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ARTICLE

Assessment of Wave Power at the Iraqi Coast of the Arabian/Persian Gulf

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ABSTRACT

The worsening of global warming due to burning fossil fuels and the global energy crisis have led to an urgent need for renewable and clean energy sources that have little impact on the environment. One of the most important and largest alternative energy sources is marine waves, which have enormous energy that can be utilized using the correct and appropriate methods. The present work aims to study the possibility of investing wave energy by extracting the wave power at the northern coasts of the Arabian Gulf using numerical models for zero crossing and spectral analysis methods (SWAN model). Numerical models were used to analyze metrological data to estimate the wave power, estimated at 0.2664 kW/m by the zero-crossing method, and 0.386 kW/m by the spectral analysis method at a depth of 19 meters. The weak wave power may be due to the shallowness of the Gulf compared to other seas, in addition to the weather conditions in the study area, which are directly affected by weather phenomena, especially wind speed. The research recommends conducting further studies on wave energy and studying the most advanced methods for extracting it because of its great economic returns for Iraq.

Keywords: Arabian (Persian) Gulf; Renewable Energy; Spectral Analysis; Wave Power; Zero-Crossing Method

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1. Introduction

The increase in global warming has led to increased demand for clean renewable energy sources with little impact on the environment. Marine wave energy is one of those renewable resources that interest in developing has increased recently. Marine wave energy refers to the energy that can be harvested from ocean waves through the use of devices called wave energy converters (WECs)[1]. Marine waves represent a significant source of renewable energy because it has huge energies and is considered a continuous resource that can be predicted, unlike solar energy and wind energy, which suffer from low production efficiency and intermittent energy[2, 3].

Waves are formed when the wind blows over an area of the sea, wind energy is converted into wave energy. We can consider a sea wave as a combination of many elementary waves that have different frequencies and directions. A wave usually loses its energy by friction with the sea floor and breaks at the shore, and waves may be reflected if the beach is rocky and steep enough[4]. Long-term sea waves can be thought of as a combination of pure sea waves and swells[5].

There are different types of marine waves, some of them have short periods, such as capillary waves with a wave period less than 0.1, and others have long periods, such as tidal waves[6]. In general, the waves suitable for energy extraction are those with periods ranging from 1–25 s and a wavelength It extends from 5–200 m as in **Figure 1**[6]. The idea of extracting energy by waves dates back to the year 1799 when the first patent in this field was registered[7, 8]. The maximum global wave energy has been estimated theoretically at about 30,000 TWh/yr, which constitutes about 20% of the world's energy consumption in 2019, but unfortunately, only less than 10% of it has been exploited for economic and technological reasons[9]. WECs devices convert the motion of ocean waves into electricity, which can be fed into the grid and used to power homes and businesses. Those who will benefit most from marine energy sources are the coastal regions, which are far away from the main cities, as it will provide them with a close and clean source of energy, exploiting wave energy can also avoid the risk of flooding on coasts resulting from sea level rise due to global warming[10–12].

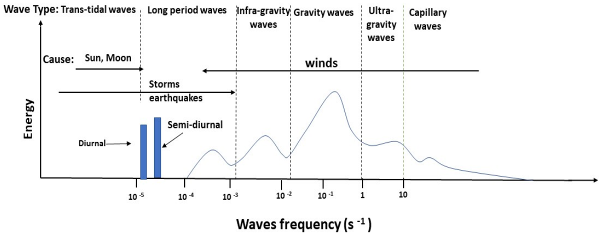

Figure 1. Types of surface waves[6].

One of the advantages of wave energy is that it has a high energy density compared to other energy sources for the seas, such as tidal energy, but it has some disadvantages that it is affected by continuous climatic fluctuations, in addition to the large economic costs of designing energy extractors WEC to withstand harsh environmental conditions, so an assessment of climatic conditions must be made when calculating Wave energy for different periods[13]. Marine waves are considered oscillating waves with large annual and seasonal changes. Therefore, the establishment and development of energy harvesting stations (WECs) require the prediction of wave energy through time series for long periods for accurate prediction of the appropriate place that has sufficient wave energy[3, 14]. These time series are not available in most regions, so specialists usually resort to Numerical and analytical models that can predict the total potential energy[15].

Several methods are used to estimate wave energy resources by finding the main wave parameters such as the wave period and the significant wave height. The most important of these methods is the zero-crossing analysis, which is done by extracting wave parameters from surface deflections, as well as the spectral analysis method, which uses several models, including the JONSWAP model to parametrically predict wave parameters, the nearshore wave simulation (SWAN) model, and WAVEWATCH III model[16].

This work aims to evaluate the wave energy of the coastal areas of the Arabian Gulf in Al-Faw Grand Port basin at the Iraqi territorial waters and to study the feasibility of establishing stations to extract and benefit from energy waves, sheds light on the prediction of wave energy by metrological parameters measuring in the study area. Although the time series is small, it can give a visualization of the potential power of the waves.

2. Material and Method

2.1. Study Area

Figure 2 shows the study area in the Grand Faw Port at the Iraqi maritime border north of the Arabian Gulf. The Grand Faw Port is located in the northern part of the Arabian Gulf, south of Basra/Iraq, at latitude: 29.98839° and longitude: 48.47099°, specifically at Ras Al-Bisha, which is located at the end of the Iraqi continental shelf. The port is 19 m deep and its total area is about 54 km^2 [17]. It embraces the eastern breakwater, the longest breakwater according to the Guinness Records. The Iraqi coast of the Arabian Gulf is about 58 km. Arabian Gulf is considered a shallow semi-enclosed continental shelf with an average depth of 35 m[18, 19]. Al-Faw Port is regarded as the mouth of the Shatt al-Arab River, which results from the confluence of the Tigris and Euphrates Rivers in southern Iraq. Therefore, this region was affected by the flow of the Shatt al-Arab River and sedimentation processes in the Arabian Gulf[20].

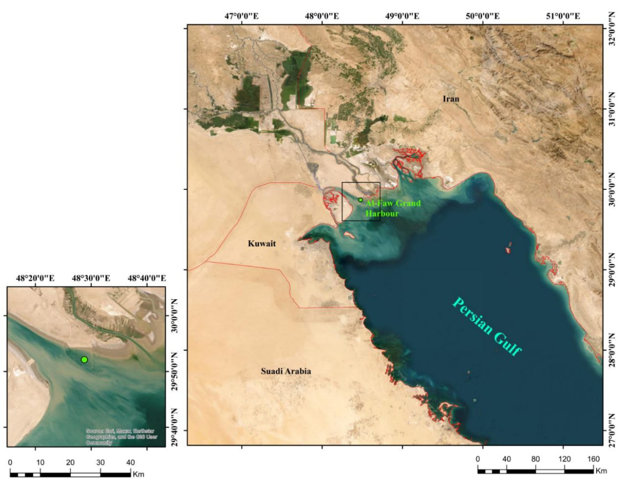

Figure 2. Al-Faw Grand Port basin in northern Arabian/Persian Gulf southern Iraq.

2.2. Data Collection

SWAN is a third-generation numerical model for estimating wave parameters in coastal and estuarine areas using wind, current, and seafloor conditions. For the required calculations, one month was chosen to run the SWAN model. The reason for this is the time should be short enough to capture the effect of rapid changes in wind speed and direction on the wave and large enough to be compatible with practical estimates[21]. May 2022 was chosen based on the available data.

Metrological parameters in the study area were measured to feed the model, in addition to measuring sea level using ultrasonic and radar devices. Wind speed and direction data used as the main input to feed the SWAN model were at 8-hour intervals (i.e., three times per day) and were measured at 10 m above sea level by the port meteorological center. The grid points were determined by the port meteorological center, so we do not have sufficient information.

Sea level gradients were measured for the same period to feed the zero-crossing model and to compare the results between the two models.

2.3. Method

Numerical modeling to find the wave parameters was done using zero-crossing and spectral analysis methods by Al Sirag Al Mudea Company. Al Sirag Al Mudea is a company that works to effectively detect objects and munitions and determine their location on the seabed in the Al-Faw Grand Port construction project in Basra, Iraq.

The zero-crossing method is the most common way to measure the wave period by calculating the propagation delay time[22]. This is done by setting a certain threshold level and measuring half the period beyond that level. In this method, polynomials represent the waves' sinusoidal shape[22]. The zero-crossing model was fed using sea surface slope measurements, wave parameters were extracted through the model as listed in **Table 1**.

Spectral distribution describes marine energy density as a function of wave frequency that can give us the amount of energy expected by a wave at a given frequency[23]. Measuring the significant wave height and wave period depends on considering that sea waves are a mixture of wind-driven waves and swells[5]. The sea states include a large number of regular waves. Therefore, the mixture of different amplitudes, frequencies, and directions is described using the density of spectral function[18].

In the SWAN wave model, propagation, dissipation, generation, and nonlinear interactions between waves are taken into account[16, 21]. The evolution of the wave spectrum is described by the wave energy balance in specific cells. The energy balance states for each cell of a given size within the wave spectrum over a given period the energy change equals the net energy import plus the net local generation.

This system is valid for every frequency component of the wave spectrum and is known as the energy balance equation. If the energy balance equation is applied to shallow coastal areas its formula i [21] equation (1):

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}\left(C_X N\right) + \frac{\partial}{\partial y}\left(C_y N\right) + \frac{\partial}{\partial \sigma}\left(C_\sigma N\right) + \frac{\partial}{\partial \vartheta}\left(C_\theta N\right) = \frac{S(\sigma,\theta,x,y,t)}{\sigma} \quad (1)$$

The left term in the equation represents the rate of change of action with time, the propagation in space on (x, y) axes, and the change in frequency and refraction due to currents and depth. The right term represents the effect of energy dissipation and nonlinear interactions between waves.

The energy of the extracted waves depends largely on the depth of the water, taking into account the diffraction and refraction that affect the wave propagation process [24]

The wave height can be calculated using the relation [24], equation (2):

$$H_{mo} = 4\sqrt{m_0} \quad (2)$$

where m_0: zero order moment of sea waves.

And sea wave period [24] equation (3):

$$T = \frac{m_{-1}}{m_0} \quad (3)$$

From the previous two equations, the wave parameters were estimated by spectral analysis using the SWAN model as listed in **Table 2**.

The SWAN model was fed by the metrological data measured in the study area in **Table 3**, shows the change in wind speed and direction throughout the measured period.

The wave energy was evaluated based on the values of the significant wave height and the wave period Tp or the zero-crossing period Tz. The evaluation of wave energy resources is mainly based on these parameters to calculate the potential of the marine area.

The wave power (P) at a specific location can be found by integrating of wave energy spectrum, as [25] equation (4):

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} c_g\left(w\right) E\left(w,\theta\right) dw d\theta \quad (4)$$

where ρ: density of seawater, g: acceleration, c_g: group velocity in terms of intrinsic frequency (w), E: wave energy with w frequency, and θ: propagation direction.

In shallow water group velocity depends on the depth [26] equation (5):

$$C_g = \sqrt{gd} \quad (5)$$

In general, the wave energy power is given by the mathematical relation [13, 21] equation (6):

$$P = \frac{\rho g^2}{64\pi} H_s^2 T \quad (6)$$

It mainly depends on the significant wave height H_S which represents the average of the highest third of the wave height [24].

For regular waves [21] equation (7):

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

3. Results and Discussion

The wave parameters in the study area were extracted using the zero-crossing method by measuring surface deviations, the wave parameters data shown in **Table 1** were obtained. the wave density was estimated by using equations mentioned previously at about 0.2664 kW/m by using wave parameters data, taking into account that the water density ρ = 1025 Kg/m^3, where the estimates were based mainly on the values of the significant wave height.

The data in **Table 1** are presented in **Figure 3** as time variances that show the dynamic behavior of the wave parameters (maximum wave height, significant wave height, and wave period) with time.

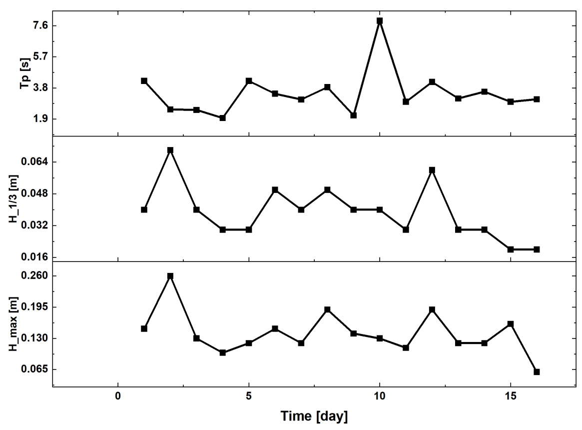

Figure 3. Variation of the maximum wave height, significant wave height, and wave period with time in the zero-crossing method for May 2022.

Wave intensity was also estimated using the spectral analysis method by estimating wave parameters in coastal areas using the SWAN model as shown in **Table 2**. An estimated value of wave intensity of 0.386 kW/m was obtained using the equations mentioned previously. The data in **Table 2** are presented in **Figure 4** as time variances that show the dynamic behavior of the wave parameters (significant wave height, and wave period) with time.

Table 1. Wave energy power by zero-crossing method.

No. of Waves	H_max [m]	H_1/100 [m]	H_1/3 [m]	T_1/3 [s]	T_z [s]
457	0.15	0.07	0.04	1.54	1.31
379	0.26	0.13	0.07	2.02	1.58
414	0.13	0.06	0.04	1.93	1.45
381	0.10	0.05	0.03	2.06	1.57
440	0.12	0.05	0.03	1.85	1.37
364	0.15	0.07	0.05	2.20	1.64
351	0.12	0.06	0.04	2.30	1.71
390	0.19	0.08	0.05	2.15	1.53
400	0.14	0.07	0.04	2.01	1.50
319	0.13	0.06	0.04	2.52	1.88
336	0.11	0.05	0.03	2.15	1.79
307	0.19	0.09	0.06	2.57	1.95
312	0.12	0.05	0.03	2.25	1.92
376	0.12	0.06	0.03	2.27	1.59
364	0.16	0.06	0.02	2.49	1.65
320	0.06	0.03	0.02	2.93	1.87

Table 2. Wave energy power by spectral analysis.

Total Waves					Sea Waves				Swell	
No. of Waves	H_m0 [m]	Tp [s]	T_m-1,0 [s]	T_m2 [s]	H_m0 [m]	Tp [s]	T_m-1,0 [s]	T_m2 [s]	H_m0 [m]	T_m2 [s]
457	0.16	4.23	1950.75	0.04	0.14	4.23	1862.88	0.04	0.03	0.53
379	0.19	2.49	1738.61	0.04	0.16	2.49	2087.14	0.05	0.03	0.56
414	0.15	2.46	1911.76	0.04	0.13	2.46	1937.90	0.04	0.03	0.59
381	0.13	1.96	2533.27	0.04	0.11	1.96	2070.40	0.05	0.02	0.62
440	0.14	4.23	2621.27	0.04	0.12	4.23	1953.88	0.04	0.02	0.63
364	0.16	3.45	2396.34	0.04	0.14	3.45	2187.20	0.05	0.03	0.60
351	0.14	3.09	2183.39	0.04	0.12	3.09	2233.27	0.05	0.03	0.54
390	0.17	3.85	2560.71	0.04	0.14	3.85	2091.47	0.05	0.03	0.61
400	0.16	2.12	2448.74	0.04	0.13	2.12	1996.00	0.05	0.03	0.60
319	0.14	7.90	2556.01	0.04	0.11	7.15	2290.14	0.05	0.04	0.49
336	0.13	2.96	5411.15	0.05	0.11	2.96	2256.34	0.05	0.03	0.68
307	0.16	4.17	3230.17	0.05	0.13	4.17	2561.47	0.06	0.03	0.57
312	0.12	3.16	3350.50	0.05	0.10	3.16	2346.91	0.05	0.03	0.55
376	0.14	3.57	3045.40	0.04	0.11	3.57	2187.25	0.05	0.03	0.64
364	0.12	2.96	5356.31	0.04	0.10	2.96	2105.25	0.04	0.03	0.73
320	0.10	3.11	7996.80	0.04	0.08	3.11	2262.09	0.04	0.03	0.80

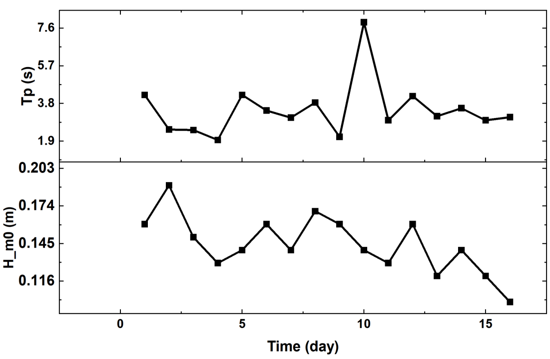

Figure 4. Variation of significant wave height, and wave period with time in the spectral analysis method for May 2022.

These values are considered small compared to other locations in the world. The reason is mostly due to the shallowness of the Arabian Gulf in general, especially in coastal areas, where water depth is considered one of the most important parameters that directly affects energy density values. Wave energy is also greatly affected by the surrounding climatic conditions, such as wind speed, which can greatly increase the amount of energy that is extracted from waves.

Meteorological parameters have a major role in finding wave parameters such as the significant wave height and wave period, also changing weather conditions have a possible effect that can double wave intensity values in marine areas. Meteorological parameters were calculated at the study site using devices to measure weather data, such as wind speed, air pressure, and temperature, as shown in **Table 3**. The data of meteorological parameters in **Table 3** are presented in **Figure 5** which shows the temporal variations of wind speed and direction which were used as input data for the SWAN program to extract wave parameters.

Table 3. Meteorological parameters for measuring wave power.

Air Temp 1 [°C]	Air Temp 2 [°C]	Barometric Pressure [Mbar]	Wind Speed [M/S]	Wind Direction [°N]	Gust Speed [m/s]	Gust Direction [°N]	Water Temp [°C]	Water Level 1 Ultrasonic [M]	Water Level 2 Radar [M]
28.95	28.90	1005.99	4.7	238	5.5	237	64.14	0.370	0.356
28.78	28.80	1005.62	4.2	230	4.5	228	68.74	−0.054	−0.069
28.38	28.38	1005.07	3.6	238	4.3	246	21.62	−0.516	−0.521
27.59	27.60	1005.27	4.1	277	4.7	277	-	−0.906	−0.909
27.80	27.81	1005.39	4.5	251	4.8	253	43.03	−1.070	−1.074
27.92	27.94	1005.81	3.9	267	4.4	267	21.34	−0.884	−0.892
27.38	27.41	1005.97	2.9	241	3.1	240	58.22	−0.379	−0.387
27.37	27.42	1006.53	3.0	252	3.5	255	13.02	0.287	0.272
28.46	28.54	1007.07	1.4	234	1.9	250	34.55	0.895	0.885
29.23	29.28	1007.52	3.3	289	3.7	289	-	1.282	1.277
31.59	31.56	1007.25	3.4	266	3.7	267	49.90	1.342	1.347
32.80	32.86	1006.72	1.8	197	2.1	179	-	1.071	1.074
32.84	32.84	1006.00	3.2	182	4.2	181	18.11	0.570	0.567
31.80	31.89	1005.18	3.5	211	4.2	211	33.60	−0.064	−0.065
32.56	32.63	1004.68	3.4	203	4.1	209	10.56	−0.755	−0.740
34.14	34.19	1004.29	3.4	221	4.6	216	38.65	−1.355	−1.336

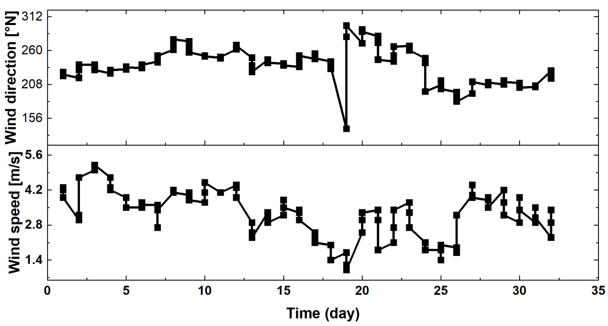

Figure 5. Variation of wind speed and wind direction with time for May 2022.

The importance of calculating wave energy season lies in the difference in estimating wave energy in different seasons, Previous literature has shown there is a discrepancy in the energy of the waves between the winter and summer seasons, as the energy of the waves in the winter can reach 10 times its value in the summer, it can also vary from week to week, depending on the weather conditions [4]. For example, Lin Y., et al. [14] noticed that the highest density of waves flow in the Taiwan Strait for the period from October to March (in the winter season) and weakest for the period from April to December. Studies also showed that waves generated by the winds are predominant in the inland seas [27], where stormy seas contain a very large amount of wave energy and contribute significantly to the annual mean values of wave energy, but severe waves can cause significant damage to energy retrieval equipment [4].

The results obtained, despite the short period, are consistent with previous studies that were conducted in sites near the study area in the Arabian Gulf Basin, such as the study of Kamranzad B., et al. [18] along the Arabian/Persian Gulf basin for the period 1984–2008, obtained wave power values ranging between 0.39 kW/m for areas close to the shore, which includes our study area, and 3.93 kW/m for areas located in the middle of the Gulf depending on the difference in wind speed, which varied in value between 5.98 and 4.53 m/s, **Figure 6** shows the variation in the distribution of wave power in different areas of the Arabian Gulf basin according to their distance from the coast. This study concluded that wind speed has a significant impact on wave strength, as any slight change in the wind speed causes a substantial impact on the strength of the wave, also there is a great variation in the values of the wave power in different seasons, where the results showed that it increases in the winter and decreases in the summer. These results were confirmed by other studies such as [28–30]. Also, Goharnejad H., et al. [28] estimated the wave power by simulating computer models of waves at a point close to our study site, and it was found that the significant wave height ranges between 0.1–0.5 m, with a wave period ranging between 2–3 s, and a wave power ranging between 0.12–0.33 kW/m. A study conducted by Mahmoodi Kumars et al.[31] in different regions of the Arabian Gulf for 20 years, found that wave power was weak due to the weak strength of the winds in the gulf and the shallow depth of most of its parts, where the middle parts of it had the highest average annual wave strength estimated at 76308 kw/h. The weakest in the areas near the beaches, which amounted to 44946.35 kw/h, with wave durations that ranged between 2.5–5 s, and the maximum wave height reaches to 1 m.

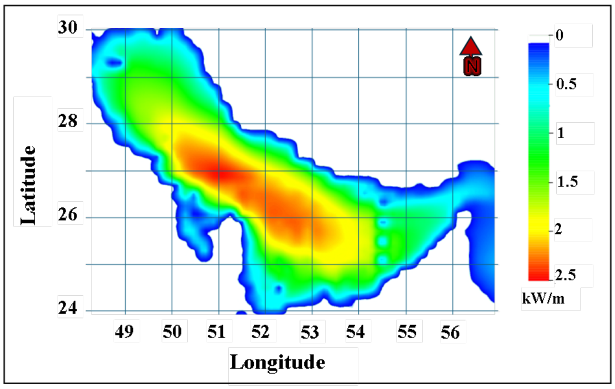

Figure 6. Wave power distribution in the Persian/Arabian Gulf[18].

Studies rarely focus on the wave resources of the Arabian Gulf, due to the low wind wave potential of this semi-closed basin, when compared to some of the wave resources of other seas, for example, the coasts of North America, which have a high energy density ranging between 20–30 kW/m, and some regions of South America that are less exposed to strong waves, which range from less than 8 to 13 kW/m[4]. While the wave energy extracted in the East China Sea was about 3–5 kW/m, which would save a lot of energy due to China having a long coastline[32]. In another study for wave energy in the Mediterranean region, the highest value of the annual average was estimated at 9.4 kW/m near the European coasts, while in the south of Crete island, it was found that the annual average of about 5.8 kW/m[33].

Despite the weakness of the wave potential in the study area, it may constitute an important resource that can be exploited if appropriate tools are used, for example, a high-power output can be obtained from low frequencies using a triboelectric nanogenerator, which is characterized by low cost compared to other energy extractors[2]. Wave energy in the Arabian Gulf basin is also subject to increase, where some research has concluded, Pourali, Mahmoud et al.[34] there is a future increase in wave energy resources in the Arabian Gulf, due to climate changes resulting from increased concentrations of greenhouse gases by a rate ranging from 21–45%. The rise in sea level in the Arabian Gulf due to global warming is also considered an important factor that will increase wave capacity in the future[35].

4. Conclusions

Climate changes and their consequences resulting from burning fossil fuels are mainly considered a threat to many communities, especially coastal communities, and areas at risk of flooding. This requires moving towards energy production in safer ways, to preserve the environment. One of the most important and effective sources is the wave energy of the world's seas, which constitute most of the globe's areas and have huge estimates of energy that only a small part has been utilized.

In the current research, Data were collected in the northern Arabian Gulf at Al-Faw Port in Basra, Iraq in 2022 (unfortunately, no data were available for a longer period) using special measuring devices. The wave power was estimated by finding the wave parameters by the surface slopes and metrological data using zero-crossing and spectral analysis (SWAN model) methods. The wave power was estimated at about 0.2664 and 0.386 kW/m for both zero-crossing and spectral analysis methods, respectively.

The parameters of meteorological make a big difference in calculating the wave power, it is possible that the assessment of wave power in the winter doubles its value in the summer, and the wind speed is a decisive factor in the calculation, where any small change in wind speed causes a major change in estimating wave power.

Wave energy will be an important source of energy in the future if appropriate methods are applied in its construction, design, and maintenance. It is possible to benefit from this clean energy, especially in cities bordering the sea.

Author Contributions

A.M.A.M. conducted the manuscript editing, data processing, and analysis, and discussed the results; N.F.S. participated in the analysis and interpretation of the results and discussed the proposed methods; and M.A.H. reviewed the manuscript, proofread, and created the maps.

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Institutional Review Board Statement

The study does not require ethical approval.

Informed Consent Statement

Not applicable.

Data Availability Statement

All authors agree to share their research data upon request.

Conflicts of Interest

The authors certify that there is no conflict of interest to declare.

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