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NUMERICAL ANALYSIS OF SIGNIFICANT WAVE HEIGHTS IN A FIVE-YEAR RETURN PERIOD IN THE SOUTHERN ADRIATIC SEA

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Original scientific paper

This paper presents the results of numerical modelling of wave generation in the local waters of the channel and island system of the southern Adriatic Sea. The dynamics of gravity wind waves in the researched area is based on the results obtained from the prognostic atmospheric model Aladin. For verification of model results, results of measurements at a waverider station located in front of the town of Split were used. The model results and measurements covered the period from 1 November 2007 to 15 November 2008. The outcome of significant wave height fields is a statistical model with basic characteristics of a short wave climate, on the basis of which a long-term wave climate forecast has also been obtained, with a return period of five years. The resulting map of the wave height area may be applied in calculations of functionality of naval constructions.

Keywords: *the Adriatic Sea, numerical model, significant wave height, waverider*

Numerička analiza značajne valne visine u petogodišnjem povratnom razdoblju u južnom Jadranu

Izvorni znanstveni članak

U radu se prikazuju rezultati numeričkog modeliranja valnog generiranja u akvatorijalnom području kanalskog i otočkog sustava južnog Jadrana. Dinamika gravitacijskih vjetrovnih valova na istraživanom području dobivena je temeljem rezultata prognostičkog atmosferskog modela Aladin. Za verifikaciju modelskih rezultata korišteni su rezultati mjerenja na valografskoj postaji smještenoj ispred grada Splita. Modelskim rezultatima i mjerenjem pokriven je period 1.11.07.-15.11.08. Rezultantna polja značajnih valnih visina predstavljaju statistički uzorak sa osnovnim obilježjima kratkoročne valne klime temeljem koje je dobivena i dugoročna prognoza valne klime s povratnim periodom od 5 godina. Tako dobivena karta područja valnih visina može se primijeniti u proračunima funkcionalnosti pomorskih građevina.

Ključne riječi: *Jadran, numerički model, valograf, značajna valna visina*

1 Introduction
Uvod

Definition of civil structures intended to protect vessels in port indoor pools is conducted on the basis of two criteria: stability and functionality. Calculations of functionality of naval constructions are as a rule carried out for lower values of activity of the marine environment ($PR \geq 5$ yrs) than the calculations of stability ($PR = 50$ to 100 yrs), because in the course of usage of constructions they may be allowed to be out of function several times. Functionality is confirmed by means of comparison with the maximum allowed values of certain parameters, such as the maximum allowed significant relevant altitudes in a specified return period in protected waters of a marina, or the maximum allowed movements of a ship moored at a wharf. According to the Croatian Register of Shipping (CRS), the marina functionality criterion is defined on the basis of the maximum significant wave height which may occur in protected waters. For the return period of five years, the value is 0,3 m. Also, by calculating functionality, the height of the crown of protective constructions is defined.

It is a common practice to conduct wind wave analyses in order to gain insight into basic wave parameters in front of researched sites, primarily the significant wave height, Hs and the wave period, TP; and then, using one of the model technologies (numerical, physical, hybrid model), the functionality of the foreseen project solutions is tested.

The aim of this paper is to define, in the area of the Split, Brač, Hvar, Korčula and Neretva Channel, the wave climate in a five-year return period regardless of the direction. The resulting wave climate would be used to illustrate a methodology that would in the future be applied to the entire area of the Adriatic Sea; furthermore, for the needs of the construction sector, it would be developed in various directions. In addition to this, on the basis of a longer series of data on the wind, it would be possible to define the wave climate for longer return periods and thus to accelerate the implementation of the calculation of stability in early design stages.

The technique used in the implementation of the analyses shown in this paper is the numerical modelling of generation, development and disappearance of gravity wind waves and wave distortions in the model domain shown in Fig. 1. The numerical model Mike 21/SW is used (www.dhigroup.com).

For the purposes of verification of the results obtained by the numerical model, data from a waverider station placed in front of the town of Split (Fig. 1 $\varphi = 43° 29,3'$; $\lambda = 16° 27,9'$) in the period from 1 November 2007 to 15 November 2008 during implementation of the Monitoring of the Adriatic Sea - Adriatic Project [1] was used. The waverider of the Datawell Company, type MKIII with a built-in GPS receiver and a digital device for recording, was used. The waverider output data contain standard wave statistics for successive 30-minute periods. Unfortunately, due to technical troubles that emerged in the work of the waverider, the recording of the dynamics of the peak spectral period Tp is not useful and is therefore not included in the below presented results.

The process of transferring energy from wind to waves and consequent generation of wave spectra has not been fully resolved yet. The general theoretical level related to the generation of waves was established by Lamb [2], Phillips and Miles [3, 4]. The pioneer numerical implementation of the theoretical basis set was defined by Donelan [5], while Schwab [6] in 1984 formed the semi-empirical parameter model, the so-called 1st generation model. From then until today, an important contribution has been made by Cavaleri and Malanotte-Rizzoli [7] and by

Janssen [8, 9, 10, 11] and Johnson [12, 13]. Currently in use is the 3rd generation model.

Considering the area studied in this paper, it is necessary to mention the papers of Sverdrup and Munk [14], Bretschneider [15], and Kahma and Calkoen [16], in which the phenomenon of generating waves is associated with the limited fetches.

2
Used numerical models
Uporabljen numerički model

In the numerical model Mike 21/SW, full spectral formulation based on the papers by Komen et al. [17] was used. For discretization of the spectral frequency domain, logarithmic scale with the minimum frequency of 0,08 Hz (wave period 12,5 s) to the maximum frequency of 0,95 Hz (wave period 1,05 s) was used, through 26 discrete steps. The mentioned range provides coverage of all relevant spectral periods that may be expected in the analyzed area. The model includes the processes covered by the wind wave generation, non-linear wave interaction, refraction and shoalling, as well as whitecapping.

Dissipation coefficients were used with constant values of 3,5 and 0,5 [16]. Reflection and diffraction have not been treated using this model. Time integration is carried out with fractional steps, whereby for the propagation of wave action multi-sequence Euler's explicit method was used. The function of sources in the wave action conservation equation is treated on the basis of the last, 3rd generation models, and their numerical integration is carried out according to the DIA (Discrete Interaction Approximation) method shown in the papers of Komen [17] and Hercbach and Jannsen [18]. Convective flux is calculated by upwind numerical scheme of the first order.

Generation of wave dynamics requires data on the wind (intensity and direction) in the spatial domain of the numerical model at 10 m above the sea surface. These data were obtained from the prognostic numerical atmospheric model Aladin that is operationally used by the Croatian Meteorological and Hydrological Institute. The model was established in a hydrostatic version based on the primitive equations with a numerical implementation developed in cooperation with several national meteorological institutions. The model is derived from the global ARPEGE (Action de Recherche Petite Echelle Grande Echelle) model of Meteo-France [19, 20, 21]. The model calculations are carried out in the spatial domain which covers the area from the Croatian Adriatic and orthographically the Alps, Dinarides and Apennines with a horizontal resolution of 8 kilometres and a temporal resolution of three hours [22, 23].

3
Spatial domain, boundary and initial conditions
Prostorna domena, rubni i početni uvjeti

Fig. 1 shows the spatial domain of the numerical model of wave generation which includes the area of the Split, Brač, Hvar, Korčula and Neretva Channel. Fig. 1 shows also the bathymetric basis based on the spatial continuous raster grid data of 7,5' ($\approx$200 m) in the longitudinal and latitudinal direction.

Fig. 2 shows the model spatial domain discretization with an unstructured grid of triangle finite volumes. Numerical distances between nodes set in the centres of finite volumes are variable, ranging from 150 m to 500 m. The model domain does not have open borders and all the rigid boundaries are completely absorbent (absence of reflection). The adoption of such assumptions about exclusion of open borders, which are apparently inherent in the nature in the links between the islands of Šolta and Hvar, and of Hvar and Korčula, caused an initial error to enter the model generation of waves in winds blowing from the west. Given the intensity, frequency and duration of the wind with prevalent W direction, and the flatness of the coastline and bathymetric gradients, it may be concluded that the entered error very rarely has an impact on model results, and namely only on the above mentioned close links between the islands.

Initial conditions (1 Nov. 2007) were defined with a zero relevant range, i.e. it is assumed that there is absence of the initial wave motion throughout the model spatial domain.

The wind rose for the period from 1 November 2007 to 15 November 2008 is based on the results obtained from the Aladin model at the position of the waverider shown in Fig. 3. Examples of the result field components of the wind speed at 10 m above the surface from the Aladin model are shown in Fig. 4. In Fig. 5, the wind speed dynamics during the period from 1 January 2008 to 1 July 2008 for the position of the waverider is shown.

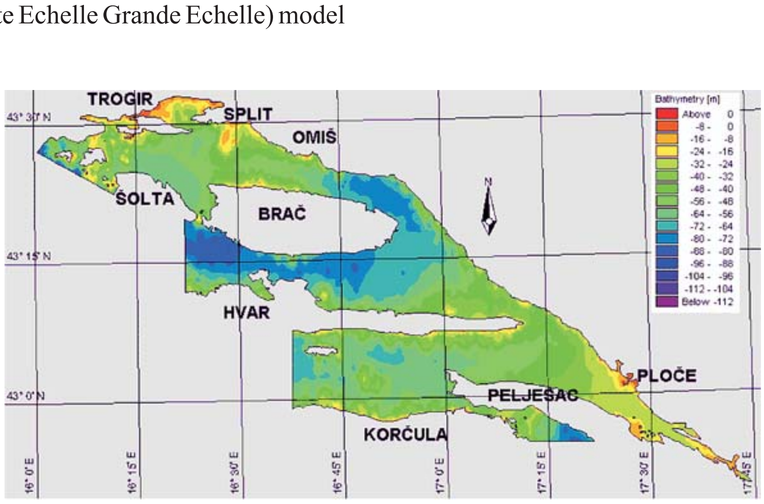

***Figure 1** Spatial domain of the numerical model of wave generation comprising the area of the Split, Brač, Hvar, Korčula and Neretva Channel with the indicated waverider station position*
***Slika 1.** Prostorna domena numeričkog modela valnog generiranja kojom je obuhvaćeno područje Splitskog, Bračkog, Hvarskog, Korčulanskog i Neretvanskog kanala s naznačenom pozicijom valografske postaje*

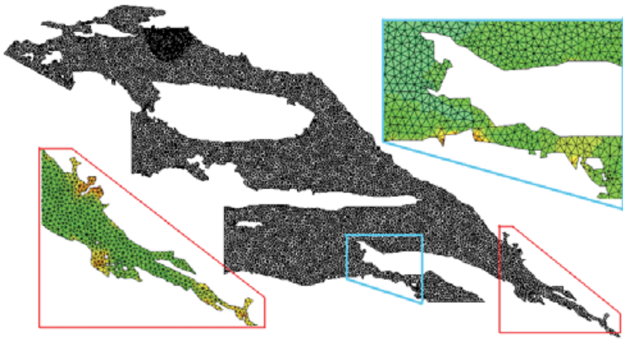

Figure 2 *Spatial domain discretization with an unstructured grid of triangle final volumes*
Slika 2. *Diskretizacija prostorne domene modela s nestrukturiranom mrežom trokutnih konačnih volumena*

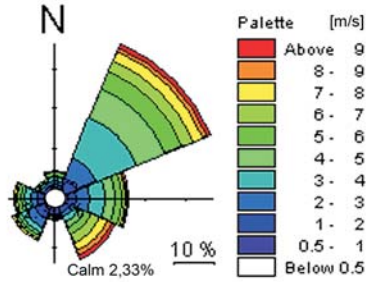

Figure 3 *Wind rose for the period from 1 November 2007 to 15 November 2008 obtained on the basis of results from the Aladin model at the waverider station site*
Slika 3. *Ruža vjetrova za period 1.11.07-15.11.08. dobivena temeljem rezultata iz modela Aladin na poziciji valografske postaje*

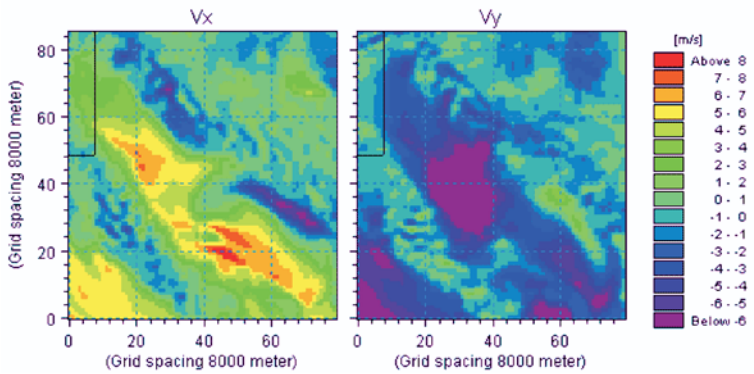

Figure 4 *Fields of wind speed components at 10 m above the surface obtained by means of the atmospheric model Aladin on 5 February 2008 at 6 pm*
Slika 4. *Polja komponenti brzine vjetra na 10 m iznad površine dobivena atmosferskim modelom Aladin za termin 5.2.08. u 18:00*

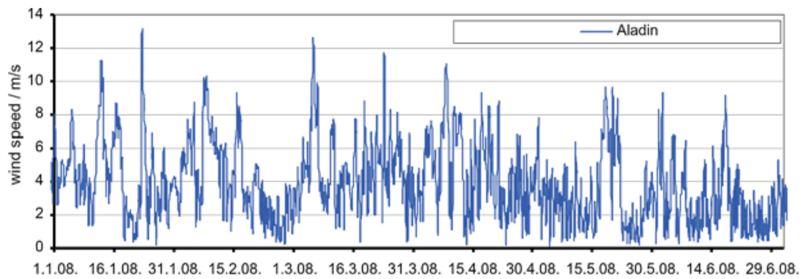

Figure 5 *Wind speeds at 10 m above the sea surface obtained on the basis of results of the Aladin model at the waverider station site located in front of Split for the period from 1 January 2008 to 1 July 2008*
Slika 5. *Brzine vjetra na 10 m iznad površine mora dobivene temeljem rezultata iz modela Aladin na položaju valografske postaje smještene ispred Splita za period 1.1.08.-1.7.08.*

4
Results of the conducted analyses
Rezultati provedenih analiza

Fig. 6 shows a comparison of the measured and modelled dynamics of significant wave heights at the wave rider station site during the analyzed period.

Given that the resulting speed fields and wind direction effects are derived from the Aladin model which has a prognostic character (the results are pre +12 h), they need to be critically analyzed. One of the possibilities is also a comparison with measured incidental wave directions. It may be reasonably assumed that prevalent course of action of wind and wave propagation in a certain period match or are under a constant angle. For example, the activity of the south direction of wave propagation in the Brač Channel follows the longitudinal axis of the Channel, which makes a softer angle than the direction of the wind action [1]. On the other hand, waves coming through the Split Channel from the west are diffracted around the cape of the island of Čiovo and face the waverider position at an angle which deviates from the direction of pure west wind. While the Adriatic libeccio is in action (SSE direction), it is expected that the direction of the wave propagation registered by the waverider corresponds to the direction of the wind action.

By comparison of the resulting wind directions obtained by the Aladin model at the position of the waverider station with registered directions of waves on the waverider, a set of time intervals (situation) of interest for further analysis of the wave generation model results (Tab. 1) is obtained. It should be noted that from the overall period of monitoring, from 1 November 2007 to 15 November 2008, only the periods in which wind speeds exceeding 5 m/s continuously appear were exempted.

Additional control of reliability of the data from the Aladin model was conducted by means of implementation of *Hs* calculation on the basis of the Groen Dorrenstein diagram. For this calculation, wind speed data from the Aladin model were used, with medium values in the course of each individual situation as shown in Table 1. The adopted lengths of wind effects are: 3 km (Bora), 20 km (Sirocco), 10 km (Libeccio) and 15 km (West Wind).

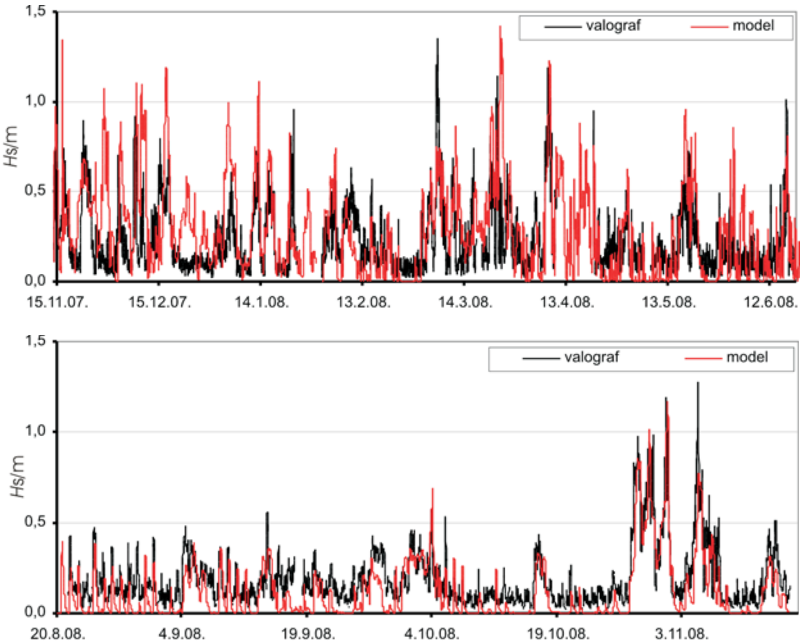

Figure 6 *Comparison of the measured (waverider) and modelled (Mike 21/SW) dynamics of significant wave heights Hs at the waverider station site*
Slika 6. *Usporedba izmjerene (valograf) i modelirane (Mike 21/SW) dinamike značajnih valnih visina Hs na poziciji valografske postaje*

Table 1 *Situations where wind speeds are continuously higher than 5 m/s and where the results of wind directions from the Aladin model are verified with measured directions of wave propagation at the waverider*
Tablica 1*. Situacije u kojima su brzine vjetra kontinuirano veće od 5 m/s i u kojima su rezultati smjerova vjetra iz modela Aladin verificirani sa izmjerenim smjerovima valne propagacije na valografu*

	Bora - NE (>5 m/s)		Sirocco - SE (>5 m/s)		Libeccio - SW (>5 m/s)
1.	09.11.07. 21:00 → 10.11.07. 00:00	1.	22.11.07. 12:00 → 25.11.07. 03:00	1.	30.10.07.15:00 →30.10.07.18:00
2.	12.11.07. 09:00 → 12.11.07. 15:00	2.	07.12.07. 18:00 → 08.12.07. 15:00		West Wind - W (>5 m/s)
3.	13.12.07. 09:00 → 14.12.07. 00:00	3.	04.01.08. 12:00 → 06.01.07. 00:00	1.	31.05.08.12:00 →31.05.08.15:00
4.	14.12.07. 12:00 → 14.12.07. 21:00	4.	11.01.08. 15:00 → 13.01.08. 21:00	2.	01.06.08.09:00 →01.06.08.15:00
5.	01.01.08. 09:00 → 01.01.08. 18:00	5.	15.01.08. 12:00 → 18.01.08. 00:00		
6.	23.01.08. 14:00 → 23.01.08. 21:00	6.	03.02.08. 09:00 → 05.02.08. 06:00		
7.	07.02.08. 09:00 → 07.02.08. 24:00	7.	10.03.08. 09:00 → 11.03.08. 09:00		
8.	15.02.08. 15:00 → 16.02.08. 00:00	8.	16.03.08. 09:00 → 16.03.08. 21:00		
9.	16.02.08. 21:00 → 17.02.08. 00:00	9.	07.04.08. 03:00 → 07.04.08. 18:00		
10.	05.03.08. 06:00 → 07.03.08. 09:00	10.	30.04.08. 21:00 → 01.05.08. 12:00		
11.	16.09.08. 06:00 → 17.09.08. 12:00	11.	17.05.08. 03:00 → 19.05.08. 06:00		
12.	19.09.08. 18:00 → 20.09.08. 21:00	12.	20.05.08. 00:00 → 21.05.08. 12:00		
13.	04.10.08. 18:00 → 05.10.08. 03:00	13.	16.06.08. 21:00 → 17.06.08. 21:00		
14.	17.10.08. 18:00 → 18.10.08. 03:00	14.	30.09.08. 18:00 → 04.10.08. 03:00		
15.	15.11.08. 00:00 → 15.11.08. 21:00	15.	28.10.08. 12:00 → 30.10.08. 00:00		
		16.	31.10.08. 12:00 → 01.11.08. 09:00		
		17.	04.11.08. 12:00 → 05.11.08. 09:00		

According to the specified duration of individual time intervals (Tab. 1) and the adopted lengths of fetch, the effect of the wind duration is not a limiting factor in the development of waves.

In this way, three sets of data for situations in the periods listed in Tab. 1 were obtained. The first set of values presents the results obtained using the Groen-Dorrenstein diagram, the second set was obtained by means of the numerical model, and the third set represents the measurement results. The comparison is given in Fig. 7 for the situations 1.-15. Bora (NE), Libeccio (SSW) and West (W), and in Fig. 8 for the situations 1.-17. Sirocco (according to Tab. 1).

Figures 7 and 8 show that during the action of Sirocco, results of the numerical model correspond better to the measured values and values calculated using the Groen-Dorrenstein diagram than in the case of Bora activities.

According to the results shown in Fig. 7, it may be concluded that strikes of Bora prevent the development of the wave heights which would be achieved in case of constant wind speeds, and this is the assumption used in the synthesis of the Groen-Dorrenstein diagram. For this reason, there occurs frequent exceeding of values obtained using the Groen-Dorrenstein diagram in comparison with the measured values.

According to the set criteria of wind duration and speed, only one situation of occurrence of Libeccio was recorded (Tab. 1). In this situation, complete matching of the modelled and measured values was achieved as a consequence of a long enough wind effect in which there is no wave distortion from the wave generation initiation site to the waverider position (Fig. 7).

During the action of the wind blowing from the west, a significant overstepping of the model values of *Hs* in relation to the measured values occurs (Fig. 7). On the other hand, model values and values obtained using the Groen-

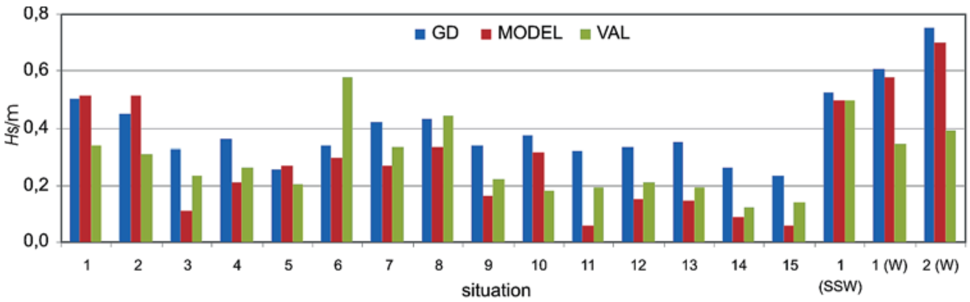

Figure 7 Comparison of the calculated, (Groen-Dorrenstein diagram – GD), modelled (MODEL) and measured (VAL) values of significant wave heights Hs in time periods under the action of Bora (1-15), Libeccio (SSW) and West Wind (W)
***Slika 7.** Usporedba proračunatih (Groen-Dorrenstein dijagram - GD), modeliranih (MODEL) i izmjerenih (VAL) vrijednosti značajnih valnih visina Hs u vremenskim razdobljima pri djelovanju bure (1-15) lebića (SSW) i zapadnjaka (W)*

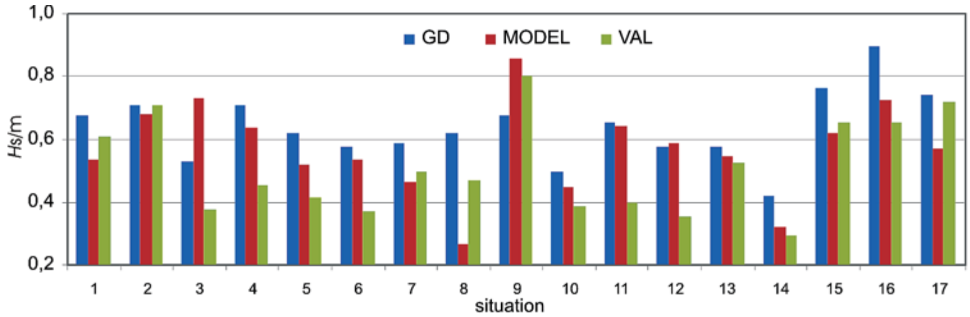

***Figure 8** Comparison of the calculated, (Groen-Dorrenstein diagram – GD), modelled (MODEL) and measured (VAL) values of significant wave heights Hs in time periods of situations 1-17 under the action of Sirocco*
***Slika 8.** Usporedba proračunatih (Groen-Dorrenstein dijagram - GD), modeliranih (MODEL) i izmjerenih (VAL) vrijednosti značajnih valnih visina Hs u vremenskim razdobljima situacija 1-17 pri djelovanju juga*

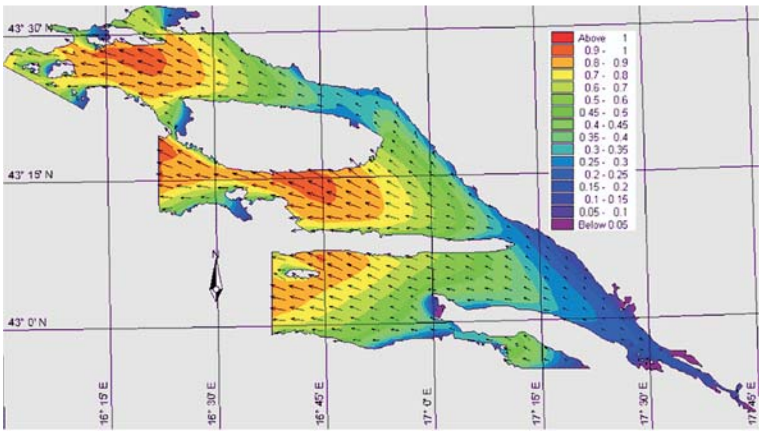

***Figure 9** Model field of significant wave heights Hs in the period of registered wave height extreme (4 November 2008 at 11 pm – action of Sirocco) at the waverider station site during the period from 1 November 2007 to 15 November 2008*
***Slika 9.** Modelsko polje značajnih valnih visina Hs u terminu registriranog ekstrema valnih visina (4.11.08. 23:00 – djelovanje juga) na poziciji valografske postaje tijekom razdoblja 1.11.07.-15.11.08.*

Dorrenstein diagram are very close. Based on these facts it may be concluded that the natural process includes also the diffraction around the top of the island of Čiovo, due to which fact the registered wave heights at the waverider were reduced. It is this case that shows a shortcoming of the numerical model, which does not allow treatment of the wave diffraction.

According to the results shown in Fig. 8, the mean values of the ratio Hs_{GD}/Hs_{MODEL} and Hs_{GD}/Hs_{VAL} amount to 1,12 and 1,25. This confirms the fact that the numerical model interprets the state of the wave climate with a degree of reliability that corresponds to the reliability of prognostic data on wind speed from the Aladin model.

Fig. 9 shows the model field of significant wave heights Hs in the period of the measured Hs_{max} extreme. (4 Nov. 2008, 11 pm – action of Sirocco) at the waverider station site for the period from 1 November 2007 to 15 November 2008. Fig. 9 shows also the wave action vectors in the same period.

By implementation of model analyses, fields of significant wave heights *Hs* in the continuous period from 1 November 2007 to 15 November 2008 were obtained, with a half-hour time increment. The *Hs* fields in all situations in which the value of wind speed of 5 m/s is achieved or exceeded at the waverider position make up statistical models that are subjected to a long-term analysis.

To forecast the long-term wave climate of the selected local waters, empirical distribution of wave heights obtained by short-term prognosis was used, and its extrapolation in the region of small probabilities. Long-term wave climate of a five-year return period regardless of the direction (Fig. 10) was defined in that way. For an analysis according to the directions, a longer series of data on the wind is required, because the data displayed in Tab. 1 show that one year is not sufficient for a correct statistical

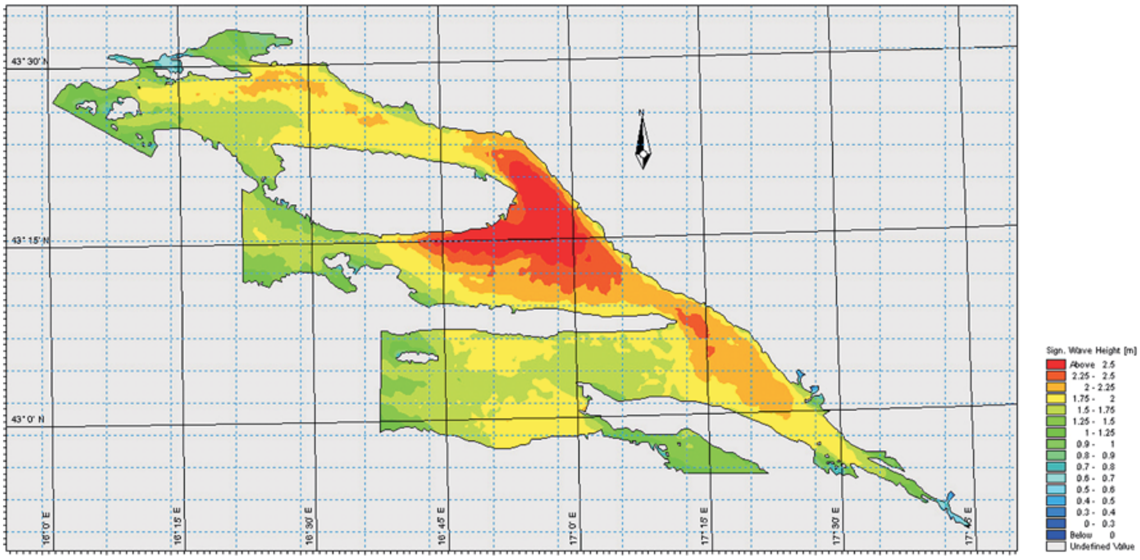

Figure 10 *Field of significant wave heights for a five-year return period*
Slika 10. *Polje značajnih valnih visina za 5 godišnji povratni period*

processing. Based on the one-year follow-up data on the wind, the obtained long-term wave climate in a five-year return period for wider use in practical calculations should be corrected on the basis of a longer series (minimum 2 years) data on the wind. For the formation of a long-term wave climate in return periods from 50 to 100 years, an analysis of 30-year wind situations is required.

5
Conclusion
Zaključak

With the numerical model of wave generation MIKE 21/SW, an analysis of dynamics of significant wave heights in the channel waters of the southern Adriatic Sea was conducted. Model analysis results were compared with the results of measurements at a waverider station during the period from 1 November 2007 to 15 November 2008. To generate waves in the model spatial domain, data on wind speeds and directions from the prognostic atmospheric model Aladin were used. Numerical analysis of wave generation was conducted in the spatial domain which covers the area of the Split, Brač, Hvar, Korčula and Neretva Channel.

The results of the researches conducted using the numerical model have shown the following:

- On the waverider position, the model describes well the dynamics of significant and maximum wave heights.
- By using the Groen-Dorrenstein diagram on the basis of data on wind speeds from the numerical model Aladin, the measured values of *Hs* are exceeded, on average by 25 %, which is related to the fact that model values of wind speeds and directions from Aladin are of prognostic character.
- The measured values of significant wave heights at the waverider position are larger than the modelled ones by 12 % on average, which is acceptable within the measurement accuracy and prognostic character of input data on the wind.
- During the action of Sirocco, the numerical model results correspond better to the measured values and values calculated using the Groen-Dorrenstein diagram than in the case of the action of Bora. It may be concluded that strikes of Bora prevent the development of the wave heights which would be achieved in the case of constant wind speeds.
- The methodology of forming a long-term wave climate shown in the paper may be extended to longer return periods in accordance with available long-term data on the wind in the areas of similar long-term characteristics.

6
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