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Wave Energy Assessment in Dumaran Island, Palawan, Philippines.

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ABSTRACT

Wave energy harvesting, if viable, is a potential energy resource for remote islands like Dumaran Island, Philippines. However, absence of high-resolution wave energy resource information in Dumaran waters hinders the development of Wave Energy Converter (WEC) to overcome current unsustainable means of supplying power, prolonging energy insecurity among its locals. The focus of this study is to assess wave energy densities for Dumaran Island using high-resolution and validated wave data for the selected sites in Sulu Sea within 100 km radius from the island by using statistical analysis. This was achieved by generating 3-hourly hindcast wave data for 40-year study period (1978 – 2018) in 6 selected sites, using MetOcean Solutions Ltd WW3 Tolman Chalikov (MSLWW3TC) numerical wave model. The wave model was then validated with MIKE 21 Spectral Wave Model FM (MIKE21SW), which generated 3-hourly wave energy data at 14 sites for 5-year study period. Subsequently, wave energy flux time-series was computed and statistically analysed. The validated wave model resulted in low RMSE and high CC results, which indicate good model performance. The study area has low wave energy content, with the average wave energy range less than 4.5 kW/m. High but unstable wave energy was observed during Northeast Monsoon across all sites, and reduction of wave energy near coastal areas due to sheltering effect of Palawan and offshore islands. The hotspot for wave energy is found in the northeast and southeast of Dumaran deep offshore waters, with average annual wave energy of 4.43 kW/m. As mean wave energy at the site is insufficient and grid connection is absent WEC implementation in Dumaran waters is not viable.

1. Introduction

With increasing energy demand in the 21st century, off-grid rural islands like the Dumaran Island face unique challenges to energy accessibility and sustainability. In the Philippines, accessibility to sustainable energy has been a long-standing goal especially as it faces unique challenges as an island country. Nevertheless, the nation had delivered 94.6% electrification rate by 2018 [1]. Despite the significant progress, energy poverty is still a matter of great concern in the Philippines.

The Dumaran Island is located northeast of the Palawan province, grouped under the Luzon Island group, as shown in Figure 1 below. The island is enclosed within the Sulu Sea with an approximate area of 435km^2, and a total coastline length of 166.17km [2]. Considering the majority coastal communities, renewable energy generated from wave power farms may make an excellent candidate as a resource base [3]. Despite this, wave energy has remained untapped and largely delayed in terms of its development of estimating potential wave resource. The absence of high-resolution wave energy resource information in Dumaran waters hinders the development of Wave Energy Converter (WEC) to overcome current unsustainable means of supplying power to the island, since the potential location for optimal deployment of WEC could not be identified nor quantify the wave energy density in its vicinity.

Figure 1 Location of Dumaran Island, Palawan, Philippines [9].

Hence, the project aims to further assess statistical analysis of wave energy resources using high-resolution wave data particularly within Dumaran waters with respect to previous literature studies of nearby locations for wave energy assessment methodology, as follows:

1) To assess wave energy densities for Dumaran Island using high-resolution wave data for the selected sites in Sulu Sea within 100 km radius from the island using statistical analyses.
2) To validate the statistical results with the MIKE21 numerical results.

There is insufficient high-resolution wave energy resource information in semi-enclosed seas, and the effects of Palawan Island during monsoon seasons. The global wave power resource map by Mørk and others [4] can be compared to a similar study by Cornett [5]. Global wave energy resources had been derived similarly for 10-year period from 1997 to 2006. In this literature, WAVEWATCH-III (NWW3) wind-wave model was used to derive the analysis of wave climate predictions. the wave energy distribution in Dumaran waters differ between the two literatures. Accordingly, average annual wave energy near Dumaran waters generally ranges within 10 kW/m [5], and 5 kW/m [4]. There are some discrepancies between the resource map as wave climate predictions had not been accounted for semi-enclosed inland seas. Furthermore, the author admits the inability of the grid to properly account shallow water effects near most coastlines, making the results less reliable. As WEC deployment near coastline would also like to be considered, the above wave energy flux becomes less reliable.

Literatures in South China Sea also shows sheltering effects and monsoon seasonal winds effects on wave energy, which pattern is not known in Dumaran waters. The presence of offshore islands obstructs the wave propagation, which is referred as sheltering effect. In effect, it reduces the significant wave height [6] which greatly influences the wave energy flux. In the context of Dumaran Island, this sheltered effect could be induced by the presence of Palawan Island itself as well as several other offshore islands within the Sulu Sea. Similar effects could be exemplified within the South China Sea, whereby the presence of small offshore islands tend to decrease wave energy. Several sheltered areas in the South China Sea in a study by Mirzae and others [7] found to be less energetic and has lower probability for the wave power to exceed 5 kW/m at any season. Seasonality throughout the monsoon cycles affects the wave power distribution and stability in the study area. This is important because the stability of wave energy is also a prerequisite to optimize WEC efficiency and performance [8], and the stability of wave power findings in South China Sea may pave the way to acquire information on wave power stability in Dumaran waters. The consistent findings between literatures [7-10], shows that wave energy flux are the highest during winter due to stronger northeaster wind. The central catalyst of this study is based on Quitoras and others [11], in which the technical and economic feasibility of wave energy resource farming were studied across 47 sites in 5 regions in Philippines; The result of the research shows that 10 – 20 kW/m wave energy flux across various Philippines' Northeast coasts. Nevertheless, the authors had acknowledged the limitations to this finding, as it relied on forecasts of publicly available wave profile data sets. need for measures to refine the data with longer data source. Improvements can be made by taking 10 years or more data source with 3 hours interval per day to increase reliability of the results, as authors push forward more research to be done for more detailed wave resource maps.

Based on the literature review, research gap includes the discrepancies between global wave energy resource maps, constraints in numerical wave models to account enclosed seas, and lack of information regarding precise wave energy near Dumaran Island and seasonality and sheltering effects on waves in Sulu Sea.

2. Methodology

The assessment methodology is based on International Energy Commission Technical Specification of Wave Energy Resource Assessment and Characterisation (IEC TS 62600-101), to ensure standardised and accurate wave energy resource estimation [12]. Procedure flowhart is shown in Figure 3.

2.1 Site Selection

The number and identification of reference sites, or data points, depends of the spatial variability of the study area [13] in terms of spatial variation includes distance to shore, difference in water depths, and presence of offshore islands. Nevertheless, the identification of the reference sites is practically an iterative procedure [13], as spatial variation of study area and its corresponding wave parameters could only be identified after defining the reference sites. Thus, descriptive statistical analysis was conducted to check whether there is sufficient variability after wave data sets acquired [14]. The statistical difference was evaluated using R whether there are any similarities in terms of mean, standard deviation (SD), maximum (Max.), range, skew, kurtosis of the wave data and whether the wave data at the corresponding sites overlap with each other from the correlation matrix [14]. All reference sites are within 100 km radius to ensure that sites are accessible to the island, shown in Figure 2. The terms also indicate shallow water, less than 100m, and deep water, ranging from 100 – 1000 m, respectively. Overall, there are total of 14 sites selected. Among the reference sites, the wave data at 6 offshore sites, denoted as sites 1 – 6, were acquired from MSL WW3 TC numerical wave model.

More data points were taken due to the large variation in water depth and other geographical factors in the study site. Subsequently, to account several nearshore and offshore areas, sites A – H were selected. The corresponding coordinates, distance to shore, water depth and data source are summarised in Table 1.

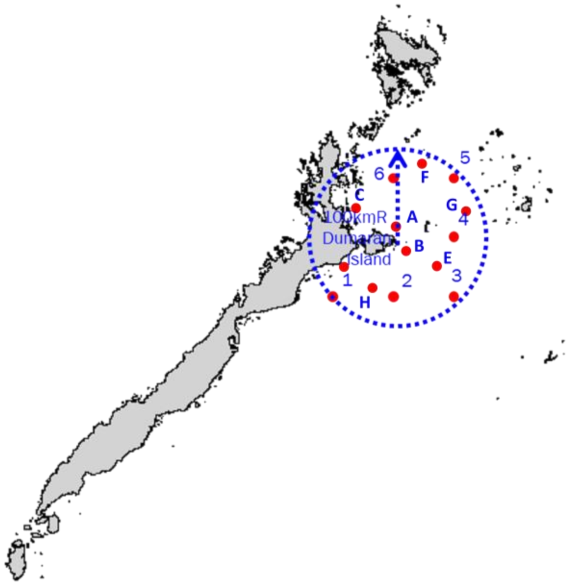

Figure 2 Reference site locations map

Table 1 Reference site location and data source details.

Site	Coordinates		Distance to shore	Depth (m)	Data source
	Lat.	Long.			
1	10°00'05"	119°29'57"	Offshore	< 50	MSL WW3 TC
2	10°00'03"	119°59'58"		> 500	
3	10°00'05"	120°30'01"		> 1000	
4	10°30'03"	120°29'58"		< 100	
5	11°00'01"	120°29'58"		< 100	
6	11°00'05"	119°59'54"		< 100	
A	11°00'05"	119°59'54"	Near-shore	< 100	MIKE21SW
B	11°00'05"	119°59'54"		< 100	
C	10°38'25"	119°44'04"		< 100	
D	10°22'43"	119°43'12"		< 50	
E	10°18'46"	120°14'15"	Offshore	> 1000	
F	11°02'17"	120°14'49"		< 100	
G	10°52'44"	120°28'08"		< 100	
H	10°05'53"	119°48'35"		> 250	

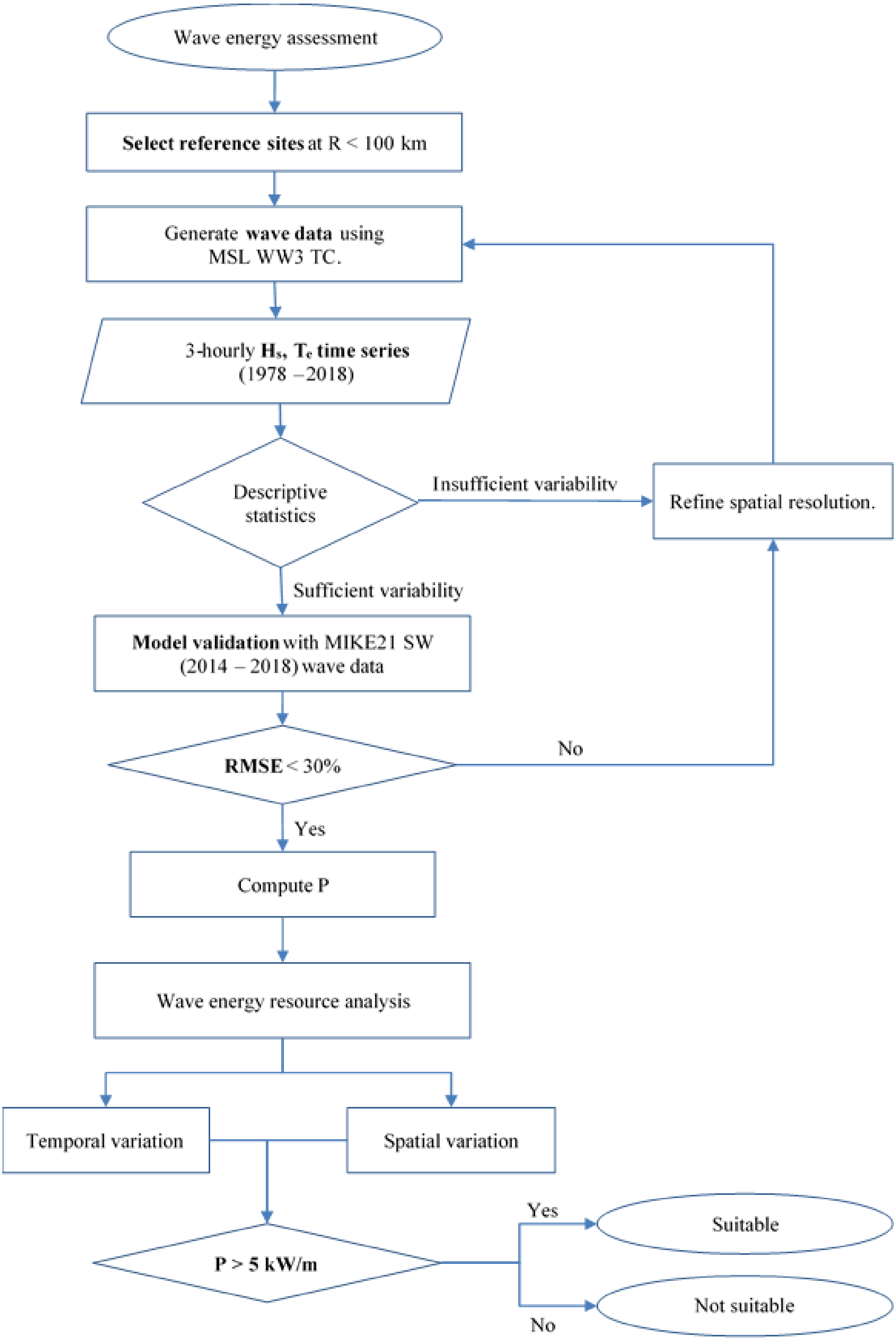

Figure 3 Flowchart for wave energy assessment in Dumaran waters.

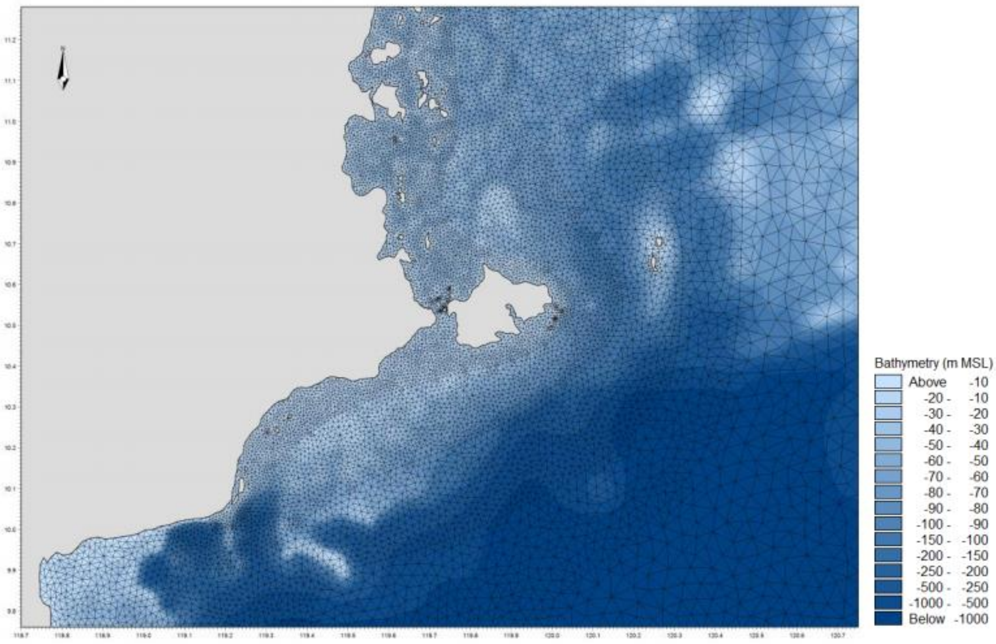

Figure 4 Dumaran waters' bathymetry based on Dr. Nik and Associates

2.2 Wave model and validation

In this study, the wave parameters such as significant wave height and energy period generated using MetOcean Solutions Ltd WW3 Tolman Chalikov (MSL WW3 TC) numerical wave model was provided by Palawan State University. Accordingly, the wave simulation was carried out for 40-year period between 1978 – 2014, and setup to output 3-hourly significant wave height, mean wave period and mean wave direction for the entire simulation period. Meanwhile, the MSL WW3 TC also had high spatial resolution of about 38 km [7]. The wave model was forced by high resolution NOAA Climate Forecast System Reanalysis (CFSR) winds of approximately 38 km and using the ETOPO2 bathymetry [7].

To ensure the MSL WW3 TC wave model had accurately estimated the wave conditions in Dumaran waters, the wave data were validated using MIKE21 SW, since the measured wave buoy data was unavailable. Accordingly, the wave parameters used to validate the MSL WW3 TC numerical model is significant wave height and wave power, whereby the wave data outputs 3-hourly for 5-year study period between years 2014 – 2018 at the corresponding 6 offshore sites (1 – 6), for model validation purposes. It is important to note that, the temporal coverage of 5 years was selected to reasonably estimate inter-annual variability of average wave power [13] and reduce uncertainties from the MSL WW3 TC wave model.

In terms of the means of model validation, comparison could be made between the two numerical wave models as the spatial resolution of the MIKE21SW model is much more refined. The wave model was set up with an unstructured triangulated mesh was generated with varying spatial resolution that progressively increases from offshore boundaries towards the study area. The wave model has a resolution of approximately 5 km at the offshore boundaries and increased to about 1 km in the vicinity of Dumaran Island.

Like the MSL WW3 TC, the wave model was also forced by Climate Forecast System Reanalysis (CFSR) wind field with spatial resolution of approximately 0.2° x 0.2°. Bathymetry data of the wave model was obtained from the General Bathymetric Chart of the Oceans (GEBCO) gridded bathymetric data set with resolution of approximately 900 m. Therefore, wave data generated from MIKE21SW model may be more accurate to validate MSL WW3 TC wave data with, due to its refined spatial resolution. The comparison between the wave models could be represented in hindcast wave height time-series of both models between January 2018 to December 2018 as a case study. Nevertheless, the RMSE and CC for wave height and period from the numerical models was computed for the 5-year model validation study period, in which the maximum allowable RMSE for Class 2 wave energy assessment is 30% [12]. The RMSE and CC equation is as follows in Equation (1) and (2) whereby x_i refers to the wave parameter at ith time from MSL WW3 TC, and y_i refers to the wave parameter at ith time from MIKE21 SW.

While further discussion regarding statistical differences between sites 1 – 6 as found in Section
0, the sites (A – H) are included as reference sites for the purpose of fully refining spatial variability of wave energy resource within Dumaran waters and accounting locations that are nearshore and with more variable in water depths.

$$CC = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \quad (2)$$

2.3 Wave energy resource assessment

The numerical wave models generate important parameters, that is significant wave height and energy period, to compute wave power. To give brief context on how these parameters are generated within the linear wave theory framework, vertical wave elevation $\boldsymbol{\eta(r,t)}$ at time t and at any point $\boldsymbol{r(x,y)}$ on the sea surface level, is assumed as superposition of various regular waves to depict random waves [15]. This may also be depicted as being composed of many waves of different frequencies, amplitudes and directions [16]. Meanwhile, wave energy resource is originated from the energy transported from local and distant winds blowing over the ocean surface [15], where more than 95% of the energy transported is found [17].

Relating back to the surface elevation, the spectral density S(f) was derived using Fast Fourier Transform algorithm. Hence, the energy period and significant wave height of the sea state can be computed in Equation (3) and (4) [18]. Accordingly, significant wave height, is denoted as Hm0. In particular, the significant wave height is defined as the average of the one-third of the highest wave height [19]. The variables such as variance density spectrum is denoted as $\boldsymbol{E(\omega,\theta)}$, whereas $\boldsymbol{\omega}$ is denoted as absolute radian frequency. Both parameters are determined by Doppler-shifted dispersion relationship [16]. It must be noted that the significant wave height may be also be assumed as the wave height in the energy domain [11], as shown in Equation (5).

Meanwhile, the energy Period, denoted as Te, refers to the mean period of non-directional variance density spectrum. However, as the spectral shape is not provided, relationship between Te with the peak period, Tp, is shown in Equation (6), whereby α is 0.86 which is the coefficient in relation to the Pierson-Moskowitz spectrum [20]. This assumption may result to more conservative wave power but are less significant than errors in wave height as $\boldsymbol{P \propto T_e H_s^2}$. Hence, the energy domain wave height and wave period are derived from the numerical wave models, in the form of hindcast historical time series.

$$H_s = 4\sqrt{\int_0^{2\pi}\int_0^{\infty} E(\omega,\theta)d\omega d\theta} \quad (6)$$

$$T_e = 2\pi \frac{\int_0^{2\pi}\int_0^{\infty} \omega^{-1}E(\omega,\theta)d\omega d\theta}{\int_0^{2\pi}\int_0^{\infty} E(\omega,\theta)d\omega d\theta} \quad (3)$$

$$H_{m0} \sim H_s \quad (4)$$

$$T_e \sim \alpha T_p \quad (5)$$

Hence, the wave power is expressed in terms of energy flux per unit crest of wave spectrum. This quantity is a unit of measurement to represent the energy content at respective locations, and is a function of significant wave height and energy period as shown in Equation (7). The equation had been simplified under deep water condition [7] and is justified, considering that all water depths at all extraction points exceed 10 m from the shore [20]. Thus, the wave energy flux can be calculated as follows:

$$P = \frac{\rho g}{64\pi} H_{m0}^2 T_e = 0.491 H_{m0}^2 T_e \quad (7)$$

It is important to note that, for the amount of available wave energy resource to be harvestable, the supply must be sufficient and steady [5]. While there is no particular consensus on minimum wave energy resource that would be deemed as ‘harvestable’, generally considers wave energy flux less than 5 kW/m to be low, thus WEC deployment is not viable [21]. Hence, as the annual average wave power is derived for each site, a viable site for WEC deployment should generally have higher that 5 kW/m of wave energy flux. Otherwise, WEC implementation is not recommended. Besides, the temporal variation of wave energy resource in this study is also represented in terms of the steadiness of wave energy flux, to consider any extreme wave events. The daily and annual variation of wave energy flux variation across the study period was assessed based on the Coefficient Variation (CV). Hence, CV was calculated to check the stability of the wave energy resource supply, based on the ratio of annual standard deviation of the wave power time series, $\sigma[P(t)]$, and the annual average wave power, $\mu[P(t)]$ as shown in Equation (8) [5].

Overall, the temporal variation of wave energy resource in this study is represented in the form of wave energy flux time-series to acquire daily and annual average wave energy flux as well as the coefficient of variability.

$$CV = \frac{\sigma[P(t)]}{\mu[P(t)]} \quad (8)$$

3. Results and Discussion

Overall, based on the descriptive statistics conducted on the 6 offshore sites, the significant wave height datasets at spatially distant sites vary considerably, but does not account for nearshore areas. Based on the wave model validation at sites 1 – 6, RMSE for significant wave height and peak wave period are generally low and high correlation coefficient, which indicates good simulation performance in exception to site near the presence of offshore islands. Based on the temporal variability of wave energy resource, higher wave energy flux occurs during Northeast Monsoon. Based on the spatial variability of wave energy resource provided by DNA, there is higher wave energy resource in the offshore regions northeast and southeast of Dumaran Island as opposed to nearshore coastal regions. Despite this, the highest amplitude of average wave energy can only reach up to 3.5 kW/m. Hence, the wave energy flux acquired is compared to the global wave energy distribution [5] [4] and in nearby regions in Philippines [11]. Ultimately, the impact on wave energy harvesting viability in Dumaran waters is further discussed.

3.1. Statistical comparison between wave data

Accordingly, the statistical differences for the wave data reveals the extent of variability between the sites. Hence, wave height data at the 6 sites, as generated from MSL WW3 TC, were evaluated whether there are sizable differences between each site based on descriptive statistics and correlation matrix, ensuring that the extraction points represent the spatial variability of the site.

The summary of descriptive statistics is shown in Figure 5, whereas the correlation matrix is shown in Figure 6. The corresponding descriptive statistical analysis using R presents the statistical comparison between sites based on the mean, SD, maximum (Max.), range, skew, and kurtosis of significant wave heights at each site in Table 2. Overall, significant wave heights between the sites are generally varied but show some correlation to other sites in its vicinity due to the similarities in water depth, distance to shore and presence of offshore islands.

Table 2 Summary of descriptive statistics at Site 1-6

Site	Mean	SD	Max.	Range	Skew.	Kurtosis
1	0.47	0.46	4.10	4.10	1.44	2.31
2	0.59	0.56	5.40	5.40	1.35	1.94
3	0.60	0.56	6.60	6.60	1.37	2.45
4	0.62	0.57	7.30	7.30	1.22	1.77
5	0.69	0.61	7.10	7.10	0.94	0.62
6	0.47	0.46	4.10	4.10	1.44	2.31

Some statistical similarities can be observed for sites that are subject to similar distance to shore and subject to similar sheltering effects. This can be observed based on the mean of significant wave heights across the sites, whereby it varies between 0.47 m to 0.69 m. Notably for site 1 and site 6, both sites have similarly low mean significant wave height and lowest standard of deviation. This might be due sheltering effect from the presence of the Palawan Island and offshore islands, respectively. Consequently, both sites are less prone to be subject to extreme peak wave heights. This is corroborated by their low range, positive skewness, and positive kurtosis.

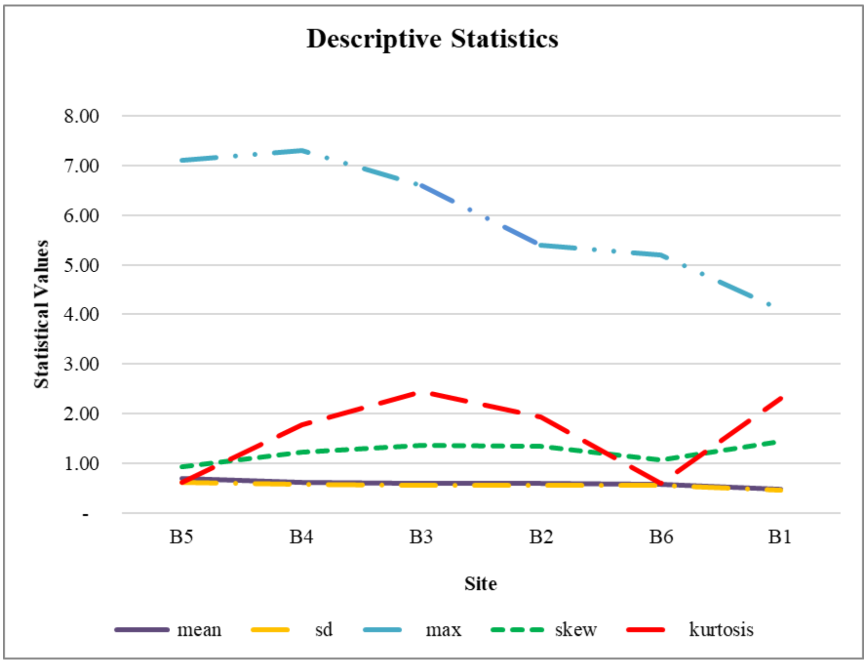

Figure 5 Descriptive statistics at each site

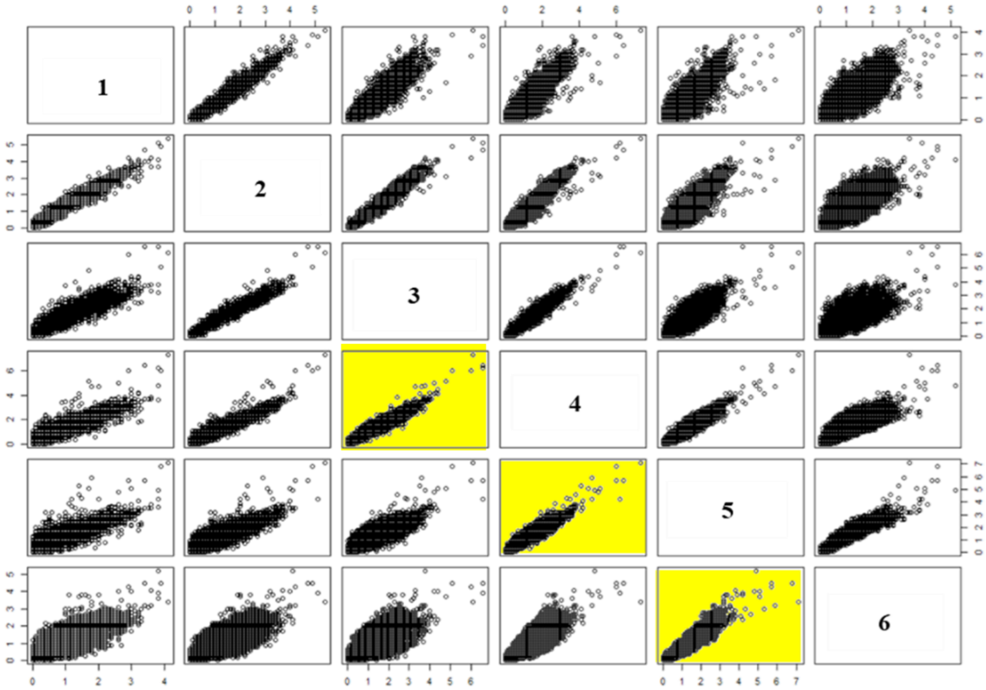

Figure 6 Correlation matrix of wave heights (bottom left) and wave period (top right) at site 1 – 6 for 40 years.

The highlighted cells, namely between site 3 and 4, site 4 and 5 alongside site 5 and 6, shows high correlation of significant wave heights. Site 3, 4, and 5 may correlate as it has similar water depth. However, due to the presence of offshore islands near both sites 4 and 6, it is important to consider this geographical variability. Essentially, there are some correlation and statistical similarities between the sites that are either in proximity to each other, or subject to similar water depth and sheltering effects from offshore islands. Nevertheless, the sites differ in other factors thus is important to be represented in the assessment. It was also noted that sites 1 – 6 had not represent area near coastal, thus the additional reference point using MIKE21SW (A – H) was justified.

3.2. Wave model validation

With exception to site 6, the MSL WW3 TC model simulation corresponds well with the more extensive simulation by MIKE21SW in terms of Root-Mean-Square error (RMSE) and correlation coefficient (CC). The corresponding RMSE and CC for significant wave height and wave period is present in Table 3 and Table 4. Overall, the RMSE values for significant wave height ranges between 0.26 m to 0.42 m. Whereas the CC for significant wave height corresponds very well ranging between 90% to 93%. As for the peak wave period, the RMSE values range between 1.25 s to 1.38 s and CC ranges between 62% to 74% for site 1 – 5. On the other hand, it is observed that there are high uncertainties in site 6 for both wave height and wave period. The high uncertainty especially for wave period at site 6 also results to high RMSE at 1.83 s. This high uncertainty may be due to the location of site 6 at relatively shallower seabed and subject to surrounding offshore islands.

To visualise the comparison between the wave models, time-series comparison for hindcast significant wave height and wave period generated between MSL WW3 TC and MIKE21SW, as shown in Figure 7. Overall, considering the RMSE, CC and time-series comparison to MIKE21SW, the MSL WW3 TC model shows good correlation in terms of wave height and wave period. This indicates good model performance and is reliable for the wave energy assessment.

Table 3 RMSE and CC values for significant wave height, Hm0.

Site	RMSE (m)	CC (%)
1	0.26	91
2	0.34	93
3	0.32	93
4	0.36	93
5	0.40	93
6	0.42	90

Table 4 RMSE and CC values for peak wave period Tp

Site	RMSE (s)	CC (%)
1	1.25	66
2	1.38	62
3	1.25	72
4	1.21	74
5	1.29	68
6	1.83	48

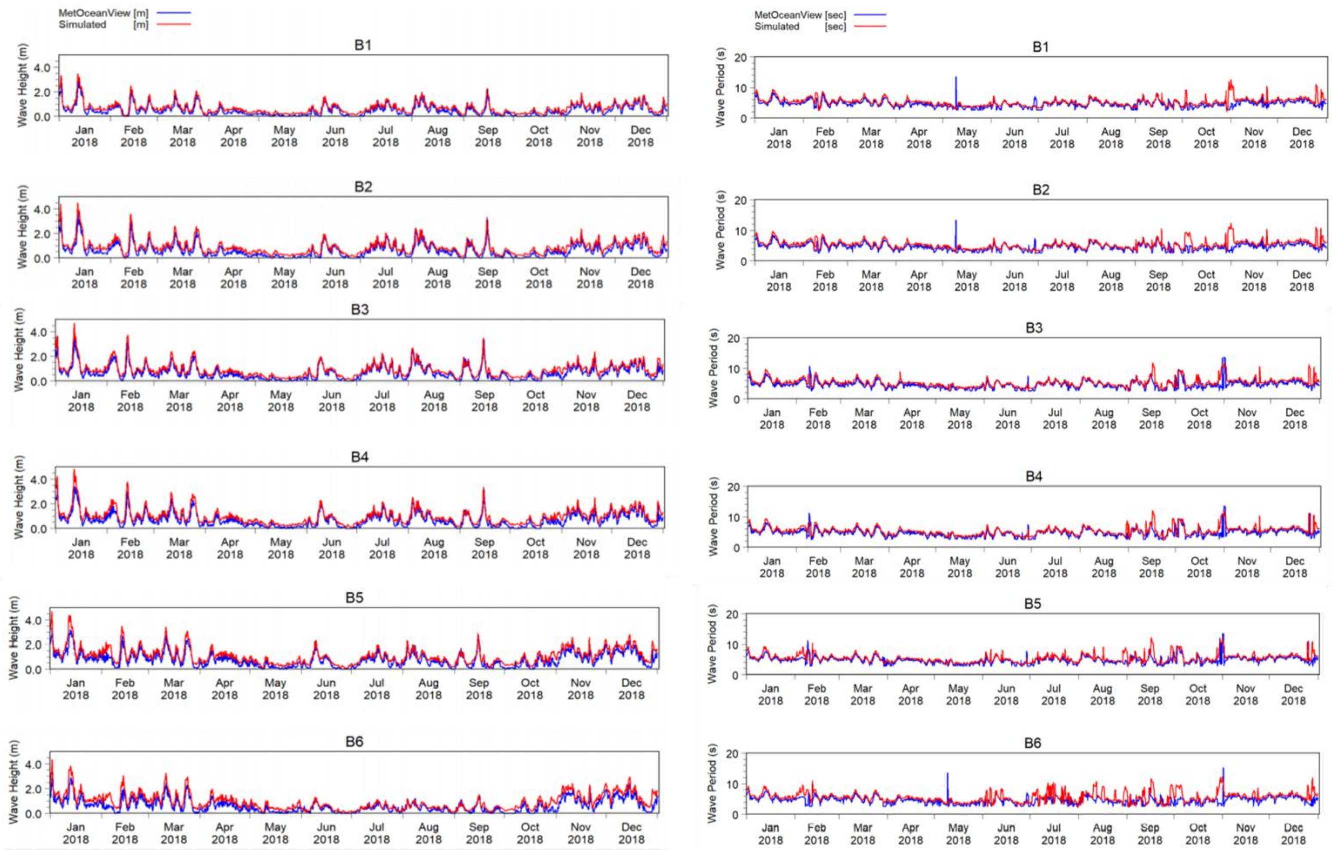

Figure 7 Comparison of hindcast significant wave height and wave period between MSL WW3 TC and MIKE21SW.

3.3 Wave energy resource temporal variability

Wave energy in Dumaran waters was found to be generally low, stable from year to year but extreme during winter monsoon season. As wave data was generated, its corresponding time series delineates how it varies inter-annually and intra-annually within the study period [13], indicating its mean value as summarised in Table 5 and in bar chart Figure 8, together with the inter-annual SD and CV.

The overall wave energy flux at these sites tends to be low between 0.77 kW/m to 4.43 kW/m. Based on Figure 9 – 11, wave energy at all sites can be described as 'choppy' throughout 40-year study period. This is because the wave energy rise and fall quickly and remains low, which may be due to the larger scale of sheltering effects from surrounding terrains [6], as the Sulu sea is semi-enclosed. For sites nearshore or near small offshore islands, this effect may cause the wave energy to be much lower. Namely, based on the time series of sites A, B, C and D which are located nearshore in Figure 12, it experiences even and low wave energy during summer monsoon. In effect, their respective mean annual wave energy are lower in comparison to the other sites, at 2.93, 2.96, 1.59 and 0.77 kW/m respectively. Site C and D are in the southwest coast of Dumaran Island, thus experience sheltering effect from the Palawan terrain which significantly reduces wave energy.

Notably though, certain sites experience more drastic peaks during the northeast monsoon, namely sites E, F and G. At these sites, the peaks which occur during the winter season ranges between 30 kW/m to 80 kW/m. In fact, a very drastic increase of wave energy is observed in Dumaran waters during the Northeast Monsoon season. Though maximum wave energy does not govern the WEC deployment, it is equally clear that extreme wave conditions may cause damage to WEC, therefore should not be underestimated.

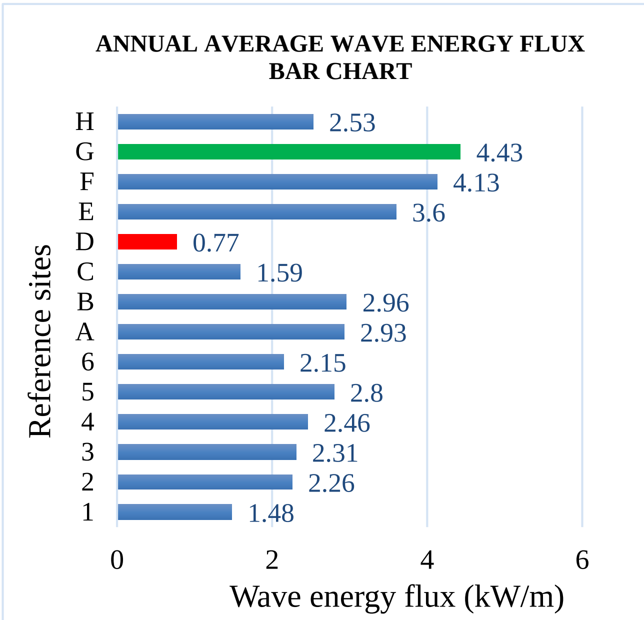

Figure 8 Bar chart of the annual average wave energy flux across all sites.

Table 5 Summary of annual average wave energy flux, maximum wave energy flux, coefficient variation and standard deviation.

Site	Pavg (kW/m)	Pmax (kW/m)	CV (%)	SD
1	1.48	35.46	3%	0.047
2	2.26	50.60	2%	0.043
3	2.31	67.00	2%	0.063
4	2.46	80.24	1%	0.039
5	2.80	57.06	6%	0.196
6	2.15	42.75	4%	0.076
A	2.93	72.58	6%	0.18
B	2.96	71.39	1%	0.04
C	1.59	28.00	8%	0.13
D	0.77	22.09	6%	0.05
E	3.60	90.98	5%	0.17
F	4.13	79.37	6%	0.24
G	4.43	89.92	1%	0.06
H	2.53	66.32	2%	0.05

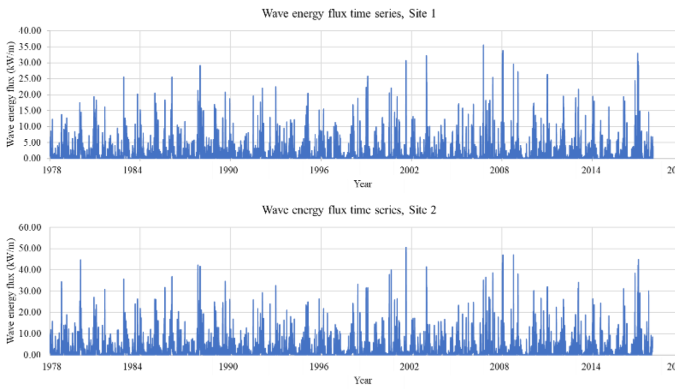

Figure 9 Wave energy flux variation across 40 years (1978 – 2018) at Site 1 and 2.

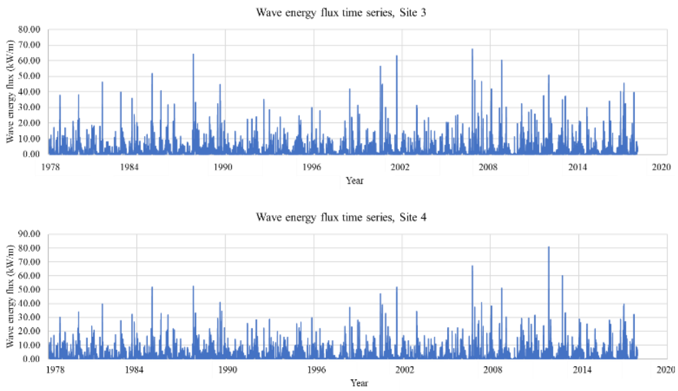

Figure 10 Wave energy flux variation across 40 years (1978 – 2018) at Site 3 and 4.

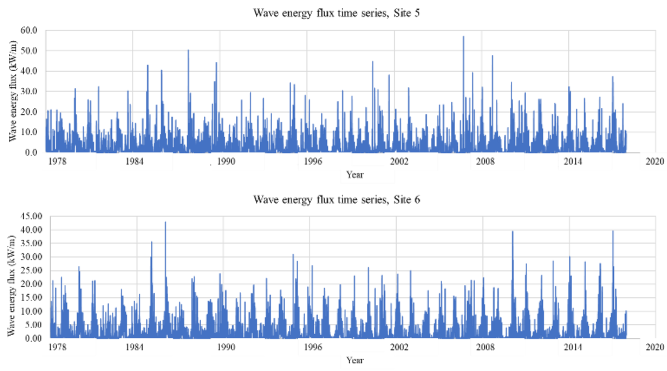

Figure 11 Wave energy flux variation across 40 years (1978 – 2018) at Site 5 and 6.

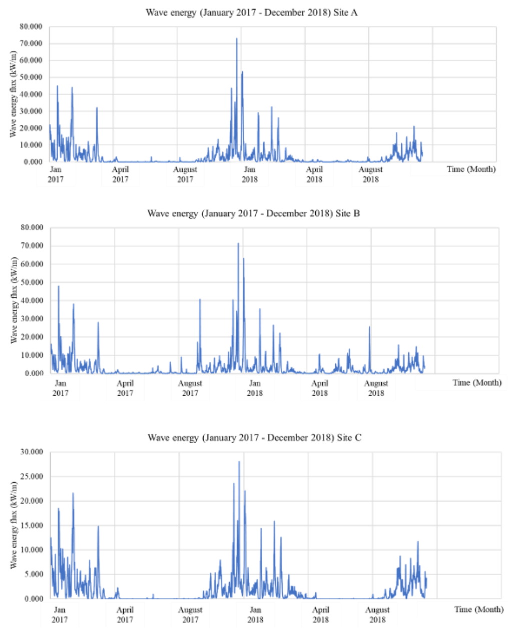

Figure 12 Wave energy flux variation across January 2017 to December 2018 at Site A – C.

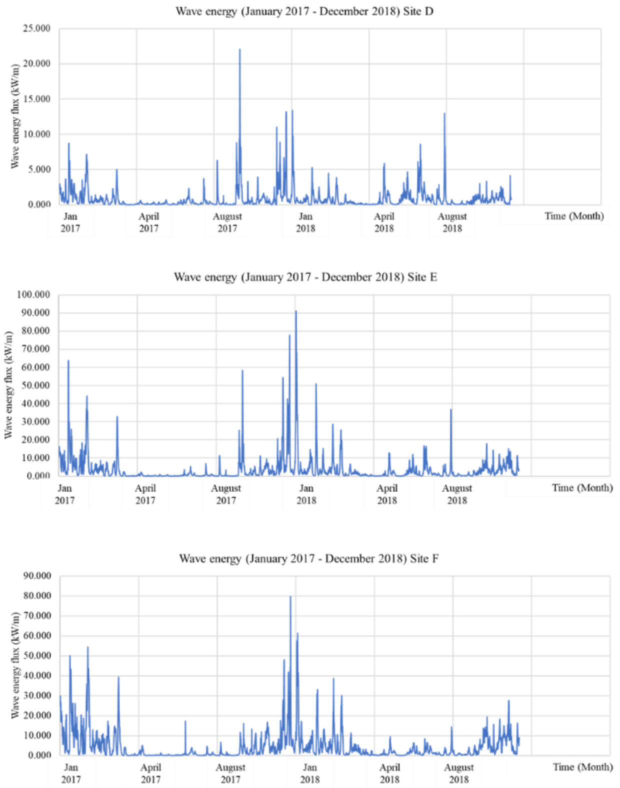

Figure 13 Wave energy flux variation across January 2017 to December 2018 at Site D – F.

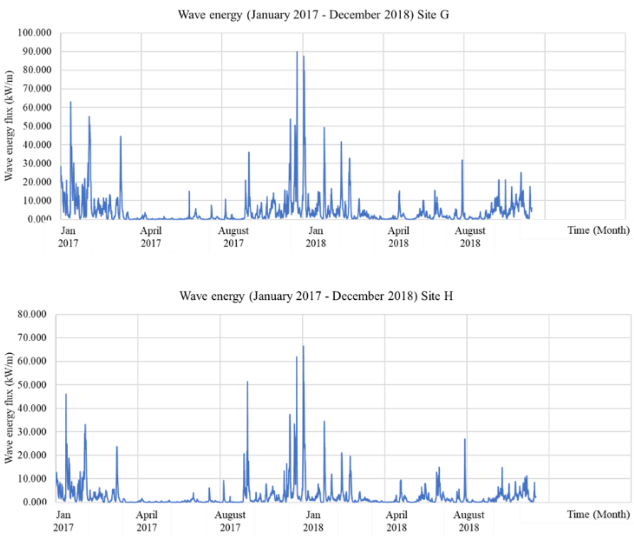

Figure 14 Wave energy flux variation across January 2017 to December 2018 at Site G – H.

3.5 Feasibility of wave energy harvesting in Dumaran waters

Based on the previous analysis, site G was identified with the highest and most stable wave energy flux. The average wave energy that can be harvested in the site is 4.43 kW/m. While there is no consensus on the minimum wave energy flux that is considered harvestable, wave energy flux of greater that 5 – 15 kW/m are usually adopted to be recommended as having potential of WEC [21]. Hence, although site G was the most viable relative to the other sites, there are several challenges in implementing the WEC due to economic and technical issues. Namely, the technology itself requires high capital expenditures (CAPEX) [11]. This is because the technology is still in its early development stage. While the local demand and price of electricity may drive the profitability of the project [11], this may demand great electricity output from the WEC to ensure that it is economical. With current development of WEC efficiency of 38% for pressure differential WEC at best [23]. Thus, further extraction of energy is not feasible, considering that current wave energy resource is less than 5 kW/m. The wave energy flux at the study site is significantly low in comparison to commonly recommended areas for wave energy generation, which as an average of 15 kW/m of wave energy potential [14]. Other technical and economical challenge also involve the existing infrastructures to connect WEC. However, in this case where the site proposed is in remote offshore, it requires grid connectivity infrastructure. The installation of such grid had been excluded in CAPEX estimation, therefore would incur very high cost.. In practice, without grid connectivity, the WEC deployment in rural regions are simply not viable [24]. Therefore, the lack of grid connection further strains the economics for WEC implementation. Consequently, WEC is not viable within 100 km of Dumaran waters.

4. Conclusions

Pertaining assessment of wave energy density, this study has demonstrated the average annual wave power in Dumaran waters to be below 4.5 kW/m, whereby site G located in offshore northeast of the island was the highest at 4.43 kW/m and the most stable (CV=1%). While the year-to-year variation is generally predictable, the intra-annual variation of wave energy shows uneven extreme peaks during northeast monsoon. On the other hand, deep water offshore regions in the northeast and southeast experience the highest wave energy flux, but only reaches up to 3.6 kW/m – 4.43 kW/m of average annual wave energy. Due to insufficient wave energy flux ($P < 5$ kW/m) and unavailable grid connection, WEC deployment is not economically and technically viable in Dumaran Island.

Meanwhile, the study concluded the model validation by using MIKE21SW numerical results showing good correspondence. The corresponding RMSE and CC values calculated based on significant wave heights and wave periods datasets between MSL WW3 TC and MIKE21SW showed overall good model performance, as RMSE values are less than 30% for both wave height and wave period as per IEC guideline. Conclusively, this study had contributed comprehensive analysis for wave energy density in Dumaran waters with validated wave data

Essentially, this study can be improved by validation of wave model with measured buoy data, expanding study area and research considerations of other marine renewable energy. The buoy measurements were not acquired in this study due to time constraints but is required by IEC standards. While model validation across most sites shows good model performance, areas in shallow seabed areas have higher uncertainties. Thus, should be validated with buoy data. This measure in future works into would further improve the study's reliability.

Besides, further study should be conducted to assess wave energy beyond 100km radius from Dumaran Island. This is recommended as higher wave energy was observed in further and deeper waters located northeast and southeast of the island. Furthermore, as the further offshore sites are far from Palawan terrain and offshore islands, less sheltering may be observed which could result in higher energy content. Consequently, extending the study area, if permitted with availability of grid connectivity infrastructure, may provide sufficient wave energy to Dumaran Island. Otherwise, another approach is venturing to other marine renewable wave energy. Namely, technologies such as OTEC should be researched further for the context of Dumaran waters. Considering the deep basin observed from bathymetry provided, the large depth variation may be favourable for OTEC developments. Hence, further research to venture into the viability of these technologies in Dumaran Island is recommended to overcome energy insecurity of its people. Altogether, further research is necessary in terms of data validation with buoy data, extending study area beyond 100km and consideration of other marine renewable energy technologies.

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