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Hydrochemical Composition of the Runoff of Abkhazian Rivers and the Distinctive Features of Its Transformation in the Coastal Zone

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Abstract—The article presents the results of hydrochemical studies of the rivers of the Abkhazian coast of the Black Sea in April 2019. The Kodor River with its plume was the main object of the study, and additional samples were drawn from the small rivers of Kelasur, Mokva, and Galizga. Kodor River water was shown to contain nutrients at high concentrations (1.35 μM phosphates, 128.5 μM silicates, and 16 μM nitrates) at the time of testing, and this enabled the active development of the phytoplankton community in the sea. High pH values and low ammonia nitrogen content confirmed that intensive production of organic matter occurred. Analysis of total alkalinity and the content of silicon and mineral nitrogen enabled the identification of frontal zones in the Kodor River plume. Detection of chemical composition differences between the rivers studied, notwithstanding their relative proximity and the same water source (glaciers of the Caucasus Mountains), is an important result. For example, Kodor and Kelasur River waters differ from the water of the Mokva and Galizga rivers, which are located to the south of Kodor, with regard to carbonate parameters, and the difference in nitrate nitrogen content is more than twofold. The differences can be caused by different degrees of leaching of soils and rocks of the river basins.

Keywords: Black Sea, Abkhazia, river runoff, plume, hydrochemistry

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1. INTRODUCTION

Rivers drain vast areas of land, and therefore the amount of river runoff, along with its chemical composition, serves as an integral indicator of the biogeochemical state of the catchment basin. The chemical composition of water, the dynamics of its parameters, and the changes in the volume of river runoff provide reliable information on the changes in hydrometeorological conditions and the intensity of anthropogenic (technogenic and household) load in the river catchment basin.

The total volume of freshwater runoff into the Black Sea is approximately 350 km^3/year, according to different estimates [2]. The Abkhazian sector of the Black Sea accounts for 30 km^3/year of river water, which is less than 10% of the total runoff. Nevertheless, this value is rather high, because the coastline of Abkhazia is only 205 km long [2]. Numerous satellite images of the Black Sea, especially those registered during the flood period, show that fresh runoff can spread along almost the entire coastline due to numerous rivers and small streams [26–28], which carry suspended matter, nutrients, and pollutants with their waters [5, 9]. Thus, the coastal zone of Abkhazia is also significantly affected by the continental runoff.

Studies of the chemistry of river runoff, as well as its influence on the coastal zone, are of both fundamental and applied significance in the case of the Black Sea region, because the Black Sea, and the Abkhazian coast in particular, is an important object of natural and recreational value. Scientific research in the coastal zone was virtually stopped due to the complicated political situation in the Republic of Abkhazia. However, some studies that reflect the current state of research on the rivers of the Republic of Abkhazia, along with the estuarine areas and the coastal zone, were published in the recent years. For example, the state of the estuarine parts of Abkhazian rivers and the impact of runoff on the coast were reported in [1, 24]. The flow rates of the rivers were measured (the value for the Kodor River was the highest, as expected) along with water turbidity (0.007 g/m^3 on average, with the maximum of 0.28 g/m^3 observed for the Kelasur River), and phytoplankton composition characterized the river waters as oligotrophic. Nitrate nitrogen levels in the coastal zone of the city of

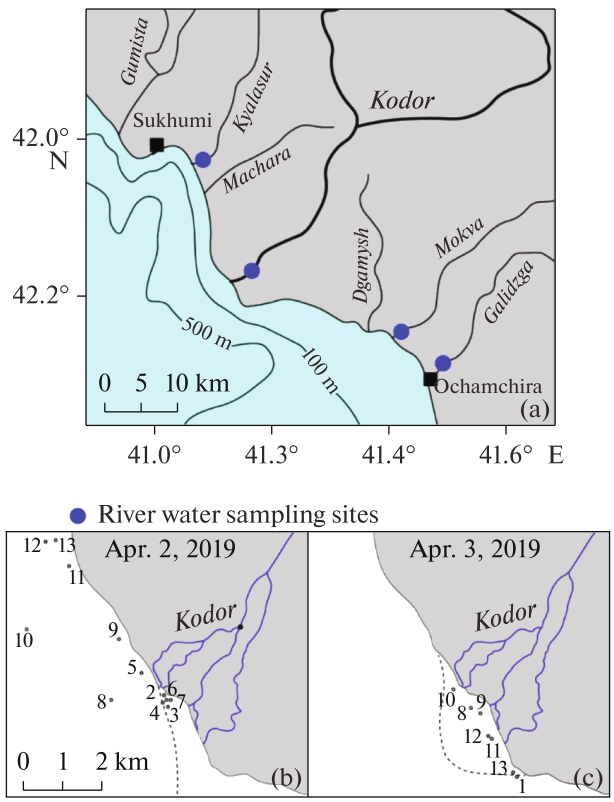

Fig. 1. (a) Study area and rivers from which samples were taken (shown by dots), (b) sketch map of stations and hydrochemical sampling on April 2, 2019, (c) sketch map of stations and hydrochemical sampling on April 3, 2019. Boundary of Kodor River plume shown by dotted line.

Sukhumi were high in May–June (up to 3 mg/L, which is equivalent to 214 μM) and minimal in October (0.92 mg/L or 65 μM) [1]. These values of nitrate nitrogen content raise serious doubts: they may be related to methodological errors or reflect the inflow of pollutants from land. Overall, published studies show that the content of pollutants, oil hydrocarbons, and nutrients does not exceed the MPC for the water near the coast of Sukhumi or for the estuarine areas of Abkhazian rivers [1]. However, the available data are not sufficient for the assessment of the impact of river runoff on the ecosystem of coastal waters of Abkhazia, and therefore this work makes a certain contribution to research on this process.

2. MATERIALS AND METHODS

The present study is based on materials collected during an expedition to the Abkhazian coast on April 1–4, 2019. The expedition addressed a broad range of problems related to the study of the effect of the Kodor River runoff on the coastal zone [11]. The main goal of the hydrochemistry division of the expedition was to study the chemical composition (nutrients and parameters of the carbonate system) of the rivers of the Abkhazian Black Sea coast and the waters in the zone of mixing of sea water and the water of the Kodor River.

Temperature and salinity at the stations were recorded by a CTD probe (Sea-Bird Electronics 19plus) manually lowered to the bottom. The sampling for hydrochemical parameter assessment was performed at 19 stations in the zone of sea water mixing with the water of the Kodor River during the sea voyages of April 2 and 3. River water was sampled in the lower reaches of the Kodor, Kelasur (Kyalasur), Mokva. and Galizga (Galidzga) rivers on April 1 and 2 (Fig. 1). The samples from the Kelasur River were collected close to the mouth of the river and somewhat upstream, and the samples from all other rivers were collected approximately 2 km from the mouth of each river. River water was collected directly into plastic sampling containers, and the sea water samples were taken from the surface by a plastic bucket and immediately moved to sample storage containers that conformed to GOST (State Standard) 17.1.5.04–81 for the specific analytes. The hydrochemical parameters were determined within 24 h after the sampling.

Mineral content of the Kodor River water was inferred from the total alkalinity according to the relation described in [17, 18]. The pH value was determined according to a potentiometric procedure on an Ekoniks-Ekspert four-channel pH meter with a combined electrode from Akvilon (Russia) The total alkalinity (Ta) was determined by direct titration (the Bruevich method) with color change as the endpoint. The content of dissolved inorganic phosphorus (PO_4^-) was determined colorimetrically according to the modified Murphy and Riley method. Dissolved inorganic silicon (Si) was quantitated colorimetrically using the formation of a blue silicon-molybdenum complex (the Korolev method). Nitrite nitrogen ($N\text{-}NO_2$) was quantitated colorimetrically using the universal color reagent. Nitrate nitrogen ($N\text{-}NO_3$) was also quantified colorimetrically after reduction to nitrite nitrogen on cadmium columns. Ammonium nitrogen ($N\text{-}NH_4$) was quantitated after a phenolate-hypochlorite reaction according to the Sagi-Solorzano method. The procedures for determining the hydrochemical parameters are described in detail in [12, 14].

In addition to the measured parameters, such parameters of the carbonate system as the content of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions in water, the total amount of inorganic carbon (DIC), and the partial pressure of carbon dioxide ($p$$CO_2$), were calculated in CO2SYS software [22].

3. RESULTS

The hydrophysical aspects of studying the Kodor River plume are presented in accompanying article [11]. In this paper, we present the results of hydrochemical studies of the Abkhazian rivers and their influence on

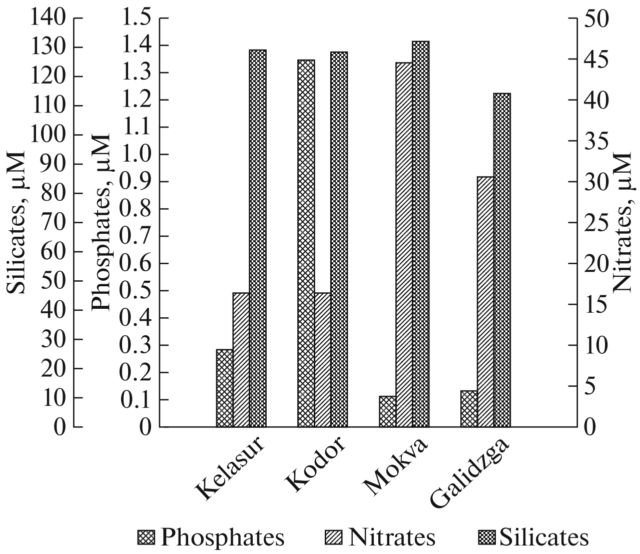

Fig. 2. Content of nutrients in water of estuaries of Kelasur, Kodor, Mokva, and Galizga rivers.

the distribution of hydrochemical parameters in the coastal zone.

Studies of the chemical composition of river water. A carbonate calcium water type with moderate mineralization is characteristic of Abkhazian rivers [24]. Studies of the chemical composition of the river waters revealed substantial differences. The content of dissolved silicates in the Kelasur, Kodor, and Mokva rivers showed almost no variation (129–132 μM), whereas the value for the Galizga River was lower at 114 μM. Phosphate concentration in the Kodor River water was distinctively high (1.35 μM), whereas the values for the other rivers were low (0.1–0.3 μM). Nitrate content in the Kelasur and Kodor river water was also dramatically different from that in the Mokva and Galizga rivers. The value for the former two rivers were at the level of 16 μM, whereas the value for the Galizga River was 31 μM and that for the Mokva River was 45 μM (Fig. 2). The pH of Kelasur and Kodor river water differed considerably (by ~0.15 units) from the water pH for the Mokva and Galizga rivers (Fig. 3a). They also differed with regard to total salinity that characterizes the content of carbonates. The alkalinity of Kelasur and Kodor River water does not exceed 1300 μmol/kg, whereas in the two other rivers it is at the 1700 μmol/kg level (Fig. 3a). As a result, the waters of the Kelasur and Kodor rivers differ from those of the Mokva and Galizga rivers with regard to the content of HCO_3^- and total inorganic carbon (Fig. 3b).

These substantial differences in the chemical composition of the rivers are related to the landscape and geochemical features of the catchment basin, as well as to the distinctive features of the water sources. The predominance of meteoric water or groundwater among the water sources of rivers during the leaching of rocks affects the pH and alkalinity of surface waters. The intensity of the leaching regimen in different regions of the karst massifs of the low and moderately high mountains of the Abkhazian coast of the Western Caucasus also plays an important role [7]. Water flow through the soils and rocks of the catchment areas of the Kelasur and Kodor rivers is apparently less intensive than the flow through the catchment areas of the Mokva and Galizga rivers, and this leads to differences in the composition, total alkalinity, and pH. Agricultural activities in different regions of Abkhazia can cause variation in the content of nutrients in the water

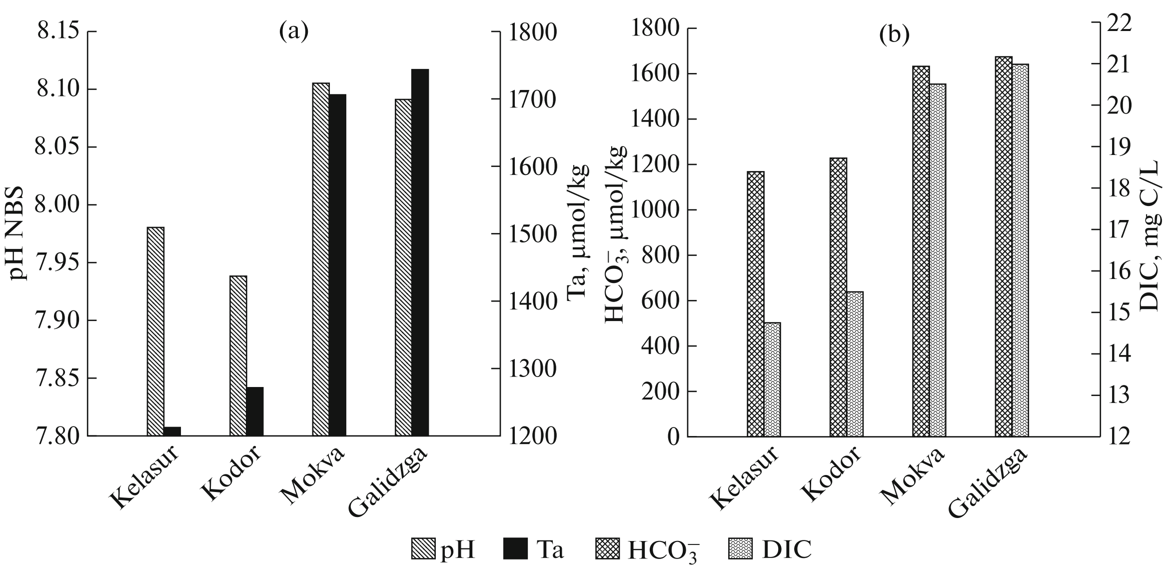

Fig. 3. (a) pH and total alkalinity (Ta), (b) content of carbonate ions (HCO_3) and dissolved inorganic carbon (DIC) in water of estuaries of Kelasur, Kodor, Mokva, and Galizga rivers.

of the rivers studied [24]. The impact of agricultural activities can be quite distinct. The washout of mineral fertilizers from fields in the basins of the rivers Razdolnaya and Tumannaya in the Far East of Russia caused a significant increase of nitrate nitrogen concentration in the river water (43 μM in the spring season), as shown in [18].

Distribution of Chemical Parameters in the Kodor River Plume

Water sampling from the surface layer of the Kodor River plume was performed on April 2, 2019 in order to study the mixing of Kodor River water with seawater and the distinctive features of the distribution of nutrients that affect water productivity and phytoplankton community composition in the coastal zone (Fig. 1). The variability of the carbonate system parameters was also studied in the estuarine area, because carbonate levels in river and sea water are fundamentally different. The water area studied spanned the area along the coast, 4 km to the northwest from one of the branches of the delta and 2 km towards the sea. The temperature in the surface layer ranged from 9°C at the mouth of Kodor River to 10.2°C in the central part of the plume and then dropped to 9.8°C in its seaward part (Fig. 4a). The salinity varied from 122 mg/kg (mouth of the Kodor River) to 18 PSU in the part of the sea free from river water. The pH distribution was as follows (Fig. 4b): 7.94 NBS units in the mouth of the Kodor River and the maximum (8.55) at the station 2–13 in the seaward part. This parameter varied from 8.35 to 8.49 NBS units in the plume; these changes are most likely associated with phytoplankton development in the surface layer. Alkalinity is in a direct correlation with salinity (Fig. 4b): it ranges from 1273 μmol/kg in river water to 3179 μmol/kg in sea water. The frontal section with a sharp gradient of increasing alkalinity (as well as salinity) runs between stations 2–3 and 2–8. The first frontal zone of the Kodor River plume, where massive precipitation of suspended matter should occur along with other geochemical and biological processes characteristic of river mouth areas [8], can be localized in exactly this area.

Inorganic phosphorus content in the surface layer ranged from undetectable to 1.35 μM (Fig. 4c). Phosphate content was maximal in the Kodor River water and close to zero in the plume, with a local maximum (1 μM) registered at the outer boundary of the plume investigated, at station 2–13. A local peak in phosphate content was observed at station 2–4, beyond the plume boundary detected in salinity and alkalinity studies, but this peak was very small (0.1 μM); it was also observed at station 2–9. In general, such a distribution demonstrates the involvement of phosphates in the active process of photosynthesis both in the plume and in the seaward part of the section. Kodor River runoff is a source of phosphates in the coastal area of the sea, and the rapid (as compared to nitrates and silicon) decrease in phosphate levels shows that phosphate availability is the limiting factor for the development of phytoplankton communities in this case.

Silicate content in the surface layer ranges from 130 μM in the river water to 8 μM in the seaward part at the last station of the section (Fig. 4c). A frontal zone characterized by a sharp decrease in the content of silicates (twofold decrease from 60 to 30 μM) is observed between stations 2–3 and 2–8, similarly to the alkalinity pattern. The content of silicates drops to 20 μM after this zone and decreases to 8 μM towards the open sea.

Nitrate nitrogen is one of the main nutrients used by phytoplankton communities. Nitrate levels in the plume ranged from 16 μM in the Kodor River water to 0.57 μM at station 2–12 with the highest salinity (Fig. 4d). The boundary of the river plume is also clearly apparent from nitrate levels: a sharp gradient is observed between stations 2–3 and 2–8 (nitrate content decreases from 10 to 4 μM). The content of nitrates is quite high both in the plume and beyond its pronounced boundaries (station 2–11), and thus nitrate availability could not be a limiting factor in the development of the phytoplankton community.

The content of ammonium nitrogen reflects the degree of oxidation of organic matter, because ammonium nitrogen is the first in the series of decomposition of organic nitrogen compounds. It ranged from 0 to 0.6 μM in the water area investigated (Fig. 4d). The maximum was noted at station 2–8 located beyond the border of the frontal section. There are no other regularities in the distribution of ammonium nitrogen over the surface.

The carbon dioxide partial pressure in the surface layer ranged from 650 μatm in river water to 250 μatm in its seaward part at station 2–12 (Fig. 4e). The partial pressure of CO_2 is below the equilibrium value with the atmosphere (400 μatm), this being indicative of the ongoing process of organic matter production. The content of total dissolved inorganic carbon (DIC) in the Kodor River plume ranges from 26.6 to 36.5 mgC/L, and its minimal value was registered for river water (15.5 mgC/L). The results of chemical analyses and related calculations are shown in Table 1.

Surface sampling was carried out at seven stations in the same area on April 3. The total alkalinity and the content of nutrients (phosphates, silicates, and nitrate and nitrite nitrogen) were determined in the samples. A smooth increase of salinity from 12.8 to 16.0 PSU at the first five stations in the following sequence: 3–8, 3–11, 3–12, 3–9, and 3–10 is apparent from Fig. 5a. However, the course of changes of the chemical parameters was not very well correlated with salinity, in contrast to the data of the previous day. For example, silicate content, total alkalinity, and nitrate content at the station 3–8 was 99 μM, 1671 μmol/kg, and 16 μM, respectively. These characteristics of the surface water at station 8 are close to river water parame-

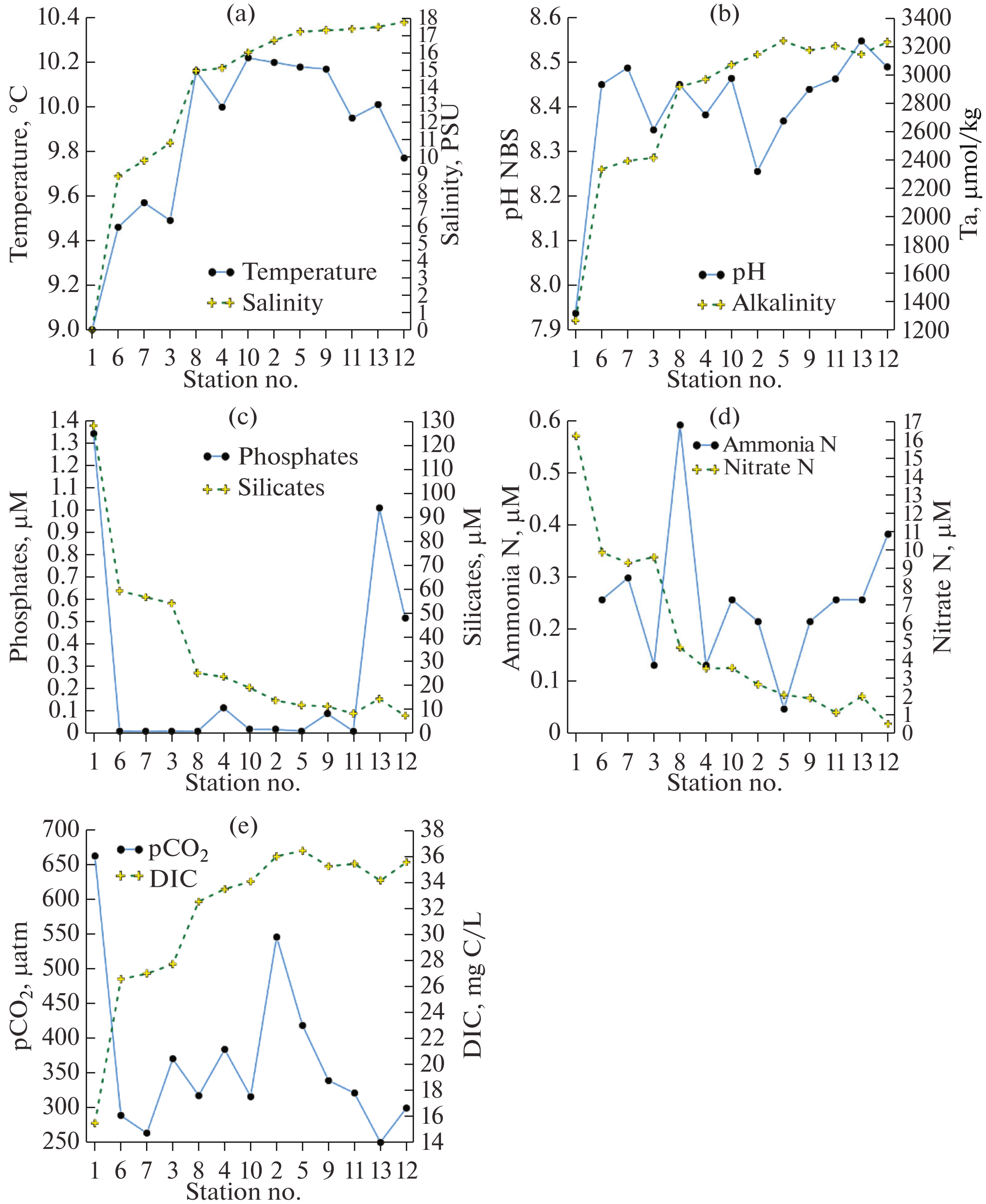

Fig. 4. Distribution of (a) temperature and salinity, (b) pH and total alkalinity Ta, (c) phosphates and silicates, (d) ammonium and nitrate nitrogen (N), and (e) partial pressure of CO_2 and inorganic carbon (DIC) at stations surveyed on April 2.

ters, notwithstanding a salinity level of 12.8 PSU. A decrease of salinity to 2384 μmol/kg at station 3–12 (relatively to the station 3–11) is evident, along with an increase in the content of silicates (60 μM) and nitrates (10.5 μM). Thus, changes that did not correlate with changes in salinity also occurred in this case. There are two putative reasons for this discrepancy. The first one is related to different depths of water sampling (with a bucket from the surface) and salinity measurements with a probe. The plume was approximately 3 m thick on April 2, as shown in Fig. 7, and therefore the difference in measurement depths was insignificant. These measurements were not performed on April 3, when the plume could have been thinner, so that the samples for salinity measurements were collected from the lower boundary of the plume and the apparent salinity was higher than the value inferred from the chemical parameters. Another reason may be related to the dynamics inside the plume and the existence of separate streams of fresh water, because the Kodor River has a delta-type mouth with several branches, which can serve as sources of water with slightly different characteristics. This was especially distinct when a drifter experiment was performed [11].

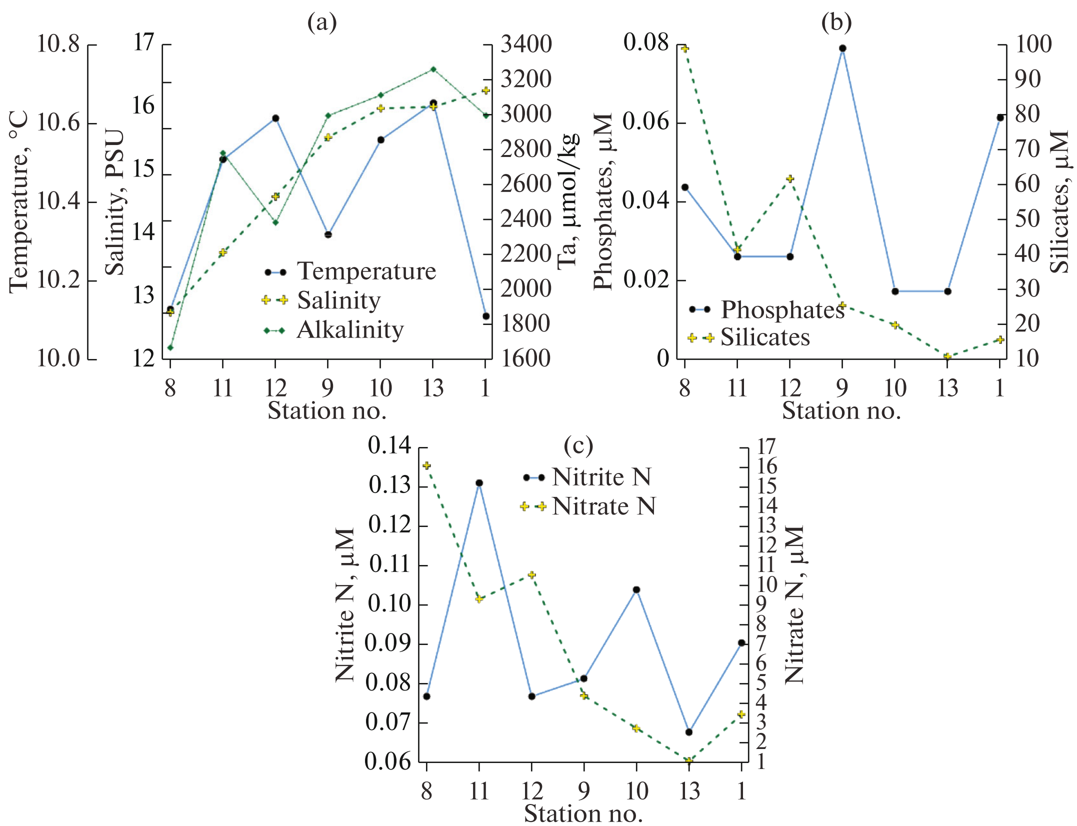

Fig. 5. Distribution of (a) temperature, salinity and total alkalinity (Ta), (b) phosphates and silicates, and (c) nitrite and nitrate nitrogen (N) at stations surveyed on April 3.

Table 1. Hydrochemical parameters of samples collected during sea voyages on April 2 and 3, 2019

Station	Lat., °N	Long., °E	*T*, °C	S, PSU	pH, NBS	Ta, μmol/kg	PO_4, μM	Si, μM	NH_4, μM	NO_2, μM	NO_3, μM	DIC, mgC/L	HCO_3, μM	CO_3, μM	CO_2, μM	pCO_2, μatm
2–2	42.814	41.132	10.20	16.730	8.26	3150.1	0.02	14.05	0.28	0.11	2.73	36.1	2838.7	140.8	26.4	546
2–3	42.813	41.134	9.49	10.800	8.35	2421.4	0.00	54.46	0.21	0.09	9.67	27.8	2189.1	105.6	18.9	370
2–4	42.812	41.133	10.00	15.130	8.38	2973.4	0.11	23.85	0.21	0.08	3.58	33.6	2614.1	162.81	18.8	384
2–5	42.819	41.127	10.18	17.220	8.37	3245.8	0.00	12.05	0.14	0.09	2.16	36.5	2836.8	185.2	20.2	419
2–6	42.811	41.135	9.46	8.890	8.45	2340.5	0.00	59.66	0.31	0.09	9.92	26.6	2084.0	117.8	14.9	288
2–7	42.812	41.136	9.57	9.790	8.49	2399.4	0.01	57.21	0.35	0.09	9.35	27.0	2104.4	134.9	13.5	263
2–8	42.812	41.117	10.16	14.980	8.45	2921.9	0.01	25.46	0.59	0.10	4.74	32.6	2517.1	183.4	15.5	317
2–9	42.826	41.119	10.17	17.310	8.44	3179.5	0.09	11.55	0.28	0.11	1.97	35.3	2715.6	209.8	16.3	339
2–10	42.829	41.090	10.22	16.020	8.46	3076.5	0.02	19.35	0.31	0.08	3.62	34.1	2623.9	205.1	15.3	316
2–11	42.844	41.103	9.95	17.370	8.46	3209.0	0.00	8.55	0.31	0.10	1.20	35.5	2721.5	220.7	15.6	321
2–12	42.850	41.098	9.77	17.780	8.49	3238.4	0.52	7.60	0.42	0.09	0.57	35.6	2716.9	235.7	14.6	299
2–13	42.850	41.096	10.01	17.510	8.55	3150.1	1.01	14.70	0.31	0.08	2.07	34.2	2581.7	256.3	12.1	250
3–1	42.795	41.149	10.11	16.296		2995.5	0.06	16.20		0.09	3.50					
3–8	42.812	41.135	10.65	12.779		1670.7	0.04	99.12		0.08	16.13					
3–9	42.810	41.138	10.32	15.554		2995.5	0.08	25.96		0.08	4.43					
3–10	42.816	41.130	10.56	16.013		3113.3	0.02	20.40		0.10	2.79					
3–11	42.805	41.141	10.51	13.727		2782.1	0.03	41.81		0.13	9.33					
3–12	42.804	41.141	10.62	14.610		2384.6	0.03	62.06		0.08	10.59					
3–13	42.795	41.147	10.13	16.035		3260.5	0.02	11.35		0.07	1.13					

Table 2. Hydrochemical characteristics of Mzymta River compared to those of Abkhazian rivers (samples were collected in river estuaries)

River	S, km^2	V, km^3/year	pH, NBS	Ta, μmol/kg	PO_4, μM	Si, μM	NH_4, μM	NO_2, μM	NO_3, μM	DIC, mgC/L	pCO_2, μatm
*Mzymta**	*885*	*1.56*	*8.4–8.7*	*1013–1141*	*0.39–0.78*	*92*	*2.9*	*0.22–0.25*	*12–22*		
Kelasuri	220	0.42	7.98	1214	0.28	129		0.07	16.33	14.7	572
Kodor	2030	4.2	7.94	1273	1.35	128		0.09	16.26	15.5	663
Galidzga	483	0.93	8.09	1744	0.13	114	1.99	0.15	30.68	21	632
Mokva	336	0.57	8.11	1707	0.11	132	0.70	0.13	44.58	20.5	598

S—catchment area, V—annual runoff volume (from Dzhaoshvili, 2002). *—data from expeditions of Institute of Oceanology, RAS, collected in May 2012–2014 (Zavialov et al., 2014).

The concentration of phosphates in the plume was low, 0.02 to 0.08 μM (Fig. 5b), similarly to the values recorded on April 2; this means that phosphates are almost completely consumed by phytoplankton. The N : P ratio was 12 in river water, and 2 and 1 at the most seaward stations 3–13 and 3–12, respectively. In general, the Redfield ratio revealed a strong predominance of nitrates at stations located within the plume. Thus, phosphate content, in contrast to nitrate content, is the limiting factor for phytoplankton activity and organic matter production. The content of nitrites in the plume (Fig. 5b) is also very low, from 0.08 to 0.13 μM, which is indicative of low involvement of mineral nitrogen in the oxidation of organic matter. The results of chemical analyses and related calculations are presented in Table 1.

4. DISCUSSION

Scientific research, including hydrology and oceanology studies, has been reduced to a minimum in Abkhazia in the last few decades; therefore, information on the chemistry of river waters in this region is very scarce. Therefore, we will use the data of the expeditions of the Institute of Oceanology RAS organized within the “Small rivers of the Black Sea” project [5, 21] to compare and explain the data on the differences of the chemical composition of the runoff of the rivers studied (Kelasur, Kodor, Galizga, and Mokva). Mzymta, the largest of the small rivers of the Black Sea coast of Russia, is clearly inferior to the Kodor River in terms of catchment basin area and the main hydrological characteristics, but superior to the Kelasur, Galizga, and Mokva rivers in this regard (Table 2). The difference in pH (higher for the Mzymta River) and total alkalinity (lower for the Mzymta River) are the most noteworthy differences between the hydrochemical characteristics of the rivers. The hydrochemical parameters of Abkhazian rivers are also different from those of the Mzymta River. The phosphate content in the Mzymta River water (0.4–0.8 μM) is higher than in all other rivers except for the Kodor River (1.35 μM), whereas the silicate content, in contrast, is the lowest (92 μM in Mzymta versus 114 μM and more in the Abkhazian rivers). The ammonium concentration in the waters of Mzymta is also higher, nitrite content is at the same level, and the nitrate level in the waters of Mzymta is comparable to that in Kodor and Kelasur rivers, whereas the nitrate levels in the Mokva and Galizga rivers are 2–2.5 times higher. Such differences can be explained by the seasonality of the regimens of these rivers. Observations on the Mzymta River were performed annually in the second half of May, immediately after the peak of the flood. However, the flood had not yet passed for Abkhazian rivers at the beginning of April, and their condition and composition of waters was closer to the winter low-water period. Therefore, the chemical composition of Abkhazian rivers after the flood would most likely have become similar to that of the Mzymta River. The difference in the carbonate parameters of Kelasur and Kodor rivers, on the one hand (pH 7.98 and 7.94, Ta 1214 and 1273 μmol/kg, respectively), and Galizga and Mokva rivers, on the other hand (pH 8.09 and 8.11, Ta 1744 and 1707 μmol/kg, respectively), is also apparent. A similar difference was observed for the Kudepsta and Mzymta rivers, for example, in 2014 (pH 8.26 and 8.62, Ta 3216 and 1013 μmol/kg, respectively) and in the other years. Notwithstanding the proximity of river catchment basins, both pH and total alkalinity values were also different. This is due to the higher carbonate content in the rocks of the Kudepsta River basin [5]. As shown in [7], the differences in the hydrochemical composition of Abkhazia mountain streams can arise due to different degrees of leaching intensity of the same calcium carbonate rocks and due to different inflow types. Apparently, this is the reason for the differences in the parameters of the carbonate system for the waters of the studied Abkhazian rivers.

The estuarine parts of rivers and marine estuarine areas are among the most challenging research objects in terms of geography due to the highly pronounced spatial variability [21, 29]. This is especially pronounced for large rivers [4, 10, 15]. However, small rivers, such as those on the Black Sea coast, are capable of generating plumes, in which complex dynamic processes occur [25] along with the active redistribu-

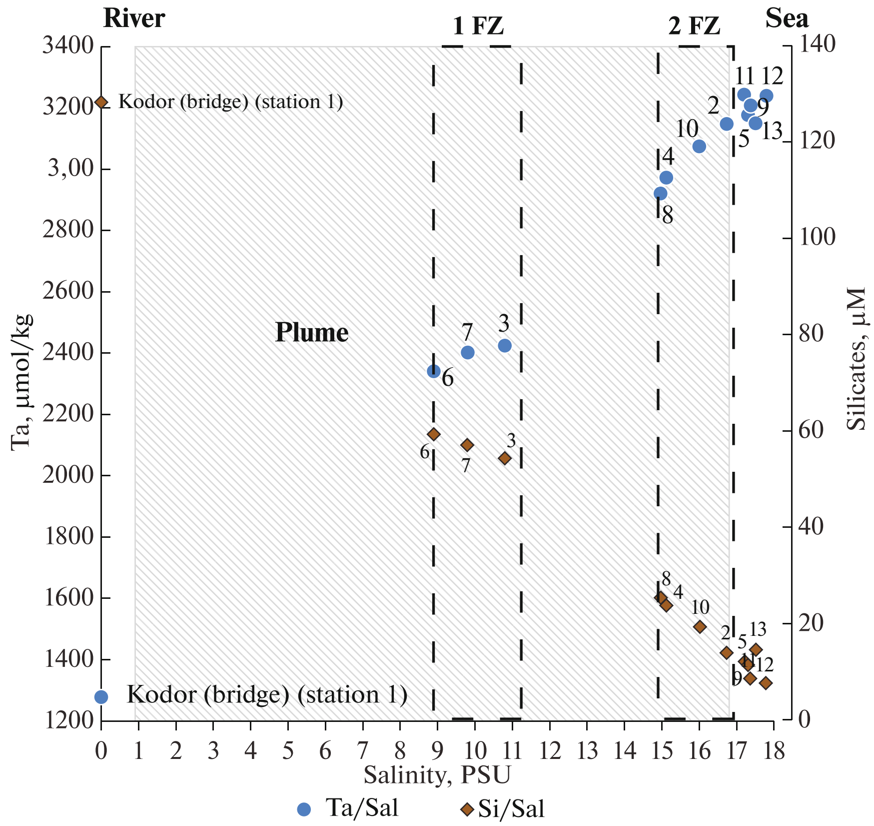

Fig. 6. Identification of frontal zones (FZ) in Kodor River plume according to alkalinity (Ta)—salinity and silicon (Si)—salinity ratios.

tion of dissolved and suspended matter [3, 6, 9]. Thus, according to hydrochemical data obtained during operations on April 2, the characteristic patterns of alkalinity—salinity and silicon—salinity ratios demonstrate the presence of two frontal zones in the Kodor River plume (Fig. 6). These ratios are reliable markers in the separation of sea and river waters [13, 16]. As shown in the figure, the stations 2–8, 2–4, 2–10, and 2–2 located on the outer boundary of the plume, which is identified according to the salinity of 16–16.5 PSU, are also distinguished by total alkalinity values (2900–3150 µmol/kg) and silicon concentration (14–25 µM). Moreover, there is a pronounced frontal zone inside the plume. This is evident from the sharp salinity gradient (from 9.46 to 10.16 PSU) at stations 2–6, 2–7, 2–3, and 2–8. In addition, a characteristic pattern of alkalinity (increasing from 2340 to 2921 µmol/kg) and silicate levels (decreasing from 60 to 25 µM) is observed. The Kodor River water acts as the initial mixing point, and the final mixing point is pure seawater at stations 2–5, 2–9, 2–11, 2–13, and 2–12, which has a salinity above 17 psi, alkalinity of 3200 µmol/kg, and silicate concentrations of 7–14 µM. The presence of two distinct frontal zones is also confirmed by the vertical distribution of turbidity at the stations (Fig. 7). High turbidity values (4–5 NTU) at stations 2–6 and 2–7 are replaced by a turbidity of 2 NTU at station 2–3 in the upper one-meter water layer in the first frontal zone. The second frontal zone, located further from the mouth of the Kodor River, is characterized by turbidity values of 2–2.5 NTU in the upper one-meter layer, whereas the turbidity in the entire layer at the seaward station 2–12 is below 1.5 NTU.

Hydrophysical studies of the Kodor River plume showed that its considerable spatial heterogeneity arises due to several significant factors. First, the structural features of the Kodor River delta lead to the formation of water masses with slightly different thermohaline characteristics by the runoff from different branches. Secondly, the distinctive bathymetric features of the coastal zone create the conditions for certain dynamic effects that affect the velocities of currents in the plume. Third, hydrometeorological impact on the catchment basin (for example, short-term rain floods) leads to the formation of a complex system of fronts in the plume [11].

The presence of frontal zones inferred from the alkalinity—salinity and silicon—salinity ratios in the plume is confirmed by biological data. Analysis of the species diversity of active autotrophic planktonic microalgae showed that the number of species was

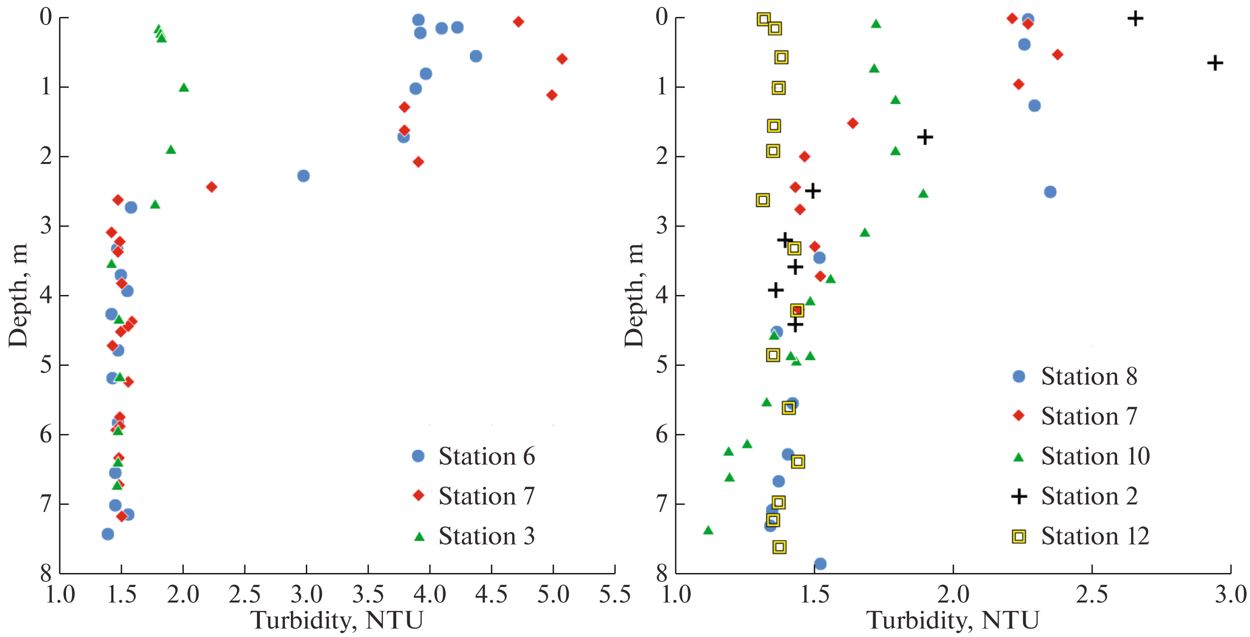

Fig. 7. Vertical distribution of turbidity at stations on April 2.

maximal at stations 2–3 and 2–5, just at the border of the zones identified by hydrochemistry studies. The maxima of phytoplankton abundance and biomass were also observed at stations 2–5 and 2–9, in the seaward part of the investigated water area, at the boundary with the second frontal zone. Optimal conditions for phytoplankton with regard to illumination, temperature, and nutritional base apparently form near these stations.

5. CONCLUSIONS

This article presents the results of studies on the hydrochemical composition of some Abkhazian rivers in their lower reaches, the Kodor River plume, and the coastal water area. Differences in the hydrochemical composition of the Kelasur, Kodor, Mokva, and Galizga rivers have been revealed. Differences in the parameters of the carbonate system are related to the source types and the intensity of rock leaching in the catchment basin of each of the studied rivers. The differences in the content of nutrients, the mineral forms of phosphorus and nitrogen (nitrates) in particular, are related to the anthropogenic load on the rivers. A plume is formed in the estuarine area of the Kodor River: in addition to being distinguished visually and by analysis of hydrophysical parameters [11], the plume boundary can be identified from the alkalinity–salinity and silicon–salinity ratios. The frontal zone is identified within the plume according to the same ratios; production–destruction processes and active precipitation of allochthonous suspension occur on the border of this zone.

The results of these studies appear very important in view of two facts. First, insufficient attention has been paid to the estuarine areas of small rivers, in contrast to those of large rivers, while the share of small river liquid and solid runoff is 25 and 45%, respectively, on a planetary scale [23]. Second, up-to-date hydrochemical data for the coast of Abkhazia and its estuarine areas are very scarce [19, 20]. In addition, sea and coastal expeditionary works in Abkhazia are most often performed in summer, while the present study addresses the state of rivers and coastal waters during early spring. Therefore, these studies can be applied in modeling and forecasting intra-annual chemical transformation processes and the development of coastal ecosystems in the Abkhazian sector of the Black Sea.

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