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Wind Regime and Wave Fetch as Factors for Seagrass Habitat Distribution: A Case Study form Bulgarian Black Sea Coast

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Abstract. The paper presents a study on the relative importance of wind regime and wave fetch for limitation of seagrass spatial distribution in Burgas Bay, the Black Sea. In Burgas Bay the relative importance of both factors is obviously changing from northern to southern coasts. The seagrass meadows facing north-northeast direction have two times smaller integral fetch and are three times more often wave impacted than those facing south-southeast. Along the southern coast the fetch (maximum and number of azimuths) is more important to allow seagrass presence, while in front of the northern coast – it is the wind speed recurrence. In the first scenario the habitat is expected to be less frequently but more strongly affected by the wave action, contrary to the second scenario, where the reversed effect is supposed.

Key words: Seagrass, wave exposure, wind regime, wave fetch.

Introduction

Seagrass communities inhabit the shallow coastal zone of oceans and seas where they are subjected to the impact of the environmental factors such as temperature, salinity, wave action, bottom substrate, riverine and suspended matter inflow, which dynamics varies significantly in time and space. One of the main natural ecological factors which determine the presence of seagrasses habitats is the wave action (Koch, 2001). In the shallow coastal zone of a micro-tidal sea like the Black Sea (Poulos, 2020) the wind waves are a key limiting factor for seagrass spatial distribution.

Thus along coasts predominantly exposed to the prevailing wave action such as the Bulgarian Black sea coast, the habitats suitable for seagrass growth are limited by wind waves. In such areas, it is a matter of scientific and practical interest to study their effect on seagrass meadows distribution, as a critical step for a complex shallow water ecosystem model design.

In temperate, mixomesohaline, mesotrophic water bodies like the surface layer of the Black Sea the diversity of seagrasses is low. It is a habitat of only wave sensitive species: *Zostera noltei*, Hornemann, *Z. marina* L., *Zannichellia palustris* L., *Stuchenia pectinata* (L.) Borner, *Ruppia cirrhosa* (Petagna) Grande (Milchakova, 2011).

Along Bulgarian coast the present natural seagrass meadows are mostly concentrated in the Burgas Bay (Berov et al., 2015). Most of the meadows are formed in

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areas protected by rocky capes which act as a wave shelter. The known shallow-water meadows are located along coastlines facing north-northeast or south-southeast directions.

The aim of this study is to explore the importance of the wind regime, fetch and coastline orientation as a precondition for seagrasses distribution along Bulgarian coast.

Due to the specific wind regime and coastline orientation, it is interesting to analyze how the wave exposure changes along the cost and what are the consequences for the seagrass meadows distribution. The working hypotheses are: 1) seagrass meadows along differently oriented coastline are under different exposure pressure and 2) the relative importance of the fetch and wind regime changes depending on the coastline orientation and thus affects presence/absence of seagrass meadows.

Material and Methods

The present study covers the area of several bays with well-established, perennial seagrass meadows, open towards different azimuth directions: south-southeast and north-north-east (Fig. 1).

Nesebar Bay is a part of Burgas Bay, enclosed between c. Emine and Nesebar Peninsula. It is widely open towards south, southeast and east. Sveti Vlas and Elenite meadows are located along its north coast, as well as the small marina of Elenite resort. (Fig. 2).

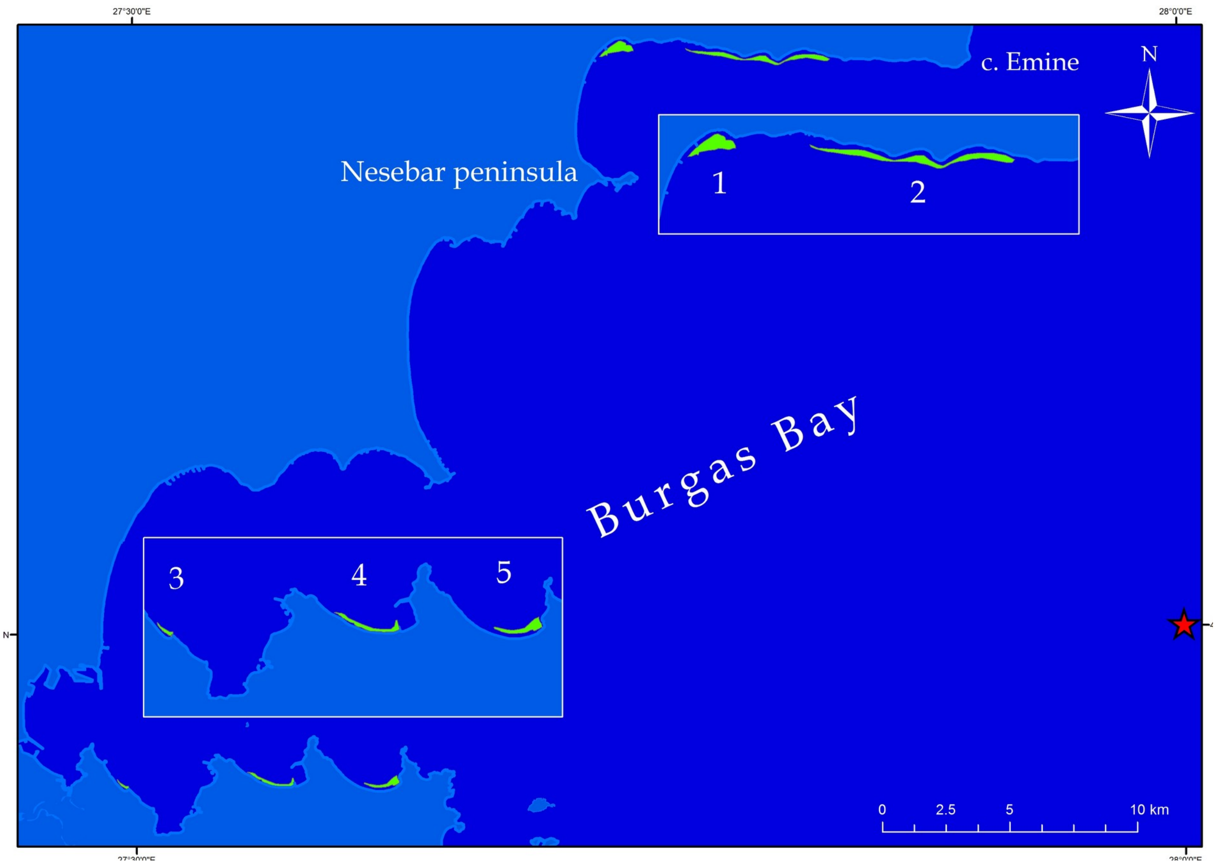

Fig. 1. Study area in Burgas Bay, Black sea: Sveti Vlas (1), Elenite (2) meadows facing south-east; Kraimorie (3), Atia(4) and Vromos Bay (5) facing north, north-east. All meadows are in light green. Red star shows location of wind data collection. Scale line = 10 km.

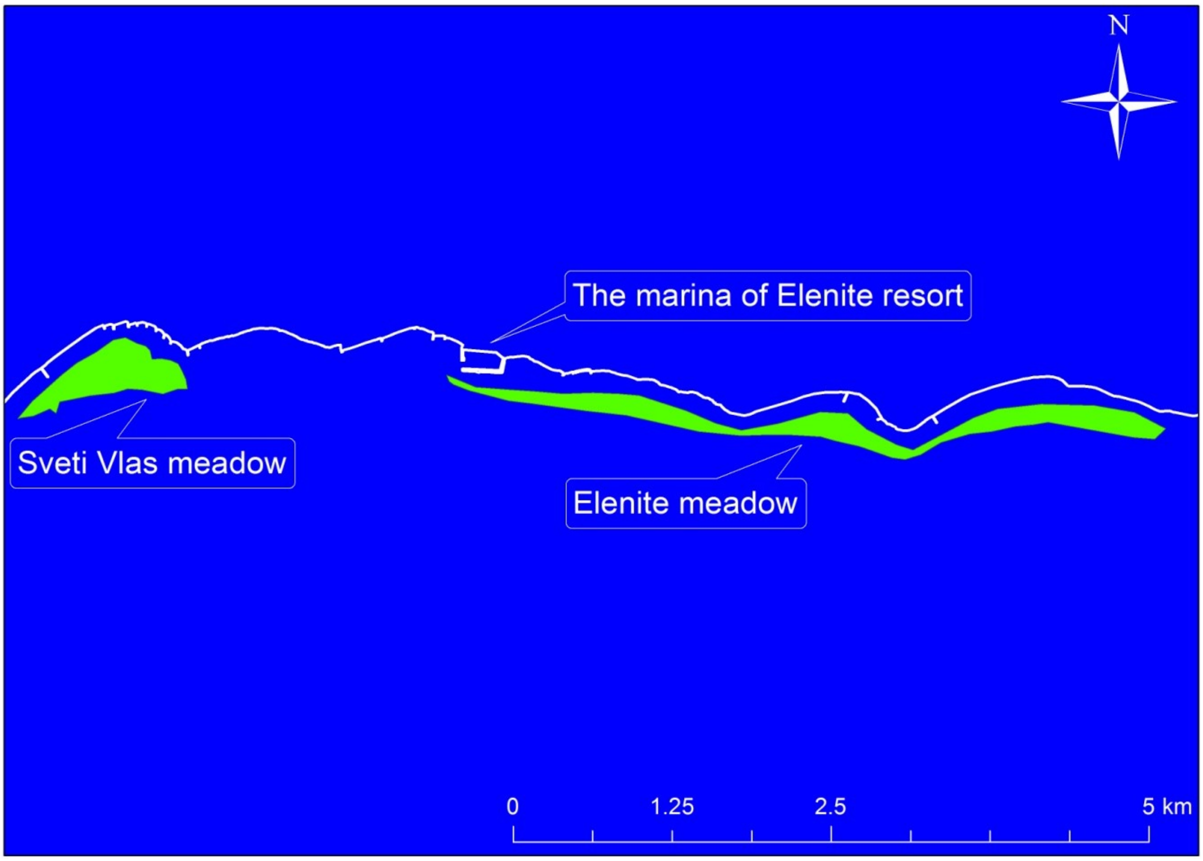

Fig. 2. Sveti Vlas and Elenite meadows and the marina of Elenite resort. Scale line = 5 km.

Vromos Bay (between c. Atia and c. Akra), Kraimorie and Atia meadows are open towards north, northeast (Fig. 1).

The methodology of wind regime, wave exposure and wave parameters calculation as well as statistical modelling and seagrass distribution in Nesebar Bay are presented in detail in Hineva (in press). Modelled data of wind speed and azimuth (available for 6 hours period) in front of Burgas Bay for a 5 year period (MHI-RAS, 2020) were used for wind regime study. The wind data, wave fetch GIS tool (Rohweder et al., 2012) and CMS v. 2.5 (University of Cantabria) modeling software were used for wave parameters calculation in “deep water” and “shallow water” conditions, respectively. The bottom orbital velocity was calculated according to Hunt’s method (Soulsby, 2006). In order to find the azimuths of limiting waves a generalized linear modelling (Zaionts, 2019) between the seagrass upper boundary and the bottom orbital velocity was used. It is assumed that if the model for a given direction was well-fitted, with large area under the ROC curve (AUC) and high percent of correct forecasts (Zaionts, 2019, Schubert et al., 2015), waves coming from that direction limit the seagrasses, while the opposite is true when the model showed a bad discriminative ability.

The seagrass meadows boundaries were outlined in two ways. In Nessebar Bay they were traced out in situ with an echosounder and GPS (September, 2018); in Vromos Bay, Kraimorie and Atia areas the upper boundaries were delineated after a Google Earth image taken on 19.9.2013 had been georeferenced in ArcGIS. The *in-situ* validation of the image was done by SCUBA diving (September, 2018). The spatial data were transformed into binary presence-absence data sets for further statistical treatment. “Presence” of a seagrass meadow means an outstanding, significant part of bottom area covered by seagrass (>20 %) perennially, continuously (i.e. not fragmented to separate patches) and more or less homogenously. Where the patches themselves irrespectively of their own percent cover, occupy less area than the unoccupied surrounding area, these were not considered as a "meadow".

The integral exposure was defined as the area between fetch curve (the maximum fetch along an azimuth) and the x axis for each studied seagrass area only for seaward directions (azimuth from 10 to 180 degrees, see Fig. 5). Calculation was done by the Image J software. Based on the "deep water" wind wave generation theory (Smirnov, 1987) two scenarios for seagrass limitation were considered: 1) small recurrence of winds able to generate highly energetic waves combined with big exposure and 2) high recurrence of moderate to fresh breeze combined with a small "window of exposure".

Results

Wind regime

The wind regime characteristics are presented in detail in Hineva E. (in press). Wind rose (Fig. 3) shows that there is significantly inhomogeneous distribution of the relative frequency of the wind blowing from various directions within each category.

The highest recurrence had winds within "calm weather to gentle breeze" (0-5.4 m/s) category. Their distribution by directions was relatively even and illustrated the approximately equal probability of winds, to blow from each direction.

"Moderate to fresh breeze" winds had significantly uneven distribution, with most frequent winds blowing from north (0°) and northeast (40°).

Winds in the category "strong breeze to gale" were the least frequent and with highly uneven distribution, prevailing from north, northwest and northeast directions. North-northeast winds have occurred under 1 % of all cases.

The observed pattern corresponds to the typical picture in front of Bulgarian coast (Valchev et al., 2014).

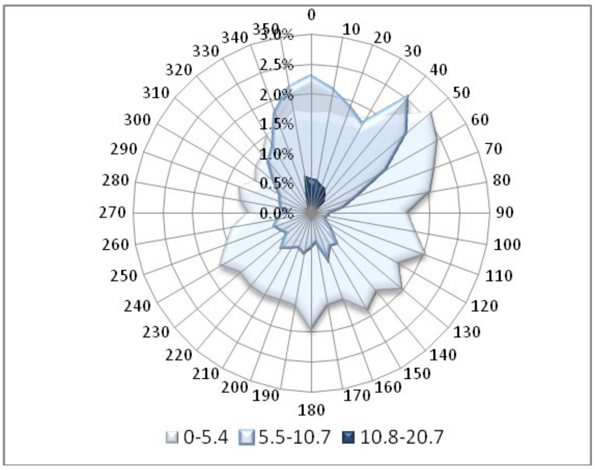

Fig. 3. Wind rose for the open sea in front of Burgs Bay: "calm weather to gentle breeze", "moderate to fresh breeze" and "strong wind to gale". The wind speeds are given in m/s, azimuth- in degrees.

Wave fetch

The coastline of Burgas Bay changes its orientation from east-west in its northern part, to north-south in its middle part and again to east-west and northwest-southeast direction in its south part (Fig. 1). The coastline indentation also differs between the regions. In the northern part of the bay the coast is almost a straight line (low coefficient of indentation) while in the remaining part it is a sequence of smaller or bigger bays and rocky capes (Sailing Directions for the Black Sea, 1956). As a result some parts of the shallow coastal zone of Burgas Bay are to a different extent exposed to waves approaching from north to south (Fig. 4). This creates a variable picture of habitats for marine macrophytes, where the impact of the wave factor is changing along the coastline.

The northern coast of Burgas Bay is mostly exposed to waves approaching from east-southeast and south direction. The maximum wave fetch in this region is at c. Emine (580 867 m from azimuth 110 °, Fig.

4). The seagrass meadows Sveti Vlas and Elenite are located along its northern coast (Fig. 1 and 2).

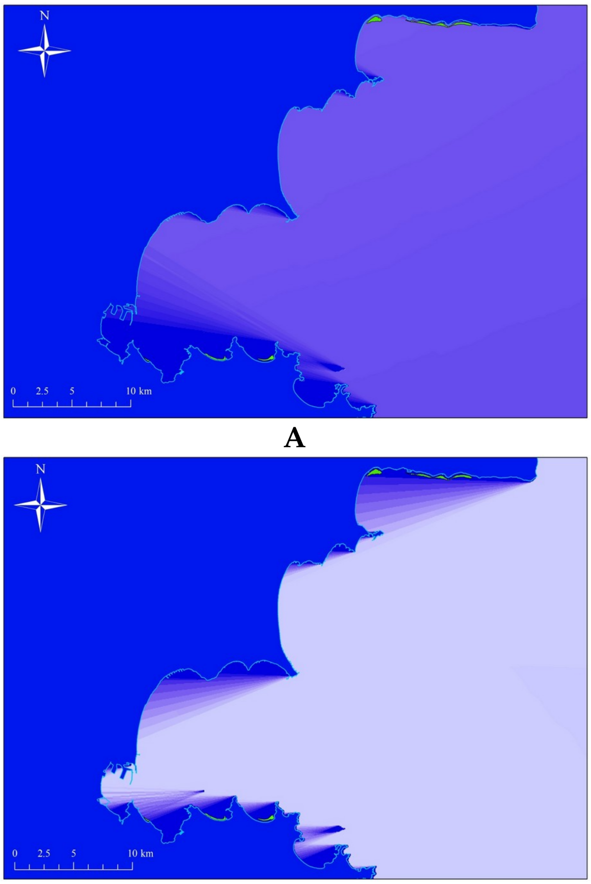

Fig. 4. Effective wave fetch along azimuth 110^0 (A) and 80^0 (B). Colour codes: light colour – exposed areas, dark colour – shadowed areas. For simplicity labels are not shown. Scale line = 10 km.

The southern coasts are predominantly exposed towards north, northeast and partially to east (Fig. 4). The maximum wave fetch here is 827 028 m from 70° azimuth. Kraimorie, Atia and Vromos Bay meadows are located in this area (Fig. 1).

The maximum wave fetch in Burgas Bay is at the western coast (1 019 211 m from azimuth 80^0 (Fig. 4)).The maximum wave fetch where seagrass meadow can persist in Burgas Bay is at the southern coast (597 961 m) located in Kraimorie (Fig.4). The same one at the northern coast is 464 811 m at Sveti Vlas meadow.

Depending on the coastline orientation the meadows are to a different extent exposed to the approaching waves (Fig. 5).

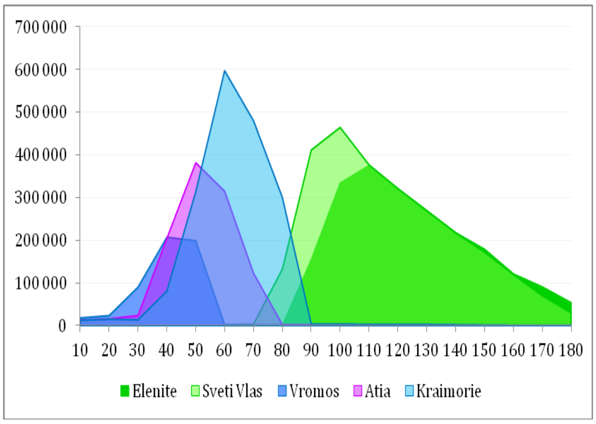

Fig. 5. The value of the maximum wave fetch from different azimuths for two groups of fields: Elenite and Sveti Vlas – open towards south-southeast, Vromos, Atia, Kraimorie – open towards north-northeast. Along x axis are azimuths and along y axis is the fetch, m.

While the meadows facing north-northeast are exposed to lower number of azimuths (smaller window of exposure), with higher maximum fetches, the meadows opened towards south and southeast are facing more azimuths and have shorter maximum fetches. The total fetch of each vegetated area (the integral of maximum fetches along each seaward azimuth) shows that meadows facing north-northeast directions have smaller total fetch (77 730 ± 11 772 conventional units) than those exposed towards south-south east directions (168 462 ± 1 105 conventional units) (Fig. 5 and 8).

The results of the statistical analysis has shown poor, satisfactory, very good and excellent discriminative ability of the constructed models (Table 1).

Results for Nesebar Bay meadows presented in detail in Hineva E. (in press) have shown that both meadows are significantly limited by the wave action, as indicated by the mostly excellent and very good discriminating ability of the logit functions (Hineva E., in press). Stveti Vlas meadow, where statistical tests has shown poor discriminating ability if waves approach from 170 and 180 degrees, is better protected than Elenite meadow due to the wave shadow of Nesebar Peninsula (Table 1, Fig. 6).

The results from statistical analysis for Kraimorie, Atia and Vromos Bay are shown in Table 2.

Kraimorie and Atia meadows are protected from the north and partially from the northeast by dry land (c. Chukhalia and c. Atia, respectively). Atia, the most protected meadow facing north-northeast, is limited only by the waves coming from 70, 80 and 90 azimuth degrees. Kraimorie one is more exposed as the waves approaching from 30 and from 60 to 80 degrees can explain the observed meadow location (Table 2.).

Vromos Bay is partially open towards north, northeast from small number of azimuths (6). From the north it is protected by the Pomorie Peninsula and the short fetch (13 033 m) limits the wave growth. The waves which approach from 20 to 80 degrees can explain the observed seagrass location. The statistical models have excellent to satisfactory discriminative ability and high enough number of correct forecasts (Table 2, Fig. 7).

When the waves come from east and southeast c. Akra creates a wave shadow over the whole bay and those waves could not limit the upper meadow boundary.

The coasts open to north-northeast are facing 10 azimuths (from 0 to 90 azimuth degrees), whose total relative frequency of moderate to fresh breeze is 15.1 % (Fig. 8). This shows that the whole area has been wave impacted approximately 3 times more often than Nesebar Bay, where only 4.8 % of cases were moderate to fresh breezes and the respective waves. The small number of statistical relationships between bottom orbital velocity and seagrass upper boundary, which have excellent discriminative ability, indicates a better protection of the meadows facing north-northeast; where the wave fetch is limited by some natural features (peninsulas, capes etc.) models have bad discriminative ability, i.e., waves approaching from those directions could not limit the seagrass. Thus the smaller window of exposure decreases the overall possibility the meadows to be regularly damaged by wave action and their persistence here to be prevented.

Discussion

It is well known (e.g. Smirnov, 1987) that the main factors which determine wave parameters in deep water conditions are: 1) wind regime (speed, recurrence and period of action) and 2) the free space (fetch) over which wind can travel in a constant direction (Rohweder, 2012).

There are generally four possible combinations of both of factors and their relevant impact on wave-sensitive seagrasses (Fig. 9 A, B, C, D). In extremely sheltered areas (Fig. 9 A) seagrasses are not limited by wind waves due to the short fetches (e.g. Rubegni et al., 2013, van Djik, 1993) or due to both the short fetches and low speed winds. In this case there is not enough wind energy which can be transferred to the sea surface in order to generate the relevant waves. The short fetch indicates that a protection from the swell is also available. Usually in such areas the rooted plants are stressed due to water stagnation and stimulated by wave action (van Djik, 1993). In the situations where both fetches and wind characteristic are high (Fig. 9 D) there is no possibility of wave sensitive seagrass species to survive in the highly energetic shallow water area (Koch et al., 2006). When at least one of them has small enough value the probability to cause seagrass absence is also small but the upper boundary of the meadow is wave limited (Koch, 2006, Infantes et al., 2009, Stevens & Lacy, 2012) (Fig. 9 B and C).

Table 1. Seagrass meadows along the coastline of Burgas Bay and the corresponding directions of the limiting waves.

№	Meadow	Limiting waves approach from azimuths:	Meadow is facing:	Source:
1	Elenite	90-180	East-southeast-south	Hineva E. (in press)
2	Sveti Vlas	90-160	East-southeast	Hineva E.(in press)
3	Vromos	20-80	North-northeast	Present study
4	Kraimorie	30, 60-80	North-northeast	Present study
5	Atia	0-90	North-northeast	Present study

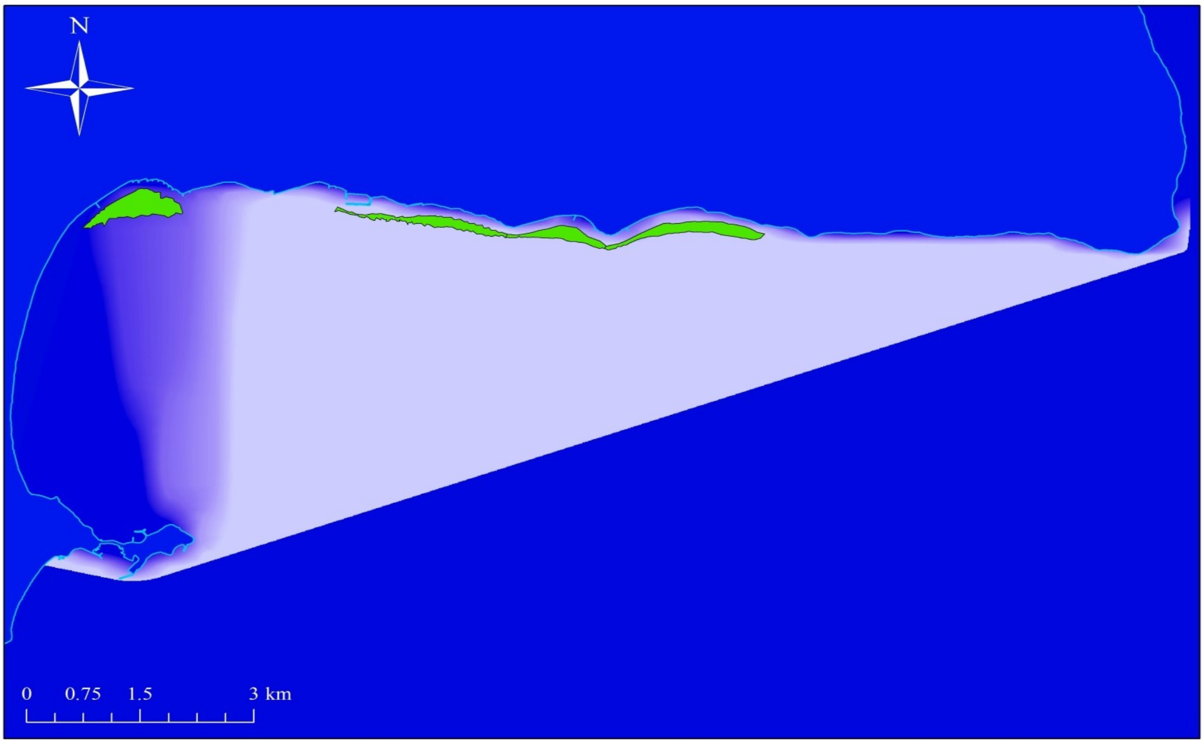

Fig. 6. Distribution of the average wave height in Nesebar Bay when approaching from azimuth 180°. "Colour codes" are the same as in Fig. 4. Scale line = 3 km.

Table 2. Parameters of the logistic model for the upper boundary of the meadows Kraimorie, Atia and Vromos Bay. Coefficient b0 and b1 – coefficients of the equations, AUC – area under the ROC curve.

№	Azimuth, degrees	b0	b1	Correct forecasts (%)	AUC	Discriminative ability (according to Hosmer & Lemeshow, 2000)
			Kraimorie meadow			
1	20	0,3	-1 278,8	51,8	0,52	poor
2	30	0,8	-39 390,8	72,7	0,72	satisfactory

3	40	0,63	-38,1	53,6	0,62	poor
4	50	0,25	-2,17	49,1	0,54	poor
5	60	0,56	-18,76	79,0	0,72	satisfactory
6	70	2,8	-22,9	73,6	0,81	very good
7	80	7,02	-58,19	84,5	0,91	excellent
8	90	3,4	-65,4	75,5	0,76	satisfactory
				Atia meadow		
1	20	1	-49,6	67,4	0,57	poor
2	30	0,8	-13,9	67,4	0,34	poor
3	40	0,4	1,5	61,8	0,64	poor
4	50	0,9	-4,4	64,0	0,47	poor
5	60	1,1	-21,0	71,9	0,53	poor
6	70	1,8	-24,7	77,5	0,71	satisfactory
7	80	2,9	-41,5	79,8	0,84	very good
8	90	2,4	-58,1	77,5	0,81	very good
				Vromos Bay		
1	20	3,12	-82,3	81	0,94	excellent
2	30	4,17	-155,5	85	0,95	excellent
3	40	4,43	-200,3	88	0,97	excellent
4	60	3,47	-175,6	85	0,96	excellent
5	70	8,35	-180,9	91	0,98	excellent
6	80	2,25	-553,6	72	0,74	satisfactory
7	90	0	0	60	0,38	poor

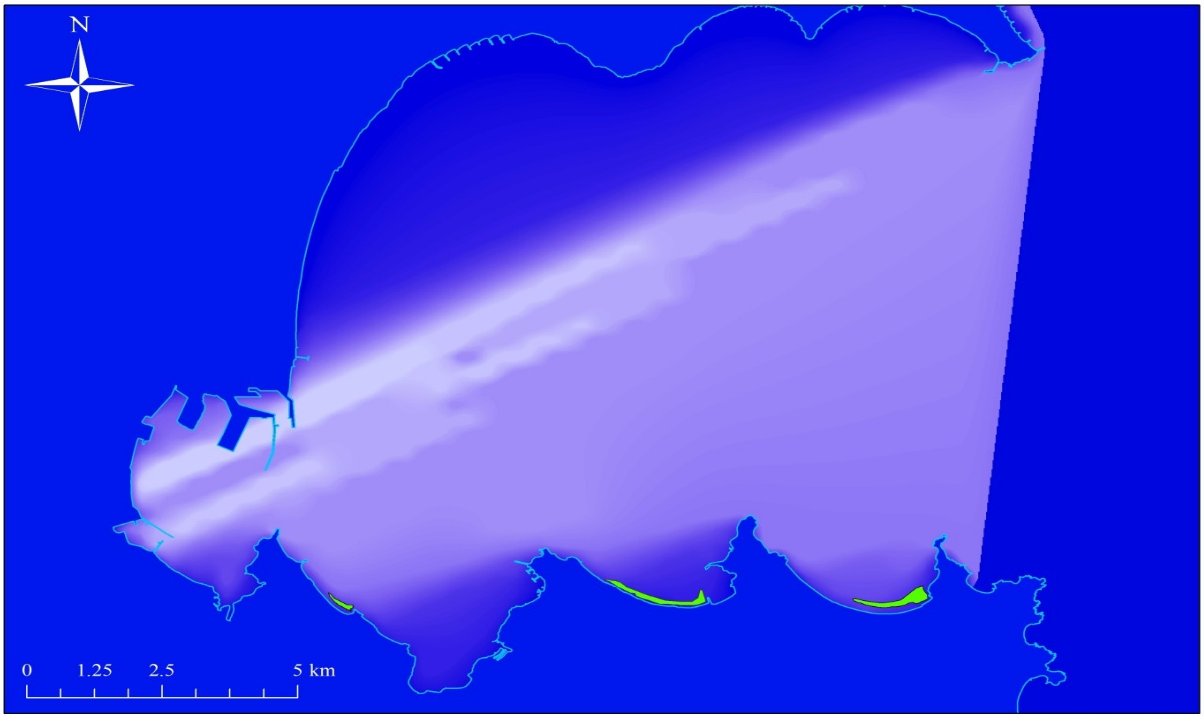

Fig. 7. Distribution of the average wave height in Kraimorie, Atia nad Vromos Bay when approaching from azimuth 70°. Port infrastructure is not assumed in modelling. “Colour codes” are the same as in Fig. 4. Scale line = 5 km.

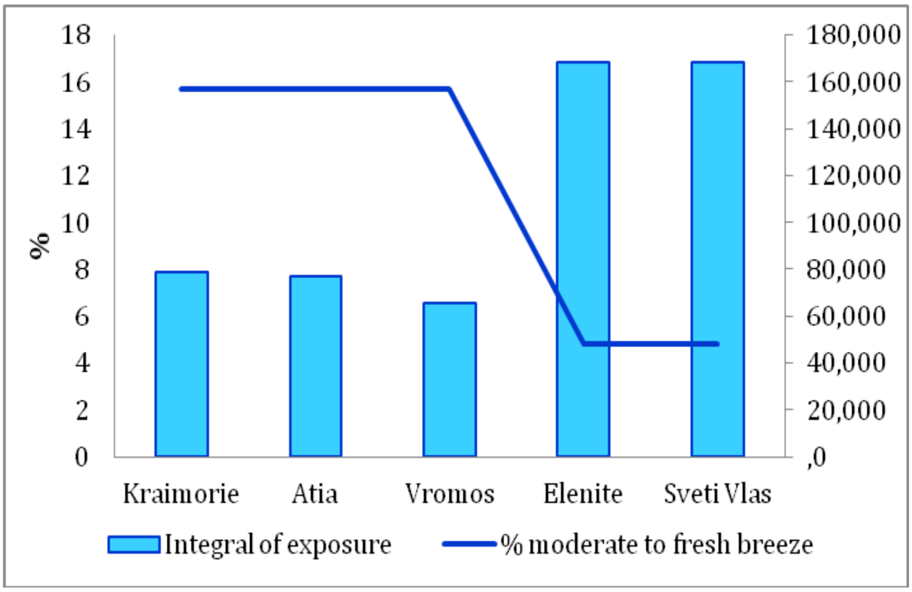

Fig. 8. Integral of exposure, percent of cases when wind has blown from north-northeast and south-southeast for the five seagrass meadows.

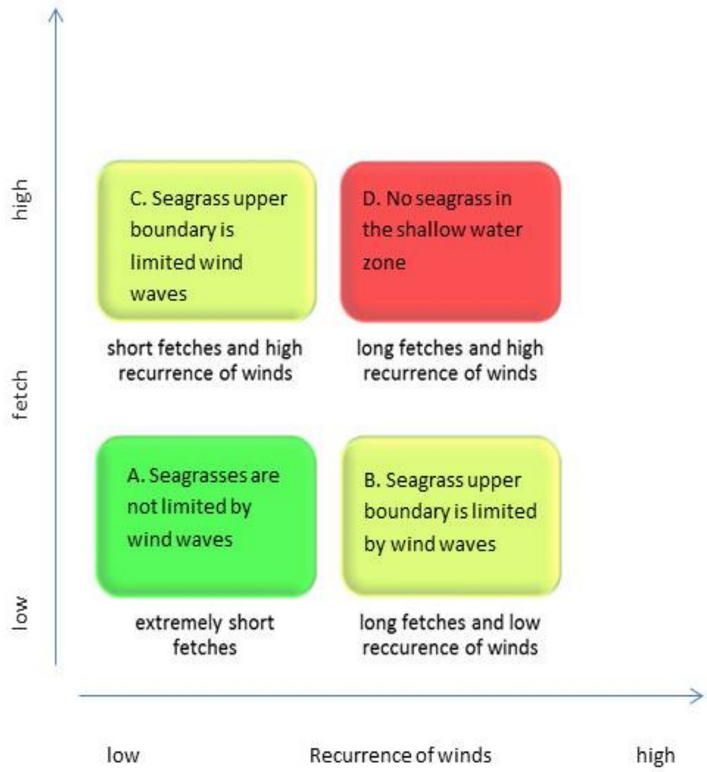

Fig. 9. Four possible scenarios for limiting wave sensitive seagrass by wind waves. “Winds” corresponds to “wind speed recurrence and duration of action” high enough to create waves able to limit seagrass presence in the shallow coastal zone.

Both types of wave generation factors have their specific features in Burgas Bay.

The wind rose for the open sea area against Burgas Bay shows that the distribution of relative frequency of wind speeds is different for each category: "gentle breeze" is relatively evenly distributed by directions, while in the other two categories the distribution is significantly uneven, as winds from north, northeast, and northwest predominate (Fig. 3).

The „gentle breeze"category obviously does not generate waves that could limit the seagrasses: the similar probability wind to blow from each direction does not explain the observed meadow distribution. Similar finding based on seasonal wind regime pattern has been reported by Keddy, 1982, who found that the measure of exposure has non-significant or poor correlation with vegetation during summer period (low wind speeds). In addition Schubert et al., 2015 have found that the "best model" which explains *Z. marina* L. distribution in the Baltic Sea is the one that considers wind speed ≥ 6 m/s (i.e. above "the gentle breeze" category). One can expect winds, within the categories "fresh to strong breeze" and "strong breeze to gale", to have a potential limiting effect. Strong hydrodynamic conditions are well known to have a destructive effect on seagrasses (e.g. Short & Willey-Echeveria, 1996, Portillio, 2014). Strong winds are the rarest along Bulgarian coast they occurred only in 0,1 % of cases from wave exposed directions (Fig. 3). Their strength creates waves with high energy, which probably have destructive effect upon seagrasses but their small probability of recurrence does not allow them to determine the perennial location of seagrass meadows. They could explain only a snap-shot picture observed immediately after a strong wind event. If for a long enough period after such an event there is no strong wind conditions, seagrasses would recolonize the previously abandoned bottom area up to the boundaries determined by less strong but more often wind waves.

The category "moderate to fresh breeze" has wide enough speed range and includes winds which have occurred often. Based on the wind rose (Fig. 3) it is expected that wave effect is strongest along coastlines open towards north and northeast and that conditions for seagrass growth there will differ from those along south-south east ones.

The maximum wave fetch along the northern parts of the coastline is significantly shorter from that along southern parts (Fig. 4). The maximum fetch alone could not explain the observed seagrass presence in Burgas Bay (poor discriminative ability of the logit function, data not shown), thus emphasizing the importance of the wind regime.

The impacts of both factors: wind regime and fetch also depends on the number of seaward azimuth directions (Fig. 5) (WFD CIS Guidance N 5). There is much higher possibility seagrasses along the coasts, open towards more seaward directions, with higher probability of "moderate to fresh breeze" to be limited by the wind wave and not to be present there. This fact is reflected in the design of simplified exposure indicators: exposure measure (Keddy, 1982), relative exposure index (Fonseca & Bell, 1998), where each term of the sum is a product of the fetch multiplied by the wind speed (average or exceedance or monthly average, etc.) and by the relevant wind percent frequency. Despite their obvious advantages and extremely wide application in aquatic ecology (e.g. Santana-Garson et al., 2010, Bekkbi et al., 2014, Mason et al., 2018), these indices focus mostly on the cumulative effect and not on the role of each type of wave generation factor for the creation of the habitat conditions.

The comparative analysis of conditions for seagrass inhabitance along the northeast and south-southeast coastlines of the study area allows for highlighting the relative importance of the wind regime versus the integral fetch. Examples of the four combinations of wave generation factors (Fig. 9) can be found in Burgas Bay.

The marina of Elenite resort along the north coast of Nesebar Bay limits the fetch and prevents the possibility of wind waves and swell to enter its aquatory (Fig. 2). It is representative of situation where both the short fetches and low wind recurrence create stagnate conditions (Fig.9A). The soft bottom macrophyte community there consists of three wave sensitive rooted aquatic plants: *Z. marina* L., *S. pectinata* (L.) Borner *Z. palustris* L. The scenario D (Fig. 9 D) is typical of the unvegetated area neighboring the meadows which lies outside the wave shadow of the adjacent capes. Examples are available both in northern and southern stretches of the coastline: the area adjacent to c. Emine (Nesebar Bay), areas neighboring the meadows of Kraimorie, Vromos etc. (Fig. 1). The situation on Fig. 9 B is represented by the Elenite and Sveti Vlas meadows opened towards a great number of directions (8-10 azimuths). The meadows are limited by wave action but can survive here having a deeper upper meadow boundary (> 2.5 m depth). These meadows are the most limited by wind waves: the statistical models have predominantly excellent to very good discriminative ability (Table 1). Regardless the higher most probable and average monthly maxima wind speeds from south-southeast; the low frequency of occurrence of those winds allows a fully open bay like Nesebar to accommodate seagrasses. In such areas the recurrence of wind is a key factor in the seagrasses presence because it creates more calm conditions, suitable for their inhabitance. The situation on Fig. 9 C is represented by the coasts exposed towards less number of azimuths (3 - 6 azimuths) with higher recurrence of "moderate to fresh breeze". The integral of all fetches in the most exposed southern coasts (open towards north-northeast) where seagrasses live is 2 times smaller than the integral of maximum fetches for most exposed northern coast (opened towards south-southeast) (Fig. 5). The wind rose (Fig. 3) shows that if a "moderate to fresh breeze" is observed the probability that it comes from north and northeast is much higher than from south-southeast. This indicates that when moderate to fresh breeze winds frequently occur, the fetch (integral) can significantly impact the seagrass distribution. The high recurrence of those winds has to be "compensated" to some extent by the smaller number of fetches of the limiting waves in order perennial seagrass meadows to be present (Tables 1 and 2). Therefore in bays open towards north, northeast the wave fetch has significant importance for presence or absence of seagrasses.

Conclusion

The combination of predominating winds and available free space for generation and growth of waves through the wave climate determines the probability of shallow water seagrass presence along Bulgarian Black Sea coast. In the regions where integral exposure is high seagrass could survive only if the wind regime creates milder wave climate corresponding to low frequency of moderate to fresh breeze. In regions where the moderate and fresh breeze occurrences are frequent, the smaller integral fetch creates suitable conditions for seagrass habitat. In the first situation the habitat is expected to be less frequently but more strongly impacted by the wave action, while in the second situation the opposite is supposed. Whether this has any consequences for the adaptation of seagrass communities to local hydrodynamic conditions is yet to be studied in future experiments.

For the Bulgarian coast the relative importance of the factors: wind regime and fetch is obviously changing from northeast to southeast coasts. Along the first ones the fetch (maximum and number of azimuths) is more important, while in front of the second, the wind speed recurrence is more important to allow for seagrass presence.

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