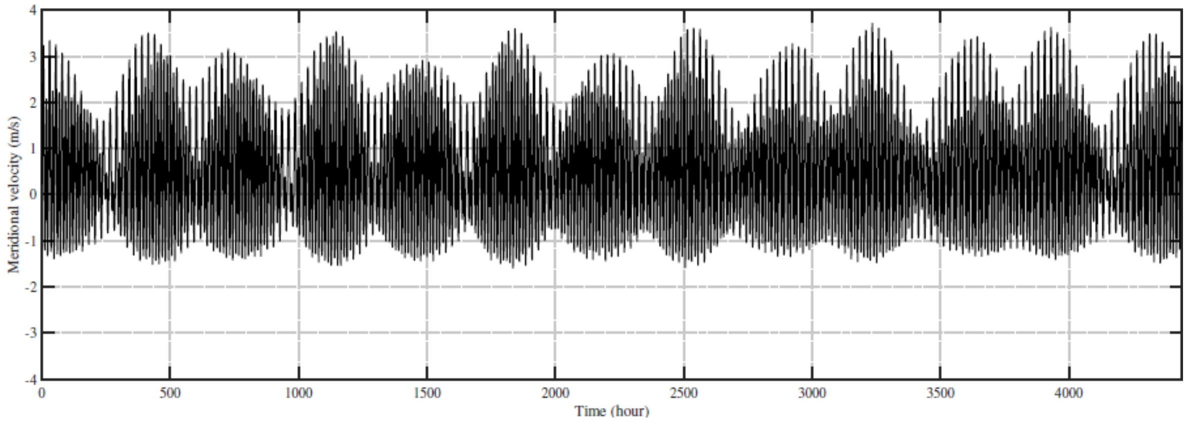


Fig. 9. Meridional current velocity at the monitoring station 10.

Table 4. Summary of meridional current velocity for all selected monitoring stations.

Station	Meridional current velocity (m/s)	
	Minimum	Maximum
3	-2.7815	3.2823
4	-2.0465	2.5844
5	-2.3491	3.2831
6	-0.4674	0.9885
10	-1.5883	3.7135
11	-1.3304	0.5652

5.3 Zonal tidal current velocities

Since the shape of the study location contains narrow straits which flowing from north to south or vice versa, it is expected that zonal current velocity is lower than meridional current velocity. This expectation is confirmed from the model as shown in Fig. 10, for example. All the current observations which are located in the straits have similar results. In fact, only two out of six locations as listed in Table 5 have high zonal velocities as they are not inside the narrow straits.

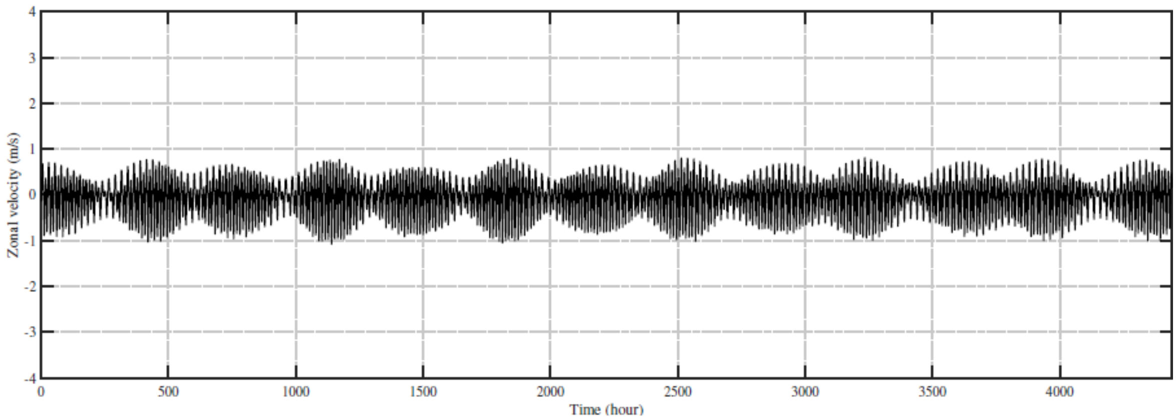


Fig. 10. Zonal current velocity at the monitoring station 10.

5.4 Absolute tidal current velocities

Another important parameter that will be taken into account is the absolute tidal current velocity. This current velocity is determined by zonal and meridional current speed. Moreover, the absolute tidal current is used to estimate tidal current power. For simplicity, only one absolute tidal current is presented, and the selected station is station 10. Although the zonal current velocity is not as strong as meridional velocity in the location, the absolute current velocity reaches up to 3.8 *m/s* as presented in Fig. 11.

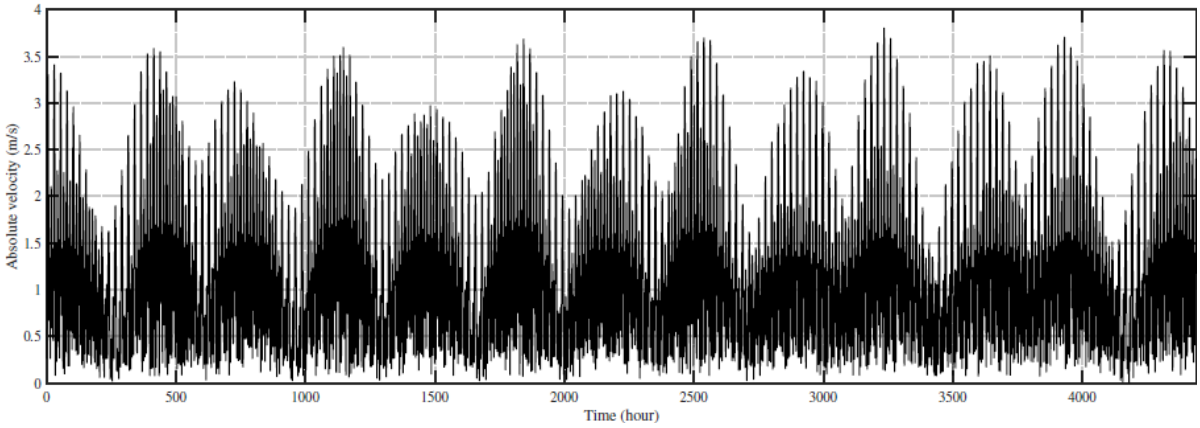


Fig. 11. Absolute current velocity at station 10.

Table 5. Summary of zonal current velocity for selected monitoring stations.

Station	Zonal current velocity (m/s)	
	Minimum	Maximum
3	-0.9429	0.4884
4	-0.9073	1.0640
5	-1.1060	0.8002
6	-1.8501	2.1307
10	-1.0805	0.8129
11	-2.3409	3.4623

5.5 Comparisons to FES2014

Since real observation of current velocity around Bali and Lombok islands is not available, in order to verify our results, the model current velocities were compared with the current velocities archived by FES2014. This database is the improved version of FES2012 which was developed by the French tidal group (FTG) and was based on finite element solutions (FES) [31]. Moreover, the present database has been validated with observations. However, we will not expect a very high correlation coefficient as well as very small RMSE as our resolution is higher than the resolution of FES2014 which is $1/16^{o}$. In order to carry out the comparisons, two stations have been selected in which they are very close to FES2014 coordinates as shown in Table 6. These two stations are located in Alas Strait and Lombok Strait, respectively. Furthermore, meridional velocity and zonal velocity were compared separately. Fig. 12 shows the comparison between meridional current velocity obtained from ADCIRC model and FES2014 model in the Alas Strait. As shown, although the models have different resolutions, they are in very good agreement in which the correlation function is 0.9686 and RMSE is 0.3540 *m*. Moreover, the bias which is the mean of the difference two models is very small. Similarly, the correlation coefficient and RMSE between ADCIRC model and FES2014 model in Lombok Strait are 0.9322 and 0.3488 *m*, respectively. It should be noted that FES2014 has to be shifted to get the best comparison. This comparison is presented in Fig. 13.

Table 6. Location of additional tidal current velocity observation.

No.	Longitude	Latitude	Location
1	116.687346	-8.626734	Alas Strait
2	115.752076	-8.747709	Lombok Strait

Furthermore, in the selected locations, zonal current velocities are very weak, but they are still acceptable. This is because the direction of the straits is facing north – south for both straits. We found that the comparisons are in a very good agreement as well. In fact, the correlation coefficient and RMSE in the Alas Strait are 0.9685 and 0.1280 *m*, respectively as revealed in Fig. 14. Similarly, zonal current velocity as observed in Lombok Strait as shown in Fig. 15 in which correlation coefficient and RMSE are 0.7965 and 0.1086 *m*, respectively.

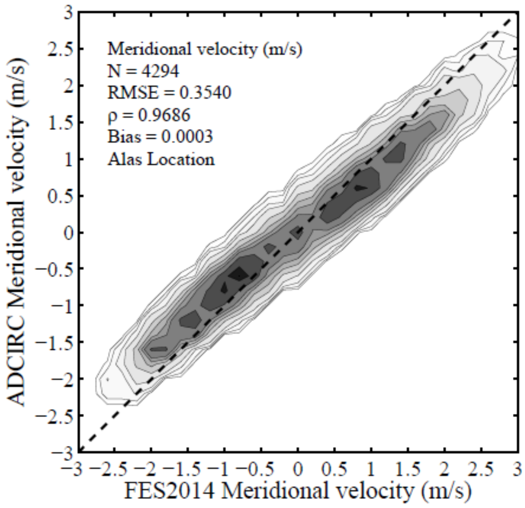


Fig. 12. Comparisons between ADCIRC and FES2014 meridional velocity at Alas Strait.

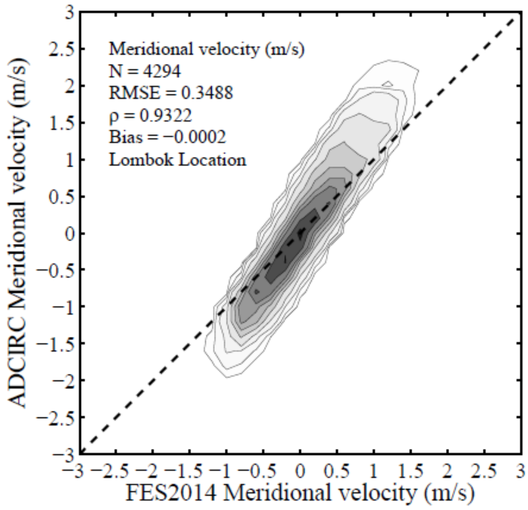


Fig. 13. Comparisons between ADCIRC and FES2014 meridional velocity at Lombok Strait.

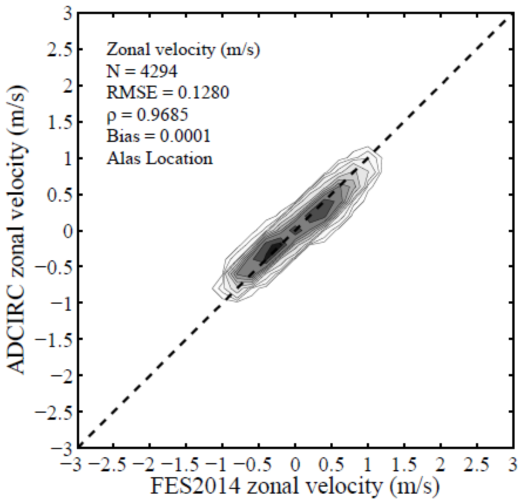


Fig. 14. Comparisons between ADCIRC and FES2014 zonal velocity at Alas Strait.

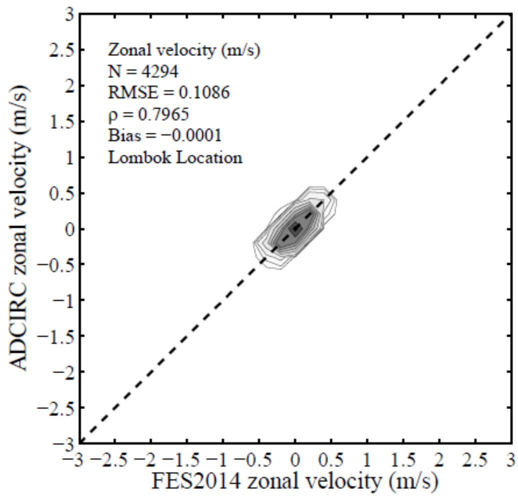


Fig. 15. Comparisons between ADCIRC and FES2014 zonal velocity at Lombok Strait.

6. Estimation of tidal power Energy

Tidal current power energy around Bali and Lombok islands has been estimated at six different locations as shown in Fig. 3. As known, tidal power energy depends on the current speed, swept area of the turbine and turbine efficiency. However, since the last two parameters could be assumed to be constant, it is a plausibility to conclude that the tidal power energy (P) depends only on current speed and it can be estimated from the following equation (in kW):

$$P = \frac{1}{2}\eta\rho A U^3 \tag{4}$$

where U is the absolute current speed of the flow in meters per second, η is the dimensionless turbine efficiency, A is the area in direction of flow of the turbine which is in squared meters and ρ is the water density which ranges between 1020 kg/m^3 and 1029 kg/m^3. Again, since the swept area of the turbine (A) could be constant, for simplicity, it can be excluded from the estimation. Hence, equation (4) can be rewritten as (in kW/m^2):

$$P = \frac{1}{2}\eta\rho U^3. \tag{5}$$

Now, for practical estimation, turbine efficiency equals 0.39 [36] has been selected, that is η=0.39 and ρ=1025 kg/m^3. Then, the estimated power energy based on the equation (5) are summarized in Table 7.

As can be seen from the table, mean power energy can exceed one kW/m^2 which is very promising. Moreover, if one can assume that the area of turbine flow is 1600 m^2 [37], then mean tidal power energy can exceed 1.8 MW (maximum power is 17.568 MW) per turbine. In order to observe the detail information of the power energy, for simplicity, the power energy at station 10 has been selected and as presented in Fig. 16. As can be seen from the figure, the power energy can exceed 10 kW/m^2.

Table 7. Summary of estimated tidal current power around Bali and Lombok islands for six different observation locations.

Station	Longitude	Latitude	Mean Speed (*m/s*)	Max Speed (*m/s*)	Mean Power (*kW/m²*)	Depth (*m*)
3	114.4238	-8.1085	1.4134	3.3154	1.0798	32.652
4	116.7155	-8.6098	0.9881	2.7816	0.4490	83.191
5	115.7827	-8.7486	1.0012	3.2981	0.5185	177.816
6	115.4620	-8.6318	0.6774	2.2813	0.1482	178.089
10	115.4233	-8.6860	1.2539	3.8015	1.0060	24.438
11	115.4423	-8.7145	1.4338	3.4836	1.1481	48.097

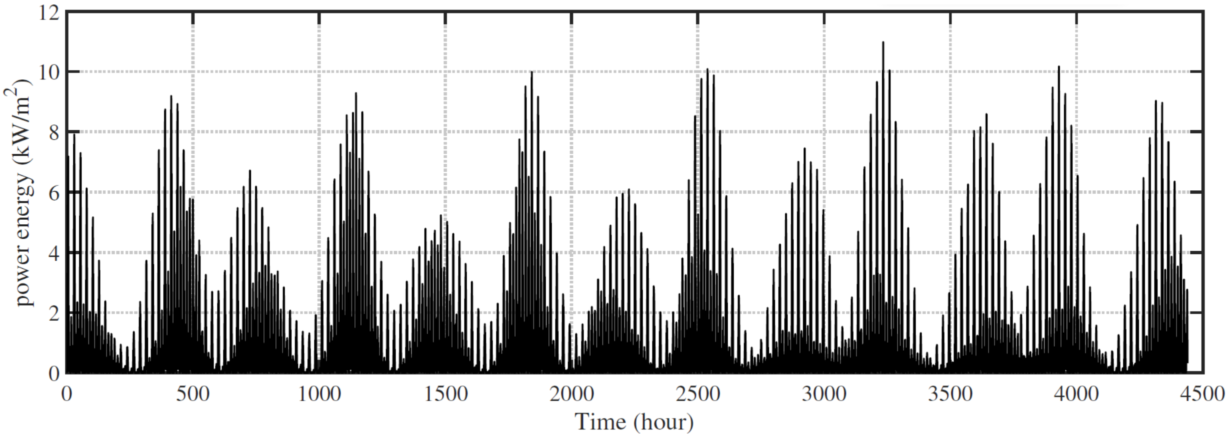


Fig. 16. Power energy at station 10 (kW/m^2).

7. Summary and conclusions

An estimation of tidal current power energy around Bali and Lombok islands has been carried out in this research. We found that tidal current velocity in the vicinity of Bali and Lombok islands reaches up to 3.8 m/s which leads to a tidal current power exceeding 10.98 kW/m^2 by assuming that the turbine efficiency is about 0.39.

Although tidal current observations are not available in the study area, our model results have been compared with the tidal current velocity which was obtained from FES2014 tidal database. We noted that our results are in a good agreement with FES2014, even though the resolutions are very different.

Assuming that the swept area of the turbine is 1600 m^2, one can obtain an electricity of up to 1.8 MW per turbine which is very promising. Hence, further work is still needed before continuing on application stage. This could include carrying out the observation in the high current velocities based on the model simulations. To this end, more funds are needed as well as research collaborations.

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