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Assessment of Wave Energy Potential along the Egyptian Mediterranean Coast

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Keywords:

Wave Energy Potential; Assessment; Levantine Basin; Egyptian Mediterranean Coast

ABSTRACT

The Mediterranean Sea, bordered by diverse nations and characterized by its unique climatic and oceanographic conditions, presents significant opportunities for renewable energy generation, particularly through wave energy. As global energy demands continue to rise and the urgency to mitigate climate change intensifies, harnessing renewable energy sources has become a critical focus for many countries. Among these sources, wave energy stands out due to its predictability, abundance, and potential for sustainable development. This paper presents a comprehensive assessment of wave energy resources along the Egyptian Mediterranean coast, utilizing hourly data from the ERA5 dataset covering the period from January 1979 to December 2024. The study focuses on the available ERA5 data grid points of Significant Wave Height (SWH) and wave energy, identifying ten strategic locations to evaluate the potential for wave energy generation. Also, the frequency of the occurrences of SWH with corresponding wave energy periods was calculated. The relationship between SWH and Mean Wave Direction (MWD) was examined with wave energy data. A comparative evaluation of the ten sites for mean wave energy and mean wave power was studied. Results revealed that the highest wave energy occurrences align with SWH between 0.25-1 m and wave periods of 3-8 s. The highest wave energy density falls within 0-1 m SWH and a directional range of 300-350°. Among the evaluated sites, Marsa Matrouh demonstrated the highest mean wave energy potential, while Alexandria exhibited the highest mean wave power output. Conversely, Port Said had the lowest potential. Overall, this study provides a foundational assessment for future wave energy exploitation along Egypt's Mediterranean coast and contributes valuable insights for regional renewable energy planning.

1. Introduction

The quest for sustainable energy sources has become increasingly critical, because of climate change and the depletion of fossil fuels. Several types of resource are commercially used today, such as solar, wind, biomass, geothermal, and hydropower; however, in order to address climate change and ensure a sustainable future, the renewable share in the power mix

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is required to increase significantly (IEA, 2019). A growing body of literature recognizes wave energy as a relatively unexploited source that could contribute to the energy mix and reduce the need for fossil fuels (Liberti et al., 2013; Falcão, 2010; Sierra et al., 2017). This issue has received considerable research attention in the last decades (Besio et al., 2016), with a variety of different wave energy converters (WECs) having already been developed (Prakash et al., 2016) and deployed in several areas worldwide (Ahamed and McKee, 2020). According to Pecher et al. (2017), wave energy is a limitless and sustainable resource that can reduce the energy dependency of coastal nations while offering vital advantages .

Many studies have been carried out worldwide to evaluate the potential of wave energy in different coastal regions, demonstrating the recent surge in interest in wave energy as a feasible renewable energy source. Early research focused on the fundamental characteristics of ocean waves, and established theoretical frameworks necessary for converting their energy. Hughes and Falnes laid the groundwork for understanding wave mechanics and energy extraction technologies. (Hughes, 2004; Falnes, 2007)

The Mediterranean Sea, characterized by its unique geographical and climatic features, offers significant potential for harnessing wave energy. In the Mediterranean region, several studies have specifically addressed wave energy potential, highlighting the variability and feasibility of harnessing this resource (Iglesias and Carballo, 2009; Iglesias and Carballo, 2010a; Iglesias and Carballo, 2010b; Iglesias and Carballo, 2010c). In addition, Bocci (2012) conducted a comprehensive assessment of the wave energy resources along the Italian coast, using numerical models to analyze the wave climate and energy output. Their findings emphasized the importance of localized studies to determine site-specific wave energy characteristics (Bocci et al., 2012). Furthermore, Besio et al. (2016) wave hindcast (1979-2013) was exploited to update existing assessments of wave energy potential in the Mediterranean Sea. With an annual available mean wave power of approximately 10kW/m along the coast, the Western basin between Sardinia, Corsica, and the Balearic Islands, as well as the northern coast of Algeria, is the most energetic region of the Mediterranean Sea. The central and eastern Mediterranean regions have moderate wave energy potentials, with mean values of roughly 6-7kW/m (Besio et al., 2016).

In Egypt, the focus on renewable energy, particularly wave energy, is limited compared to other regions. Several investigations were carried out on surface waves north of

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the Egyptian Mediterranean coast (Nafaa et al. 1991; Hereher 2015; Elsharkawy et al., 2016). However, recent studies have begun to emerge. For example, Ayat (2013) generated a wave power atlas based on 15-year time-averaged wave data. With a capacity of more than 4 kW/m, the study determined that the Egyptian shoreline, which runs between the Libyan border and the Nile Delta, is the most energetic coast in the Southern Mediterranean Basin (Ayat, 2013). Zodiatis et al. (2014) integrated hindcasting platform to produce a 10-year database for the wave energy potential in the Levantine Basin and the environmental parameters that affect it. The western and southern beaches of Cyprus Island, the sea area of Israel and Lebanon, and the Egyptian coastline, particularly the area surrounding Alexandria, are the areas with the highest wave energy potential values (Zodiatis et al., 2014). Elsharkawy et al. (2017) revealed that wave frequency in front of Port Said was concentrated between 0.22 - 0.35 Hz, and the bulk of wave energy existed in the interval 100 - 9000 J, which could be considered as a moderate wave energy resource.

Additionally, the ERA5 dataset has been increasingly utilized in marine energy studies due to its high-resolution climate data. ERA5 data have been successfully employed to assess wave energy potential in various regions, demonstrating the dataset's reliability for long-term wave climate analysis (Mahmoodi et al., 2019; Rusu, 2021; Rusu and Rusu, 2021; Shi et al., 2022; Sun et al., 2022). Additionally, Tonbol et al. (2023) verified that the ERA5 wave data were accurate, with the exception of the shallow nearshore regions. In contrast, measured wave data from a directed wave buoy from February 1999 to February 2000 were compared with the ERA5 data. The following error statistics were obtained: bias= 0.014 m and RMSE = 0.3 m (El-Zeiny et al., 2024).

Despite these advances, a comprehensive assessment of wave energy potential along the Egyptian Mediterranean coast remains scarce. This paper seeks to fill this gap by utilizing the ERA5 dataset to evaluate the significant wave height and wave energy across ten strategically selected locations. By building upon the foundational work of previous studies and employing robust data analysis methods, this research aims to provide a thorough understanding of the wave energy landscape in Egypt, paving the way for future developments in marine renewable energy.

The findings of this study are intended to inform policymakers and stakeholders about the viability of wave energy as a renewable resource in Egypt, highlighting areas with the

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highest potential for development. By elucidating the wave energy landscape along the Egyptian Mediterranean coast, we contribute to the broader discourse on sustainable energy solutions and the role of marine renewables in mitigating climate change impacts. Through this assessment, we aim to pave the way for future research and investment in wave energy technologies, ultimately advancing Egypt's transition towards a more sustainable energy future.

2. Data and Methods of Analysis

2.1. Study Area:

The Egyptian Mediterranean coast stretches over a distance of approximately 1200 km, from Sallum (25°E) to Arish (33°30′E), and from the Egyptian Mediterranean shoreline to 32°N latitude. Data for ten strategically selected locations along the Egyptian Mediterranean coast were obtained from the ERA5 dataset as shown in Figure (1). The coordinates of these locations were chosen based on their accessibility for future development Table (1). In addition, Table (1) shows the depth of each location, which obtain from https://topex.ucsd.edu/cgi-bin/get_srtm15.cgi(Tozer et al., 2019).

2.2. Data Sources:

This study utilized the ERA5 dataset, which is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), from the Earth observation component of the European Union's Space program (Copernicus) website (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download). The ERA5 dataset provides high-resolution climate data, including significant wave height, wave period, and wave direction. The dataset covers the period from 1979 to the present and has a spatial resolution of approximately 31 km, making it suitable for regional wave energy assessments. The specific variables extracted from the ERA5 dataset for this study from 1st January 1979 to 31st December 2024 include the following: Significant Wave Height (SWH), Mean Wave Period (MWP), and Mean Wave Direction (MWD).

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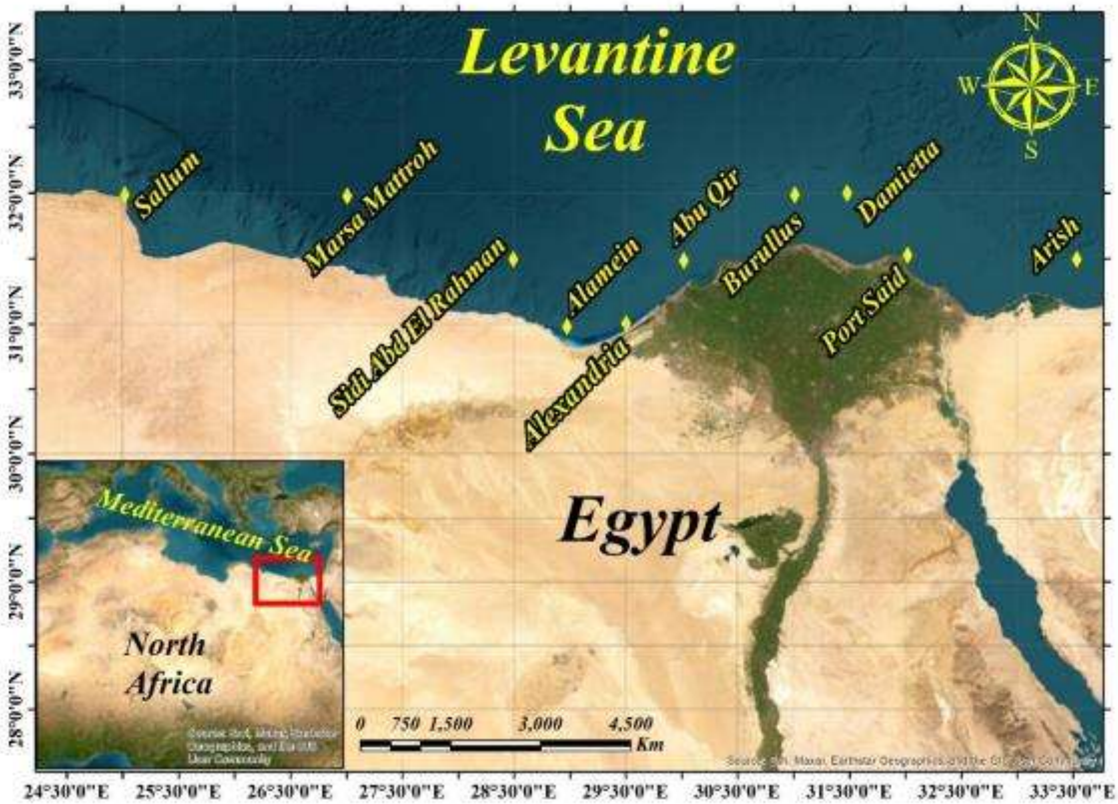

Figure (1): The Egyptian Mediterranean coast with its ten stations

Table (1): the ten strategically selected locations along the Egyptian Mediterranean coast

Stations	Longitude (E)	Latitude (N)	Depth
Sallum	25.0	32.0	-73.0
Marsa Matroh	27.0	32.0	-3147.0
Sidi Abd El Rahman	28.5	31.5	-1873.4
Alamein	29.0	31.0	-56.6
Alexandria	29.5	31.0	-21.1
Abu Qir	30.0	31.5	-96.6
Burullus	31.0	32.0	-118.1
Damietta	31.5	32.0	-108.0
Port Said	32.0	31.5	-8.0
Arish	33.5	31.5	-146.6

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2.3. Theoretical background:

To assess the wave energy potential at each location, the wave energy flux (E) was calculated using the following formula:

$$E = \frac{1}{8}\rho g H^2 \tag{1}$$

Where:

E is the wave energy flux (Ws)

ρ is the seawater density (approximately 1028 kg/m³)

g is the acceleration due to gravity (approximately 9.81 m/s²)

H_s is the significant wave height (m)

The wave energy potential was then expressed in terms of the energy per meter of wave front (W/m) at each location. The energy flux or power (P) transmitted by a regular wave per unit crest is given by:

$$P = E \times C_g \tag{2}$$

where Cg is the group velocity, and is defined as follows:

$$C_g = \frac{1}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right)\frac{L}{T} \tag{3}$$

in which *h* is the local water depth, *L* is the wave length, *T* is the wave period, $k = 2\pi/L$ is the wave number and $C = L/T$ is the wave celerity .

The wave length, depth and period are related through the dispersion equation:

$$L = T\sqrt{\frac{g}{k}\tanh(kh)} \tag{4}$$

In shallow water (h < L/2), the following explicit equation for L can be used without noticeable error:

$$L = \frac{gT^2}{2\pi}\left\{tanh\left[\left(\frac{4\pi^2 h}{gT^2}\right)^{3/4}\right]\right\}^{2/3} \tag{5}$$

In deep water ($h > L/2$), $C = L/T = 2C_g$ and $L = gT^2/2\pi$ (Cornett, 2008).

Measured sea states are often specified in terms of significant wave height H_s and either peak period T_p or mean period T. The energy period T_e is rarely specified and must be estimated from other variables when the spectral shape is unknown. For example, in preparing the Atlas of UK Marine Renewable Energy Resources, it was assumed that $T_e = 1.14T$ (ABP, 2004).

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2.4. Data Analysis:

In our methodology, we calculate the frequency of the occurrence of SWH alongside the corresponding wave energy periods, thereby facilitating a deeper understanding of the wave climate in the region. Additionally, we examined the relationship between the SWH and MWD to correlate wave energy data more effectively. The Ocean Data View ® (ODV) software was used to visualize the spatial distribution of wave energy potential along the Egyptian Mediterranean coast for all available stations. The maximum, minimum, highest and second frequency occurrences are displayed. A comparative evaluation of the ten selected sites was conducted, focusing on mean wave energy and mean wave power, which provided insights into the relative potential for energy generation at each location during the study period and the last 5 years.

3. Results

3.1. ERA5 Grid Points Distribution:

The figure (2-a) displays the all the available ERA5 data grid points for maximum and minimum SWH and Wave Energy along the northern coast of Egypt during the study period. From this figure, the highest maximum SWH values (about 6-7 m) were predominantly located in the western part of the study area, roughly between longitudes 26°E and 28.5°E. As we move eastward, a clear decreasing trend is observed in the maximum SWH. The central and eastern parts of the coast (east of 29°E) exhibit progressively lower maximum SWH values (around 3-4 m). In addition, the spatial pattern of the maximum wave energy closely mirrored the pattern of the maximum SWH. The highest maximum wave energy values (above 30 kWs) are also concentrated in the western part of the study area. Wave energy generally decreases as we move eastward, with the lowest values (around 10-20 kWs) observed in the easternmost regions.

However, the minimum SWH values were consistently very low across the entire northern Egyptian coastline, generally below 0.12 m. There is no significant spatial trend observed in the minimum SWH. The values remain within a narrow low range across both the western and eastern parts of the coast. As anticipated, under extremely calm sea conditions, the corresponding wave energy levels are also very low, generally below 0.02 kWs. Similar to the minimum SWH, no discernible spatial trend was observed for the minimum wave energy.

Figure (2-b) displays the all the available ERA5 data grid points for the 1st and 2nd highest frequencies of occurrence for SWH and Wave Energy along the northern coast of Egypt during the study period. The most frequently occurring SWH values are generally low across the entire coastline, typically below 1 m. There appears to be a slight increase in the most frequent SWH values (around 0.75 to 0.9 m) in the western part of the study area (around 26°E to 28°E). The eastern part of the coast (east of 30°E) generally had the slightly lower most frequent SWH values (around 0.45 to 0.75 m). The wave energy associated with the most frequent SWH is also generally low across the coastline, typically below 1 kWs. Similar to the most frequent SWH, there seems to be a tendency for slightly higher wave energy values in the western part of the study area (around 0.6 to 1 kWs). The eastern part generally exhibits lower wave energy values associated with the most frequent SWH (around 0.2 to 0.6 kWs).

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The second most frequently occurring SWH values were generally higher than the most frequent values (as shown in Figure (2-b)), typically ranging between 1 and 2 meters. The spatial pattern was less pronounced than the most frequent SWH. However, there is still a suggestion of slightly higher second most frequent SWH values in the western and central parts of the coast (around 1.5 to 2 m). The easternmost part tended to show somewhat lower second most frequent SWH values (about 1 to 1.5 m). The wave energy associated with the second most frequent SWH was significantly higher than that associated with the most frequent SWH. The spatial pattern again reflects the trend observed for the second most frequent SWH, with higher energy values in the western and central parts (around 4.5 to 6 kWs). The eastern part tended to have lower wave energy values associated with the second

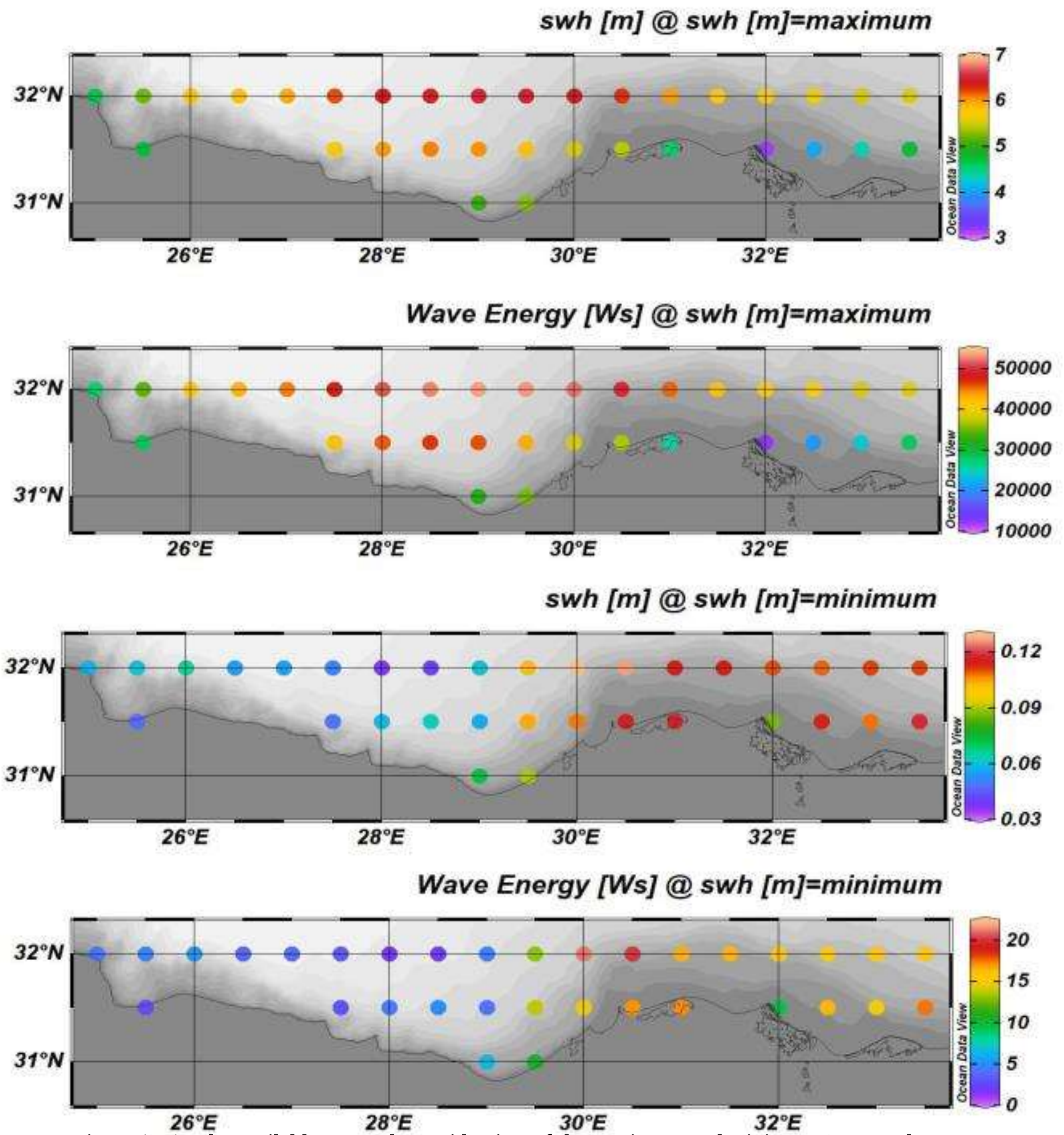

Figure (2-a): The available ERA5 data grid points of the maximum and minimum SWH and Wave Energy during the study period

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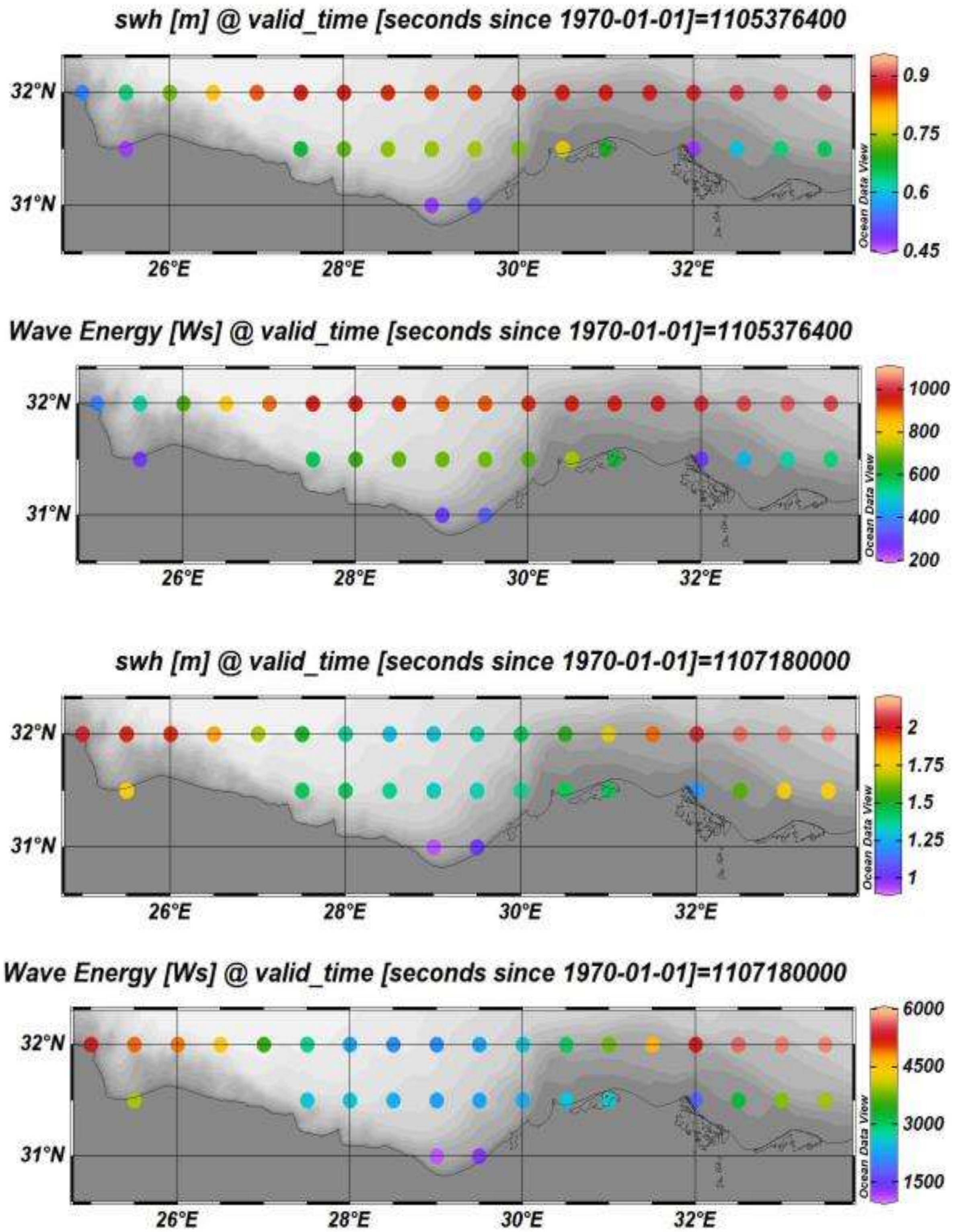

Figure (2-b): The available ERA5 data grid points of the 1st and 2nd high frequency of occurrence for SWH and Wave Energy during the study period

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3.2. Histogram

The frequencies of occurrence (in percentage) of SWH and wave energy period (Te) at the ten different locations over a study period are depicted in Figure (3). In general, for most locations, the highest frequencies of wave occurrences were concentrated at lower significant wave heights (typically below 1 m) and shorter wave energy periods (between 2 and 4 s). While the general trend of low SWH and short T_e dominance is consistent, there are subtle variations in the distribution and frequency peaks across the different locations, western locations (Salloum, Marsa Matroh, Sidi Abd El Rahman, and Alamein), these locations seem to exhibit a slightly wider spread of SWH and T_e compared to the eastern locations. There might be a slightly higher occurrence of moderate wave heights in this region. The central locations (Alexandria, Abu Qir) showed a clear concentration of high frequency at lower SWH and T_e values, suggesting a relatively calmer wave climate compared to the westernmost locations. The eastern locations (Damietta, Ras El Bar, Port Said, Arish), similar to the central locations, also showed a strong dominance of low SWH and short T_e. The frequency contours appear somewhat compressed toward the lower left. Across all locations, the frequency of occurrence for high SWH (above 2-3 m) was very low.

3.3. Scatter Plot:

Figure (4) provides a valuable visual comparison of the wave climate along the Egyptian Mediterranean coast. It highlights the spatial variability in SWH, MWD, and the resulting Wave Energy over the study period for the same ten locations along the Egyptian Mediterranean coast. For most of the western and central locations (Salloum to Damietta), the most frequent wave conditions appeared to involve moderate wave heights (roughly 1-2.5 m) arriving predominantly from the northwest sector (from 270° to 360°). The easternmost location, El Arish, showed a tendency toward more frequent moderate wave heights (around 0.5-1.5 m) from the north to northeast sector (from 0° to 45°). Higher energy events occur within this directional range but appear less frequently, and are associated with larger wave heights.

3.4. Spatial and temporal variations in the annual mean wave energy and power

The annual mean wave energy (top graph) and the annual mean wave power (bottom graph) variations along the northern coast of Egypt at selected stations are presented in Figure (5) during the study period (1979-2024) and the last 5 years (2020-2024). There was a significant spatial variation in mean wave energy along the coast. Both the long-term average and the recent 5-year average show a peak in mean wave energy around Marsa Matroh (greater than 1.9 kWs over the study period and 1.7 kWs over the last 5 years). While the easternmost stations, particularly Port Said (less than 0.7 kWs over the study period and the last 5 years), consistently exhibit the lowest mean wave energy values.

Similar to mean wave energy, mean wave power also exhibited significant spatial variation along the coast. However, Marsa Matroh (about than 9.5 kW/m over the study period and 8.5 kW/m over the last 5 years) consistently showed peak mean wave power, but Alexandria (greater than 10 kW/m over the study period and 9 kW/m over the last 5 years) had the

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highest mean wave power for both the long-term and recent periods. Port Said (less than 5 kW/m over the study period and the last 5 years) and Arish exhibited the lowest mean wave power values. The observed trend in mean wave energy is generally mirrored by the mean wave power.

4. Discussion

In light of climate change and the depletion of fossil fuel resources, the search for sustainable energy sources has grown more urgent. Commercial sources include solar, wind, biomass, geothermal, and hydropower. However, a substantial increase in the proportion of renewable energy sources in the power mix is necessary to combat climate change and secure a sustainable future. Wave energy is becoming more widely acknowledged in the literature as a promising, underutilized source that can be used to supplement the energy mix and lessen the demand for fossil fuels. The comprehensive assessment of the wave energy potential along the Egyptian Mediterranean coast was performed using the long-term hourly ERA5 dataset (1979-2024). The study analyzed the all the available ERA5 data grid points for SWH and wave energy, the frequency of the SWH and corresponding wave energy periods, the relationship between the SWH and MWD, and a comparative evaluation of ten strategic locations for mean wave energy and power.

The results revealed a clear spatial variability in wave energy resources along the Egyptian Mediterranean coast. The western part of the study area, particularly around Marsa Matrouh, exhibited the highest maximum SWH and wave energy values. This suggests that the western region experiences more energetic wave conditions than the central and eastern parts of the coast, where a decreasing trend in maximum SWH and wave energy is observed. Conversely, minimum SWH and wave energy values are consistently low across the entire coastline, indicating periods of calm sea conditions. This result agrees with Ayat (2013), who studied the wave power and generated an atlas based on 15-year time-averaged wave data. The study determined that the most energetic coast of the Southern Mediterranean Basin is the Egyptian coast lying between the Nile Delta and the Libyan border, with a potential of more than 4 kW/m.

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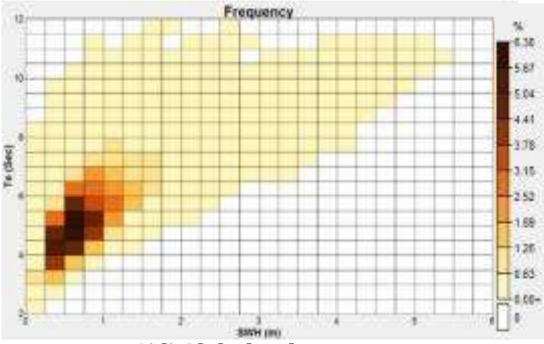
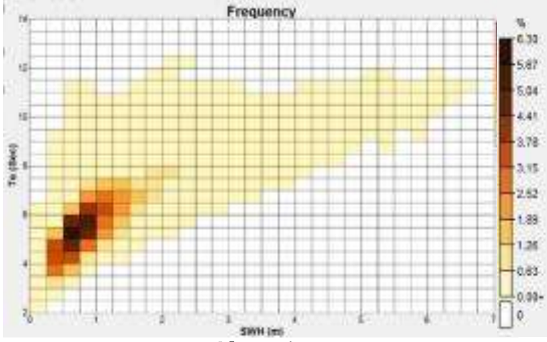
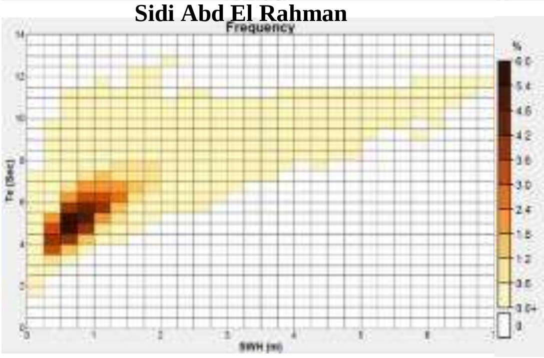
Sallom



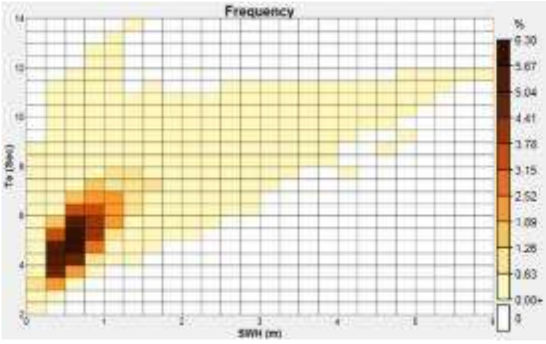
Marsa



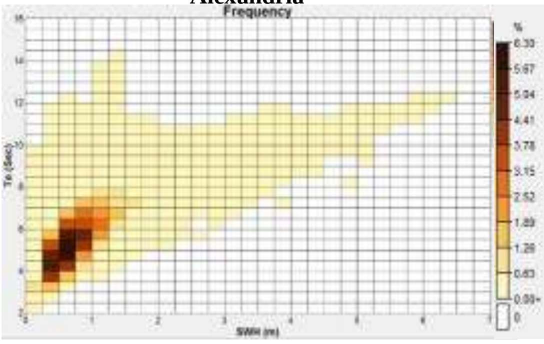
Sidi Abd El Rahman



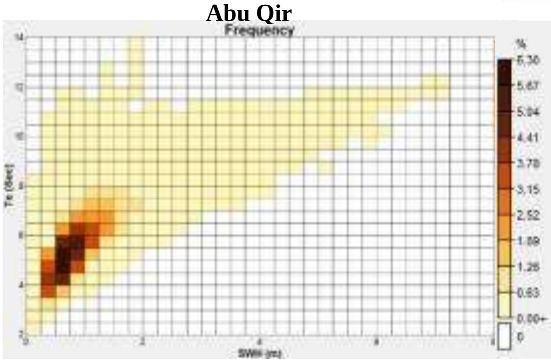
Alammi



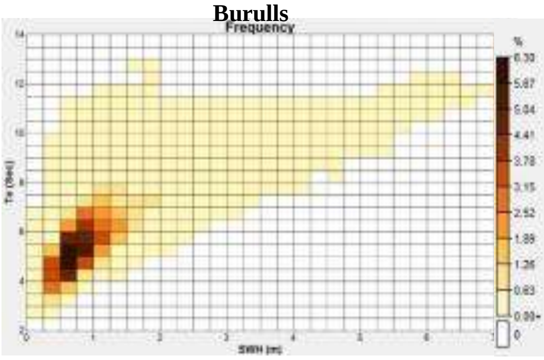
Alexandria



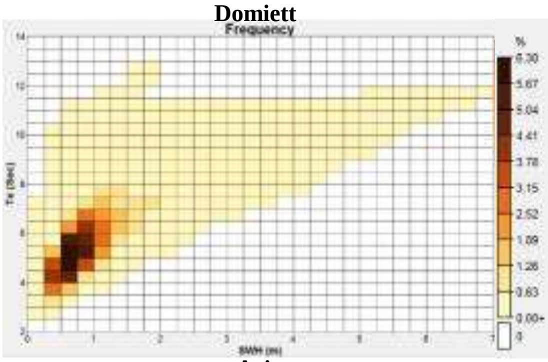
Abu Qir



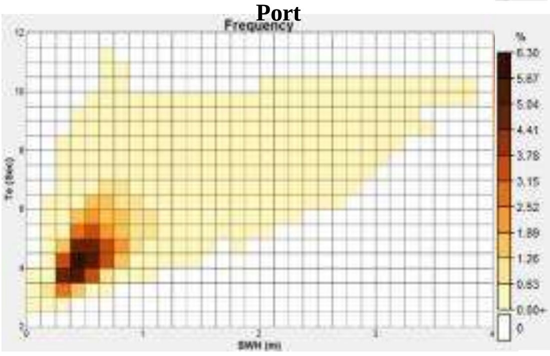
Burulls



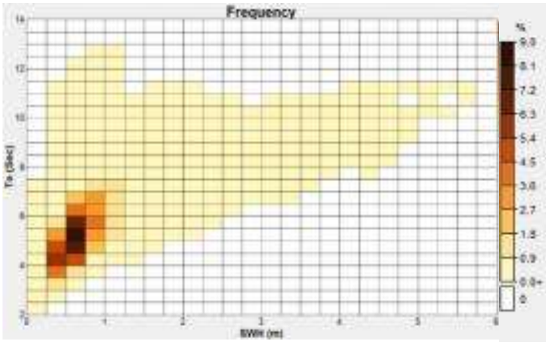
Domiett



Port



Aris



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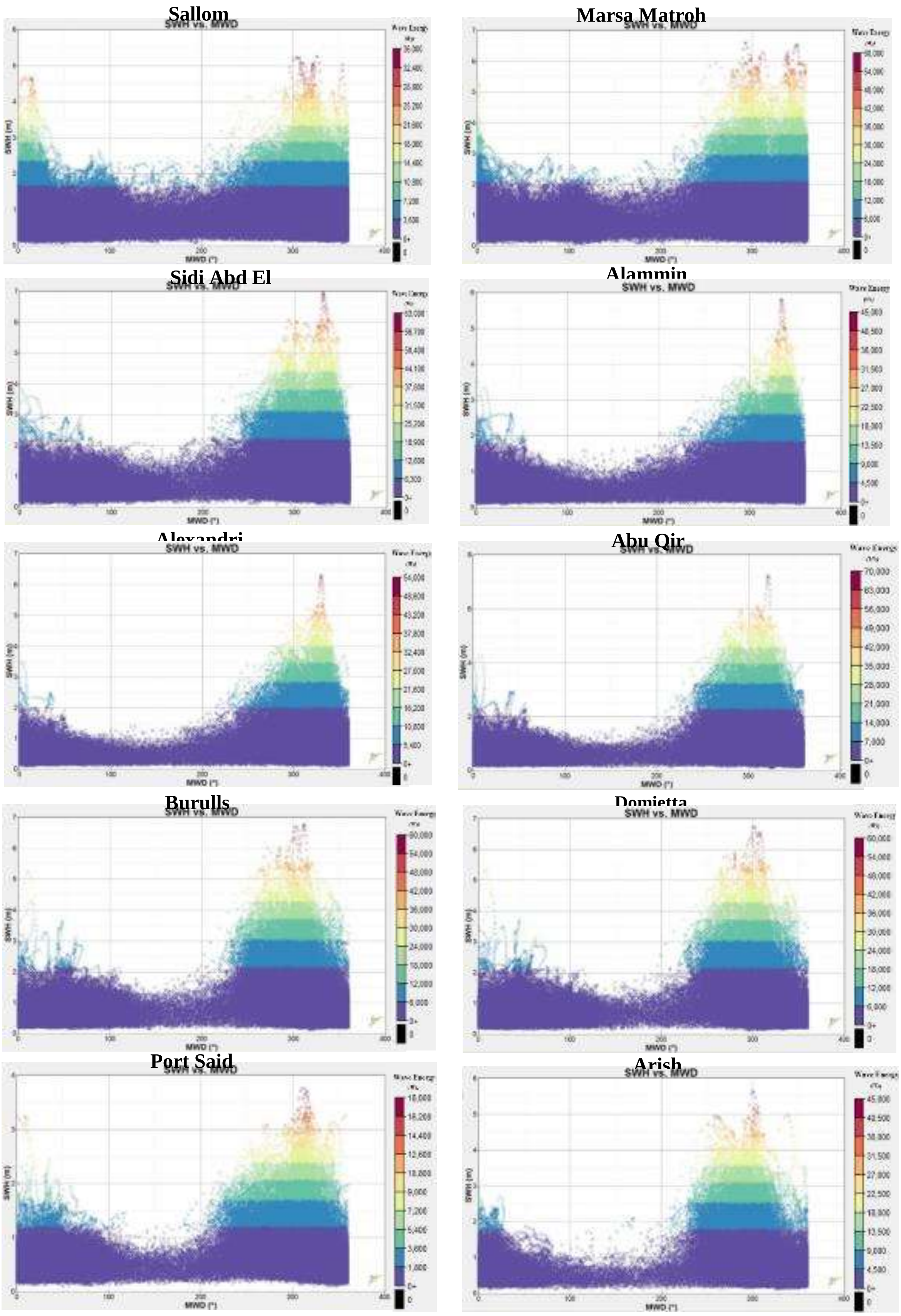

Figure (4): The scatter plot for SWH and MWD with calculated Wave Energy over the study Period

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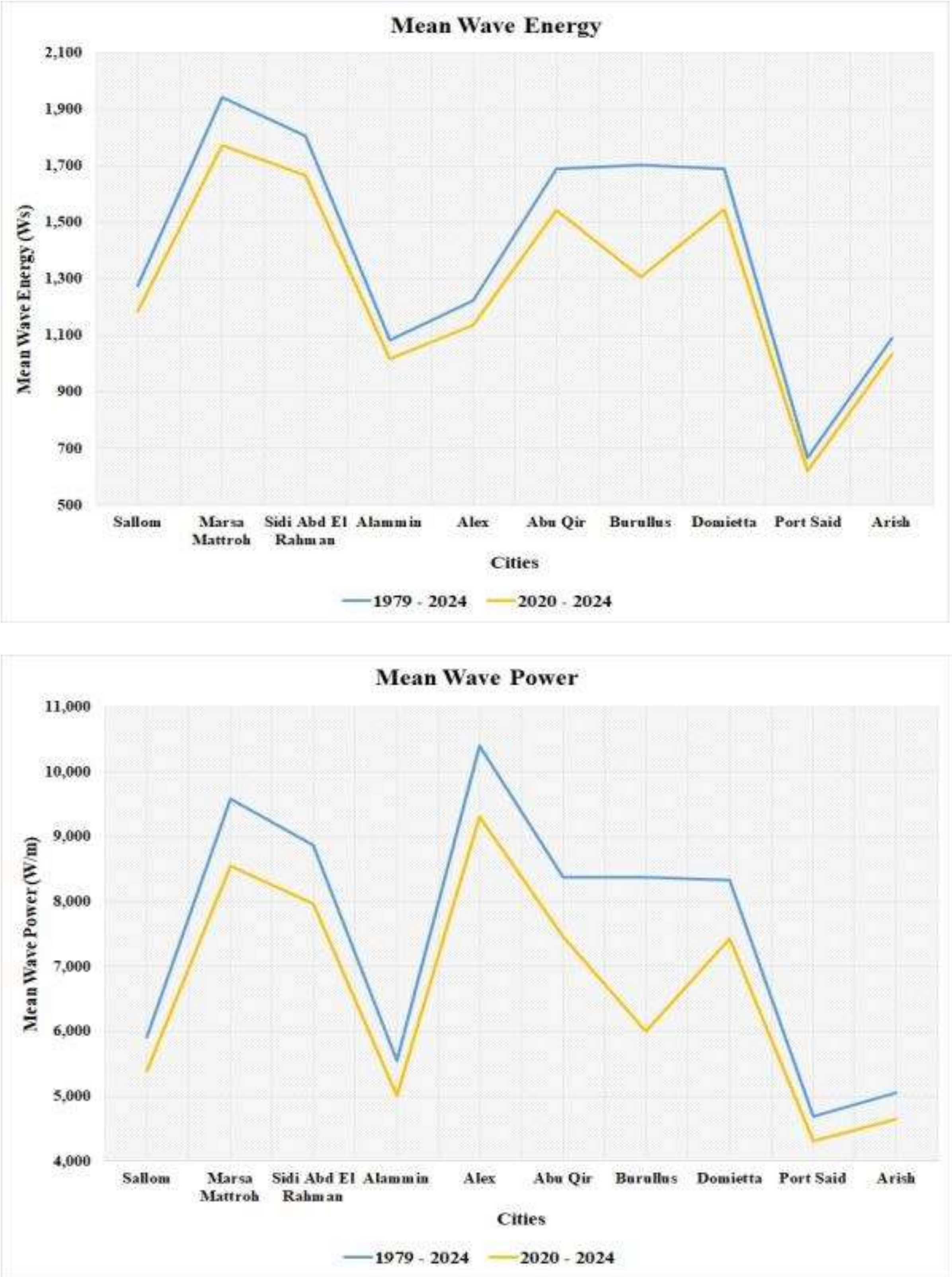

Figure (5): the spatial annual mean wave energy and power variation during the study period and the last 5 years at the selected stations

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Analysis of the frequency of wave occurrences indicated that lower SWH values (below 1 m) and shorter wave energy periods (2-4 s) were most frequent across all ten locations. However, subtle regional variations exist. The western locations showed a slightly wider spread of SWH and wave energy periods, suggesting a more variable wave climate. Central and eastern locations exhibit a more concentrated frequency at lower SWH and periods, indicating relatively calmer conditions. Notably, high SWH (above 2-3 m) is rare across the entire Egyptian Mediterranean coast.

The examination of the relationship between SWH and MWD reveals that the most frequent wave conditions for most western and central locations involve moderate wave heights (1-2.5 m) arriving predominantly from the northwest (270-360 degrees). El Arish, in the east, shows a tendency for more frequent moderate waves (0.5-1.5 m) from the north to northeast (0-45 degrees). Higher energy events are associated with larger wave heights within these directional ranges, but they occur less frequently.

The comparative evaluation of the mean wave energy and power at the ten sites highlights significant spatial variations. Marsa Matrouh consistently demonstrates the highest mean wave energy potential over both the long-term and the recent 5-year periods. Interestingly, while Marsa Matrouh also shows high mean wave power, Alexandria exhibits the highest mean wave power output, which agrees with Zodiatis et al. (2014). To create a 10-year database for the wave energy potential in the Levantine Basin and the environmental factors influencing it, a hindcasting platform was integrated. The western and southern coasts of Cyprus Island, the sea area of Israel and Lebanon, and the Egyptian shoreline, particularly the area surrounding Alexandria, are the areas with the highest wave energy potential values. This difference likely arises from the combination of wave energy and the corresponding wave periods at each location, and influences the exploited power by wave energy converters. Conversely, Port Said consistently shows the lowest mean wave energy and power values (less than 0.7 kWs and 5 kW/m), indicating the least favorable conditions for wave energy harvesting among the selected sites, which is less than that reported by Elsharkawy et al. (2017). The investigation revealed that wave energy existed in the interval 100 - 9000 J, which could be considered as a moderate wave-energy resource.

5. Conclusion

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In conclusion, this study provides valuable insights into the wave energy potential along the Egyptian Mediterranean coast. The analysis revealed a geographically diverse wave climate, with the western region, particularly around Marsa Matrouh, presenting the most promising areas for wave energy development based on mean wave energy. However, Alexandria's higher mean wave power suggests that the specific characteristics of its wave climate might be more conducive to efficient energy extraction. The eastern part of the coast, exemplified by Port Said, appears to have the lowest wave energy potential.

These findings have significant implications for policymakers and stakeholders in Egypt's renewable energy sector. The identification of potential high-energy locations can guide future research, development, and investment in wave energy technologies. Further studies could focus on the different seasons to understand the temporal variability of wave conditions and energy potential. Furthermore, wave models could be applied to the coastal water in the potential locations. Correspondingly, further studies could focus on detailed nearshore assessments, the suitability of different wave energy converter types for the identified locations, and the environmental and socio-economic impacts of potential wave energy farms. This research contributes to a better understanding of Egypt's marine renewable energy resources and paves the way for a more sustainable energy future for the country.

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