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MARINE CHEMISTRY

Features of Hydrophysical and Hydrochemical Conditions in Blagopoluchiya Bay (Novaya Zemlya Archipelago)

S. V. Stepanova* and A. A. Nedospasov

Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia

**e-mail: s.stepanova87@gmail.com*

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Abstract—The report presents the results of hydrophysical and hydrochemical studies in Blagopoluchiya Bay (Novaya Zemlya Archipelago) based on data of integrated expeditions of the Institute of Oceanology in the Kara Sea in 2007, 2013, and 2014. The main focus was the influence of the Ob and Yenisei rivers, as well as of the runoff of meltwaters from the coasts of the archipelago on the hydrochemical and hydrophysical structures of the bay waters. The features of water exchange between the bay and adjacent aquatic area are considered, along with the renewal mechanisms for deep waters in the bay (deeper than 100 m). The possible occurrence of stagnant effects in deep layers of the bay is evaluated.

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INTRODUCTION

The morphological peculiarity of many bays of the Novaya Zemlya Archipelago (Blagopoluchiya, Tsivol'ka, Stepovoi, etc.) consists in the presence of quite deep depressions at the centers of bays and elevations (sometimes of islands) at bay inlets. The peculiarities as such may cause the occurrence of stagnant effects and even hypoxia in the near-bottom layers of the bays, like what takes place in some Norwegian fjords under the inflow of denser saline seawaters [13]. Studies of possible occurrence of such processes are of special importance for the bays of the Novaya Zemlya Archipelago due to the presence of submerged radioactive objects, as well as of the potential accumulation of contaminants (including radionuclides). The latter can be supplied to bays with coastal runoff and aeolian transfer from land areas where nuclear tests were carried out in the 1950s–1980s [1]. This report presents the results of studies in Blagopoluchiya Bay where surveys of Novaya Zemlya Archipelago bays were started in 2007 during an expedition of the Institute of Oceanology in the Kara Sea, when the largest data set was obtained.

Blagopoluchiya Bay is a fjordlike aquatic area of the Kara Sea on the eastern coast of Severny Island of the Novaya Zemlya Archipelago [7]. A depression over 170 m maximum depth is located in the central part of the bay. The bay is partially separated from the Kara Sea with Kamni Island at the inlet of the bay. According to available bathymetric maps, the maximum depth of the western channel no more than 37 m; the eastern channel is as deep as 57 m. Based on the features of the bottom relief, the potential occurrence of hypoxia in deep layers of Blagopoluchiya Bay was assumed. The characterization of conditions became one of the main objectives of these studies, along with analysis of the hydrological and hydrochemical structures of bay waters during in summer–autumn.

MATERIALS AND METHODS

The surveys in Blagopoluchiya Bay were carried out in mid-September 2007 (cruise 54 of the R/V *Akademik Mstislav Keldysh*), in mid-September and October 2013 (cruises 125 and 126 of the R/V *Professor Shtokman*), and in late August 2014 (cruise 128 of the R/V *Professor Shtokman*). In total, 26 stations were set up in the bay and surroundings; the location scheme is shown in Fig. 1. In addition to the surveys at the stations, during debarkations, samples were collected from watercourses flowing into the bay [6].

Using survey data, we plotted the longitudinal and transverse sections of the bay to show the hydrological and hydrochemical structures of waters. The longitudinal profile crosses Ukromnaya Bight, the depression at the center of the bay, and the eastern (deepest) channel at Kamni Island. This section was based on data obtained in 2013 and 2014. The transverse section was oriented northwest to southeast, crossing Kamni Island and both of the channels. The data for this section for 2007 and 2013 (see above).

The study used data on temperature, salinity, total alkalinity and pH values, dissolved silicon, mineral and organic phosphorus, nitrate and ammonium nitrogen, and dissolved oxygen. The hydrochemical

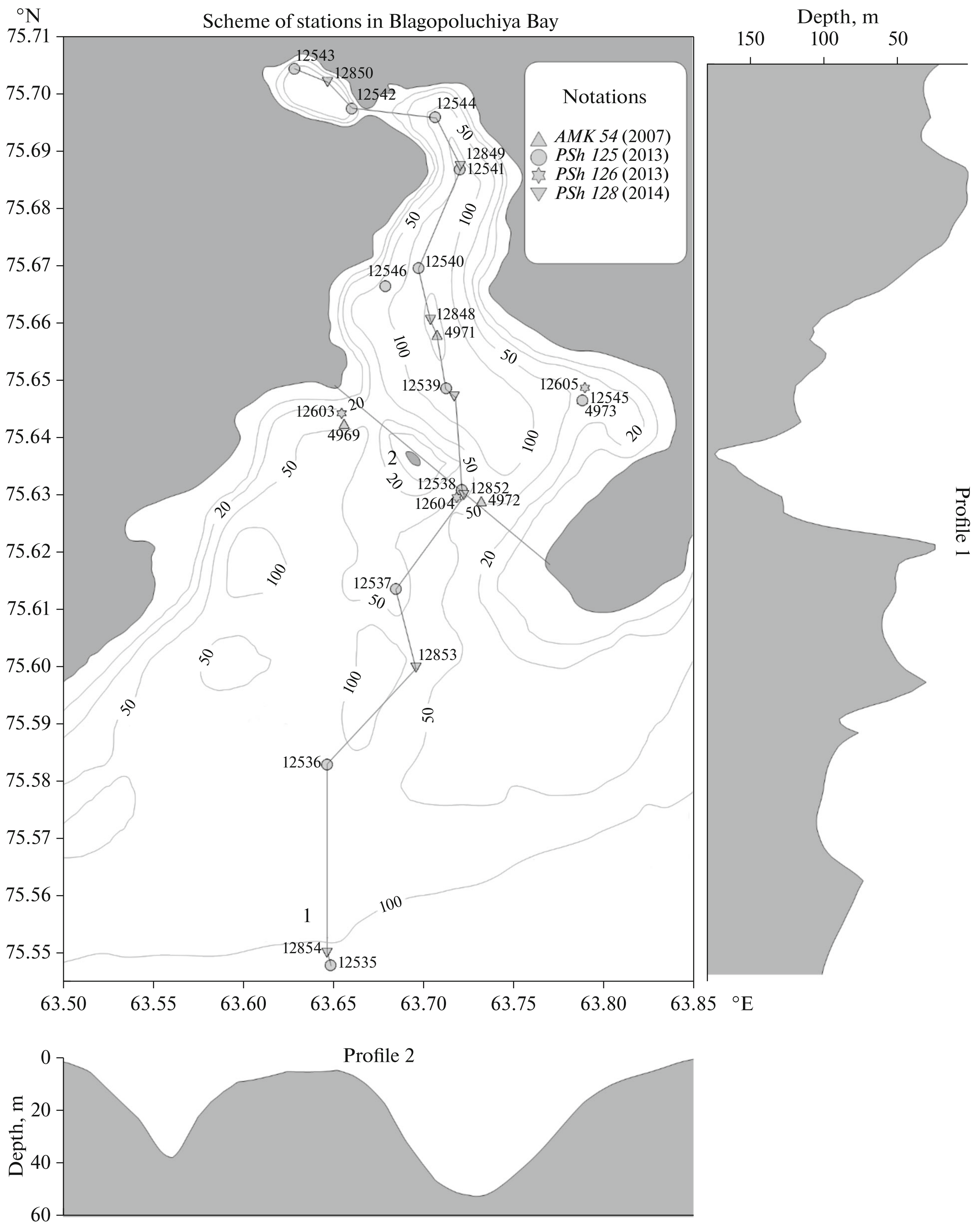

Fig. 1. Location scheme of stations over Blagopoluchiya Bay in 2007, 2013, and 2014.

parameters were determined in the on board laboratory using standard procedures [8, 11]. The temperature and salinity data were obtained by CTD probing. In 2007 and in October 2013, an SBE 19 plus CTD probe was used. In September 2013 and in 2014, a SBE 911 probe was mainly used.

The calculations related to the processes of water renewal are of special interest in view of environmental significance. Along with the temperature and salinity values, the oxygen content and pH value should be regarded as the key parameters in the studies. The study [12] presents an example of quite detailed calculations using long-term hydrophysical and hydrochemical data. However, only some of critical conditions—the possible occurrence of oxygen deficiency (hypoxia) in deep layers of the bay—could not be calculated in our study because of the deficient data set. The stoichiometric ratios between oxygen and carbon and between phosphorus and carbon are suitable for use in calculations. The main principles and algorithms of these ratios are well known and described in detail, e.g., in [10]. The data on total primary production (TPP) for 2013 and 2014 rendered by A.B. Demidov were used. The hydrochemical parameter values were converted for carbon to reduce all characteristics to identical units of measure.

RESULTS AND DISCUSSION

General hydrophysical and hydrochemical features of Blagopoluchiya Bay. An important feature of the hydrological structure of the Kara Sea is the presence of a surface desalinated layer (SDL) formed by riverine runoff mainly from the Ob and Yenisei rivers. The propagation of riverine waters depends primarily on the volume of runoff and wind conditions. It is conventional to distinguish three modes of riverine water propagation: western, eastern, and central. For the western type of propagation, desalinated waters can reach the eastern coasts of the Novaya Zemlya Archipelago. The central type of propagation is characterized by the supply of desalinated waters far northwards. For the eastern type of propagation, the riverine waters are kept close against the coast and transferred as a boundary current to the Severnaya Zemlya Archipelago and farther to the Laptev Sea [4, 9].

The western mode of the propagation of riverine waters was seen in 2007 when the desalinated waters reached the coasts of the Novaya Zemlya Archipelago. The thickness of the surface desalinated layer (16–17 psu) amounted to 12 m at the station located above the Novozemel'skaya Depression. Deeper (to 15 m), there was a thin pycno-halocline of the salinity that increased up to 32 psu [4]. A similar hydrochemical structure was also found at the inlet to Blagopoluchiya Bay. However, the pycno-halocline was located at a shallower depth of 6 m. Moreover, the eastern channel (station 4972) was characterized by a very desalinated surface layer with 11 psu salinity at a depth of 0.5 m, whereas the vertical salinity distribution in the western channel showed a smaller desalination of the surface layer (17 psu at a depth of 1 m; Fig. 2).

Thus, the complex hydrological structure of the waters at the inlet to the bay and beyond the bay allowed us to conclude that the SDL waters under the action of winds and background sea currents can not only reach the coasts of the Novaya Zemlya Archipelago but also the bay. The difference in the salinity distribution in the upper layer can testify to water desalination in the bay owing to the runoff of meltwaters and to the prevalent outflow of desalinated waters through the eastern channel.

The distribution of hydrochemical parameters in 2007 agreed well with the hypothesis of the influence of continental waters on those of the surface of the bay. In the latter (stations 4969, 4971–4973), the effect of continental runoff is well traced by the total alkalinity value (*Alk*) and silicon concentration. The *Alk* value varied within 1.55–1.70 mg-equiv/L, and the silicon concentration, within 34.5–36.5 μg-atom/L. These total alkalinity and silicon content values were characteristic of SDL waters at the same time [5]. No other waters with similar parameters were recorded.

No impact of the runoff of the Ob and Yenisei rivers nearby the Novaya Zemlya Archipelago was observed in 2013 and 2014, so the bay surface waters were desalinized owing to the runoff of meltwaters from the coasts.

The supply of snowfield meltwaters from the coasts to Blagopoluchiya Bay takes place during the summer time mainly in the corner part of the bay into which the largest watercourses flow, as well as in Ukromnaya Bight. However, small brooks are seen just along the whole perimeter of the bay. Our hydrochemical studies yielded much higher concentrations of various phosphorus and nitrogen forms in the bay waters, as well as of silicon, compared to those characteristic of the stations in the bay and at the outlet of the bay at the same time. The table presents the average values and variation ranges of nutrient concentrations, along with total alkalinity and pH values, for 2007, 2013, and 2014. The pH values in watercourses were usually over 8 NBS units, whereas meltwaters had lower values (about 7.0–7.5 NBS units). We should also note the wide spread in total alkalinity values varying from one watercourse to another within the range from 1 mg-equiv/L (e.g., in the zones of mixing of Ob and Yenisei waters and seawaters) to 3 mg-equiv/L or more (higher than the value for Kara Sea surface waters for the same time of surveys). It was assumed that the behavior of nutrients and the parameters of a carbonate system might be caused by the leaching of the rocks constituting the bay coasts. The reliability of this hypothesis was confirmed in laboratory studies [6].

The intensity of water desalination in the bay varied in different years. In 2013, salinity values below 25 psu were recorded only in the surface layer (to a depth of 5 m) in Ukromnaya Bight (Fig. 3). The influence of riv-

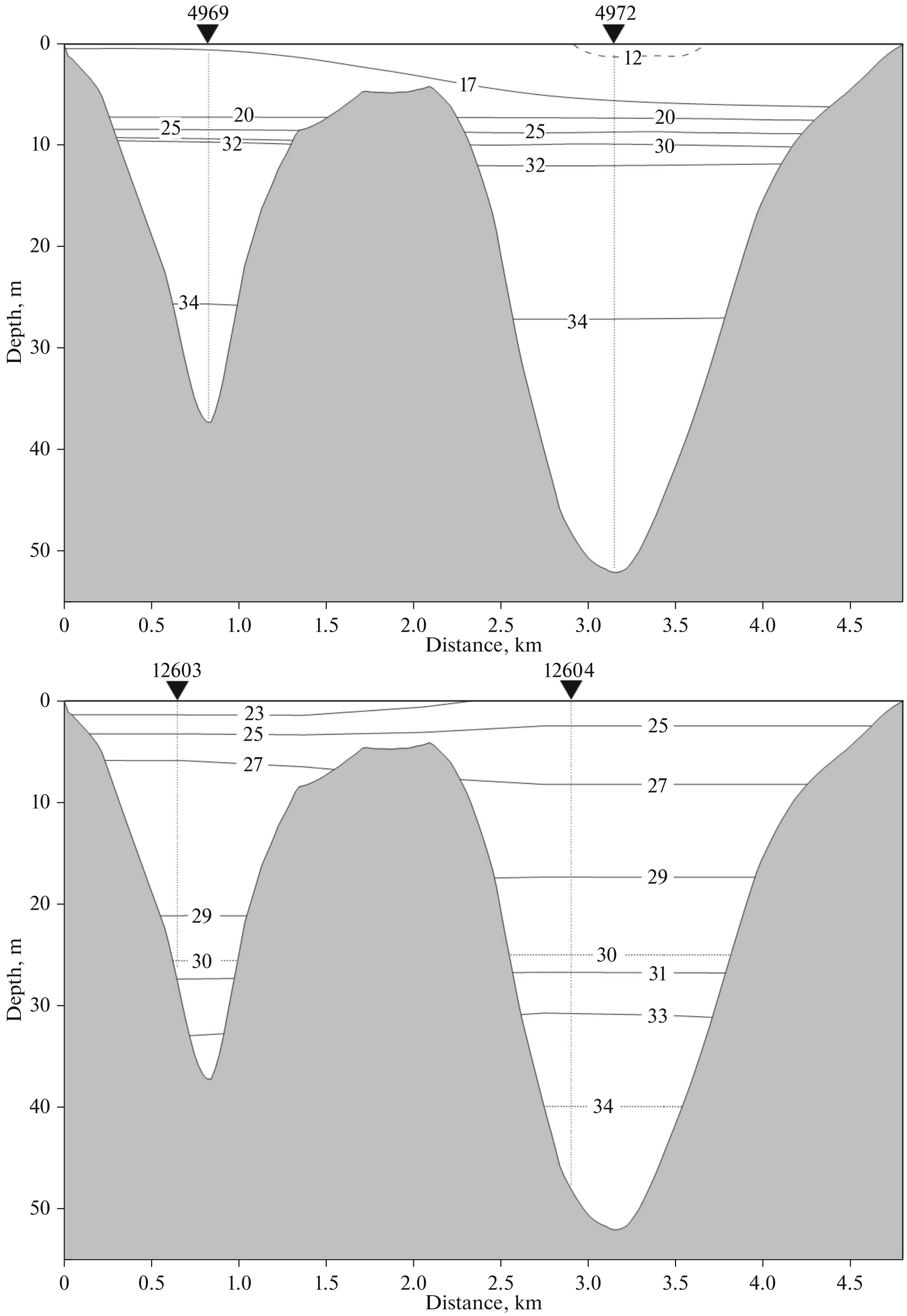

Fig. 2. Vertical water salinity distribution (psu) along transverse profile in September 2007 (top) and October 2013 (bottom).

Average values and variation ranges of hydrochemical parameters in 2007, 2013, and 2014

Years	Sampling sites	pH	*Alk*	NO_2	NO_3	NH_4	Si	PO_4
2007	1	**8.27** (7.84–8.54)	**2.09** (1.62–3.54)	**0.13** (0.00–0.49)	**5.42** (0.95–4.94)	–	**32.94** (22.24–50.17)	**0.36** (0.04–1.19)
	2	**8.11** (7.90–8.21)	**1.74** (1.58–2.46)	**0.09** (0.06–0.16)	**2.20** (1.09–4.91)	–	**33.45** (31.71–36.18)	**0.27** (0.15–0.40)
	3	**8.11** (8.09–8.13)	**1.64** (1.55–1.71)	**0.07** (0.06–0.08)	**3.06** (0.15–5.96)	–	**34.84** (33.01–36.48)	**0.24** (0.18–0.32)
2013	1	**8.21** (7.80–8.62)	**2.45** (0.74–4.47)	**0.00**	**3.72** (3.04–4.48)	**2.97** (1.28–5.34)	**29.06** (6.40–42.44)	**0.02** (0.00–0.04)
	3	**8.08** (8.03–8.12)	**2.10** (1.33–2.26)	**0.01** (0.00–0.02)	**0.58** (0.00–1.54)	**0.95** (0.39–1.62)	**1.69** (0.73–5.18)	**0.09** (0.03–0.20)
	4	**8.08** (8.06–8.09)	**2.23** (2.20–2.26)	**0.02** (0.00–0.04)	**0.17** (0.00–0.38)	**0.66** (0.17–1.24)	**0.68** (0.49–0.93)	**0.12** (0.08–0.18)
2014	1	**8.11** (7.98–8.20)	**1.86** (0.90–2.62)	**0.10** (0.00–0.28)	**5.25** (3.06–8.14)	**2.34** (1.54–3.26)	**14.44** (7.93–26.84)	**0.94** (0.50–1.53)
	2	**8.08** (7.94–8.21)	**1.64** (1.14–2.21)	**0.09** (0.00–0.15)	**1.89** (0.49–2.83)	**2.00** (1.58–2.40)	**4.95** (2.09–6.90)	**0.81** (0.50–1.18)
	3	**8.07** (7.96–8.11)	**2.03** (1.33–2.22)	**0.02** (0.00–0.05)	**0.65** (0.00–2.03)	**0.84** (0.33–1.38)	**2.32** (1.41–5.01)	**0.56** (0.35–1.03)
	4	**8.09** (8.07–8.10)	**2.25** (2.20–2.29)	**0.02** (0.00–0.04)	**0.61** (0.23–0.98)	**1.67** (1.48–1.86)	**1.83** (1.41–2.24)	**0.52** (0.47–0.56)

Sampling sites: 1—watercourses; 2—mixing zone; 3—surface waters of the bay; and 4—surface waters at the outlet of the bay. Average values are boldface and ranges are in parentheses.

erine runoff on salinity was slightly pronounced in the majority of the bay. More intense desalination was recorded in September 2014, and the desalinated layer (below 30 psu) was well traced up to station 12848 above the deepest point of the bay. The surface layer of Ukromnaya Bight showed values of 25 psu or less, since it was a year before.

In October 2013, hydrophysical studies were carried out in the western and eastern channels of Blagopoluchiya Bay. In addition to 2007, variations were seen in the salinity distribution within the surface layer. However, on the contrary, the eastern channel showed a somewhat lower salinity of surface waters than in the western channel (Fig. 2).

The influence of runoff of land waters from the Novaya Zemlya Archipelago is also reflected in the distribution of the hydrochemical parameters, especially of total alkalinity. Moreover, the vertical distribution of alkalinity shows a more intense impact of meltwaters on the aquatic area of the bay in 2014: a thin subsurface layer of total alkalinity values below 2.2 mg-equiv/L was recorded, which was well traced to station 12848. In 2013, the effect of land runoff from the Novaya Zemlya Archipelago was well pronounced in surface waters of Ukromnaya Bight and in the northernmost part of the major aquatic area of the bay (up to station 12544). In general, the total alkalinity value varied slightly over the entire bay: the range of the variations amounted to 2.2–2.4 mg-equiv/L. The vertical distribution of silicon content, which is also good tracer of riverine water, was similar in 2013 and 2014. We should mention that the upper 50-m layer was markedly depleted in silicon (below 5 μg-atom/L) despite a quite high silicon concentration in watercourses flowing into the bay. In general, the silicon content in surface waters of the bay was a little higher than in the coastal zone (table).

Thus, the effect of meltwater runoff from the coasts of the Novaya Zemlya Archipelago in the aquatic area of the bay manifests itself in the formation of a thin subsurface layer (about 5 m) with a thickness and extent that varies from year to year. This layer is sufficiently well traced by the salinity and total alkalinity value. The nutrient concentrations in this layer in the absence of the influence of SDL waters are close to those recorded in surface waters of the Kara Sea at the same time [5]. The effect of meltwater runoff is more pronounced in Ukromnaya Bight and, reasonably, along the bay coasts. Somewhat increased nutrient concentrations and lower values of salinity and total alkalinity are seen here.

In keeping with the aims of the study, the vertical distribution of relative oxygen content in the bay waters was of special interest. The summer season was characterized by oxygen supersaturation in bay surface waters (up to 110% in 2014), which pointed to biological activity of the waters during the survey time. The near-bot-

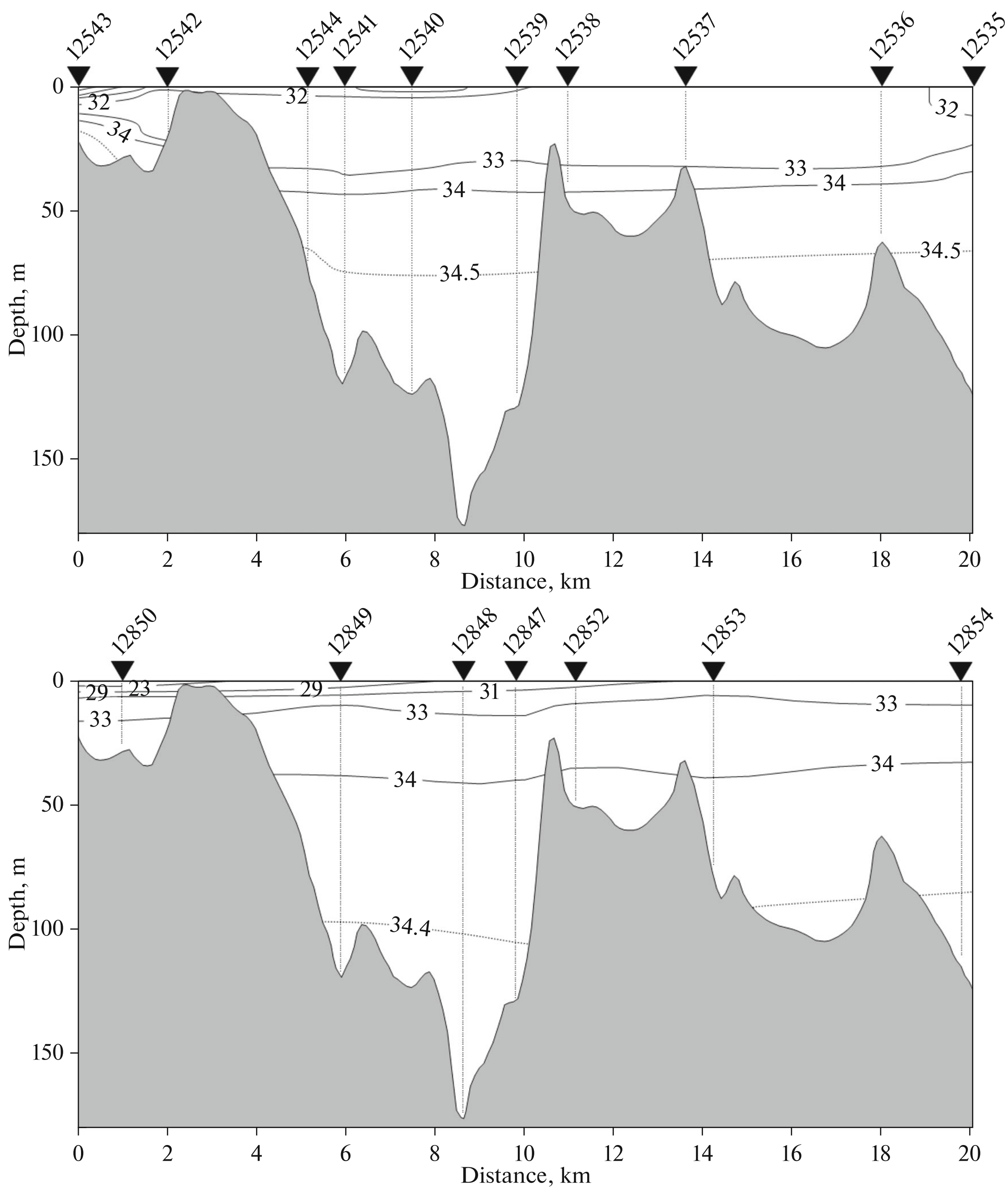

Fig. 3. Vertical water salinity distribution (psu) along longitudinal profile in September 2007 (top) and October 2013 (bottom). See Fig. 2 for notation.

tom waters were less saturated in oxygen, and yet a decrease in the degree f saturation appeared not as significant as assumed from the topographical features of the bay. The minimum recorded degree of oxygen saturation was 75% in the deep waters of the bay in 2014 (Fig. 4).

Water exchange processes. Analysis of available data for 2013 and 2014 allows some conclusions on water exchange processes both within the bay and between the its aquatic area and the open sea.

Let us first consider in more detail the features of the vertical distribution of hydrophysical parameters, comparing the conditions within the bay and going toward it.

The hydrological structure of coastal waters was characterized by the occurrence of a quite warm (over 4°C) upper quasi-uniform layer (UQL) about 10 m in thickness. A layer of gradual variation in the hydrochemical parameters down to 40 m was observed. The salinity increased from 32 psu at the lower boundary of

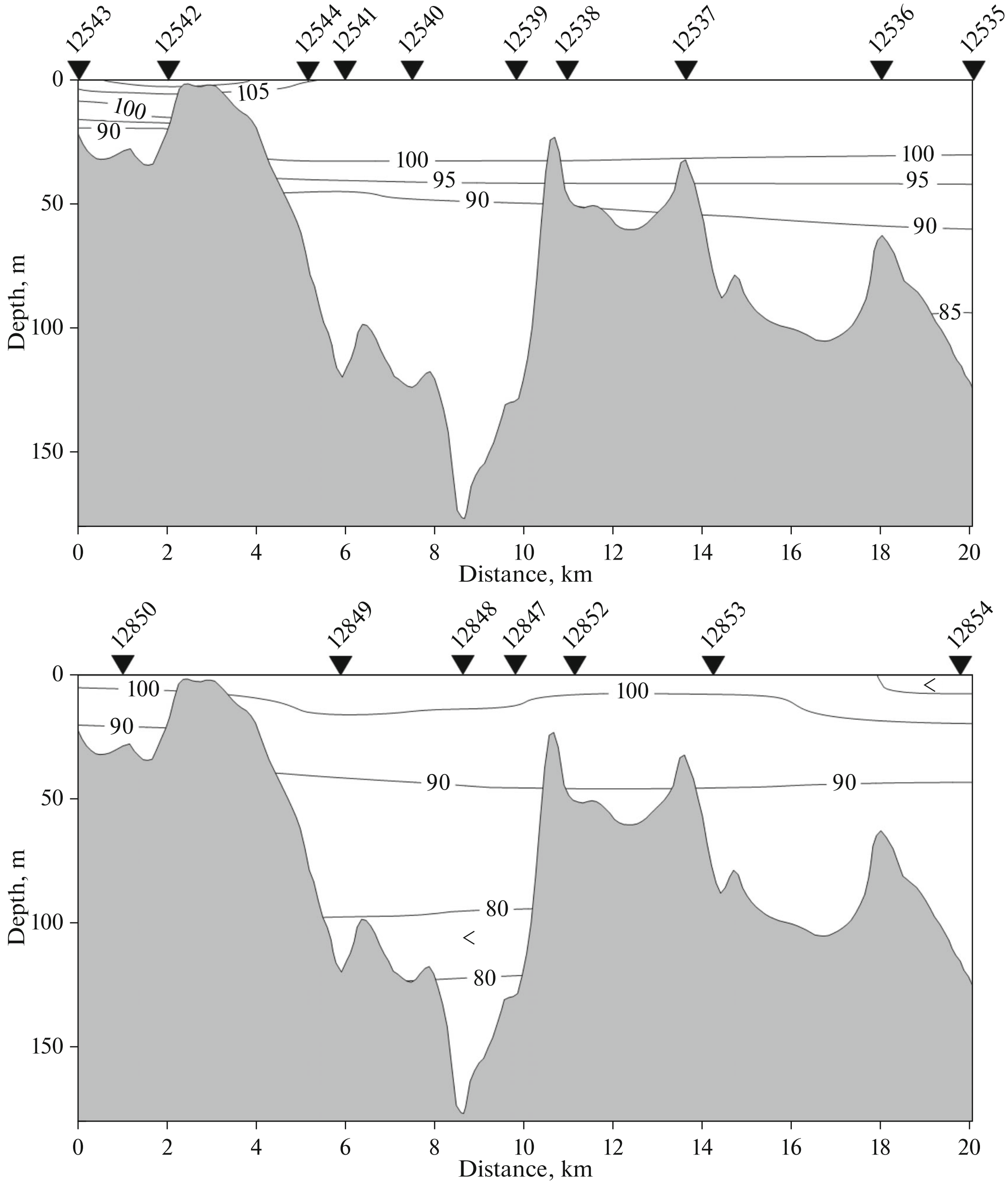

Fig. 4. Vertical dissolved oxygen distribution (%) along longitudinal profile in September 2007 (top) and October 2013 (bottom). See Fig. 2 for notation.

the UQL to 34.1 psu. The temperature at a depth of 40 m was –0.5°C. A cold intermediate layer (–1.18°C at a depth of 68 m) that formed during the winter convective mixing of waters was located deeper. Below this layer, the salinity gradually increased with depth up to 34.65 psu in the near-bottom layer at a depth of 120 m. The increase in salinity is accompanied by a smooth temperature increase up to –0.9°C (Fig. 5).

The hydrological structure of waters within the bay is transformed under local factors. Differences are first manifested in the upper 50-m layer. Unlike the coastal area, we can distinguish here the upper 5-m layer desalinated by meltwaters (about 31 psu). Below, a quasi-uniform layer is seen down to 40 m. The lower boundary of this layer is that of a jump in the hydrophysical parameters at a depth of 40–45 m, which was also not recorded in the coastal area. In turn, the salinity here is over 34 psu. Below, at depths to 68 m, waters within and beyond the bay did not differ in the values of hydrophysical parameters. However, unlike the coastal zone, the increase in salinity in the bay with depth from 70 m to the bottom was accompanied by a gradual

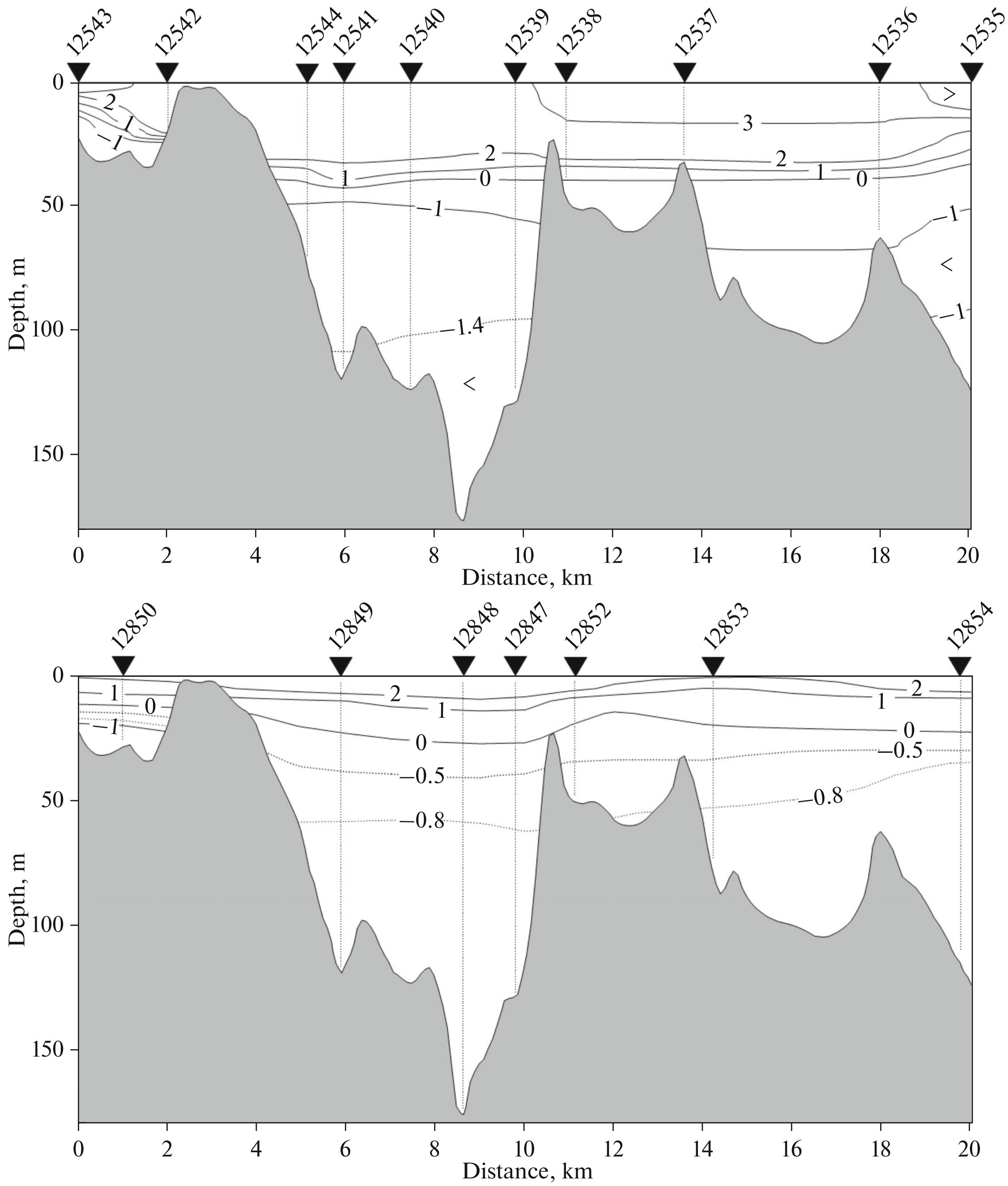

Fig. 5. Vertical water temperature distribution (°C) along longitudinal profile in September 2013 (top) and August 2014 (bottom).

decrease in temperature (lower than −1.4°C below 100 m).

The occurrence of a layer of identical hydrophysical parameters at a depth of 68 m or less, below which the water structure is quite different within and beyond the bay, shows that the exchange between the waters of the bay and the coastal zone can proceed at these depths as well. This means that the bay channels can be deeper than it was thought from cartographic data and field surveys (as deep as 70 m). One must note that, despite the higher temperatures, the density of deep waters in the coastal zone is higher than that of the cooler bay waters at equal depths. The difference is as high as 0.13 kg/m^3 at the depth of 120 m.

Vertical distribution of the parameters in the coastal zone in 2014 was a little different from that in the bay. The water hydrological structure in Blagopoluchiya Bay in 2014 was characterized by the presence of a thicker desalinated subsurface layer (about 29 psu) at the depths shallower than 15 m compared to 2013.

Deeper that 50 m, the salinity distribution was quite the same as in the preceding year and increased to 34.43 psu in the near-bottom layers. Temperature differences here are quite significant both in near-surface and deep layers (Fig. 5). Summer warming is weakly expression and was observed only in the upper 10–15 m. The key structural feature consisted in the absence of a gradient layer at depths of about 40–45 m. The increase in salinity was accompanied by a gradual decrease in temperature down to −0.9°C in the near-bottom layers.

Thus, one can speak about a considerable transformation of the hydrological structure in Blagopoluchiya Bay that proceeded from September 2013 until August 2014. Analysis of the data points to quite free horizontal mixing of the bay and coastal waters at depths to 60–70 m. However, more pronounced water stratification in the bay can probably form some barriers to water exchange with the open sea. Despite the presence of sills, water renewal in deep layers of the bay is possible, and by various mechanisms. Thus, the situation in 2013 could have resulted from the intense winter convection of waters. The considerable increase in temperature in the deep waters of the bay recorded in 2014 could likely have been caused by advective transfer of waters into the deep basin of the bay from the coastal zone. This is possible under the deepwater rise in the coastal zone by the upwelling, which could have occurred at the eastern coasts of the Novaya Zemlya Archipelago [3]. It is probable in this case that water exchange in the near-bottom layers took place even in 2013 before intense vertical mixing processes. This assumption does not contradict the observed distribution of hydrophysical parameters. First, waters with similar characteristics (of Barents Sea origin according to available field data) were found in deep layers of the coastal zone in both cases [3]. Second, as mentioned above, the deep waters of the coastal zone in 2013 had a higher density than the cool bay waters despite the higher temperature. Moreover, this assumption also well explains the distribution of hydrochemical parameters in the deep waters of the bay. Thus, the lower oxygen saturation and pH values may actually have resulted from the fact that the deep layers of the bay contained waters supplied from the coastal zone during upwelling and were not affected by vertical winter convection.

Calculation of the potential occurrence of hypoxia conditions. As mentioned above, this calculation was one of the main objectives of this study. The described features of the geophysical structure showed that winter convection in the bay can reach the bottom, if not every year. Thus, the occurrence of critical conditions is most probable in the summer period of stable density stratification with a sufficient amount of auto- and allochthonous organic matter.

To characterize the potential hypoxia occurrence in Blagopoluchiya Bay, we calculated the volume of waters located deeper that 100 m (0.108 km^3), the area of the bay (37.2 km^2), and the annual flow (0.1 km^3). To evaluate the annual flow into Blagopoluchiya Bay, the area of the catchment basin was calculated: about 500 km^2; annual precipitation data were also used, with allowance for 200 mm of evaporation [7]. The extension of glacial and snow covers over the drainage basin was taken to be stable.

First, the concentration of organic matter in the bay at depths over 100 m was estimated, as well as the amount of organic matter required for the occurrence of hypoxia. The concentration of organic matter was estimated using available data on the content of organic phosphorus at these depths, which were converted into estimates for organic carbon by means of coefficients in the stoichiometric equation. The concentration of organic phosphorus at the considered depths varied slightly from year to year: 0.5 μg-atom/L, which was 0.6 mg C/L; i.e., the deep layers of the bay contained a total of 65 t of carbon. The increase in the concentration of organic matter in the deep waters of the bay required for hypoxia formation can be estimated by the oxygen content. That of 2 mL/L was taken as the indicator for oxygen deficiency, because it is commonly considered as the lower bound of the oxygenic optimum for the zoobenthos [2]. Using the difference between the actually determined oxygen content and the above value, it was found that the occurrence of hypoxia in the bay at depths over 100 m requires an increase in the content of labile organic matter by 2.15 mg C/L, i.e., by 230 t of carbon.

Later, we calculated the amounts of auto- and allochthonous organic matter which would be supplied to the bay. To estimate the amount of allochthonous matter, we used the data on the content of organic phosphorus in watercourses flowing into the bay. These values were converted to the estimate for the concentration of organic carbon using the stoichiometric equation. According to this estimate, the average concentration of organic matter in waters flowing into the bay was 0.28 mg C/L. In view of the volume of runoff, the watercourses can supply about 28 t of carbon to the bay.

To characterize autochthonous organic matter, data on the integrated primary production (IPP) for September 2013 and August 2014 were used. The primary production is quite difficult to calculate, so, it is difficult to consider the annual variations in the IPP values, as well as parameters characteristic of a particular season, in view of the availability of data on the treated aquatic area only for one season. To estimate with certainty the orders of magnitude without errors, the average IPP values (38 and 97 mg C/m^2 in September 2013 and August 2014, respectively) were taken and extrapolated to the corresponding months (August and September). According to the results of these calculations, about 150 t of carbon can be produced over the entire area of the bay.

Thus, the deep layers of the bay (deeper than 100 m) contain about 65 t of carbon. To form hypoxia conditions at these depths, the organic matter content should increase by 230 t of carbon. As well, 28 t of carbon can be supplied to the bay with meltwater runoff and about 150 t of carbon are produced in the bay waters. As seen from the results, the amount of allo- and autochthonous organic matter supplied to the bay is lower that the values sufficient for the occurrence of hypoxia conditions at depths over 100 m. Moreover, the amount of additional organic matter required is about three times as high as the calculated content in deep-water layers. In view of the relatively small variability of the hydrochemical parameters within these layers, the occurrence of stratification, and the quite free exchange between the bay and coastal waters, it is improbable that conditions leading to a drastic increase in organic matter content in near-bottom layers will appear.

CONCLUSIONS

Thus, despite the relative shallowness of channels, water exchange with the open sea is unhindered in the upper layers and the channels near Kamni Island are probably somewhat deeper compared to the cartographic data. Moreover, renewal of deep waters in the bay is possible and various mechanisms of this process are probable. Thus, in addition to convective mixing, renewal of deep waters in Blagopoluchiya Bay can be a result of a rise in denser waters in the coastal zone via upwelling. Stoichiometric calculations using available data have shown the impossibility of hypoxia in deep-water layers of the bay, at least under current conditions.

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