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Preliminary Assessment of Tidal Stream Power Using 3-Dimensional Hydrodynamic Model in the Lembeh Strait

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Preliminary Assessment of Tidal Stream Power Using 3-Dimensional Hydrodynamic Model in the Lembeh Strait

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Abstract. This paper provides a preliminary assessment of potential energy of tidal currents in the Lembeh Strait, North Sulawesi. Using two and three dimensional ocean hydrodynamic model, the assessment was done. A nesting method has been applied in order to simulate tidal currents in the Sulawesi Sea and the Lembeh Straits. Three dimensional simulation results at the Lembeh straits was validated using observation data, which are obtained from filed measurement campaign on 3 to 23 April 2016. Estimation of tidal current or tidal stream power was focused in the Lembeh Straits. The simulation results show power density during a tidal cycle can reach maximum value about 72.346,23 W/m2 at full moon condition. This amount of power is stored in the area between Sarena Island and Sulawesi Island. The result of tidal stream power estimation also reveals strong tidal currents that associated with maximum power occur during flood tide condition.

1. Introduction

Energy is one of the most important things for the needs of human life. Up to this date, 80% of the world's energy still uses fossil energy such as coal, oil and gas, then nuclear power at 6.5%, and renewable energy by 13.5% by 2015 [1]. Great efforts have been made to meet the world's energy needs by using renewable energy. One of the world's growing trends is the use of renewable energy from the ocean or the so-called Ocean as Renewable Energy Resources (ORE) [2]. As the ocean covers 70% of the Indonesia archipelago and it does represents an enormous amount of energy in the form of wave, wind, tidal, ocean current and thermal resources [3]. One of the reliable and promising ocean energy sources is marine current energy [4]. Marine current have very high power density and are present in many place of Indonesia Sea especially in a strait type sea.

This article estimates the maximum power potential from the ocean current of the Lembeh Strait region in North Sulawesi, Indonesia. This region has high tidal currents and has been proposed as an excellent site for harnessing ocean current energy [5]. The Lembeh Strait is located between northern Sulawesi and Lembeh Island, stretching from the Sulawesi Sea (to the northwest) to the Maluku Sea (to the southeast) [6]. The Lembeh

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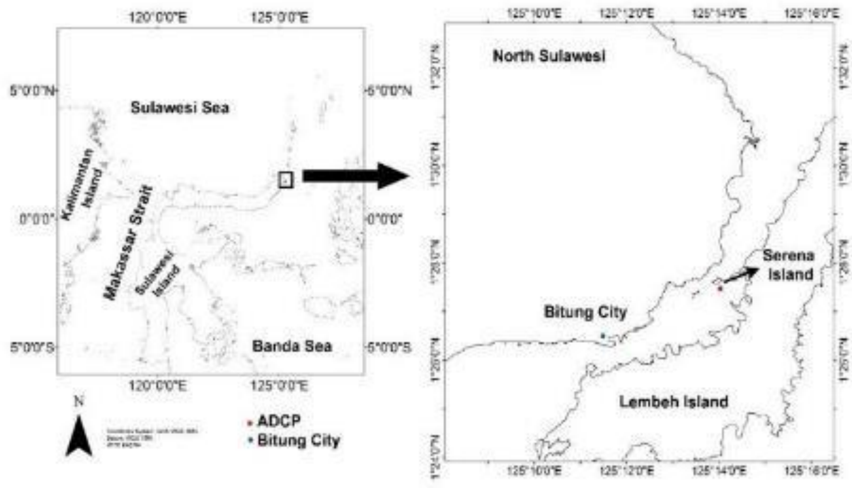
Strait (Fig. 1) is a narrow strait located at the northeast of Sulawesi, with a length of 16 km, width of 2 km, and a depth of 5–90 m. The major city on the west coast of the Lembeh Strait is Bitung, with a population of approximately 188,000 [7]. While on the Lembeh Island, there are multiple small villages, each with less than 1000 inhabitants. The rise in tourism/business surrounding this strait has led to increasing demands for hotels, resorts, and other business infrastructure.



(a) (b)

Fig. 1. Map of Lembeh Strait: (a) in the North of Sulawesi (b) detailed view of the Lembeh Strait.

The Lembeh Strait geometry shape that resembles a funnel mouth results in an extreme tidal flow rate, even in places such as around Sarena Island turbulent currents (rotating) at varying speeds and can reach up to 2.5 meters/sec. The tides in this area are mixed and mainly semidiurnal, which fluctuate slightly with an annual tidal range of 2.4 m [5].

The strait is strongly influenced by two monsoons: the wet northwest monsoon from

Nomenclature

$\bar{y}$	the average of the model simulation speed data
$\bar{x}$	the average of the observed speed data
N	total sample
y_i	model simulation speed data
x_i	observation speed data
P	tidal stream power per unit area of flow (kW/m^2)
A	turbine rotor swept area (m^2)
ρ	mass type (kg/m^3)
V	current velocity (m/s)

November to March and the dry southeast monsoon from May to September [8].

1.1. Data

Main data used for this article consist of field measurement of ocean current speed from Acoustic Doppler Current Profiler (ADCP) and Acoustic Wave and Current Profiler (AWAC) in Lembeh Strait (Fig. 1) and bathymetry from an expedition held by the Pusat Penelitian dan Pengembangan Geologi Kelautan (P3GL) in April 2016. Another supporting data was gathered from the General Bathymetric Chart of the Oceans (GEBCO) with the specification of 30 arc-second global grid of elevations and tidal prediction from Badan Informasi Geospasial (BIG) Indonesia. Comparisons were made between the two dimension model elevation and the tidal elevation of the (BIG) tide at 1.55° LU - 125.753° BT to validate the numerical model. For the three-dimension model, the verification process uses data taken from (ADCP). Data of the current velocity taken starts from 1 April to 23 April 2016 at the point 1.458° LU - 125.253° east. The verification process is also done by statistical calculations using bias and Root Mean Square Error (*RMSE*). The formula of the bias and *RMSE* equations used is as follows,

$$bias = \bar{y} - \bar{x} \tag{1}$$

$$rmse = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{2}$$

Equation (1) shows the bias function that is the difference between this estimator's expected value and the true value of the parameter being estimated; Equation (2) represents Root *Mean Square Error* (*RMSE*) as the standard deviation of the residuals (prediction errors). In these equations $\bar{x}$ and $\bar{y}$ represent the average of the observed speed data and the average of the model simulation speed data; x_i and y_i represent observation speed data and model simulation speed data; N represent the total sample.

1.2. Hydrodynamic Model

The two-dimension (2-D) hydrodynamics model, MIKE 21 Flow model was used to compute the current conditions in Maluku Sea and the northern coast of North Sulawesi. While the three-dimension (3-D) hydrodynamics model, MIKE 3 Flow Model was used to compute the flow conditions in Lembeh Strait. To properly analyze the Lembeh's hydrodynamics, and as a result to conduct reliable energy computations, in this work a 3-D model was implemented.

Mike 3 Flow Model system is based on the numerical solution of three dimensional incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consist of continuity, momentum, temperature, salinity and density equations and it is closed by a turbulent closure scheme.

For the 3-D model, the free surface is taken into account using a sigma-coordinate transformation approach. In this manner barotropic effects, which is important in the case of Lembeh Strait, can be taken into account. The grid used in both models is using the finite element method and a triangular element type with the number of elements in 2-D model as much as 2126 pieces and 1254 pieces nodes. For the three-dimension model there are 1995 elements and the number of stain points are 1373 pieces. In the two-dimension study areas, the maximum depth is 4802 meters and a minimum depth of 0.1 meters above the mean sea level (MSL) (Fig. 2). While on the 3-D model the maximum depth is 593 meters and a minimum depth of 0.1 meters above sea level on average (MSL). Making this model refers to longitude/latitude projection with GCS datum WGS 1984 and the unit used is meter.

After the simulation of 3-D hydrodynamic model has been done, the potential of marine currents energy that can be generated from ocean current model were calculated. The result of this calculation is a power density at each point in the model domain. The power density calculations are performed using the Fraenkel Equation [9]. The Fraenkel equation is formulated as follows,

$$\frac{P}{A} = \frac{1}{2}\rho|V^3| \tag{3}$$

In this equation, P/A represents the power density per unit area in watt/m^2; ρ represents the mass type in kg/m^3; V represents the current velocity in m/s.

To calculate the electrical energy of the ocean currents, used one type of turbine, namely the Gorlov Helical Turbine. The specifications of the turbine used are as follows [10]:
cut in speed = 0,5 m/s
rated speed = 2,58 m/s
rated power = 7 kW

The above specifications are the factors to be considered in marine turbine. Cut in speed is the minimum speed required for a marine current turbine to operate. That is, for speeds that below the cut in speed velocities, turbines will not generate electrical power. While rated speed is the maximum speed that can be converted by turbine currents. That is, the value of power generated by the turbine with flow speed of rated speed and speed above rated speed will be the same value. Rated power is the maximum power that can be generated by marine turbine currents. Furthermore, the magnitude of the turbine blade diameter is 0.3 meters with 0.544 meters height is used as the value of the cross-sectional area in the calculation of the power density.

2. Validations and hydrodynamic results

The numerical model was validated by comparing the numerical results with field data of water level and current velocity. For this purpose, an ADCP (Acoustic Doppler Current Profiler) was deployed in Lembeh Strait (Fig.1) for overall 20-day period. During the validation period, the numerical model was forced with the main tidal harmonics (Table 1). The RMSE and bias between measured and computed time series of water level and current velocity direction and magnitude were computed (Table 2). It can be observed that the resulting RMSE and bias are close to the unit for both variables.

Table 1. Main tidal constituent in Lembeh Strait.

Constituent	Amplitude (cm)	Phase (*)
M2	0,41	274,66
S2	0,27	307,78
K1	0,17	135,04
O1	0,13	115,13
N2	0,07	263,17
P1	0,05	132,20
K2	0,06	311,7
Q1	0,02	118,40

Table 2. Root *Mean Square Error* and bias between computed and measured time series of sea level ($RMSE_\zeta$) and flow velocity magnitude in direction of *u* and *v* (*$RMSE_u$* and *$RMSE_v$* respectively) and bias (*bias (u)* and *bias (v)* respectively) [11].

Water level		Current velocity			
			Surface layer	Middle layer	Bottom layer
$RMSE_\zeta$	0.00312 m	$RMSE_u$	0,003	0,093	0,132
		$RMSE_v$	0,132	0,046	0,081
		bias (u)	0,016	0,042	0,045
		bias (v)	0,072	0,004	0,056

The excellent agreement between measured and computed time series of numerical and measured velocities can be observed in Fig.4 at three points of the water column: surface, mid depth and bottom.

3. Model Result

To see the current pattern in the Lembeh Strait thoroughly, the models were observed in two conditions of neap-tide and spring-tide. For the spring-tide conditions, a period of time is chosen when its tidal range has the greatest value. For neap-tide conditions, a period of time is selected when its tidal range has the smallest value. Which is on April 8, 2016 for the spring-tide and on 16 April 2016 for neap-tide. The direction of current flow in the Lembeh

Strait is dominated with the north-south current direction. With the largest magnitude in north-south direction is 1.6 m/s. The current movement towards flood condition is to the north, while towards the ebb condition the current movement is going south (Fig. 5).

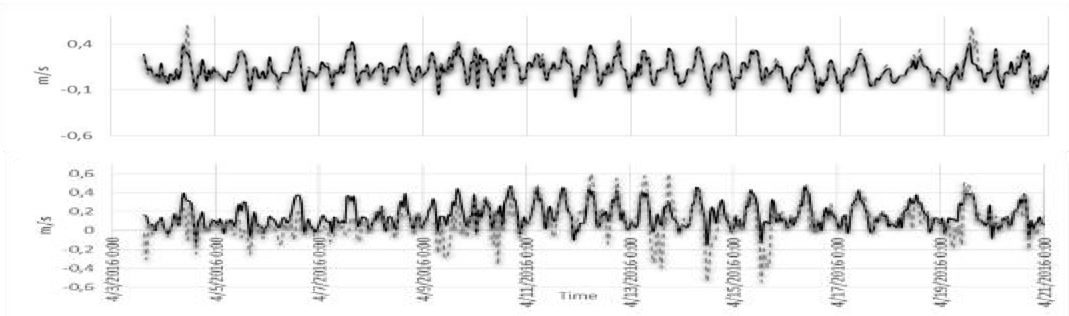


Fig. 2. Comparison between computed and measured current speed for the mid-depth and bottom layers in the ADCP location during the validation period.

4. Results and Discussion

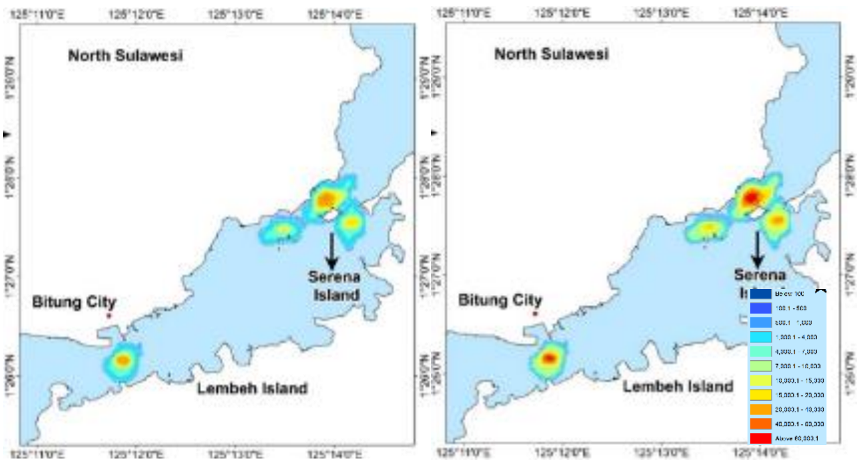
Having obtained the current pattern in the Lembeh Strait, calculations were made to determine the power density potential of the Lembeh Strait which can be utilized using Gorlov Helical Turbine as already stated before. Using the Fraenkel Equation and the specification of the Gorlov Helical Turbine, a potential power density calculation was conducted in Lembeh Strait. In addition, in this article we also calculated the power density that can be generated in one tidal cycle (24 hours), both for spring tide and neap tide conditions to obtain the most potential point in the Lembeh Strait to implement the current turbine.

The power density pattern at spring tide condition and toward the ebb conditions at 3 m depth ranges from 100 W/m^2 up 6,000 W/m^2. It can be seen that there are some points that have the potential of electrical energy and the greatest condition is in the area between Serena Island and Sulawesi Island. The same result with the condition toward the flood, where there is a considerable power at the same location, with a maximum power density at 4,000 W/m^2. A particular results shown in the neap tide and toward flood condition that ranges between 100 W/m^2 up to the range of 2,000 W/m^2 while maximum power density is at 1,500 W/m^2.

The representation of power density pattern in the spring tide and toward ebb condition at the bottom layer can be seen in figure 7 (left-side plot). The power density ranges from 100 W / m2 up to the range of 4,000 W/m^2. While the power density at toward flood condition can be seen at figure 7 (right-side plot) where there is also a considerable power at the same location, with maximum power density at 6,000 W/m^2.

Table 3. Power density calculated in different tide conditions.

Condition		mid depth (12 m)	bottom (24 m)
Neap Tide	Toward flood	360,75	430,25
	Toward ebb	900,45	1050,65
Spring Tide	Toward flood	3105,2	3150,31
	Toward ebb	6120,67	6258,01



(a) (b)

Fig. 3. Power density in a 1 tidal cycle (24 hours) at the bottom layer (around 24 m): (a) at spring tide (b) at neap tide.

The highest power density that can be generated in one tidal cycle in between Serena Island and Sulawesi Island (P1) is 72,346,23 W/m^2, that condition was at the spring tide condition. Whereas during the neap tide condition, the maximum power density that can be generated in one cycle is 34,451 Watt /m2. At Point II the maximum power density that can be generated is 35.753 Watt / m2, while the farming time is 13,921 Watt / m2. For maximum power density at Point III which can be generated is 45,763 Watt / m2 and when the farm is 16,394 Watt / m2. With such a power density condition, one potential point for the development of currents in the Lembeh Strait is the point 125.232 BT, 1.463 LU is Point I. This is because the point has the largest power density that can be generated per tide cycle, either during full moon or farm.

5. Conclusion

Lembeh Strait is a potential place for the installation of electric turbines because it has a maximum speed at the tide-to-tide phase of the full moon at the narrowing area between Serena Island and Sulawesi Island (Point I) at a depth of 24 m with 1.85 m/s, evenly for 1 month that has exceeded the cut in speed turbine for 0.82 m/s. While further investigation should be done by paying more attention to the condition of the mesh and the bathymetry.

To produce more accurate potential points, smaller grid sizes are needed so that more detailed flow patterns can be produced.

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