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Determination of Wave Parameters of Bandirma Bay Using Wave Prediction Methods

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Abstract: Coasts are with complex dynamics where the interaction of the air, water, and land is effectively perceived. Wave height is the most important parameter that affects the coastal zone and the most significant parameter of coastal engineering problems. For this reason, wave statistics and wave height estimations are important. In Türkiye, as in the rest of the world, wave predictions are based on wind measurements or wind models. However, since there is no measurement of wave data that can be used in wave climate studies on the Turkish coasts and since such research has just started, wave models are obtained by various methods in the design process. In this study, wave predictions for Bandirma Bay were carried out with methods proposed in the literature (CEM, JONSWAP, SMB, Wilson) using the 12-month hourly average wind speed data of the State Meteorological Service for 1991, and the results were discussed and compared to those reported in other studies in the literature.

Dalga Tahmin Yöntemleri Kullanılarak Bandırma Körfezi için Dalga Parametrelerinin Belirlenmesi

Anahtar Kelimeler
Bandırma Körfezi,
CEM,
Dalga tahmini,
JONSWAP,
SMB,
Wilson

Öz: Kıyılar; hava, deniz ve kara etkileşimlerinin etkin bir şekilde gözlemlendiği karmaşık dinamiklere sahip bölgelerdir. Belirgin dalga yüksekliği, bir kıyı bölgesini etkileyen en önemli parametredir. bu parametre kıyı ve liman mühendislikleri problemleri için de büyük önem arz etmektedir. Bu nedenle dalga istatistikleri ve dalga yüksekliği tahmini önemlidir. Ülkemizde de dünyada olduğu gibi dalga tahminleri rüzgâr ölçümlerine veya rüzgâr modellerine dayanmaktadır. Ancak, ülkemiz kıyılarında dalga iklimi çalışmalarında kullanılabilecek ölçülmüş dalga verisi olmadığından ve bu tarz çalışmalar yeni başladığından, kıyı yapıları tasarım sürecinde çeşitli yöntemlerle dalga modelleri elde edilmektedir. Gerçekleştirilen bu çalışmada, Bandırma için ölçülen Devlet Meteoroloji İşleri Genel Müdürlüğü'nün 1991 yılına ait 12 aylık saatlik ortalama rüzgâr şiddeti verileri kullanılarak literatürdeki CEM, JONSWAP, SMB, Wilson gibi dalga tahmini yöntemleri kullanılarak Bandırma körfezi için dalga tahmini gerçekleştirilmiş ve literatür çalışmaları ile sonuçlar karşılaştırılmıştır.

1. INTRODUCTION

Coasts are areas with complex dynamics where the interaction of the air, water, and land is effectively observed. The most important parameter affecting the coastal zone and the most significant parameter of coastal engineering problems is wave height [1]. Wave height is the vertical distance between the wave crest and the wave trough. The estimation of wave height through wave statistics is important. In Türkiye, as in the rest of the world, wave predictions are based on wind measurements or models. Additionally, as a parameter with important roles in coastal engineering activities such as coastal planning, coastal structure design, sediment transport, and coastal erosion analyses, wave height can also be estimated by methods such as artificial intelligence techniques, numerical models, and parametric methods [2].

Since direct wave measurements are costly and difficult, wind data are used for wave prediction. The main wave prediction methods in the literature are the Sverdrup, Munk, and Bretschneider (SMB) method [3], Wilson method [4], JONSWAP method [5], Donelan method [6], Shore Production Manual (SPM) method [7], and Coastal Engineering Manual (CEM) method [8].

In this study, wave predictions for Bandirma Bay were carried out using four widely applied methods reported in the relevant literature: CEM, JONSWAP, SMB, Wilson. These methods were selected due to their proven reliability in various coastal engineering applications and their compatibility with available 12-month hourly average wind speed data.

1.1. Physical Conditions

Bandirma is a gulf region protected by the Kapidag Peninsula in the south of the Marmara Sea. Since the Marmara Sea is an inland sea, it has a soft wave climate, and the heights of the waves coming into this gulf are quite small. The gulf is closed to west and northwest waves due to the Kapidag Peninsula and is only open to northeast and east waves with 20º-70º angles as shown in Figure 1 [9].

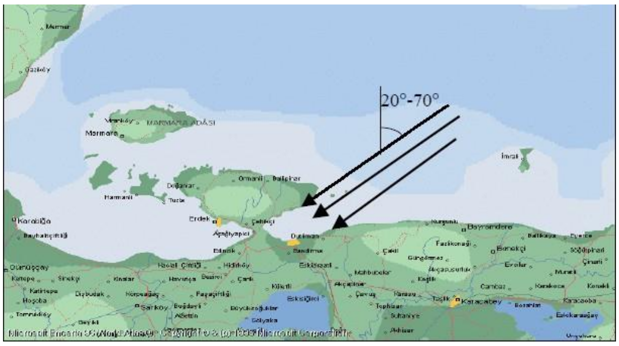

Figure 1. Bandirma bay and wave directions [9].

2. MATERIAL AND METHOD

One of the factors affecting wave formation is wind speed. Wind speed is the speed of the wind in the atmosphere. This speed should be known before wave predictions. However, due to factors such as the fact that the measurement sites are encompassed by settlement borders over time, incorrect measurements and potentially incorrect calculations may be a problem [10].

Considering this situation, it was seen that the measurement site was idle, the State Meteorological Service (DMI) data of 1991 were used in the study, and this information is provided in Appendix A [11].

The surface area on the sea where the wind creates the waves is called fetch (F) [12]. Wind speed, U, fetch distance, F, and wind blowing time, t, determine the height and period of wind-driven waves [13]. The situation in which the fetch and wind blowing time are sufficient is a fully developed sea state. The opposite is called a developing sea state. If the wind blowing time is shorter than the required wind blowing time, this constitutes a fully developed sea state, and there is a time-limited situation, while if the fetch distance is smaller than the required fetch distance, there is a fetch-limited situation. The effective fetch distance (F_e) is calculated by measuring the fetch lengths at 7.5º intervals in a band of 45º from the wave direction ± and using Equation 1 [14]. Figure 2 shows effective fetch lengths for Bandirma Bay.

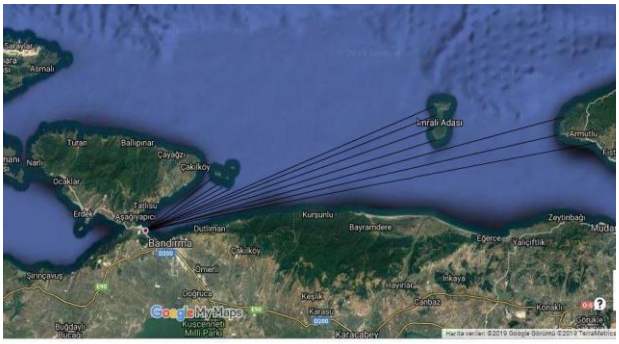

Figure 2. Effective fetch lengths

$$F_{eff} = \frac{\sum F_i \cos \alpha^2}{\sum \cos \alpha} \tag{1}$$

Significant wave heights are calculated depending on the effective fetch lengths, wind blowing time, and wind speed at a height of 10 m from the sea. Fetch is the distance of the swell area of the wave. Significant wave height was estimated using the CEM, JONSWAP, SMB, and Wilson methods considering fetch-limited, time-limited, or fully developed sea states.

2.1. CEM Method

The calculation in the CEM method is made as in Equations 2 and 3 depending on the significant wave height H_s, wave period T_z, minimum wind blowing time t_{min}, effective fetch length F_e, wind speed at 10 m U_{10}, and gravitational acceleration g:

$$\frac{g\, H_s}{U_*^2} = 4.13 \times 10^{-2} \left(\frac{g\, F_e}{U_*}\right)^{0.5} \tag{2}$$

$$\frac{g\, T_z}{U_*} = 0.651 \left(\frac{g\, F_e}{U_*^2}\right)^{1/3} \tag{3}$$

Here, U_* is the frictional speed, and it is calculated as in Equation 4:

$$U_* = U_{10}\, (C_D)^{0.5} \tag{4}$$

Here, C_D is the coefficient of friction, and it is calculated as in Equation 5:

$$C_D = 0.001\,(1.1 + 0.035\, U_{10}) \tag{5}$$

In time-limited cases, the effective fetch distance (F_e) is calculated using Equation 6 depending on the minimum wind blowing time (t_{min}).

$$\frac{g\, F_e}{U_*^2} = 5.23 \times 10^{-3} \left(\frac{g\, t_{min}}{U_*}\right)^{1.5} \tag{6}$$

2.2. JONSWAP Spectrum Method

The JONSWAP method is frequently used in developing sea states. The significant wave height H_S defined for a fetch-limited case is calculated as in Equation 7, and wave period T_Z is calculated as in Equation 8:

$$H_s = 0.0163\, F^{0.5}\, U \tag{7}$$

$$T_z = 0.439\, F^{3/10}\, U^{2/5} \tag{8}$$

For time-limited cases the formulae given in Equations 9 and 10 are used [5]:

$$H_s = 0.0146\, t^{5/7}\, U^{9/7} \tag{9}$$

$$T_z = 0.419\, t^{3/7}\, U^{4/7} \tag{10}$$

Here, H_S is the significant wave height (m), T_Z is the mean wave period (s), F is the fetch length (km), U is the wind speed (m s^{-1}), and t is the wind blowing duration time (s). The formulae written for the fetch-limited case are valid if the condition in Equation 11 is met:

$$t > 1.167\ F^{0.7}/U^{0.4} \tag{11}$$

Otherwise, time-limited formulae should be used.

2.3. SMB Method

The first method of determining design values using wind data was presented by Sverdrup and Munk [15]. The wave prediction curves given by Sverdrup and Munk were revised by Bretschneider using empirical data [16]. Therefore, this method is often referred to as the Sverdrup-Munk-Bretschneider (SMB) method.

Using the nomogram given for the SMB method shown in Appendix B, T_S and H_S can be found with the help of the fetch distance, wind speed, and wind blowing time [16]. During the use of this nomogram, T_S and H_S values are found by the interpolation intersecting the wind speed with the given fetch distance and blowing time [13].

However, if the intersection first encounters the blowing lines (time-limited waves), it is understood that the event and fetch can be taken as infinite. If the fetch levels are encountered first (fetch-limited waves), it is understood that the fetch distance controls the event, and the wind blowing time is insignificant [17]. The significant wave height H_S for time-limited waves and fetch-limited waves and period T_S are calculated as in Equations 12, 13, and 14, respectively:

$$\frac{g\,H_s}{U^2} = 0.283\, tanh\left[0.0125\, \left(\frac{g\,F}{U^2}\right)^{0.42}\right] \tag{12}$$

$$\frac{g\,H_s}{U^2} = 0.283\, tanh\left[0.0125\, \left(\frac{g\,F}{U^2}\right)^{0.42}\right] \tag{13}$$

$$\frac{g\,t}{U} = K\, e^{\left\{\left[A\left(ln\left(\frac{g\,F}{U^2}\right)\right)^2 - B\, ln\left(\frac{g\,F}{U^2}\right) + C\right]^{1/2} + D\, ln\left(\frac{g\,F}{U^2}\right)\right\}} \tag{14}$$

Here, K=6.5882, A=0.0161, B=0.3692, C=2.2024, and D=0.08798. These expressions contain the fetch geometry ϕ as in Equation 15 [13]:

$$\phi = \frac{g\,F}{U^2} \tag{15}$$

The fetch parameter is given in graphical form in Figure 3. These equations are valid only for the deep-sea state. This method can also be applied using the nomogram given in Appendix B.

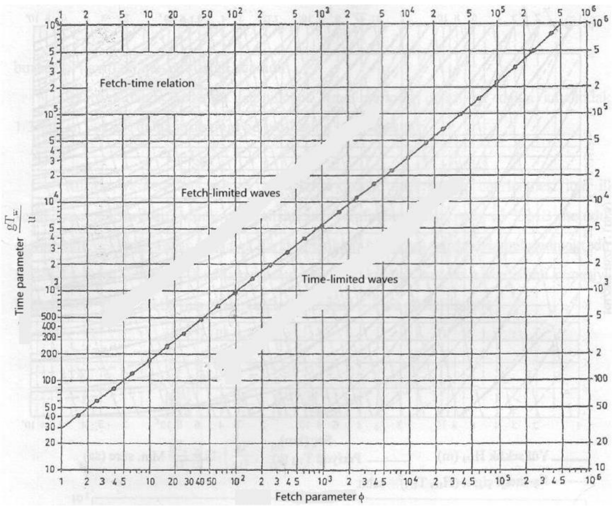

Figure 3. ϕ Fetch parameters [13].

Using these equations,

a) T, U, and F are determined based on the available wind data,

b) In Equation 14, the fetch parameter ϕ is determined,

c) The parameter g T/U is calculated,

d) If the value found by using steps (b) and (c) remains above the curve when marked in Figure 3, the significant wave height is determined by the fetch, and the fetch parameter found in step (b) is used. If this value is below the curve, the significant wave height is calculated based on the wind blowing time, and for this, the smaller value of ϕ, which is determined by intersecting the curve using the time parameter (g t/ U), is used,

e) Based on these calculated values of ϕ, H_S and T_S are calculated using Equations 12 and 13 [18].

2.4. Wilson Method

In this method, the minimum wind blowing time for the fetch-limited condition to end is calculated using Equation16:

$$t_{min} = 1.0\ F^{0.73}\ U^{-0.46} \tag{16}$$

Here, t_{min} is the fetch distance in an hour, and U is the wind speed (m s^{-1}) at 10 m above sea level. The significant wave height and period in the fetch-limited condition are expressed by Equations 17 and 18:

$$H_S = 0.30\ \frac{U^2}{g}\left[1 - \left[1 + 0.004\ \left(\frac{g\,F}{U^2}\right)^{0.5}\right]^{-2}\right] \tag{17}$$

$$T_S = 8.61\ \frac{U}{g}\left[1 - \left[1 + 0.008\ \left(\frac{g\,F}{U^2}\right)^{1/3}\right]^{-5}\right] \tag{18}$$

If the wind blows at a speed lower than t_{min}, fetch-limited case assumptions cannot be met. In the Wilson method, if the formation of waves is time-limited, an equivalent fetch distance F_{eq} is found using Equation 19. by replacing t_{min} with the wind blowing time in Equation 16. Wave parameters are recalculated using this equivalent fetch value in Equations 17 and 18.

$$F_{eq} = 1.0\ t^{1.37}\ U^{0.63} \tag{19}$$

Here, F_{eq} (km) is the equivalent fetch distance, t (s) is the wind blowing duration, and U is the wind speed (m s^{-1}) at 10 m above sea level [19].

3. RESULTS

The significant wave heights H_S and periods T_Z obtained by wave estimation methods which are CEM, JOBSWAP, Wilson, and SMB, using wind data from the meteorological station located around Bandirma Bay are shown in Table 1. The results were compared to TPAO measurements in the literature using bias and RE (relative error) statistics. Bias and RE is calculated using Equations 20 and 21.

Table 1. Simplified wave model results for Bandirma Bay

Method	**H_S (m)**	**T_S (s)**
CEM	0.42	3.30
JONSWAP	0.83	3.09
Wilson	0.81	3.47
SMB	1.71	5.92

The observed wave is the TPAO wave height value used for comparison, which is 0.55 m at a 10% risk time [20].

$$bias = \frac{1}{N}\sum_{i=1}^{N} P_i - Q_i \tag{20}$$

$$RE = \frac{1}{N}\sum_{i=1}^{N}\frac{|P_i - Q_i|}{Q_i} \times 100 \tag{21}$$

In these equations, P_i represents the estimated values, and Q_i represents the observed values. In Table 2, the error statistics of the estimation-based methods are given by comparing them to the results of other studies conducted in the Marmara Sea [21], the Black Sea [19], and Lake Ontario [22].

Table 2. Comparative error statistics of simplified estimation methods

Forecast Method	Error Statistics	Bandirma Bay	Sacu et al. (2018)	Akpinar et al. (2011)	Etemad et al. (2007)
CEM	bias	0.1	-0.25	-0.53	-0.36
	RE	18	74	-	68
JONSWAP	bias	0.53	-0.23	-0.5	-
	RE	96	67	-	-
Wilson	bias	0.59	-0.19	-0.49	-0.21
	RE	107	58	-	51
SMB	bias	1.9	-	-	-
	RE	345	-	-	-

In this study, bias values were found to be positive, unlike those in the literature. This was because no calibration was made in the formulae in this study, as opposed to other studies in the literature. Nevertheless, it can be observed in the comparisons that simplified methods are inadequate.

4. DISCUSSION AND CONCLUSION

In this study, while the results of simplified methods for wave models were found as shown in Table 2, calculations were made according to the average values of 1/3 of the data for high speeds. However, as seen in the comparative error analyses in Table 2, since the TPAO data were gathered according to a 10% risk, calculations were made according to the average values of 1/10 of the high speeds.

According to the results of this study, the CEM method gives the closest result to the observed TPAO values with an error rate of 18%. This is consistent with previous studies that highlight the accuracy of the CEM method in regions with moderate wind climates. On the other hand, the values found using simplified wave estimation methods gave results above the observed values of up to 300%, contrary to the results in other studies in the literature. This difference was due to the fact that this study was conducted without performing any calibration process.

It is recommended that these values be taken into consideration in any coastal and marine engineering studies and that more care be taken when using simplified wave models. It is also suggested that, if possible, some numerical methods should be used, calibration processes should be carried out, and sensitivity analyses should be performed in engineering studies to be conducted for the same site.

For more detailed wave analyses for Bandirma Bay, improving the temporal and spatial quality of existing measurements will increase the reliability of studies to be carried out in the future.

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Appendices

Appendix A. Wind direction, speed and frequency [11].

Speed (kt)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	TOTAL
0-1	59	127	80	116	97	141	79	86	36	45	24	24	31	15	39	76	1075
1-2	114	305	85	146	117	189	130	165	31	47	19	18	26	32	23	169	1616
2-3	99	393	10	10	21	127	72	118	34	30	9	29	15	35	12	89	1103
3-4	78	542	9	3	5	50	27	68	21	10	6	8	16	26	3	25	897
4-5	70	648	7	0	0	7	8	23	18	12	2	7	5	8	4	6	825
5-6	85	623	4	0	0	1	3	30	27	10	6	6	1	4	0	9	809
6-7	128	600	0	0	0	0	4	8	26	6	4	3	0	2	0	3	784
7-8	148	451	0	0	0	0	2	5	11	2	2	2	0	0	0	0	623
8-9	101	338	1	0	0	0	0	0	2	2	0	1	0	0	0	0	445
9-10	34	172	0	0	0	0	0	0	2	1	0	1	0	0	0	0	210
10-11	25	140	1	0	0	0	0	0	1	1	0	0	0	0	0	0	168
11-12	14	67	0	0	0	0	0	0	1	0	0	0	0	0	0	0	82
12-13	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
13-14	2	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34
14-15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
15-16	4	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16
16-17	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
17-18	6	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
18-19	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
Total	983	4464	197	275	240	515	325	503	210	166	72	99	94	122	81	377	8273
Pct. (%)	11.27	51.18	2.26	3.15	2.75	5.90	3.73	5.77	2.41	1.90	0.83	1.13	1.08	1.40	0.93	4.32	100

Appendix B. SMB method [16].