THE BLACK SEA LEVEL VARIATIONS AND THE RIVER-SEA INTERACTIONS

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Abstract. The paper presents the Black Sea morphometry and hydrographic characteristics, its network of tributaries and the fresh water supply. The published and directly measured by the author data from Sulina and Constanta gauges (situated on Romanian shore), as well as from stations in Bulgaria, Ukraine, Russia and Georgia have been used for analysing the sea level variations. The time series taken into consideration cover the period from 1858 to 1998. The water budget of the Black Sea and the sea level variations at different coastal zones have been analysed for highlighting the influence of the river – sea interactions. The Danube River water supply has an important influence on the sea level fluctuations. A trend of the sea level variations in time for different coastal zones was evidenced. Considerations on eustatic and subsidence processes along the Black Sea coasts are given.

Key words: hydrographic basin, water level, water discharge, water budget, eustatic and subsidence processes

INTRODUCTION

The sea level rise is at present a world wide phenomenon. The same water level rising trend is observed in the Black Sea even if this sea is a semienclosed one. This was the starting point for presenting the data on the Black Sea water level variations and their relationships with the fresh water river supply. The analysis is based on level data measured on the Romanian coast as well as on the published data from other coastal zones around the Black Sea. A short history of studies concerning the water level evolution within the Black Sea is presented.

1. HISTORY, LEVEL OF KNOWLEDGE AND SIGNIFICANCE

1.1. Short history

The systematic observation and measuring of the Black Sea water level were organized by the riparian countries since the middle of XIX-the century. From the literature (1, 2, 3, 6, 7, 8, 12, 15, 16, 17, 18, 20) results that the oldest data on the Black sea water level were given by the Sulina station at the mouth of one of the Danube Delta distributary starting in 1858, followed by the data series on the Ukrainian coast (Odessa from 1870, Ocheakov from 1874, Sevastopol and Kertch from 1875), on the Caucasian coast (Potty from 1875) and on the Bulgarian shore (Varna, from 1880). Later, gauging stations were established in Constanta (1896) and Batoumi (1923). The author of the present paper has described the history of the Black Sea level assessment in his earlier articles (3, 4).

At the Constanta station the data became reliable from 1933 with the first tide gauge installed in the harbour. The author of the present paper based on long series data from Sulina station (since 1858), for homogenising the length of data series from other coastal stations extended them by correlation with Sulina data.

1.2. Level of knowledge

The assessment of the Black Sea water level change evidenced its trend in time. The seasonal and annual level changes are linked with the seasonal and annual changes in the fresh water supply of the Black Sea tributaries.

The figure 1 presents the limits of the Black Sea drainage basin and some information on its relief altitude. There are two planes of altimetry reference within the Black Sea: Sulina and Varna. These reference surfaces were linked with those of the Baltic Sea at Kronstadt.

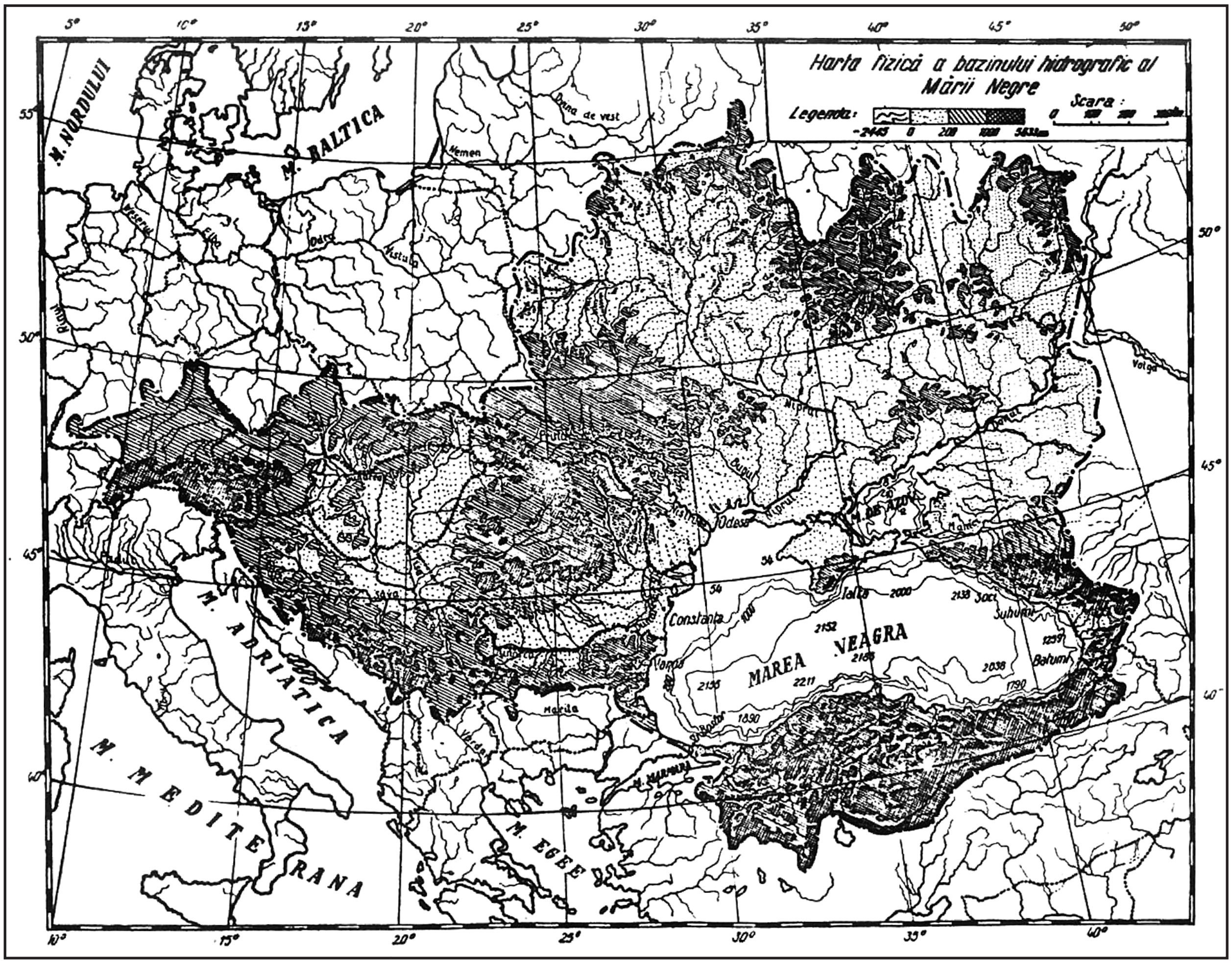

Fig 1 The Black Sea drainage basin [4] (after Atlas Mira)

1.3. Significance

The systematic observation of the sea level variation is of the utmost importance to assess the geophysical mobility of the Earth crust and the global changes as well as the vulnerability of coastal zones to erosional processes.

2. MORPHOMETRIC AND HYDROGRAPHIC CHARACTERISTICS OF THE BLACK SEA DRAINAGE BASIN

2.1. Size

The drainage basin of the Black Sea lies between 38° and 57° northern latitude and 8° and 44° eastern longitude. The area of the drainage basin is about 2,405,000 km^2. The average altitude of this basin is about 591 m.

2.2. Hydrographic network of the drainage basin and annual fresh water supply

The characteristics of the main rivers flowing into the Black Sea are presented in Table 1. The table highlights that the Danube River is the Black Sea largest tributary supplying about 54 % of the total river freshwater input.

Table 1 The main tributaries of the Black Sea and their annual water supply

Rivers	Area of drainage basin (km^2)	Length (km)	Volume of water discharge (km^3/year)	Author
Danube	817,000	2 857	196.2	Bondar C.
Dnieper	503,360	2 200	44.2	Snishko S.
Don	422,000	1 870	21.9	Snishko S.
Dniester	72,100	1 350	6.6	Snishko S.
Southern Bug	63,740	806	2.8	Snishko S.
Kuban	57,900	870	9.3	Snishko S.
Riony	13,390	327	8.4	Bondar C.
Other rivers	455,510		73.7	Bondar C.
Total	2,405,000	-	364.9	

3. THE BLACK SEA BASIN CHARACTERISTICS (AFTER A.M. KUDINA AND IU.V. TEREHINA, 1990)

3.1. Size

The Black Sea basin is limited by 40°55′ and 46°32′ northern latitude and 27°27′ and 41°42′ eastern longitude. The total length of the shoreline is about 4 020 km, the area of the basin (water free surface) – 423,000 km^2, the total volume of water – 538,124 km^3, the average depth – 1 272 m, the maximum depth – 2 245 m.

3.2. Climate

The main climatic features of the Black Sea basin are:

- the monthly mean air temperature ranges between –10°C and +30°C;
- the average yearly precipitations are of about 562 mm/year, corresponding to a total volume of 237.7 km^3/year;
- the annual average evaporation is of about 935 mm/year, corresponding to a total volume of 395.6 km^3/year.

3.3. The water exchange through the straits

The Black Sea is linked to the Mediterranean Sea by the Bosporus system of straits and to the Sea of Azov by the Kertch strait.

The water exchange through the Bosporus is:

- water inflow – about 176 km^3/year;
- water outflow – ca. 371 km^3/year.

The water exchange through the Kertch strait is:

- water inflow – about 49.8 km^3/year;
- water outflow – ca. 33.4 km^3/year.

4. THE CHARACTERISTICS OF THE BLACK SEA LEVEL VARIATION

The Black Sea is an almost closed sea where the long term water level changes are influenced by the resultant of the water budget of the basin. On the background of these long term level variations are superimposed short term, sometimes daylong, fluctuations, produced by the wind, the distribution of atmospheric pressure, universal attraction etc.

4.1. Average annual water budget of the Black Sea

The table below presents the mean values of the water budget components published by different authors.

Table 2

Water inflow (km^3/year)		Water loss (km^3/year)	
River discharges	364.9	Evaporation	395.6
Precipitations	237.7	Outflow by straits	432.8
Inflow by straits	225.8		
Total	828.4	Total	824.4

The variability in time and in space of these components of the annual and seasonal water budget generate changes in the resultant of the budget and consequently changes in the total water volume within the Black Sea basin affecting the water level and the water exchange through the straits.

The variations in time of the budget components could be seen on time-intervals longer than 10 days. The annual and seasonal changes are more representative.

4.2. Annual level variations and their trend

Figure 2 shows the chronological graphs of average annual levels and of the Danube River average annual water discharges into the Black Sea. The variations of the level and of the Danube water discharges are synchronous. The trend of the mean annual levels is of rising. The quantification of this process of the average annual level rising is described below.

5. ANALYSIS OF THE BLACK SEA AVERAGE WATER LEVEL VARIATION

5.1. Linear long term variation of the Black Sea average annual levels

For evidencing the long term variation of the average annual level the following empiric linear regression formula was used:

$$H\text{ (cm)} = ah + bh \times t\text{ (years)} \qquad (1)$$

where *ah* and *bh* are constant parameters computed using the method of smallest squares. The parameter *ah* represents the mean sea level at the moment $t = 0$, while *bh* is the annual rise of the sea level. The computation showed that the parameter *bh* is always positive, meaning that the Black Sea water level is continuously rising for the period of time taken into discussion.

The table below presents multiannual average data of the Danube River water discharges, of the water level at different locations on the Black Sea coastal zone as well as the values of above mentioned parameters from the empirical linear regression function.

Table 3

Locations	Time period	Average	*Q/ah*	*ΔQ/bh* (cm/year)
The Danube river mouth zone Q (m^3/s)	1858 - 2004	6293	6053	2.61
Sulina H (cm)	1858 - 2004	33.6	16.4	0.234
Constanta H (cm)	1858 - 2004	6.6	- 10.8	0.236
Varna H (cm)	1880 - 1962	114.2	112.6	0.0193
Odessa H (cm)	1870 - 1997	57	47.4	0.148
Sevastopol H (cm)	1870 - 1997	83	74	0.137
Yalta H (cm)	1870 - 1997	7.4	-1.09	0.132
Kertch H (cm)	1875 - 1961	11.9	2.74	0.209
Poti H (cm)	1923 - 1966	85.5	76.1	0.108

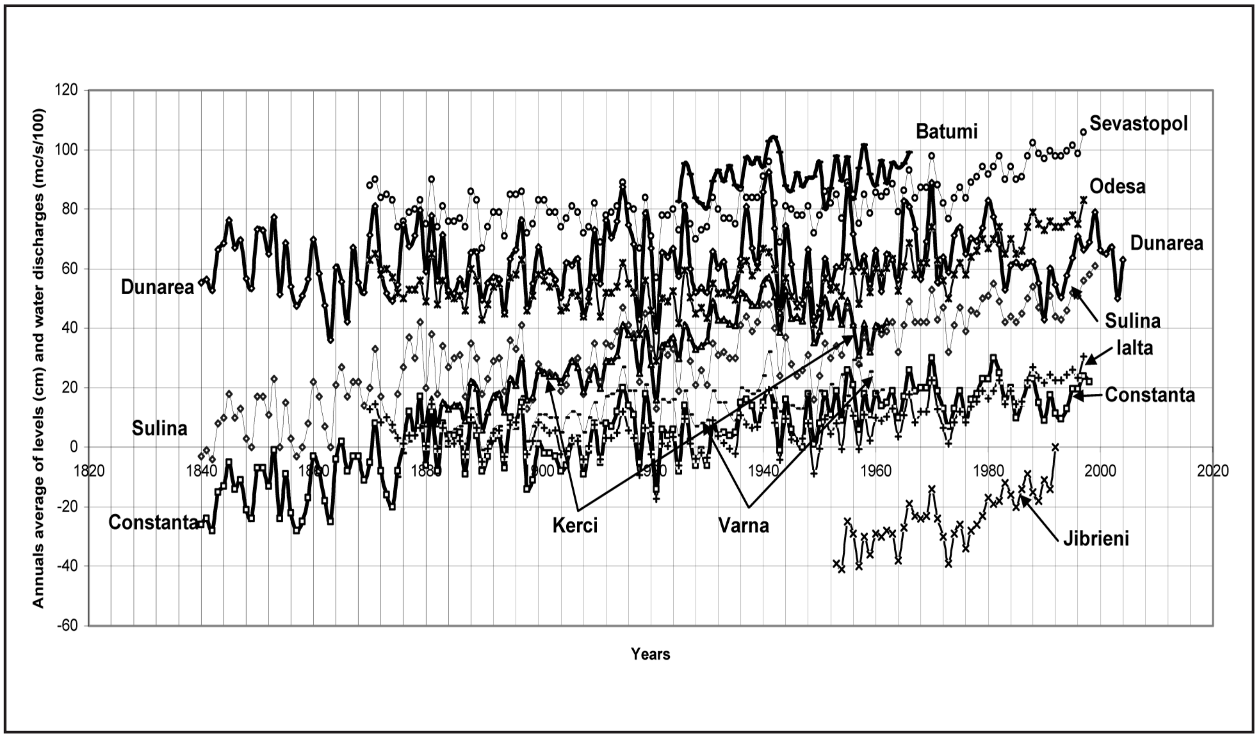

Fig. 2 The chronological graphs of average annual levels and of the Danube River average annual water discharges into the Black Sea at Sulina, Constanta, Varna, Jibrieni, Odessa, Sevastopol, Yalta, Kertch and Batumi for various time intervals from 1858 to 2004

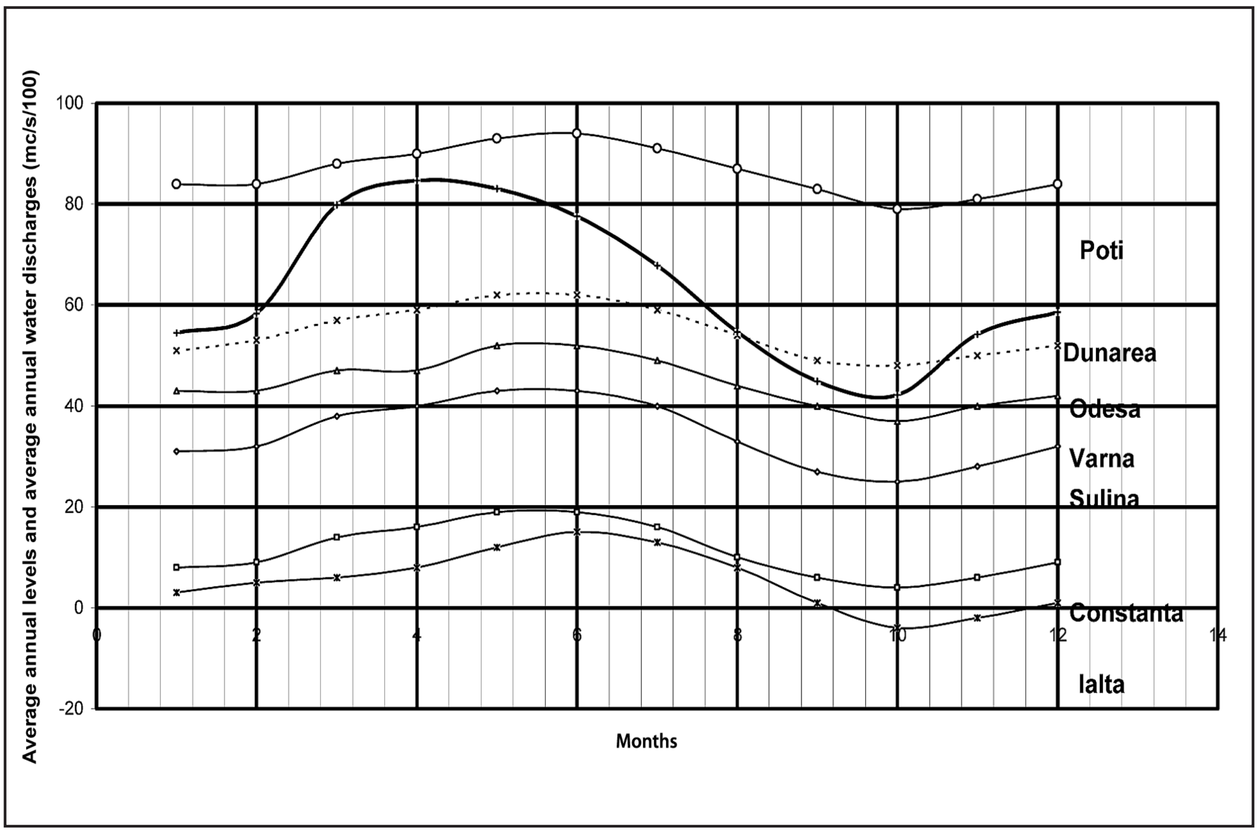

Fig. 3 The seasonal Black Sea level changes and their dependence on the Danube River mean monthly water discharges for the 1933 – 1960 interval

The data show that the average annual water discharge of the Danube River is increasing by about 2.6 m^3/year, while the water level rises by 0.019 – 0.236 cm/year. This positive trend of the level can be observed at every location on the Black Sea coastal zone. One must underline that the values of the trend coefficients (*bh*) include the variations of the hydrologic budget of the sea, the general rising trend of the World Ocean level (eustatic rising), as well as the local differential vertical movement of the crust.

5.2. Global eustatic process within the Black Sea

Berembeim I.D. (1960) proposed a practical method for evidencing and quantifying the influence of the Danube River annual water supply on the annual average water level in the Black Sea. He computed the linear regression with finite differences between the annual variation of the mean sea level (ΔH) and the annual variation of the water volume brought by the Danube River into the Black Sea (ΔV). This regression is expressed by the function:

$$\Delta H \text{ (cm/year)} = a + b \times \Delta V \text{ (km}^3\text{/year)} \quad (2)$$

where *a* and *b* are parameters determined by the method of the smallest squares.

The table below shows the periods of time, the available computed data and the values of the linear regression parameters.

Table 4

Locations on the Coastal Zone	Period of time	a	b	r	*a – bh* (eustatic rising)
Sulina H(cm)	1858 - 2004	0.332	0.190	0.822	0.098
Constanta H(cm)	1858 - 2004	0.284	0.195	0.801	0.048
Varna H(cm)	1880 - 1962	0.0045	0.097	0.977	-0.015
Odessa H(cm)	1870 - 1997	0.173	0.145	0.799	0.025
Sevastopol H(cm)	1870 – 1997	0.152	0.129	0.763	0.015
Yalta H(cm)	1870 – 1997	0.154	0.135	0.780	0.022
Kertch H(cm)	1875 – 1961	0.586	0.130	0.680	0.377
Poti H(cm)	1858 – 1999	0.227	0.136	0.816	0.119

The parameters *a* and *b* from the regression $\Delta H (\Delta V)$ have the following meaning:

a, is the free element of the regression representing the water level variation from one year to another when the variation of the Danube discharge are null.

b, is the element of scale showing how much varies from year to year the average sea level at a unity variation of the water volume supplied by the Danube River from year to year.

Compared to the regression (1), the parameter *a* from the second function (2) represents a global expression of the sea level rising when the Danube water supply is constant from year to year. In this way the parameter *a* contains the vertical movement of the crust, as the computation showed, is larger than the trend of the sea level variation in time (*bh*). Subtracting the trend (*bh*) from the term *a* one can obtain the rising of the average sea level due to the mean ocean level rising. The last column of the table, (*a – bh*) expresses in cm/year the approximate eustatic rising of the mean ocean level.

5.3. Seasonal sea level changes produced by the variations of the water volume in the basin

The seasonal Black Sea level changes and their dependence on the Danube River mean monthly water discharges for the period 1933 - 1960 are shown in the figure 3. One can observe a shift of about two months between the seasonal variations of levels and of water discharges.

5.4. Short term variations of the water level near the coastline

In the nearshore zone under the influence of winds, of the atmospheric pressure distribution and tides short term water level changes occur. These short term level changes are represented in the figures 4, 5 and 6.

The figure 4 presents diagrams of level changes produced by winds on the Romanian coast of the Black Sea, at Sulina, Sfântu Gheorghe, Portita and Constanta. The octagon represents the reference level when the sea is calm (no wind). The positive values of the level when the winds are blowing from the sea are placed outside of the octagon, while the negative values of the level, when the winds blow from the land are inside the octagon. The four lines outside and the other four inside express the rise or fall of the level corresponding to wind speeds of 5, 10, 15 and 20 m/s. On the Romanian coast of the Black Sea the level can rise up to 60 – 80 cm when the offshore strong winds are blowing. Vice versa, the winds from the land can lower the level by about 60 cm.

The sea level variations produced by the atmospheric pressure changes or by sudden changes of wind direction could reach 10 – 20 cm with periods of 1 – 5 hours (Fig. 5).

The Black Sea tides are of semidiurnal type with maximum amplitude of 12 cm and period of about 15 hours 25 minutes (Fig. 6).

6. CONCLUSIONS

- Due to important river water supplies, the water budget of the Black Sea is exceeding.
- The seasonal and annual variations of the sea level are the consequence of variations of the sea water budget.
- Under the influence of natural factors the long term variation of the sea level has a continuous rising trend.
- The eustatic rising of the Black Sea level has an average value of about 0.09 cm/year.
- The vertical movement of the crust in the Black Sea coastal zones could be evaluated to 0.02 to 0.24 cm/year.

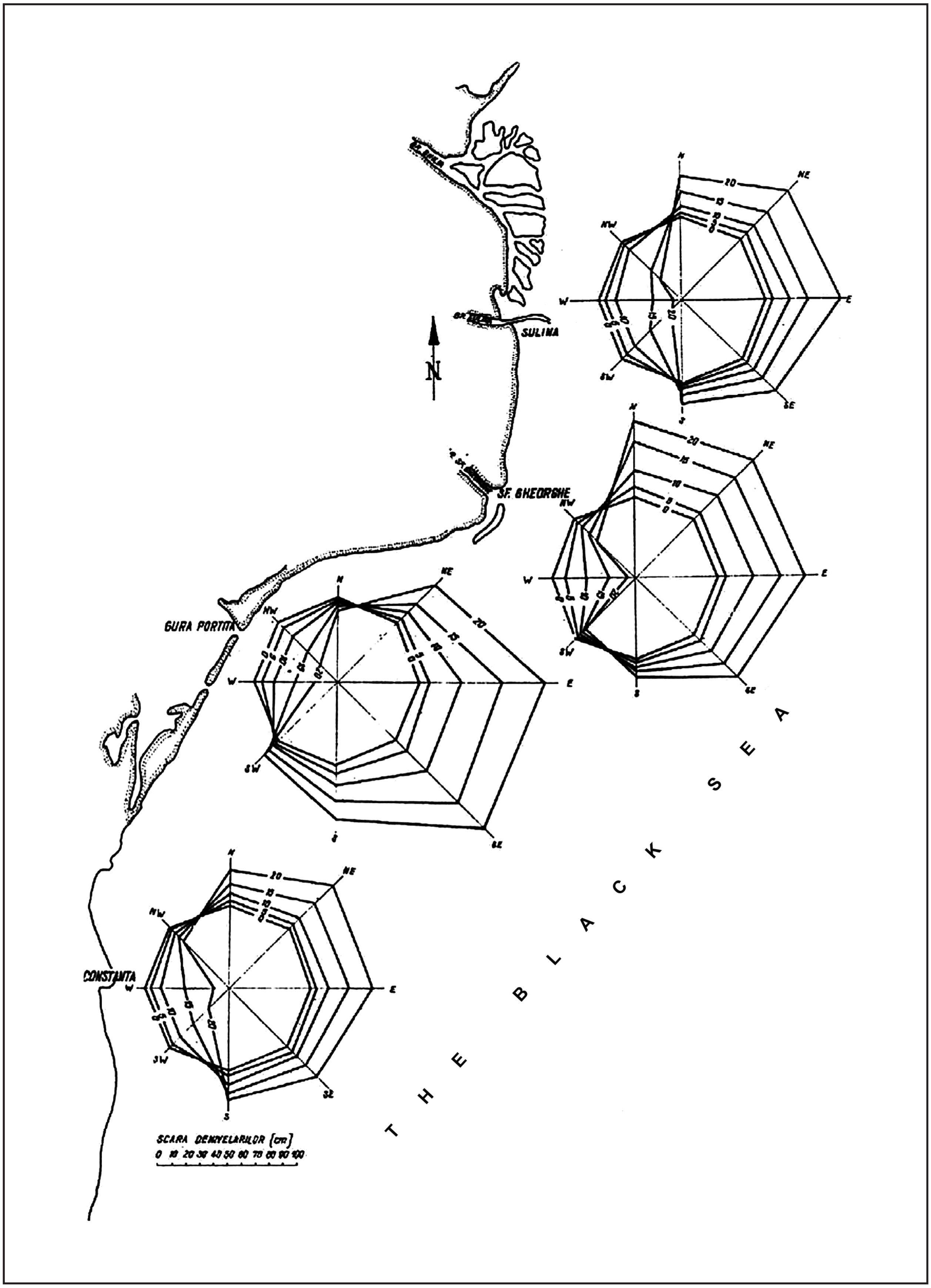

Fig. 4 The diagrams of level changes produced by winds on the Romanian coast of the Black Sea

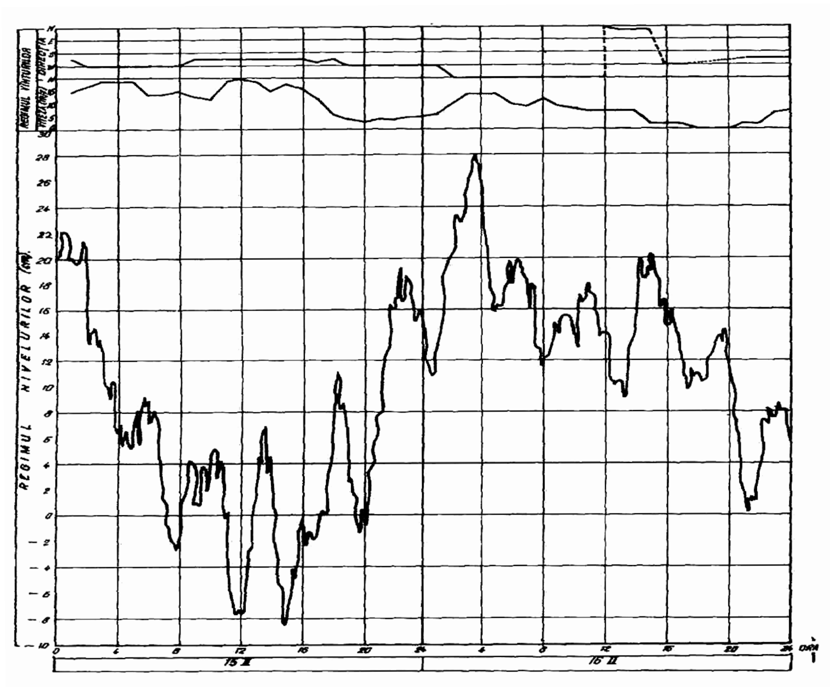

Fig. 5 Seiches recorded by tide gauge in the Constanta harbour on 1962, (the 15th and the 16th of) February

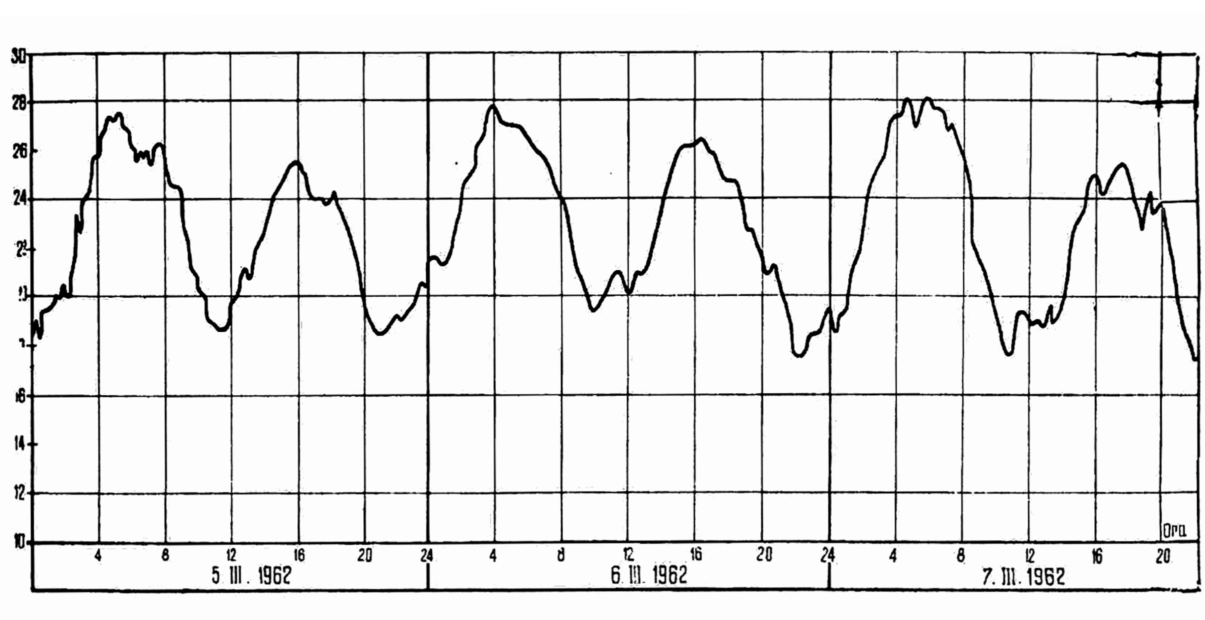

Fig. 6 Black Sea tide charts image for Constanta harbour, measured (during the days of the full moon, namely, from the 5th to the 7th of) March, 1962

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