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Extreme values of surface wave heights in the Northern Adriatic

Nenad Leder, Ante Smirčić and Ivica Vilibić

State Hydrographic Institute, Split, Croatia

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Extreme return values of significant wave heights were calculated using the data of wave heights measured in the open part of the northern Adriatic (platforms PANON and LABIN, lighthouse Sv. Ivan na pučini), by approximating the distribution of monthly extremes by Fisher-Tippet curve (F-T I). Parameters of F-T I distribution of extremes were estimated using three methods: graphic method, method of moments, and maximum likelihood method. Comparison of the results obtained from each method has shown that extreme return values of significant wave heights obtained using the maximum likelihood method best agree with the data of direct instrumental measurements. The greatest significant wave heights are to be expected in the winter period, from December to February. Absolute calculated monthly maximum of a significant wave height occurs in February, being 7.54 m for the return period of 100 years. Major deviations are evident in the summer period (overestimated values), due to a small number of measured data and their dispersion. Extreme expected value of significant wave height in the northern Adriatic for the return period of 100 years is 8.57 m, from which a maximum wave height of about 14 m is estimated, being considered real as regards the maximum measured value of 10.8 m.

Keywords: wind generated surface waves, theory of extremes, northern Adriatic

1. Introduction

The paper deals with the data of wave heights measured in the northern Adriatic: gas fields IVANA and IKA, drills AMANDA I and II, and the region near the lighthouse Sv. Ivan na pučini (Fig. 1) in the period between 1978 and 1992.

Surface wave heights were measured using waverider DATAWELL, constructed in the Netherlands. The records were analogous, collected at the synoptic hours (01, 04, 07 h, etc.) with durations of 5, 10 and more minutes, depending on the current sea states. The wind speed and direction were also measured continuously. The results of statistical and spectral analyses of

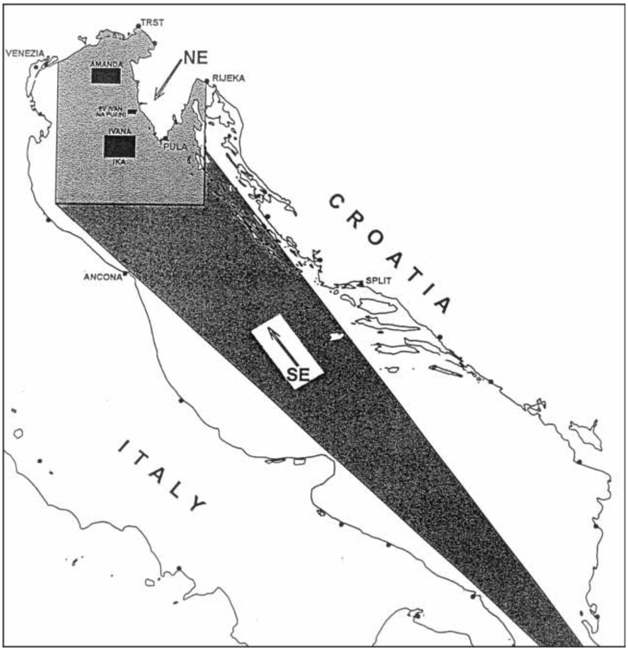

Figure 1. Measuring area with maximum fetches for Sirocco and Bora.

these data were published in the earlier papers (Smirčić, 1986; Gačić and Smirčić, 1986; Smirčić, 1989).

This paper presents the distributions of extreme significant wave heights calculated using the theory of extremes. The monthly (annual) distributions will be approximated by Fisher-Tippett first-type curve (F-T I). The parameters of F-T I distribution were estimated using three methods: graphic method, method of moments and maximum likelihood method. The results will be compared with the data, as well as with the results calculated by Maršić (1989) and Smirčić et al. (1996). These information will improve the knowledge of the behaviour of surface waves in the Adriatic Sea; moreover, it can be widely applied during any hydrotechnical project in and under the sea, geophysical and geological investigations of the seafloor, as well as during exploitations of the undersea resources in the Northern Adriatic.

2. The data

Extreme significant wave heights for the North Adriatic (Table 1) were calculated using the wave data, collected in the period from 1978 to 1986 and in 1992, when the drilling platforms were positioned in the North Adriatic. Wave height analogous records were digitized with the estimated accuracy of 0.1 m. The data were not continuously recorded, due to the movements of the

Table 1. *Monthly maximum significant wave heights (m). Wave heights which are estimated from the wind data contain the symbol (*).*

Month	Year									
	1978	1979	1980	1981	1982	1983	1984	1985	1986	1992
January	5.12	2.81	3.75	4.46	2.41	5.00	2.77	3.26*		
February	4.28	3.17	1.82		1.71	4.09	1.56	1.91*	6.16	
March	1.59*	2.30*	2.77		3.35	3.84		2.51*		1.85
April	3.20*	2.36	2.44	1.56	3.02		1.95	2.08*		2.15
May	2.80*	2.68	2.55	1.32	1.69		2.11	2.11*		1.15
June		1.95	1.59	3.90*	1.69			2.23*		1.38
July		3.90*	1.59		2.80*			1.86*		1.85
August		3.00*	2.11	4.20*	3.90*			3.75*		1.31
September		3.20*	1.46	4.20*	3.00*			3.26*		3.62
October		2.10*	3.54	4.70*			1.89	2.98*		3.38
November	3.42		3.65	3.90*	5.30*		3.22	3.37*		2.46
December	3.13	6.58	3.37	3.60	5.20	4.15		2.93*		4.00

platforms or to malfunction and missing of the waverider. Particularly, in 1986 there is only one complete month of measurements, but that extreme represents the true annual extreme as confirmed with the onboard visual measurements and general synoptic conditions throughout the year. We therefore believe that this set of surface wave data can be qualitatively analysed in the sense of the calculation of the extremes.

Significant wave height was calculated from the data for each situation with strong wind using two approaches:

1) using relation (Hasselmann et al., 1973):

$$H_s = 4\sqrt{m_0} \tag{1}$$

where m_0 stands for the area below the energy spectrum, *i.e.* for the variance of the sea level displacement:

$$m_0 = \int_0^\infty S(\omega) d\omega \tag{2}$$

where $S(\omega)$ is the wave energy spectrum as function of frequency ω;

2) as the mean value of 1/3 of the highest wave heights during one measurement; that value is approximately equal to the one defined by (1), as well as to the visual wave estimations (Hasselmann et al., 1973).

The number of months fully covered with wave mesurements is 54.

During the months covered only by wind measurements, significant wave heights were calculated from extreme wind speeds using quadratic regression (Smirčić, 1985), as follows:

$$\begin{aligned} H_s &= 0.0135\nu^2 + 0.003\nu + 0.500 \quad \text{for Sirocco,} \\ H_s &= 0.0031\nu^2 + 0.111\nu + 0.474 \quad \text{for Bora,} \end{aligned} \tag{3}$$

where ν stands for the wind speed at 10 m height. Correlation coeficients are 0.91 and 0.83 for Sirocco and Bora winds, respectively. Consequently, the errors of the calculated significant wave height are estimated to be 0.4 m for winds less than or equal to 16 m/s and 0.7 m for winds over 16 m/s. The number of extremes calculated using wind data, mostly in the summer season (April–September) is 29, so that the total number of monthly extremes during the 10-year period is 83 (Table 1).

It should be pointed out that the maximum wave heights can be statistically calculated from the significant wave heights, multiplying them by factor k = 1.58 (Smirčić et al., 1996).

3. The theory of extremes

The theory of extremes is a part of the statistics which is widely applied in many human activities, because it gives the distribution of frequencies and numerical values of rare events. The first principles of theory of extremes were given in 1709 by Bernoulli (Gumbel, 1958; Jenkinson, 1969). An important step forward was done by Fisher and Tippett (1928), who introduced the stability principle, from which Gumbel (1958) derived the distribution of the extremes in the form of:

$$F(x) = e^{-e^{-y}} \tag{4}$$

where $F(x)$ represents the probability that all the data are smaller than input variable x, which is related to the transformed variable y by three separate solutions (Fisher and Tippett, 1928). Here the first Fisher-Tippett solution (F-T I) will be used :

$$y = \frac{x - A}{B} \tag{5}$$

F-T I distribution has often been used for surface waves (Jahns and Wheeler, 1972; Nolte, 1974; Cavaleri et al., 1986). Moreover, F-T I distribution has only two unknown parameters, which is favourable for the small series as given here (10 data or less). Moreover, Galambos (1978) investigated domains of attraction of the extreme distributions and concluded that the do-main for F-T I distribution contains all the distributions with boundaries and without them, such as Gauss, log-Gauss, Weibull distributions etc.

Furthermore, it is necessary to introduce the return period $T(x)$ which is defined as the mean period (in years) between the occurrence of two values higher than x. So, the probability that x will be exceeded in any year is given as:

$$\frac{1}{T(x)} = 1 - F(x) \tag{6}$$

Calculation of unknown parameters A and B will be performed using three different methods: graphic method, method of moments and maximum likelihood method.

Graphic method is based on the linear fit of the equation (4) transformed into the form $x = x(F(x), A, B)$. Then the aproximation by Gringorten (1963) will be applied:

$$F_i = \frac{i - 0.44}{n + 0.12} \tag{7}$$

where $i = n$ is the highest extreme, $i = n - 1$ is the next lower one *etc.*:

$$i = n + 1 - m, \ \text{where } m = 1,...,n \tag{8}$$

The least-squares method is used for the linear regression fit through the empirical points.

Method of moments uses the zero- and the first-order moments m_0 and m_1, respectively, to calculate the parameters A and B. Gumbel (1958) showed that the estimates of parameters A and B can be obtained using the relations:

$$\begin{aligned} A &= \mu - 0.45\sigma \\ B &= \frac{\sigma}{1.2825} \end{aligned} \tag{9}$$

where μ and σ are the mean value and standard deviation of the original data.

Maximum likelihood method is based on the assumption that the parameter Q_j has the most probable value when function

$$l(Q_1, Q_2, \ldots, Q_k) = \prod_{i=1}^{n} f(x_i; Q_1, Q_2, \ldots, Q_k) \tag{10}$$

has the maximum, assuming that the variables x_1, x_2, ..., x_n are independent. In order to simplify the solution, variable y (eq. 5) will be transformed to:

$$y = \alpha(x - \beta); \qquad \alpha = \frac{1}{B}, \;\; \beta = A \tag{11}$$

Let α_1 and β_1 mark the first estimates of the parameters, and let the true solutions of the maximum likelihood method be $\overline{\alpha}$ and $\overline{\beta}$ differing from the values $\alpha^{(1)}$ and $\beta^{(1)}$. Using Taylor's expansion of the first estimates of parameters α_1 and β_1 and disregarding the second derivates, the system of equations for $\alpha^{(1)}$ and $\beta^{(1)}$ is obtained (Gumbel, 1958):

$$[\alpha^{(1)}, \beta^{(1)}] = \left[\frac{\partial L}{\partial \alpha}, \frac{\partial L}{\partial \beta}\right] \cdot M \tag{12}$$

where:

$$\frac{\partial L}{\partial \alpha} = \frac{n}{\alpha} - \frac{1}{\alpha}\sum_{i=1}^{n} y_i + \sum_{i=1}^{n} e^{-y_i} \tag{13}$$

$$\frac{\partial L}{\partial \beta} = n\alpha - \alpha \sum_{i=1}^{n} e^{-y_i} \tag{14}$$

$$M = \begin{bmatrix} \dfrac{0.6079\,\alpha^2}{n} & \dfrac{-0.25702}{n} \\ & \\ \dfrac{-0.25702}{n} & \dfrac{1.108}{n\alpha^2} \end{bmatrix} \tag{15}$$

The second estimates $\overline{\alpha}$ and $\overline{\beta}$ can be calculated now, and they serve to calculate the next differences $\alpha^{(2)}$ and $\beta^{(2)}$. This procedure is repeated untill the differences become small enough, usually 3 or 4 times.

Standard error of the maximum likelihood method is given by:

$$S_T^2 = \frac{1}{n\alpha^2}(1.1086 + 0.514\,y_T + 0.6079\,y_T^2) \tag{16}$$

where variable y_T is defined by relation (5).

4. Results and discussion

The values of parameters A and B, and extreme heights of surface waves in the northern Adriatic for return periods of 5, 10, 20, 50 and 100 years, calculated using the graphic method, method of moments and the maximum likelihood method, are shown in Tables 2–4, respectively.

Table 2. *Parameters A and B and extreme significant wave heights calculated for each month, a year, and the year according to Carter and Challenor (1981), and for return periods of 5, 10, 20, 50 and 100 years. The values are calculated applying the graphic method on F-T I distribution.*

Month	A	B	Return period (years)				
			5	10	20	50	100
1	3.235	0.866	4.53	5.18	5.81	6.62	7.22
2	2.358	1.367	4.41	5.43	6.42	7.69	8.65
3	2.241	0.681	3.26	3.77	4.27	4.90	5.38
4	2.102	0.456	2.79	3.13	3.46	3.88	4.20
5	1.785	0.498	2.53	2.91	3.27	3.73	4.08
6	1.732	0.748	2.86	3.42	3.96	4.65	5.17
7	1.983	0.812	3.20	3.81	4.39	5.15	5.72
8	2.572	0.906	3.93	4.61	5.26	6.11	6.74
9	2.751	0.714	3.82	4.36	4.87	5.54	6.03
10	2.639	0.880	3.96	4.62	5.25	6.07	6.69
11	3.237	0.718	4.31	4.85	5.37	6.04	6.54
12	3.575	1.021	5.11	5.87	6.61	7.56	8.27
Year	4.269	0.904	5.63	6.30	6.95	7.80	8.43
Year C&C	4.868	0.928	6.26	6.96	7.62	8.49	9.14

Table 3. *Parameters A and B and extreme significant wave heights calculated for each month, a year, and the year according to Carter and Challenor (1981), and for return periods of 5, 10, 20, 50 and 100 years. The values are calculated applying the method of moments on F-T I distribution.*

Month	A	B	Return period (years)				
			5	10	20	50	100
1	3.222	0.823	4.46	5.07	5.67	6.43	7.01
2	2.345	1.288	4.28	5.24	6.17	7.37	8.27
3	2.242	0.621	3.17	3.64	4.09	4.67	5.10
4	2.100	0.425	2.74	3.06	3.36	3.76	4.06
5	1.772	0.483	2.50	2.86	3.21	3.66	3.99
6	1.709	0.717	2.78	3.32	3.84	4.51	5.01
7	1.969	0.746	3.09	3.65	4.18	4.88	5.40
8	2.534	0.886	3.86	4.53	5.17	5.99	6.61
9	2.710	0.716	3.78	4.32	4.84	5.50	6.00
10	2.634	0.804	3.84	4.44	5.02	5.77	6.33
11	3.227	0.676	4.24	4.75	5.23	5.86	6.34
12	3.570	0.954	5.00	5.72	6.40	7.29	7.95
Year	4.266	0.852	5.54	6.18	6.80	7.59	8.19
Year C&C	4.753	0.881	6.07	6.74	7.37	8.19	8.81

Table 4. *Parameters A and B and extreme significant wave heights calculated for each month, a year, and the year according to Carter and Challenor (1981), and for return periods of 5, 10, 20, 50 and 100 years. The values are calculated applying the maximum likelihood method on F-T I distribution.*

Month	A	B	Return period (years)				
			5	10	20	50	100
1	3.220	0.813	4.44	5.05	5.64	6.39	6.96
2	2.381	1.122	4.06	4.91	5.71	6.76	7.54
3	2.245	0.622	3.18	3.65	4.09	4.67	5.11
4	2.100	0.438	2.76	3.09	3.40	3.81	4.11
5	1.756	0.546	2.57	2.98	3.38	3.89	4.27
6	1.778	0.500	2.53	2.90	3.26	3.73	4.08
7	2.016	0.588	2.90	3.34	3.76	4.31	4.72
8	2.504	1.037	4.06	4.84	5.58	6.55	7.27
9	2.670	0.937	4.08	4.78	5.46	6.33	6.98
10	2.643	0.797	3.84	4.44	5.01	5.75	6.31
11	3.251	0.646	4.22	4.70	5.17	5.77	6.22
12	3.621	0.775	4.78	5.36	5.92	6.64	7.19
Year	4.255	0.866	5.55	6.20	6.82	7.63	8.24
Year C&C	4.713	0.838	5.97	6.60	7.20	7.98	8.57

It should be pointed out that the best estimates of the return values are for the periods no longer then double of the original series. However, good results are achieved if the theory is extended to the return period of 100 years; furthermore, that period is widely encouraged in the literature (see *e.g.* Cavalleri et al., 1986).

The values are given for each month and for the year. However, annual extreme wave heights can be better calculated using the relation given by Carter and Challenor (1981):

$$F(x) = P(X < x) = \prod_{m=1}^{12} e^{-e^{-(x-A_m)/B_m}} \tag{17}$$

where A_m and B_m represent parameters for each month calculated using any method. The values of annual extreme significant wave heights calculated by this formula for return periods of 5, 10, 20, 50 and 100 years are also given in Tables 2–4. Moreover, Table 5 contains total errors, calculated from the source and maximal likelihood method errors, applying the theory given by Draper and Smith (1981), for return period of 100 years.

Comparison between the extreme wave heights calculated by the graphic method and the method of moments shows that the first procedure gives

Table 5. *Total errors (T_{100}) of extreme significant wave heights $H_{s,100}$ for each month and a year, and for return period of 100 years.*

Month	$H_{s,100}$ (m)	T_{100} (m)
1	6.96	1.31
2	7.54	1.71
3	5.11	1.13
4	4.11	0.96
5	4.27	1.07
6	4.08	1.09
7	4.72	1.27
8	7.27	1.85
9	6.98	1.71
10	6.31	1.45
11	6.22	1.16
12	7.19	1.27
Year	8.57	1.28

higher values for all return periods. The largest difference (38 cm) is found in February for the return period of 100 years. As the values calculated by the method of moments serve as input for the maximum likelihood method, they will not be discussed further.

The regression fits calculated by the maximum likelihood method usually intersect the fits calculated by the graphic method, meaning that at some periods maximum likelihood method increases or decreases the values of extreme significant wave heights (Figs. 2–4). The largest differences are in

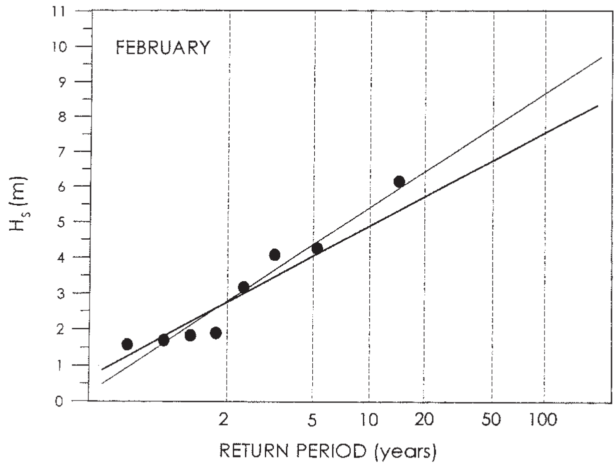

Figure 2. The distribution of extreme significant wave heights H_s for February as a function of return period T, calculated from the data (●) using the graphic method (thin line) and maximum likelihood method (thick line).

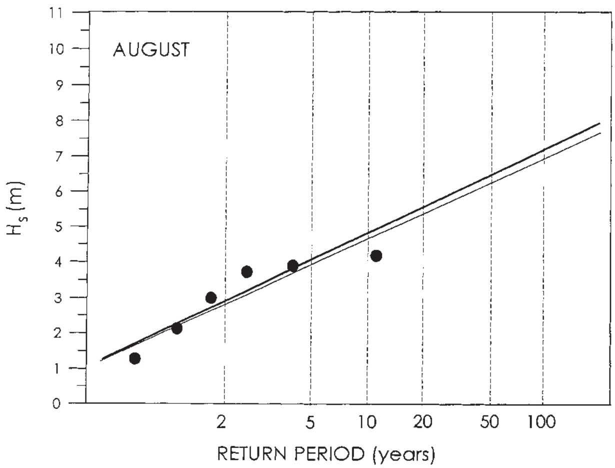

Figure 3. The distribution of extreme significant wave heights H_s for August as a function of return period T, calculated from the data (●) using the graphic method (thin line) and maximum likelihood method (thick line).

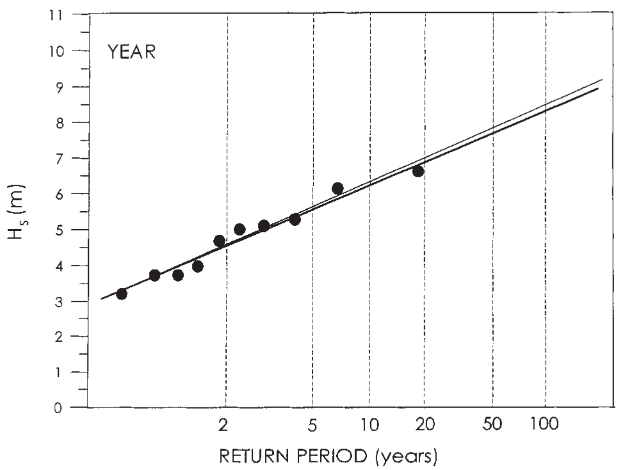

Figure 4. The distribution of extreme significant wave heights H_s for a year as a function of return period T, calculated from the data (●) using the graphic method (thin line) and maximum likelihood method (thick line).

February, and the lowest ones for annual extremes. In February, the graphic method gives extreme significant wave height higher by 1.11 m than the maximum likelihood method does (return period of 100 years). Furthermore, the graphic method gives the highest significant wave of 5.63 m for the return period of 5 years, estimated from annual extremes, while for the return period of 100 years the maximum is calculated from the data in February (8.65 m). Thus, the graphic method gives physically inconsistent results here.

On the contrary, the maximum likelihood method gives consistent results (Table 4). Many authors prefer to apply the maximum likelihood method on the distribution of extremes (Gumbel, 1958; Makjanić, 1977). So, the analysis of extreme significant wave heights will be done using the results calculated by that method.

The highest wave heights are expected to occur in the winter period, with monthly maximum in February (7.54 m for the return period of 100 years). The lowest values occur during spring and summer. Significant wave heights in August (7.27 m) and September (6.98 m) are obviously overestimated, probably because of a small number of data and their large dispersion; consequently, the total error is very large there (Table 5).

Absolute extreme of the significant wave height in the open part of the northern Adriatic is 8.57 m for the return period of 100 years, estimated using relation by Charter and Challenor (1981) on the monthly extremes calculated by the maximum likelihood method (Table 4). This value is considered realistic, because it is in agreement with empirical data. Namely, the extreme maximum wave height measured over ten years in the Northern Adriatic is 10.80 m (February 1986), while the maximum likelihood method gives the value of 10.40 m (6.60 m × 1.58) for the return period of 10 years, which is within the error of the estimate. Thus, for the northern Adriatic the extreme maximum wave height of 13.54 m (8.57 m × 1.58) can be forecasted for the return period of 100 years. To confirm this result, Maršić (1989) applied the same method and F-T I distribution to the data from the period 1978–1984, and got the significant wave height of 8.69 m for the return period of 100 years. However, Smirčić et al. (1996) calculated the extreme significant wave height of 11.49 m using the same data and for the same return period, which is not realistic for the Adriatic Sea.

5. Conclusions

The paper discusses the main characteristics of the wave data measured in the northern Adriatic as well as the differences of the wave heights calculated by different methods: graphic method, method of moments and maximum likelihood method. Although the time series is not continuous, the estimated values and the errors are reliable and in agreement with the empirical data. The errors are higher in the summer season, due to lack of extended measurements during summer. However, 10-year return annual significant wave height using maximum likelihood method, which seems to be the most favorable here, has the value of 6.60 m, and the empirical value of 6.58 m is quite close to the theoretical one. Furthermore, it should be mentioned that statistically calculated maximum wave height is 10.4 m, close to the measured one of 10.8 m. On that basis, the maximum wave height for the 100-year return period is estimated to be about 13.6 m. That value, although calculated with an error of ±2.0 m, can be widely applied in the calculations necessary for *e.g.* constructions of drilling platforms *etc*.

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SAŽETAK

Ekstremne vrijednosti visina valova za područje sjevernog Jadrana

Nenad Leder, Ante Smirčić and Ivica Vilibić

Koristeći podatke valnih visina mjerenih u otvorenom dijelu sjevernog Jadrana (platforme PANON i LABIN, svjetionik Sv. Ivan na pučini) izračunate su ekstremne povratne vrijednosti značajnih visina, na način da je razdioba mjesečnih ekstrema aproksimirana Fisher-Tippett krivuljom prvog tipa (F-T I). Parametri F-T I razdiobe ekstrema procijenjeni su pomoću tri metode: grafičkom metodom, metodom momenata, te metodom maksimalne vjerojatnosti (maximum likelihood). Usporedba rezultata pojedinih metoda pokazala je da se povratne ekstremne vrijednosti značajnih valnih visina dobivene metodom maksimalne vjerojatnosti ponajbolje podudaraju s podacima direktnih instrumentalnih mjerenja. Najveće značajne visine vala treba očekivati u zimskom razdoblju, od prosinca do veljače. Apsolutni izračunati mjesečni maksimum značajne valne visine je u veljači i iznosi 7.54 m za povratni period od 100 godina. Značajnija odstupanja zapažaju se u ljetnim mjesecima (precijenjene vrijednosti) zbog malog broja i velikog raspršenja mjerenih podataka. Ekstremna očekivana vrijednost značajne visine vala u sjevernom Jadranu za povratni period od 100 godina iznosi 8.57 m, iz čega se može procijeniti maksimalna visina vala od oko 14 m, što se smatra realnim s obzirom na maksimalnu izmjerenu vrijednost od 10.8 m.

Corresponding author's address: N. Leder, State Hydrographic Institute, Zrinsko Frankopanska 161, 21000 Split, Croatia