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Analysis of Observations and Methods of Calculating Oceanic Hydrophysical Fields

Contemporary state of the investigation of the influence of the discharge of rivers on the hydrologic structure of the Black Sea*

N. P. BULGAKOV AND I. YU. YURKOVA

Abstract — We generalize and analyze the state of investigations of the influence of river waters on the hydrologic structure of the Black Sea. Specific features of the water regime and hydrography of rivers flowing into the sea, data on the discharge of rivers, and intrayear and interyear variability of the discharge are presented. We discuss and analyze works studying the transformation of river waters, routes of desalinized sea waters, and their influence on the thermohaline structure and dynamic regime of the sea.

INTRODUCTION

The Black Sea is regarded as a well-studied sea basin. However, the interest in it has recently grown due to the degradation of the sea ecology and necessity of its improvement. The variety of problems arising in this connection is very wide. In this study, we consider the problem of influence of the discharge of rivers on the hydrologic regime of the Black Sea.

The largest rivers flowing into the Black Sea are Danube (Romania, Ukraine), Dniester, Dnieper, Southern Bug (Ukraine), Rioni, Chorokh, Kodori, Inguri (Georgia), Sakarya, Kizil Irmak (Turkey), and Kamchiya (Bulgaria) (see Fig. 1). A brief physical and geographical description, water regime, regions of feeding and discharge of rivers are presented in [1–9].

According to Zaikov's classification [10], which is used by all authors in their investigations, the total discharge into the Black Sea Q_r consists of the discharge of rivers of the Bulgarian and Romanian coasts $Q_{B\text{-}R}$, northwest region (from Danube to Karkinit Bay) $Q_{N\text{-}W}$, Crimea Q_{Cr}, Sea of Azov Q_{Az}, Caucasus Q_C, and Turkish coast Q_T:

$$Q_r = Q_{B\text{-}R} + Q_{N\text{-}W} + Q_{Cr} + Q_{Az} + Q_C + Q_T.$$

The total water-catchment area of the sea basin is $\sim 1.9 \cdot 10^6\,\text{km}^2$. The northwest part of the sea constitutes about 80% of the total water-catchment area. The

*Translated by Peter V. Malyshev and Dmitry V. Malyshev
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distribution of the discharge volume along the Black Sea perimeter is presented in [3, 11–16].

Different authors present different data on the average annual total discharge of rivers (see Table 1). Table 1 shows that the values of the average annual total discharge differ by 5–17%. This, probably, can be explained by different intervals chosen for observation and by the exclusion of the discharge of rivers of the Crimea and Krasnodar Territory from consideration due to their insignificant volume, which was made by some authors, depending on the final purpose of their research [11].

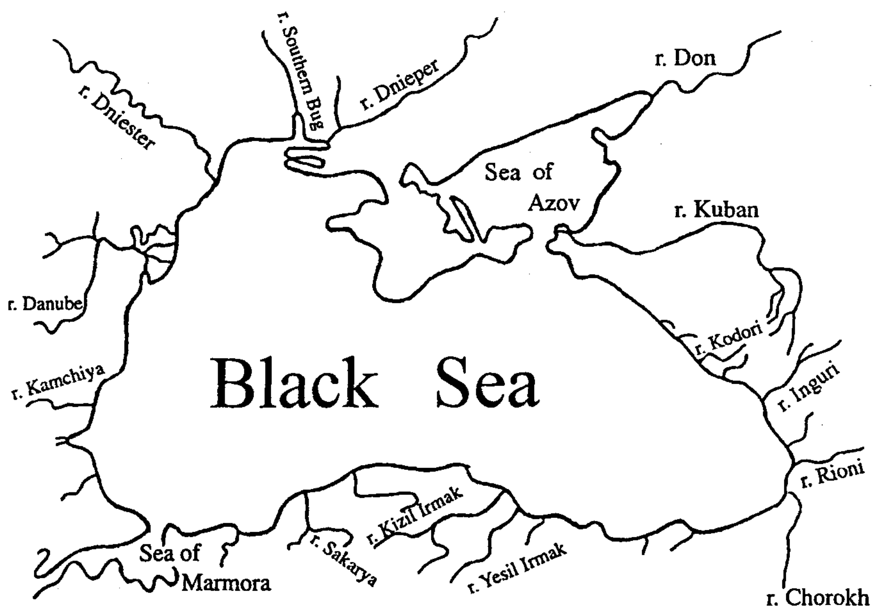

Figure 1. Main rivers of the Black-Sea region.

Table 1.
Many-year-average annual total discharge of rivers of the Black-Sea basin

Author	Discharge ($km^3\ yr^{-1}$)
É. N. Altman (1986)	338.2
D. Ya. Berenbeim (1961)	356.0
A. K. Leonov (1960)	309.2

It is established that the largest amount of river water is discharged at the northwest part of the sea (from Danube to the Karkinit Bay): it is equal to 3/4 of the total river discharge. According to [3], the discharge at the northwest region constitutes, on the average, 79.59% of the total discharge; the discharge at the Caucasian coast constitutes 11.90%, at the Turkish coast it gives 7.83%, and the Bulgarian and Crimean coasts contribute 0.34% each.

According to [11] (the observations were carried out in 1923–1940 and 1945–1980), the discharge of rivers is as follows: 79% at the northwest region, 0.5% is at the Bulgarian and Romanian coast, 13% at the Caucasian coast, and 7.5% at the Turkish coast, which is slightly lower than the corresponding data presented in [3]. This can be explained by the fact that, in [11], the discharge at the Turkish coast was determined not on the basis of actual data but with the use of module coefficients, which decreased the accuracy of calculations.

The analysis of variations in the annual total discharge for a long-term period (1923–1940, 1945–1980) shows that its maximum negative and positive anomalies were observed in 1949 and 1970 years, respectively. According to the data in [11], the average annual total discharge was 245.9 $km^3 yr^{-1}$ (73% of the standard) in 1949, and 491.6 $km^3 yr^{-1}$ (145% of the standard) in 1970.

In the intrayear course, 60% of the discharge volume are referred to the spring–summer period and 16% to the autumn period. Its maximum value is observed in May, and the minimum value is observed in September (see Fig. 2). The intrayear distribution of the discharge over the sea regions is not uniform, which is explained by differences in the physico-geographic conditions of the catchment areas and in the regimes of river feeding.

Let us consider the characteristics of the catchment areas of rivers flowing into the Black Sea and their water regime.

NORTHWEST REGION

The line passing from the Cape Tarkhankut to Cape Kaliakra is regarded as the sea boundary of the northwest region [13]; the largest rivers flowing into the Black Sea in this region are Danube, Dnieper, Dniester, Southern Bug, and Ingul. A brief morphologic description of the estuaries of rivers and the entire northwest region is presented in [2, 4–6, 9, 13, 17].

According to [11], the many-year-average annual discharge in the northwest region is equal to 267.1 $km^3 yr^{-1}$, and the Danube gives 75–80% of this volume. The regulation of the Dnieper in 1955 did not affect its annual and intrayear discharge. The maximum value of its discharge was 392 $km^3 yr^{-1}$ in 1970, and the minimum value was 150 $km^3 yr^{-1}$ in 1921. The variation in the total discharge of rivers of the northwest region for a long-term period is presented in Fig. 3, which is plotted on the basis of the results of calculations of the discharge of fresh water in the northwest part of the sea in 1921–1986 [16]. Data on the average annual discharge of rivers of the northwest region, according to [13], are presented in Table 2.

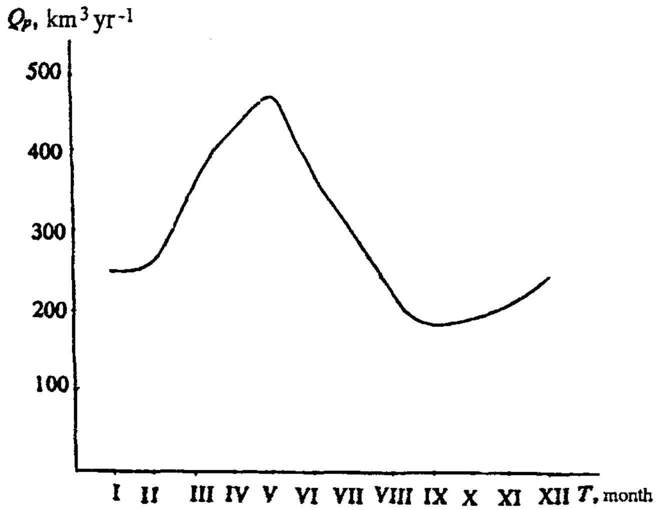

Figure 2. Intrayear variation in the total discharge of rivers of the Black Sea basin.

Table 2.
Average annual discharge of the rivers of the northwest region [8]

Rivers	Discharge Q ($km^3\ yr^{-1}$)
Danube	198
Dnieper	52
Dniester	10
Southern Bug	3
Others rivers	1

In the intrayear course, 61% of the annual discharge volume fall on the spring–summer period. On the average, its maximum value is observed in May and the minimum value is observed in October.

RIVERS OF THE CRIMEA

Rivers of the Crimea are classified into three groups, depending on the direction of the discharge of surface waters: rivers of the northwest slopes of the Crimean mountains, rivers of the Southern Coast of the Crimea, and rivers of the northern slopes of the Crimean Mountains. Rivers of the first two groups flow into the Black Sea.

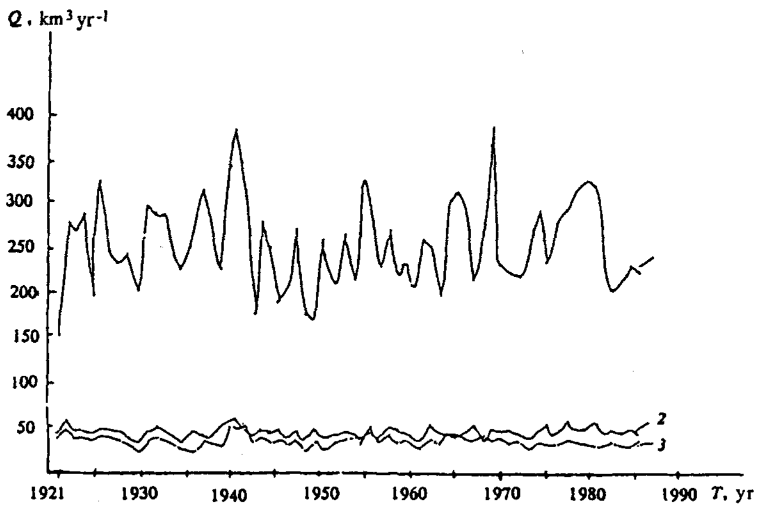

Figure 3. Long-term variation in the total discharge of rivers [16]: (1) the northwest region, (2) Caucasian coast, (3) Turkish coast.

There are considerable divergences in the estimates of the discharge volume of the Crimean rivers. According to the data presented in [11], [3], and [12], it is equal to 0.34 $km^3 yr^{-1}$ (0.1% of the total discharge of the rivers flowing into the Black Sea), 1 $km^3 yr^{-1}$ (0.34%), and 5 $km^3 yr^{-1}$ (1%), respectively.

The water discharge of the Crimean rivers is insignificant. The richest Belbek river has an average annual discharge of 0.09 $km^3 yr^{-1}$ (2.75 $m^3 s^{-1}$). The rivers are characterized by the freshet regime. During freshets, their discharge can increase by several hundred times, but they can dry up during a low-water period. The maximum amount of water is observed in the spring–summer period. The rivers are fed by snow and rain.

RIVERS OF THE CAUCASIAN COAST

The largest rivers of the Caucasian coast are Kodori, Inguri, Rioni, and Chorokh. The rivers of the Kolkhida region have underdeveloped mouths and flow into the sea mainly through one branch.

According to [4], [3], and [12], the total discharge of rivers from the Caucasian coast is, respectively, 43.1 $km^3 yr^{-1}$ (13% of the total discharge of all rivers of the Black Sea basin), 35 $km^3 yr^{-1}$ (11.90%), and 41 $km^3 yr^{-1}$ (12%) (the Kodori, Inguri, and Chorokh rivers contribute 38 $km^3 yr^{-1}$ to this amount). The Rioni and Chorokh rivers contribute 49% to the total discharge of all rivers of the Caucasian coast [11].

Mixed feeding due to precipitation, snowmelt, and the ablation of firn fields is typical of the rivers of the Caucasian coast. The main part of the discharge (66% of the annual volume) falls on April–August. The maximum discharge is observed in May. 16–17% of the annual discharge fall on autumn and winter. The minimum value is observed in September and January. A comparatively late freshet (May–June) is formed due to the melting of snow and glaciers. Rainwater plays an important role in the discharge. Pluvial freshets are observed throughout the entire year and cause a drastic increase in the average monthly discharge. This explains a very large difference between the maximum and minimum average monthly values of water discharge. The interyear variation in the discharge of rivers of the Caucasian coast is described in [16]. On the basis of these data, we plotted a graph of the discharge variation in 1921–1986 (see Fig. 3).

RIVERS OF TURKEY

Unlike the rivers of former socialist countries, which are well studied in numerous works devoted to the hydrologic regime of the Black Sea, the hydrologic regime of the rivers of Turkey is rather poorly described in the scientific works published in the former Soviet Union.

More than 160 rivers flow into the Black Sea from the territory of Turkey, including about 40 rivers on the part of the coast from the Bulgarian border to the river of Enidzhe. At least 40 rivers are located between the rivers of Enidzhe and Kizil Irmak, and more than 80 rivers flow further to the east up to the river of Chorokh. The measurements of water discharge for some rivers of Turkey flowing into the Black Sea were initiated in 1938. Kizil Irmak, Yesil Irmak, and Sakarya are the largest rivers of this region.

One of the first investigations of the basic hydrographic characteristics and extreme and average water discharges of some Turkish rivers was performed in [18]. According to [18], the total discharge at the investigated catchment area of 107,000 km^2 is equal to 11.7 $km^3\,yr^{-1}$. By using these data, E. N. Solyankin determined that the total discharge of all rivers of the Black-Sea basin of Turkey is equal to 25–26 $km^3\,yr^{-1}$ [19]; according to G. Tikseron, it is equal to 35.8 $km^3\,yr^{-1}$ [20]. In the later work [20], V. I. Reshetnikov determined the standard total discharge of the rivers of Turkey into the Black Sea to be equal to 43.96 $km^3\,yr^{-1}$, with regard for the discharge of the river of Chorokh formed in Turkey. According to D. Ya. Berenbeim [12], the total discharge is equal to 25 $km^3\,yr^{-1}$; according to Kiril Mishev [3], it is equal to 23 $km^3\,yr^{-1}$.

The presented many-year-average values of annual discharge of the Black-Sea coastal rivers of Turkey obtained by various authors differ by more than 20 $km^3\,yr^{-1}$, and, therefore, require further investigation.

The variation in the total discharge of the rivers of Turkey is most completely described (for the period of 1921–1986) in [16] (see Fig. 3). The maximum value equal to 51.2 $km^3\,yr^{-1}$ was observed in 1940, and the minimum value equal to 24.6 $km^3\,yr^{-1}$ was observed in 1949. In the intrayear course, 71% of discharge correspond to the winter–spring period. The maximum value of the discharge of the rivers of Turkey was observed in April, and the minimum value was observed in August.

Approximate values of the total discharge of the rivers of Turkey into the Black Sea are presented in Table 3 [20].

DISCHARGE OF RIVERS OF THE BULGARIAN AND ROMANIAN COASTS

The rivers of the Bulgarian part of the Black-Sea coast collect their waters in the mountains of Strandzha and Stara-Planina and in the eastern part of the Danube hilly plain. Several decades ago, their discharge into the Black Sea was about 4 $km^3 yr^{-1}$. At present, the discharge of these rivers into the sea decreased to about a half of this value. This is explained by the extensive utilization of the river waters for irrigation and industrial and everyday needs. According to the contemporary data, the discharge of the rivers of the Bulgarian and Romanian coasts is 2–3 $km^3 yr^{-1}$ (0.5%–1% of the total discharge of the rivers of the Black-Sea basin). The long-term variation in their total discharge ranges from 2.8 $km^3 yr^{-1}$ in 1970 (147% of the many-year-average annual discharge) to 1.3 $km^3 yr^{-1}$ in 1950 (68%). The largest Bulgarian river is the Kamchiya river; its discharge is equal to 0.7 $km^3 yr^{-1}$. The second in the the amount of water is the Veleka river; its discharge is equal to 0.2 $km^3 yr^{-1}$. The discharge of the Sredetska (Mandra) and Devnya rivers is approximately the same [21]. The major part of the discharge of the rivers of the Bulgarian and Romanian coasts falls on April–June (33% of the annual discharge); by autumn, one observes a decrease in the discharge.

The variation in the discharge of rivers of the northwest region, Caucasus, and Turkey with regard for anthropogenic factors (withdrawal of water for needs of the national economy) is described in [16]. On the basis of analysis of the diagrams of variation in the total amount of precipitation and in the discharge of rivers as a result of anthropogenic action in 1921–1986, the authors concluded that, in the last decades, the growth of anthropogenic pressures on the rivers has coincided with the tendency to the natural growth of humidification in the basin. According to their calculations, the rate of the former process is smaller by a factor of four than the rate of the latter. Hence, at present, there is no decrease in the discharge of the rivers and, moreover, one observes the tendency to its growth.

Table 3.
Intrayear distribution of the discharge of the rivers of the Black-Sea basin of Turkey [20]

Parameters	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
W ($km^3 yr^{-1}$)	4.22	5.45	5.84	6.69	6.51	4.00	2.20	1.32	1.41	1.62	1.62	3.08
%	9.6	12.4	13.3	15.2	14.8	9.10	5.0	3.00	3.20	3.70	3.70	7.00

TRANSFORMATION OF RIVER WATERS IN THE NORTHWEST REGION

The transformation of river waters in the northwest region was described for the first time in the monograph of V. S. Bolshakov [13]. This monograph still remains the only investigation in this direction. The author made an attempt to clarify the basic details of the transformation mechanism at all stages from the discharge of rivers into the sea to the complete loss of individuality of river waters. On the basis of analysis of observation data of expeditions in the northwest part of the Black Sea in 1948–1965, he investigated the specific features of the hydrologic conditions in the regions of discharge of rivers.

The author distinguished 4 stages of the transformation occurring in specific space zones located concentrically with respect to the mouths of rivers and estuaries.

Stage 1. Preliminary phase. It takes place in the estuaries located near mouths where seawater is admixed to river water in the process of water exchange between estuaries and the sea. The average salinity of the surface water of the Black Sea is assumed to be equal to 18‰. We regard it as the seawater salinity. In the Dnieper estuary, the salinity of river water increases to 3‰ (17% of the salinity of seawater). In the Dniester estuary, the salinity of river water increases on the average to 5‰ (28% of the salinity of seawater).

Stage 2. Main zone. The transformation takes place in the zones between the mouths of rivers or estuaries and hydrofronts (lines on the sea surface along which the destruction of the layer of almost fresh water is observed). The salinity in this zone increases to 6–8‰ (35–47% of the salinity of seawater).

Stage 3. Hydrofront zone. In the hydrofront zone, the salinity of water sharply increases from 6–8 to 10–12‰ (56–67% of the salinity of seawater). The destruction of the layer of almost fresh water under conditions of vertical turbulent mixing and wave mixing occurs when the thickness of the layer of river water decreases to 0.5 m and below. Sharp variations both in colour and transparency of water are also observed here. Sea waves of degree 2–3 are rapidly damped as they reach the hydrofront. The hydrofront zone is characterized by very high mobility. The most probable location of the hydrofront coincides with the 10‰ isohaline.

Stage 4. Terminal zone. River waters completely lose their individuality and do not differ from surface seawater in summer or bottom water in winter in a rather broad part of the sea between the hydrofronts and the 17‰ isohaline, which bounds the zone of pure seawater (in summer).

According to the observations of V. S. Bolshakov, the main and hydrofront zones are individual for each of the main three rivers (Danube, Dniester, and Dnieper) in the northwest region. The terminal zone is, in fact, the same for these three rivers and, at present, it can only speculatively be divided into sectors of influence.

It is interesting to estimate the influence of river discharge on the hydrology of the nearshore waters of the northwest region. The first attempt to reveal the relationship between average monthly salinity and water discharge in certain years was made by D. Ya. Berenbeim in [12]. According to his data, the coefficient of correlation between the average monthly salinity of waters near Odessa and the average monthly discharge of waters through the dam of the Kakhovskaya hydroelectric power plant for 1956–1959 was equal to 0.75. According to [13], the coefficient of correlation between the average monthly water discharge of the Danube river and the average monthly salinity of the sea near Constantsa for a ten-year period is equal to 0.53. The coefficient of correlation between the same quantities for the Danube and the region near Varna in 1957–1963 is equal to 0.73. It follows from the comparison of the indicated correlation coefficients that the dependence of salinity near Varna on the Danube discharge is stronger than that near Constantsa; however, such a conjecture requires further investigation. Bolshakov drew a conclusion that the dependence of the annual course of variation in water salinity near Odessa, Constantsa, and Varna on the annual course of river discharge is more straightforward than the dependence of the average monthly salinity on the average monthly discharge. It follows from the estimates for the correlation coefficients presented above that the river discharge affects the annual course of variation in salinity in the northwest region. The average monthly level of salinity is subject to the influence of other natural factors such as wind, flood-ebb phenomena, precipitation, evaporation, etc.

The scheme of transformation of river waters developed by Bolshakov [12, 13] explains the existence of hydrofronts rather well, although the outlines of depth and the thickness of the layer of river water must be determined more precisely. Bolshakov considered only the immediate transformation of river waters, whereas the problem concerning the routes of low-salinity waters formed in large volumes on the northwest shelf and their influence on the entire sea remains unsolved.

The problem indicated was considered in [17, 22], where the qualitative analysis of the field of salinity, field of currents, and many-year recurrence of winds in the region of the Black-Sea coast of Bulgaria was carried out. On the basis of this analysis, it was concluded that the transfer of river waters from the northwest part of the Black Sea, which is mainly directed to south-southwest, affects the hydrologic characteristics of water in this region (see Fig. 4). The stream of continental discharge from the northwest part of the Black Sea transformed by 80–95% (the salinity of water is equal to 14.50‰–17.20‰) is traced along the almost entire Bulgarian coast. In the earlier work [17], it was noted that salinity grows by more than 2‰ in the upper twenty-meter layer in the direction from the north to south. At the south end of the Bulgarian Black-Sea coast, temperature and salinity in this layer are practically constant, which can indicate the termination of transformation and mixing of river waters in this region. According to the data of observations, the process of mixing involves water layers down to depths of 40–50 m.

In [23], on the basis of analysis of more than 20 hydrologic surveys carried out in 1979–1989 in the western part of the Black Sea, along the continental slope a quasistationary convergence zone was detected into which brackish waters flow and where their intense transformation takes place. According to [24], the nearshore convergence zone, passing through the centres of anticyclonic eddies, girdles the entire Black Sea along its perimeter and forms the natural border between the nearshore (warmer and less saline) waters and waters of the open sea (with higher salinity and lower temperature). In the spring–summer period, the growth of anticyclonic activity is observed, which is connected with freshets on rivers. The ecological importance of the nearshore zone of convergence consists of the fact that it is the area of accumulation of contaminants, dissolved and suspended in water, which are brought here from the shore side and from the open sea, sunk to depth with the downward motion of waters, and transformed due to the natural (hydrodynamic, hydrochemical, and hydrobiological) factors of self-purification of the sea. If the level of contamination exceeds the self-purification ability of the sea, the nearshore zone of convergence can become the centre of stable contamination of deep waters. It should be noted that, according to [23], the nearshore convergence zone does not coincide with the hydrofront zone considered in [13], in which the destruction of the layer of almost fresh water occurs. Moreover, the nearshore convergence zone can be the border of the terminal zone of transformation of river waters [13]. However, this problem requires further investigation.

In [25], the intensification of anticyclonic eddies in the spring–summer period connected with freshets on rivers was noted. It is explained, on the one hand, by the drift of cold brackish shelf waters along the continental slope and, on the other hand, by the inflow of newly formed waters of a cold intermediate layer.

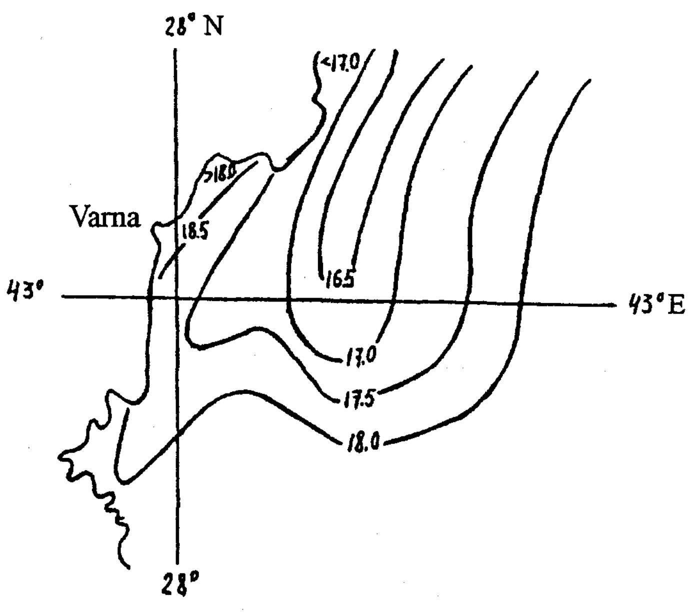

Figure 4. Horizontal distribution of the salinity of surface waters along the Bulgarian coast [22].

According to [26], the discharge of rivers induces the process of desalination only in the surface layer of the sea. As a result, the stable stratification of water masses increases and the processes of vertical turbulent intermixing are inhibited. Against the background of insignificant integral desalination, the seasonal and constant haloclines are intensified.

The work [27] is devoted to the investigation of the influence of the discharge of rivers on internal waves. Numerous observations of river discharge performed in 1965–1975 [11] are taken as the initial data. The authors considered two years characterized by extreme discharge of rivers. For these years, the diagram of the distribution of density over depth was constructed for the central part of the sea, and it was established that the decrease in discharge in 1973 as compared with 1970 resulted in an increase in density in the layer 0–500 m. In deeper layers, practically no variation in density was observed. Numerical calculations and theoretical analysis showed that the maximum values of velocity components and amplitudes of waves for the maximum discharge exceed the corresponding quantities for the minimum discharge. The higher the discharge, the deeper the location of the maximum values of the wave amplitude and vertical component of velocity. The authors drew a conclusion that a decrease in the discharge of river waters can result in a significant decrease in the depth of the layer with the largest intensity of wave motion and in a decrease in maximum values of the amplitudes of internal waves. All these factors lead to a decrease in the vertical transfer in deeper layers of the sea.

The analysis of the influence of the discharge of rivers on the physicochemical characteristics of seawater was carried out in [28]. The data presented in [28] describe the variation in various components of the chemical composition of seawater year by year, season by season, and month by month for an almost 30-year period of observations.

In [29], the thermal influence of the river discharge (the Dnieper, Dniester, and Danube rivers) on water masses of the Black Sea was evaluated. Rivers produce a warming effect upon the Black–Sea waters in April–August and a cooling effect in September–March. To calculate the amount of heat transferred with river waters, the forecast of the discharge of rivers for 1985, 1990, and 2000 was used [30]. The calculation was carried out under the condition of a decrease in the discharge by 10, 20, 30, 40, and 50% of the many-year average level. The variation in the temperature of water in the Black Sea was determined for the medium discharge (P = 50%) and for years characterized by extremely low discharge (P = 95%). It was established that a decrease in the discharge of rivers causes an insignificant increase in the temperature of water in the adjacent regions. Its variation does not exceed 0.1°C if the discharge affects the water layer 0–20 m. If the volume of the region subject to the influence of discharge increases, then the variation in temperature becomes practically indiscernible.

CONCLUSIONS

1. The maximum amount of river waters flows into the northwest part of the Black Sea (the Danube, Dniester, and Dnieper rivers).

2. In the intrayear course, 60% of the total discharge of all rivers of the Black-Sea basin fall on the spring–summer period. For the northwest region, the maximum discharge is observed in April–May, and the minimum discharge is observed in August–September.

3. The growth of anthropogenic pressures on rivers coincides with the tendency of natural increase in the humidification of the basin. The rate of the former process is smaller than the rate of the latter. Therefore, at present, one does not observe any decrease in the discharge of rivers.

4. As a result of the correlation analysis, the dependence of the salinity of nearshore waters in the northwest region on the discharge of rivers is revealed. It is established that the annual course of variation in salinity is almost completely determined by the river discharge. Winds, flood-ebb phenomena, precipitation, and evaporation affect the average monthly value of salinity. There is an inverse dependence between the salinity of nearshore waters and the discharge of river waters.

5. V. S. Bolshakov proposed a scheme describing the transformation of river waters in the Black Sea on the basis of the analysis of the river discharge before 1965. His work [13] still remains the only one in this direction.

6. On the basis of the qualitative analysis of the fields of salinity, currents, and recurrence of winds, it is established that the intense transformation of brackish waters takes place along the continental slope in the nearshore convergence zone and is not observed to the south of the Cape Kaliakra.

7. It is established that the transformed river waters drift from the northwest part of the Black Sea to the south-southwest at some distance from the coast.

8. Due to the convergence of waters, the convergence zone passing through the anticyclonic eddies along the continental slope accumulates the major part of suspended and dissolved contaminants brought from the coastal areas and from the open sea and can become the centre of contamination of deeper waters.

9. As follows from the presented survey of publications, some problems remain inadequately investigated; in particular, the following questions remain open:

— How does the transformation of brackish waters formed as a result of the interaction between river waters and seawater proceed ?

— How do river waters affect the internal waves and temperature regime of the sea ?

— How do rivers of the northwest part of the Black Sea affect its hydrologic structure in the years characterized by extreme discharge of rivers ?

— What are the specific features of the propagation of brackish waters formed in the region of the northwest shelf in years with low and high discharge of rivers ?

— What are the amplitudes of deviations of the space distributions of salinity and temperature of seawater from their climatic norms ?

— What are the anthropogenic factors affecting the brackish waters of the western part of the Black Sea at present and what role do these waters play in the contamination of the adjacent regions and the sea as a whole ?

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